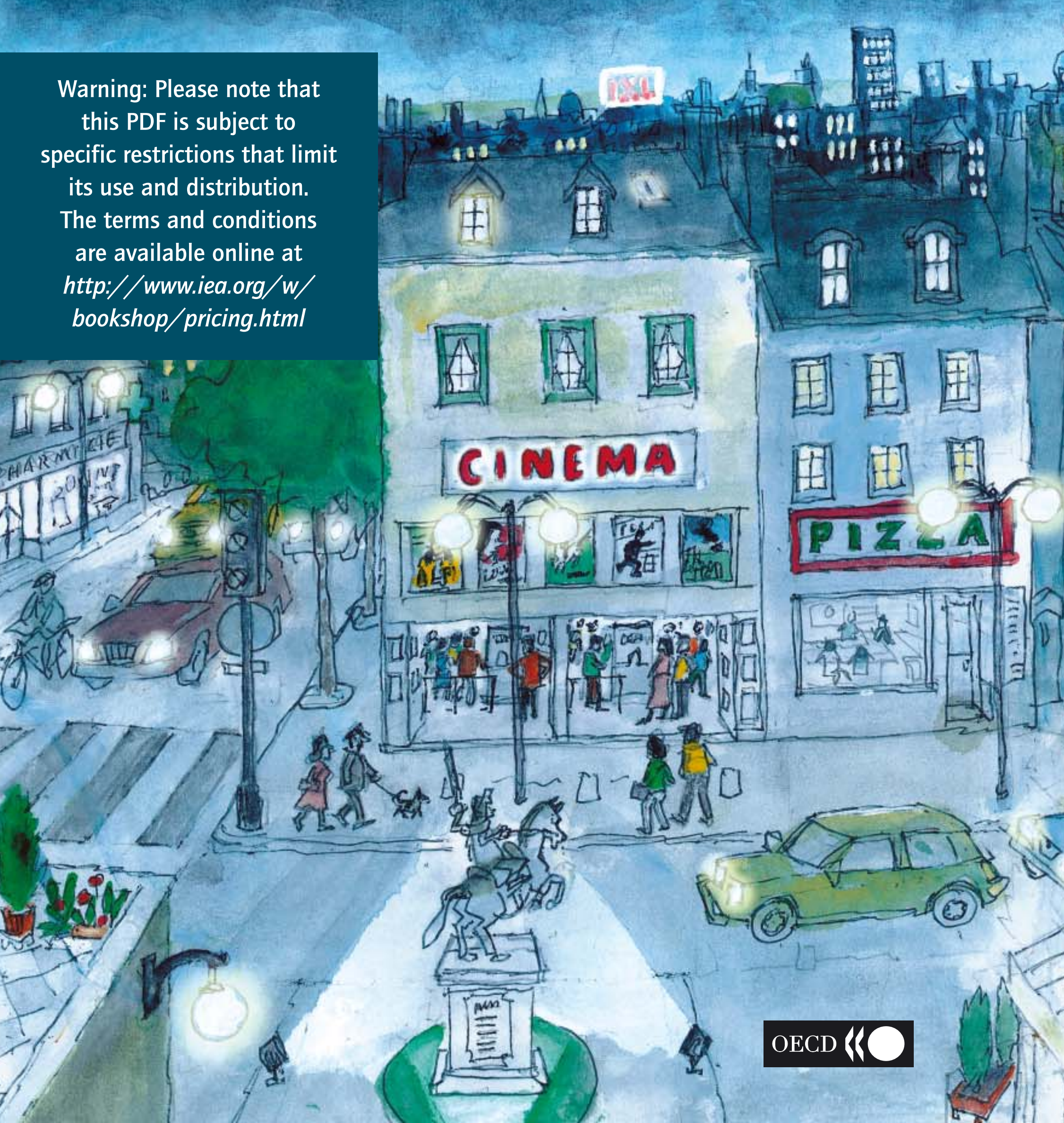
INTERNATIONAL ENERGY AGENCY

LIGHT'S LABOUR'S LOST

Policies for Energy-efficient Lighting

In support of the G8 Plan of Action



ENERGY EFFICIENCY POLICY PROFILES

OECD

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INTERNATIONAL ENERGY AGENCY

The International Energy Agency (IEA) is an autonomous body which was established in November 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme.

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- to maintain and improve systems for coping with oil supply disruptions;
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FOREWORD

When the incandescent lamp was first commercialised the main mode of transport was the horse, trains were powered by steam, balloons were the only means of flight and the telegraph was the state of the art for long-distance communication. Much has changed in the intervening 127 years, but much has also remained the same. In 1879 the incandescent lamp set a new standard in energy-efficient lighting technology, but today good-quality compact fluorescent lamps need only one-quarter of the power to provide the same amount of light. Yet most of us continue to rely on the "horse" of the incandescent lamp instead of the "internal combustion engine" of the compact fluorescent lamp. Nor is this the only way in which lighting energy is being wasted. We illuminate rooms when we're not there, we over-light spaces, we squander available daylight and we underutilise the most efficient street lighting and non-residential building lighting technologies.

This might not matter were it not for the severe challenges we face in securing a clean, sustainable and affordable energy system. Electricity generation is the main source of energy-related greenhouse gas emissions and lighting uses one-fifth of its output. Despite having many higher-efficiency and lower-cost alternatives, we continue to use less efficient and more expensive lighting technologies.

Is this because we are inherently attached to these older technologies, or is it simply because we stick to what we know when unaware or unsure of the merits of the alternatives? In each of the main lighting end-use sectors (commercial buildings, households, industrial lighting, outdoor lighting and vehicle lighting), this book shows that not only do more cost-effective and higher-efficiency alternative choices exist, but that they could be deployed very quickly were the current market barriers to be addressed. Doing this would allow our economies to be stronger and cleaner without sacrificing anything in our quality of life. Moreover, the policies that can bring about this change have been tested and found to work. What is needed is more comprehensive and vigorous implementation in each economy and lighting sector.

This book shows us why and how we should do so.

Claude Mandil
Executive Director, International Energy Agency

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TABLE OF CONTENTS

EXECUTIVE SUMMARY 25

OVERVIEW AND RECOMMENDATIONS 31

1 THE MEANING OF LIGHT 61

So what is the meaning of light? 64

2 IN THE EYE OF THE BEHOLDER:
HUMAN FACTORS IN LIGHTING 67

To see or not to see 68

Human response to light 68

What is light and how do we see? 69

Lighting quality: a primary driver of lighting energy needs 74

Lighting guidelines and design criteria 84

Recommended illuminance levels and implications
for lighting energy demand 85

Uniformity, surface reflectance, colour rendering and
glare thresholds 94

Discussion 97

3 THESE LOVELY LAMPS:
LIGHTING TECHNOLOGIES AND DESIGN 99

These windows of the soul 100

General performance characteristics of lighting technologies 101

Efficacy, lumen maintenance and temperature 101

Rated lamp life and useful lamp life 104

Lamp colour characteristics 105

Lamp types 107

Incandescent lamps 110

Tungsten halogen lamps 112

Linear fluorescent lamps 115

Compact fluorescent lamps 119

Cold-cathode fluorescent lamps 123
Low-pressure sodium lamps 124
High-intensity discharge lamps 125
Induction lamps 130
Vehicle lamps 132
Summary of lamp characteristics 134
Control gear 137
Ballasts 137
Lighting-control systems 141
Fixtures and luminaires. 148
Daylighting. 158
Energy savings from daylighting 162
Daylighting components and design solutions 164

4 LAZY LUMENS: THE ENERGY USED BY LIGHTING 167

Why the lumens are lazy 168
Efforts to estimate global lighting energy consumption 168
A note on the current methodology 169
Lighting markets: light, energy, economic and environmental characteristics. 172
Global light consumption, energy use, costs and CO_2 emissions 173
Residential lighting 183
Commercial sector 209
Industrial sector 234
Outdoor lighting 237
Vehicle lighting 241
The business of light: global illumination 250
The lamp industry 251
The lighting market 257

The potential for energy savings 266
What technology opportunities are available? 269
Lighting energy savings in non-résidential case studies 275
Previous savings estimates 277

Barriers to energy-efficient lighting . . . 285
Common barriers 286
Matching policy interventions to barriers 290

5 BLAZING THE TRAIL: POLICIES AND PROGRAMMES FOR ENERGY-EFFICIENT LIGHTING 297
Measure for measure: an introduction . . . 297
Government policies and programmes: common types 298
Policies to improve lighting-component efficiency . . . 309
Australia and New Zealand 312
OECD Europe 317
Japan 323
Korea 326
North America 330
China 342
Other non-OECD countries 344
Energy performance building codes and certification policies . . . 345
United States 345
Europe 354
Other OECD and non-OECD countries 362
Review of other energy-efficiency programmes influencing lighting . . . 365
Market-transformation programmes 365
Utility programmes 373
Other instruments 377
International initiatives 383
Policies to encourage better use of daylight 387
Daylight-saving time 387

6 LIGHT'S LABOUR'S FOUND: THE IMPACT OF CURRENT AND FUTURE POLICIES . . . 389
Beacons of hope . . . 389
Impact of current policies . . . 390
Estimating consequences of current policies 390

Assumptions and data for the Current Policies and No Policies scenarios 393
Projected energy trends and impacts of current policies 398
Costs and benefits of current policies 407
Impact of future policies: aiming for LLCC efficiency levels from 2008 409
Assumptions for the LLCC from 2008 scenario 410
Projected energy trends and impacts of the LLCC from 2008 scenario 415
Costs and benefits of the LLCC from 2008 scenario 418
Projected trends in vehicle lighting 422
Vehicle-lighting fuel-use scenarios 423
Conclusions 427

7 O'LED WHERE ART THOU? EMERGING SOLID-STATE LIGHTING TECHNOLOGIES AND OPPORTUNITIES 433

The state of the art 434
Physical principles and performance characteristics 434
SSL applications 448
The LED market 460
The "Great White Hope" 461
Energy savings, technology targets and investment 461
Quantum dots: a leap in the light? 465
LEDs for fuel lighting: a fast track to clean development? 466
Why it might not happen: the barriers to be overcome 471
OLED where art thou?. 473
Lifting the LED wait: policies and programmes to accelerate SSL . . . 474
International R&D programmes for SSL 475
Into the light: some recommendations 477

8 THE AGE OF ENLIGHTENMENT: FUTURE STRATEGIES FOR ENERGY-EFFICIENT LIGHTING 479

At the end of the tunnel 480
Policy objectives 481

Procedural objectives 482
Situational objectives 482
Technology objectives 484
Development objectives 487
Summary of policy objectives 488
Lessons learned from current and past efforts 488
Programmes for the future 504
Government programmes 505
Government–industry partnerships 513
Utility and energy-service programmes 514
International co-operation 515
Explicit policy recommendations 517

GLOSSARY 521

ABBREVIATIONS AND ACRONYMS 531

REFERENCES 539

TABLES

- Table 1.1 Price (constant year-2000 GBP) of 1 Mlmh of light in the United Kingdom from 1300 to 2000 62
- Table 2.1 International recommended illuminance levels circa 1999 86
- Table 2.2 Comparison of 2002 revision of CIBSE guidelines for lighting levels with 1994 levels 89
- Table 2.3 JIES recommended office illuminance levels 91
- Table 2.4 Illuminance levels recommended by IESNA, according to type of space 92
- Table 2.5 Illuminance levels recommended by IESNA for office tasks 93
- Table 2.6 Recommended illuminance levels in Australia . . . 93
- Table 2.7 Hypothetical example of the impact of the choice of uniformity factor on total illuminance requirements 95

- Table 3.1 Comparison of standard T5 and T8 lamps under optimum operating temperatures 117
- Table 3.2 Comparison of incandescent and CFL performance 122
- Table 3.3 Summary of lamp characteristics 135
- Table 3.4 Impact of zoning and manual switches on lighting operating hours in open-plan offices 142
- Table 3.5 Description of 17 demonstration projects employing lighting-control retrofits 147
- Table 3.6 Energy savings impacts of 17 demonstration projects employing lighting-control retrofits 148
- Table 3.7 LORs for troffers, according to the choice of reflector material 154
- Table 3.8 Energy savings and illuminance maintenance for daylight-responsive control systems 162
- Table 4.1 Residential lighting electricity consumption by lamp type in the United States in 2001 188
- Table 4.2 Estimated national average residential lighting characteristics for a sample of IEA member countries 189
- Table 4.3 Use of CFLs in IEA countries 203
- Table 4.4 Use of lighting-conservation control measures in Canadian buildings in 2000 214
- Table 4.5 Lighting characteristics of commercial buildings in California in 1995 219
- Table 4.6 Estimated average lighting characteristics of commercial buildings in the OECD in 2000 222
- Table 4.7 Total efficiency of combinations of lamp and luminaire for outdoor street lighting 239
- Table 4.8 Exterior-lighting characteristics for light-duty vehicles 244
- Table 4.9 Exterior-lighting characteristics for trucks 245
- Table 4.10 The top nine Chinese lighting-product manufacturing enterprises in 2003 254

- Table 4.11 Estimated global lamp sales in 2003 259
- Table 4.12 Estimated lighting energy consumption in Japan were no energy-savings policy measures to be implemented 280
- Table 4.13 Energy and CO_2 savings from current and potential policy measures for energy-efficient lighting 281
- Table 4.14 Projected commercial-sector lighting energy consumption in the UK and forecast savings from existing policies 284
- Table 4.15 Barriers and suitable policy interventions for efficient lighting (Greenlight Australia programme) 294
- Table 5.1 Use of labels, standards and targets for lighting and related equipment 310
- Table 5.2 Minimum efficacy requirements for LFLs in Australia 314
- Table 5.3 Initially proposed lighting efficiency policy measures, Greenlight Australia programme 315
- Table 5.4 Minimum efficacy requirements for LFLs in New Zealand 316
- Table 5.5 Japan's Top Runner requirements for fluorescent lamps 324
- Table 5.6 Korea's MEPS and target requirements for incandescent lamps 327
- Table 5.7 Korea's MEPS and target requirements for fluorescent lamps 328
- Table 5.8 Korea's MEPS and target requirements for CFLs 328
- Table 5.9 US and Canadian MEPS for fluorescent lamps . . . 332
- Table 5.10 US and Canadian MEPS for incandescent reflector lamps 332
- Table 5.11 US and Canadian MEPS for replacement fluorescent lamp ballasts 333

- Table 5.12 US and Canadian MEPS for non-replacement fluorescent lamp ballasts 333
- Table 5.13 Estimated savings from US lighting-related MEPS . 335
- Table 5.14 Estimates of US national savings from implementing additional lighting MEPS 338
- Table 5.15 Mexican MEPS for CFLs 339
- Table 5.16 Californian MEPS for GLS incandescent lamps . 341
- Table 5.17 Chinese MEPS for double-capped fluorescent lamps 343
- Table 5.18 Chinese MEPS for self-ballasted CFLs 343
- Table 5.19 Sample of building-area LPD requirements under ASHRAE 90.1-2004 349
- Table 5.20 Energy flows covered in European building-code calculation procedures pre-2003 355
- Table 5.21 Draft European standards for lighting energy performance in buildings developed under the auspices of CEN 356
- Table 5.22 Maximum LPD thresholds permitted in Chinese standard GB 50034-2004 for office buildings . . 364
- Table 5.23 Summary of international CFL MEPS and labelling schemes 386
- Table 6.1 Energy-cost savings, equipment purchase-cost changes and carbon emission reductions under the Current Policies scenario compared with the No Policies scenario 408
- Table 6.2 Energy-cost savings, equipment purchase-cost-changes and carbon emission reductions under the LLCC from 2008 scenario compared with the Current Policies scenario 421
- Table 7.1 Technology-roadmap price and performance improvements for LEDs 462
- Table 7.2 Technology-roadmap price and performance improvements for OLEDs 462
- Table 7.3 Description of the SSL market scenarios and maximum S-curve values 465

FIGURES AND PLATES

- Figure ES.1 Global lighting electricity consumption in 1995–2030 under the No Policies, Current Policies and LLCC from 2008 scenarios 27
- Figure OR.1 Estimated per-capita consumption of electric light in 2005 34
- Figure OR.2 Global lighting electricity consumption by end-use sector in 1995–2030 under the Current Policies scenario 35
- Figure OR.3 Estimated global average share of electric-light production by lamp type and end-use sector in 2005 40
- Figure OR.4 Average lighting-system efficacy by region in 2005 44
- Figure OR.5 Global lighting electricity consumption in 1995–2030 under the No Policies, Current Policies and LLCC from 2008 scenarios 51
- Figure OR.6 Global lighting-cost savings under the LLCC from 2008 and No Policies scenarios compared to the Current Policies scenario 52
- Figure 1.1 Consumption of lighting by candles, gas, paraffin and electricity in the United Kingdom between 1700 and 2000 64
- Figure 2.1 The relative spectral sensitivity of the human eye (the CIE standard photopic observer) 72
- Figure 2.2 A simple demonstration of the importance of contrast for visual acuity 76
- Figure 2.3 Relative visual performance as a function of luminance and contrast 77
- Figure 2.4 Measured desktop illuminance and user opinion of the illuminance level 80
- Figure 2.5 Desktop illuminance levels chosen by participants in a mock-up office 81

- Figure 3.1 Examples of lumen depreciation for T8 fluorescent and pulse-start metal halide lamps 103
- Figure 3.2 Temperature characteristics of fluorescent lamps 104
- Plate 3.3 CIE chromaticity diagram 429
- Figure 3.4 Types of electric lamp 110
- Figure 3.5 Features of the common incandescent GLS lamp 111
- Figure 3.6 Efficacy of incandescent lamps as a function of input power 112
- Figure 3.7 Common types of halogen lamp 114
- Figure 3.8 Features of LFLs 116
- Figure 3.9 Ballast-integrated CFL models 120
- Figure 3.10 Features of low-pressure sodium lamps 124
- Figure 3.11 Features of HID lamps 126
- Figure 3.12 Examples of ceramic metal halide lamps 131
- Figure 3.13 Examples of induction lamps 131
- Figure 3.14 Configurations for headlamp optics 133
- Figure 3.15 System efficacy for a number of light sources used for general lighting 137
- Figure 3.16 Historic evolution of luminous efficacy for major light sources used in general lighting 138
- Figure 3.17 Examples of electronic ballasts for HID and fluorescent lamps 139
- Figure 3.18 Lighting energy savings and payback period for 13 demonstration projects employing lighting-control retrofits 146
- Figure 3.19 Expected loss of light resulting from dirt build-up in enclosed troffer luminaire 155
- Figure 3.20 Antiglare shielding for direct luminaires 156
- Figure 3.21 Suspended direct–indirect luminaires 157

- Figure 3.22 Strategies for increasing low-glare daylight penetration 161
- Figure 4.1 Estimated per-capita consumption of electric light in 2005 173
- Figure 4.2 Estimated regional share of electric-light consumption in 2005 174
- Figure 4.3 Estimated global average share of electric-light production by lamp type in 2005 175
- Figure 4.4 Estimated global average share of electric-light production by lamp type and end-user sector in 2005 177
- Figure 4.5 Estimated regional share of stationary-lighting electricity consumption in 2005 178
- Figure 4.6 Average lighting-system efficacy by region in 2005 181
- Figure 4.7 Average proportion of household-lighting energy consumption by room in four EU countries . . 186
- Figure 4.8 Average number of light sources per household in samples from four EU countries . 191
- Figure 4.9 Annual-average hourly load curves in metered households in four EU countries 193
- Figure 4.10 Seasonal variation in residential lighting demand: example of a New Zealand household 195
- Figure 4.11 Average annual household-lighting electricity consumption versus income in China 198
- Figure 4.12 Average annual residential electric-light consumption versus GDP 199
- Figure 4.13 Number of people with *no* access to electricity in 2002 and projected number in 2030 if no new measures are implemented 200
- Figure 4.14 Estimated global lighting energy consumption by commercial-building type in 2005 210
- Figure 4.15 Estimated global lighting energy intensity by commercial-building type in 2005 211

■ Figure 4.16 Estimated regional share of light output by source in the commercial-building sector in 2005 212

■ Figure 4.17 Estimated light output by source in OECD commercial buildings in 2005 217

■ Figure 4.18 Estimated power of installed lighting systems in North American educational buildings by type of space 218

■ Figure 4.19 Normalised lighting power density distribution for a sample of Californian offices 221

■ Figure 4.20 Estimated average commercial-building lighting energy intensities by OECD region in 2005 . . 227

■ Figure 4.21 Installed lighting power density by lamp type for a sample of Danish schools 230

■ Figure 4.22 Global trade in electric lamps in 2003 256

■ Figure 4.23 Residential lamp sales by lamp type in the United States and California in 2000 260

■ Figure 4.24 Estimated global CFL sales by region in 1990–2004 261

■ Figure 4.25 Estimated global CFL stock 262

■ Figure 4.26 HID lamp sales in 1990–2002/3 in the United States and China 265

■ Figure 4.27 Estimated annual per-capita lamp sales by country or region 266

■ Figure 4.28 Estimated share of lamp sales by volume, by country or region 267

■ Figure 4.29 Estimated share of light sales by lamp type, by country or region 268

■ Figure 4.30 Estimated equipment and labour costs vs. annual operating hours for providing 1 Mlmh of light, by light source 270

■ Figure 4.31 Estimated total costs versus average annual operating hours for providing 1 Mlmh of light, by light source 271

■ Figure 4.32 Estimated total costs by light source operated for 2 500 hours/year to provide 1 Mlmh of light 272

- Figure 4.33 Annual lighting electricity consumption in a sample of French households before and after replacing incandescent lamps with CFLs 273
- Figure 4.34 Savings and simple payback times vs. the number of incandescent lamps replaced with CFLs in a sample of Italian households . . 274
- Figure 4.35 Japanese lighting energy consumption scenarios for 1995–2010 282
- Figure 4.36 Relationships between actors influencing the efficiency of installed lighting 290
- Figure 5.1 Evolution of the number of countries with equipment standards and labelling regulations, including those addressing lighting 313
- Plate 5.2 The EU household lamp label 430
- Figure 5.3 Thresholds applied in the EU household lamp label 318
- Figure 5.4 The UK Energy Saving Recommended endorsement label 322
- Figure 5.5 Japan's Top Runner efficacy requirements for fluorescent lamps 325
- Plate 5.6 The Japanese energy label 430
- Plate 5.7 The Korean mandatory energy label 431
- Plate 5.8 Korea's Energy Boy certification label 431
- Plate 5.9 The ENERGY STAR endorsement label 431
- Figure 5.10 MEPS for incandescent lamps 341
- Figure 5.11 China's endorsement label 343
- Plate 5.12 The Thai energy label 431
- Figure 5.13 Status of US commercial building code adoption in 2005 347
- Plate 5.14 Germany's building Energy Passport and a notional dual-rating building energy certificate 432
- Figure 6.1 Linear fluorescent lamp ballast sales by type in the United States 391

- Figure 6.2 Linear fluorescent lamp ballast sales by type in the European Union 392
- Figure 6.3 Regional share of electric-light consumption in 2030 under the Current Policies scenario 395
- Figure 6.4 Per-capita consumption of electric light in 2030 under the Current Policies scenario 395
- Figure 6.5 Global average share of electric-light production by lamp type in 2030 under the Current Policies scenario 396
- Figure 6.6 Global average share of electric-light production by lamp type and end-use sector in 2030 under the Current Policies scenario 397
- Figure 6.7 Global lighting electricity consumption by end-use sector in 1995–2030 under the Current Policies scenario 398
- Figure 6.8 Regional share of stationary-lighting electricity consumption in 2030 under the Current Policies scenario 399
- Figure 6.9 Average lighting-system efficacy by region in 2030 under the Current Policies scenario 400
- Figure 6.10 Global lighting electricity consumption in 1995–2030 under the No Policies and Current Policies scenarios 404
- Figure 6.11 Lighting electricity savings by region in 1990–2030 under the Current Policies scenario compared with the No Policies scenario 405
- Figure 6.12 Global lighting electricity savings by end-use sector under the Current Policies scenario compared with the No Policies scenario 406
- Figure 6.13 Global average share of electric-light production by lamp type in 2030 under the LLCC from 2008 scenario 413
- Figure 6.14 Global average share of electric-light production by lamp type and end-use sector in 2030 under the LLCC from 2008 scenario 414

- Figure 6.15 Global lighting electricity consumption in 1995–2030 under the No Policies, Current Policies and LLCC from 2008 scenarios 417
- Figure 6.16 Regional share of lighting electricity consumption in 2030 under the LLCC from 2008 scenario 418
- Figure 6.17 Lighting electricity savings by region under the LLCC from 2008 scenario compared with the Current Policies scenario 419
- Figure 6.18 Global lighting electricity savings by end-use sector under the LLCC from 2008 scenario compared to the Current Policies scenario . . . 420
- Figure 6.19 Global lighting-cost savings under the LLCC from 2008 and No Policies scenarios compared to the Current Policies scenario . . . 421
- Figure 6.20 World vehicle lighting-related fuel use under four scenarios 425
- Figure 6.21 Relative trends in world light-duty lighting-related fuel use under four scenarios . . 426
- Figure 7.1 Composition of a modern LED 435
- Figure 7.2 Steps to making an LED 438
- Figure 7.3 Reported light output vs. efficacy for Cree WLEDs circa October 2004 440
- Figure 7.4 Recent historic and projected future efficacy improvements for WLEDs circa October 2005 441
- Figure 7.5 LED white-light lamp with built-in heat exchanger 442
- Figure 7.6 Light output over operating life of LEDs 443
- Figure 7.7 LED backlit television screen 449
- Figure 7.8 Solar-powered LEDs used as architectural lighting in bollards 451
- Figure 7.9 Common illuminated exit signs 454
- Figure 7.10 LED street-light projects 458

- Figure 7.11 The New York 2004 LED street-light competition winner 459
- Figure 7.12 Projected US primary energy savings in 2020 for SSL 463
- Figure 7.13 Handheld solar-PV-powered WLED lighting system 467
- Figure 7.14 Cost of fuel-based lighting and solar-PV-powered LED lighting 468
- Figure 7.15 Effect of improving WLED efficiency on PV and battery sizing and overall system cost 470

BOXES

- Box 3.1 A brief history of lamps 108
- Box 3.2 The economics of CFLs compared to incandescent lamps 121
- Box 3.3 Case study: High-wattage ceramic metal halide lamps 129
- Box 3.4 Electronic HID ballasts save money in four ways 140
- Box 3.5 Case study: Energy savings from a new detector in Sweden 145
- Box 3.6 Case study: Integrated lighting system for US post offices 145
- Box 3.7 Energy-savings potential for occupancy sensors 149
- Box 3.8 National Center for Atmospheric Research (NCAR) 150
- Box 3.9 General performance criteria for luminaires . . 152
- Box 3.10 Energy-efficient torchières 159
- Box 3.11 Case study: Coca-Cola Amatil (CCA) in Australia 164
- Box 4.1 Case study: The US Sub CFL Programme . . . 207

- Box 4.2 Mandatory use of low beams during daytime for security reasons . . . 247
- Box 4.3 Daytime use of dipped headlights vs. daytime running lights . . . 248
- Box 4.4 Subsidies: a disincentive to invest in efficient lighting . . . 291
- Box 7.1 Solid-state lighting performance milestones . . . 437
- Box 7.2 Case study: LEDs in traffic lights in Stockholm 453
- Box 7.3 The Hella LED headlamp . . . 456

EXECUTIVE SUMMARY

A GLOBAL VIEW

When William Shakespeare wrote *Love's Labour's Lost* he would have used light from tallow candles at a cost (today) of GBP 12 000 for a measure of light.[1] The same amount of light from electric lamps now costs GBP 2, while the supply of artificial light in the country of Shakespeare's birth has increased 350 000 times! In both historic and economic terms, human civilisation revolves around artificial light. As the first service offered by electric utilities, lighting ranks among the end-uses dominating global power demand. Worldwide, grid-based electric lighting consumes 19% of total global electricity production, slightly more electricity than used by the nations of OECD Europe for all purposes. Lighting requires as much electricity as is produced by all gas-fired generation and 15% more than produced by either hydro or nuclear power. The annual cost of this service including energy, lighting equipment and labour is USD 360 billion, which is roughly 1% of global GDP. Electricity accounts for some two-thirds of this.

The energy consumed to supply lighting entails greenhouse gas emissions of an equally impressive scale: 1 900 Mt of CO_2 per year, equivalent to 70% of the emissions from the world's light passenger vehicles. Nor do all of these emissions result from electricity generation. Fuel-based lighting, used both in vehicles and areas beyond the range of electricity grids, amplifies these consumption figures and lighting's secondary effects on public health and the environment. At present, 1.6 billion people live without access to electric light, a greater number than when Thomas Edison commercialised the incandescent light bulb in the 1880s. The paraffin- and diesel-fuelled lighting they use is much less efficient than even the most inefficient incandescent lamp, is a large emitter of CO_2 and is very costly. These combined uses provide only 1% of global lighting but are responsible for 20% of lighting CO_2 emissions. In an era of tight oil markets they consume 3% of world oil supply – more than the total output of Kuwait.

1. One megalumen-hour.

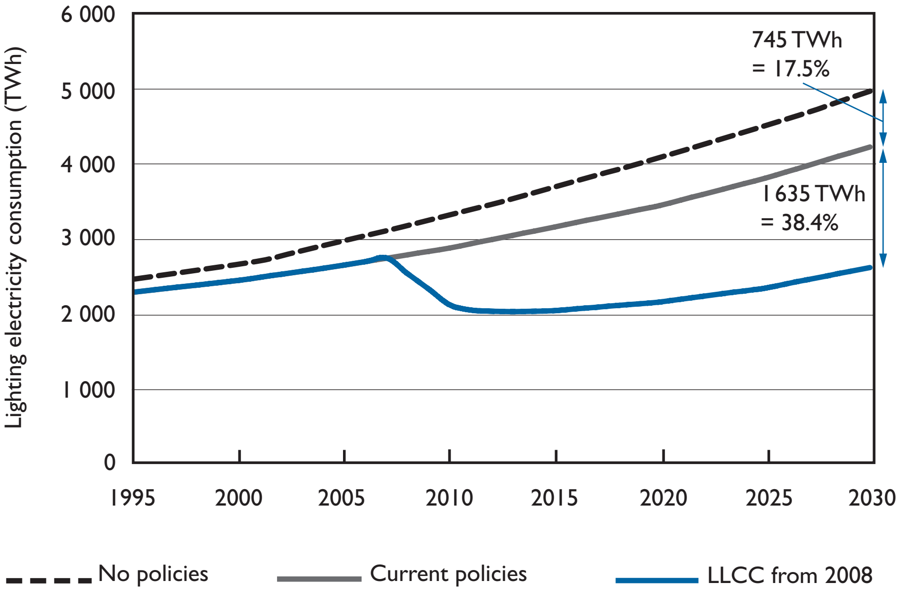
The rate at which humanity has managed to increase its use of artificial light is both striking and sobering. In the span of 200 years, the typical (English) person's annual consumption of artificial light has increased by a factor of 12 000, from 5 kilolumen-hours at the beginning of the 19th century to 60 megalumen-hours today, although no higher share of disposable income is being spent on it. Global in scale yet by no means homogeneous, the demand for artificial light is far from being saturated. While an average North American consumes 101 megalumen-hours each year the average inhabitant of India uses only 3 megalumen-hours. With current economic and energy-efficiency trends, it is projected that global demand for artificial light will be 80% higher by 2030 and still unevenly distributed. If this comes to pass and the rate of improvement of lighting technologies does not increase, global lighting electricity demand will reach 4 250 TWh: almost twice the output of all modern nuclear power plants. Furthermore, without further energy-efficiency policy measures, lighting-related annual CO_2 emissions will rise to almost 3 gigatonnes by 2030.

SOURCES OF WASTE

This energy- and carbon-intensive future need not become a reality. Simply by making better use of today's cost-effective efficient-lighting technologies and techniques, global lighting energy demand need be no higher in 2030 than it is now. In the current lighting environment there are enormous sources of waste. Light is routinely supplied to spaces where no one is present. Over-lighting occurs even though visual functions are insensitive to light levels beyond certain thresholds. There are vast differences in the efficiency of competing lighting sources and in the way lighting systems are designed to deliver light to where it is needed. Moreover, the advent of powerful and affordable artificial lighting has allowed poor architecture to prosper. Uninspired building design has taken us into dark boxes where the largest, cleanest and highest-quality source of light – daylight – often cannot reach.

Each of these areas holds major potential to reduce lighting energy needs without compromising lighting service, and the technologies to do so are widely available today. The IEA estimates that were end-users to install only efficient lamps, ballasts and controls that will save them money over the life cycle of the lighting service, global lighting electricity demand in

Figure ES.1 Global lighting electricity consumption in 1995–2030 under the No Policies, Current Policies and LLCC from 2008 scenarios*



* These scenarios are explained in Chapter 6 of the main text and also in the Extended Summary. The Current Policies scenario is the lighting component of the Reference Scenario in the IEA's *2004 World Energy Outlook* (OECD/IEA, 2004).
Abbreviation: LLCC = Least Life-Cycle Cost.

2030 would be just 2 618 TWh. This is almost unchanged from 2005 and would actually be lower between 2010 and 2030 (see the LLCC from 2008 scenario in Figure ES.1).

In the intervening years, staggering cumulative savings of almost 28 000 TWh of final electricity and over 16 000 Mt of CO_2 emissions would be made beyond what is expected with the continuation of current policies. Moreover, these savings are realised just by making good use of today's routinely available efficient-lighting technologies. Nor are these technologies expensive when the operating costs are also considered, because they save far more money in avoided energy bills than they cost. Using these life cycle cost optimised lighting choices would save end-users cumulative net costs worth USD 2.6 trillion to 2030. As the efficient-lighting technologies are more cost-effective than the standard technologies, the net cost of CO_2 abatement is negative. Cutting CO_2 emissions through cost-optimised lighting technologies saves end-users USD 161 of expenditure for each tonne of CO_2 avoided. However, achieving these gains will require strong additional action by governments as current market conditions are far from these energy- and cost-optimised circumstances.

SO WHY DOESN'T EFFICIENT LIGHTING HAPPEN BY ITSELF?

If efficient lighting is so economical, why does the market not deliver it automatically? The explanation can be found in a number of barriers that limit deployment of cost-effective lighting technologies. End-users and market actors are often unaware of the savings potentials and lighting-quality advantages and without information are inclined to use the technologies that they have always used. Some efficient lighting has higher initial costs and thus users are less likely to invest in it unless they are aware of the future savings. Most lighting is not installed and directly paid for by the end-user, thus different cost incentives exist for installers and users. Furthermore, most public and private organisations manage their equipment and operations budget separately and thereby create an incentive to minimise equipment costs at the possible consequence of higher operating costs. These and similar obstacles all slow the rate at which markets learn about and adopt cost-effective choices.

Policy makers in many countries have long understood these difficulties and have been implementing measures to encourage more efficient lighting since the 1970s. Moreover, these measures have resulted in impressive returns. In cumulative terms the policies implemented since 1990 saved almost 8% (2 960 TWh) of cumulative lighting electricity consumption to 2005 and 1 670 Mt of CO_2 emissions; they are also forecast to save another 14 500 TWh and 8 500 Mt of CO_2 (17% of the total) from 2006 to 2030 without being strengthened. In addition they have been remarkably cost-effective in avoiding net costs of USD 253 billion by 2005 and are on course to save USD 1.5 trillion by 2030.

Nonetheless, the broader goal of stabilising global lighting electricity demand at or below 2005 levels will only be achieved by substantially strengthening and expanding current policy settings.

BEACONS OF HOPE

A number of technologies are profiled in this book. All of them exist and are fully commercialised. They include incandescent, fluorescent and high-intensity discharge lamps; the ballasts and transformers that drive them; the luminaires in which they are housed; and the controls that operate them. Incandescent lamps have been with us since the 19th century and still have an energy-to-light conversion efficiency of just 5%, which is five times lower than that of equivalent good-quality compact fluorescent lamps (CFLs). Without a palpable change in lighting quality, a market shift from inefficient incandescent lamps to CFLs would cut world lighting electricity demand by 18%. In the service sector, the use of high-efficiency ballasts, slimmer fluorescent tubes with efficient phosphors and high-quality luminaires produces savings that are just as impressive. For street and industrial lighting there are great savings to be had from discontinuing the use of inefficient mercury vapour lamps and low-efficiency ballasts in favour of higher-efficiency alternatives. The waste of light can also be readily reduced by the use of time-scheduled switching, occupancy sensors and daylight-responsive dimming technologies, all of which are mature and fully proven techniques with high savings returns.

For the near future solid-state lighting is emerging as a promising lighting technology. Over the last 25 years it has undergone sustained and dramatic improvements in efficiency that hold the prospect of it outperforming today's mainstream lighting technologies in a growing number of applications. If current progress is maintained, solid-state lighting may soon make inroads into general lighting. Moreover, solar-powered solid-state lighting already offers a robust, low-energy and economic solution to the needs of households reliant on fuel-based lighting.

MAKING IT HAPPEN

Governments have a key role to play in accelerating the adoption of energy-efficient lighting. They can set standards to prohibit the sale of the least efficient lighting technologies where high-efficiency, good-quality and cost-effective alternatives exist. They can institute regulations applying to the energy performance and quality of lighting systems installed in major applications: commercial buildings, new residential construction, outdoor lighting, industrial lighting and vehicle lighting. They can help develop innovative financing and fiscal schemes to overcome first-cost barriers and provide information and training to lighting specifiers, designers and installers. They can educate the public at large about the benefits of efficient lighting. They can ensure that the energy costs and performance of lighting are visible in the market by labelling the energy performance of equipment and certifying the performance of entire light-using systems such as buildings and outdoor lighting. They can encourage better building design with more effective use of daylight through education, training and incentives. They can lead by example through pioneering efficient-lighting technologies and practices in their own buildings and by setting appropriately ambitious targets. And they can establish programmes and provide support to bring more sustainable, affordable and high-quality lighting to the world's light-poor.

All these measures will bring results but need careful design and targeting. They also need to be ambitious, broadly based and effectively implemented to realise their potential. Many governments have found that comprehensive and broad-ranging programmes with a clearly defined mandate and adequate resources enable the most effective response, but so far not one has done enough to attain the full cost-effective savings potential and some have not yet begun to try. Taken as a whole, the rapid adoption of such measures will produce a brighter future and help prevent light's labour's from being lost.

OVERVIEW AND RECOMMENDATIONS

LIGHT'S LABOUR'S LOST

Lighting is a large and rapidly growing source of energy demand and greenhouse gas emissions

Since its earliest incarnation as firelight to its most recent as electric light, artificial light has been at the core of human civilisation. It has freed us from the temporal and spatial constraints of daylight by allowing us to function equally well night and day, indoors and outdoors. It shapes our perceptions, literally colours our lives and mirrors our moods. So pervasive has it become that most of us live surrounded by artificial light: room lights, indicator lights, mobile phone displays, headlamps, advertisement signage and computer screens. Artificial light has become of primary importance to human social and economic activity, yet it is so commonplace that we have almost ceased to notice it. It is not only the service that is taken for granted, however; so are its costs – and these are more than just financial.

Lighting was the first service offered by electric utilities and continues to be one of the largest electrical end-uses, but less well appreciated is that lighting is also one of the biggest causes of energy-related greenhouse gas emissions. Globally it accounts for 650 Mtoe of primary energy consumption and results in the emissions of almost 1 900 million tonnes (Mt) of CO_2. This is 70% of the emissions of the world's passenger vehicles and three times more than emissions from aviation.

Worldwide, grid-based electric lighting consumed about 2 650 TWh of electricity in 2005; some 19% of total global electricity consumption and slightly more than the total electricity consumption of OECD Europe for all purposes. The amount of electricity consumed by lighting is almost the same as that produced from all gas-fired generation and about 15% more than that produced by either hydro or nuclear power. Over half of this electricity consumption is in IEA member countries, but their share is declining; by 2030, non-OECD countries are expected to account for more than 60% of global lighting electricity demand.

The energy bill for electric light costs end-users USD 234 billion each year and accounts for two-thirds of the total cost of the electric-lighting service (USD 356 billion, which includes lighting equipment and labour costs as well as energy).

Indoor illumination of tertiary-sector buildings uses the largest proportion of lighting electrical energy, comprising as much as the residential and industrial sectors combined. On average, lighting accounts for 34% of tertiary-sector electricity consumption and 14% of residential consumption in OECD countries. In non-OECD countries these shares are usually higher. Outdoor stationary lighting, including street, roadway, parking and architectural lighting as well as outdoor signage, uses less than one-tenth of total lighting electricity consumption. In addition to spatial illumination and signage, there are a number of important niche lighting applications. These include backlighting of computer screens, mobile phones, televisions and other information and communications technology devices.

Yet lighting energy use is not confined to electric grid powered applications. Each year 55 billion litres of gasoline and diesel is used to operate vehicle lights. This amounts to 3.2% of total vehicle fuel use and is equivalent to the consumption of 1.05 million barrels of oil daily. At present this consumption is not reflected in the fuel performance figures quoted under standard test-driving cycles because auxiliary devices, including lights, are not activated during testing. Therefore this aspect of vehicle energy performance is currently invisible to end-users. Nonetheless, it is estimated that the fuel used to power vehicle lighting costs end-users approximately USD 66 billion annually.

Liquid fuel, most commonly in the form of paraffin (kerosene), is also used to provide lighting for more than one-quarter of the world's population, who have no access to the electricity network. It is a stark statistic that there are more people in the world with no access to electric light today than was the case when Thomas Edison first popularised the electric light-bulb in the 1880s. This is an important development issue because fuel-based lighting is expensive, inefficient and the cause of thousands of deaths each year from respiratory and cardiac problems related to poor indoor air quality. Fuel-based lighting also gives inadequate lighting levels, which lowers task-effectiveness during the hours of darkness and leads to eyestrain and long-term visual defects.

An estimated 77 billion litres of fuel is used annually for domestic fuel-based lighting, equivalent to 1.3 million barrels of oil per day at an estimated cost of USD 38 billion each year. The resulting 200 Mt of annual CO_2 emissions is greater than the total energy-related emissions from Turkey.

When the cost of fuel-based lighting is added to that of grid-based electric lighting, the total cost of the lighting service amounts to about 1.2% of global gross domestic product (GDP) and the energy costs alone total some 0.9% of global GDP.

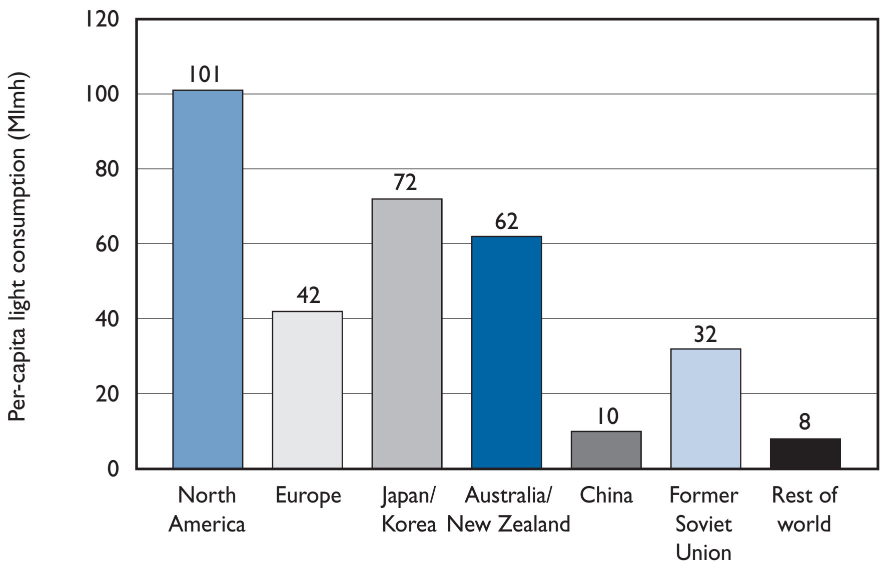
CONSUMPTION OF LIGHT

Globally 133 petalumen-hours (Plmh) of electric light was consumed in 2005, an average of 20 megalumen-hours (Mlmh) of light per person. But the use of this light is very unevenly distributed. A typical North American uses 101 Mlmh of electric light each year (Figure OR.1), while the typical inhabitant of India uses just 3 Mlmh. Despite these inequalities, even the lower figures are remarkably high when seen in a historical context and illustrate the extraordinary progress that has been made in artificial illumination. A typical person living in England at the beginning of the 19th century, for example, would have consumed just 5 kilolumen-hours (klmh) of artificial light a year, but by the beginning of the 21st century this consumption was over 12 000 times this figure.

Over the last decade, global demand for artificial light grew at an average rate of 2.4% per annum. Annual growth was slower in IEA countries (1.8%) than in the rest of the world (3.6%). Growth rates in IEA countries are lower than in previous decades and may be indicative of the beginnings of demand saturation for the first time in history. Nonetheless, the overall growth in demand is expected to continue for the foreseeable future, driven by new construction, rising average illumination levels in non-OECD countries, ongoing electrification and a trend towards more outdoor lighting.

However, caution needs to be exercised in interpreting simple counts of total source-lumens (the lumens emitted by lamps), because this is a poor measure of overall lighting service. A better understanding of the quality of lighting provided requires information on how effectively lumens are

Figure OR.1 **Estimated per-capita consumption of electric light* in 2005**

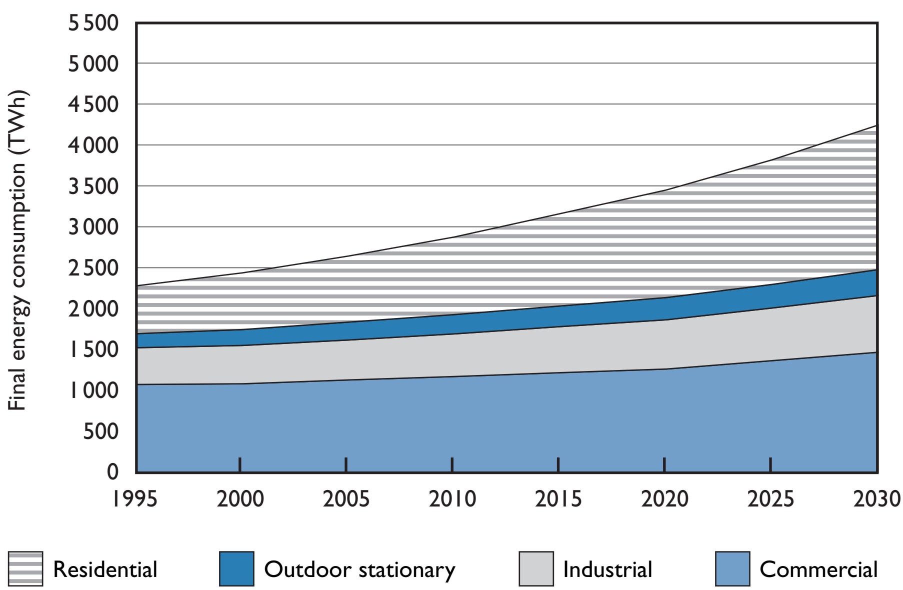


* Source-lumens.
Abbreviation: Mlmh = megalumen-hours.

delivered to aid visibility and what level of lighting is needed to provide visual comfort and improve productivity. Assessing service levels thus also entails knowledge of the most appropriate lighting environment for the lit space, the distribution and absorption of light, whether people are present when light is delivered and the extent to which electric-lighting needs are offset by daylight. Data on these factors are either sparse or non-existent, and therefore regional variations in overall lighting service can only be estimated from anecdotal evidence and case studies.

With current socio-economic patterns and policies, the global demand for grid-based electric light is forecast to attain 239 Plmh by 2030, representing an average annual growth rate of 2.4% over the next two and a half decades. However, this projected growth is the aggregate result of many, sometimes divergent, trends. Average consumption of source-lumens per unit floor area of tertiary-sector buildings in IEA countries is likely to fall, for example, as measures that improve the efficiency of lumen delivery and reduce lumen wastage continue to take effect. As demand for artificial light grows, so does the energy consumption required to supply it, yet thanks to numerous efficiency improvements the latter is doing so at a far slower rate. Over the last decade global electricity consumption for lighting applications grew at 1.5% per annum, less than three-quarters of the rate of growth in demand for light. Over the next 25 years, global electricity consumption for lighting with current socio-economic trends and policies is projected to rise to over 4 250 TWh, an increase of 60% overall at an average rate of 1.9% per annum (Figure OR.2). The rate at which growth actually occurs will depend on a range of factors, including those that influence demand for artificial light and the efficiency of the lighting technologies that supply it.[1]

Figure OR.2 **Global lighting electricity consumption by end-use sector in 1995–2030 under the Current Policies scenario**



1. The key drivers of GDP, building floor area, population and electricity prices used in the future scenarios shown here are harmonised with those in the Reference Scenario of the *World Energy Outlook* (OECD/IEA, 2004).

RECOMMENDED LIGHTING LEVELS

Demand for light should be driven by human needs but is actually influenced strongly by local installation practices concerning how much light is provided for specific spaces. Most countries, including all IEA countries, issue official recommended illumination levels that installers of lighting systems are requested – or in some cases required – to attain in the spaces they illuminate. Levels are dependent on the type of space to be lit and the functions envisaged within it, and are based on perceived understanding of how light levels influence both the functional efficiency of anticipated tasks within the spaces and visual comfort. However, current recommended values vary widely among IEA countries in a manner that is hard to explain from consideration of technical factors alone. In some cases recommended light levels for the same type of space can differ by a factor of 20!

Moreover, recommended lighting levels have changed substantially over the years. In general they rose from the 1920s to the 1980s, but since then they have generally been declining. These evolutions mirror changes in knowledge concerning the optimal lighting levels for different situations and are in response to relatively recent research which shows that more is not always better where lighting levels are concerned. As lighting energy consumption is proportional to the lighting level attained, there are important energy-efficiency opportunities to be realised from updating recommended lighting levels in line with international best practice and from retrofitting older, over-lit lighting installations.

In less-developed countries the situation is frequently the opposite. Most countries do not issue guidelines on recommended lighting levels and lighting systems are usually installed via rules of thumb applied by electrical fitters. Under-lighting is commonplace largely because of the lower affordability of lighting and less demanding societal expectations. Ironically, this does not preclude substantial over-lighting from occurring in more prestigious buildings, perhaps because high light levels and affluence are still strongly associated.

LIGHT POLLUTION

Much as artificial lighting provides a very useful service, it has also engendered a new problem, that of light pollution. The light emitted by outdoor illumination devices has become so pervasive and is so poorly directed that in most of our urban environments it is no longer possible to see the majority of stars at night because the glare from artificial light is scattered back from the sky vault. Light pollution is not only a waste of light energy but also diminishes our perception of the wider universe. A variety of simple remedies exist but are seldom employed, mostly because there is a lack of awareness of the issue.

LIGHTING TECHNOLOGIES, QUALITY AND COST-EFFECTIVENESS

The image that most people have of a light bulb is that of an *incandescent lamp*. Joseph Swann and Thomas Edison may have been gratified to know their technology would still be in common use over 120 years after its development, but in policy terms it has become a cause for concern. Incandescent lamps typically emit 12 lm/W, representing an energy-to-light conversion efficiency of just 5%! The remaining energy is delivered as heat. By contrast, the most efficient general lighting sources available nowadays achieve efficacies of 150 lm/W. The low efficacy of incandescent lamps helps to explain why they provide only 7% of total delivered light despite accounting for 79% of global lamp sales by volume and 30% of electric-lighting energy consumption. While incandescent lamps are used mostly for residential lighting, they are still found in many non-residential applications.

The greatest amount of light, 64% of the total, is delivered by *fluorescent lamps,* which have efficacies of 30–110 lm/W. Fluorescent lamps are used mostly to provide general-purpose indoor lighting in the non-residential sector; however, in some countries (such as Japan) fluorescent lighting is also the main source of household lighting. Cultural traditions and preferences appear to play a large role in determining the choice of residential lighting systems, with significant implications for energy consumption. Fluorescent lamps account for 20% of global lamp sales and 45% of electric-lighting energy consumption.

The next major group of lighting technologies are *high-intensity discharge (HID) lamps,* including mercury vapour lamps, high- and low-pressure sodium lamps and metal halide lamps. These high-power lamps provide large amounts of light at medium to high efficacy levels (35–150 lm/W) and are used primarily for outdoor lighting (including street lighting), and for indoor lighting in spaces with high ceilings. HID lamps account for 1% of global lamp sales, use 25% of global electric-lighting energy and provide 29% of the delivered light. Among HID lamps, mercury vapour lamps constitute an old and inefficient technology which, despite having low cost-effectiveness compared with the alternatives, still accounts for a significant share of total HID lighting applications.

Both HID and fluorescent lamps require ballasts to regulate input voltages and frequencies to enable the ignition and subsequent operation of the lamp. Ballasts need power in order to function, ranging from a few percent to as much as 40% of the total lighting system consumption, depending on the efficiency of the ballast adopted. Most IEA countries have adopted requirements that prohibit the use of the least efficient ballast technologies for linear fluorescent lamps (LFLs), but significant differences in performance still remain.

These three broad lighting technologies contain some important subgroups. Since their development in the 1980s, *compact fluorescent lamps (CFLs)* have gradually captured market share at the expense of incandescent lamps and by 2003 had attained global sales of 1 229 million lamps. Although this is only 8% of the annual sales of incandescent lamps, it represents 19% of the delivered light because of the much longer operational lifetimes of CFLs (from 5 to 15 times as long as an incandescent lamp). For an equivalent light output, CFLs use between one-fifth and one-quarter of the electricity that incandescent lamps use, and hence they are an important higher-efficiency option. Despite appreciably higher lamp prices, the overall cost of lighting from CFLs is far cheaper than that from incandescent lamps, because their operating costs are so much lower. Compared with the incandescent technology that they have replaced, the 3.5 billion CFLs in use today are saving 229 TWh of electricity annually and are avoiding at least 65 GW of power plant. If all incandescent lamps worldwide were to be replaced by CFLs, an additional 728 TWh of electricity would be saved per annum and global lighting energy demand would be lowered by 27%.

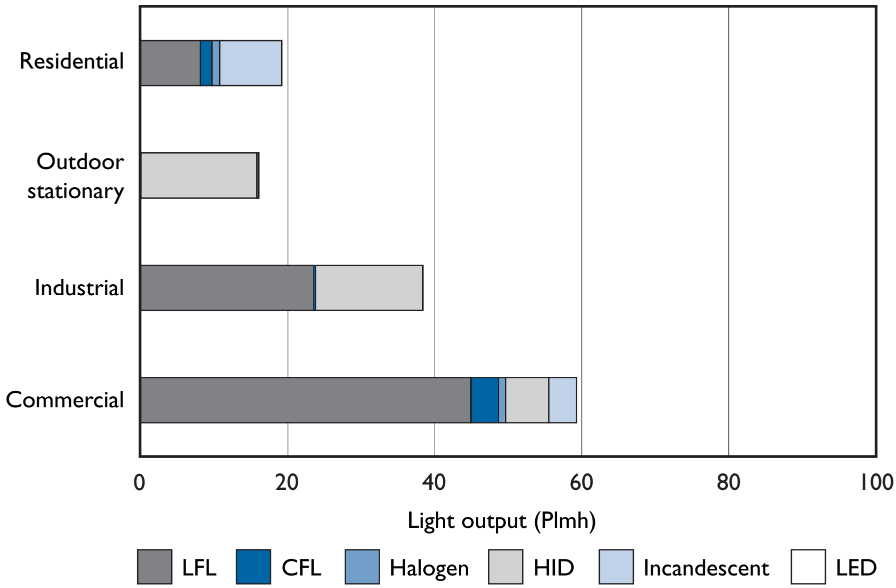
Linear fluorescent lamps (LFLs) are the most important lighting technology and provide the bulk of global lighting. This technology comprises three main groupings: T12s, T8s and T5s. The T12s are the older technology and are significantly less efficient than the other two; nonetheless, they still provide a large share of LFL lighting in many parts of the world, including in the IEA countries that operate lower-voltage electricity networks. Among the three types of LFL, standard T8s are of intermediate efficacy, but in their most efficient form (the so-called "Super T8s") their efficacy levels match those of the most efficient and newest LFL technology, T5s. A key factor influencing LFL efficacy is the quality of the phosphors used in the internal lamp coating. T5s always use high-quality triphosphors and T12s usually use low-quality halophosphors; T8s can be found with either.

Tungsten halogen lamps are another form of incandescent lamp. Their efficacy levels are slightly higher than those of conventional incandescent lamps but are still much lower than those of fluorescent lamps. There are several varieties of these lamps, although they are most commonly used to provide tightly focused spotlighting. Some halogen lamps operate at mains frequency and voltage while others require a step-down transformer that has its own losses. *Metal halide HID lamps* include a relatively new subset, known as ceramic metal halide lamps, which can provide a high-efficiency alternative to conventional halogen spotlights and are being used increasingly for display lighting. The most compact form of these lamps can also be used to substitute halogen lamps in certain domestic-lighting applications. Compact ceramic metal halide lamps are also now available as a high-efficiency alternative for mercury vapour street lighting.

High-wattage halogen lamps are also found in residential pedestal lamps known as "torchières", which are used to create a mood effect by reflecting intense light off the ceiling and walls. When viewed as a system this type of lighting is the least efficient of all commonly used electric-lighting systems. They add a large amount of heat into the living space as a by-product; as well as the possibility that this heat might require additional air-conditioning energy for its removal, it can also present a fire risk. In some countries they have disappeared from the market for this reason.

Because the efficacy of these various lighting sources varies so profoundly, their relative level of use has a large impact on overall lighting energy consumption (Figure OR.3). The factors influencing whether low-efficacy technologies can be substituted by higher-efficacy technologies can be complex and are discussed at length in the main text of this book; nonetheless, optimising the light-source mix has great potential to save energy.

Figure OR.3 **Estimated global average share of electric-light production* by lamp type and end-use sector in 2005**



* Total = 133.1 Plmh, source-lumens.
Abbreviations: CFL = compact fluorescent lamp; HID = high-density discharge; LED = light-emitting diode; LFL = linear fluorescent lamp; Plmh = petalumen-hours.

LUMINAIRES AND LIGHTING DESIGN

In a typical lighting system only 30% of the lumens emitted by the lamp make a useful contribution to the lit environment experienced by the users of the lighting system. The cause of this low utility coefficient is a combination of losses from light being trapped in the luminaire (the lamp housing), light absorption on surrounding surfaces and light being directed to areas where it is not needed. There is a very large range of luminaires available commercially and these can have significantly different optical properties, which have a large impact on the efficiency of the lighting system. Just as important is the quality of the design of the lighting system for the required task. A good lighting design can provide high-quality lighting for much lower energy levels than would be expected with a "boiler plate" lighting system. Modern computer technology has significantly increased the capacity to optimise lighting-system designs. However, this practice remains the exception rather than the rule and most systems are installed by electrical contractors with limited knowledge of high-efficiency opportunities.

LIGHTING CONTROLS

The choice of lighting controls from simple manual switches and dimming switches to presence detectors and light-level sensors has a large impact on total lighting energy use. The current under-specification of lighting control systems is causing a large proportion of electric light to be delivered to spaces where no one is present, or for which there is already adequate daylight. Research shows that simply providing users with the capacity to control lighting levels in the space they occupy can significantly lower lighting energy use. Using more sophisticated automatic controls will save even more energy (20–35% is typical) and can be highly cost-effective. It remains the case, however, that even simple on–off manual switches are often under-installed in relation to the need and that the use of automatic lighting controls is rare.

NEW LIGHTING TECHNOLOGIES: SOLID-STATE LIGHTING

Since their initial development in the early 1960s, the performance of solid-state lighting (SSL) devices such as light-emitting diodes (LEDs) has improved at a spectacular rate. Over the intervening period their light output per unit of electrical energy input has doubled every 24 months. SSL has now reached an important crossroads. Monochromatic LEDs typically have high efficacies and long lifetimes and have attained a quality and cost-effectiveness sufficient to enable them to have made major inroads into certain niche lighting markets, such as exit signs, indicator lights, mobile phone displays, traffic signalling and rear vehicle brake lights. Producing high-quality, cost-effective white-light emitting diodes (WLEDs) for general illumination is more challenging, but there are increasing signs that LEDs could be close to entering this market too. The best commercially available WLEDs currently have efficacies of 50 lm/W (which is four times that of a typical incandescent lamp and close to that of a CFL), but they still have many challenges to overcome before being serious contenders for general-purpose illumination. Even so, of all lighting technologies, LEDS appear to have the greatest scope for improvement and may yet transform the global lighting market. The SSL industry has set itself a target of attaining WLED efficacy levels of 200 lm/W, higher overall light output and competitive prices by 2010. If these targets are attained SSL could become the general-lighting system of choice and the overall efficiency of lighting could rise considerably. Much will depend on future levels of product development, which is in part contingent on the level of RD&D funding committed to the technology.

Moreover, there is one major new niche market waiting to be developed by the use of WLEDs: the replacement of off-grid fuel-based lighting. In recent months WLEDs have been integrated into lamps that can be powered by paperback-sized photovoltaic panels to provide 10–100 times more task-illuminance than common fuel-based lanterns and which will pay for themselves within one year. If the international community were to back further development and deployment of this technology, there might be an opportunity to dramatically raise the quality of millions of lives.

DAYLIGHT

Beyond more efficient lamps, energy efficient lighting choices include "free" lighting – daylight. In fact, while there is an enormous potential to substitute daylight for electric lighting, it can be technically challenging to harness daylight in an acceptable manner (primarily because of the high variability of natural light, and other issues such as glare and heat). So it is actually far from "free" in practice. Having noted this, good technical solutions exist to all these problems and the added design costs associated with harnessing daylight are completely outweighed by the benefits that accrue from its deployment. Apart from allowing lighting energy savings of up to 70%, day-lit buildings appear to be much preferred by their occupants and are attributed with a host of additional benefits, including better health and higher productivity. The latter in particular has been found to be of far higher value than the energy savings, which of themselves will comfortably repay the incremental costs of daylight deployment.

COST-EFFECTIVENESS

As a broad rule of thumb the most efficient lighting systems are the most cost-effective and their deployment frequently offers astonishingly rapid payback times. Despite more than 30 years of energy efficient lighting initiatives, which are discussed in Chapter 5, most businesses will still be hard-pressed to find an investment with better internal rates of return than are routinely attained from installing energy-efficient lighting.[2] The literature is replete with examples of highly cost-effective lighting retrofits, and in the case of new installations the economics are even better.

THE ROLE OF GOVERNMENT

So… what's the problem? Why should government be involved?

The existence of more energy-efficient lighting does not guarantee that it is widely taken up in the market place. The reasons behind this are manifold and differ by end-use sector; however, two factors predominate. First, in the absence of knowledge about the overall cost of the lighting service associated with each technology, users tend to choose the technologies they are most familiar with and which have the lowest initial capital costs. These are usually the older, less efficient technologies. Second, there are a variety of other market imperfections and barriers that militate against the adoption of lighting systems with the lowest overall cost-to-quality quotient. An example is split incentives inherent in landlord–tenant arrangements, which prevail in the tertiary-building sector, wherein a landlord may have little motivation to make capital investments in efficient lighting to lower the tenant's energy bill.

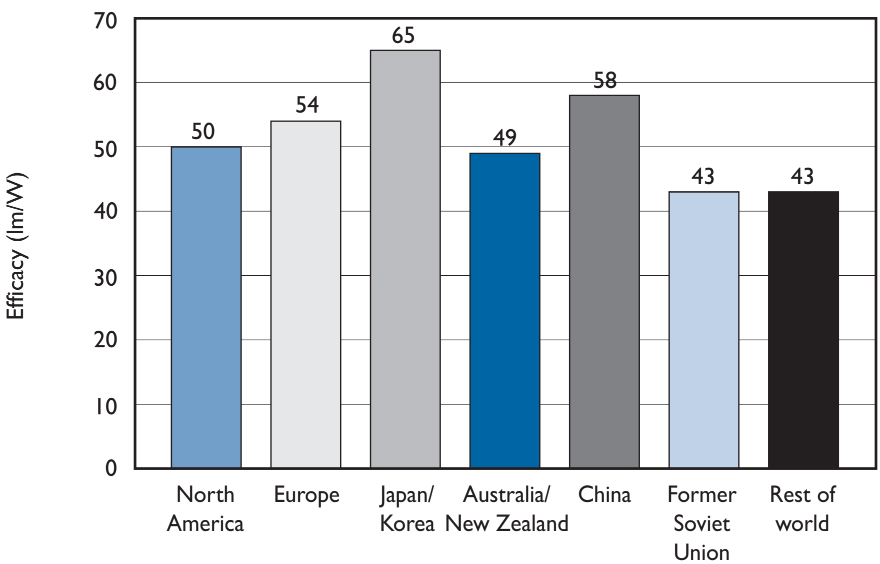
In fact the role of government in stimulating the adoption of efficient lighting has long been recognised and has led to an extensive history of energy efficient lighting policies and programmes. There have certainly been hundreds and probably thousands of different initiatives implemented since the first energy crisis of the early 1970s, and these

2. Various sources claim that investments in energy-efficient lighting offer a rate of return of 30–50% per year based on energy savings alone. It is further claimed by some sources that the value of associated worker-productivity benefits can be 10–100 times greater than the energy benefits.

have also coincided with a substantial improvement in average lighting-system efficacies. In 1960 the average lighting system had an efficacy of about 18 lm/W, whereas by 2005 this had risen to roughly 48 lm/W (Figure OR.4). The rate of improvement appears to have been relatively constant from 1960 to 1985, at about 2.8% per year, but from 1985 onwards it slowed to 1.3% per year. This decline in the rate of efficiency improvement mirrors that seen in other end-uses and sectors and may imply that efforts to conserve energy slowed as adjusted real energy prices fell back in the mid-1980s. The current environment of higher energy prices and concerns about energy security and climate change may provide a stimulus to reverse this tendency.

The main determinants influencing differences in average regional lighting-system efficacy today are the relative shares of fluorescent lighting to incandescent lighting and of mercury vapour HID lighting to other forms of HID lighting. The quality of fluorescent lighting, including ballasts, also has a significant impact. In many countries, including those within the OECD, the high proportion of residential lighting using incandescent lamps drags the overall efficacy level down. This can explain why a country

Figure OR.4 **Average lighting-system efficacy by region in 2005**



such as China, which has only recently introduced requirements influencing lamp efficacy, can have a higher overall efficacy than some OECD regions.

RESIDENTIAL SECTOR

In the residential sector, incandescent bulbs remain the dominant technology in most countries, largely because they are very cheap – so much so that their relatively short lifespans and high energy costs are not an impediment to their marketing. Consumers regard them as disposable. In addition, incandescent bulbs offer a warm colour, are available in an enormous range of styles and sizes, and can be dimmed – features that many consumers find attractive. While incandescent lighting, including traditional incandescent lamps and tungsten halogen lamps, are comfortably the most common type of lamp in the residential sector, they now provide a minority of total residential-sector light. The majority, 53%, is provided by fluorescent lighting, of which CFLs supply 13% and LFLs supply the rest. This may be a surprising finding but it reflects both the fact that the share of residential lighting provided by incandescent or fluorescent lighting varies considerably from one region to another and the fact that fluorescent lighting has been increasing its share of residential lighting in almost all countries over the last few years. In particular, CFLs are now making significant inroads into the residential-lighting market, stimulated by a sharp drop in price and an increasing variety of CFLs, including much smaller lamps that can fit into almost any incandescent lamp fixture. While many of the earlier barriers to the development of the CFL market (high price, lack of dimmability, a history of "cold" colour output, relative bulkiness and a narrow range of decorative forms) have been fully or partially addressed, there are still ongoing barriers to be tackled. These barriers include a continuing lack of awareness of CFL benefits; many consumers know CFLs are energy-saving lamps, but few have any idea of their much lower life-cycle costs, and consequently most remain averse to paying a higher price for a CFL than for an incandescent lamp. Another barrier is presented by ongoing lamp-quality problems – a lack of product-quality policing has allowed substandard and unreliable products onto many markets, which undermines consumer confidence in the technology. In general, the low level of public awareness of lighting energy use remains a major impediment to the uptake of energy-efficient residential lighting. The comparatively high running costs of incandescent bulbs are poorly understood or may be dismissed because of the relatively small sums of money involved, at least for each lamp. In addition, most consumers receive electricity bills infrequently and have no way of understanding which part of the bill is accounted for by lighting.

While in some IEA member countries the energy efficiency of some types of lamps is labelled, the coverage is far from complete and the labels may not provide all the information relevant to consumers (energy costs, colour characteristics, dimmability, durability, etc.). Often, the more efficient lamps are labelled but the less efficient ones are not. Consumers may therefore not be in a position to make rational choices between lighting options, particularly if the information they need is not available at the point of sale. Finally, labelling lamps alone may be insufficient, as the choice of light fitting may determine – for the life of that fitting – the type of lamps that can be used.

With limited exceptions (the United Kingdom and some US and Australian states), there are no controls or standards on residential-lighting energy efficiency in IEA member countries. This reflects, in part, the fact that light fittings and lamps are largely chosen by householders and cannot effectively be "policed". However, with new houses often being fitted with low-voltage halogen lamps, recessed incandescent "cans" or other lighting choices that effectively preclude more efficient lamps being installed without major renovation work, the wider use of mandatory limits on lighting power density (common in commercial building codes) should also be considered for residential buildings. More generally, however, the difficulty in "policing" the use of lighting in the home suggests that minimum energy performance requirements for the lamps themselves may be a better policy choice. In short, a significant strengthening of policies is required to mitigate the rapid growth of energy demand and greenhouse gas emissions associated with lighting in the residential sector.

COMMERCIAL AND INDUSTRIAL SECTORS

In the commercial and industrial sectors, and at least in premium buildings, lighting systems are generally chosen and managed with a more careful eye to the economics, as well as with regard to productivity and welfare impacts on the building occupants. Also, unlike the case in the residential sector, many countries have minimum energy performance requirements for lighting in commercial buildings. Therefore, with the natural turnover of building fit-outs, worst lighting practices have often been upgraded over time.

However, premium buildings such as corporate headquarters and downtown office blocks comprise a small share of the total building stock. Analysis in some IEA member countries shows that energy-efficient lighting is deployed in well under half of commercial buildings, and the figure may be lower elsewhere. Issues include: low-quality systems installed in non-premium, industrial or small retail buildings; high consumption in display lighting; the relatively poor diffusion of advanced lighting controls, sensors and other automation systems; and poor arrangements for switching (whole buildings or floors on one switch). Inefficient lighting is also a major source of internal heat load, meaning that additional energy must be expended to remove waste heat from lighting through the building's cooling and ventilation system.

The nature of the commercial building market poses significant challenges for energy-efficient lighting. Short lease terms – notably for retail buildings – may not allow sufficient payback time on more efficient equipment. In addition, tenants may have little or no control over lighting systems that are installed by the building owner or manager. In other cases, the electricity costs associated with lighting may be rolled-up into an overall monthly leasing charge, removing any incentive for the tenant to install efficient lighting. Sub-metering systems that would allow tenants to feel the direct cost of their lighting systems are rare. Finally, commercial and industrial lighting may also suffer from the same problem observed for residential lighting: the perception that the costs are too small to worry about, combined with a lack of awareness of the high cost-effectiveness of the energy-savings alternatives.

Within the regulatory environment, key issues include the stringency of overall power density requirements (usually expressed in terms of maximum permissible power per unit floor area [W/m^2] thresholds) and the nature of general lighting requirements (which may require high and/or uniform levels of illumination, even though this may lead to over-lighting of infrequently used or "non-critical" areas of buildings and may pose a regulatory barrier to the use of daylight). Few building codes demand automation systems or optimal use of available daylight, and not all codes require zonal or individual luminaire switching. It has been demonstrated, for example, that switching or automation systems based on a "manual on, automatic off" logic are highly effective in saving energy, particularly where daylight is available and where lights are gradually dimmed rather than abruptly switched. Also, while many countries have minimum energy performance requirements for ballasts or for lamps, they may not have them for whole luminaires (lamp, ballast and fitting). This may be the case even though the performance of each component of this system, together with the integration of the components into the whole luminaire and the luminaire into the building, is relevant to the total energy consumption per unit of useful light output at the working plane.

MUNICIPAL OUTDOOR LIGHTING

Mercury vapour HID lighting is a superseded technology that has much lower efficacies and higher overall operating costs than its competitors (sodium and metal halide HID lamps); nonetheless, this technology continues to be widely used for outdoor public lighting, because its first costs are relatively cheap. Many municipalities are either unaware of the life-cycle cost and quality advantages of alternative HID technologies or have perverse cost-management incentive structures that reward lowest-cost capital procurement to the detriment of minimised operating costs. The inability of many municipalities to finance capital investment projects is also a constraint limiting the uptake of higher-efficiency options.

THE BENEFITS OF ENERGY EFFICIENT LIGHTING POLICIES

There is a growing wealth of experience with energy efficient lighting policies

At various times all IEA countries have implemented policies to encourage more efficient lighting and all currently have some policies in place. These policies can be divided into those that apply to the lighting-system components and those that apply to the system as a whole. The former include regulatory measures, such as energy labelling and lamp and ballast minimum energy efficiency requirements, but can also include information, incentives (such as subsidies for the purchase of efficient equipment) and agreements with industry to discontinue production and marketing of outdated technologies.

The latter most commonly include guidelines or mandatory requirements regarding the efficiency of new and/or retrofit lighting installations. Since 1989 a progressively larger number of US states and Canadian provinces have introduced mandatory building codes that specify minimum energy performance requirements for new lighting systems. This mostly involves the imposition of maximum lighting-system power-density limits (power use per unit floor area) but increasingly involves specification of minimum requirements for lighting controls too. Six EU countries have similar requirements and the remainder are in the process of developing them under the auspices of the 2001 Energy Performance in Buildings Directive. The impact of these measures is uncertain, largely because the level of compliance is not fully known, but is thought to be highly significant. For the United States and Canada, it is estimated that a mixture of federal component standards, state building regulations that have come into force from 1990 onwards, and numerous utility energy-conservation programmes are currently saving 171 TWh of lighting energy demand each year compared with what would have been the case had they not been implemented. This is 20% of current lighting energy consumption in the region and amounts to annual savings of over 500 kWh (the energy consumption of a typical refrigerator) per capita. Similar programmes in other IEA countries launched over the same time frame are estimated to be lowering total lighting energy consumption by 4–19%. These kinds of assessments may only give part of the picture, however, as measures that directly influence component efficiency or average installed wattages per unit area are easier to evaluate than those which encourage the deployment of daylight or more effective lighting control. There is a degree of evidence, for example, that lighting energy consumption in some European countries has been limited by relatively successful efforts to curb lamp operating hours and utilise daylight.

There have also been many positive experiences with energy efficient lighting policy in less developed countries. CFL subsidy programmes in Brazil, Mexico, Peru, South Africa, Martinique and the Philippines, among others, have had major impacts on the average efficiency of residential lighting and have contributed to the reduction of system peak-power loads. Programmes to improve the energy efficiency of LFLs have been successfully implemented in countries such as Thailand, Mexico and China. In general, there has been less activity in the commercial sector and most developing countries do not have building energy codes. Of the few that do, even fewer have provisions for lighting. China's newly developed building lighting code is an important exception. Such is the rate of new construction that it has been estimated that if this code is fully complied with, an increment of 10.7 TWh of electricity demand will be avoided each year in commercial buildings alone. This is equivalent to offsetting the need for a new Three Gorges Dam project every eight years! In fact these figures are conservative because they take no account of the electricity saved from lower internal heat gains and hence lower air-conditioning loads. Most electricity networks in China are summer peaking, and each lighting watt saved avoids an additional 0.3–0.5 W of air-conditioning power demand.

A HIGH COST-EFFECTIVE SAVINGS POTENTIAL

There is a very large cost-effective potential to reduce energy demand and greenhouse gas emissions through more energy-efficient lighting

Even in those regions with the most developed policy frameworks, the potential for further cost-effective savings from strengthening lighting-efficiency policies and from their implementation remains great.

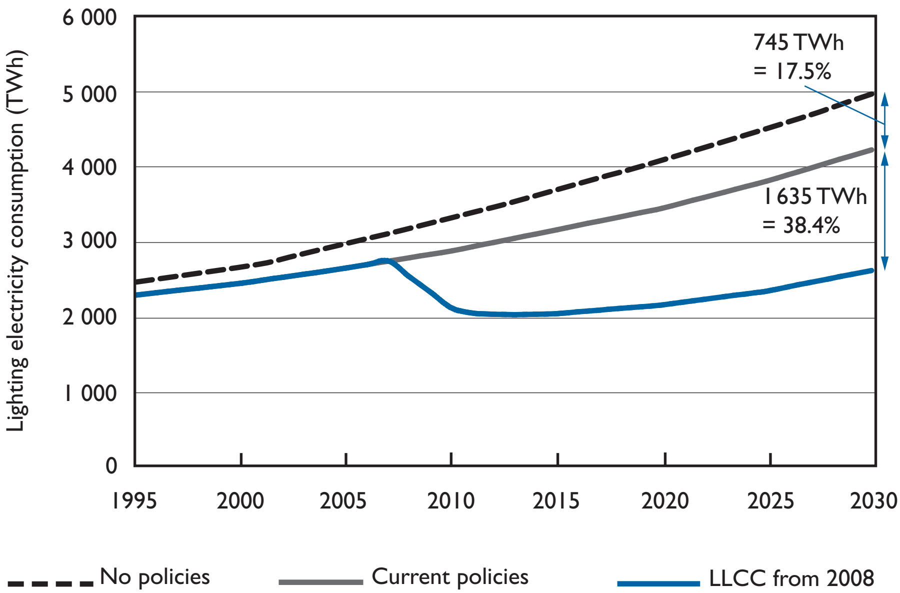
The current global average cost of electric light is about USD 2.8/Mlmh, of which two-thirds is the energy cost and one-third is the cost of equipment (lamps, luminaires and control gear) and labour needed to install and maintain the lighting systems. The use of lighting systems that minimise life-cycle costs[3] (*i.e.* so-called "least life-cycle cost" [LLCC] lighting systems) lowers the average cost of light by more than one-quarter.

It is estimated that the systematic deployment of LLCC lighting solutions from 2008 onwards would substantially reduce global energy consumption attributable to lighting. The resulting electricity consumption for lighting would be 38% lower in 2020 than would be expected if continuing with the current set of policies,[4] avoiding the consumption of 1 311 TWh of electricity and 763 Mt of CO_2 emissions (Figure OR.5). By 2030, annual savings would reach 1 635 TWh and 973 Mt of CO_2, respectively.

3. The life-cycle cost of a lighting system is the sum of its initial cost (the sum of the purchase price and the installation cost) and the discounted operating costs (the energy and maintenance costs discounted over time to take account of the time-dependent value of money). In this analysis a real discount rate of 5% is assumed.

4. The Current Policies scenario is the equivalent for lighting only of the Reference Scenario in the *World Energy Outlook* (OECD/IEA, 2004). It assumes that energy-efficiency policies implemented between 1990 and 2005 remain in place until 2030 but that they are not strengthened or expanded. The No Policies scenario indicates what would have happened had the current policies not been implemented. The LLCC from 2008 scenario indicates what would happen if all lighting systems installed from 2008 onwards were to have an efficiency that minimises the life-cycle costs of the lighting from the end-user's perspective. It is not a policy scenario *per se,* although it does indicate the scope for policies to be strengthened and hence is not directly comparable to other policy scenarios, such as the Alternative Policy Scenario in *World Energy Outlook.*

Figure OR.5 Global lighting electricity consumption in 1995–2030 under the No Policies, Current Policies and LLCC from 2008 scenarios

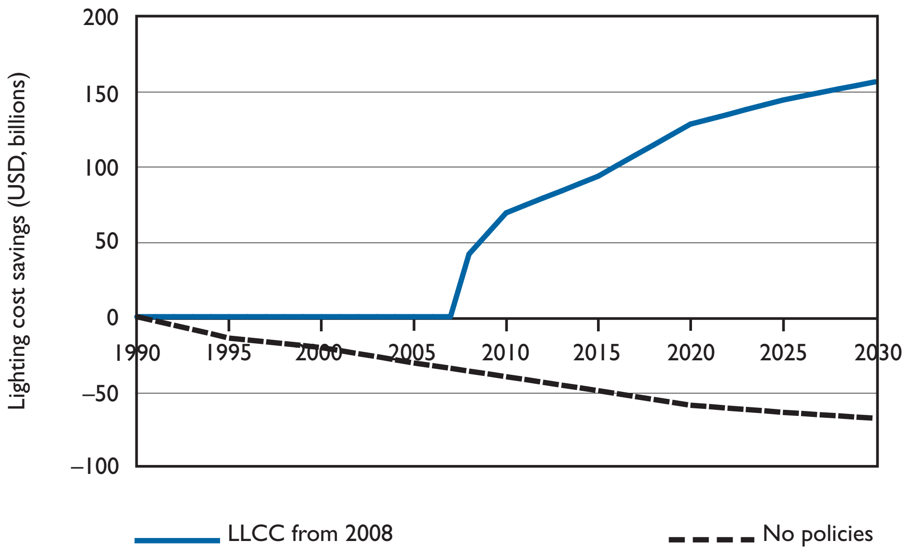


Abbreviation: LLCC = Least Life-Cycle Cost.

The full adoption of LLCC lighting will save end-users USD 126 billion in total annual lighting costs (equipment, energy and labour) by 2020 and USD 153 billion by 2030 (Figure OR.6). The global net present value of these cost savings, assuming a 5% real discount rate and discontinuation of benefits after 2030, is USD 742 billion – equivalent to USD 112 per capita. Although there are similar cost-effective energy-savings potentials in all the world regions examined[5], the per-capita benefits are highest in OECD countries, where lighting consumption is greatest (reaching USD 219 in North America, for example). By contrast, the magnitude of cost-effective savings as a proportion of per-capita income will be greater in non-OECD countries. Since by definition implementing LLCC lighting saves end-users money, the global average cost of avoiding CO2 emissions through these measures is estimated to be negative, at **USD –161 per tonne of CO_2**.

5. The overall cost-effective savings potential ranges from 31% in Japan/Korea to 51% in the Former Soviet Union. It averages 38.4% globally.

Figure OR.6 Global lighting-cost savings under the LLCC from 2008 and No Policies scenarios compared to the Current Policies scenario



The high potential for energy savings in lighting reflects the fact that although there are already many cost-effective energy-efficient lighting technologies available on the market, they are currently underutilised. The estimated savings potentials presented in the previous paragraph are based on today's artificial-lighting technology and today's average prices; however, new lighting technologies under development promise higher levels of efficiency and could further increase the cost-effective savings potentials to 2030. Furthermore, the above estimates take no account of the cost-effective potential to increase daylight utilisation beyond the selective use of automatic dimming systems in spaces that already have access to daylight. Finally, the calculations take no account of the reduction in parasitic lighting-induced energy loads such as air-conditioning, nor the typical high peak-power coincidence factor of many lighting loads that increases the value of their savings compared to average electricity loads.[6] If all these factors were to be fully taken into consideration, the cost-effective savings potential could be substantially greater.

6. The value of avoided summertime air-conditioning loads as a result of less heat from efficient lighting is usually greater than the increase in costs for extra wintertime space-heating demands because (i) globally, more utilities are summer peaking than winter peaking, (ii) peak power is more expensive to service than is demand at other times, (iii) electricity is much more expensive to store than most heating fuels, and (iv) electricity is the only practical means of powering air-conditioning, but many fuels can be used for space heating.

To achieve market transformation for energy-efficient lighting, governments must put in place an integrated, comprehensive policy approach, drawing on a wide range of measures

All IEA member countries have policies designed to encourage wider uptake of energy-efficient lighting. However, the trends in technology choice, energy demand and greenhouse gas emissions documented in this study suggest that these policies are insufficient. Despite substantial improvements in average lighting-system efficiency, inefficient systems and practices are still commonplace in all IEA and non-IEA economies. Different countries have had varying degrees of success in addressing specific lighting issues, but all have substantial opportunities to improve the overall energy efficiency of the lighting service provided within their borders through the adoption of more comprehensive policy settings.

It is proposed that a comprehensive, integrated policy approach based on best practices in each element of the policy mix is needed to successfully transform the lighting market and achieve its cost-effective efficiency potential. Such an approach requires not only all lighting technologies and applications to be encompassed, but also the engagement of all relevant actors, including manufacturers, retailers, building owners and managers, building occupants and householders, building designers, lighting design and installation professionals, electricity utilities and municipalities. A best-practice policy approach means that each element of the policy mix should draw on best-practice models from around the world, adapted to local requirements, with the mix of measures designed to reinforce each other and to deliver optimal policy outcomes.

So, what is best practice in energy-efficient lighting? There is, of course, no universal answer; different countries are at different starting points, have different lighting markets and needs, and have different policy measures already in place. However, in general such a policy package will incorporate measures to ensure future lighting installations all perform to at least a minimum overall efficiency level while encouraging the early adoption of systems that perform to higher efficiency levels. The recommendations below are therefore offered as a checklist for countries that choose to review their lighting policies.

RECOMMENDATIONS ON POLICY OBJECTIVES

Policy measures are needed to address the following objectives:

- Phase out or substantially reduce the use of low-efficacy lamps and control gear, most notably:
  - Mercury vapour HID lamps.
  - Incandescent lamps.
  - Low-efficacy LFLs (T12s and halophosphor T8s).
  - Halogen uplighters.
  - High-loss ballasts (for both fluorescent and HID lamps).
  - High-loss halogen transformers.
  - Low-efficacy vehicle lighting (especially where daytime running lights are required).
  - Fuel-based lighting in developing countries.
- Encourage the adoption of high-efficiency luminaires and discourage the use of their low-efficiency counterparts.
- Encourage or require the use of appropriate lighting controls (switches, presence sensors and daylight dimming for indoor lighting and presence sensing with off-peak circulation dimming for outdoor lighting).
- Ensure lighting systems are designed to provide appropriate lighting levels; guidelines or requirements for the latter should be based on the findings of international research on human lighting needs – countries that currently recommend significantly higher lighting levels than their international peers may wish to review the technical basis of those recommendations.
- Stimulate better lighting design practice to encourage task lighting, individual user control of lighting needs and dynamic integration with daylight rather than uniform artificial illumination.
- Encourage greater and more intelligent use of daylight in the built environment, resulting in energy, health and productivity benefits.
- Reduce light pollution.

- Stimulate the development and early adoption of new, more efficient lighting technologies.
- Overcome market barriers to efficient lighting and negate the overemphasis on first costs in favour of life-cycle costs.
- Protect consumers from poor-quality lighting components such as low-quality CFLs and LFLs with a lifespan, light output or efficacy that does not meet declared and/or minimum values.

To help encompass these objectives it may be useful, but not essential, to establish broad-based efficient-lighting programmes with overarching quantified policy targets. These could include targets for:

- Minimum average installed efficacy targets for each end-use sector (e.g. depending on circumstances, indicative targets could be 90 lm/W for tertiary- and industrial-sector indoor lighting, 50 lm/W for residential lighting, 110 lm/W for public street and roadway lighting, 30 lm/W for vehicle headlamps and 80 lm/W for vehicle brake lights) within a prescribed time frame.
- Minimum average luminaire output ratios (e.g. greater than 70% for non-residential indoor lighting and 50% for residential indoor lighting).
- Minimum average adoption rates of lighting controls by sector and types of floor space.
- Minimum daylight-utilisation factors for both new and existing buildings.
- Global development objectives for the substitution of fuel-based lighting (e.g. less than 500 million people to be solely dependent on fuel-based lighting by 2015, etc.).

RECOMMENDATIONS ON POLICY MEASURES

The fulfilment of such policy objectives requires the adoption of specific policy measures, which in turn may require the establishment of a mixture of implementation programmes and regulatory measures.

We recommend that countries consider the following.

1. Adoption of mandatory energy performance requirements for lighting systems in all lighting end-uses.

Mandatory energy performance standards may be developed for residential, commercial/industrial and outdoor applications, whereas today such requirements usually only cover the commercial/industrial sector. Wherever possible, requirements should be performance-based and not prescriptive with respect to certain technologies. Performance requirements are needed at the level of both whole lighting systems and system components (lamps, ballasts and luminaires/fittings, since these are often "mixed and matched"), and should be based on realistic test procedures. Performance requirements should target the LLCC for the lighting system, using (shadow) energy prices adjusted to reflect the value of associated greenhouse gas emissions. They also need to take into account: (i) an appropriate mix of peak and off-peak electricity prices (reflecting the incidence of lighting demand in peak system demand, and the duration of peak system costs); and (ii) the indirect parasitic energy implications of lighting (higher air-conditioning loads, but lower space-heating loads). Performance requirements should be updated regularly (at 3- to 5-year intervals) to reflect changes in life-cycle costs.

2. Adoption of mandatory building codes, or other regulations, that set maximum lighting power density limits for all building types.

Performance requirements are necessary at the level of whole buildings (*i.e.* lighting applications), since even with highly efficient components, lighting applications can be inefficient, *e.g.* through excessive lighting density. In the majority of IEA countries specific lighting requirements are either not yet in place or only apply to indoor lighting of newly constructed non-residential buildings. Policy-makers should consider the establishment of requirements where none exist, the broadening of current requirements to encompass all building types including residential buildings and major retrofits of existing buildings, and the establishment of requirements for outdoor lighting.

3. Building codes requiring lighting control systems that allow separate switching and regulation for each room or work area, rather than whole floors or buildings.

Inadequate deployment of switching and controls for lighting systems is an important source of energy inefficiency. Increasingly, controls are able to regulate luminaire output as a function of daylight availability, occupation of the illuminated space and/or time of day. Such controls should be encouraged, or required, when cost-effective on a life-cycle-cost basis.

4. Strengthening of the enforcement of existing regulatory requirements, particularly building codes.

While all IEA countries have energy provisions in their building codes and many have implemented or are developing lighting provisions, the enforcement of these provisions appears to be seriously neglected and reported compliance levels remain low. Countries are urged to pay much greater attention to this issue as its neglect is currently seriously undermining the effectiveness of public-policy objectives.

5. Adoption of whole-building energy-performance codes and building energy-performance certification.

IEA member states are increasingly adopting building codes that assess whole-building energy performance as opposed to just prescribing performance limits for specific components. This is to be encouraged as it enables all aspects of building energy performance to be taken into account, including lighting, on an equal basis. Many IEA countries are also adopting building energy performance certification and disclosure labelling, which enables market actors to see the energy efficiency of the building stock and take more rational market decisions accordingly. This practice is encouraged but it is also proposed that the certificates might be designed to report lighting energy both within the whole-building rating and as a separate element. The latter will allow short- to medium-term tenants (especially in the tertiary-building sector) to consider the viability of lighting-system upgrades independently of more costly fabric and heating, ventilation and air-conditioning-based measures.

6. Comprehensive labelling of lamps, fittings and whole systems, backed up by effective point-of-sale and reference information.

Mandatory, comparative energy-performance labels should be carried by all lamps and all lamp fittings/systems (where the lamp and fitting are sold together as one unit, or where the fitting only allows one type of lamp to be used). In this case, the fitting should be labelled "As sold", *i.e.* tested with the lamp actually fitted for sale. Where this is not possible, a generic warning label could be considered, *e.g.* "Warning: this light fitting is not suitable for low-energy lamps". "Low-energy lamps" would be defined with reference to the performance standards referred to in the first recommendation above. Point-of-sale information and reference materials should be provided to explain the meaning of labels and to assist consumer research. Currently, labelling is often voluntary, covers only a portion of the lamps on the market and generally does not apply to fittings.

7. Market-transformation initiatives to overcome market barriers for energy-efficient lighting technologies.

Such initiatives may be technology-neutral (*e.g.* provide assistance for the commercialisation of lamps that achieve a certain performance level) or technology-specific, targeted to overcoming specific barriers unique to one technology (such as the relative bulk of CFLs). There are numerous successful examples of such programmes, from the US ENERGY STAR and Green Buildings initiatives to the China Greenlights programme and the United Kingdom's Energy Efficiency Obligation. It is recommended that all countries consider such initiatives, and for those that already have them to consider extending their ambition.

8. Governmental removal of barriers to the efficient operation of energy service providers.

Energy service providers such as energy service companies (ESCOs) comprise an important delivery mechanism for energy-efficient lighting, particularly for the business sector. However, ESCOs have generally suffered as a result of the liberalisation of electricity markets, which has reduced the market presence of efficient-lighting options. Market regulators may wish to review the extent to which demand-side service options are able to compete fairly under current regulatory frameworks and to consider implementing policies to address any problems identified. Some recently implemented approaches with great promise include systems benefits charging, energy-efficiency obligations and white-certificate schemes.

9. Governmental support of public-interest R&D into new lighting sources and applications.

Some countries provide significant support for R&D efforts designed to bring to the market new lighting concepts and technologies. Given the limitations of some existing energy-efficient lighting technologies, ongoing support is required to deliver broadly acceptable and energy-efficient lighting solutions. Where such research is "near to market", public–private partnerships may be an important delivery mechanism.

10. Donor and development agencies and multilateral banks working with developing countries to promote solid-state off-grid lighting.

The plight of the 1.6 billion people using fuel-based lighting could be significantly improved were they to have access to affordable and superior-quality lighting. Recent advances with WLEDs have dramatically improved the cost-effectiveness, durability, longevity and overall viability of standalone photovoltaic-powered lighting systems. It is recommended that an international development effort be considered to accelerate the spread of this technology to those in most need of it.

It is recommended that policy makers establish comprehensive policy portfolios such as these at the earliest opportunity and, most importantly, identify and commit appropriate resources for their successful implementation.

THE MEANING OF LIGHT

One of the most remarkable yet least discussed stories in the history of human development is the quest for affordable and readily available light. These days we scarcely pay attention when we enter a room bathed in electric light, yet today's artificial lighting levels would have been remarkable to our not so distant ancestors. From the late 19th century, when Thomas Edison created the first mass-produced incandescent light-bulb, electric lighting has transformed our economies and way of life. Modern electric lighting has become a ubiquitous feature of advanced societies, essential to their productivity (adequate lighting levels for work tasks and reduced dependence upon daylight) and for the welfare of their citizens (enabling reading, study and housework to be undertaken at night or indoors away from a window and improving safety of movement and security outdoors). In order to understand the importance and colossal scale of artificial lighting in today's world, it is worth taking a few moments to review this transition. This is important not so much to understand how we arrived at the situation that exists today, but to comprehend the scale and value of lighting as a service and to grasp the ongoing trajectory of lighting developments.

This book's title mimics that of a play by the most celebrated playwright in the English language, William Shakespeare. When he penned *Love's Labour's Lost* in late 16th-century England, tallow candles and firelight were the main sources of artificial illumination. As a test bed for the development of lighting, England is a convenient case to examine, being perhaps the only country with such long, complete records on lighting. It was also the first country to industrialise and hence to have had periods when all new lighting technologies of the last 400 years have been deployed. In 1594, the English used an average of slightly over 2 kg of tallow candles per person each year to provide some 0.7 klmh (kilolumen-hours) of light output per capita. In today's terms this light cost over GBP 12 000 (USD 21 000) per megalumen-hour (Mlmh) (Table 1.1).

In many ways the history of the development of artificial light is a metaphor for the history of human civilisation. Through it we can chart the acceleration in industrial progress, including the increase in technological learning rates. Over the 600 years from 1300 to 1900, the real price of light from tallow candles decreased by about 32 times in the

Table 1.1 Price (constant year-2000 GBP) of 1 Mlmh of light in the United Kingdom from 1300 to 2000

Year	Technology				
	Tallow candles	Whale oil	Gas light	Paraffin light	Electric light
1300	40 000				
1600	12 598	24 567			
1700	11 024	15 748			
1825	2 835		1 938		
1860	2 047		310	1 550	
1883	1 417		194	326	930
1900	1 260		119	171	341
1950			41	186	8
2000			12	209	2

Source: Fouquet and Pearson, 2003.
Abbreviation: Mlmh = megalumen-hour.

United Kingdom. By contrast it took only 112 years from its first development for the real price of gas light to fall 32 times and just 44 years for the price of electric light to fall by the same factor. Within the history of lighting we can see the rise and fall of technologies, e.g. the rise and decline of whale oil lighting (which was always more expensive than tallow candles but was preferred by the wealthy because it was less smoky), and the rise of gas lighting (which provided the first integrated urban energy-supply networks and pioneered the development of today's municipal gas systems before becoming marginalised as a purely off-grid option with the advent of electric lighting). Paraffin (kerosene) lighting arrived in the 1860s, some 35 years after gas lighting. Despite its real price falling from GBP 1 550 to less than GBP 200 per megalumen-hour by 1900, its cost since then has remained almost unchanged. Consequently, paraffin is used as a lighting source today only by those who have no access to electric light.

The net result of these developments has been a dramatic increase in the affordability of artificial light and its direct corollary, an explosion in the use of artificial lighting. In the four centuries that have elapsed since Shakespeare's time, the real gross domestic product (GDP) per capita in England has grown over 19 times and the real price of light has fallen 6 300 times. In 1600, 1 Mlmh of light cost the same as the annual output of 14 people. In 2000 the annual output of a single person could purchase that amount of light 8 500 times over. In 1700 the average annual per-capita consumption of artificial light in the United Kingdom was 800 lmh (lumen-hours) (from tallow candles). In 2004 it was 61 Mlmh, some 76 000 times more light per person. Intriguingly, this massive growth is two-thirds of the growth in the affordability of light, which is expressed by the cost of a lumen-hour as a percentage of per-capita annual productive value. In 1600 the English people spent 1.1% of their GDP in artificial light and in 2000 this figure was 0.7% for the same service. The analysis shown later in this book reveals similar shares of GDP being spent on artificial illumination in other OECD countries.

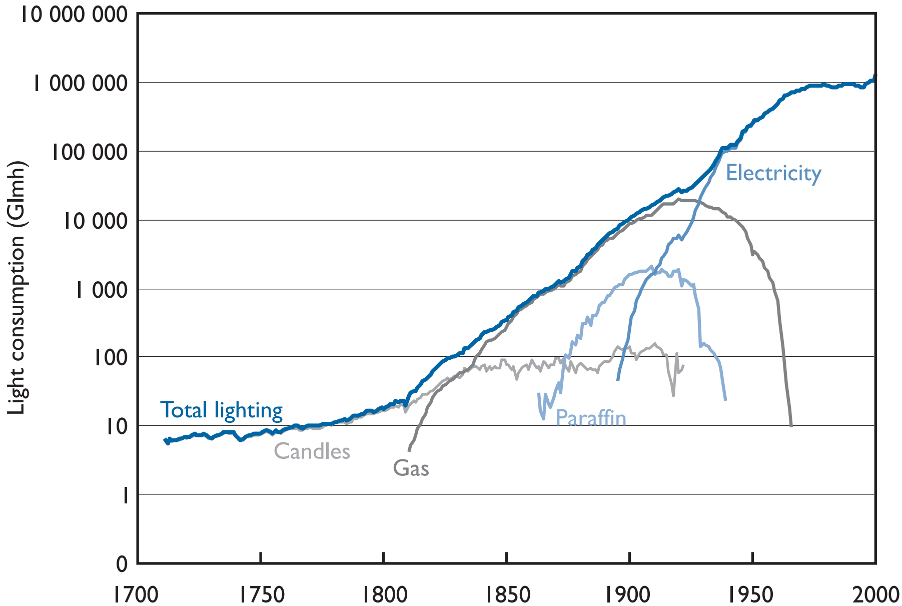
This implies that the major influence on the consumption of artificial light is its affordability – the cheaper it becomes and the wealthier we are, the more we use. Perhaps this is so, but while it is undoubtedly true for developing societies, there is recent evidence which may indicate that some economies are near to sating their appetite for artificial light for the first time in history. This is discussed in Chapter 4.

In the United Kingdom the consumption of artificial lighting grew logarithmically from 1800 to 1975 before levelling off onto a slower growth trajectory (Figure 1.1). Other countries undergoing industrialisation and its associated economic growth will have experienced similar trends, although most likely at faster rates.

As will be seen in later sections of this book, neither the development of lighting technologies nor the growth in demand for artificial lighting has yet stabilised. On a global level lighting services are still in an era of rapid growth in demand, albeit at a slower rate than following the breakthrough represented by electric lighting.

Small wonder that a service that was once the sole preserve of the ultra wealthy has today become an anonymous commodity that leaves its users oblivious to its presence. Most inhabitants of the industrialised world would only notice the lighting if "there is something wrong with it". Large amounts of artificial lighting is now the norm rather than the exception, but the lighting affluence of the majority should not blind us to the magnitude of the exception. One-quarter of the world's population has no access to electric light and must make do with much poorer lighting technologies that were long abandoned by the rest of us.

Figure 1.1 **Consumption of lighting by candles, gas, paraffin and electricity in the United Kingdom between 1700 and 2000**



Source: Fouquet and Pearson, 2003 (reproduced with permission).
Abbreviation: Glmh = gigalumen-hours.

SO WHAT IS THE MEANING OF LIGHT?

There have also been many technological developments with regard to electric lighting, each of which has left a legacy leading to today's lighting systems. In cartoons the world over, a "bright" idea or revelation is symbolised by the sudden appearance of an incandescent light-bulb over the hero's head – an allegory for the psychological impact of modern lighting. Yet in today's world, where rapidly rising demand for energy (including that required to feed billions of incandescent light-bulbs) is contributing to equally rapid growth in greenhouse gas emissions, the incandescent light-bulb should rather be a symbol of waste. Incandescent bulbs are both energy-hungry and short-lived, although many newer lighting technologies are not much more energy efficient, as will be seen in Chapter 3.

Few households and businesses are aware of the overall impact of lighting in terms of energy use, economic costs and environmental consequences. In the domestic sector, homes often have dozens of lights and there is a common perception that the energy costs of lighting are low. Any individual lamp has minimal impact, yet in aggregate, and particularly at the level of cities, regions and countries, the impact is very great. In this sense, lighting is a case study in the wider problem of energy efficiency – wherever each example of inefficient energy use (such as an incandescent light-bulb) is relatively small, it will never be addressed, even if the "many little inefficiencies" (Laitner, 2002) together add up to one enormous inefficiency at the national and global levels.

In fact, as detailed in p. 177, lighting accounts for 19% of global electricity consumption, and the total is still rising. The commercial and services sectors depend on good lighting to allow employees to work effectively and to ensure safety, and lighting represents a surprisingly high share of total electricity use in these sectors – up to 60%. Even so, best practice is still not widespread. More efficiency in the use of lighting will lower total energy costs significantly, contribute to greater energy security and have a positive impact on the environment. In most countries lighting is a significant contributor to peak load demands, and therefore to peak prices and reliability risks. In summer-peaking regions, daytime commercial-sector lighting loads add to the demand for air-conditioning, and both add to the afternoon peak. In winter-peaking regions, lighting demand is at its most sustained when days are short and lighting demand in the residential sector overlaps with that in the commercial sector. For countries with capacity concerns, this can be a major problem.

Since the IEA first took an active role in promoting energy-efficiency policies in its member countries in the 1970s, lighting has been an important area in which significant energy savings are available. This was most recently recognised in the IEA report *Cool Appliances: Policy Strategies for Energy-Efficient Homes,* published in 2003. Energy savings in lighting use are achieved through minimising the hours of use (not to do without, but to avoid use when not needed) and the installed lighting power, while in the long term energy efficiency is achieved through the deployment of more energy-efficient technologies or systems.* In the past few decades,

* There is some confusion concerning the meaning of energy-efficient lighting. Obviously, replacing one light that is marginally more efficient than the existing one is an improvement and should be encouraged. Some argue that replacing a 60 W incandescent bulb with a 40 W incandescent bulb, if that provides the necessary lumens for a specific task, is an efficiency gain. Some argue it is not. Undoubtedly, however, "oversizing" is an issue, as it is for boilers, for example.

many new energy-efficient lighting technologies have come to the market in all end-use sectors. Yet for the consumer, there are so many factors that contribute to choosing lighting that energy consumption is often low on the priority list. This is exacerbated by a low general awareness of lighting-energy issues.

There have been many efforts by governments, utilities, the lighting industry, non-governmental organisations and others to promote energy-efficient lighting. Some of these promotions have been short-term awareness campaigns or design competitions, while others have been long-term standards or financial incentives. Undoubtedly there has been success, yet more is needed. As stated in *Cool Appliances:* "For maximum impact, appliance [including lighting] energy policies would need to be strengthened and broadened in coverage. In some cases, they would need to be redesigned, supported with an adequate legal and institutional framework, given adequate resources and appropriately administered." (OECD/IEA, 2003, p. 15)

The fact that electricity consumption for lighting and related greenhouse gas emissions is projected to grow over the coming decades (pp. 390–409) should be of real concern for policy-makers. But policy-makers also need to be aware that improved policies can make a significant impact on improving energy efficiency. The deployment of energy-efficient lighting has not achieved its market potential, and there is a need to take a fresh look at what new initiatives or reinvigorated existing ones can be implemented to achieve more of the cost-effective potential.

There are many reasons for the sluggishness in the penetration of energy-efficient lighting. Some relate to various market barriers, some to popular perceptions of new technologies in terms of cost or quality, and some relate to the structure and activities of the lighting market itself. Finally, some relate to government or utility promotion.

This book explores the major issues, be they technological, behavioural or policy orientated, related to achieving greater deployment of cost-effective energy-efficient lighting and provides some guidance, based on lessons learned in IEA countries and beyond, on how to make this happen.

IN THE EYE OF THE BEHOLDER: HUMAN FACTORS IN LIGHTING

Key messages

- The eye functions over a vast range of light levels; once it has adapted to the prevailing conditions, visual performance is relatively insensitive to the amount of light.
- Good contrast is more important for visual task fulfilment than high light levels.
- People prefer daylight: research suggests that the cyclical variations in daylight may be important drivers of our circadian rhythms and that greater use of daylight may bring important productivity benefits.
- Recommended light levels are a key driver of lighting energy use, but national recommendations *vary by up to a factor of 40* for equivalent spaces and tasks.
- Surveys of user preferences have found that preferred lighting levels in working environments are often lower than national recommended values.
- The recommended uniformity of lighting (the degree to which light levels are the same across adjacent working surfaces) also has a major impact on lighting energy requirements.
- In principle, significant lighting energy could be saved by adopting the lowest reasonable recommended light levels in national guidelines.
- Lighting designs that encourage task lighting (higher illumination around the task area) together with lower ambient lighting will be the most energy efficient.

TO SEE OR NOT TO SEE

Everyone is aware that light is needed to see, but the design of an appropriate lighting system necessitates more in-depth knowledge about required lighting levels, illuminance spectral properties and light distribution within a space. These in turn are dependent on the human need for and response to light and the manner in which the light emitted by a lighting system interacts with its environment. Yet beyond normal curiosity, what interest would an energy policy maker have in issues that seemingly belong to the domain of lighting professionals? The answer is that this is an area where one of the largest potentials for lighting energy savings exists and where current practice is least efficient. Awareness of these fundamental technical issues will better enable policy makers to design measures that can bring about greatest savings at lowest cost without loss of service.

This chapter explores these issues and examines how they influence the nature and energy consumption of lighting systems.

HUMAN RESPONSE TO LIGHT

The energy efficiency of a lighting system is gauged by the amount of energy it uses to fulfil its required tasks, which in turn are dependent on the human need for and response to light. The minimum requirement of a lighting system is to provide visibility to enable the performance of visual tasks; however, the nature of these tasks can be quite different from space to space and this gives rise to different lighting needs. At the less demanding end lighting may simply be needed to enable safe movement within a space and to enhance security. In a more demanding environment, lighting can be required to enable the conduct of precision manual tasks, such as those in an operating theatre, for example. But light also has an important role in creating the aesthetic characteristics of an illuminated space and has a direct influence on human health and well-being. The extent to which a lighting system fulfils these multiple factors determines its "quality", but as the importance placed on each of these is contingent on the nature and function of the space being illuminated, the optimum lighting configuration will also vary. Happily, high-quality lighting and low-energy lighting are generally complementary objectives, and it transpires that there is a large potential to save energy through the specification of lighting that correctly responds to these human factors.

What is light and how do we see?

From a scientific perspective the term "light" is applied exclusively to electromagnetic (EM) radiation in the part of the spectrum commonly emitted by the Sun and which continuously bathes our planet. This is a relatively small part of the wider spectrum of EM radiation, the boundaries of which extend from ultra high frequency gamma rays at the most energetic level through to very low frequency radio waves at the least. The human eye is a physiological sensor that has evolved to respond to the presence of this solar radiation and enables us to make use of it to interpret our surroundings. The optically active parts include the cornea, an aperture (the pupil), the lens and a photosensitive surface (comprised of the retina and fovea). Light enters the eye through the cornea, is passed through the pupil and the lens and is absorbed by either the fovea or the retina, where it is converted into electrical signals that can be processed by the brain.

Prior to the development of artificial light, the only illumination available to humans was from daylight and moonlight. Such light may reach the eye directly, but most commonly it undergoes multiple scatterings and reflections in the natural environment before it is seen, and these alter not only its directional origin and intensity but also its spectral composition. Although the spectrum of light emitted by the Sun is relatively stable, the spectrum of daylight received at the Earth's surface is less stable because of absorption and scattering in the Earth's atmosphere. A quasi-deterministic variation occurs throughout the day and the year dependent on the thickness of the atmosphere to be traversed and the predictable solar declination. However, cloud conditions and atmospheric turbidity also have a strong influence on the spectral composition, directional origin and intensity of daylight, and these are much less predictable. The complexity of factors influencing the natural light people are able to see does not end with the properties of the light emerging from the sky's vault. The majority of this light has been reflected from objects at, or near to, the ground before it reaches the eye. This introduces new variation into the spectral composition, directional intensity and absolute intensity of the natural light that we see.

The highly complex and variable nature of naturally lit environments is the context in which human sight has evolved over millions of years, and this carries a legacy that influences how we respond to all light sources today, be they natural or artificial. Our eyes are insensitive to infrared light most probably because it is absorbed by water vapour, which produces rapid variability in intensity during periods of broken cloud that would be hard to cope with. By contrast animals that hunt by night, when all light levels are low and therefore fluctuations are within narrower ranges, or live predominantly in deserts, where water vapour has a less prominent role, are more likely to see in the infrared part of the spectrum.

The eye's response to variable light levels

The functionality of the human eye is well adapted to these continuous fluctuations. The amount of light entering the eye is controlled by the degree to which the eye remains orientated towards a light source, the diameter of the pupil and the degree of shielding from eyelids or eyelashes. Each of these regulatory mechanisms has a different rate of response, which is indicative of the eye using different approaches to adapt to varying light levels. Furthermore, the degree of retinal stimulus is dependent not only on the amount of light exposure and the light's spectral composition (discussed on pp. 71–73) but also on the rate of change in these stimuli. Light levels in the natural world vary over extremely wide ranges, from 150 000 lux for direct sunlight to just 0.5 lux for moonlight, but the human eye is able to function across this vast range both by regulating the amount of light incident on the retina and fovea and because of a set of adaptive neural and photochemical cellular responses to changing light levels. None of these responses are instantaneous, so the eye cannot function properly when there are simultaneous rapid and extreme changes in light levels. Rather, the eye is constantly adapting to changes in luminous intensity (Boyce, 2003).

The amount of light incident on the retina is controlled by eye movement, pupil contraction or dilation, and shielding (in extreme cases). The retinal cellular response is more complex. The retina is effectively made up of three layers: a layer of photoreceptors, a layer of collector cells and a layer of ganglion cells. In broad terms the photoreceptors produce electrical voltage spikes at frequencies that vary in response to the level of incident light, then the collectors pool these signals and feed them to the ganglia, which convey them into the brain, where they are processed. When the eye scans a normal but variably lit space, it is the rapid neural response which adjusts the sensitivity of response so that the eye can cope with a wide range of rapidly varying luminous-intensity levels. Iris constriction or dilation plays a secondary role and occurs over a slower period (from 0.3 to 1.5 s, as opposed to less than 200 ms for neural response) (Boyce, 2003). Photochemical adaptation is the slowest response (up to 60 min) and is the eye's way of changing its sensitivity to prolonged differences in light levels. Whenever changes in light levels occur faster or over a larger range than the eye can adapt to, it creates visual discomfort as either glare (when there is a sudden sharp increase in light levels) or black shadow (when light levels are suddenly reduced).

Knowledge of these factors is important for lighting design and to be able to optimise lighting energy efficiency, because artificial-lighting systems need to provide lighting that enables a high degree of visual discrimination (*i.e.* avoids glare or shadow) while satisfying visual aesthetics for the minimum energy use.

The eye's response to broad light levels

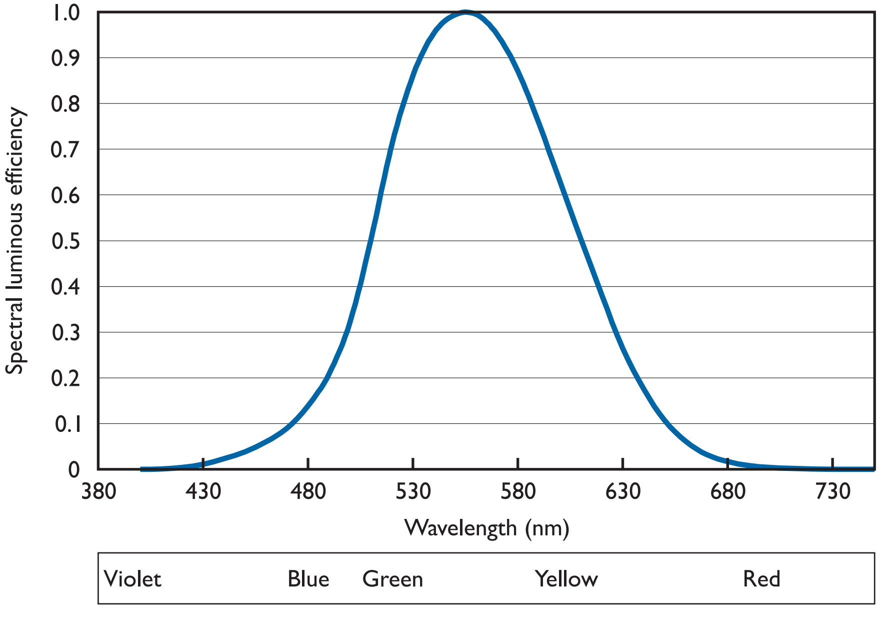
In fact the photoreceptors in the retina fall into two distinct categories: rods and cones. The cones are far more preponderant around the fovea, which is the part of the retina directly beneath the pupil and hence exposed to the most light. The rods are preponderant over the rest of the retina. The cones tend to dominate the visual response in higher lighting levels (*i.e.* levels above 10 lux, which are common during daytime or with most artificial lighting), known as photopic conditions, while the rods become dominant at very low lighting levels, known as scotopic conditions, such as occur in near darkness (Boyce, 2003). Intermediate luminance conditions are known as mesopic conditions, during which both rods and cones are involved in sight. Knowledge of the behaviour of rod photoreceptors and their interaction with cone photoreceptors is important when designing lighting systems intended to operate in ambient mesopic or scotopic luminance conditions such as may occur for street lighting, night-time vehicle lighting and some types of emergency-lighting applications. For most lighting applications, however, it is the photopic response of the eye that matters.

The eye's response to the spectral properties of light and photometric quantities

The strength of the eye's visual response to light is highly sensitive to the wavelength of the light. The peak response is to light with a wavelength in the yellow/green part of the spectrum, but there is a much lower visual response to light in the red or blue end of the spectrum. The Commission

Internationale de l'Eclairage (CIE; International Lighting Committee) has defined the visual response of a "standard photopic observer" to light of varying wavelength (Figure 2.1). Understanding this curve is essential to comprehend the way that the energy performance of a light source (lamp) is defined. The "efficiency" of a lamp is expressed as the radiative energy of the light it emits per unit of energy it consumes. However, this takes no account of the eye's ability to see and hence is not a very good metric of the energy performance of a lamp, which should consider the quality of the service provided as a function of the energy it consumes. Accordingly, a lamp's energy performance is defined by the lamp's "efficacy", which in broad terms is the ratio of the visually useful light emitted to the energy consumed. The "visual usefulness" of the emitted light is determined by integrating its radiant energy at each wavelength with the relative luminous efficiency of light at that wavelength for the standard photopic

Figure 2.1 **The relative spectral sensitivity of the human eye (the CIE standard photopic observer)**



Source: Kofod, 2001 (reproduced with permission).
Abbreviation: CIE = Commission Internationale de l'Eclairage (International Lighting Committee).

observer, *i.e.* by weighting the light's intensity at each wavelength by the magnitude of the human visual response at that wavelength and summing this over the lamp's spectrum. When this is done the light output of a lamp is measured in terms of "luminous flux" (with units of lumens [lm]) and the efficacy is the ratio of the lumens emitted per watt of power consumed. The luminous flux of a light source is based on the total light output of the source in all directions. Another important metric is the "luminous intensity", which is the luminous flux emitted per unit solid angle in a particular direction. The unit of luminous intensity is the candela (cd), which is defined as 1 lumen per steradian (sr). Clearly lighting design requires information about both the total light output of a source and its directional intensity, which is why a light source's luminous flux and luminous intensity are important.

The efficacy of different light sources is discussed in Chapter 3, but it is important to appreciate that this is based on an idealised (average) human visual response under photopic lighting conditions. The CIE has also published a relative luminous efficiency function for a standard scotopic observer that has a very similar shape to the photopic function but is shifted to the left, *i.e.* is more sensitive at shorter wavelengths and less so at higher wavelengths. Consequently a light source can have a quite different efficacy under scotopic conditions compared with photopic conditions, and this could be important when considering low-lighting night-time applications.

Colour and sight

Colour vision is an ability to discriminate the wavelength composition of incident light, and this dramatically increases the amount of information that can be extracted from a visual scene. In the natural world this capacity not only increases the richness of our visual experience but may allow us to tell the temperature of an object without touching it, whether fruit is ripe without picking and eating it, and the time of day from the colour of the sky. Humans have three photopigment types, and this allows us to make roughly 1 million wavelength discriminations. Creatures with two photopigments can discriminate 10 000 wavelength compositions of light, and those with just one can discriminate approximately 100 shades of grey (Boyce, 2003). The animal world is full of examples that illustrate the importance of these visual discriminations. For example, the black and white stripes of zebras appear quite obvious and striking to us with our multichromatic vision, but they are useful defensive camouflage in breaking up the outline of the zebra's body against the monophotopigmented vision of predatory lions. The lion sees the light reflected off the zebra as easily as we do but has more difficulty in identifying that it is a zebra. Another important feature of colour vision is that it only functions in photopic conditions. Scotopic vision is essentially colour-blind and mesopic vision operates with reduced colour discrimination.

Lighting quality: a primary driver of lighting energy needs

Defining the quality of light delivered by lighting installations is rather challenging and is still not a fully determinable parameter, despite decades of research. Yet most countries issue lighting-quality guidelines that have a direct influence on the amount of light provided and hence on the amount of lighting energy required. The recommendations in the guidelines have evolved considerably and frequently over the last 80 years and yet remain divergent from one jurisdiction to another, with large associated implications for lighting energy demand. Energy efficiency policy makers may feel reluctant to interfere in lighting-quality recommendations, but when international specifications are so divergent and lighting energy demand is proportional to the amount of light delivered there is obviously a need to ensure that local specifications are soundly based.

It is clearly important for energy efficiency policy makers to understand the nature and basis for these recommendations if they are to be assured that they are optimised to provide good-quality lighting for as little energy use as is reasonable. So how should this nebulous concept of "lighting quality" be defined in practical terms and how important is it to have high-quality lighting?

Evidently the quality of light will depend in part on why light is needed (*i.e.* the nature of the visual tasks to be performed) and hence is dependent on the types of activities that are being conducted in the illuminated space. The lighting requirements for surgery will be quite different from those required for a car park or office lighting, for example. But lighting quality is not linked just to the ability to perform tasks. It also encompasses the influence lighting has on mood, alertness and health. Although the total cost of lighting is very large it is often trivial by comparison with the cost of workers' wages and the value of their output, thus most assessments of lighting quality are preoccupied with the influence lighting may have on successful task completion and task productivity. The determination of light's impact on overall productivity needs to be treated with care, however, because it is governed on one level by visual task performance and on another by a less readily quantifiable characteristic – visual comfort. Despite the uncertainties, lighting has been demonstrated to influence:

- Worker productivity, morale and staff retention.
- The level of sales in retail outlets.
- The number of accidents that occur while driving.
- Perceptions of space and mood.

Lighting has also been reported to influence many other factors, such as the levels of street crime, although in this particular case it appears the evidence is less conclusive (Boyce, 2003). Some of the main research findings are reviewed below.

Illuminance and luminance

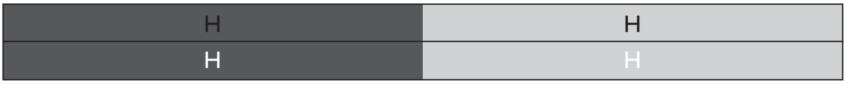
Before discussing the research, two key lighting metrics need to be introduced: illuminance and luminance. "Illuminance" is the luminous flux falling on a unit area of a surface and is measured in units of lumens per square metre (lm/m^2), called "lux". "Luminance" is the directional equivalent of illuminance and is defined in units of candela per square metre, called "nit". The luminance of a light source or light-reflecting object indicates how bright that source or object is when viewed from a given direction, whereas the illuminance indicates how much light is thrown onto a given plane. For reasons of simplicity, lighting-quality guidelines tend to specify levels of illuminance, but it should be appreciated that the visual system is responding to the luminance of the surfaces illuminated by the lighting system, not the illuminance *per se*. Thus illuminance levels only provide an indirect benchmark of lighting effect.

Measures of visual performance

One of the main means to determine the quality of light is measuring the degree by which it helps human visual processes. Traditionally these have mostly been judged from tests of visual acuity, which is the measure of ability to resolve the detail of a target object with a fixed luminous contrast, where the luminous contrast of the target is its visibility relative to its background. A well-known relative visual acuity test is the standard eye test used by opticians, where subjects are required to read progressively smaller text fonts on an eye chart. The visual acuity score is based on the number of mistakes recorded as the fonts become smaller. Other types of visual performance tests measure the speed of response of the human visual system, its ability to detect fluctuations in luminance, or the ease with which two colours can be discriminated. A wealth of research has been conducted along these lines and in broad terms can be divided into (i) research where the performance of an *in situ* productive task is tested under varying light conditions and (ii) research where an artificial yet standardised visual performance test is conducted with subjects under laboratory controlled conditions (such as the opticians' eye chart). The broad body of this research has found that visual acuity, while varying substantially from subject to subject, is significantly influenced by both luminous contrast and luminance. As the contrast or luminance increases, visual acuity improves; however, in both cases the rate of improvement is highly non-linear and quickly reaches a saturation level where there is negligible improvement from further increase. Furthermore, visual acuity is more sensitive to changes in contrast than it is to changes in luminance (Figures 2.2 and 2.3).

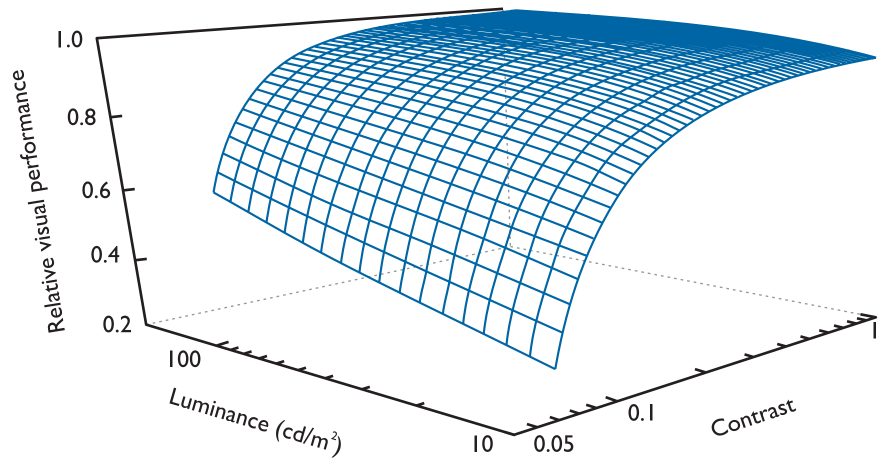
From a lighting energy demand perspective it is the illuminance that matters, not the luminance or contrast, but from the visual acuity perspective the luminance and contrast provided by the lighting system's interaction with the illuminated space are the important factors. There is

Figure 2.2 A simple demonstration of the importance of contrast for visual acuity



The left-hand column is 80% grey-shaded, the right-hand column is 20% grey-shaded. The contrast of the black font in the top left-hand quadrant and the white font in the lower-left quadrant is only 0.2, while the contrast of the black font in the upper-right quadrant and the white font in the lower-left quadrant is 0.8.

Figure 2.3 **Relative visual performance as a function of luminance and contrast**



Source: Boyce, 2003 (reproduced with permission).

considerable scope through proper design to select surface colour and reflectivity characteristics to provide good contrast and luminance characteristics for effective visual performance, but all other things being equal, increasing illuminance will proportionately increase luminance. Numerous tests have been conducted to evaluate the impact of illuminance level on task performance, but the comparability of results is not as good as for luminance and contrast response tests because these factors, which are so important for visual performance, are less easily controlled variables during the illuminance tests. In one group of visual performance tests the dependency of data entry speed on illuminance level was found to be invariant for light levels above 100 lux but to depreciate at levels below this threshold. The earliest and crudest illuminance tests examined weaver productivity as a function of season in a day-lit work environment and established that productivity was higher in summer than in winter. The earliest tests of the impact of electric lighting levels on productivity looked at the speed of manual electric coil winding under different illuminance levels and found no correlation until levels were dropped to 30 lux or less.

The importance of visual performance to lighting design

What does this mean for illuminance and lighting energy requirements? First, while increasing illuminance will help visual acuity, there is no significant benefit above a certain level. The illuminance level beyond which little further benefit occurs varies from person to person, and there is also a well-established age-related deterioration in visual acuity such that older people generally require higher illuminance levels. Second, improving contrast through measures that do not require higher lighting levels is an effective means of raising visual acuity. In the case of modern office work this implies that correctly setting screen font size and colour is more important for effective reading than the level of backlighting provided. Third, while the results shown in Figure 2.3 show the average response of a great many subjects, there is appreciable variation between individuals; this strongly implies that it is important to allow individuals to have control of their lit environment when tasks requiring visual acuity are to be conducted. Fourth, while the research suggests rapidly diminishing returns in visual acuity performance from increasing luminance, it would also imply that the level at which a compromise design luminance level might be struck should depend on the importance placed on visual acuity performance compared to other factors (including energy savings). Thus the luminance level desired for surgery (where visual acuity is vitally important) will be very different from that for street lighting (where far less resolution of detail is needed). Fifth, as visual acuity is needed when a visual task is to be performed, there is clearly a benefit from accurately identifying how much visual acuity is required for each task and setting lighting accordingly. For example, in an office environment the lighting over the principal task area where reading, writing, sorting and typing are to be performed will need to provide a significantly better luminance than is required for the ambient illumination of the rest of the space. This concept of providing well-defined but flexible task lighting, having localised user control blended with lower-level ambient illumination away from the task area, is increasingly recognised as one of the key means of providing high-quality low-energy lighting.

Measures of visual comfort

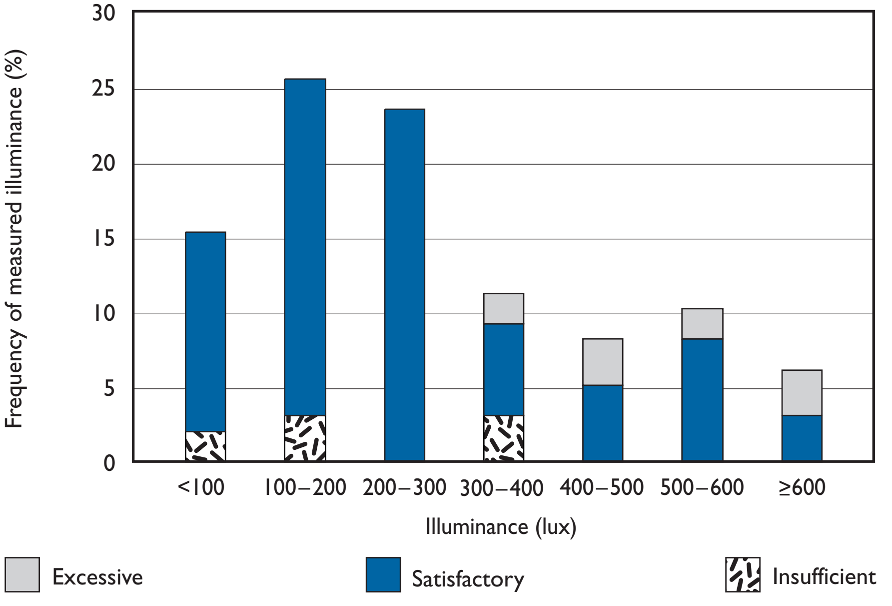
Visual comfort is much harder to define than visual discomfort, and hence in practice visual comfort is usually deemed to be satisfied by the avoidance of discomfort. Visual discomfort occurs with glare, flicker, shadow, veiling reflections[1] and excessive or insufficient lighting uniformity. Even here the concept of lighting discomfort only makes sense in the context of the lighting application and is not universally definable or measurable. As an extreme example, a stroboscopic lighting effect that could be stimulating in a nightclub might be highly stressful in an office. In the case of severe lighting discomfort, subjects can experience irritated eyes, eye muscle fatigue, headaches, stress and aches and pains similar to those related to poor posture (Boyce, 2003). Most of these factors can have causes other than poor lighting, but lighting-induced mechanisms are known and to a large degree are determinable from photometric measurements. The further away from extremes the lighting is, the more subjective the expression of discomfort becomes, and there is established evidence that perceptions of lighting discomfort and its corollary "quality" are strongly driven by expectation and cultural factors once unambiguous discomfort is avoided.

Furthermore, research into user preferences for different illuminance levels has led to a rethink regarding the appropriateness of illuminance level recommendations that were based on narrow visual acuity test findings. Surveys of user preferences have often found that preferred lighting levels are lower than the optimum for visual acuity test results, although they do show considerable user variation (Boyce, 2003). A recent example is a survey of French office workers who were asked to comment on how comfortable they found their workplace lighting levels, which were simultaneously measured *in situ* (Enertech, 2004). The results, shown in Figure 2.4, illustrate the percentage of respondents who found the lighting in their office satisfactory, excessive or insufficient as a function of the average measured illuminance.

Some 64% of all desks had illuminance levels less than 300 lux, but 92% of their users were satisfied. Almost 16% of desks had illuminance levels less than 100 lux, yet only 13% of these were dissatisfied. By contrast, dissatisfaction because of excessive lighting was only found in the range of 400 to more than 800 lux and was expressed by one-third of users in this situation. These findings were reinforced by the discovery that many people in the sample had made *ad hoc* "do-it-yourself" (DIY) amendments to their lighting systems to reduce over-lighting. In many cases fluorescent tubes had been removed or handmade paper light diffusers added, which strengthened the impression that the installed illuminance was often too high for user

1. Luminous reflections from surfaces that change the contrast of the visual task.

Figure 2.4 **Measured desktop illuminance and user opinion of the illuminance level***



Source: Enertech, 2004 (reproduced with permission).
* From a sample of 98 offices in France.

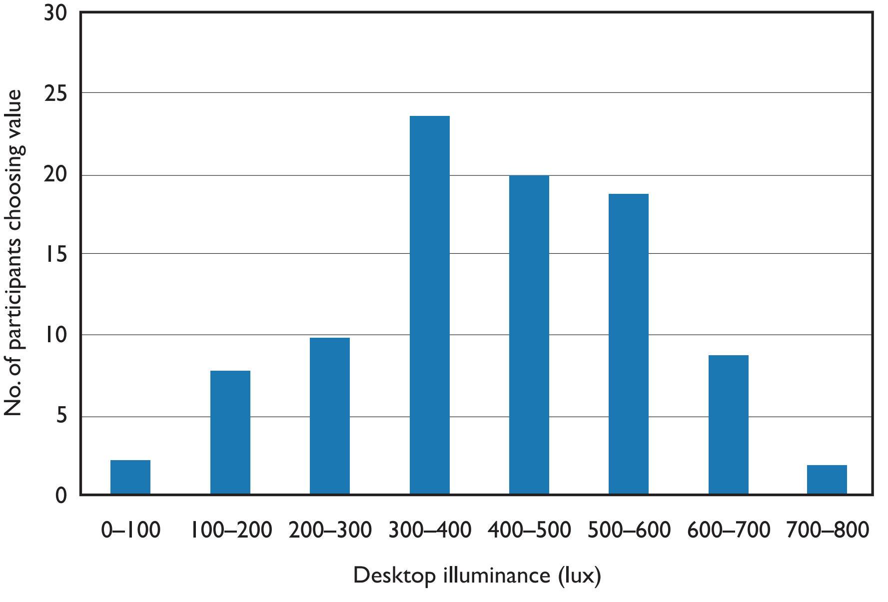
comfort. Overall it seems that the most popular illuminance setting for people working with computer screens was 200 lux. If people were in the habit of reading paper documents and writing on paper they preferred an illuminance of about 300 lux on average. These values are significantly lower than specified in European lighting recommendations (see pp. 88–90).

A contemporary Canadian study (Veitch and Newsham, 2000; Newsham *et al.*, 2004) found that North American office workers preferred illuminance levels of around 400 lux (Figure 2.5), about 25% higher than the French results. This difference may be related to cultural differences, sample variation or some other factor related to the experimental design. It could also confirm that human visual performance is not very sensitive to relatively small changes in illuminance, but in both cases the preferred illuminance levels were lower than the levels research has suggested are optimum for visual acuity. The realisation that light quality may be driven by more than simple visual acuity and that user preference might be the best measure of true light quality (Boyce, 2003) has led many countries to revise their recommended illuminance levels downwards in recent years.

Consequences for lighting design

The eye normally adapts to whatever it is viewing, but if either the visual target or the background are too bright or the contrast is too great, vision is impaired through glare. To avoid glare, bright luminaires need to use diffusers, baffles or other types of shielding to minimise the likelihood of a direct eye-to-lamp line of sight; however, these reduce the amount of light that escapes from the luminaire and hence lower the efficiency of light delivery. The same techniques combined with careful location of the light source in respect to the task area are used to minimise disability glare (veiling reflections) caused by reflections from computer screens.

Figure 2.5 **Desktop illuminance levels chosen by participants* in a mock-up office**



Source: Veitch and Newsham, 2000; Newsham *et al.*, 2004 (reproduced with permission).
* North American.

Flicker used to be a problem for fluorescent lamps powered by lower-frequency magnetic ballasts but is avoided entirely by using high-efficiency and high-frequency electronic ballasts. Some research has found that the use of electronic ballasts correlates with higher worker productivity (ALG, 2003).

Avoidance of shadow and uniformity problems is a key issue with important implications for lighting energy consumption. Many lighting guidelines specify minimum levels of uniformity, but there is a lack of agreement about how uniform lighting should be. Research suggests that when people are asked about their preference for light levels they give quite different responses depending on the context. In tests where two desks are adjacent in a windowless room there is a preference for the illumination on both desks to be quite similar (a uniformity of 0.7 or above), but when desks are in a day-lit space it appears that people are much happier to have appreciably different illuminance levels. These results imply that a high degree of expectation influences the preferences people express on this topic. Uniformity is important for lighting energy use because the more light levels away from the task area are required to be similar to the levels at the task area, the higher the total amount of light that needs to be delivered and hence the more energy required.

Light and circadian rhythms

All animals, including humans, have an internal biological clock that governs a number of important physiological functions according to daily cycles known as circadian rhythms. Circadian rhythms have been shown to be set by exposure to light, and this has stimulated a wealth of research that has investigated the sensitivity of the response to light levels and spectra. Bright light suppresses the production of melatonin, which is a hormone produced in the brain at night; its levels in the body follow a daily cycle. The melatonin levels affect the production of other important hormones such as oestrogen and serotonin. For the circadian system to function properly the body needs exposure to high levels of light at specific times of the day and with an appropriate spectrum. Recent research has suggested that daylight is particularly helpful in this and may have associated health benefits (CIE, 2004). It is speculated that this may arise because daylight illuminance levels and spectral shifts follow a quasi-regular dynamic cycle, whereas electric-lighting characteristics do not.

Daylight and productivity

The most compelling evidence of a link between lighting and productivity is not from visual acuity tests under artificial light but from tests of daylight availability. In 1999 the results of two longitudinal field studies that investigated the long-term effects of daylight provided by skylights installed in a retail chain and in three elementary-school districts were reported (HMG, 1999a, 1999b). Productivity was measured in terms of annual sales for the retail chain and standardised test scores for the schools. A wide range of other demographic and physical variables were controlled in the experimental design so that their influence could be independently determined and factored out of the results, using standard epidemiological survey techniques. The results were striking. Sales in retail stores without skylights were significantly lower than those in stores with skylights. The maths and reading test results of children who had spent a year in the classrooms with the most daylight were significantly higher than those of children who had spent a year in classrooms without any daylight. Beyond the link with daylight the cause of these benefits is not clear, so it would be premature to conclude that daylight is necessarily superior to artificial light *per se*, but it does correlate with a wide body of research which shows that people have a strong preference to be in spaces with an external view and available daylight.

Colour factors

There seem to be clear cultural and chromatic-matching issues that influence preferences for lighting chromatic characteristics. In more northerly latitudes there is a market preference for lighting with low correlated colour temperature (CCT), while in more equatorial latitudes the preference is usually for higher CCTs. In part this may be explained by a desire for the chromaticity of artificial light to not overly diverge from that of natural light given that the average colour of daylight tends to be warmer (*i.e.* toward lower CCT values) in less equatorial latitudes and cooler (*i.e.* toward higher CCT values) in more equatorial latitudes. But cultural preferences are also a strong factor; for example, the standard CCT of fluorescent tubes in Japan is 5 000 K, whereas in the United States 3 500 K is common. Seminal work looking at preferences for different CCTs as a function of illuminance level in the 1940s found that the higher the illuminance the higher the CCT preferred and that there was a broadening range of acceptability as CCT increased. However, despite the conclusions of this work becoming firmly embedded in lighting recommendations, questions have been raised about its full validity (Boyce, 2003). More recent and thorough investigations suggest that the CCT of the lamp is a minor and inconclusive factor in determining lighting acceptability, at least in office environments. Similarly, while light sources with a colour rendering index (CRI) (see pp. 105–107) below 60 are unacceptable for indoor lighting because of the unnatural colours they render and those with a CRI above 80 tend to give more saturated surface colours that allow a perception of greater brightness and visual clarity, there is little evidence to suggest that people really make finer distinctions based on CRIs or that there is a strong preference either way for specific CRI levels between 80 and 100.

Conclusions

Good-quality light is obtained by optimising illuminance, colour rendering and contrast for each space subject to the activity to be performed within it. As some aspects of these factors are universal and others are subjective, it is important to optimise individual control when long occupancy by any individual is anticipated. Once the lighting needs within a space have been determined, the energy-efficient alternatives can be examined; however, as set out on pp. 84–98 there is an appreciable international divergence regarding what the lighting needs are for the same type of space and activities, and this suggests that there is a considerable opportunity to save energy by establishing true best practice in lighting requirements.

LIGHTING GUIDELINES AND DESIGN CRITERIA

Most countries or subnational jurisdictions publish lighting installation guidelines that may or may not be incorporated into mandatory legal requirements through building codes. These lighting guidelines are intended to inform lighting installers about the minimum and/or desired lighting quality for specific environments. The guidelines will typically specify design light levels (illuminance levels), uniformity requirements, glare limits and colour requirements, which vary depending on the nature of the activity expected in the space. These factors influence either the total demand for light or the efficacy of the lighting system and hence have a direct impact on lighting energy demand. This section reviews current recommendations and draws some conclusions about the potential for recommendations to be optimised to enhance energy efficiency without loss of lighting quality.

Recommended illuminance levels and implications for lighting energy demand

The installed illuminance levels are one of the key drivers of lighting demand and hence lighting energy demand. Nationally or regionally recommended illuminance levels have evolved considerably over time, but in the majority of international jurisdictions the most recent recommendations are tending to converge at significantly lower levels than those that existed in recent decades, hence suppressing lighting energy demand (Kofod, 2001).

Variations reported in the literature

A comprehensive review of recommended lighting levels in 1999 found some astonishing results (Mills and Borg, 1999). Recommended levels varied by 10- to 20-fold for various office-building activities across 19 countries. There was a 6- to 10-fold variation for schools, a 15- to 30-fold variation for retail stores, a 6- to 10-fold variation for hospitals, and a 25- to 40-fold variation for factories. When international recommended lighting levels were compared for specific activity and building combinations the following variations were found:

- Reading tasks (75 to 1 000 lux).
- Detailed drafting (200 to 3 000 lux).
- Hospital-patient rooms (30 to 300 lux).
- Testing and assembly of electronic components (200 to 5 000 lux).
- Fine knitting and sewing (50 to 2 000 lux).

At the time, Belgium, Brazil and Japan had among the highest recommended illuminance levels for the tasks and building types examined, while Australia, China, Mexico, the Former Soviet Union/Russia and Sweden had among the lowest levels. In North America recommended illuminance levels were generally about average, but in some situations they were among the lowest (Mills and Borg, 1999). Table 2.1 shows the complete set of national recommendations applying at that time.

Table 2.1 International recommended illuminance levels circa 1999

Country and standard	Offices					Classrooms		Retail stores		Hospitals			
	General	VDT tasks	Desk tasks	Reading	Drafting	General	Chalk-boards	Ambient	Tasks/ till areas	Common areas	Patient rooms	Op. rooms	Op. table
Australia (1990) AS1680.2–1990	160	160	320	320	600	240	240	160	240	240	–	500	–
Austria (1984) Önorn O 1040	500	500	–	–	750	300–500	300–500	300–750	500	200	100	1 000	20 000–100 000
Belgium (1992) & L13–006	300–750	500	500–1 000	1 000	1 000	300–750	750–1 500	200–1 500	500–1 500	–	–	–	–
Brazil (1990) NBR 5413/82	750–1 000	–	–	200–500	3 000	200–500	300–750	300–750	–	75–150	100–300	300–750	10 000–20 000
China (1993)	100–200	150–300	150	75–150	200–500	75–150	–	75–150	100–200	50–200	150	–	–
Czech Republic CSN 360450	200–500	300–500	300–500	500	750	200–500	500	200	500	50–100	100–200	1 000–2 000	10 000–20 000
Denmark DS700	50–100	200–500	–	500	1 000	200	500	50–100	500	200	50–200	–	–
Finland (1986) Finnish IES	150–300	150–300	500–1 000	500–1 000	1 000–2 000	150–300	300–750	150–300	500–1 000	–	50–100	1 000–2 000	30 000–75 000
France* (AEF 1992&93)	425	250–425	425	425	850	325	425	100–1 000	425	100	50–100	300–1 000	20 000–100 000
Germany (1990) DIN 5035	500	500	500	–	750	300–500	300–500	300	500	200	100–300	1 000	20 000–100 000
Japan (1989) JIS Z 9110–1979	300–750	300–750	300–750	300–750	750–1 500	200–750	300–1 500	150–750	750–1 000	150–300	100–200	750–1 500	20 000

Table 2.1 (continued)

Country and standard	Offices					Classrooms		Retail stores		Hospitals			
	General	VDT tasks	Desk tasks	Reading	Drafting	General	Chalk-boards	Ambient	Tasks/ till areas	Common areas	Patient rooms	Op. rooms	Op. table
Mexico Mexican IES (proposed)	200	–	600	900	1 100	400	900	200	600	60	60–200	600	14 000
Netherlands (1991) NEN 3087 NSW	100–200	500	400–500	400	1 600	500	500	300	500	200	150	2 000	100 000
Sweden (1993–94) Ljuskultur 1990	100	300–500	300	500	1 500	300–500	500	200–500	500	150	150	750	–
Switzerland (1997) SLG/SEV 8912	500	300–500	300	500	1 000	300–500	300–500	500	750	300	100–300	1 000	>10 000
UK (1994) IES/CIBSE	500	300–500	300	500	750	300	500	500–1 000	500–1 000	–	30–50	400–500	10 000–50 000
USA/Canada (1993) IESNA	200–500	300	200–500	200–500	1 000–2 000	200–500	500–1 000	200–500	200–500	100–200	50–100	1 000–2 000	–
FSU (1995) (draft)	300	200	300	300	500	300	500	300	300	150	300	400	10 000–50 000
Proposed European guidelines CEN TC 169–1996	500	500	500	500	750	300–500	500	300	500	200	100	1 000	10 000–100 000

Source: Mills and Borg, 1999.
* Schools 1981, VDT 1997.
Abbreviations: CIBSE = Chartered Institute of Building Service Engineers; FSU = Former Soviet Union; IES = Illuminating Engineering Society; IESNA = Illuminating Engineering Society of North America; Op. = operating; UK = United Kingdom; USA = United States; VDT = visual display tasks.

Historical trends and differences in practical illuminance definitions

The historical trend in most countries was for recommended light levels to increase from the 1930s until the 1960s or 1970s. Thereafter the recommended levels have tended to fall, but in some cases they have oscillated or remained constant. Furthermore, some important differences in how recommended levels are specified need to be considered. Many countries specify a range of values that lighting systems should aspire to be within, while some only specify minimum values or single average values. Moreover, recommended lighting levels in the past were usually applied to the initial illuminance provided by the lighting system, but as this generally diminishes with use (see pp. 104–105) the specifications are more commonly rated in terms of the "maintained illuminance", which is the illuminance at roughly 80% of lamp service life. In fact many countries use the "service illuminance", which is the average value over a maintenance cycle (as opposed to 80% of maximum life). These distinctions are important and the merits of each method are still a subject of debate; however, they in no way explain the large variation observed among international illuminance recommendations.

A comprehensive review of recommended illuminance levels has not been conducted since the Mills and Borg (1999) study; however, a number of key developments have occurred among OECD countries, as reported below.

Developments in the European Union

In the European Union, the Energy Performance in Buildings Directive of 2002 requires all member states to develop building energy codes based upon whole-building energy performance (European Commission, 2002). Lighting energy performance must be included within the whole-building energy-performance metric and this has led the European Commission to request the development of a lighting energy performance methodology by the Comité Européen de Normalisation (CEN; European Committee for Standardization). In the same year the newly issued European Standard EN 12464-1 on lighting in indoor work places included recommended illuminance levels in the workplace. EU member states are not obliged to adopt the provisions of this technical standard, but they are obliged to have a national standard in place to enable lighting energy performance to be included in the whole-building energy-performance metric.

It is not yet clear how many member states have, or intend to, harmonise their light level recommendations with the EU standard, but evidently doing so would minimise intercommunity differences in lighting levels. However, the potential impacts of adopting this standard on lighting energy consumption are a cause for concern in some countries where lower recommended lighting levels are currently specified. For example, the United Kingdom's Market Transformation Programme reviewed this standard and assessed its implications for UK commercial-sector lighting energy use were it to be adopted and fully acted upon (MTPROG, 2005b). Table 2.2 shows a comparison of the former UK recommended values, issued by the Chartered Institute of Building Service Engineers, and the current values, which were harmonised with the CEN 2002 standard.

Table 2.2 **Comparison of 2002 revision* of CIBSE guidelines for lighting levels with 1994 levels**

Sector	Subsector	1994 level (lux)	2002 level (lux)	Ratio 2002:1994
Retail	Sales floor	500–1 000**	300	0.3–0.6
Offices	Computer workstation	300–500	500*	1.7–1.0
	Archive	100	200	2.0
Education	Lecture theatre	300	500	1.7
	Blackboard	300	500*	1.7
	Teaching workshop	300	500	1.7
	Stairs	100	150	1.5
	Kitchens	150–500	500*	3.3–1.0
Hotel/catering	Kitchens	150–300	500*	3.3–1.7
	Bedrooms	50–100	No guide	
Libraries	Circulation	300	100	0.3
	Shelves	150	200	1.3
	Reading area	300	500*	1.7
Healthcare	Many examination areas, laboratories & offices	300	500	1.7
	Bed-head reading	150	300*	2.0
	Corridors (day) & dayroom	100–200	200	2.0–1.00
	Corridors (night)	3–5	50	16.7–10.0
	Ward night	0.1–10	5	50–0.5

Source: MTPROG, 2005b.
* Based on UK adoption of European Standard EN 12464–1.
** Denotes task lighting.
Abbreviation: CIBSE = Chartered Institute of Building Service Engineers.

An analysis of the potential impact of full adoption of these standards on UK lighting energy use (MTPROG, 2005b) concluded that:

- Retail lighting could save up to 5.5 TWh but is unlikely to do so because display lighting is part of the marketing strategy of retail establishments and the Chartered Institute of Building Service Engineers (CIBSE) code is most likely interpreted as a minimum standard in this sector.
- Office lighting could use 1.1 TWh more electricity if the higher illuminance levels are not applied as task lighting only.
- Educational establishments could use 67% more electricity if blackboard task lighting levels were applied to classrooms in general, although this is considered to be unlikely in practice.
- Healthcare establishments could use 27% or 0.3 TWh more electricity if lamps with a high CRI are used throughout instead of just in examination areas.
- Warehousing could use an extra 0.6 TWh of electricity if all high-pressure sodium lights were replaced with ceramic metal halide lamps.

Thus UK lighting energy use could rise by 2 TWh or, less probably, decline by 3.5 TWh from full harmonisation and adoption of the CEN recommended illuminance levels. This real-life example illustrates the importance of considering all aspects of a lighting standard and being sure that it is not encouraging unnecessary energy use.

Japan

In Japan the recommended illuminance levels are reviewed reasonably regularly but do not appear to have changed significantly since the 1970s. Recommended lighting levels in the workplace are significantly higher than in other OECD countries. In part this may be explained by cultural factors, but it seems unlikely that there is any physiological basis for such high values and thus high light levels are either a matter of cultural preference or may indicate a different importance placed by the guidelines body on visual acuity performance as opposed to energy conservation and other concerns. The recommended illuminance levels for key tasks in office environments are shown in Table 2.3.

Table 2.3 JIES recommended office illuminance levels

Sector	Subsector	Recommended illuminance (lux)
Working area	Office (a)	1 500
	Office (b)	750
	Designing/drafting room	1 500
	VDT/CAD	750
	Training room, archive, meeting room	750
	Central control room	750
	Medical examination room	750
	Cooking room	750
	Guard room	500
Executive area	Executive office, executive conference room	750
	Executive reception room	500
	Executive restaurant	500
	Corridors	200
Communication area	Reception room	500
	Conference room	750
	TV conference room	750
	Presentation room	500
	Hall	750
	Reception	750
	Lounge	500
	Entrance hall (day)	1 500
	Reception hall (night)	500

Source: Japanese Industrial Standard JIS Z 9110–1979.
Abbreviations: JIES = Japanese Illumination Engineering Society; TV = television; VDT/CAD = visual display tasks/computer-aided design.

North America

Recommended illuminance levels in the United States are developed by the Illuminating Engineering Society of North America (IESNA) and many have become American National Standards adopted by the American National Standards Institute (ANSI). IESNA divides its recommended illumination levels into eight classes ranked from A (lowest) to G (highest). Until the latest edition, the IESNA guidelines were like other international guidelines in that they only specified recommended horizontal illuminance values. The latest edition has departed from this by also including vertical illuminance recommendations.

Some examples of the IESNA recommendations are seen in Table 2.4 (which shows a synthesis of typical average illuminance values applied by localised space function) and Table 2.5 (which indicates some specific recommendations for office spaces, including vertical illuminance).

In fact the IESNA design method is more flexible than it was and it encourages lighting designers to adapt the illuminance to the specific circumstance of the application. Once a basic level has been chosen for the task based upon the value for the activity space taken from the look-up table (such as Table 2.5, for example), it should be adapted as necessary to take account of other factors, such as daylight availability, the time of day the space is likely to be used (based on a consideration of time-of-day visual adaptation) and the average age of the occupants. Furthermore, unlike preceding versions, the new procedure is not based solely on illuminance.

Table 2.4 **Illuminance levels recommended by IESNA, according to type of space**

Space type	**IESNA illuminance category**	**Illuminance**	
		Footcandles (lm/ft^2)	**Lux (lm/m^2)**
Assembly	B–C	7.5	81
Athletic	F	100	1 076
Bathroom	B	5	54
Boarding	C	10	108
Class	E	50	538
Dining	C	10	108
Display	E	50	538
Food preparation	E	50	538
Hall	B	5	54
Healthcare	E	50	538
Office	D–E	40	430
Shipping/receiving areas	D	30	323
Shop	E	50	538
Storage	C	10	108
Task	E	50	538
Unknown	D–E	40	430
Utility	B	5	54

Source: Navigant, 2002 (based on IESNA, 2000).
Abbreviations: ft = feet; IESNA = Illuminating Engineering Society of North America.

Table 2.5 Illuminance levels* recommended by IESNA for office tasks

Office task	Horizontal illuminance (Footcandles)	Vertical illuminance (Footcandles)	Local task lighting type
Filing	50	10	
Open-plan, intensive VDT use	30	5	Undershelf & task
Open-plan, intermittent VDT use	50	5	Undershelf & task
Private office	50	5	Undershelf & task
Lobbies, lounges and reception	10	3	
Mail sorting	50	3	
Copy rooms	10	3	
Conference/meeting rooms	30	5	

Source: IESNA, 2000.
* Footcandles are expressed as lumens per square foot (lm/ft^2) and are converted into lux by multiplying by 10.76.
Abbreviation: IESNA = Illuminating Engineering Society of North America.

Australia

Australian recommended lighting levels for commercial and industrial applications are specified in Australian Standard 1680, Parts 1, 2 and 3. The recommended illuminance levels are summarised in Table 2.6.

Table 2.6 Recommended illuminance levels* in Australia

Task	Recommended illuminance (lux)
Fine (detailed) manufacture, inspection tasks	800
Drawing boards, proofreading, colour matching	600
Office work, computer rooms, fine woodwork	320–400
Schoolrooms, kitchens, shop counters	240
Canteens, warehouses, rough machine work, waiting rooms	160
Loading bays, storage	80
Corridors, walkways, indoor car parks, stairs	40

Source: Ellis, 2001 (reproduced with permission).
* Based on Australian Standard AS 1680.

Uniformity, surface reflectance, colour rendering and glare thresholds

Uniformity

A straight listing of task illuminance recommendations can paint a slightly false picture of the implied light levels and lighting quality. The quality is also dependent on the uniformity, glare and colour characteristics of the illumination and on the reflectance of the illuminated surfaces. Of these, the uniformity requirements are the most debated. Research suggests that if lighting is insufficiently uniform, people are more likely to experience visual discomfort; however, research also shows the same outcome for too much uniformity. In the former case there can be a distracting contrast between the more and less illuminated space, while in the latter case all the surfaces can appear the same and there is a lack of contrast. As explained on pp. 76–77, contrast is more important for visual acuity than is luminance (and by corollary illuminance) above very low luminance levels, so a scene that is exposed to a low but less regular illuminance may be easier to discriminate than one which is exposed to a high, uniform, diffuse illuminance because of the greater contrast in the luminance of differently illuminated surfaces. Research has found that excessive uniformity not only makes it difficult to see but also causes visual fatigue. Interestingly, research explicitly attempting to define the range of uniformity or non-uniformity in the horizontal illumination of a workspace that would contribute to better performance failed to find any significant effect (ALG, 2003).

In current guidelines, uniformity requirements are always specified in terms of the uniformity of illuminance on a horizontal plane (the working plane); however, some lighting designers have argued that consideration of the uniformity of vertical illuminance is almost as important and should not be neglected.

In energy terms, minimum horizontal uniformity requirements are important because they determine how much lower ambient lighting can be than task lighting. If the lighting guidelines propose a high uniformity threshold, the illuminance levels away from task will have to be close to those on task in order to comply, which raises energy consumption. Interestingly, despite the evidence that excessive uniformity gives as poor an outcome as lack of uniformity, all lighting guidelines currently express only minimum uniformity values and not maximum ones. Clearly, there is a concern that lighting is more likely to be underspecified than overspecified, which could be justified if one considers the apparent economic interests of lighting contractors. However, there may also be a lesser risk that some lighting contractors will make their designs overly uniform because it provides a simple compliance pathway and minimises the need for thought about the design.

Putting this issue to one side, the treatment of task illuminance and minimum uniformity requirements away from task in existing guidelines is subject to the same variations seen for task illuminance recommendations and potentially has a large consequence for lighting energy demand. Consider an individual office of 25 m^2 in floor area: the task area at the desk might be just 1 m^2 and hence only occupies 1/25th of the total floor area. If the task illuminance of 500 lux is provided by a desk lamp and the ambient area illuminance is provided by recessed ceiling lamps, the minimum total light-delivery capacity of the lighting system will vary depending on the task to off-task uniformity requirement, as shown in Table 2.7. This case illustrates that total lighting demand can vary by a factor of almost four depending on the uniformity factor of the lighting design.

Table 2.7 **Hypothetical example of the impact of the choice of uniformity factor on total illuminance requirements**

Task illuminance (lux)	Uniformity factor	Minimum amount of light required on working plane for whole office (lm)
500	0.2	2 900
500	0.8	10 100

* For a 25 m^2 office with a 1 m^2 task area.

European Standard EN 12464-1 specifies a uniformity of ≥0.5 for the illuminance of surrounding areas and a uniformity of ≥0.7 between and within task areas (*i.e.* two adjacent desks should have a uniformity of illuminance of ≥0.7). The standard also lists explicit values based on the task illuminance; thus for a task illuminance of 500 lux the illuminance of the immediate surrounding areas should be 300 lux, which in the example in Table 2.7 would imply a minimum total lumen requirement of 7 700 lm were all the office space to be considered the "immediately surrounding area" to the task illuminance. This example also illustrates the importance of interpretation in lighting guidelines.

In North America IESNA recommends that ambient lighting should be about one-third of the level of task lighting, *e.g.* an implied minimum uniformity of 0.33 (ALG, 2003). For the example above this would imply total minimum lumen requirements of 4 460. However, the IESNA recommendations are more subtle and explicit than the others as they distinguish between uniformity close to the task area and uniformity across the field of view. For the field of view they propose that uniformity should not be less than 10:1 and only propose the maximum 3:1 ratio for areas close to the task area.

Surface reflectance, glare and colour rendering

Surface reflectance has a large impact on the amount of light delivered to the working plane and guidelines sometimes specify values to be considered or make suggestions. None of the major guidelines in the OECD prescribe values. As an example, the European Standard EN 12464-1 proposes that the following reflectance ranges are "useful":

- Ceiling 0.6–0.9.
- Walls 0.3–0.8.
- Working planes 0.2–0.6.
- Floor 0.1–0.5.

Although the ranges are strikingly broad, they do follow the usual recommendation for higher ceiling reflectance and lower floor reflectance. Lighter surfaces have higher reflectance and thus absorb less light, so light surfaces in the ceiling and walls are helpful in redirecting light towards the working plane; however, if all surfaces are white it will create an achromatic environment, which may make the lighting seem excessively uniform and a space feel "cold". Therefore the balance to be struck for any space is always a design compromise between visual effect, light-distribution demands, and energy and lighting-system cost considerations.

Maximum glare requirements are often set quantitatively for discomfort glare and qualitatively for veiling reflections. Different methods for determining discomfort glare are applied in different OECD regions, but the current best compromise appears to be the CIE Unified Glare Rating, which is also used in the EN 12464-1 standard (Boyce, 2003).

Finally, some guidelines also specify minimum colour-rendering values depending on the space to be lit. This is not as important for lighting energy consumption as is the recommended illuminance level or minimum uniformity, but it does have a significant second-order influence. Light sources with high CRIs are often less efficacious under photopic conditions than other sources and hence may require more energy to provide the same illuminance level. There are many pertinent nuances regarding the precision of the CRI demanded and the implied influence on light-source efficacy that are open to debate. For example, the European Standard EN 12464-1 proposes that indoor light sources should never have a CRI of less than 80, which effectively excludes the use of high-efficacy high-pressure sodium lighting, some variants of which attain CRIs in the 70s as an indoor light source, as well as the use of some cheaper fluorescent lamps.

The science regarding the influence of CRI on visual performance, visual comfort and lighting preference does not appear to lead to definitive or conclusive findings, at least not within narrow CRI ranges. For example, Knez (1997) found that moods induced in males were considerably more negative for lighting with a CRI of 95 at a CCT of 3 000 K than for a CRI of 55 at the same CCT, but for females the results were the opposite. In general though, research has struggled to identify any clear link between light chromaticity, mood and performance.

Discussion

Clearly, very large differences in recommended illumination levels continue to exist even between OECD countries, and these show there is no common interpretation of lighting needs. On the face of it there is little or no evidence to suggest that the OECD countries applying lower lighting levels and minimum uniformity requirements are suffering from poorer light quality and associated productivity, psychological or physiological losses. While the possibility of some productivity effect cannot be wholly discounted just because it has not been measured on a macro scale, the most telling aspect of the research on the influence of lighting on productivity and health has been how little effect is detectable across broad light-level ranges, with the possible exception of daylight compared with electric light. This may not be surprising when one considers that humans have evolved to function effectively on a planet where natural lighting levels vary by seven orders of magnitude.

What is clear is that designing to higher lighting levels implies proportionately higher energy use. Thus there is a strong case for energy efficiency policy makers to keep these recommendations under review and to insist on their having a proven and broadly based scientific foundation in cases where recommendations are higher than international norms. Similarly, policy makers should be mindful of the potential for the misinterpretation of any ambiguous language in national lighting recommendations, which in the case of uniformity specifications, for example, might lead a lighting designer to overspecify the installation.

THESE LOVELY LAMPS: LIGHTING TECHNOLOGIES AND DESIGN

Key messages

- Today's common lamp technologies stem from innovations between 1878 and 1995. The energy performance of the incandescent lamp has barely evolved since the 1930s.
- The majority of energy used by electric lamps is converted to heat, not light, but the share is substantially higher for some lamp types than others.
- The efficacy of electric lamps ranges from 5 to 200 lm/W, depending on the lamp technology and total light output. Thus the most efficient lamp requires just 2.5% of the energy of the least efficient to produce a given amount of visible light.
- In practice, different lamp technologies are used for different applications depending in part on the "quality" of the light they produce. This encompasses the colour characteristics of the light produced, the amount of light produced, the speed of ignition and time taken to reach full output, the ease of control and the manner in which they distribute light within a space.
- The efficacy range among lamps providing similar lighting "quality" is narrower than the range across all lamps; however, they can still be very large. For example, a high-quality CFL will typically use one-quarter to one-fifth of the power of an incandescent lamp providing similar light output.
- There are important differences in lamp lifetime, durability, temperature sensitivity, first cost and maintenance costs that influence in which applications they are used.
- There are significant differences in the energy efficiency of ballasts, which are used to start and control fluorescent and HID lamps.

- The efficiency of luminaires (the lamp housing) varies dramatically. Many luminaires emit only a small proportion of the light that is released into them by the lamp they contain.
- The quality of the lighting design, which includes the type and position of luminaires and the reflectivity of the room surfaces, has a major impact on the amount of light required to adequately illuminate a space.
- More appropriate use of manual and automatic lighting controls can save a great deal of lighting energy by avoiding illumination of unoccupied spaces and by dimming artificial light in response to available daylight.
- There is great potential to minimise artificial-lighting demand by designing or adapting buildings to make better use of daylight.

THESE WINDOWS OF THE SOUL

Energy-efficiency policy seeks to encourage the deployment of more energy-efficient lighting, but, as described in the previous chapter, lighting must be responsive to human needs. Matching these two requirements is not always straightforward and often the consumer – regardless of the sector – has only a limited idea of the options that are available, or of the trade-offs inherent in any lighting choice. In general, though, consumers are always interested in receiving a good-quality and economical lighting service, even if they are less concerned by the technologies inherent in the specific lamp and fixtures on offer.

Awareness of the technical and commercial opportunities and constraints and how they affect market-driven technology trade-offs is also fundamental for good policy-making. When equipped with the pertinent information a policy maker is well placed to evaluate arguments, take informed decisions and seize opportunities. This chapter aims to provide this information by introducing the various mainstream lighting technologies and discussing their technical characteristics that are relevant to energy-efficiency policy.

GENERAL PERFORMANCE CHARACTERISTICS OF LIGHTING TECHNOLOGIES

Conventional electric lamps produce visible light either through the process of incandescence, (line) emission from a gas discharge and/or fluorescence. Lighting sources (lamps) using these processes range from the standard incandescent bulb that has been commercially available for more than a century to various types of fluorescent lamps, halogen lamps, high-intensity discharge (HID; sodium, metal halide and mercury vapour) lamps. Their widespread use in today's market arises because each technology has some competitive edge, dependent on the application. However, a lighting system is comprised of more than just the lamps: it can also include ballasts, luminaires and controls. This section begins with a general primer on lighting performance characteristics and then introduces each of the major lighting technologies and reviews their characteristics. Solid-state lighting is discussed separately in Chapter 7.

A lighting system is made up of lamps, luminaires (the lamp housing that helps to distribute the light into the space) and the control gear (which controls switching, ignition and regulation system). Assessing the best lighting system for each specific task requires a range of performance characteristics to be considered. Beyond selecting a lighting system capable of delivering the desired quantity and quality of light to the illuminated space, the choice of technology is influenced by considerations of economy, durability and aesthetics. While the notion of the quantity of light is straightforward, as discussed in the preceding chapter, the notion of quality is more complex. It entails consideration of the distribution of light, avoidance of glare and the spectral characteristics of the delivered light. The economy of the lighting system is dependent on the balance of the operating costs – which include the energy and maintenance costs – and the installation costs – which include the cost of the lighting system and the labour costs to install it. In practice different lamp technologies can have a wide range of performance characteristics, which are discussed below in a general sense before the specific characteristics of each lamp technology are introduced.

Efficacy, lumen maintenance and temperature

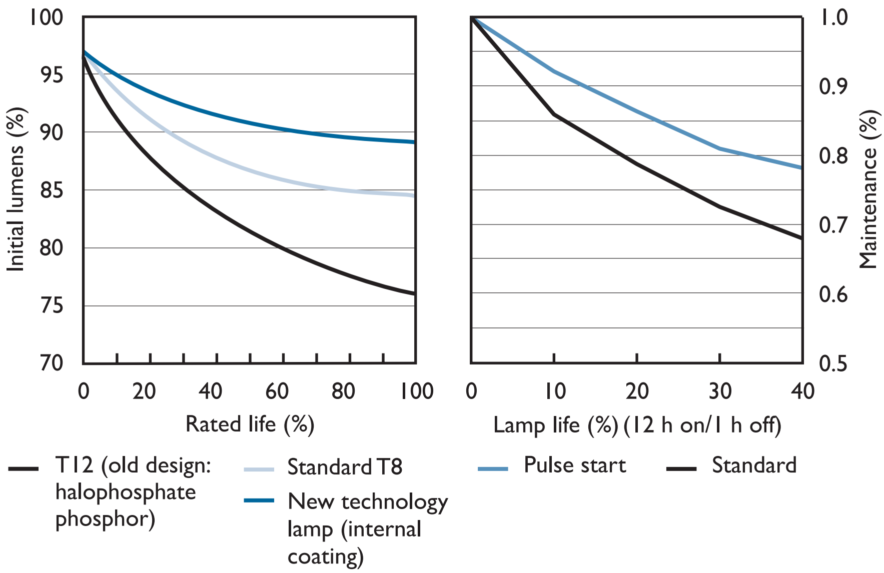
The efficacy of a lamp is defined as the ratio of the light output to the input power and is measured in units of lumens per watt (lm/W). The higher the efficacy the lower the energy required to deliver a given amount of light. The efficacy of a lighting system is not determined just by the efficacy of the lamp, however, as many lighting systems also require energy-consuming control gear (most commonly ballasts) (see pp. 137–141). Thus a better determination of the energy performance of a lighting system is given by a comparison of system efficacy values, which takes this into account. Data on lamp efficacies are given on pp. 107–137 and summarised across lamp types at the end of that section.

A true comparison between lighting systems is further complicated by the fact that the light output and hence efficacy of most lamp types diminishes over time through a phenomenon called "lumen depreciation". Depending on the lamp type, light output will diminish by 0–40% over the operational lifespan. The lumen depreciation characteristics of the lighting system need to be considered when selecting an appropriate lighting system to deliver the required lighting levels; as a result, lighting designers usually install systems based on their "maintained lumen" levels, where the maintained lumen rating is the expected lumen output at some percentage of the lamp life (usually 70 or 80%). This means that the initial lighting level will be higher than required. Some examples of lumen depreciation curves for fluorescent and HID lamp technologies are shown in Figure 3.1.

For most lamp types the power level drawn tends to remain constant as the light output depreciates, and as a result the efficacy also declines over the course of the operating life. The inverse relationship is true for low-pressure sodium lamps (see pp. 124–125), which tend to have constant light output but draw more power over the course of their operating life, although this also results in efficacy depreciation. Tungsten halogen lamps (see pp. 112–115) are unique in that their efficacy only varies by a few percent over the life of the lamp. For the remaining types of lamp the degree of lumen depreciation depends on the technology considered. It is particularly rapid for HID and fluorescent lamp types during the first 100 operating hours, thus by industry consensus manufacturer lamp light output and efficacy ratings are established after that time. Nonetheless the extent of ongoing depreciation can be significant and is an important factor to consider when comparing systems.

All electric lamps will operate over the range of temperatures found inside buildings, but some fluorescent lamps will not operate efficiently if the temperature is too low, which can limit their applications in certain

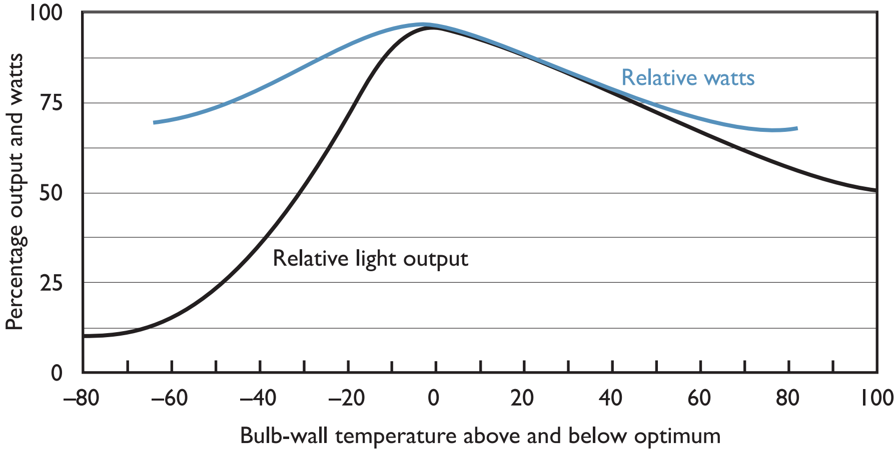
Figure 3.1 **Examples of lumen depreciation for T8 fluorescent and pulse-start metal halide lamps***



Source: ALG, 2003 (reproduced with permission).
* Left: T8 fluorescent. Right: pulse-start metal halide.

outdoor environments. Despite this they can be applied in environments with temperatures as low as –29 °C with the proper lamp, ballast and luminaire (ALG, 2003). The efficacy of many electric lamps is insensitive to temperature, but this is not the case for fluorescent lamps or solid-state lighting devices (discussed in Chapter 7). For fluorescent lamps, both the light output and input power decline the further the lamp tube-wall temperature is from a design optimum; however, as the decline in light output is greater than the decline in power, the further the lamp-wall temperature is from the optimum the more the efficacy drops (Figure 3.2). This means that estimated *in situ* lamp efficacy needs to be corrected to take account of the operating environment. It also means that lamp efficacy can be optimised through housing the lamp in a luminaire designed to maintain the optimum thermal environment in the vicinity of the lamp. Alternatively, fluorescent lamps can be made less sensitive to ambient temperature variations through the use of amalgam technology.

Figure 3.2 **Temperature characteristics of fluorescent lamps**



Source: ALG, 2003 (reproduced with permission).

For most lamp types the efficacy increases as a diminishing function of the rated power until it stabilises at a plateau. For this reason, within any given lamp technology lower-power lamps tend to be less efficacious than their higher-output equivalents. This factor is one of many that needs to be considered when designing an efficient lighting system.

Rated lamp life and useful lamp life

Lamp lifespans vary enormously between technologies from 1 000 h to over 100 000 h. Although the lifespan reported by manufacturers is a single value, it is actually derived statistically and represents the total operating period at which 50% of the given lamp type have failed under standard test conditions. A better indication of failure characteristics is given by the full lamp mortality curve, which expresses the percentage of lamps still operating after a given time. The maturity of the lamp technology and a manufacturer's experience with it can usually be determined by a careful examination of these curves such that those with low failure levels over the first 50–80% of the lifespan are indicative of a mature product for which a manufacturer has gathered a large amount of lamp-life data. The equivalent curves for newer or less reliable lamps will have a greater proportion of early-life failures and usually greater numbers of failures well beyond the rated lifespan. For lamps that use electrodes (HID and fluorescent lamps), the mortality curve is more or less sensitive to the length of the average operating period, such that shorter and more frequent operating periods result in a shorter overall lifespan compared to longer and less frequent operating periods. The on–off switching frequency used in standard test procedures thus produces values that are only indicative of the lifespan to be expected *in situ* for these lamps.

The practical lamp life is more complex than a simple measure of the lamp failure rate because it needs to consider the extent of performance deterioration that may lead to the lamp being retired before it has completely failed. Performance deteriorations can include:

- Lumen and efficacy depreciation, resulting in insufficient and uneconomic light delivery.
- Colour (or spectral) shifts that result in the lamp no longer being useful for its designated application.
- Progressive instabilities so that the constancy of light delivery is no longer adequate (usually applies to HID lamps).
- Cycling (a phenomenon that afflicts high-pressure sodium lamps [see p. 127] such that they start, warm up, cease to function, cool down and then restart, with the process then repeating).

Practical lamp replacement rates, especially in the non-residential sector, are influenced not only by these factors but also by the labour costs associated with lamp replacement. These can be a significant proportion of total lighting costs and as it is quicker, and hence less expensive per lamp, to replace all lamps in a lighting installation at the same time rather than as each separate lamp fails, many enterprises employ group lamp replacement practices. This is sensible economically, but further foreshortens the practical lamp life from the rated lamp lifespan quoted by manufacturers.

Lamp colour characteristics

The intensity of light emitted by any given lamp varies across the range of the visible light spectrum with the result that different lamp types have different colour characteristics. Two metrics, the correlated colour temperature (CCT) and the colour rendering index (CRI), are used to describe this and both are defined according to international standards that are adhered to by lamp manufacturers around the world. The distinction between the two is that while the CCT describes the colour appearance of the lamp itself, the CRI describes the colour appearance of the surfaces being illuminated by the lamp. The CCT is expressed in degrees kelvin and corresponds to the chromaticity that matches that of a "black body" heated to the same temperature.

In fact the chromaticity of a lamp, which is loosely expressed via the CCT and CRI, is more accurately defined through inspection of the "*x*,*y*" coordinates on the Commission Internationale de l'Eclairage (CIE; International Lighting Committee) chromaticity diagram (Plate 3.3). The CIE diagram simultaneously provides a sense of the visual appearance of the light sources and an indication of how visually "warm", "cool" or tinted a space lit with the specific lamp will appear. In general, lamp designers aim to give their lamps chromaticity characteristics that make the light look relatively natural, *i.e.* that correspond to the chromaticity of daylight as it varies by season and time of day. Previous generations of fluorescent lamps were only available with a "cool white" CCT of 4 100 K, but the development of new generations of rare-earth phosphors has now enabled a much broader range of colour temperatures to be produced for fluorescent lamps. In North America this has resulted in "warmer" CCT fluorescent temperatures of around 3 500 K becoming prevalent. Interestingly, an inspection of lamp sales around the world reveals an apparent user preference for "cooler" CCT temperatures the closer the illuminated location is to the equator, and the converse applies for the closer it is to the poles. This may be explained by the desire for the chromaticity of light sources to be matched with that of the local daylight, which tends to be "cooler" (*i.e.* have a higher CCT) the closer one is to the equator.

Most of us have experienced situations where the colour of an item viewed indoors turns out to look quite different when taken outside. This can arise because of differences in the colour-rendering properties of electric lamps compared with those of daylight. The CRI is a reasonably reliable measure of the degree to which the colours of an object illuminated by a lamp will match those of the same object illuminated by daylight, where a maximum score of 100 implies a perfect match and a score of 0 a perfect mismatch. In part because they emit light across a full visible spectrum, incandescent lamps have CRI scores of almost 100 while other light sources are usually less. However, the other reason incandescent CRI scores are so high is because they are measured by comparison with incandescent lamps. This means that the CRI is a somewhat loaded measure, *i.e.* to achieve a high score requires a lamp's spectrum to be similar to that of an incandescent lamp.

In the relatively recent past there was a significant trade-off between lamp efficacy and CRI such that cool white fluorescent sources had a CRI of 62, standard metal halide lamps 65–79, high-pressure sodium 22, and low-pressure sodium 0 (all these lamps are described on pp. 107–137). Recent generations of these technologies have significantly better CRIs such that those for most fluorescent lamps are in the range of 70–95, metal halide lamps in the range of 65–90 and compact fluorescent lamps (CFLs) in the range of 82–85 (ALG, 2003).

There is an ongoing debate about the extent to which lighting chromaticity characteristics and especially CRIs need to be faithfully adhered to when considering high- for low-efficacy lamp substitutions. Efficient light sources are available across every range of CCT, but still none has a CRI that attains 100; however, this thought needs to be tempered by several other considerations. First, the human eye can not distinguish differences in CRI of less than 3–5. Second, choosing a lamp with a CRI of 100 does not guarantee that the delivered illumination also has a CRI of 100 because this depends on light interactions with the luminaire, room shape, surface colours and reflectance, overall illumination level and whether daylight is present. Third, while there is some evidence to suggest that a high CRI may enhance visual acuity, the sensitivity of visual performance to CRI becomes insignificant for CRIs above a minimum level. Fourth, human vision adapts to chromatic differences.

LAMP TYPES

Despite minor differences, lamps available around the world use largely the same technology and the same or very similar varieties of lamps can be found in all countries. This section introduces each of the main lamp types currently available commercially and describes their energy, cost and lighting characteristics. A brief chronology of the development of lamps up to the present is given in Box 3.1; the relationship between the most common lamp types is shown in Figure 3.4.

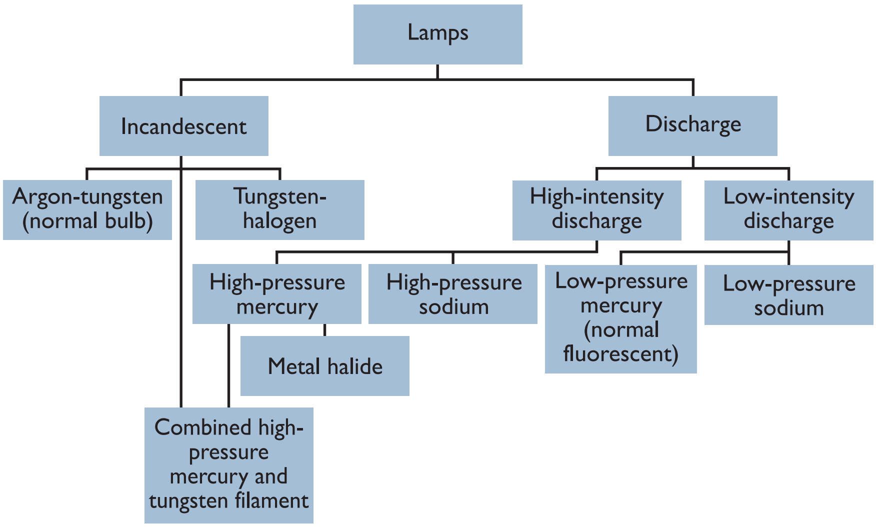
Box 3.1 A brief history of lamps

- Circa 3000 BC: Candles are invented. Some time later, oil lamps are developed.
- 1792: William Murdoch lights his house and office by means of gas.
- 1802: Humphry Davy demonstrates arc lighting.
- 1815: Humphry Davy invents the miners' safety lamp.
- 1835: James Bowman Lindsay demonstrates a light-bulb-based electric-lighting system to the citizens of Dundee, Scotland.
- 1840: First paraffin (kerosene) lamps.
- 1841: Arc lighting used as experimental public lighting in Paris, France.
- 1853: Ignacy Łukasiewicz invents the petroleum lamp.
- 1854: Heinrich Göbel invents the first true light-bulb, using a carbonised bamboo filament.
- 1867: A.E. Becquerel demonstrates the first fluorescent lamp.
- 1875: Henry Woodward patents the electric light-bulb.
- 1876: Paul Jablochkoff invents the Jablochkoff candle, the first practical carbon arc lamp, for public street lighting in Paris.
- 1878/9: Thomas Edison and Joseph Wilson Swan both patent the carbon-thread incandescent lamp. Swan successfully sues Edison but eventually sells his patent rights to him.
- 1885: Incandescent mantle invented, revolutionising gas lighting.
- 1893: Nikola Tesla uses cordless low-pressure gas-discharge lamps, powered by a high-frequency electric field, to light his laboratory.

- 1903: Peter Cooper Hewitt demonstrates the mercury vapour lamp, *i.e.* a fluorescent lamp.
- 1910: William Coolidge invents a way to make a tungsten filament that outlasts all other types of filament.
- 1911: Georges Claude develops the neon lamp.
- 1932: The first low-pressure sodium lamp is developed by Philips and used mainly for street lighting.
- 1937: LFLs are first commercialised.
- 1948: Halophosphor LFLs pioneered.
- 1959: The first tungsten halogen lamp is developed.
- 1962: Nick Holonyak Jr develops the first practical visible-spectrum LED.
- 1965: Metal halide HID lamps are commercialised.
- 1970: Commercialisation of high-pressure sodium vapour HID lamps.
- 1972: John Campbell patents first practical CFL.
- 1978: T8 LFLs are commercialised.
- 1980: CFLs are commercialised.
- 1980: Tungsten halogen lamps are commercialised.
- 1981: Thorn Lighting exhibits the world's first ceramic metal halide lamp at the Hanover World Light Fair.
- 1992: Induction lamps are commercialised.
- 1995: T5 LFLs are commercialised.

Sources: Wikipedia, 2005a; CADDET, 1991; General Electric, 2004; Lamptech, 2005.

Figure 3.4 **Types of electric lamp**



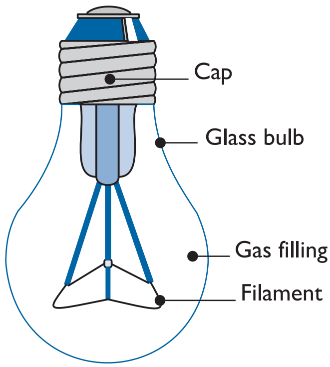
Source: CADDET, 1991.

Incandescent lamps

Incandescent lamps consist of a bulb containing a wire filament that is heated and emits light. Up to 95% of the energy emitted by incandescent lamps is in the invisible infrared (heat) end of the light spectrum and hence their efficiency is inherently low. Incandescent bulbs may have different types of bulb finishes to modify the brightness of the filament, internal reflecting substances on the bulb to control the direction of the light, halogen gases and special tungsten filaments. Tungsten is used because it has a relatively high melting point and a relatively low rate of evaporation at high temperatures. The filament is surrounded by a gas (argon in standard incandescent lamps) to reduce the tungsten evaporation rate and this raises the temperature at which the filament can operate and hence the light output. However, the gas also conducts heat away from the element, which lowers the overall efficacy.

The first practical incandescent lamp was developed in 1878 and design improvements continued to be made up to 1936, at which time efficacy levels had increased by a factor of approximately 10 (CADDET, 1991). No further

Figure 3.5 **Features of the common incandescent GLS lamp**



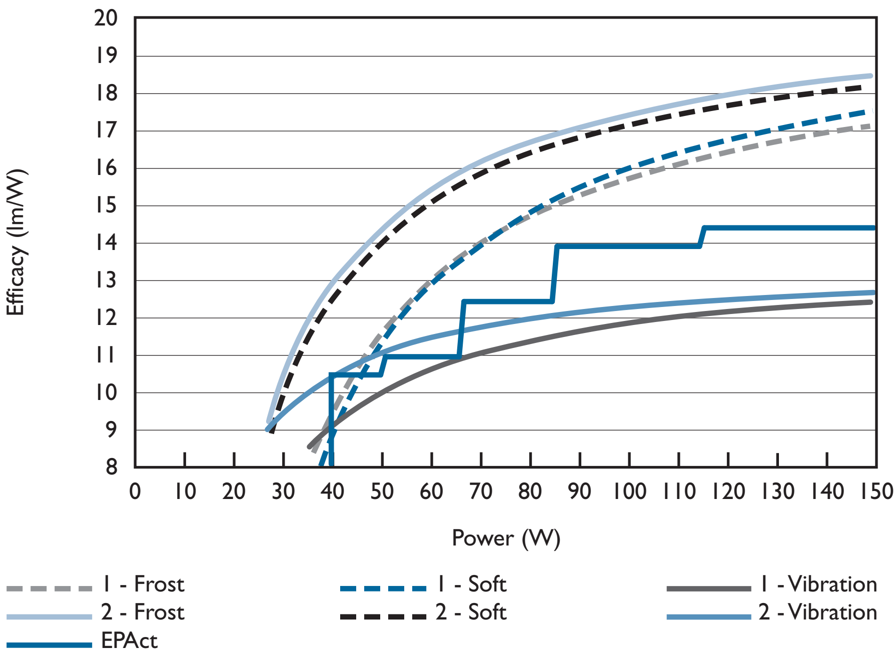
Sources: CADDET, 1991 (left); Courtesy of European Lamp Companies Federation (right).
Abbreviation: GLS = general lighting service.

developments occurred until the halogen lamp was developed in 1958 (see pp. 112–115). The most common type of argon-filled incandescent lamp is known as a general lighting service (GLS) lamp (Figure 3.5).

The lifespan of an incandescent bulb is not affected by the number of times it is ignited, but at an average of just 1 000 h it is significantly shorter than that of other alternatives. Incandescent lamps create comfortable colour lighting, are easy to dim, operate over a wide range of temperatures and, above all, are cheap to purchase and readily available in many types of retail outlets. Their chromaticity characteristics give near perfect colour rendering, but they are only able to produce warmer light with CCTs in the range of 2 400 to 3 100 K, which is roughly equivalent to daylight between sunrise and an hour after sunrise. The most common incandescent lamps distribute light diffusely in all directions from a near pear-shaped bulb; however, they can be housed inside reflectors to provide narrower or shaped light distribution when required. Incandescent lamps are also commonly available in a large variety of decorative forms such as candle and flame shapes.

Their low price, warm colour and long-standing familiarity have led to incandescent lamps being the most commonly purchased lamp globally, and they are particularly prevalent in residential lighting applications in most countries. However, they suffer from very poor efficacy, which leads

Figure 3.6 **Efficacy of incandescent lamps as a function of input power**



Source: Navigant, 2005 (reproduced with permission).
Abbreviation: EPAct = Energy Policy Act.

to disproportionately high energy and overall lighting-service costs. Although the efficiencies of incandescent lamps have been improved since their first development, they still have the lowest lighting output efficacies of any modern electric lamp type, ranging from 6 to 18 lm/W. Figure 3.6 illustrates the relationship between incandescent lamp efficacy and input power for some common lamp types.

Tungsten halogen lamps

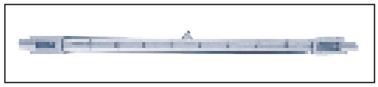
Tungsten halogen lamps are a higher-efficiency derivative of incandescent lamps that were initially developed in the 1950s but not commercialised until the 1980s. They are distinguishable from a GLS in that the bulb encasing the filament is filled with high-pressure halogen gas that enables higher filament and bulb wall temperatures than are possible with standard incandescent lamps. The higher filament temperature not only increases lamp efficacy but also generates a "whiter" light. Moreover, the halogen gas limits evaporation of the tungsten filament and, by a chemical regeneration process known as the "halogen cycle", redeposits evaporated tungsten on the hot surface of the filament. Consequently, the lumen depreciation (which is due to bulb wall darkening) found in standard incandescent lamps becomes negligible in halogen lamps, while the service life of the filament is longer. A high bulb wall temperature is required for the halogen cycle to work, and this is only possible if a temperature-resistant transparent material is used, *e.g.* fused silica or quartz. The relative expense of these materials and their high operating temperatures result in it being more pragmatic to encase the filament in a small capsule, which is then most commonly surrounded by a secondary glass bulb.

The most efficient varieties of tungsten halogen lamp use a multi-layer dichroic metallic coating on the inside of the capsule, similar to the reflective coatings used in low-emissivity glazing. The coating is transparent to visible light but reflects infrared heat back onto the element. This raises the element temperature and efficacy by 40–60% compared to other designs. The same infrared technology has been successfully incorporated into standard incandescent lamps on an experimental basis; however, the lamp cost is beyond the energy-savings payback at some residential energy rates and, so far, has been judged too expensive for the consumer market by manufacturers (ALG, 2003; Rubenstein *et al.,* 1998).

Tungsten halogen lamps have efficacies of 18–33 lm/W, CRIs of above 95 and rated lamp life of 2 000 to 6 000 h. The infrared dichroic tungsten halogen lamps have the highest efficacies, in the range of 28–35 lm/W (filament tube only). All halogen lamps are fully dimmable, but their efficacy declines steeply as they are dimmed.

There are several subsets of halogen lamps that deliver different quantities of light with varying directional spreads and are aimed at diverse applications (Figure 3.7). The most common forms employ a conical reflector designed to distribute the light in either very narrow spotlighting applications or slightly broader floodlighting applications. The intense light output from a small, near point-source makes halogen lamps particularly suitable for directional accent lighting. The reflector is typically designed

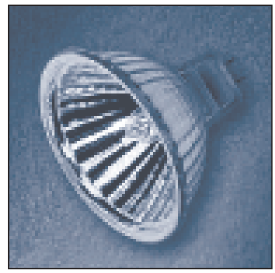
Figure 3.7 **Common types of halogen lamp**



Linear double-ended halogen lamp.

Halogen capsule lamp.

Halogen PAR lamp.



Halogen reflector lamp.

Sources: Courtesy of Philips Lighting (top and centre); Courtesy of European Lamp Companies Federation (bottom right and bottom left).

to allow infrared heat to escape from the back of the lamp, reducing the heat in the beam by more than 60% compared to lamps using aluminised reflectors. The compact dimensions and strong directional properties of halogen lamps have resulted in their common use as downlighters installed in shallow false ceilings in residential kitchens and bathrooms. Halogen lamps have also superseded incandescent lamps in the vast majority of vehicle headlamp applications because of this quality.

In their smallest forms halogen lamps can be made as tiny capsules that can draw as little as 5 W of power for 60 lm of light delivered. Halogen lamps are available at mains voltages or at low voltages (6, 12 and 24 V) using a step-down transformer. The lamps using a transformer have longer lamp lives but will incur additional energy losses in the transformer.

High-voltage halogen lamps have very high power ratings (300–500 W) and are generally supplied as double-ended capsules that are used in torchière uplighters to create high-intensity indirect mood lighting. Because of fire safety concerns, high-voltage halogen lamps used in such uplighters have been banned in some jurisdictions (e.g. California), but are still widely available elsewhere. They are especially common in some European countries. At full power halogen torchières generally have efficacy levels of 15–20 lm/W, but at partial power levels this falls to a paltry 2 or 3 lm/W (even worse than incandescent bulbs). The average energy consumption of halogen torchières has been estimated at 438 kWh/year per lamp in US households (USDOE, 2004), which is about the same as for a new refrigerator.

Linear fluorescent lamps

A linear fluorescent lamp (LFL) is a low-pressure discharge lamp that consists of a soda lime glass tube internally coated with phosphors and tungsten wire electrodes coated in a thermionic emitter sealed into each end of the tube. This is filled with one or more inert gases (usually argon) and trace amounts of mercury. Ultraviolet light is emitted by passing an electric current between the electrodes, creating a low-intensity arc that excites the mercury vapour and thereby produces ultraviolet radiation. This in turn excites the phosphors lining the glass tube, and these then emit visible light. Fluorescent lamps need a ballast (see pp. 137–141) to regulate the input current and voltage in a way that will initiate the lamp discharge and then maintain it at the required level. Fluorescent lamps are also diffuse-light sources, which means the light is emitted almost evenly from each point on the lamp wall. These characteristics require the lamp to be housed in a luminaire that enables the light to be redirected to where it is needed, and this means an assessment of the lamp's performance must be based on how successfully it functions in conjunction with the luminaire.

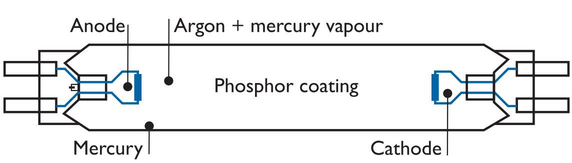
Fluorescent tubes have much higher efficacy levels (60–104 lm/W) and much longer operating lives (7 500–30 000 h) than those of incandescent lamps. While the highest CRI rating attained by fluorescent lamps is 95 and may typically be around 86, these lamps can be designed to provide a larger range of CCTs than incandescent lamps, ranging from 2 700 K (as found with an incandescent lamp) to 7 500 K (daylight). These characteristics combined with reasonable lamp prices have led to LFLs dominating lighting in the workplace, especially in offices and public buildings. Their low energy and maintenance costs per unit of delivered light led to their rapidly replacing incandescent lighting as the main source of lighting in the commercial sector following their commercialisation in 1937.

Despite having a long history, LFLs are continuing to be developed and they still have potential for further improvement. In the 1970s almost all linear fluorescent tubes were of the T12 variety (Figure 3.8), which had a diameter of 12 eighths of an inch (38 mm), and for many years standard 40 W and 20 W T12 tubes were the workhorse of electric lighting. The phosphors used in these lamps tended to give a blue white light, and lamps were prone to flicker. Following the energy crises of 1973, new "energy-saving" T12 lamps using krypton gas were marketed. This lowered the power consumption of the 40 W tubes to 34 W in 110–120 V systems and to 36 W in 220–240 V systems; however, light output fell by 10–12% and the efficacy of the lamps was increased by only 3–6%.

In the early 1980s manufacturers introduced the T8 tube, which at a diameter of 8 eighths of an inch (26 mm) was slimmer and typically had a 20% higher efficacy. In countries operating mains voltages of 230 or 240 V these lamps could be directly substituted into existing T12 luminaires and so they rapidly gained market share at the expense of the T12s; however, in those countries operating to 120 V the T8 lamps required installation of specific tailor-made luminaires, and this slowed the rate at which they have entered the market.

The development of more efficient T8 lamp technology depended on the development of phosphors that could withstand higher tube-wall power loading, which will occur with a narrower tube, without accelerating depreciation compared to T12 designs. The development of rare-earth phosphors in the mid-1970s overcame this problem and allowed the

Figure 3.8 **Features of LFLs**



Source: CADDET, 1991 (left); Courtesy of European Lamp Companies Federation (right).
Abbreviation: LFLs = linear fluorescent lamps.

Table 3.1 Comparison of standard T5 and T8 lamps under optimum operating temperatures

Lamp type	Power (W)	Length (mm)	Light output (lm)	Efficacy (lm/W)	Efficacy with typical ballast (lm/W)
T5	14	549	1 350	96	84
T5	21	849	2 100	100	89
T5	28	1 149	2 900	104	95
T5	35	1 449	3 600	104	95
T8	18	590	1 300	81	67
T8	36	1 200	3 200	100	89

Source: Borg, 1997.

development of tubes with both higher efficacy and smaller size. This not only allowed the volume needed to ship and store lamps to be reduced but also enabled more compact and efficient luminaires to be developed. The T8 market is differentiated between lower-efficacy T8 tubes that use halophosphors and higher-efficacy ones that use triphosphors. The triphosphors are not only more efficient but also provide better colour rendering, although there is a modest price premium for this higher service level. In some countries these lamps are known as "Super T8s". Even beyond this there are T8 lamps with a CRI above 90, achieved by adding an additional phosphor; however, this reduces the efficacy.

In 1995 an even slimmer (16 mm) fluorescent tube known as the T5 (diameter of 5 eighths of an inch) entered the market. This lamp has an even higher efficacy, up to 105 lm/W, compared to 96 lm/W for a Super T8. T5s and T8s do not have exactly the same power ratings and light output per lamp, so direct performance comparisons are difficult to make; however, a triphosphor T8 operated with an efficient electronic ballast (see pp. 137–141) will typically have a lamp/ballast system efficacy of 89 lm/W, compared to 95 lm/W for a T5 operating with an electronic ballast (Table 3.1). The difference is slightly greater at lower wattages.

However, there are other benefits associated with T5 lamps, albeit ones that can depend on the precise circumstance of the lamp's usage. T8s have optimal light output and efficacy at a temperature of 25 °C and are rated accordingly, whereas for T5s the optimum is at 35 °C. For most real lighting situations T5s are more likely than T8s to be operating at or near their optimum, because most luminaires do not fully dissipate the heat generated by the lamp. As shown in Figure 3.2, the light output and efficacy of fluorescent tubes tends to deteriorate quite markedly away from peak, and this may give the T5s an additional 10% *in situ* system efficacy benefit compared with T8s in many real installations. Moreover, T5s use a coating on the inside of the tube wall that prevents mercury from being absorbed into the glass and the phosphor. Not only does this allow the amount of mercury required to be cut from ~15 to 3 mg per lamp, but it also reduces the rate of lumen depreciation to only 5% after 12 000 h, compared to 15% for the older T8s. The higher lumen maintenance allows lighting installations that use less power to be specified because there is less need to overspecify the initial light levels to compensate for lumen depreciation in later life. These mercury-blocking coatings are also used in some newer generations of T8 lamps, and this has enabled mercury content to be reduced to 3 mg per lamp.

T5s will generally have better luminaire output ratios (LORs; the ratio of light emitted by the luminaire to the light emitted by the lamp) than T8s because their extra narrowness allows a greater proportion of light to escape from the luminaire without being shaded by the lamp itself. In addition, the narrow tube results in the light emission being closer to a true linear point-source, which allows better directional control to be applied. The combination of temperature and luminaire benefits has been estimated to give T5s an additional 15% advantage in system efficacy (Govén, 1997).

Some advantages of T5s are market-based rather than being inherent to the technology. For example, they are routinely supplied in luminaires using aluminium with a very high reflectance (~95%), compared to levels of 85–87% that are more characteristic of conventional aluminium reflectors, and this raises the light output from the luminaire accordingly.

T5s are designed to be shorter than T8s so that they can be used in luminaires that are more readily integrated into the metric 600, 1 200 or 1 500 mm building modules which are the standard in many European countries (Borg, 1997). This also means that they do not fit into existing T12/T8 luminaires and thus can only be deployed when a new fixture is used. Inevitably this has slowed their market adoption rate compared to the speed at which T8s began to replace T12s. It is now possible to buy adaptor kits, however, which enable T5s to be fitted into some T8 fixtures, albeit at a risk of compromising the performance of the luminaire optics, dependent on the specific installation.

Despite the advantages, there were also some difficulties when T5s were first introduced to the market. Their higher brightness per unit surface area led to greater direct problems than had been experienced with T8s and this required some additional luminaire redesign. In practice it appears that the best choice of efficient fluorescent tube will depend on the application and the choice of luminaires available to meet it. Super T8s appear to be currently best suited to some roles, and T5s to others. Nonetheless, in the right circumstances T5s can be up to 35% more efficient than their T8 counterparts.

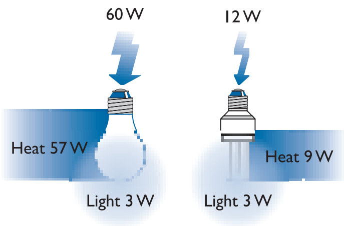
Aside from the three main LFLs mentioned here, there are several other variants that are designed to fit into specific luminaire shapes. Circular fluorescent tubes are popular in some markets and can be in T12, T8 and T5 specifications. This type of lamp is frequently used to illuminate living-rooms and lounges in Japanese households, for example. U-shaped lamps and short tube lengths are also relatively common. In general though, the addition of bends reduces lamp efficacy and makes luminaire optics more challenging, so linear tubes are by far the most common form of fluorescent lamp.

Despite their high efficiency, fluorescent tubes have limitations. They are not well suited for precise light-beam control and require operation with electronic ballasts if they are to be dimmed. The improved availability and lower price of electronic ballasts compared with a decade ago means the dimmability constraint is far less of an issue than it was.

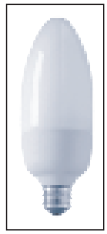
Compact fluorescent lamps

The development of rare-earth phosphors in the late 1970s also enabled the production of compact fluorescent lamps (CFLs) (Figure 3.9). These were first commercialised in the early 1980s and are offered in two types: with the ballast either integrated into the lamp or not. The former are intended as direct substitutes for incandescent lamps and are designed to fit into existing incandescent lamp fixtures, while the latter are orientated more at commercial-building retrofits and new buildings as alternatives to incandescent lighting installations. CFLs usually consist of 2, 4 or 6 small fluorescent tubes that are mounted in a base attached to a ballast for ballast-integrated models, or are plug-in tubes for the non-integrated

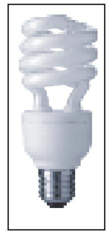
Figure 3.9 **Ballast-integrated CFL models**



Heat losses from GLS lamps and CFLs.



Spiral CFL.



Candle-shaped CFL.

Stick CFL.

Sources: Faktor licht, 2000 (reproduced with permission) (far left); Courtesy of Philips Lighting (centre left and centre right: Courtesy of European Lamp Companies Federation (far right).
Abbreviations: CFL = compact fluorescent lamp; GLS = general lighting service.

variety. Integrated lamps use either a screw-in base or bayonet cap in the same way as standard incandescent lamps. More recent models are available in a variety of screw-in diameters and so will fit into a much larger range of lamp sockets than earlier generations. The lumen-packages (light output) of integrated CFLs are designed to match those of equivalent incandescent lamps, but as their efficacies are from four to five times higher the wattage ratings are proportionately lower. CFL power rating ranges from 4 to 120 W and their efficacies from 35 to 80 lm/W.

The high efficacy compared to incandescent lamps is the great advantage of CFLs and means they will consume one-quarter to one-fifth of the energy to provide the same level of light. About 25% of energy consumed by CFLs is converted to visible light, compared with just 5% for a GLS incandescent lamp. This relatively high efficiency means many CFLs are cool enough to touch while operating and hence are safer. Another important benefit is that they have much longer lifetimes compared to incandescent lamps and have rated lifespans of 5 000 to 25 000 h. However, there are a number of limitations that have slowed their rate of market penetration. The largest barrier has been their high initial cost: when first launched, CFLs were 20–30 times more expensive than their incandescent equivalents. CFL prices have steadily declined since and now retail for as little as four times the price of an incandescent lamp; however, even at this level price remains a barrier. Despite the high purchase price the life-cycle costs of CFLs are a fraction of those for incandescent lamps because of their low energy costs (Box 3.2).

Box 3.2 The economics of CFLs compared to incandescent lamps

CFLs are far more cost-effective than incandescent lamps over the life cycle of the lamp as they have far lower energy costs and much longer lifetimes (see the table for a typical example). A CFL costs 20 times more to purchase than a single incandescent lamp; however, even if the additional costs of fitting and travelling to buy the additional incandescent lamps required are ignored, incandescent lamps costs more than three times as much as CFLs when the energy costs are included. The implied cost of energy conserved with a CFL is just USD 0.008 cents per kilowatt-hour which is less than one-tenth of typical electricity tariffs. Despite this, consumers need to be aware of and trust the benefits of CFLs before they are likely to risk investing in a lamp, which at face value is 20 times more expensive than a traditional incandescent lamp. Rational discounting of the future value of money does not explain any consumer reluctance to forgo incandescent lamps in favour of CFLs. For example, were the lamps in the example in the table to be operated for an average of 2 hours per day, the implied discount rate would have to reach the enormous value of 110% before the cost advantage of CFLs over incandescent lamps would disappear.

Typical characteristics and costs of CFLs

	Incandescent lamp	CFL
Initial cost of bulb (USD)	0.50	10.00
Light output (lm)	900	900
Lamp power (W)	75	15
Efficacy (lm/W)	12	60
Lifespan of bulb (h)	1 000	10 000
Calculations over a 10 000 h operating period, assuming an electricity tariff of USD 0.1/kWh		
Electricity consumption (kWh)	750	150
Cost of electricity (USD)	75.00	15.00
Cost of lamps (USD)	5.00	10.00
Total cost of lamps and electricity (USD)	80.00	25.00
Total savings for CFL (USD)	–	55.00
Implied cost of conserved energy (USD/kWh)	–	0.008

Coupled to the price barrier CFLs have had a number of quality and suitability issues to address. The first CFLs had limited CCT ranges and tended to be available only in the higher CCT cooler-light values. Current generations are available in a wider range of CCT levels than incandescent lamps, including the same warm hues provided by incandescent lamps. CFLs using magnetic ballasts (see pp. 137–141) were prone to delayed starts and long warm-up times and could suffer from flicker. With the introduction of higher-quality lamps using electronic ballasts these problems have been overcome, and further production up-scaling and cost reductions have now resulted in cost prices that have made CFL lamps a good alternative for standard incandescent lamps. As with other fluorescent lamps the CRI of CFLs is not as high as for incandescent lamps. Typical values range from 82 to 86, which is good enough for most applications but may be a barrier in some situations. The highest-quality CFLs have CRIs of up to 90 (Table 3.2). Another more serious obstacle that constrained residential CFL sales until very recently was the problem of their suitability for use in existing fixtures. Early CFLs were only available in a limited range of sizes and were not small enough to fit into many standard incandescent fixtures. In the last few years, however, numerous designs of super-compact CFLs have become available,

Table 3.2 **Comparison of incandescent and CFL performance**

Lamp type	Wattage (W)	Luminous flux (lm)	Colour rendering index	Efficacy (lm/W)
Normal incandescent	40	430	99	11
	60	730	99	12
	75	960	99	13
	100	1 380	99	14
CFL with standard ballast*	9	415	82	46
	13	620	82	48
	18	825	82	46
	25	1 085	82	43
CFL with electronic ballast**	7	400	85–90	57
	11	600	85–90	55
	15	900	85–90	60
	20	1 200	85–90	60

Source: CADDET, 1991.
* Philips Lighting, product information, 1990.
** OSRAM, product information, 1990.
Abbreviation: CFL = compact fluorescent lamp.

allowing them to be used in almost any standard incandescent lamp fitting. In some markets CFLs are now also available in decorative forms such as flame shapes for candelabra fittings.

When CFLs were first introduced there were also luminaire design issues to be addressed in commercial-building applications. The higher surface brightness of CFLs compared to other fluorescent lamps of that period led some CFL luminaire designs to produce too much direct glare, and so improved configurations had to be developed. These difficulties were relatively quickly overcome and in many parts of the world CFLs have largely replaced incandescent lamps in the majority of commercial buildings.

During more than a decade, many demand-side management (DSM) programmes around the world have been carried out to encourage customers to switch to CFLs from incandescent bulbs; these are discussed in Chapter 5.

Cold-cathode fluorescent lamps

Cold-cathode fluorescent lamps are used to illuminate some types of retail showcases, publicity signage, back-lit signs, light boxes and liquid crystal display (LCD) screens used in computer monitors and flat-screen televisions. They are like very thin low-pressure fluorescent lamps, but the means by which they establish an electrical discharge is different. Conventional fluorescent tubes heat the cathode (negatively charged electrode) to create a discharge current flow via thermionic emission. As their name suggests, "cold-cathode" fluorescent lamps do not do this; rather, they function by bombarding the cathode with ionised particles created in the discharge. Initiation of the discharge is facilitated by coating the electrode with a substance (sometimes a rare earth) to encourage electron emission and then priming the emission with a source of beta radiation. As with other fluorescent lamps, cold-cathode fluorescent lamps are quite efficient and convert about 20% of the applied electrical energy into useful light.

Neon lights are the best-known example of cold-cathode fluorescent lighting, but this technology is also used in emergency-exit lighting, backlighting for LCD screens in televisions and computer monitors. For backlighting of monitors or televisions a very thin fluorescent tube (4 mm diameter) that produces large amounts of light is used. The cold-cathode fluorescent lamps are set in highly reflective aluminium U channels to direct the light output forwards and into the LCD screen matrix. They are powered by a direct current (DC) supply, usually 12 V, and have efficacy levels of about 80 lm/W. The competition with solid-state lighting in this application and for exit signs is discussed on pp. 454–455.

Low-pressure sodium lamps

Low-pressure sodium lamps have been in use since the 1930s and comprise the lamp with the highest photopic efficacy rating (up to 200 lm/W) (Figure 3.10). As with fluorescent lamps and HID lamps (see pp. 125–130), they require a ballast to operate. They are also quite large, about 122 cm (4 ft) long for the 180 W size, which makes light distribution from fixtures harder to control. They require a brief warm-up period for the lamp to reach full brightness. The key weakness of low-pressure sodium lamps is their very poor colour rendering, which is accounted for by the extremely narrow emission spectrum of light from sodium vapour. Ironically, this also accounts for their high efficacy level, because the light spectrum is very close to the peak photopic light sensitivity for human vision.

Low-pressure sodium designs were improved in the 1960s when visible-light transparent, infrared-reflecting coatings based on tin oxide were added to the inside of the tube to produce what are called SOX lamps. As with halogen lamps these coatings trap the heat in the lamp, which raises the operating temperature and increases the efficacy. Progressive evolutions of these coatings have produced further efficacy gains, yet have also changed the colour of surface reflections in the film. Standard tin

Figure 3.10 **Features of low-pressure sodium lamps**

Source: Lamptech, 2005 (reproduced with permission).

oxide SOX coatings produce a yellow/orange colour and the indium oxide (SOI) lamps have a greenish hue, while the highest-efficacy SOX-E coatings impart a reddish colour to reflected light. Overall, SOX lamps have a CRI of 0 (they do not render colour) and lifespans of 10 000 to 16 000 h. Typical power ratings range from 26 to 180 W.

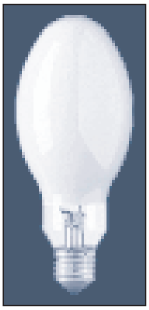
Low-pressure sodium lamps are used where colour is unimportant because it renders colours as tones of yellow or grey, making them appropriate only for certain types of street lighting and security lighting.

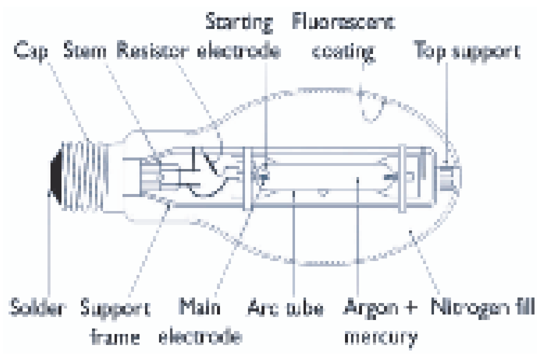
High-intensity discharge lamps

HID lamps generate light by creating an electric arc across tungsten electrodes. This assembly is housed inside a transparent tube made out of fused alumina or quartz and filled with various gas and metals that define the type of HID in question. The gas aids the electric discharge arc to be established, while the metals emit light once they are heated to the point of vaporisation. The three main families of HID lamps are mercury vapour, high-pressure sodium and metal halide (Figure 3.11). A less common variety is that of xenon short-arc lamps (p. 134). As with fluorescent lamps, HID lamps require control gear to start and maintain stable operating conditions, and this necessitates additional power beyond that used by the lamp itself.

HID lamps offer important advantages compared to incandescent lamps and some compared to fluorescent lamps, which makes them well suited to certain applications. They can be very efficient, have long lifespans, are relatively temperature-insensitive and produce a large quantity of light in a small package. As a result they have traditionally been used when high levels of light are required over large areas and economy in both energy and maintenance costs are important. This last aspect follows because provided sufficient height is available, high-power HID lamps can be used in superior optical performance luminaires and thereby fewer lamps are required to illuminate a given area compared to fluorescent lamps. One of the general principles of lighting design is that the acceptable amount of light from a single luminaire increases with ceiling height, and this means that indoor environments best suited to HID lamps are those with high ceilings, such as commonly found in industrial spaces, warehouses, large retail spaces, sports halls and large public areas. The temperature insensitivity, light throw and potential efficacy benefits of HID lamps also

Figure 3.11 **Features of HID lamps**





Source: Photos courtesy of European Lamp Companies Federation; Lamptech, 2005 (mercury vapour graphic).
Abbreviation: HID = high-intensity discharge.

enable them to dominate external-lighting applications such as street and roadway lighting, car parks, some types of security lighting and pathways. More recently, however, some newer types of low-power HID sources have been used in small retail and residential environments, where they can provide display lighting with greater economy than is possible with halogen lamps for similar colour rendering and colour temperatures.

Mercury vapour lamps

Mercury vapour lamps are the oldest HID lamp and have been widely used around the world. The high-pressure versions have efficacy levels of 23–60 lm/W and lifespans of 6 000–28 000 h. Mercury vapour lamps originally produced a bluish-green light, but they are now available in a colour-corrected whiter light, giving a range of CRIs of 15–62 and CCTs of

2 900 to 5 700 K. The higher CRI values are achieved by using phosphor coatings, but these reduce the efficacy. The highest-efficacy and CRI mercury vapour lamps have a high vapour pressure and use separate (non-integrated) ballasts, but in some parts of the world self-ballasted lower-pressure blended mercury lamps are still common despite their very poor efficacy (14.4–29 lm/W), mediocre light quality (CRI of 50–62) and short lifespan (6 000–12 000 h). In general, mercury vapour lamps are cheap and so still have a market presence, despite their performance characteristics and life-cycle costs being notably worse than those offered by the more efficient metal halide and high-pressure sodium lamps discussed in the next sections.

High-pressure sodium lamps

Standard high-pressure sodium lamps have the highest efficacy of all HID lamps, with ratings of 70–140 lm/W, but produce a golden light of warm appearance with low- to mid-range CRIs. As a result they tend to be used where chromaticity considerations are less important than economy. Pressurising the sodium vapour causes the emission spectrum to broaden compared with low-pressure sodium lamps, producing a higher and more acceptable CRI (*e.g.* 25). As a result, high-pressure sodium lamps are now much more commonly used than low-pressure sodium lamps for street- and external-lighting applications, despite their poorer efficacy. Colour-corrected high-pressure sodium lamps that produce a whiter light are now also available (with CRIs as high as 83), but as with other HID lamps this reduces their efficacy. Despite this, their efficacy is much higher than that of mercury vapour lamps. This type of high-pressure sodium lamp is suitable for some indoor applications. Overall, high-pressure sodium lamps have CRIs of 21–83, CCTs of 1 900 to 2 500 K and lifespans of 5 000 to 28 000 h. Typical power ratings range from 40 to 400 W.

Metal halide lamps

Metal halide lamps cannot attain efficacies as high as high-pressure sodium lamps, but they produce a whiter, more natural light. They are closely related to mercury vapour lamps but include other metal elements which are dosed as a metal halide, such as sodium iodide and scandium iodide, in combination with the mercury, which is used as a buffer gas in order to create a lamp voltage of typically 90–100 V. Traditional "probe start" metal halide lamps have a starting electrode in combination with a thermal shorting switch to eliminate any electrical potential between the main electrode and the starting electrode once the lamp is lit, thereby avoiding the failure of the glass/metal seal. The more modern "pulse start" lamps use high-voltage pulses in the same way as high-pressure sodium lamps and do not need a starting electrode. Metal halide lamps have lifespans of 6 000 to 20 000 h, CRIs of 65–92, CCTs of 3 000 to 6 500 K and initial efficacy ratings of 47–105 lm/W; however, like mercury vapour lamps they tend to suffer from significant lumen depreciation (see Figure 3.1), and their efficacies at 40% of lamp life are much lower than their initial ratings. The pulse-start metal halide lamps are much superior in all regards compared to the probe-start lamps, although both are still available on the market. Typical power ratings range from 35 to 1 500 W, though there are lamps for special applications which extend to 12 000 W.

Disadvantages of traditional HID lamps

Despite their potential for high light and good initial efficacy levels, low temperature sensitivity and good optical characteristics, HID lamps have some important negative aspects that result in them being a second best choice to other lamp types in some situations. With the exception of some metal halide lamps their colour rendering is of poor to medium quality and so they are not appropriate where faithful colour representation is needed. They have a high percentage of flicker, which can be a cause of annoyance. They have long start-up and warm-up times and typically require several minutes after ignition to reach their full light level. They have poor dimmability characteristics such that their CRIs tend to drop when dimmed and the light output falls far faster than the power input, resulting in poor part-load efficacy levels. Finally, if they are extinguished they must cool off before being relit, which when added to the long ignition and warm-up times can take from 5 to 15 minutes. Also, standard metal halide lamps often have a large spread in their individual colour points, which is not acceptable in more critical applications such as shop lighting. This last issue means they are not well suited to emergency lighting, which can be an important economic consideration because the added costs of providing back-up emergency-lighting systems may offset the fixture cost savings of HID lighting as compared to other choices. In addition the metal halide and mercury vapour lamps can have very significant lumen depreciation, causing their light output to be as low as 50% of initial rated values at the end of their rated life.

Ceramic metal halide lamps

Nonetheless there are many applications where HIDs are clearly the best and most economic choice, and some new generations of HID are overcoming some of the difficulties in the older technologies. One such lamp with great energy-savings potential is the ceramic metal halide lamp, which includes a ceramic tube inside the lamp that heats a mixture of mercury, a rare gas argon and a multitude of halide salts to create a bluish light that can be close to daylight with a CRI of up to 96, with an excellent colour-point stability. The high CRI, high efficacy and good optics of ceramic metal halide lamps make them suitable for reflector lamps and a competitor to some tungsten halogen lamp applications, for which they can produce up to five times as much light for the same input power. For example, they can be used to provide high-efficacy display lighting. Ceramic metal halide lamps were first demonstrated in the early 1980s but were not properly commercialised until the mid-1990s, after problems due to heat causing the seals to crack were overcome. The first products had lower power ratings, typically 35 or 70 W, and were suited for retail display, but much higher-wattage lamps have become available since (IESNA, 2003) and are suitable for high-CRI, high-efficacy outdoor lighting or high-bay indoor lighting (Box 3.3). Some other applications for these lamps include television and film making as well as digital photography and architectural lighting.

Box 3.3 Case study: High-wattage ceramic metal halide lamps

Although metal halide lamps have better colour-rendering properties than other HID lamps, their lifespan is short. For the purpose of supplying a high-quality, energy-efficient white-light source, instead of conventional metal halide lamps the Japan Storage Battery Co. Ltd developed and commercialised a ceramic metal halide lamp named "eco-cera". This has a unique arc-tube configuration and is most suitable as a lighting system for high-ceilinged indoor and outdoor facilities. Since the CRI of the eco-cera lamp is as high as 90, close to that of natural light, this lamp is appropriate for lighting urban highways, streets and parks. It has also been used in a variety of factories and gymnasiums.

Conventional metal halide lamps use quartz for the arc-tube material; however, the light-emitting matter enclosed by the arc tube reacts with quartz at high temperatures, causing the lamp life to be shortened. This limitation has been ameliorated in ceramic metal halide lamps by the use of translucent alumina ceramics as the arc-tube material. Ceramic metal halide lamps of 35, 70 and 150 W were initially developed and came into wide use as lighting systems for shops and other indoor environments. However, the development of higher-power lamps of 200 W or more was challenging, because the detrimental effect of heat on the arc-tube seals caused leakage of the light-emitting material. In October 2000, the Japan Storage Battery Co. succeeded in commercialising 220 W and 360 W eco-cera lamps.

Compared with conventional metal halide lamps, the eco-cera lamp leads to energy savings of 33–43%, extends lifetime by 33% from 9 000 to 12 000 h, and achieves a lumen maintenance as high as 80%, even toward the end of its life. Moreover, in comparison with a conventional metal halide lamp CRI of 65, the eco-cera has superior colour rendering and there is almost no colour shift over its operating life. Furthermore the eco-cera lamp can be operated with existing mercury vapour and metal halide lamp ballasts, thus fixtures using these lamps can easily be upgraded to provide higher-quality, more energy-efficient illumination simply by replacing the lamps. The eco-cera uses 73% less mercury than the mercury vapour lamp, and its increased lighting efficiency enables the number of lamps installed to be decreased by 26–37%. The energy and resources needed to produce lamps can therefore also be saved, resulting in a further reduction in environmental impact.

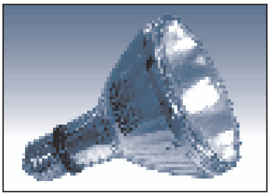
Source: CADDET Energy Efficiency, 2003a.

Ceramic metal halide lamps have rated lifespans of 6 000 to 20 000 h, CRIs of 80–96, CCTs of 3 000 to 4 300, initial efficacies of 67–104 lm/W and superior lumen and efficacy maintenance than standard metal halide lamps (10–30% higher). Typical power ratings range from 20 to 400 W (Figure 3.12).

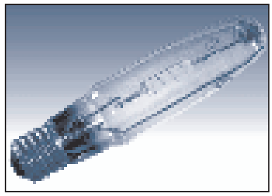
Induction lamps

Induction lamps are durable, have reasonable efficacy and provide good colour rendering (Figure 3.13). They often have very long lifetimes of 100 000 hours, or 25 maintenance-free years, which is made possible by the fact that they do not use electrodes, which are often the cause of

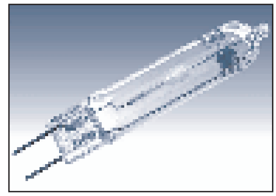
Figure 3.12 **Examples of ceramic metal halide lamps**



Philips 35 W Mastercolour CDM-R PAR30 reflector.



Philips 400 W HPS retro-white high-wattage CDM.

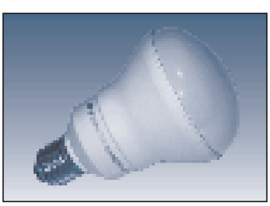


GE Lighting E20 W ceramic metal halide-TC compact with 3-part arc tube.

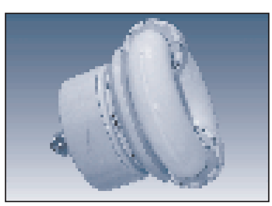
Source: Lamptech, 2005 (reproduced with permission).

other lamp failures. Their efficiency is about the same as that for standard fluorescent lamps and they have the advantage of instant start and restart. Furthermore, on–off cycling does not affect lamp life. While these lamps are significantly more expensive than most alternatives, their life-cycle cost is competitive when access is difficult because of the low maintenance costs. Induction lamps operate by supplying high-frequency power to an induction coil, which generates an electromagnetic field within the lamp. This field excites the plasma material inside the glass housing, causing the mercury atoms to emit ultraviolet light. When the ultraviolet light passes through the phosphor coating it is converted into visible light in very much the same manner as in fluorescent lamps.

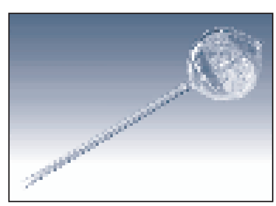
Figure 3.13 **Examples of induction lamps**



GE Lighting 23 W Genura self-ballasted electrodeless reflector.



Hongyuan 60 W Saturn 2 self-ballasted electrodeless.



TUE 1 000 W electrodeless sulphur microwave lamp.

Source: Lamptech, 2005 (reproduced with permission).

Typical power ratings range from 12 to 100 W for standard induction lamps; however, one unique variant is the sulphur microwave lamp, which has a power rating of 1 000 W. This lamp was developed in the late 1980s to exploit the spectral properties of sulphur, which has an emission spectrum centred near the optimum response of the human eye. Unfortunately sulphur is highly corrosive and thus requires an electrodeless lamp design. Power is coupled to the discharge using a magnetron operating in the microwave frequency range, but this limits efficiencies to 70% at best and requires a large bulb size and high input power. Sulphur lamps have very long lifetimes (60 000 h) and high efficacy (130 lm/W for the lamp and 95 lm/W for the system); however, their high cost and power means they are suitable only for producing very high light levels, for which there are few practical applications. Sulphur lamps were trialled in several applications, most notably using the 3M Light Pipe system, but the green colour, restriction to high wattages, inefficiency of the magnetron and great noise from its cooling fans saw the lamp discontinued in 2000 (Lamptech, 2005).

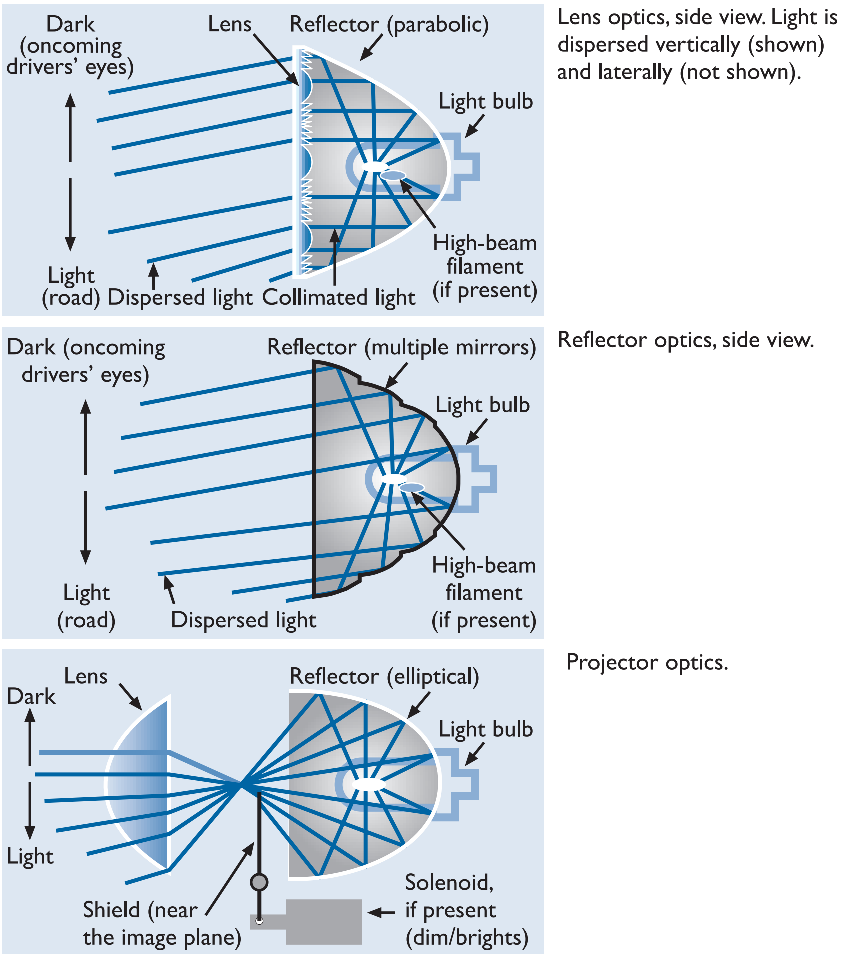
Vehicle lamps

Vehicles use a large number of lamps, including headlamps, indicator lights, side lights, brake lights, reversing lights, fog lights, interior indicator lights, dashboard illumination, passenger lights, reading lights, etc. All of these lamps are powered by energy delivered from the vehicle battery, which is charged by the alternator driven off the vehicle engine, and so are a direct cause of fuel consumption.

The most important vehicle lamps in energy terms are the headlights, which are required to deliver plenty of light and can be activated for proportionately long periods (Figure 3.14). Vehicle headlights are positioned in pairs and are required to produce a dipped (low) and a full (high) beam. This can be done by using either individual lamps or a single lamp for both functions. Full beams throw their light straight ahead, maximising the range of vision but causing glare to oncoming traffic, whereas dipped beams direct their light downwards and slightly to the side away from the oncoming traffic and thereby provide forward visibility without excessive glare.

Incandescent lamps were the traditional technology for headlamps, but these have been almost completely replaced by halogen lamps in today's vehicles because of their higher efficacy, high light power, good beam

Figure 3.14 **Configurations for headlamp optics**



Source: Wikipedia, 2005b.

control and higher CCTs. A typical European halogen headlamp will draw 55 W and emit 1 550 lm at an overall lamp efficacy of 28.2 lm/W. Traditionally, US headlamps were required to be sealed beam units, which resulted in halogen technology not entering the US market until 1978, some 16 years after Europe. When they were introduced the approach was to use the efficacy gain to draw less power and provide the same amount of light, so the first US halogen headlamp produced 700 lm when dipped and 1 200 lm when on full beam. There are still differences in regulatory requirements that limit the maximum forward luminance of headlamps in Europe and North America. The maximum permitted luminance output of US halogen full-beam headlamps is 150 000 candela, and that in Europe is 225 000 candela in Europe (Wikipedia, 2005b).

There are two alternative headlamp technologies to halogen lamps, the xenon short-arc discharge lamp and light-emitting diodes (LEDs) (solid-state lighting). Xenon headlamps were first introduced onto the European vehicle market in 1991 and have since gained a significant market share in high-end European and Japanese vehicles, but they have yet to become popular in North America. A xenon headlamp is a type of HID lamp with an efficacy level four times greater than that of halogen headlamps, but much of this improvement is used to provide more light rather than draw less power. A typical xenon headlamp might use 35 W of power to emit 3 200 lm at an efficacy of 91.4 lm/W. As with halogen lamps, the beam control and chromaticity characteristics of xenon lamps are good, but xenon lamps are currently more expensive and hence tend only to be used on premium products. The main cause of this expense is that because of the risk of glare, xenon HID lamps in Europe are required to have automatic levelling systems that ensure the beams are correctly aimed regardless of the vehicle's position and without action by the driver. The addition of these levelling devices adds significantly to the cost, which is why this technology is still only found in high-end vehicles.

Automotive headlight applications using LEDs are not yet in volume production, but prototypes now exist that give performance roughly equal to that of existing halogen headlamps. These prototype designs currently require a large number of the most powerful LEDs available. The relatively high expense, regulatory delays and LED operational concerns (especially with heat removal) have so far prevented them from entering the market, though they are increasingly being adopted for signalling functions such as brake lamps and turn signals (see Chapter 7).

Summary of lamp characteristics

Table 3.3 gives a summary of the main technical features of lamps, and the range of system efficacy (*i.e.* the efficacy of the lamp and ballast, if required) of different lamp types is illustrated in Figure 3.15. The evolution of lamp efficacy over time is shown in Figure 3.16.

Table 3.3 Summary of lamp characteristics

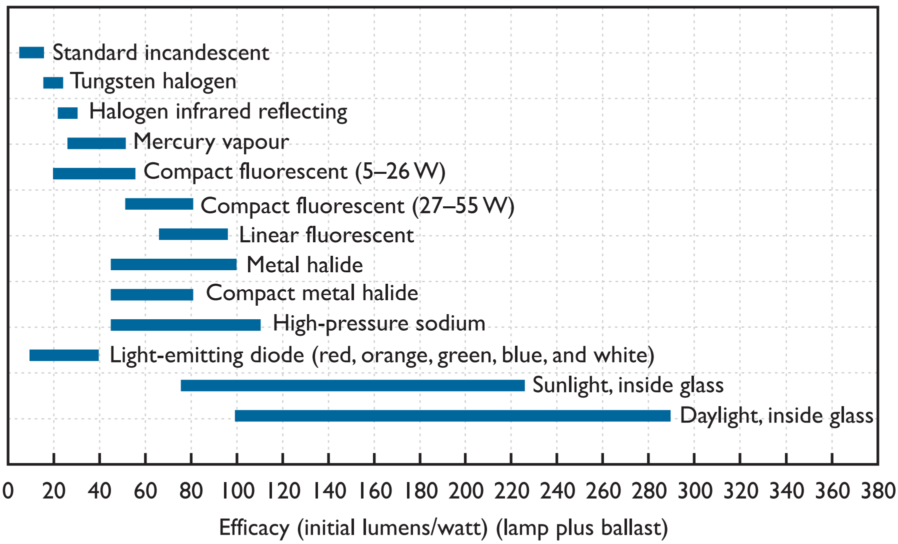
Lamp category	Characteristics	Applications
Incandescent lamps	Very low efficacy and low life. Low investment costs, high running costs. Dimmable. Reflector lamps for concentrated light beams. 10–15 lm/W with lamp life of 1 000 h. Very high CRI and low CCT.	For general, local, ambient and spot lighting. Not suitable where high lighting levels are necessary.
Halogen lamps (low voltage)	Very small lamps, capable of producing highly directable light beams. Some losses in the transformer. Low to mid efficacy with low to mid lifespans. 15–33 lm/W with lamp life of 2 000 to 6 000 h. Very high CRI and low CCT, but slightly higher than incandescent.	Highly suitable for spotlighting.
Halogen lamps (high voltage)	Slightly higher efficacies than incandescent lamps. 15–25 lm/W with lamp life of 2 000 to 6 000 h. Very high CRI and low CCT, but slightly higher than incandescent.	Suitable for spotlighting or illuminating large areas (floodlighting).
LFLs	Mid to high efficacy depending on type, with highest efficacy when used with electronic ballasts. 60–100 lm/W with lamp life of 7 000 to 20 000 h. High to very high CRI, with broad range of CCT available.	Wide application. Highly suitable for general indoor illumination, especially to provide economic, even illumination and for all low- and mid-bay lighting. Not suitable for spotlighting.
CFLs, ballast integrated	Directly interchangeable with incandescent lamps: greater energy efficiency, much longer life expectancy. Not dimmable. Also available as reflector lamps. 35–80 lm/W with lamp life of 5 000 to 15 000 h. High CRI and broad range of CCT available.	For almost all areas where incandescent lamps are used: general, local and spot lighting.
CFLs, modular (external ballasts)	Compact lamp with high efficacy. Dimmable when used with specially designed electronic ballasts. 60–80 lm/W with lamp life of 10 000 to 20 000 h. High CRI and broad range of CCT available.	Alternative to incandescent lamps (more efficient), but with longer life and slightly higher efficacy than equivalent ballast-integrated CFLs.
Metal halide lamps	Mid- to high-efficacy lamps covering a broad lumen-package range. Warm-up time of a few minutes. Dimming difficult and sometimes suffers from poor lumen maintenance. 47–105 lm/W with lamp life of 6 000 to 20 000 h. High CRI and broad range of CCT available.	Suitable for mid- and high-bay indoor lighting and outdoor lighting, whenever long operating hours apply. Most commonly used for industrial and street lighting.

Table 3.3 (continued)

Lamp category	Characteristics	Applications
Ceramic metal halide lamps	High-efficacy lamps covering a low to high lumen-package range. Warm-up time of a few minutes. Dimming difficult. 67–104 lm/W with lamp life of 6 000 to 15 000 h. High CRI and low- to mid-range CCT available.	Suitable for indoor display lighting (as a substitute for halogen lamps) and for mid- and high-bay indoor lighting. Also provide high-efficacy, high-CRI street and architectural lighting.
High-pressure sodium lamps	High- to very high efficacy lamps covering a broad lumen-package range. Poor to moderate CRI and relatively long warm-up periods. 70–120 lm/W with lamp life of 5 000 to 30 000 h. Low to mid CRIs and low CCTs (orange-yellow hued light).	Economic street lighting and industrial lighting where high CRI is not required.
Super high pressure sodium lamps	Start-up time a few minutes. Not dimmable. Reasonable efficacy. High light output per lamp. Colour change possible at end of useful life.	Suitable for lighting objects (shop window displays) or as general downlighting in high-ceilinged rooms.
Low-pressure sodium lamps	Very high efficacy. Monochromatic light, no colour rendering. 120–200 lm/W with lamp life of 10 000 to 16 000 h. Zero CRI and very low CCT.	Low-cost outdoor lighting for applications where colour rendering is not required.
High-pressure mercury vapour lamps	Low- to mid-efficacy lamps covering a broad lumen-package range. Poor to moderate CRI and relatively long warm-up periods. 23–60 lm/W with lamp life of 6 000 to 28 000 h. Low- to mid-range CRI and CCT.	Mostly used for street, security and industrial lighting. Low first costs but uneconomic over the lamp life cycle compared to equivalent alternatives.
Self-ballasted blended mercury vapour lamps	Very low to low-efficacy lamps covering a broad lumen-package range. Poor to moderate CRI and relatively long warm-up periods. 14–29 lm/W with lamp life of 6 000–12 000 h. Mid-range CRI and CCT.	Mostly used for street, security and industrial lighting in non-OECD countries. Very low first costs but highly uneconomic over the lamp life cycle compared to equivalent alternatives.
Induction lamps	Very long life of 30 000 to 100 000 h and mid to high efficacy of 55–80 lm/W. High CRI and wide range of CCT available.	Relatively high first costs mean they are most economic when used in inaccessible areas with high maintenance costs, such as tunnel lighting.

Source: Adapted and updated from CADDET Energy Efficiency, 1995.
Abbreviations: CCT = colour correlated temperature; CFL = compact fluorescent lamp; CRI = colour rendering index; LFLs = linear fluorescent lamps.

Figure 3.15 **System efficacy for a number of light sources used for general lighting**



Source: ALG, 2003 (reproduced with permission).

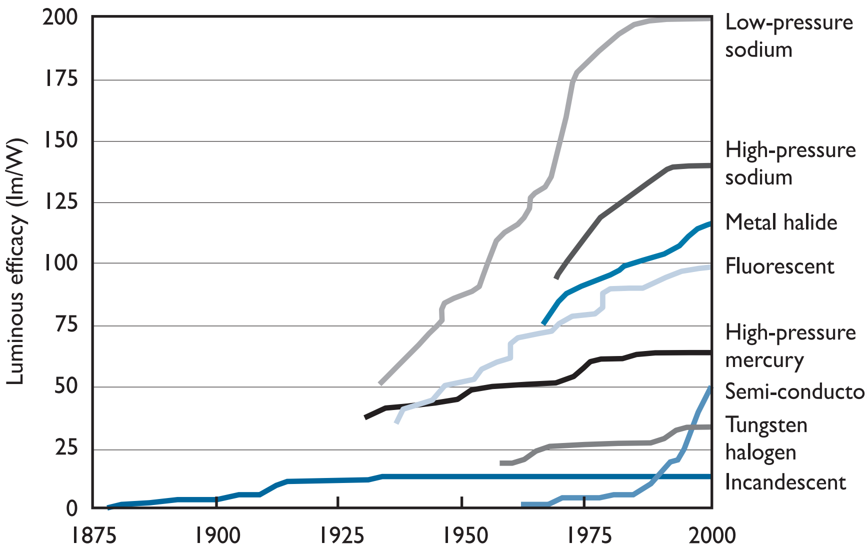
CONTROL GEAR

Ballasts

All discharge lamps (fluorescent, low-pressure sodium and HID lamps) require ballasts to function. Ballasts are devices that supply a high voltage to initiate a discharge arc and then limit the current to levels that allow the discharge arc to be stabilised during normal operation. They may include capacitors to correct the power factor.[1]

1. Power factor (PF) ratio: this represents the amount of power that a customer is actually using as a fraction of what the utility must supply. This ratio is used to determine how efficiently a ballast uses total input power. To calculate the PF ratio, the power (watts) is divided by the root mean square of the ballast volt-amps. Ideally, lighting equipment should have a PF greater than 0.9 and as close to 1.0 as possible. PFs of less than 1.0 occur when the voltage and current are out of phase or when the sinusoidal shape is distorted.

Figure 3.16 **Historic evolution of luminous efficacy for major light sources used in general lighting**



Source: Lamptech, 2005 (reproduced with permission).

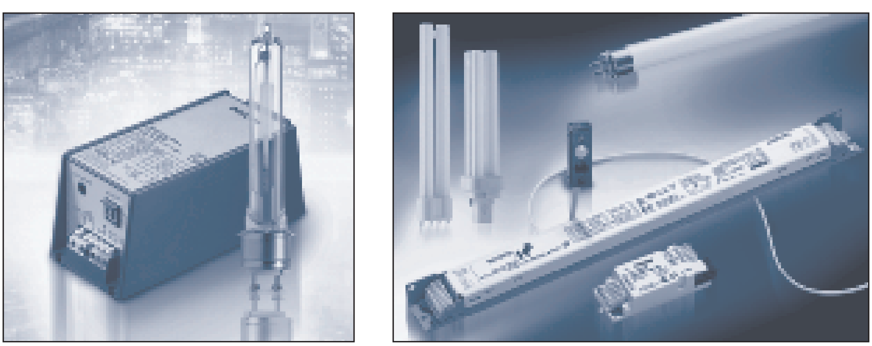
There are two broad categories of ballasts: electromagnetic (also known as core and coil ballasts) and electronic (also called high-frequency or solid-state ballasts). Electromagnetic ballasts comprise a magnetic core of several laminated steel plates wrapped with copper windings. In the past, poorer-quality electromagnetic ballasts have been made using aluminium wires and low-grade iron cores.

Ballasts require energy to function and can have radically different power requirements depending on the ballast design. Furthermore, differences in ballast operation between one design and another influence the effective efficacy of the lamp itself, and this must be taken into account when considering the overall efficacy of a combination of lamp and ballast. Accordingly, ballasts are tested by comparing the performance characteristics of the ballast under test combined with a reference test lamp to those of an equivalent reference ballast combined with a reference lamp. Testing in this way allows differences in power, lumen output and colour rendering to be compared.

The consumption of a relatively inefficient but conventional electromagnetic ballast driving two 36 W linear fluorescent tubes might be 20 W, giving a total circuit power of 92 W, of which losses in the ballast would amount to 22%. The latest generation of high-efficiency magnetic ballasts, sometimes called low-loss magnetic ballasts, reduce losses to about 12%. They also enable lamp-dimming capability, although they cannot dim below 20%. Low-loss electromagnetic ballasts are actually hybrid ballasts and are also known as cathode-disconnected ballasts because they use a magnetic core-and-coil transformer and an electronic switch for the electrode heating circuit. After starting the lamp, these ballasts disconnect the electrode heating circuit.

Electronic ballasts use electronic reactors to allow lamps to be operated at much higher frequencies. They not only have lower ballast power losses but also raise the operational efficacy of the lamps. At frequencies above 20 kHz the lamp efficacy can rise by 10–15%, while typical electronic ballast losses might be 4 W per 36 W lamp. Compared to the example discussed in the preceding paragraph, the use of a standard electronic ballast would reduce the system circuit load to 80 W while raising the light output by 15%, thereby improving the total system efficacy by 24%. Similar advantages also apply to electronic ballasts for HID lamps (Figure 3.17; Box 3.4).

Figure 3.17 **Examples of electronic ballasts for HID and fluorescent lamps***



Source: Courtesy of Philips Lighting.
* Left: HID lamp ballast. Right: fluorescent lamp ballast.
Abbreviation: HID = high-intensity discharge.

Box 3.4 Electronic HID ballasts save money in four ways

- **Lamp light output is increased.** Electronic ballasts increase the mean lumen output of HID lamps. Recent field tests showed that a 400 W metal halide lamp operated with an electronic ballast produced 15% more light output after 8 000 h than the same lamp with a magnetic ballast.

  More light output means that in new installations or major renovations, up to 15% fewer fixtures are required to deliver the same light levels that would be provided by a standard metal halide system. If the goal is to replace the ballasts without reducing the number of fixtures, then a lower-wattage lamp can be used to get the same mean lumen output.

- **Electronic HID ballasts have lower energy losses.** Electronic ballasts require less energy to operate. Ballast energy use varies depending on the wattage and type of lamp, but in higher-wattage lamps the savings can be significant. For example, a typical magnetic ballast for a 400 W metal halide lamp consumes 50–70 W, whereas an electronic ballast consumes as little as 5–20 W, depending on the model.

- **Lamp life is up to 30% longer.** The light output from all HID lamps depreciates over time, but HID lamps with electronic ballasts stay brighter longer than the same lamps with magnetic ballasts. Longer lamp life lowers lamp and labour replacement costs and is particularly beneficial in high-bay applications or other hard-to-reach places.

- **Electronic HID ballasts are available with a dimming option.** Electronic HID ballasts with dimming provide additional savings when full light output is not required. Some electronic ballasts are continuously dimmable down to 50% of lamp power and can be used with advanced controls, such as photocells, wall-box dimming, occupancy sensors and programmable control systems.

Source: NRC, 2006.

Electronic ballasts also have other advantages, including: smaller size and lower weight; much less lamp flicker; less lamp noise; improved lumen maintenance; better starting and operational control of the lamp and thereby longer lamp life; a power factor of one without the need for a power factor correction capacitor; facilitation of more accurate lamp and circuit control that enables full dimming capability and automatic daylight-dimming sensors to be used; elimination of harmonic distortion in the supply current; the capacity to operate multiple luminaires off one ballast; and the potential to be seamlessly integrated into building energy management systems (BEMS). Their disadvantage is a comparatively higher price although the price differential has fallen significantly in recent years.

The latest ballasts integrate new functions into the ballast service. Electronic ballasts incorporating photocells can automatically dim the output of a fluorescent lamp to take account of daylight availability and thereby save significant amounts of energy. Some ballasts include circuits that automatically detect and adapt to the input voltage, allowing a single ballast to be used on multiple voltages. Others include load circuits that detect the lamp type and which can simultaneously control several lamps with different power requirements. Another new feature is the use of intelligent circuitry to optimise lamp starting and restarting, which allows fluorescent lamp life to be increased and is important if the lamp is being activated frequently through, say, the use of energy-saving occupancy sensors.

Lighting-control systems

Since human behaviour is a major factor in how lights are used and people often forget to switch lighting off when they leave a space, control systems that automatically regulate lighting in response to need can have a positive effect on energy consumption. Improvements in the technology and greater affordability of lighting controls combined with economic and environmental considerations are leading to the increased deployment of advanced lighting controls, particularly in the commercial and public sectors, where lighting represents a sizable share of total energy costs. Nonetheless, automatic lighting controls are used in only a small fraction of the cases where it would be currently economic to deploy them. Various forms of control systems are currently available. Their appropriateness depends on the specific applications and patterns of energy usage. Controls range from manual switching and dimming to occupancy sensors, photosensors, centralised controls and timers.

Manual controls

The simplest form of control is manual switching, yet as basic as this seems there are a great many buildings where large amounts of lighting energy are being squandered for lack of simple on/off manual light switches. A recent survey of lighting in offices in southern France gives an excellent illustration of the energy implications of the lack of manual switches (Enertech, 2005). The lighting in 30 open-plan offices was metered for one year and the average annual hours of use for the lighting system were determined as a function of the number of zones (defined as an area of the lighting installation controlled by a single switch) used to control the lighting over the open area (Table 3.4).

Table 3.4 **Impact of zoning and manual switches on lighting operating hours in open-plan offices***

	Average number of hours each zone is lit per year**					
	1 zone	**2 zones**	**3 zones**	**4 zones**	**5 zones**	**7 zones**
Zone 1	3 206	2 058	1 645	1 164	3 585	1 051
Zone 2		1 338	1 240	986	3 554	952
Zone 3			492	739	2 845	842
Zone 4				105	1 813	685
Zone 5					1 757	375
Zone 6						216
Zone 7						50
Average hours of use	3 206	1 698	1 126	749	2 711	596
No. of offices in sample	11	9	4	4	1	1

Source: Enertech, 2005.
* Metered over 1 year in 30 offices in southern France.
** According to no. of zones in building.

The results are striking. Slightly more than one-third of the offices had a single switch and in this case the average number of hours that the lighting operated over the year was 3 206. Splitting the area into two individually switched zones reduced average use to 1 698 h, representing an average saving of 47%. Splitting the area into four individually switched zones reduced the average hours of use to 749, representing an average saving of 77%. On average, were all the open-plan offices to utilise four manually controlled zones annual lighting system use would seemingly decline from 2 045 h at present to 749 h: a saving of 63%. Despite the statistical limitations of the sample, which comprised only 30 buildings, similar results have been found in other surveys and illustrate the importance of giving users control over their lit space if unnecessary lighting is to be avoided.

Switching can be more sophisticated than simple on/off controls, however. Manual dimming allows occupants to adjust light output or illuminance in response to lower task-lighting needs and higher daylight availability and allows users to adapt lighting levels to their own personal preference, which is a well-documented means of improving user satisfaction and light-related productivity. Fluorescent lamps and HID lamps require electronic ballasts in order to be fully dimmed and to maximise efficacy at reduced output. Happily, the cost of electronic dimming ballasts has declined significantly in recent years and the price differential compared to simpler non-dimming ballasts is no longer such a significant barrier to their deployment.

Automatic controls

Automatic lighting controls are a mature technology that are being adopted only slowly in buildings and thus still offer a huge unrealised potential for cost-effective energy savings. Occupancy sensors can be used to prevent illumination from being delivered to unoccupied spaces. There are three types of occupancy sensor, all of which are based on the detection of motion: passive infrared, ultrasonic and hybrids. Passive infrared sensors react to heat-emitting bodies moving in the field of view. Ultrasonic sensors emit an inaudible sound pattern and react to the reflection of the sound; they can react to minor changes in motion. Hybrids use both technologies, minimising the risk of false triggering. Occupancy sensors can be combined with dimming controls or stepped switching so that illuminance levels might be lowered to low ambient levels when the occupants leave a space.

Photosensors automatically adjust electric-lighting levels in response to the detected illuminance level to maintain a pre-set level. They can be used either to turn a lamp on or off or to dim it in response to variations in daylight availability. This capability also allows for superior lumen maintenance throughout the course of the lamp's life. Furthermore, the design light level can be programmed to lower as night falls to take account of an established preference, known as adaptive compensation, for lower light levels in the evening. Photosensors can also be used to reduce the thermal load on a building's cooling system. Solar heat gain occurring during the day can be taken into account for a whole-building energy-use analysis.

Centralised controls are also known as building automation systems, and if their primary function is energy management they are known as building energy management systems (BEMS). Whether they are BEMS, which incorporate a range of energy-management functions beyond just lighting, or whether they are dedicated lighting controls, such systems can be programmed to control lighting throughout the day, depending on building-use patterns and daylight availability.

Timers switch lights on and off at pre-set times. Normally they can be manually overridden when necessary. User acceptance of automatic lighting controls is obviously important, and old-style electromechanical timer switches that could leave people stranded in a suddenly dark stairwell or toilet cubicle are clearly less popular energy-conservation choices. Modern lighting controls are far more sophisticated and actually increase user lighting amenity. Occupancy sensors and timer switches are usually configured to a manual-on auto-off arrangement so that a user has to intentionally activate the lighting, but if timers are applied they would usually be in combination with very low level, ambient, emergency-egress lighting to ensure that users can always find their way safely around a space, and would include a temporary manual override with suitably long deactivation delays.

Case studies of energy savings from lighting controls

All of these control systems reduce energy consumption. The actual savings depend on the specific circumstances, although the benefits can be quite significant, as shown in the examples in Boxes 3.5–3.8. Tables 3.5 and 3.6 and Figure 3.18 show the characteristics and measured savings potentials of 17 projects using lighting controls as reported by CADDET (1991).

Table 3.6 shows the energy-savings impacts from the use of the lighting controls described in the demonstration projects listed in Table 3.5. The data points in Figure 3.18 are the values for the first 13 case studies in Tables 3.5 and 3.6, for which the payback period from using the lighting controls was determined.

Box 3.5 Case study: Energy savings from a new detector in Sweden

A new type of acoustic detector that has been developed can sense the presence of people before they enter a room, or when they are around corners in rooms where furniture and fittings act as "screens", where conventional occupancy sensors may not work efficiently. The acoustic presence detector senses combinations of both audible and inaudible sounds, in accordance with a patent based on Swedish development work.

This new acoustic detector has been used in a low-energy stairway-lighting project for a high-rise building, where the lights were switched off when not required. The electricity consumption of the building's entrance, staircases and lift halls was reduced by 73%, from 64.3 to 17.4 kWh/day. More recent projects using the detectors have realised energy savings of 64–87%, with payback times as short as six months.

Source: CADDET Energy Efficiency, 2002a.

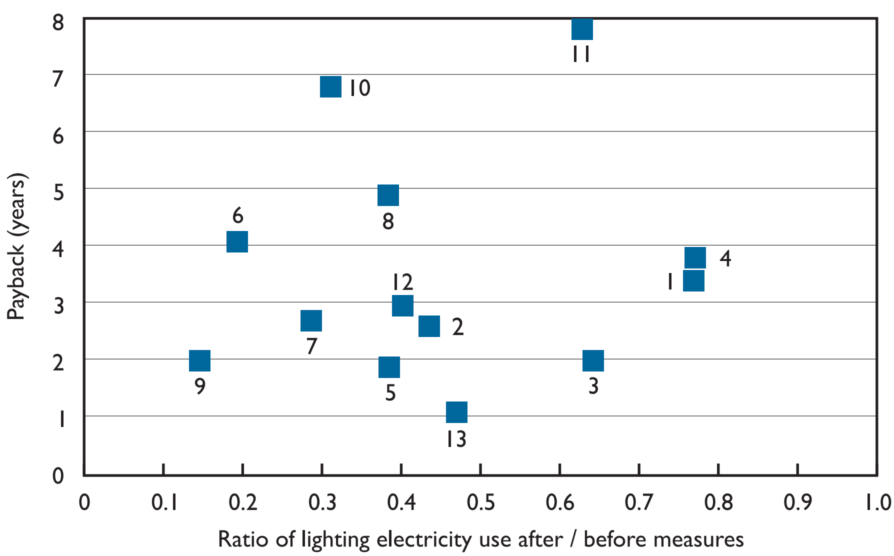
Box 3.6 Case study: Integrated lighting system for US post offices

This research project was funded by the United States Post Service (USPS) and the DOE and conducted by Lawrence Berkeley National Laboratory (LBNL). When combined with lower ambient lighting and occupancy sensors, a specially developed light fixture dramatically improved the quality of lighting for postal workers and substantially lowered lighting energy consumption. The research team designed a lighting system that allows the reduction of ambient lighting while increasing the provision of task-oriented lighting. The existing task-lighting fixtures were replaced by custom-built light fixtures using two 36 W twin-tube CFLs, under-driven for a total system power of 50 W, with electronic ballasts and special optics replacing the existing task-lighting fixtures. The ambient lighting, which consisted of fluorescent lamps (2.4 m long) with magnetic ballasts, was replaced with tandem wrap-around fixtures (of the same length) using dimmable T8 fluorescent lamps with electronic ballasts.

The integrated lighting system reduced lighting load in small to medium-sized US post offices by up to 71%. This included a 72% reduction in ambient lighting load and a 65% reduction in task-lighting load. Ambient lighting was reduced from 837 kWh to 234 kWh/week. These savings are attributable to more efficient lamps, a reduction in ambient lighting intensity related to efficient task lighting, and a tighter regulation of the ambient lighting schedule. Task lighting was reduced from 90 kWh to 32 kWh/week. These savings are also attributable to more efficient lighting, as well as to the occupancy sensors that turned the task lighting off when not needed.

Source: CADDET Energy Efficiency, 2003b.

Figure 3.18 **Lighting energy savings and payback period for 13 demonstration projects employing lighting-control retrofits**



Source: CADDET, 1991.

Table 3.5 Description of 17 demonstration projects employing lighting-control retrofits

Demo project code name	Covered area (m²)	Year	Measures taken
Australia			
1. Adelaide Dental Hospital, Adelaide	3 070	1986	Controls: time scheduling
2. Panorama College, Adelaide	4 670	1987	Controls: time scheduling
3. South Australian Department of Mines and Energy Head Office, Adelaide	55	1985	Controls: occupancy sensing
4. Monash House, Melbourne	2 412	1987	Controls: time scheduling. Luminaires: delamping
The Netherlands			
5. Gasunie Office Building, Groningen	~500	1982	Controls: at daylight, off Luminaires: new lamps
6. Gasunie Office Building, Groningen	~500	1982	Controls: at daylight, off Luminaires: delamping with low brightness and desk lamps
7. Gasunie Office Building, Groningen	~250	1982	Controls: at daylight, partial dimming Luminaires: new lamps
8. Gasunie Office Building, Groningen	~250	1982	Controls: at daylight, full dimming
9. Gasunie Office Building, Groningen	~500	1982	Controls: at daylight, off Luminaires: delamping with pendant luminaires
Sweden			
10. Vattenfal Head Office	700	1989	Controls: at daylight, off or dimming Luminaires: new pendant luminaires
United Kingdom			
11. Headquarters of Chase Manhattan Bank, London	~15 000	1987	Controls: time scheduling
12. Headquarters of Chase Manhattan Bank, London (No. 12 will be the result for replicators of No. 11)	~15 000	–	Controls: time scheduling
13. Jacob's Welt, Civic Offices, Bradford	8 600	1980	Controls: time scheduling
United States			
14. Office building in Emeryville, California	423	1989	Controls: dimming Luminaires: delamping, electronic ballasts
15. Office building in Emeryville, California	423	1989	Controls: dimming, time scheduling Luminaires: delamping, new electronic ballasts
16. Office building in Emeryville, California	423	1989	Controls: at daylight, dimming; time scheduling Luminaires: delamping, electronic ballasts
17. Office building in Green Bay, Wisconsin	~50	1986	Controls: daylight, dimming Luminaires: delamping, new reflectors, electronic ballasts

Source: CADDET, 1991.

Table 3.6 Energy savings impacts of 17 demonstration projects employing lighting-control retrofits

Demo code	Lighting electricity intensity, savings and payback period				
	Before retrofit (kWh/m^2)	After retrofit (kWh/m^2)	Savings (kWh/m^2)	Change (%)	Payback (years)
1*	69	53	16	–23	3.4
2	14.8	6.4	8.4	–57	2.6
3	32.3	20.7	11.6	–36	2.0
4*	70	54	16	–23	3.8
5	42	16	26	–62	1.9
6	42	8	34	–81	4.1
7	42	12	30	–71	2.7
8	42	16	26	–62	4.9
9	42	6	36	–86	2.0
10	32	9.8	22.2	–70	6.8
11	75	47	28	–37	7.9
12	75	30	45	–60	3.0
13	60.2	28.1	32.1	–53	1.1
14	125	73	52	–42	–
15	125	62	63	–50	–
16	125	57	68	–54	–
17	–	–	–	–	–

Source: CADDET, 1991.
* In project Nos. 1 and 4 the electrical energy results concern total electricity use.

FIXTURES AND LUMINAIRES

The use of naked lamps will generally result in poor light distribution and a high degree of glare, so to improve this situation lamps are generally housed inside a luminaire. The primary purpose of a luminaire is to distribute, diffuse and direct light emitted by one or more light sources (lamps). The term luminaire (or light fixture) commonly refers to the whole of the physical housing for a lamp, including sockets, holders, fittings, reflectors to direct light where desired, light shielding and diffusion components (such as lenses, diffusers, and louvres to shield the light from non-desired directions, reduce visual discomfort, prevent glare, and distribute light evenly). A luminaire will typically also house the lamp ballast when one is required.

Box 3.7 Energy-savings potential for occupancy sensors

In 1997, researchers examined the energy-savings potential for occupancy sensors in buildings distributed across 24 states, representing a typical cross-section of the commercial building stock (Maniccia *et al.*, 2000). Occupancy and "lighting on" hours were measured in 158 rooms: 42 restrooms, 37 private offices, 35 classrooms, 33 conference rooms and 11 break rooms. Each room was measured for about two weeks (between February and September 1997). The installed occupancy sensors did not actually switch the lights on and off according to occupancy; rather they simply logged when the rooms were occupied and whether or not the lights were (manually) switched on.

The data collected comprise the first detailed reported study of when different space types are occupied throughout the day and when those spaces are lit. The table shows the savings potential for occupancy sensors in the five space types during normal hours and after hours.

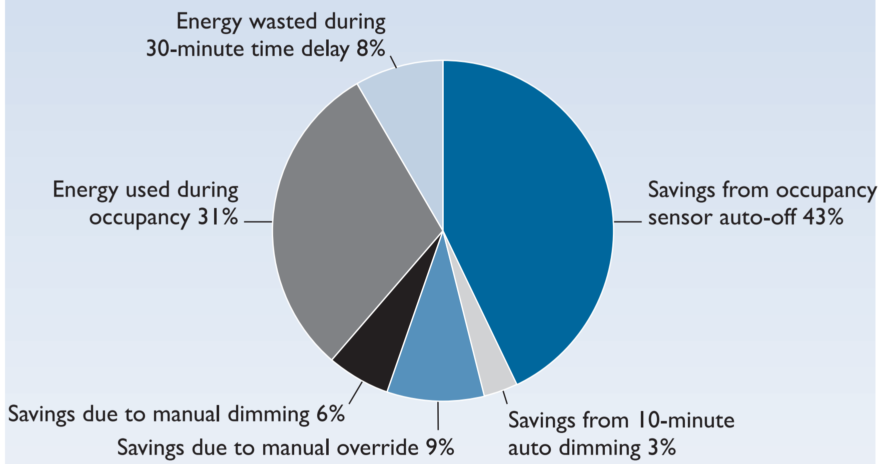
Space type	Savings potential (%)		
	All hours	Normal hours	After hours
Restroom	60	18	42
Conference room	50	27	23
Private office	38	25	13
Break room	29	14	15
Classroom	58	23	35

Source: ALG, 2003 (reproduced with permission).

Box 3.8 National Center for Atmospheric Research (NCAR)

In a study of the NCAR building, the effect of occupancy sensors on lighting operating hours for 51 private offices was measured over several months using an in-place building management system (Maniccia *et al.*, 1999). Using a ten-hour lighting schedule as the baseline, researchers calculated an average energy saving of 43% from the use of occupancy sensors alone. These savings occurred both during the day and at night. At night, occupancy sensors reduced lighting hours that would have been wastefully provided by a simple scheduling system. During the day, the occupancy sensors reduced lighting hours by switching off lights in rooms when occupants vacated their offices temporarily. Additional energy savings occurred when occupants did not use their electric lights because they judged available daylight to be adequate and when the occupants used manual dimmers to reduce their light levels.

Energy savings from lighting controls, National Center for Atmospheric Research, United States



Source: ALG, 2003 (reproduced with permission).

The characteristics of the luminaire and its interaction with the chosen lamp have a significant impact on the overall energy efficiency and quality of the lighting installation. An efficient luminaire optimises the system performance of each of its components, but defining a suitable metric for luminaire efficiency is not straightforward, because it depends in a rather complex manner on the circumstances of its use and the overall lighting requirements. The simplest first-order metric is LOR, which is the ratio of lumens emitted from the luminaire to the total lamp lumen output. LORs can range from 0.3 to 0.96, which is indicative of a very large difference in the proportion of source-lumens that are able to make a useful contribution to the lighting service. However, this metric takes no account of the effectiveness of the luminaire at directing light to where it is needed and in the proportions it is needed. For example, a luminaire could have a high LOR but also produce glare and visual discomfort for the room occupants, whereas another may have a lower LOR but produce more comfortable lighting (see Box 3.9).

To better understand all these characteristics a lighting designer needs to study the photometric data for the luminaire, which indicate the intensity of the light distribution as a function of the angle from which the luminaire is viewed. Reputable luminaire manufacturers publish this information in addition to the LOR, although typically this is only made available for luminaires intended for non-residential applications.

In an attempt to remedy this situation the US ENERGY STAR programme has developed a labelling system for high-performance residential luminaires. To obtain the label, the luminaires are assessed according to energy efficiency and power (meeting a minimum efficacy), operation (they must illuminate quickly, produce light with good colour rendering and operate quietly), reliability and durability (the fixtures must be constructed of heat and ultraviolet-stable glass or optical grade plastics), and safety (the luminaires must be listed by a recognised testing agency for compliance with the National Electric Code).

Correctly matching the lamp with the luminaire is essential for good performance. If installed in the wrong fixture, even the most efficient lamp may work inefficiently. Ideally, fixtures are designed for specific lamps to optimise the amount of light delivered for a specific application. The electricity savings can be significant. For example, a luminaire that is designed especially for a CFL gives 10 times as much illumination as an incandescent fixture fitted with the same CFL (USDOE, 2006).

Box 3.9 General performance criteria for luminaires

Lighting specifiers have the confusing task of choosing among the vast number of luminaires on the market. Advanced lighting design involves evaluating the luminaire's construction, ease of installation, durability and performance against the criteria listed below.

- **Task visibility.** Does the luminaire provide the source/task/eye geometry that enhances task visibility? Is the task illuminance appropriate for performing the visual work?
- **Visual comfort.** Does the luminaire minimise the glare that reduces task visibility and causes discomfort?
- **Colour appearance.** Does the lamp provide sufficient colour contrast for the industrial task being performed? Does the lamp's spectrum support peripheral vision where needed? Does the lamp enhance skin tones where visual contact and interpersonal communication are performed? Is the lamp's colour-rendering ability and warmth or coolness appropriate for the type of space and its finishes?
- **Light distribution on surfaces.** What kind of light pattern does the luminaire produce, and is it harsh or soft when it hits the ceiling, wall or floor? Will the light pattern highlight important features in the space? Will the wall scallops interfere with the rhythm of artwork on the walls, or reinforce the rhythm of the artwork layout?
- **Light distribution on task plane.** What kind of light pattern does the luminaire produce on the work plane? It should be even, or people may have difficulty seeing their work in the darker areas.
- **Modelling faces and objects.** Does the luminaire provide appropriate light for modelling faces and objects? A concentrated downward light distribution often makes faces appear ghoulish. Faces seen in a space with uplight only may appear flat or dull. A combination of diffuse light with some downward highlighting produces the most pleasant results.
- **Flicker.** If magnetic ballasts are used, will lamp flicker produce a strobe effect or cause headaches? Clear HID lamps also produce more noticeable flicker than phosphor-coated lamps.

- **Shadows.** Will the lighting create annoying shadows? Point-sources are usually worse for shadowing, especially when used in concentrated downward lighting.
- **Appearance of space and luminaires.** Does the lighting system appearance support the style, rhythm and finishes of the space?
- **System flexibility and control.** Can the luminaire be switched or dimmed to save energy or reduce illuminances when needed?
- **Ease of relocation.** If tasks or furniture layouts are flexible, can the lighting system easily respond to moves?
- **Daylighting integration.** Does the electric and daylight system work effectively as a system? When the windows, skylights and electric luminaires are well designed, electric lights can be dimmed or switched off when daylight is available, without compromising the visual environment.
- **Light trespass/light pollution.** Does the outdoor-lighting design minimise light pollution or "sky glow" that may be emitted upward from decorative walkway lights, lensed cobra heads of street lights, building floodlights or security lights? And does the design minimise light trespass (unwanted light from street lights, petrol station canopies, bright signs, sports lights, security lights or building lighting that spills onto neighbouring and community properties)?

Source: ALG, 2003 (reproduced with permission).

The main types of luminaire available for LFLs are broadly categorised by their shape, intended position and light-distribution characteristics. In spaces with low ceilings so-called "troffer" luminaires, which are designed to reflect light emitted upwards back downwards out of the luminaire and on to the working plane, are commonplace because they are compact. If slightly higher ceilings are present more versatile pendant luminaires can be used. These may distribute the light: downwards and sideways, in which case they are known as "direct" luminaires; upwards and sideways, in which case they are called "indirect" luminaires; both downwards and upwards, in which case they are known as "direct–indirect" luminaires. Each of these configurations results in a different light distribution and coefficient of utilisation (CU).[2] If light is emitted upwards a light-coloured ceiling needs

2. The percentage, or share, of light emitted by the lamps in a luminaire that illuminates the working plane.

to be used to reflect a large proportion of the light back downwards onto the walls or areas immediately around the task area, otherwise there will be a serious reduction in the CU of the luminaire/room combination.

Troffers are comprised of a reflector, housing, lamps and shielding, which can be a lens, louvre or similar. The component with the greatest impact on the LOR is the reflector, which is intended to direct light to where it is required but can have quite different reflectance levels and optical performance. In simpler designs this is made of sheet metal painted white and may have a reflectivity of 60–80%; however, anodised polished aluminium can achieve 90%, while silver film attains up to 96%. The impact this can have on the LOR is shown in Table 3.7, which also reveals the typical loss of light output that occurs if luminaires are left uncleaned.

The example in Table 3.7 shows the gain in LOR that can be attained by using efficient reflector materials, but such luminaires are also at greatest risk of producing glare. This underlines the importance of reflectors being optically designed for the luminaire geometry and illustrates the need for prudence in attempting reflector retrofits of existing luminaires. Care also has to be applied when attempting delamping, e.g. removing one or more of the lamps from an existing multilamp luminaire in the event that the other lamps have been replaced by more efficacious lamps, because the removal of a lamp or increase in lamp output can adversely affect glare depending on the luminaire configuration.

In recent years newer materials that allow high reflectance with a diffuse finish have been developed. These can produce total reflectivity of up to 98.5% but minimise reflected-glare problems. New solutions using semi-specular or semi-diffuse materials require less precision with the lighting

Table 3.7 LORs for troffers, according to the choice of reflector material

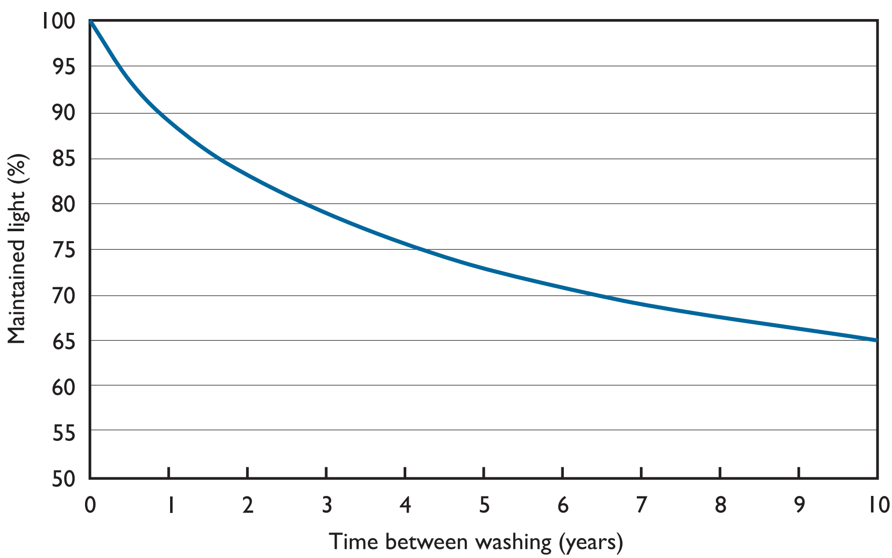
Fixture	Light delivered/ light produced (%)
Seasoned and uncleaned white troffer fixture with seasoned lamps	35–45
Seasoned and cleaned white troffer fixture with new lamps	50–67
Aluminium reflector with new lamps	65–73
Silver reflector with new lamps	81–85

Source: CADDET, 1991.
Abbreviation: LORs = light output ratios.

design than the ultra high reflectance options but still permit reflectances up to 85% to be attained while minimising glare (ALG, 2003).

Light loss through dirt accumulation may also have a major impact on lighting-system efficacy, and a failure to have a maintenance plan increases the probability of designers overspecifying the system in order to compensate. Figure 3.19 shows how light output from a typical troffer luminaire can decrease as dirt accumulates over time.

Figure 3.19 **Expected loss of light resulting from dirt build-up in enclosed troffer luminaire**



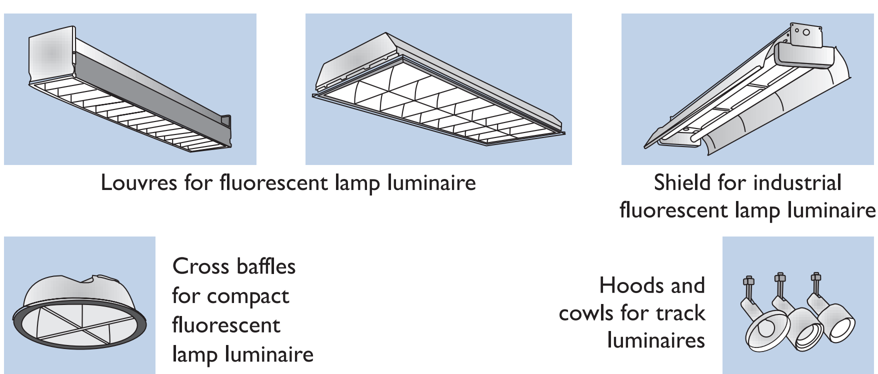
Source: CADDET, 1991.

Direct or reflected glare is typically avoided in high-reflectivity troffers and direct or direct–indirect luminaires by applying diffusers and diffuse, semi-specular or specular shielding devices. The shielding is sometimes comprised of light-diffusing vertical baffles or louvres, which prevent direct visibility of the lamp unless looking straight up. It also helps scatter some of the light onto surfaces other than the working plane, which enables a balance between lighting of the task and surrounding areas to be established. An alternative approach is to cover the entire troffer with transparent/translucent optical plastics. Some older designs used white plastics that could absorb up to 50% of the emitted light. Prismatic clear plastics or glass lenses absorb far less light and minimise glare by refracting the transmitted light. An efficient luminaire will control direct glare from the user's normal viewing angles while allowing the maximum amount of source-lumens to reach their desired destination.

An alternative approach can be to use a perforated grill with an internal reflective coating directly beneath the lamp that reflects light emitted from the lamp back onto a diffusing reflector, but this solution usually incurs some penalty in the LOR. Direct luminaires include: recessed and surface-mounted luminaires used for ambient lighting; wall-washers, accent lights and display lighting; decorative pendant downward lights; track lighting; task lighting; and shelf lighting (Figure 3.20).

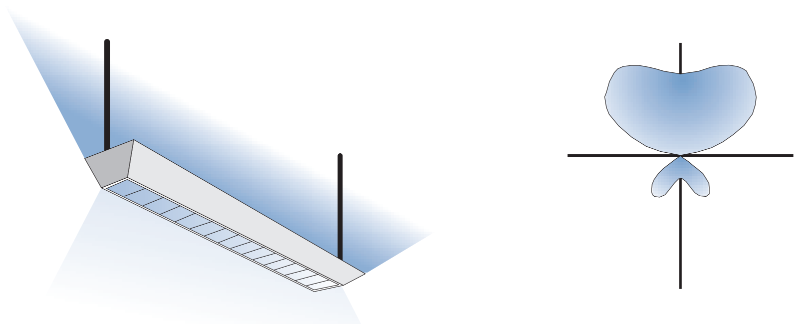
While direct lighting is the most efficient way to put light on the working plane and hence can have a high CU, it is more likely to produce shadows, extremes of contrast and glare than indirect or direct–indirect solutions. Depending on the room characteristics a more uniform low-glare illumination can be provided by indirect or direct–indirect lighting, albeit at the expense of some reduction in the CU. As indirect-lighting systems bounce light off ceilings and walls before it reaches the work plane, its efficiency is very sensitive to the reflectivity of these surfaces. High albedo surface colours should be used to maximise the efficiency. Indirect luminaires include suspended uplights, cove uplights, torchières and wall-mounted uplighters. To be most energy efficient, indirect lighting should be used to provide low-level general lighting while localised task lighting is used to provide higher illumination on the task area. Direct–indirect lighting solutions can sometimes provide this outcome through a single luminaire (Figure 3.21).

Figure 3.20 **Antiglare shielding for direct luminaires**

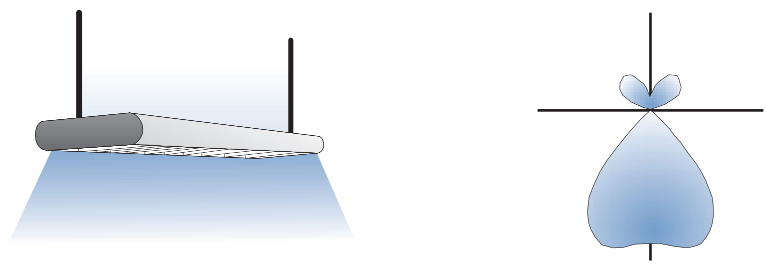


Source: ALG, 2003 (reproduced with permission).

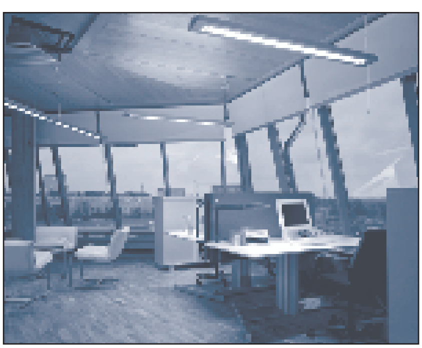
Figure 3.21 Suspended direct–indirect luminaires



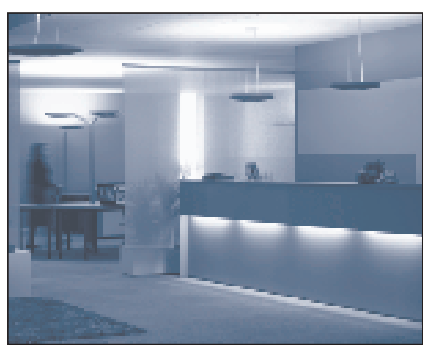
Suspended direct–indirect fluorescent luminaire (mostly up) and the typical photometric distribution (right)



Suspended direct–indirect fluorescent luminaire (mostly down) and the typical photometric distribution (right)



Pendant direct–indirect luminaires integrated with daylight.



T5 torchières, direct–indirect pendant lamps and wall washers.

Sources: ALG, 2003 (reproduced with permission); Photos courtesy of Fagerhult Lighting.

It is generally recommended that the choice of luminaires for the commercial sector should be determined by a lighting designer to ensure that task lighting is implemented properly. There are established procedures for determining the illuminance that is required and delivered for specific tasks.

Uplighting torchières are a form of purely indirect lighting, but when illumination is provided by halogen lamps they are extremely inefficient. Box 3.10 gives some commercialised examples of alternative, high-efficiency torchières. Indirect suspended luminaires are also commonplace and are used when there is a strong desire to avoid shadow and provide a diffuse, uniform illumination. These function by casting light off ceilings and walls so that it undergoes multiple scattering before reaching the working plane.

DAYLIGHTING

The development of electric light enabled the design of buildings that include windowless rooms and deeper plan layouts with lower floor-to-ceiling heights which limit daylight penetration from the perimeter. Electric light may have freed building design from the constraint of needing to provide each space access to natural light, but it has also led to the routine squandering of a natural resource. It is well established that people prefer to be in rooms with an external view, and recent research findings suggest that daylight has a health and productivity dividend in part associated with helping to maintain regularity of circadian rhythms (see pp. 82–84); however, intelligent daylight harvesting also results in important energy savings and is the best choice for low-energy lighting design of new buildings. Over the last two decades there has been a steady increase in interest in the use of daylight in architecture, especially in European countries. Depending on cloud conditions, daylight luminance levels may be highly variable. However, they are almost always more than high enough to provide necessary minimum internal illuminance levels, providing the design allows enough daylight to enter the building and be distributed appropriately.

Daylight is much brighter than the light produced by lamps and even in cloudy weather can provide 50 000 lux, which is 100 times the illuminance required to satisfy most task-lighting requirements. Thus, even if only 1%

Box 3.10 Energy-efficient torchières

Portable indirect uplighting torchières became very common in residential and some commercial environments from the 1980s onwards. Most versions have used high-power (250–500 W) halogen lamps because of their high light intensity and low first cost; however, not only are these very energy inefficient, they also operate at very high temperatures and are a significant fire risk. In recent years energy-efficient versions using high-lumen CFLs or T5 fluorescent tubes have become widely available, especially in North America, where the US EPA has championed their development under the ENERGY STAR programme. More recently still, higher-efficiency ceramic metal halide versions have been developed. These lamps typically used one-quarter of the power of the halogen torchières for the same light output.

Energy-efficient portable torchière uplighters

Source: Courtesy of Faktor Licht.

of the available daylight can be utilised, light with 500 lux at the level of the working plane can be employed. Of course, natural light varies according to the time of day, weather and season, so it needs to be combined with artificial lighting and appropriate control systems.

So what are the energy consequences, design necessities and limitations of designing buildings to use more daylight?

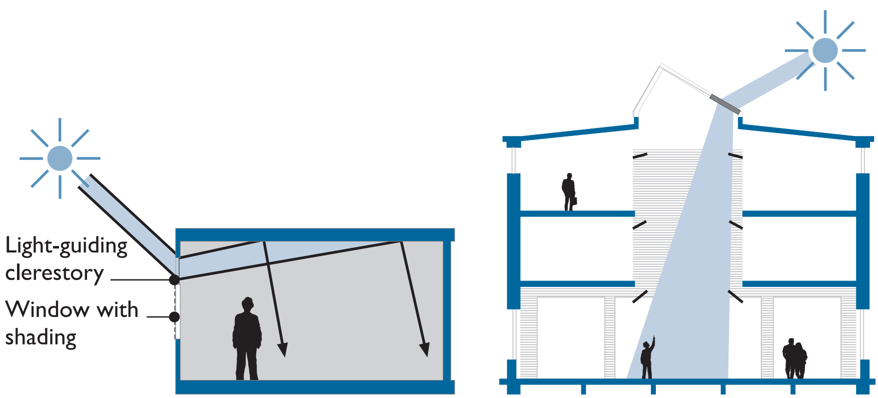
Before attempting to answer this question it is important to consider some key issues concerning daylight deployment. Daylighting designs[3] need to allow enough daylight ingress so that illumination needs are met while avoiding too much concentration of light, which produces glare. Furthermore, while solar gains are generally welcomed in the winter because they help offset heating needs, they can be a major hindrance in the summer, when they can easily cause overheating and increase demand for air-conditioning. This problem can affect all building types but is particularly acute in commercial buildings, which increasingly need to remove heat because of large internal gains from the growing utilisation of office equipment. The third factor to consider is the thermal conductivity of glazing. If inefficient high U value glazing is used (*e.g.* typical single glazing and poor-quality double glazing) the window is likely to be a net cause of energy loss related to heat transmittance. The fourth factor is the extent to which daylight is distributable within the building without compromising other aspects of the building form. Well-designed day-lit buildings can overcome all these problems through intelligent use of the following techniques.

- Low-conductance glazing (such as double- or triple-glazed windows, with spacers, low-conductance frames and low infrared emissivity reflective coatings) will minimise heat losses from the window if this is a relevant issue in the local climate.
- Minimisation of glare through: employment of light-diffusing strategies such as light wells and light shelves; using static or dynamic external shading devices that either block or diffuse direct solar gains or reflect direct sunlight onto a diffusing surface such as a ceiling; careful orientation of window position and size in relation to the task area; the use of tinted solar-control glazing, although this solution, while commonplace, tends to maintain the view while reducing daylight gains and also alters the chromaticity of daylight.

3. Buildings that are designed to maximise the use of daylight.

- Minimisation of unwanted solar gains by avoiding direct sunlight through the same techniques described in the previous point.
- Daylight distribution deep into the building plan can be facilitated by: using purpose-designed louvres that reflect light onto the ceiling before it is diffusely scattered deep into the building plan; the use of light internal surfaces to aid light reflection (especially for the ceiling); strategic use of light wells, light shelves and louvres, for which reflectance into the internal space is dependent upon the incident angle and which help to steer incoming light onto the ceiling; the use of light guides such as fibre optic systems and light columns; the use of hollow-building designs such as those with central atria (Figure 3.22).

Figure 3.22 **Strategies for increasing low-glare daylight penetration**



Source: IEA/SHC, 2000.

Building designs with high daylight utilisation are the antithesis of standardised architecture because they require solutions to be tailored to the local climate, latitude and site. Higher-latitude designs place more emphasis on floor plans that are conducive to daylight admission because of the more limited supply of daylight. In more equatorial latitudes, with high sun and daylight availability, avoidance of cooling loads is a higher priority, and this has led most architecture to try to minimise solar gain and inadvertently curb daylight as a consequence. However, new technologies and the reapplication of older techniques are increasingly being utilised to enjoy the energy benefits of daylight without adding to the cooling burden.

Careful integration of the daylighting system with the rest of a building's design must begin early in the design process if a high-quality work environment is to be produced (IEA/SHC, 2000). However, if the electric-lighting system is fully activated at the same time that daylight is present, no energy will be saved at all; optimal daylighting strategies supply sufficient daylight and ensure that it is harvested. The latter is best done by using light-level detectors to automatically regulate the illuminance levels supplied by the electric-lighting system in response to daylight availability and the design illuminance levels on the task area (see pp. 141–148). This technique can save significant amounts of lighting energy in standard buildings, but will save even more in those where daylight is available to a greater proportion of the floor area.

Energy savings from daylighting

Reported savings in lighting energy consumption from daylight design and harvesting vary between 15% and 80%. Because preponderant building occupancy patterns are high for non-domestic buildings during the day, and lower for domestic buildings, there is a greater potential to save energy by using daylighting in non-domestic buildings. One report suggests that increasing the use of daylight in commercial buildings can reduce lighting energy use by 15–30% (Syomei-Gakkai, 1996). However, it is very difficult to evaluate the global energy-savings potential in office buildings through the use of daylighting, and estimates vary substantially from study to study. A more recent study from Bodart and De Herde (2002) concludes that daylighting can reduce artificial-lighting consumption by 50–80%.

The IEA Implementing Agreements Energy Conservation in Buildings and Community Systems (ECBCS) and Solar Heating and Cooling (SHC) issued a joint publication, *Daylight in Buildings* (IEA/SHC, 2000), which presents the results from a variety of controlled experiments designed to test the energy savings achievable with daylight-responsive control systems. One example from Ecole Nationale des Travaux Publics de L'Etat (ENTPE) in France tested four different commercially available control systems integrated into test office cells with a single vertical window. Two control systems were tested in February 1998 and two in December 1999 under the same experimental conditions. The four systems belong to two different families of control systems, two being open-loop systems and the other two closed-loop systems. The area close to the window receives enough daylight for all illumination needs to be provided by daylight on some occasions, while deeper into the room a mixture of artificial light and daylight is needed, and deeper still almost all light is needed from artificial light. The energy-savings results are shown in Table 3.8. Energy savings are between 60% and 70% in the day-lit area, 30% and 40% in the mixed-light area and 5% and 20% in the artificial-light area.

These findings confirm both the value of having the daylight-responsive control systems and the extra savings that can be achieved by increasing the availability of daylight deeper into the floor plan. They further prove that daylight-responsive lighting controls function properly and will provide savings wherever daylight is made available.

Table 3.8 **Energy savings and illuminance maintenance for daylight-responsive control systems***

	"Luxstat" (Servodan)	**"Els" (Etap)**	**"Luxmate" (Zumtobel)**	**"Trios" (Philips)**
Open or closed loop system?	Open	Closed	Open	Closed
Sensor	Vertically, on the window	On the luminaire, facing down	On the ceiling, looking at the window	On the ceiling, facing down
Type of ballast	HF ballasts	HF ballasts	Digital ballasts	HF ballasts
Areas controlled	3	1	3	1
Energy savings				
Daylight area (%)	75	45	60	60
Mixed light area (%)	45	30	30	30
Artificial light area (%)	10	20	10	5
Iluminance maintenance				
Daylight area (%)	94	100	100	100
Mixed light area (%)	96	100	85	95
Artificial light area (%)	100	100	100	100
Others		Luminaires never switch off		

Source: IEA/SHC, 2000.
* Tested by Ecole Nationale des Travaux Publics de L'Etat (ENTPE), France.
Abbreviation: HF = high-frquency.

The extent to which daylight is currently being harvested in buildings is not very well known because there has been no formal attempt to gather a statistically significant sample. An informal survey of experts conducted for the current book suggests that daylight might currently be offsetting about 25% of electric-lighting needs in average commercial buildings, but that there could be some important regional variations. The European building stock is the oldest in the OECD and tends to include more buildings designed to make use of daylight. Buildings constructed prior to the electric-lighting era typically have higher ceilings and plenty of windows to allow deeper light ingress, although this does depend on the precise era of their construction, the building function and region considered. Perhaps this legacy has encouraged modern European architects to pay attention to the value of daylight, but in the modern era there continues to be an active stream of European architecture that has helped popularise building designs that make good use of daylight. A similar renewal of interest in daylight has become evident in the rest of the OECD in the last decade. Box 3.11 presents a case study from Australia on the exploitation of daylight.

Daylighting components and design solutions

In practice there are many problems to be overcome if day-lit buildings are to become the preferred option for new building designs. Reaping the daylight dividend requires optimisation of energy savings through the integration of daylight, control systems and occupant response. To do this broadly needs democratisation of best practice in daylight design and control; however, there remain a great many research and implementation findings that need to be transferred to design professionals and industry for this to happen. At present most design professionals have insufficient knowledge of how to implement successful daylighting solutions. According to the IEA's Task 31, greater expertise and familiarity with new design and evaluation tools is required, and there is also a need to integrate the diverse technologies encompassing glazing, shading, electric lighting, smart controls and human factors in a manner that optimises overall performance. As a result only a small fraction of daylighting potential is currently being captured, and many existing day-lit buildings are beset with problems such as excessive glare (IEA, 2005).

Box 3.11 Case study: Coca-Cola Amatil (CCA) in Australia

The Western Australian (WA) bottling factory at Kewdale was its first Australian site to implement an energy-saving lighting project.

From 1998, a number of different control systems were reviewed, including both dimming and switching. In 1999, in order to achieve better control, the control system was incorporated into a Citect system.* This has allowed the company to control the lighting levels according to production schedules. In the warehouse area, colour rendition is important in production, thus metal halide lamps are used. When daylight levels are high, all of the lamps apart from those in critical work areas will turn off. As daylight levels drop, a proportion of the lamps will be turned on, and at night or when daylight levels are very low all of the lamps will be on. Included in the system is a buffer to prevent lamps turning on and off quickly. Another feature of the system is the control of individual lamps. Conventionally, entire circuits are used to control high-bay lighting. The new system is highly flexible and can be easily reprogrammed when requirements change, without altering wiring. In 1999, improvements were made to allow more automated control of lighting, so that lights are on in a given area only if it is in use. In addition to the direct energy savings and their associated benefits, the project has resulted in considerable heat reduction within the factory.

At the Kewdale site, energy reductions represented an AUD 45 000 annual saving and a reduction in greenhouse gas emissions of more than 400 tonnes of CO_2 annually. Following the success of this project, other CCA plants in Australia have updated their lighting systems, with similar reductions in lighting electricity consumption. The CCA's lighting electricity consumption has since dropped by 30–40% at all of its Australian sites.

Source: CADDET Energy Efficiency, 2003c.
* See www.citect.com.

Happily, modern technology is increasingly available to lend a helping hand. In the last decade user-friendly daylighting design software has become readily available, so it is now much easier to analyse the daylight implications of potential new designs than was formerly the case. Daylighting design tools such as the Advanced Daylight and Electric Lighting Integrated New Environment (ADELINE) software, developed through international collaboration over the last decade, can assist designers in quantifying the energy-savings potential from the use of natural lighting resources (IEA, 2005). A wide range of different graphical, analytical and simple computer-aided tools, useful in the early and detailed design phases, are available for practical use. However, the application of these tools has been restricted in the past because of a lack of algorithms addressing new technologies and new research results, *e.g.* visual-comfort classification. There is therefore a continuing need for algorithm and tool development and extensions that reflect these new technologies, such as performance prediction methods, new sky models and user-friendly interfaces. The development of these tools is a focus of the IEA Task 31. New methods and updated design tools must also be continuously validated to ensure correct results and give practitioners confidence in tool application.

Other daylighting technology advances include the following.

- New glazing varieties with improved optical and thermal transmission performance are now commercialised and allow excessive solar heat gain to be avoided by filtering out the infrared part of the solar spectrum without adversely limiting daylight transmission.
- More sophisticated louvre coatings and façade constructions provide specular and diffuse reflection of daylight into the interior while minimising glare and unwanted heat gains.
- Innovative antiglare light-diffusion devices such as the microdots painted on the windows of the new European Commission Berlaymont building in Brussels, Belgium.
- A large variety of light-well and light-shelf designs.

All these techniques can be deployed to increase the utilisation of daylight in buildings and to offer significant savings opportunities.

LAZY LUMENS: THE ENERGY USED BY LIGHTING

Key messages

- Lighting accounts for 19% of global electricity consumption and gives rise to CO_2 emissions that are equivalent to 70% of those from the world's light-duty vehicles.
- About 2.4 million barrels of oil per day are used to provide lighting for vehicles and for 1.6 billion people living in non-electrified households in developing countries.
- Current national estimates of lighting energy use are far from definitive: most fluctuate wildly from one survey to another. There is a need to invest resources to gather more reliable data.
- A large proportion of total lighting energy is used by inefficient and outdated technologies, *e.g.* incandescent lamps, mercury vapour lamps, low-efficacy fluorescent lamps with low-efficiency ballasts, etc.
- There are major differences in lighting efficiency and energy use across IEA economies, with best practice and poor practice being found in each, albeit often not in the same areas.
- There are very large differences in lighting energy use in similar building types within the same economy.
- The economies that optimise the use of fluorescent light, avoid unnecessary lighting and make most use of daylight have the lowest lighting energy needs.
- Demand for artificial light is strongly linked to per-capita GDP, but there are important variations among economies.
- Lighting retrofits can save significant amounts of energy cost-effectively.
- There are important barriers that limit the automatic adoption of efficient lighting in the current market.

WHY THE LUMENS ARE LAZY

Designing effective and efficient policy measures for energy-efficient lighting demands a thorough understanding of the lighting market, or rather of lighting markets, and of how energy is being used to provide a lighting service. From this the opportunities for greater deployment of more efficient lighting technologies and practices become apparent and energy-savings potentials can be both identified and quantified. This chapter describes the current market situation for lighting in terms of the deployment of technologies, their energy use, efficiency, economics and environmental impacts. The first section presents global and regional estimates for each of the major lighting end-use sectors: commercial, residential, industrial and outdoor stationary lighting. It also gives a summary of the less often considered issue of fuel-based lighting, used both for the provision of indoor illumination in developing countries and to provide lighting for vehicles. The second section reviews the global lighting market and industry in terms of sales, value and employment. The third section discusses the cost-effective potential for energy savings through greater deployment of energy-efficient lighting and lighting systems. Finally, the main market barriers that are impeding the full cost-effective potential from being achieved are reviewed.

Efforts to estimate global lighting energy consumption

The information presented in this chapter has been assembled from numerous sources, organised in a detailed bottom-up model developed by the IEA and analysed to produce global, regional and sectoral estimates of lighting energy use, artificial illumination and lighting's economic and environmental impacts. It is the first time that an analysis of this type and depth has been attempted at the global scale and is the result of several years of effort within the IEA Secretariat. The most recent previous estimate concluded that global lighting electricity energy consumption was 2 016 TWh in 1997 (Mills, 2002). That analysis, conducted for the IEA, was based on a compilation of estimates for 38 countries, representing approximately 63% of the world's population. However, there are many reasons for revaluating these figures. First, the source material used is now out of date and in some cases has been surpassed by more reliable figures. For example, two figures were used for commercial-lighting energy use in the United States: 246 TWh and 340 TWh (Energy Information Administration [EIA] estimate) (Vorsatz *et al.,* 1997). Since that time a more reliable study has been conducted, the US Lighting Market Characterization study (Navigant, 2002), which reports values based on a sophisticated marriage of the findings of almost 25 000 utility lighting audits and the national Commercial Building Energy Consumption Survey of 5 430 national representative buildings. This found that US commercial buildings consumed 391 TWh of electricity for lighting in the year 2001. Second, there has been exceptionally strong economic growth in some countries since that time, most notably in China, and this is likely to significantly alter the total. Third, the quality of data reported in most countries cited in the review is highly questionable, while for many others data were unavailable. Given this, the IEA conceived the need to derive new estimates based upon an alternative methodological approach, as outlined on pp. 169–172.

The new IEA analysis estimates that global lighting electricity consumption in 1997 was 2 350 TWh, which is 17% higher than the values used by Mills. Although there are reasons to believe the current analysis is more reliable, there are many uncertainties and inconsistencies in the available sources of data and thus this analysis is far from being the final word in terms of the definitive characterisation of the international lighting market. Much more remains to be done to improve the calibre of these and future estimates; however, for the first time enough data have become available and been assembled to enable an in-depth global analysis to be attempted and past trends and future projections analysed. The hope is that the lighting-market characterisation results presented in this chapter and the projections of future and past lighting-market characteristics presented in Chapter 6 will provide a sounder basis to inform policy development than would have been the case without such an analytical effort.

A note on the current methodology

The approach adopted in this new IEA analysis is to use all available data to independently simulate lighting demand and supply in order to characterise the total installed lighting systems and estimate their energy use. Lighting demand is analysed via a purpose-built bottom-up model that divides the world into seven regions: IEA North America, OECD Europe, Japan/Korea, Australia/New Zealand, the Former Soviet Union, China and the Rest of the World. For the commercial sector the building stock is divided into seven broad categories: offices, educational buildings, healthcare, retail, hotels/motels, warehousing and others. The total floor area of each commercial-building type was further subdivided into space functions with common lighting characteristics, *e.g.* offices, corridors, toilet blocks, reception areas, storage/utility areas, etc. In each of these areas the default assumption is that the lighting system is designed to provide delivered light levels that match illumination requirements specified in national recommendations or regulations. This is then converted into default lighting power density levels (expressed in units of W/m^2) once the relative mix of lamp, luminaire and room coefficient of utilisation (CU) values are known or can be derived using the method described below. The lighting power density levels are subsequently converted into energy consumption figures if the hours of usage and lighting-control characteristics are known.

Luminaire output ratio and CU: default assumptions

In order to estimate average luminaire and room losses, the IEA analysis took the highly detailed data available in the US Lighting Market Characterization study (Navigant, 2002) as its starting point. This gave information on the precise mix of lamps per type of space function in the US commercial-building sector of 2001. By applying the information on lighting usage and energy intensity (expressed in units of kWh/m^2) it is possible to determine the relative source-lumen losses due to luminaire losses (which can be expressed by the luminaire output ratio [LOR]) and room losses (which can be expressed by the CU) for the US commercial-building stock. In the event that no other regionally specific data are available the United States, values are assumed to be indicative of the typical losses incurred in commercial buildings in other regions.

Deriving the lamp mix and hours of use

At the same time as the above, national data were gathered on typical lighting operating hours by building type, and on sales by each of 12 major lamp types (see pp. 107–137): linear fluorescent lamps (LFLs) (T5s, T8s [halo- and triphosphor types] and T12s), incandescent lamps (halogen spotlights, incandescent reflector lamps and standard incandescent general lighting service (GLS) lamps, high-intensity discharge (HID) lamps (high-pressure sodium, mercury vapour and metal halide lamps), compact fluorescent lamps (CFLs: ballast-integrated and non-integrated varieties) and light-emitting diodes (LEDs). Sales data were also gathered on ballasts according to efficiency level. From these data, including known divisions of lamp and ballast sales by lighting sector and known lamp and ballast lifetime characteristics, it was possible to apply a lamp replacement-stock model to estimate numbers of lamps and ballasts in the commercial-building sector by type. If reliable data were also available characterising the installed lamp base and use in the commercial sector for any given country, as in the United States, for example, these were used to prime the model. If such data were partially available, but were not very consistent or reliable, as in Europe (see discussion on pp. 172–250), these were also used to help prime the model. Otherwise, the lamp sales data were used in isolation to derive shares of lamp type by space function.

Once the generic lamp mix for the entire sector was known, the US Lighting Market Characterization study data were used to derive the relative distribution of lamp types by space function, *e.g.* if in the US commercial sector LFLs provided ten times as much light in offices as did incandescent lamps, this ratio was initially assumed for other regions but then adjusted for the relative amount of light provided by LFLs and incandescent lamps in the two regions. This approach takes account of how lamp types are used in practice and respects the allocation of lamps by space type most commonly found. Similarly, data and estimates are often available on the annual average hours of use of lighting in different building types and regions, but they may not be available by space function. In this case the average value is made to respect the local data but the relative values by space function are adjusted to match the US data.

Calibrating between data-sources

The process outlined above allows all available data-sources to be used to estimate installed lighting power levels and full-time equivalent hours of use, based on the factors that influence lighting supply and demand. The resulting calculations are then used to produce estimates of total lighting energy consumption. In the case of the United States they explicitly match the US DOE value for 2001 (Navigant, 2002) because they reconstruct the same data-sources used in that study. By so doing, however, they establish that for the Navigant data to be correct the combined luminaire and room losses collectively add up to losses of about 75% of source-lumens, *i.e.* on average about 1 in 4 lumens emitted by lamps used in US commercial buildings was providing a useful visual service in 2001.

For other regions, the consistency of the estimates they produce depends on the consistency of the supply- and demand-side data-sources available. If there are well-respected and credible national estimates of commercial-building lighting energy consumption, the loss functions in the model are adjusted to be consistent with those. However, if the modelling process establishes that the national or regional lighting supply- and demand-side data are inconsistent, an attempt is made to reconcile the data based on a judgement of its credibility. When few supply or demand data are available, defaults are used based on international values and some interpretation of local circumstances, e.g. for the Rest of the World region it was not necessarily assumed that installed illumination matches Commission Internationale de l'Eclairage (CIE; International Lighting Committee) recommended values when this is known to not be the case in many localities.

LIGHTING MARKETS: LIGHT, ENERGY, ECONOMIC AND ENVIRONMENTAL CHARACTERISTICS

Lighting markets vary significantly because different end-users in different sectors of the economy have different lighting needs and budgets. In addition, there is a broad variety of lighting technologies, certain of which have characteristics that lend themselves to greater application in one sector than another. The majority of lighting is required for indoor illumination and within this there are three main sectors: residential, commercial and industrial. Lighting is also required for external illumination, including all public lighting (such as street, car park, stadium, roadway and tunnel lighting) and outdoor illumination (such as security, pathway, architectural and private car-park lighting). Further differentiations can be made depending on the type of subspace to be illuminated and on economic factors. Residential indoor lighting comprises electric lighting for electrified households and fuel-based lighting for most non-electrified households. Among the electrified group the typical lighting needs and technologies used will vary from utility areas such as kitchens and bathrooms to recreational areas such as living rooms. In the commercial and industrial sectors the most appropriate choice of lighting is influenced by the functional purpose of the building and interior spaces, the height of the ceilings and the occupancy characteristics.

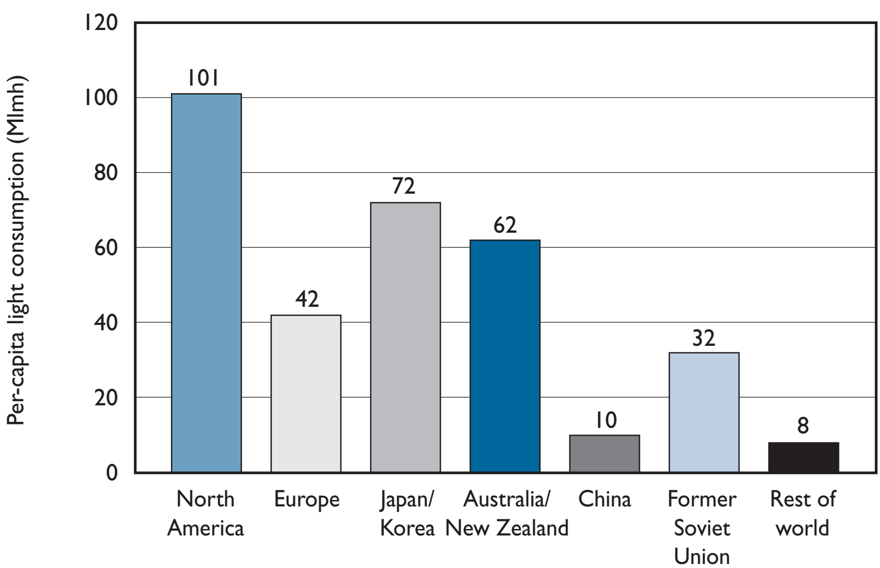
Therefore, policies designed to promote energy-efficient lighting need to be informed of the distinct characteristics and take account of their different needs and opportunities. The current lighting characteristics and associated energy consumption levels are discussed for each of the main sectors in the rest of this section.

Global light consumption, energy use, costs and CO_2 emissions

Consumption of artificial light

For 2005 it is estimated that the global consumption of artificial light was 134.7 petalumen-hours (Plmh), of which 99.0% (133.3 Plmh) was for electric grid connected lighting, 0.9% (1.3 Plmh) for vehicle lighting and 0.1% (0.086 Plmh) for off-grid fuel-based lighting. Overall this amounts to an average annual consumption of 21 megalumen-hours (Mlmh) of artificial light per person; however, the use of this light is very unevenly distributed. An average North American uses 101 Mlmh of artificial light each year, while the average inhabitant of India uses just 3 Mlmh (Figure 4.1).

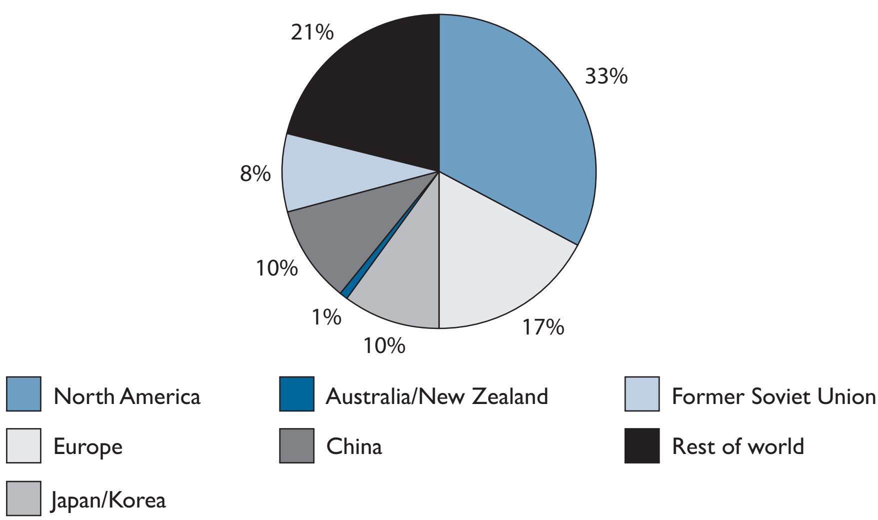
Figure 4.1 **Estimated per-capita consumption of electric light* in 2005**



* Source-lumens.
Abbreviation: Mlmh = megalumen-hours.

An even larger difference applies when comparing the consumption of artificial light between people with access to electricity and those without. The former consume an average of 27.6 Mlmh per capita per annum, while those relying on fuel-based lighting consume just 50 kilolumen-hours (klmh): a difference of more than 500-fold. Despite these inequalities even the lower figures are remarkably high when seen in a historical context, and they illustrate the extraordinary progress that has been made in artificial illumination. A typical person living in England at the beginning of the 19th century, for example, would have consumed just 5 klmh of artificial light each year (Fouquet and Pearson, 2003), but by the beginning of the 21st century this consumption was over 12 000 times this figure. The regional share of global artificial-light consumption is shown in Figure 4.2.

Figure 4.2 **Estimated regional share of electric-light consumption* in 2005**



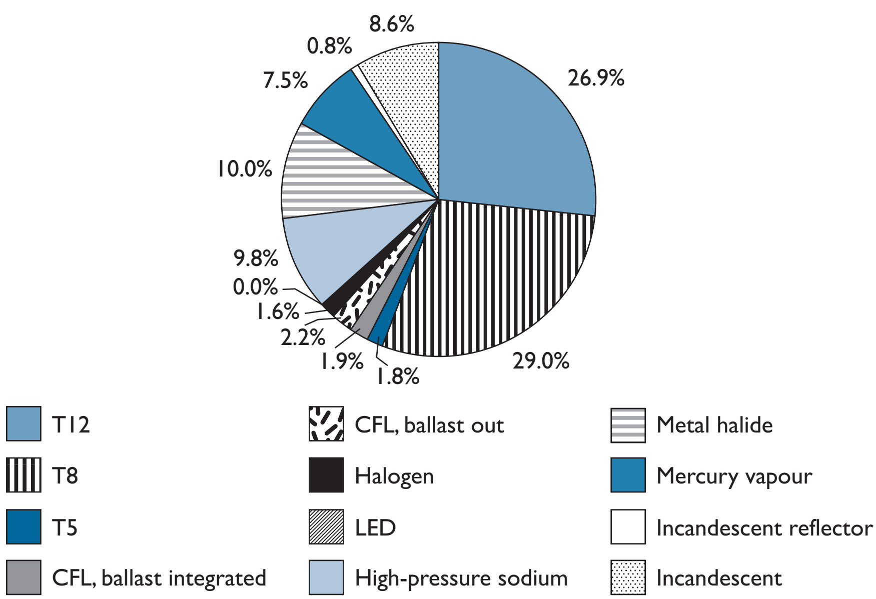
* Total = 133.1 Plmh, source-lumens.

However, caution needs to be exercised in interpreting simple counts of total source-lumens (the lumens emitted by lamps, as cited in the above paragraph), because this is a poor measure of overall lighting service. A better understanding of the quality of lighting provided requires information on how effectively lumens are delivered to aid visual tasks and what level of lighting is needed to provide visual comfort and productivity. Assessing true lighting-service levels thus also requires knowledge of the most appropriate lighting environment for the lit space, the distribution and absorption of light, whether people are present when light is delivered and the extent to which electric-lighting needs are offset by daylight. Data on these factors are much sparser, or non-existent, and so regional variations in overall lighting service can only be estimated from anecdotal evidence and case studies.

Estimated light production by lamp technology

The share of light produced by each light source has been estimated by region and sector. Global aggregate results are shown in Figure 4.3. Incandescent sources (incandescent, reflector and halogen lamps) provided some 14.7 Plmh of light (11.0% of the total), HID sources

Figure 4.3 **Estimated global average share of electric-light production* by lamp type in 2005**



* Total = 133.1 Plmh, source-lumens.
Abbreviations: CFL = compact fluorescent lamp; LED = light-emitting diode.

provided 36.3 Plmh (27.2%) and fluorescent sources 82.3 Plmh (61.8%). From these data it is also clear that inefficient light sources, and in particular incandescent lamps, mercury vapour lamps and T12 LFLs, are still providing a large part of the global lighting service (45% of source-lumens).

Estimated light production by sector and lamp technology

Figure 4.4 shows the estimated global aggregate share of light produced by major light-source type in each sector. The residential sector consumes some 19.2 Plmh of light (14.4% of the total), the commercial- and public-building sector 59.5 Plmh (44.6%), the industrial sector 38.5 Plmh (28.9%) and the outdoor stationary sector, which comprises street, roadway, security, outdoor signage and car-park lighting, uses 16.1 Plmh (12.1%). These figures ignore the much smaller amount of light produced by vehicle lighting and off-grid residential fuel-based lighting.

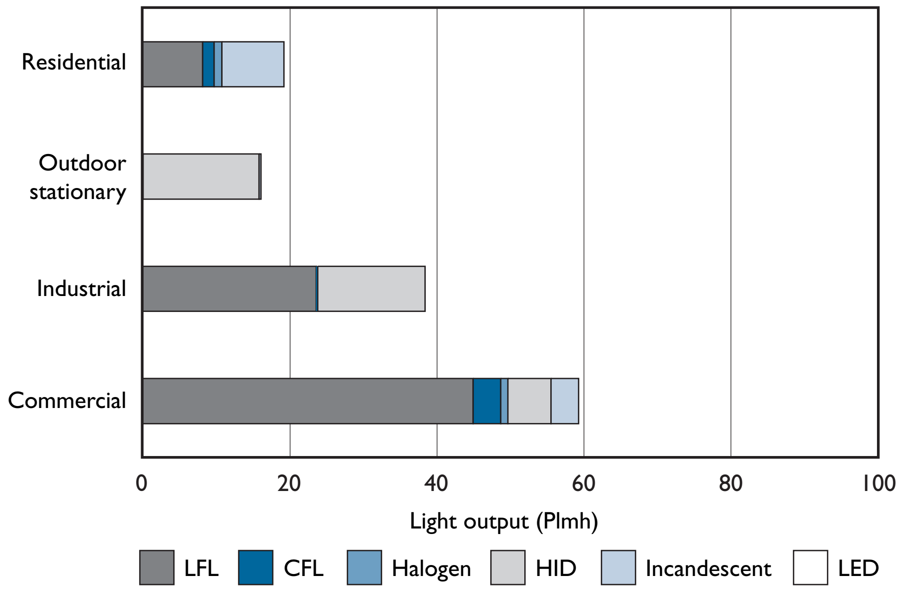
Rate of growth in demand

It is estimated that over the last decade global demand for artificial light grew at an average rate of 2.4% per annum. Growth was slower in IEA countries, at 1.8% each year, than in the rest of the world, where it averaged 3.6%. Growth rates in IEA countries are lower than in previous decades and for the first time in history may be indicative of the beginnings of demand saturation. Even so, the overall growth in demand is expected to continue for the foreseeable future driven by new construction, rising average illumination levels in non-OECD countries, ongoing electrification and a trend towards more outdoor lighting.

Global lighting energy use

It is estimated that the provision of lighting results in the consumption of 650 Mtoe of primary energy globally – 8.9% of total global primary-energy consumption in 2003. Lighting energy use is dominated by stationary electric lighting, but it also includes vehicle lighting and off-grid fuel-based lighting, both of which use substantial amounts of energy. A discussion of the consumption of each of these sectors now follows.

Figure 4.4 **Estimated global average share of electric-light production* by lamp type and end-user sector in 2005**



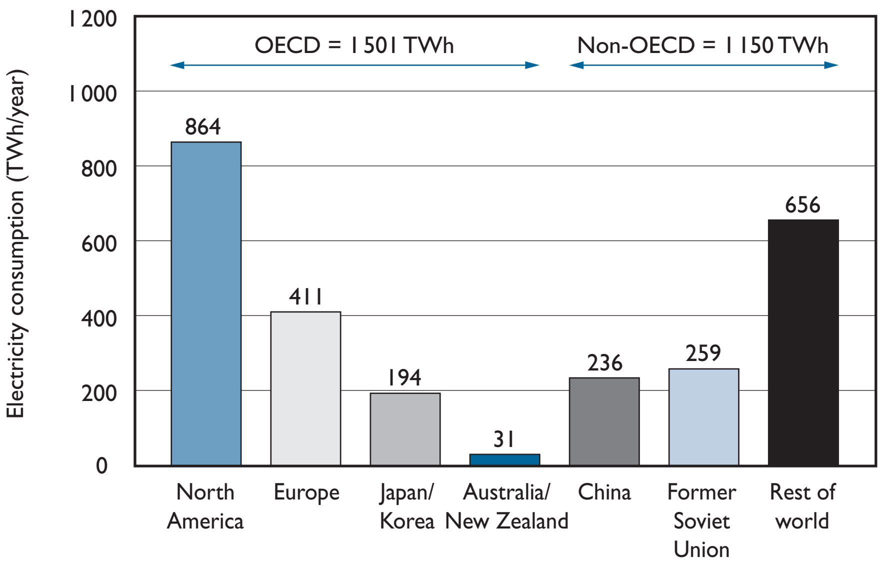
* Total = 133.1 Plmh, source-lumens.
Abbreviations: CFL = compact fluorescent lamp; HID = high-intensity discharge; LFL = linear fluorescent lamp; Plmh = petalumen-hours.

Stationary electric lighting

Lighting was the first service offered by gas and electric utilities and continues to be one of the largest electrical end-uses. For 2005 it is estimated that grid-based electric lighting consumed 2 651 TWh of electricity: 19% of all global electricity consumption and slightly more than total electricity consumption in the European Union (Figure 4.5).

Lighting uses almost the same amount of electricity as is produced by gas-fired generation and about 15% more than is produced by either hydro or nuclear power. The OECD countries account for about 57% of this. However, the fastest rates of economic growth are happening outside the OECD, and thus the share taken by OECD countries is declining; by 2030 non-OECD countries are expected to account for more than 60% of global lighting electricity demand.

Figure 4.5 Estimated regional share of stationary-lighting electricity consumption in 2005



* Total = 2 651 TWh.

Indoor illumination of tertiary-sector buildings uses the largest proportion of lighting electricity – as much as the residential and industrial sectors combined. On average, lighting accounts for 34% of tertiary-sector electricity consumption and 14% of residential consumption in OECD countries. In non-OECD countries these shares are often higher because there is less use of miscellaneous electrical end-uses. Outdoor stationary lighting, including street, roadway, parking and architectural lighting as well as outdoor signage, uses less than one-tenth of total lighting electricity consumption.

In addition to spatial illumination and signage there are also a number of important niche lighting applications where lighting is not the primary function of the equipment but is a significant factor influencing its energy consumption. These include backlighting of computer screens, mobile phones, televisions and other information and communications technology devices. This consumption is not included in the global figures attributed to lighting energy demand presented above and is not a major focus of the analysis presented in this book, but it could reasonably be argued that this energy use is also part of the lighting load.

Indirect space-conditioning energy use

Similarly, the indirect energy use or savings attributed to lighting has not been accounted for in the analysis presented here. As all currently used lighting devices produce more energy in the form of heat than light, lighting can make a significant contribution to the internal heat gains of a building. During periods when heating is required this thermal energy helps to offset the need for space heating and hence reduces space-heating energy demand, but during periods where cooling is required the thermal energy from lighting adds to the indoor cooling load and increases cooling energy demand. There is a global trend towards more space cooling and in OECD countries the majority of commercial-building stock is now air-conditioned (IEA, 2004). In non-European OCED countries most of the residential-building stock is now air-conditioned, while in Europe the share is growing but from a much lower base. Conversely, almost all OECD building stock has heating of some description.

These figures may lead one to conclude that the heating energy offset by heat from lighting is likely to be greater than the cooling energy incurred; however, this is probably not the case. Most commercial buildings now have so many internal gains from people, office equipment and other equipment that on average they probably have the cooling system in operation as much as the heating system, although there is a lack of data from which to make a definitive judgement. Moreover, if the total sum of lighting-induced thermal energy flows might roughly cancel each other out over the whole OECD building stock, this is not likely to be the case when peak energy flows are examined. In practice space cooling is almost exclusively provided by electrical energy, which is not easily stored, while space heating is provided by a multitude of energy forms, most of which are much more readily stored. The result is that the energy flows that drive up air-conditioning have an appreciably greater impact on peak power demand in most OECD regions than those that increase space heating. A thorough analysis of these factors is beyond the scope of this study, but it is likely that over the OECD as a whole the heat produced by lighting makes a net contribution to the overall primary-energy consumption for space conditioning, increases total peak power demand and increases associated greenhouse gas emissions.

In non-OECD countries this conclusion is probably even truer. Rapidly emerging economies such as China, India and Brazil as well as many Southeast Asian, Middle Eastern, African and Latin American economies are predominantly in need of electrically powered space cooling rather than heating. Furthermore, the greatest strain on the energy networks is to keep up with rapidly growing demand for electricity. Most non-OECD electricity networks are summer peaking, driven in large part through demand for cooling and air-conditioning. Thus the thermal energy produced by lighting will almost certainly significantly amplify demand for space cooling in non-OECD countries as a whole and will be a net contributor to overall energy demand.

Domestic fuel-based lighting

For most of us it would be simple to imagine that lighting energy use is confined to electric grid connected applications; however, this is not the case. Fuel, most commonly in the form of paraffin (kerosene), is also used to provide lighting for more than one-quarter of the world's population, who have no access to the electricity network. An estimated 77 billion litres of fuel is used annually for fuel-based lighting – some 1.3 million barrels of oil a day. This amounts to 65.6 Mtoe of final energy use.

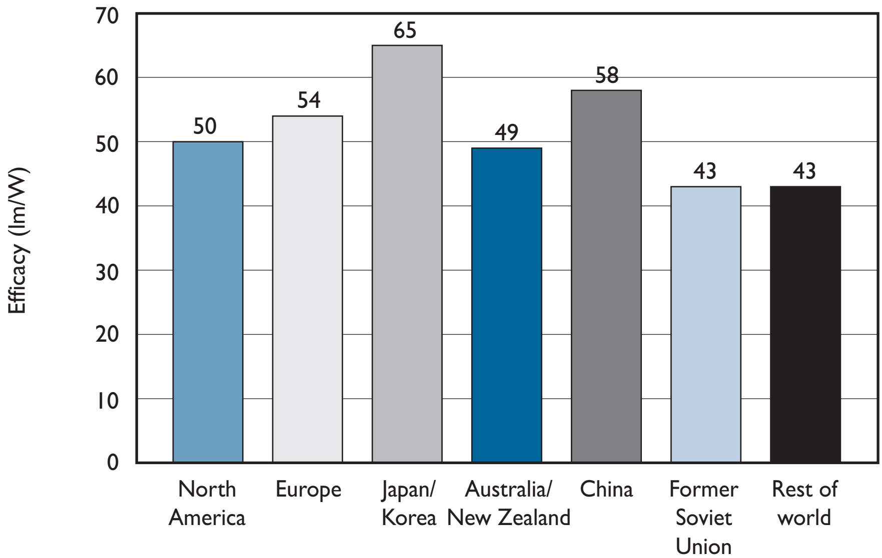
Vehicle lighting

Furthermore, each year 55 billion litres of gasoline and diesel is used to operate vehicle lights, amounting to 47.1 Mtoe of final energy use. This is 3.2% of total vehicle fuel use and is equivalent to the consumption of 1.05 million barrels of oil daily. At present this consumption is not reflected in the fuel performance figures quoted under standard test-driving cycles because auxiliary devices including lights are not activated during testing. Therefore this aspect of vehicle energy performance is currently invisible to end-users.

Average system efficacy

In 1960 the average lighting system had an efficacy of about 18 lumens per watt (lm/W), yet by 2005 this had risen to roughly 50 lm/W (Figure 4.6). The rate of improvement appears to have been relatively constant from 1960 to 1985 at about 2.8% per year, but from 1985 onwards it slowed to 1.3% per year (McGowan, 1989). This decline in the rate of efficiency improvement mirrors those seen in other end-uses and sectors and may imply that efforts to conserve energy slowed as adjusted real energy prices fell back in the mid-1980s. The current environment of higher

Figure 4.6 **Average lighting-system efficacy by region in 2005**



energy prices and concerns about energy security and climate change may provide a stimulus to reverse this tendency.

The main determinants influencing differences in average regional lighting-system efficacy today are the relative ratios of fluorescent lighting to incandescent lighting and of mercury vapour HID lighting to other forms of HID lighting. The quality of fluorescent lighting, including ballasts, also has a significant impact.

There is little difference among OECD countries with the exception of Japan and Korea, where the average efficacy of lighting systems is about 27% higher than in the rest of the OECD. This can be explained by the very low usage of incandescent lamps and high usage of fluorescent lamps in these economies compared with the rest of the OECD. In the rest of the world there are some significant differences. Overall the average efficacy of lighting delivered in the OECD is 53 lm/W and in non-OECD countries it is 46 lm/W; however, this masks important national variations.

Taking the available data at face value, the efficacy of the average lighting system in China is slightly higher than in the OECD because of a comparatively high use of fluorescent lighting, including higher than average use of CFLs and T8 and T5 lamps. However, a word of caution must be added here; in China, as in many countries, there are multiple data-sources and there is some inconsistency in the data available. Furthermore, there is a lack of statistically representative public-domain test data with which to compare lamp efficacy levels with product class. Readers should thus be aware that there is a significant margin of error in some of the data reported here. In the countries of the Former Soviet Union the available data-sources imply there is a low usage of efficient lighting technologies, with almost no CFLs being used and most HID lighting produced by mercury vapour lamps; as a result the average system efficacy is relatively poor, at 43 lm/W. Elsewhere in the world the situation is diverse, but overall the efficacy of lighting systems is not usually as high as in the OECD or China. The same situation that applies to the Former Soviet Union also holds in the Rest of the World region, with a large proportion of incandescent and poor-quality fluorescent lighting in use; however, the share of all lighting taken by HID lighting is smaller than in the OECD and as a result the average system efficacy is lower, at 43 lm/W.

All of this discussion concerns the efficacy with which source-lumens are delivered and takes no account of average luminaire performance or the CU. On average, it is probable that luminaires used in OECD countries will be of a higher quality than the average of those used elsewhere, but there is a dearth of data from which to make a meaningful comparison and thus it is not possible to do so at this juncture. This is a considerable limitation in the analysis because luminaires and lighting design have a large influence on overall system performance.

Global cost of lighting

It is estimated that the energy used by electric light in 2005 cost end-users USD 234 billion, at an average cost of about USD 2.8 per megalumen-hour. This is two-thirds of the cost of the total electric-lighting service of USD 356 billion, which includes equipment and labour costs estimated at a total of USD 122 billion. Together this is almost as much as the combined gross domestic product (GDP) of the ten newest EU member states. In addition it is estimated that the end-user energy costs of fuel-based lighting amount to USD 38 billion per annum and that those for vehicle lighting amount to approximately USD 66 billion, making a total lighting energy bill of USD 338 billion per annum. Combined global expenditure on the lighting service is thus about 1.2% of world GDP, while expenditure on lighting energy costs alone is about 0.9% of world GDP.

Global CO_2 emissions from lighting

It is not commonly appreciated that lighting is one of the biggest causes of energy-related greenhouse gas emissions. Global lighting-related CO_2 emissions are estimated to be 1 528 Mt from grid-based electric lighting, 190 Mt from fuel-based lighting and 181 Mt from vehicle lighting. This makes a total of 1 900 Mt of CO_2, which is 70% of the global emissions of light-duty passenger vehicles. The emissions from fuel-based lighting alone are greater than all energy-related CO_2 emissions from Thailand, for example, while total lighting-related emissions are about 83% of all emissions from the countries of the Former Soviet Union, or of those from France, Germany, Italy and the United Kingdom combined. Reducing lighting energy consumption by raising efficiency is thus a major route towards CO_2 abatement.

Residential lighting

Globally, an estimated 811 TWh of final electricity was consumed by residential lighting in 2005, amounting to about 31% of total lighting electricity consumption and about 18.3% of residential electricity consumption. This produced 17.4 Plmh of light at an average source-lumen efficacy of 21.5 lm/W, which is far lower than in other lighting end-use sectors. Low luminaire LORs and poor CUs are also typical of residential lighting, and this means that only a small proportion of source-lumens make a useful contribution to overall illumination. However, a lack of statistically representative data on this aspect of system performance means it is not possible to make a plausible estimate of the useful system efficacy. Moreover, poor control results in the illumination of empty rooms and an even smaller proportion of the emitted light being used for a useful purpose, so total system efficacy will only be a fraction of the source-lumen efficacy of 16.8 lm/W. Residential lighting is thus the least efficient of all grid-based electric-lighting end-user sectors and is also the one with the highest theoretical potential for improvement.

Incandescent bulbs remain the dominant technology in most countries, largely because they are very cheap – so much so that their relatively short lifespans and high energy costs are no impediment to their marketing. Consumers regard them as disposable. In addition, incandescent bulbs offer a warm colour, are available in an enormous range of styles and sizes, and can be dimmed, features that many consumers find attractive. While incandescent lighting, including traditional incandescent lamps and tungsten halogen lamps, are comfortably the most common type of lamp in the residential sector, they now provide a minority of total residential-sector light. The majority, 53%, is provided by fluorescent lighting, of which CFLs supply 13% and LFLs supply the rest. This may be a surprising finding but reflects both the fact that the share of residential lighting provided by incandescent or fluorescent lighting varies considerably from one region to another and the fact that fluorescent lighting has been increasing its share of residential lighting in almost all countries over the last few years.

In particular, CFLs are now making significant inroads into the residential-lighting market, stimulated by a sharp drop in price through increased competition and an increasing variety of CFLs. These include much smaller lamps that can fit into almost any incandescent lamp fixture. While many of the earlier barriers to the development of the CFL market (high price, lack of dimmability, a history of "cold" colour output, relative bulkiness and a narrow range of decorative forms) have been fully or partially addressed, there are still ongoing barriers to be tackled, including a continuing lack of awareness of their benefits (many consumers know CFLs are energy-saving lamps, but few have any idea of their much lower life-cycle costs; consequently most remain averse to paying a higher price for a CFL than an incandescent lamp) and ongoing lamp-quality problems (a lack of product-quality policing has allowed substandard and unreliable products onto many markets, undermining consumer confidence in the technology).

In general the low level of public awareness of lighting energy use and the options to abate it remain major impediments to the uptake of energy-efficient residential lighting. The comparatively high running costs of incandescent bulbs are poorly understood or may be dismissed because of the relatively small sums of money involved, at least for each lamp. Also, most consumers receive electricity bills infrequently and have no way of understanding which part of the bill is accounted for by lighting.

While in some IEA member countries the energy efficiency of some types of lamps is labelled, the coverage is far from complete and the labels may not provide all the information relevant to consumers (energy costs, colour characteristics, dimmability, durability, etc.). Often, the more efficient lamps are labelled but the less efficient ones are not. Therefore consumers may not be in a position to make rational choices between lighting options, particularly if the information they need is not available at the point of sale. Finally, labelling lamps alone may be insufficient, as the choice of light fitting may determine – for the life of that fitting – the type of lamps that can be used.

With limited exceptions (the United Kingdom and some US and Australian states), there are no controls or standards on residential-lighting energy efficiency in IEA member countries. This reflects, in part, the fact that light fittings and lamps are chosen largely by householders and cannot effectively be "policed". However, with new houses often being fitted with low-voltage halogens, recessed incandescent "cans" or other lighting choices that effectively preclude more efficient lamps being installed without major renovation work, the wider use of mandatory limits on lighting power density (common in commercial-building codes) should also be considered for residential buildings. More generally, however, the difficulty in "policing" the use of lighting in the home suggests that minimum energy performance requirements for the lamps themselves may be a better policy choice, especially if complemented by market-transformation initiatives to stimulate the uptake of fluorescent lighting in place of incandescent lamps. In short, a significant strengthening of policies is required to mitigate the rapid growth of energy demand and greenhouse gas emissions associated with lighting in the residential sector.

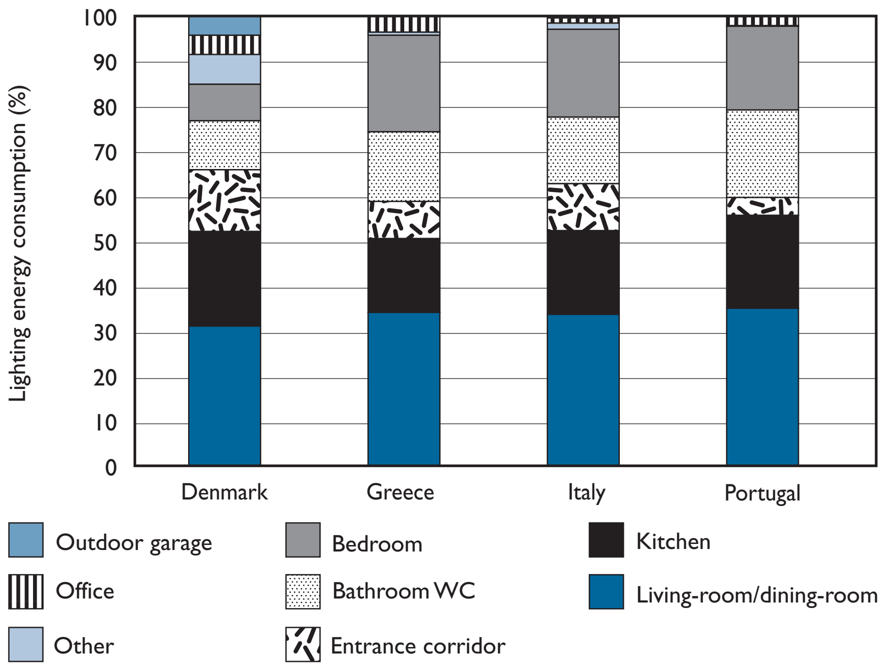
Residential-lighting characteristics in IEA countries

An estimated 372 TWh of electricity was used for domestic lighting in IEA countries in 2005, about 14.2% of total residential electricity consumption. This is an increase of 17% from 319 TWh in 1995, or some 1.5% per annum. The majority of this energy was used by low-efficiency incandescent lamps, but they are not the dominant residential light source in all IEA countries, notably Japan. The most popular incandescent lamps have rated power inputs of 60 W, yet a wide range of input power levels is available and in some EU countries (*e.g.* Denmark, Sweden and Germany) the most common wattage is lower (typically 40 W).

Lighting in the living room and kitchen usually accounts for over 50% of total household lighting, while lighting in bedrooms, hallways and bathrooms accounts for most of the rest (Figure 4.7). Overall, the 1990s saw a trend toward more lamps of all types per household across many

IEA countries, with lower average lighting outputs per lamp. In France, for example, many new residences often do not have ceiling-mounted lamp fixtures but are frequently equipped with numerous wall-mounted sidelights intended to create a mood-lighting effect. The increased emphasis on mood lighting has caused average lighting energy consumption to rise across the IEA member countries.

Figure 4.7 **Average proportion of household-lighting energy consumption by room in four EU countries**



Source: EURECO, 2002 (reproduced with permission).

Number and distribution of light sources

It is estimated that the average IEA household in 2005 had 27.5 lamps, of which 19.9 were incandescent lamps, 5.2 LFLs, 0.8 halogen lamps and 1.7 CFLs; however, these figures mask appreciable differences from country to country. There is quite a lot of similarity in the lighting behaviour and practices of European, North American and Australian/New Zealand households. In all these regions the use of LFLs is mostly confined to the kitchen and bathroom;[1] however, recessed spotlights ("cans" of either halogen or incandescent form), halogen track lights and standard incandescent lamps are also common in both locations. In Europe and Australia/New Zealand, recessed lighting in the residential sector almost invariably uses halogen lamps, whereas in North America standard incandescent lamps, halogens and, to a lesser extent, CFLs are used. In the rest of the house the choice of lighting tends to be between incandescent lamps, CFLs and, to a lesser degree, halogen lamps, with incandescent lamps continuing to be by far the most common.

Larger differences are found between the number and power of light sources used and the arrangements of the luminaires. The relative use of higher light output, ceiling-suspended luminaires (such as pendant lights) compared to less-luminous wall-mounted sconce luminaires, standing lamps and table lamps varies considerably from country to country depending on local cultural preferences and practice, but these choices have an appreciable bearing on the CU of residential lighting. The efficiency of residential luminaires is notoriously poor by comparison with those found in the commercial sector, and there is a wide variation in performance.

Both CFLs and halogen lamps have been in use since the 1980s and both have captured a significant market share in some IEA countries. Halogens can be either low-voltage dichroic and capsule lamps or high-voltage lamps. The low- and high-voltage types have completely different energy-consumption characteristics. Low-voltage halogen lamps use a step-down transformer, which can be associated with standby losses but otherwise are an intermediate-efficiency lighting source. High-voltage halogen lamps have very high power ratings (300–500 W) and are generally used in torchière uplighters to create high-intensity mood lighting. Sales of high-voltage halogen torchières grew dramatically in IEA North America and Europe in the 1990s and in 1996 accounted for 10% of all lamps sales in the United States. Sales in North America are believed to have declined steeply since that time, primarily as a result of fire-risk safety concerns, but sales were still growing in Western Europe in 1998. At full power halogen torchières generally have efficacy levels of 15–20 lm/W, but at partial power levels this falls to a paltry 2 or 3 lm/W. It has been estimated that high-voltage halogen torchières have

1. There is an average of three LFLs per household in these countries.

increased lighting energy consumption more than CFL sales have lowered it in many IEA countries. Energy consumption for halogen torchières has been estimated at 438 kWh/year per lamp in the United States.

United States

According to the US Lighting Market Characterization study (Navigant, 2002), based on a detailed sample of 161 households cross-matched to complementary data in the Energy Information Administration's nationally representative Residential Energy Consumption Survey (RECS) of 4 832 households, the average US household used 1 946 kWh of electricity for lighting in 2001. This gives a total site electricity consumption of 208 TWh from 4.6 billion lamps. The average household had 42 lamps, burning for an average of 2 hours per lamp per day; 91% of these are incandescent lamps of some variety (Table 4.1).

The total housing stock comprises 14.2 billion square metres of floor area, so on average each square metre of residential floor area used 15.1 kWh of electricity for lighting per year, at an average efficacy (source-lumens) of 18 lm/W. A retrospective analysis of the Navigant data shows that each US household was using an average of 36.3 Mlmh of light (source-lumens) per year, or some 13.6 Mlmh per capita per annum.

Table 4.1 Residential lighting electricity consumption by lamp type in the United States in 2001

Lamp type	Share of lamps (%)	No. of lamps per household	Average power (W)	Average operating hours/day	Share of lighting electricity use (%)
Incandescent	91.0	36	67	1.9	90
Standard, general service	80.0	34	63	1.9	76
Standard, reflector	9.0	2	102	2.4	11
Halogen, general service	1.0	0.2	200	2.3	1
Quartz halogen	1.0	0.1	205	2.5	1
Fluorescent	9.0	6	38	2.2	10
Compact, screw-in, reflector	1.6	1	18	2.3	1
Miscellaneous fluorescent	8.0	5	41	2.2	9
Total	**100.0**	**42**	**63**	**2.0**	**100**

Source: Navigant, 2002.

Japan

Retrospective analysis of a survey of Japanese residential lighting conducted in 2004 shows that on average each household used 46.5 Mlmh of light (source-lumens) per annum (JELMA, 2005), equating to some 16.5 Mlmh of light per capita per annum. An average household used 939 kWh of electricity for lighting per annum, or 10 kWh/m² per year. Remarkably, there was an average of only 17 lamps per household, comprising 9.7 LFLs (57%), 3.8 standard incandescent lamps (22%), 1.4 CFLs (8%), 0.3 halogen lamps (2%) and 1.8 other lamps (11%). A large proportion of LFLs are circular lamps designed to fit into a central pendant lamp. While there are less than half as many lamps in typical Japanese households as there are in US ones, they operate for almost twice as long (3.7 hours per day on average, compared with 2.0 hours in the United States). Scaled up to the national level this makes an estimated stock of 776 million lamps in the residential sector, with an average efficacy of 50 lm/W, giving rise to an estimated total electricity consumption of 43.5 TWh in 2005 (JLA, 2005). The average efficacy of lamps in Japanese households is comfortably the highest among OECD countries, but lighting electricity consumption per household is not the lowest because of high average illuminance levels and relatively long average operating times (Table 4.2).

Table 4.2 Estimated national average residential lighting characteristics for a sample of IEA member countries

	Lighting electricity consumption (kWh/ household per year)	No. of lamps per household	Average lamp efficacy (lm/W)	Light consumption (Mlmh/m² per year)	Installed lighting power (W/m²)	Lighting electricity consumption (kWh/m² per year)	Lamp operating time (hours/day)	Household floor area (m²)
UK	720	20.1	25	0.21	14.7	8.6	1.60	84
Sweden	760	40.4	24	0.16	14.0	6.9	1.35	110
Germany	775	30.3	27	0.22	15.6	9.3	1.48	83
Denmark	426	23.7	32	0.10	5.7	3.3	1.59	134
Greece	381	10.4	26	0.09	7.8	3.7	1.30	113
Italy	375	14.0	27	0.09	10.6	4.0	1.03	108
France	465	18.5	18	0.22	16.1	5.7	0.97	81
USA	1 946	43.0	18	0.27	21.5	15.1	1.92	132
Japan	939	17.0	49	0.49	8.1	10.0	3.38	94

Sources: ECODROME, 1998; EURECO, 2002; JELMA, 2005; Navigant, 2002; Palmer and Boardman, 1998.
Abbreviations: Mlmh = megalumen-hours; UK = United Kingdom; USA = United States.

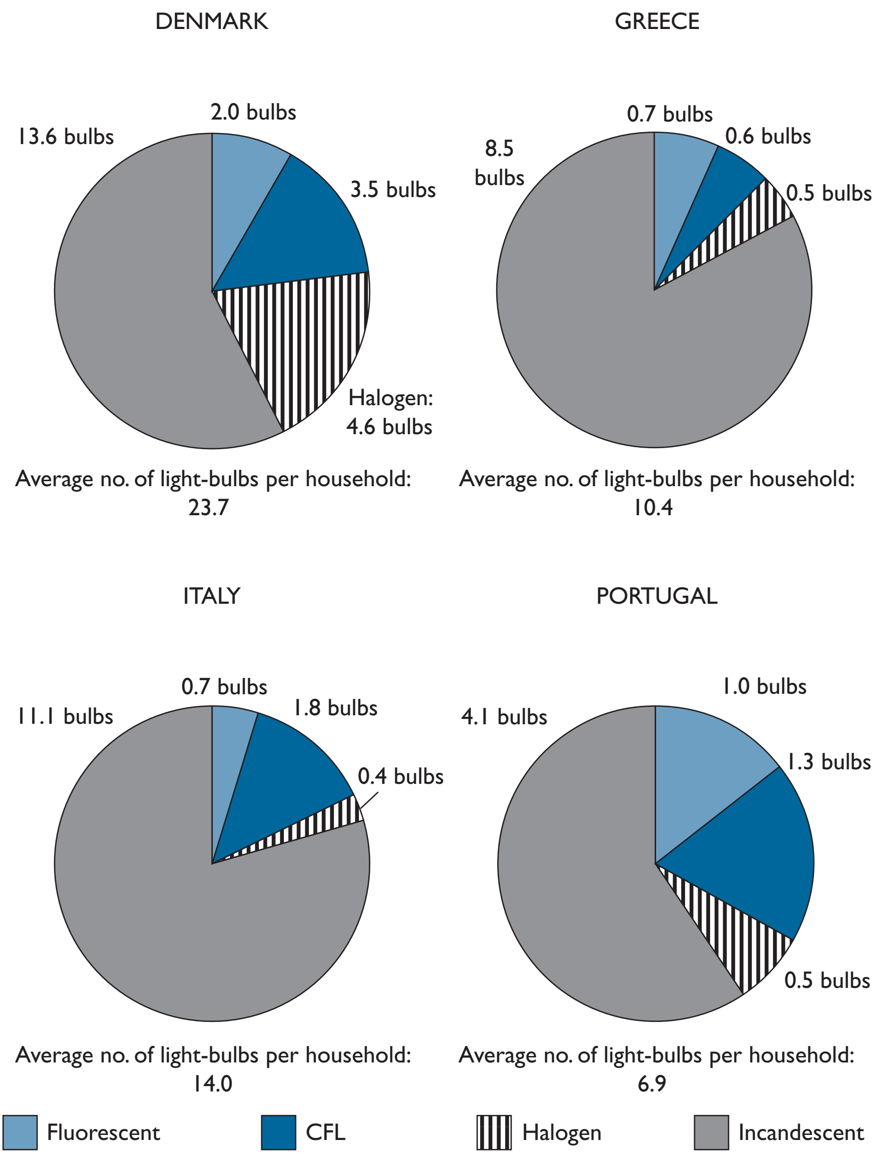
Europe and Australia/New Zealand

European and Australian/New Zealand households appear to use less electricity for lighting than North American or Japanese households, but there is significant variation among the European countries. The highest reported figure is for Finland, where the average household was estimated to have consumed 920 kWh of electricity for lighting in the year 1993, and the lowest is for Belgium, at 291 kWh/year in 1994 (Palmer and Boardman, 1998). The methods used to assess average lighting loads vary considerably in their reliability from country to country and there is large uncertainty regarding the validity of some of the reported values; thus, it is instructive to look at the variations found in the more limited set of detailed end-use metering studies that have been conducted so far. Among these the highest national average household value is 758 kWh per annum for a sample of UK households (Electricity Association, 1998). By contrast, an end-use metering campaign of 100 Portuguese households found an average value of just 179 kWh per household per year (EURECO, 2002); however, the same study reported that it was likely that not all lights had been metered in the Portuguese sample.[2] Other values derived from end-use metering campaigns include: France, from 465 kWh/year (ECODROME, 1998) to 500 kWh/year (Sidler, 1996); Denmark 426 kWh/year, Greece 381 kWh/year and Italy 375 kWh/year (EURECO, 2002). An overall assessment of available data suggests that the average European household consumes about 561 kWh of electricity per annum for lighting – some 6.2 kWh per square metre of floor space per year. Northern European countries tend to consume more than southern countries, in part because of a longer coincidence of household occupancy and hours of darkness over the course of the year. The European average household-lighting electricity-consumption figure is remarkably close to that for the average Australian household of 577 kWh per annum (AGO, 2004a).

The lower household-lighting energy-consumption figures found in European and Australian/New Zealand households compared with other IEA countries is not explained by the average efficacy of the lamps in use. The incandescent lamp is by far the most common residential-lighting technology in European and Australian/New Zealand households, albeit halogen lamps comprise a slightly larger proportion of lighting in many North European and Australian/New Zealand households than in the United States and Canada (Figure 4.8).

2. The EURECO (2002) study reports that because of the uncertainties for Portugal regarding whether all light sources were metered, the values are most probably underestimates.

Figure 4.8 **Average number of light sources per household in samples from four EU countries**



Source: EURECO, 2002 (reproduced with permission).
Abbreviation: CFL = compact fluorescent lamp.

The average efficacy of residential lighting varies in the above surveys from 25 lm/W (United Kingdom) to 38 lm/W (Portugal), with values of 26.0 lm/W in Greece, 26.6 lm/W in Italy and 31.7 lm/W in Denmark. As the average efficacy of residential lighting is only marginally higher in Europe than the figures reported for the United States and considerably lower than those for Japan, the difference in average household-lighting electricity consumption is explained by less electric illumination. Based on an analysis of available national data covering eight European countries (see Table 4.2 for some of these), the highest annual average consumption of light per household is 21 Mlmh (source-lumens) in Germany and the lowest is only 7 Mlmh per annum in Portugal.[3] Viewed as a whole, these figures suggest that Europeans prefer lower residential ambient lighting levels and are more likely than the Japanese or North Americans to use task lighting.

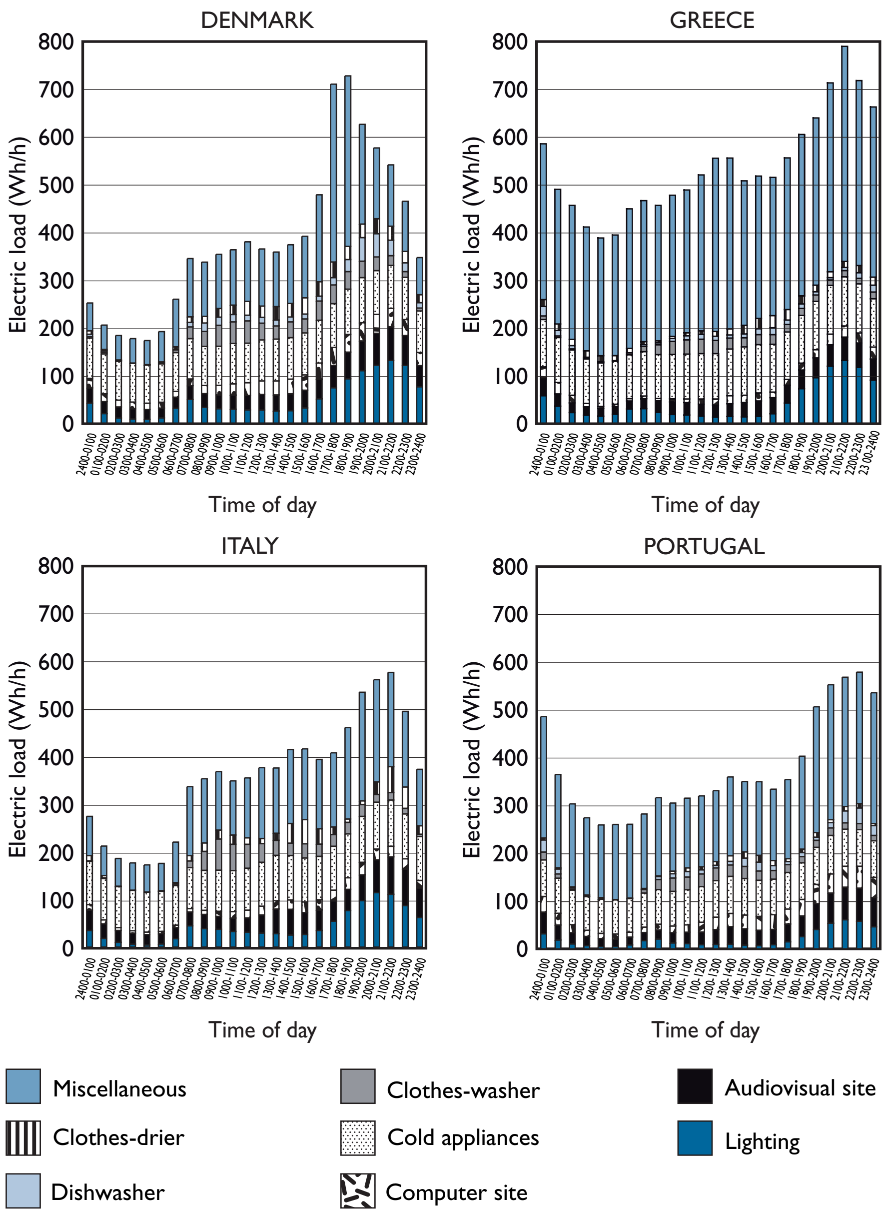
Peak power and installed lighting loads

Residential lighting follows a highly variable but relatively predictable daily and seasonal load profile. The peak demand always occurs in the evening, once people have returned from work and the sun has set. In European countries it is typically between 9 and 10 p.m., but in other countries it can occur a little earlier (between 6 and 10 p.m.) (Figure 4.9). Usually there is also a much smaller early morning peak, between 6 and 8 a.m. In Europe, the EURECO end-use metering campaign, which measured all electrical end-uses in samples of households in four EU countries, found that lighting accounted for between 10% (Portugal) and 19% (Italy) of residential peak power demand. By contrast, a French end-use metering study, which examined all electric loads except space or water heating, found that lighting accounted for 40% of electricity-specific peak power demand in the metered sample of households (ECODROME, 1998).

On average, the daily evening residential-lighting peak is about 2.8 times the size of the average demand, but the further the location is from the equator the more important seasonal variations become. End-use metering results from a French survey at a latitude of about 47° (ECODROME, 1998), for example, found that the daily lighting peak was 45% higher than the annual average in the middle of winter, giving a year-round peak to average lighting power demand ratio of 4.1:1. Lighting is

3. There is some doubt about this figure, which is likely to be an underestimate, but a figure of 9.9 Mlmh per household per annum for Greece, based on an end-use metering survey of 100 households (EURECO, 2002), is more reliable.

Figure 4.9 Annual-average hourly load curves in metered households in four EU countries



Source: EURECO, 2002 (reproduced with permission).

thus the most fluctuating of the major domestic power loads and hence has important implications for system peak power requirements.

To better understand its implications it is appropriate to consider the installed lighting load and the patterns of its use. According to sources covering eight EU countries the installed power demand of residential electric lighting varies between 5.7 W/m^2 in Denmark (EURECO, 2002) to 15.6 W/m^2 for Germany (Palmer and Boardman, 1998), with an average value of about 13.9 W/m^2. The relatively high efficacy of Japanese residential lighting results in average installed power of 8.1 W/m^2, but in the United States the figure is higher, at 21.5 W/m^2. Extrapolating from these figures one can estimate that were all residential lighting in the OECD activated simultaneously, the result would be a demand of about 613 GW. Happily this event is extremely unlikely to occur and at any one time only a small proportion of the total installed-lighting load will be activated. On average only about 20% of the installed load is used during the daily peak, but during the annual peak this rises to ~29%. These figures will tend to be higher in regions with less floor area per capita, where there is less superfluous installed lighting available.

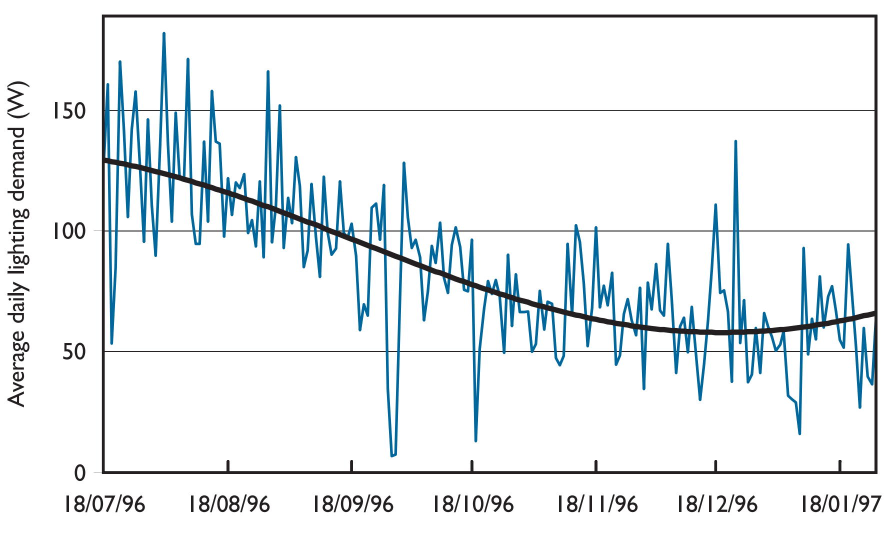
Overall it is estimated that the sum of the OECD national residential-lighting, seasonal peak-power demands amounts to about 175 GW, not including transmission and distribution losses, and the annual average daily peak amounts to 126 GW. Of course the actual figure at any one time will be lower because there will not be a perfect coincidence of peak demand across all OECD households; nonetheless, residential lighting is clearly a major contributor to peak power demand and this makes it a natural target for demand-side management (DSM) programmes. The figures above do not include compounding loads caused by heat from lighting increasing the demand for air-conditioning. The magnitude of this can be very significant, but its impact on the system peak depends on local electricity system characteristics. In regions where the electricity system is summer peaking, such as most of North America, Japan, Australia and southern Europe, China, India, etc., lighting loads will add to air-conditioning loads during peak hours[4] and increase lighting-related power loads by up to 50%. Conversely, in winter-peaking areas where a significant proportion of space heating is provided by electric resistance heaters or heat pumps, e.g. France and Norway, heat from lighting will tend to offset some peak power space-heating demand.

4. Most power drawn by lighting is converted to heat. In regions where air-conditioning is commonplace this adds to the air-conditioning load, thus lighting makes an extra contribution to overall power demand. The amount will depend on the overall efficiency of the air-conditioning system, but if it is assumed that the average system has a coefficient of performance (COP) of 2.0, each watt demanded by lighting will result in an overall power demand of 1.5 W.

Amount of electric-lighting energy used during hours of daylight

One of the key benefits of the use of daylight-saving time is the economy of lighting electricity consumption by increasing the proportion of hours when buildings are occupied that coincide with daylight being available. In practice this leads to lighting savings only in those spaces that have access to daylight and hence estimating total savings needs to take account of building design considerations. Residential lighting demand is quite sensitive to the availability of daylight, especially in the late afternoon and early evening hours, and hence shows a strong seasonality in mid and high latitudes. Failure to adequately adjust for this can be an important source of error in estimates of residential lighting use, especially if sampling is taken only during one part of the year. Figure 4.10 shows the seasonal variation in lighting demand for a New Zealand house and reveals the close correspondence between the fluctuations in demand and a seasonally averaged value that takes account of the number of hours of daylight.

Figure 4.10 **Seasonal variation in residential lighting demand: example of a New Zealand household***



Source: Bishop *et al.*, 1998 (reproduced with permission).
* House w06.

To explore the potential for more daylight savings to be realised the EURECO (2002) study examined the amount of electric light that was consumed from half an hour after daybreak to half an hour before sunset from samples of households in four European countries. The national average share was 26.5%, varying from 18.1% in Greece to 32.0% in Italy. On average, lighting energy use during daylight hours amounted to just 85 kWh per household, which implies that there is only a limited scope to reduce lighting energy use by increasing the use of daylight in the European households investigated. The authors of the current report are not aware of any similar analyses in other regions, but it is possible that were the average use of daylight to be less in North American and Japanese households, some of the increment in average household-lighting electricity use compared to European households (see Table 4.2) might be explained.

Residential-lighting characteristics in non-OECD countries

With some exceptions the quality and availability of data on residential-lighting electricity consumption are not as high in non-OECD countries as in OECD countries, but enough is known to observe some important similarities and differences as well as to enable regional estimates to be formulated. As in the OECD, incandescent lamps are the most common type used in non-OECD households, but the share varies considerably from country to country, and in several non-OECD countries fluorescent lighting provides the majority of all residential light.

Former Soviet Union

Data from Russia suggest that almost all residential light is provided by incandescent lamps, which are estimated to account for 98% of installed lamps. LFLs provide almost all the remainder, with negligible shares for CFLs and halogen lamps (Aizenberg *et al.,* 2001). The average reported number of lamps per household is seemingly very low, at just 3.8 in 2000, but annual average lighting electricity consumption per household is still 394 kWh, which suggests that a much higher proportion of installed lighting is in use during the peak than in OECD countries. The high preponderance of incandescent lamps means the efficacy of the average residential lamp is probably between 10 and 15 lm/W. From these figures the estimated per-capita consumption of electric light is about 2 Mlmh per annum in the residential sector.

China

The extraordinary economic growth experienced in China over the last two decades has led to a rapid increase in residential-lighting electricity consumption on both a national and per-capita basis. In 2003 the average household used 181 kWh of electricity per year for lighting, or 49.2 kWh per capita (ACMR, 2004). Lighting accounted for almost 28% of residential electricity consumption, which is a higher share than generally found in OECD households but is typical of rapidly developing economies. The average household had 6.7 lamps in 2003, of which 43% were fluorescent and the remainder incandescent, resulting in an average residential lamp efficacy of 27 lm/W. Residential per-capita consumption of electric light was about 1.4 Mlmh per annum.

Rest of the World

In the Rest of the World the average consumption of electricity for residential lighting in 2005 is estimated to be 84 kWh/year per capita. There is considerable uncertainty regarding the true figure: this estimate is based on a synthesis of information from a large variety of sources. Lighting tends to account for a significantly higher share of residential electricity consumption in non-OECD countries compared to the OECD. Values of 9–84% are reported (Mills, 2002), but an average figure of 32% is derived here.

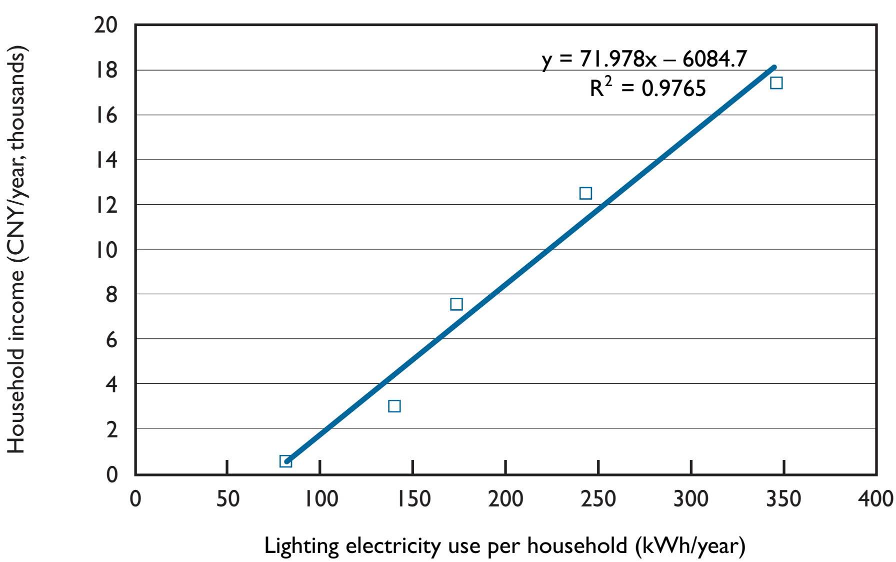
The relative share of fluorescent lighting is often higher than in the OECD or Former Soviet Union and it is not uncommon to find LFLs providing the majority of the light (as is the case in India, the Philippines, etc.). In India most electrified homes have at least four LFLs (Shah, 2004) and national LFL sales are about one-third of total incandescent lamp sales in quantity (Ramaswamy, 2004). In Brazil, incandescent lamps traditionally provided the majority of residential lighting needs, but since the power crisis of 2001 CFLs have been heavily promoted and now occupy a very large share of the residential-lighting market (see the discussion of CFLs on p. 204). In many countries, however, incandescent lamps dominate residential lighting, as they do in much of the OECD.

Residential lighting demand and economic wealth

Various authors have attempted to relate demand for residential-lighting electricity consumption to economic wealth and have concluded that while the relationship exists it explains only part of the variation observed. An analysis by Mills (2002) plotted the relationship between data on household annual lighting electricity consumption and GDP (purchase-power adjusted) per capita for 38 countries and found that a linear fit had an R^2 of only 0.39 (in other words that variations in per-capita wealth explained only a small proportion of the variation in lighting electricity consumption observed). Not surprisingly, better fits can be attained if data within a single country are compared as this removes variations caused by differences in number of hours of darkness, variations in the prevalent lighting technology and cultural factors.

An analysis of a survey of household-lighting electricity consumption in China (ACMR, 2004) suggests that there is a near-linear relationship between average household-lighting electricity consumption and household income (Figure 4.11); however, this type of linear relationship is less likely to hold true as average income levels rise and income becomes less of a constraint on total service provision.

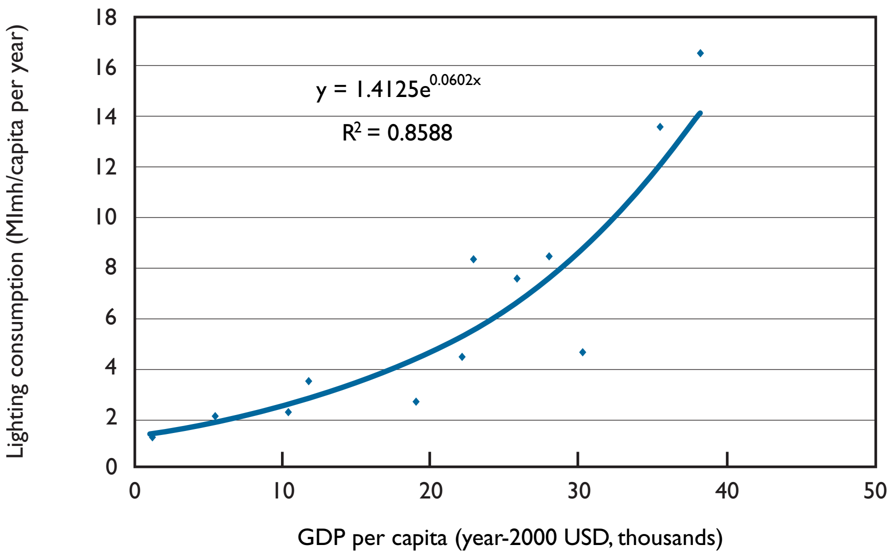
Figure 4.11 **Average annual household-lighting electricity consumption versus income in China**



Source: Retrospective analysis of data in ACMR, 2004.
Abbreviation: CNY = Yuan renminbi.

Interestingly, there appears to be a much better fit in the international data when the per-capita demand for light (expressed as source-lumen-hours) is compared to per-capita GDP (Figure 4.12). From this it would appear that most of the variation in residential light consumption can be explained by an exponential function of per-capita GDP, although important differences still exist between countries. Not surprisingly the relationship is much poorer if the data are expressed as per-capita lighting electricity consumption, but less obviously it is also much worse when GDP is expressed in terms of purchase-power parity.

Figure 4.12 **Average annual residential electric-light consumption* versus GDP****



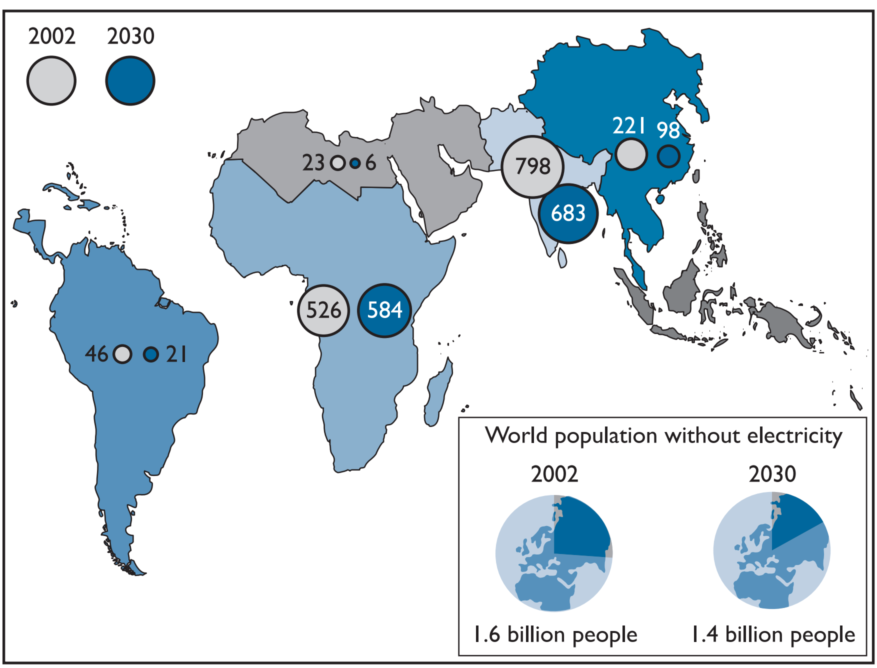
* Source-lumens.
** Data include estimates for 11 IEA member countries and China.
Abbreviations: GDP = gross domestic product; Mlmh = megalumen-hours.

These data tell us that if the average household around the world had lighting with the same efficacy as in Japan, global residential electricity consumption would be one-third of its actual value. By contrast, if all households demanded the same amount of illumination per unit of GDP (normalised via the formula in Figure 4.12) as in Denmark, global residential-lighting consumption would be 45% lower than at present. If demand for illumination per unit GDP were at Danish levels, but with Japanese efficacy levels, global residential-lighting energy consumption would be only 19% of current levels. These striking findings illustrate the very large implications of current practice and the magnitude of variations that exist between communities.

Fuel-based lighting

It is a stark statistic that at 1.6 billion, there are more people in the world with no access to electric light today than was the case when Thomas Edison first popularised the electric light-bulb in the 1880s (Figure 4.13). Roughly 14% of urban households and 49% of rural households in the developing world had no access to electricity in 2000, and in the least privileged parts of Africa only about 1% of households had access to electricity (Mills, 2005a). Many more people have only intermittent electricity supplies and have it either at home or at their place of work, but not both.

Figure 4.13 **Number of people with *no* access to electricity in 2002 and projected number in 2030 if no new measures are implemented**



* *Source:* OECD/IEA, 2004.

Of all the benefits from electrification, light is the most important and the one that all newly electrified households make use of. A simple comparison of the performance of fuel-based light compared to electric light quickly explains why. A basic wick lantern provides roughly 1 lux (1 lm/m^2) at a distance of 1 metre. Typical residential electric lighting will provide about 500 lux (Mills, 2005a). At the light levels routinely found for fuel-based lighting it is possible to make out features and move safely around a space, but it is extremely difficult to effectively conduct visually oriented tasks such as reading and weaving, etc. Furthermore, poor light quality is not the only issue. Fuel-based lighting is expensive, inefficient and the cause of thousands of deaths each year from respiratory and cardiac problems related to poor indoor air quality. Paraffin (kerosene) is the most common fuel used for lighting, but diesel and petrol are also common. Fuel lamps of varying quality and performance are used. At the lowest end, crude vessels hold unpressurised fuel with a wick dipped into it. These produce very low levels of light at extremely low efficacies (e.g. about 8 lm at an efficacy of 0.08 lm/W), which are comparable to or worse than a candle (10 lm at 0.2 lm/W) but will typically burn much longer. More commonly, wick-based hurricane lamps produce about 40 lm of light at an efficacy of 0.11 lm/W. If a pressurised hurricane lamp is used with a mantle, the light output rises to around 400 lm for an efficacy of 0.8 lm/W. The annual operating costs of these lamps are about USD 9, 29 and 76 per lamp, respectively, assuming fuel costs of USD 0.5 per litre and 4 hours of operation per day; thus the wealthier the family the more likely they are to use the pressurised hurricane lamps and vice versa. These costs and performance levels bear no comparison with a grid-connected 60 W incandescent lamp, which will cost as little over the year as the crude wick lamp but produce 100 times more light.

Mills (2005a) has produced global estimates of the amount of energy used to produce fuel-based lighting, as well as its cost and CO_2 emissions. Based on available sources, Mills assumes there are 1.5 billion fuel lamps in use for an average of 4 hours per day, drawing 0.035 litres of fuel per hour. This gives an overall consumption of 77 billion litres (2 800 PJ) of fuel annually for fuel-based lighting, equivalent to 1.3 million barrels of oil per day at an estimated cost of USD 38 billion (USD 77 per household). Given recent global fuel price increases this cost figure is probably conservative. These figures are remarkable on many levels. Despite generally having only a fraction of the wealth of families living in electrified households, families using fuel-based lighting are paying almost as much for their lighting service on a per-capita basis but a much larger share of their disposable income. This is in spite of the delivered lighting service being far poorer. Globally, fuel-based lighting produces about 70 teralumen-hours (Tlmh) of light per annum, which is about 0.5% of the light produced by residential electric lighting. If CO_2 emissions are considered, however, the situation is quite different. Fuel lighting gives rise to 189 Mt of CO_2 emissions, which is about 29% of all residential-lighting (electricity- and fuel-based) emissions and more than all energy-related emissions from the Netherlands.

As if all of this is not bad enough, with current rates of electrification and population growth the number of people living without electricity is projected to be almost as high in 2030 (1.4 billion) as in 2005 (1.6 billion) (WEO, 2004). If this materialises it would constitute another 25 years of light deprivation for almost one-quarter of the world's population. A potential solution to this plight is discussed in Chapter 7.

The use of CFLs in the residential sector

As discussed earlier in this section, the high proportion of incandescent lamps used is the main cause of the poor efficacy of household lighting around the world. Although there are countries where LFLs predominate they are the minority and there appears to be little competition between LFLs and incandescent lighting in those countries where incandescent lighting is common. The best prospect to raise residential-lighting energy performance is therefore to substitute incandescent lamps with CFLs, which do compete head on with incandescent lamps.

The number of CFLs per household appears to be growing in the OECD, albeit at a moderate rate. A review of CFL ownership across the OECD in 1999 estimated that there was an average of 0.8 CFLs per household, with ownership levels ranging from just 0.1 CFL in Australia/New Zealand and North America to 3.2 CFLs in OECD Europe (Table 4.3).

Table 4.3 also shows more recent data, in parentheses, when they are available, and these invariably show higher ownership levels than was the case in 1999. In the United States, for example, average CFL ownership had risen to 0.7 lamps per household by 2001 and today it is likely to be higher still as average annual sales growth rates of 19% are reported for the 2001–2004 period (Nadel and Liu, 2005). In the United Kingdom, CFL ownership rose from 0.7 lamps per household in the late 1990s to about 2 in 2005. In Denmark, ownership increased from 2.4 to about 3.6.

Table 4.3 **Use of CFLs in IEA countries***

Country	No. of households (millions)	Proportion of households with ⩾CFL (%)	CFLs in use (millions)	Average no. of CFLs per household owning a CFL	Average no. of CFLs per household for all households	Average no. of lamps per household
Australia	6.7	12	0.8	1.0	0.1	15
Austria	3.2	27	2.6	3.0	0.8	30
Belgium	4.0	29	4.3	3.7	1.1	31
Canada	10.6	5	0.5	1.0	0.1	27
Czech Republic	n/a	n/a	n/a	n/a	n/a	n/a
Denmark	2.5	56 (71)	5.9	4.2	2.4 (3.6)	26 (24)
Finland	2.4	n/a	n/a	1.0	n/a	n/a
France	34.0	26	4.5	1.9	0.5	n/a (18)
Germany	37.5	53	86.0	4.3	2.3 (2.2)	28
Greece	4.0	4 (26)	0.3	2.0	0.1 (0.6)	14 (10)
Hungary	n/a	20	n/a	n/a	n/a	n/a
Iceland	0.09	50	0.09	2.0	1.0	20
Ireland	1.4	21	0.6	2.0	0.4	20
Italy	19.9	55 (67)	21.8	2.0	1.1 (1.8)	20 (14)
Japan	40.8	100	40.8	1.0	1.0 (1.4)	21 (17)
Luxembourg	n/a	n/a	n/a	n/a	n/a	n/a
Netherlands	6.5	60	15.6	4.0	2.4	36
New Zealand	1.2	8	0.2	1.5	0.1	23 (18–23)
Norway	1.3	77	n/a	n/a	n/a	35
Portugal	4.9	n/a (50)	n/a	n/a	n/a	n/a (7)
Spain	10.0	15	6.0	4.0	0.6	15
Sweden	4.1	10	1.6	4.0	0.4 (1.4)	40
Switzerland	3.4	75	11.0	4.3	3.2	n/a
Turkey	n/a	n/a	n/a	n/a	n/a	n/a
United Kingdom	24.5	23 (20)	16.8	3.0	0.7 (0.7; 2.0)	20
United States	100.0	12	14.4	1.2	0.1 (0.7)	30 (43)
IEA	**323.0**	**33**	**246**	**2.2**	**0.8**	**25**

Source: Kofod, 1999.
* Figures in parentheses present alternative data: Denmark (EURECO, 2002), Greece (EURECO, 2002), Italy (EURECO, 2002), Germany (Palmer and Boardman, 1998), Japan (JELMA, 2005), New Zealand (Bishop *et al.*, 1998), Portugal (EURECO, 2002), Sweden (Palmer and Boardman, 1998), United Kingdom (DEFRA, 2005; Palmer and Boardman, 1998), United States (Navigant, 2002).
Abbreviations: CFL = compact fluorescent lamp; n/a = not available.

Despite these encouraging signs the number of CFLs installed is far below that of incandescent lamps and there is plenty of scope for higher penetration. Interestingly, CFL ownership as a proportion of total installed residential lighting is sometimes significantly higher among non-OECD countries. In China, of an average of 6.7 lamps per household, 1.5 (23%) were reported to be CFLs in 2003 (ACMR, 2004). In Brazil, precise ownership figures are not available, but CFL sales averaged 24% of incandescent lamp sales by volume from 2000 to 2004.[5] If it is assumed that 90% of the incandescent lamps and 75% of the CFLs were destined for the residential sector and that the average CFL lasts six times as long as the average incandescent lamp, by the end of 2004 there should have been about as many CFLs per household as incandescent lamps on average.

The number of installed lamps per lamp type is not necessarily representative of the overall proportion of lighting by lamp type as some studies have found that energy-saving lamps such as CFLs are predominately deployed in those sockets with higher than average lighting use and hence account for a disproportionately high share of the total lighting load. For example, the EURECO (2002) study found that across four EU countries CFLs were operated for about 60% longer on average each year than other installed lamps.

Residential lighting: situational analysis

Residential lighting poses unique problems for lighting energy efficiency. First, houses are often built and let to tenants without lighting systems installed. The choice of lighting systems or fittings is therefore often made by the house occupant after the construction (or letting) process is complete. In addition, movable lighting sources (lamps) typically form an important component of total lighting use in the residential sector. For this reason, and unlike in the commercial-building sector, building energy codes virtually never prescribe maximum lighting energy requirements for residential housing.[6] In those cases where builders or landlords do install lighting systems, they are free to do so without any regulatory guidance on energy efficiency (or lighting quality, for that matter). Since the builder or landlord will generally not occupy the building or pay the energy bills

5. G. Januzzi, Associate Professor, State University of Campinas, São Paulo, Brazil, personal communication, 2005.
6. The United Kingdom is the only IEA country to prescribe maximum lighting energy requirements in the residential sector. California also imposes requirements.

associated with the lighting system, they have no incentive to install energy-efficient systems. Rather, their incentive is to minimise "first cost", or the capital cost of the lighting system, and this generally leads to the least efficient systems being installed.

In other cases, builders or landlords may install light fittings but not bulbs (or lamps). In this situation, the nature of the fitting itself may determine what kind of bulb can then be installed. Recessed fittings, for example, may not be suitable for CFLs (which may be too bulky or long), and conventional bayonet or screw fittings may preclude the use of LFLs. Over time, if not upon initial purchase or lease, the house occupant will make the key decisions on lighting systems, such as the choice of bulb. As a result, and again unlike in the commercial sector, residential lighting systems rarely benefit from the services of a professional lighting designer. The highly decentralised nature of decision-making in this sector has direct consequences for the design of energy-efficiency policy.

Retailers of bulbs and lighting systems have a significant influence over householder choice of lighting systems. Light-bulbs and lamps suitable for residential applications are readily available in a wide range of retail outlets, ranging from grocery stores, corner shops, large department stores and specialty lighting stores, to appliance or building-supply stores. However, the European Union's Action for Training in Land Use and Sustainability (ATLAS) project estimates that 40% of all general lighting sources are purchased from supermarkets (European Commission, n.d.). CFLs are beginning to be displayed more prominently in retail outlets, including supermarkets, although still much less so than incandescent bulbs. Halogen lamps and LFLs are more normally sold in lighting, appliance or building-supply stores. Except during the construction or renovation of residential buildings, the individual owner or tenant undertakes the purchase and maintenance individually, although in multi-family dwellings, a building management company is often responsible for the purchase and maintenance of lamps in common areas.

Lighting energy demand in the residential sector is also affected by occupancy patterns and lifestyle factors, which interact with the characteristics, including costs, of different lighting technologies. In living-rooms, people generally like to be able to dim lights, and some of the most energy-efficient lighting sources, such as LFLs and CFLs, are not generally dimmable (at least, the versions of these technologies sold on residential markets are not). By contrast, LFLs and CFLs are more likely to be found in kitchens, bathrooms and outdoors, where dimming is not usually demanded and bright light is preferred.

A significant trend in many IEA countries, consistent with the wider trend towards investment in home decorating, is to install "mood lighting" and spotlighting (for architectural features or artworks) systems. These systems may lead to a greater number of lamps per home and also to a preference for less efficient lighting types (such as low-voltage halogens for spotlighting and dimmable high-voltage halogens or incandescent lamps for mood lighting). At the same time, both CFLs and LFLs are available with dimming and can be used, with appropriate light fittings, for both mood and spotlighting.

The colour characteristics of lighting (often measured by the "colour temperature" of a lamp in degrees Kelvin; see pp. 105–107) may also be an important choice factor in the residential sector. Where a mood-lighting effect is sought, warm colour tints (yellow, orange) are preferred to colder colour tints (blue, white) in many, but not all, OECD homes. Traditionally incandescent lighting more easily reproduced these warmer tones, whereas early-generation fluorescent lighting was often noticeably tinted blue or white. However, modern fluorescent lamps are available in a broad range of colour temperatures and may even be labelled to allow customers to choose the colour they wish, but it may be that some consumers were "turned off" fluorescent lighting for this reason and have therefore not tried more modern products.

It is not only the lamps that determine the efficiency of residential-lighting energy systems: the choice of luminaire, or light fitting, can also be critical. Certain luminaires or light fittings are only suitable for use with a specific lamp or bulb. To a certain degree, CFLs can be interchanged with incandescent bulbs (indeed, they were designed precisely for this market niche; see Box 4.1, for example), but fittings for tubular fluorescent lamps and most halogen lamps are specific to those lamp types. Thus, once a householder selects a light fitting – which they may do without any knowledge of the energy efficiency of the lamp that will eventually be required for this fitting – the efficiency of the lamps used in that fitting tend to be locked in for the life of the fitting. As shown on pp. 309–345, many countries now require that lamps be labelled for their energy efficiency. However, the key decision may be the initial choice of a light fitting, and light fittings are not labelled in any IEA country. Therefore the consumer can be "trapped" into purchasing less efficient lamps for long periods. This is a policy design gap that policy makers could rectify.

Depending on the intended location, the aesthetic appearance of luminaires or light fittings is often a more important factor than their functionality or cost-effectiveness in the household sector. Early CFLs, while compact when compared with tubular fluorescent lamps, were still more bulky than the incandescent lamps they were designed to displace.

With most residential light fittings having been designed over many decades to fit the highly standardised dimensions of incandescent bulbs, the additional length and bulk of CFLs acted as a significant disincentive for residential buyers. This illustrates a kind of "path dependence" that often acts as a barrier to the entry of new, more efficient technologies.

The lighting industry and the efficiency-policy community together have had at least two important responses to this problem. First, in early 1998, the US Department of Energy successfully undertook a major "market transformation" exercise to help develop and market "subcompact fluorescent lamps", which would be smaller, lighter and less expensive than the then-existing CFLs (see Box 4.1). Second, the European Union recognised the problem of the lack of availability of suitable and attractive light fittings for CFLs and other high-efficiency light sources, and therefore established in 1999 the European Design Competition "Lights of the Future" to procure such fittings. This initiative is described on p. 371.

Box 4.1 Case study: The US Sub CFL Programme

In 1998, the US DOE launched its Subcompact Fluorescent Lamp Program to accelerate the introduction of a new generation of smaller, brighter and less expensive CFLs. The programme was based on technology procurement in order to induce manufacturers to develop and sell new CFLs, based on specifications developed in co-operation with the multi-family housing industry. The specific goals were: to induce at least two manufacturers to commercialise new CFLs; to have new CFLs developed that are less than five inches (12.5 cm) long; to reduce retail prices significantly below the then-current USD 15–22; and to achieve sales of at least 1 million units. These goals were developed on the basis of market research and the analysis of market barriers. Both the cost and size of CFLs were identified as major constraints to their expanded deployment.

The DOE decided on a technology procurement approach because: new products were needed in the marketplace to address the identified market need; aggressive pricing was needed to make the new products attractive to the identified market; the technical change needed to meet the size requirements was relatively modest; and the multi-family industry expressed strong interest in the approach. Key design requirements were developed, the main actors participated (although some were not engaged early enough, as later analysis discovered) and a request for proposals was solicited to potential suppliers. The programme was divided into two phases. The first, for five months, was to test the logistical operation of the programme and to test market reaction to products offered. It used products already on the market. The second phase, lasting 24 months, allowed suppliers to develop new-to-market products.

Three companies were chosen for phase 1 and five for phase 2. The DOE funded technical research, market research, interaction with potential buyers and manufacturers, development of technical specifications, request for proposals (RFP) development and issuance, award evaluation, CFL performance testing and promotion. The budget was a modest USD 342 000. There was no budget for subsidising the CFLs sold.

Results were positive. Sixteen new lamp models were introduced onto the market, two 15 W CFLs achieved a size less than five inches, prices were reduced to between USD 4.95 and USD 8.20, and more than 1.5 million CFLs were sold by August 2000.

Source: Ledbetter, 2001.

A final characteristic of the residential-lighting market is that lighting controls and sensors are much less widely used than in the commercial sector (where the penetration of these technologies is still relatively low). For exterior lighting, motion sensors have become reasonably commonplace, but for interior lighting, very few motion or infrared detectors, light-sensitive dimmers, time-lapse switches or other control devices are used. In part, this can be explained by the lower number of running hours of a typical household lamp when compared with commercial applications. However, with the performance of such controls continuing to improve and their costs falling, there may be significant opportunities to transfer this technology into the residential sector.[7]

Furthermore, there is a moving target in the sense that households, for example, are increasing the number of lamps they use. There are many more mood and task lights than there were a decade or two ago. In home remodelling, there is also a move towards more recessed lighting, often using low-voltage halogens. Thus, achieving the cost-effective potential requires a thorough, comprehensive strategy that factors in changes in consumer behaviour. For example, giving away one CFL to a household that has added ten new lamps in the past year is really going to have only a limited impact.

Commercial sector

Globally, an estimated 1 133 TWh of final electricity was consumed by commercial lighting[8] in 2005, amounting to about 43% of total lighting electricity consumption and just over 30% of total electricity consumption in the commercial sector. This produced 59.5 Plmh of light at an average source-lumen efficacy of 52.5 lm/W. This is far higher than for residential lighting but not as high as for outdoor stationary lighting. In addition, a significant proportion of the source-lumens serve no useful purpose because of: absorption in luminaires (expressed through the LOR), room losses (expressed through the CU) and delivery of light to either empty spaces or spaces where there is already adequate daylight. Unfortunately, these loss factors cannot be easily quantified because there is a lack of statistically representative data; however, it is clear that only a small proportion of source-lumens make a useful contribution to overall illumination in the commercial sector, albeit that the CU and LOR values are generally significantly higher than in the residential sector. Commercial lighting is thus the most important lighting end-use in terms of energy use and light output and is of intermediate efficiency compared with the other sectors.

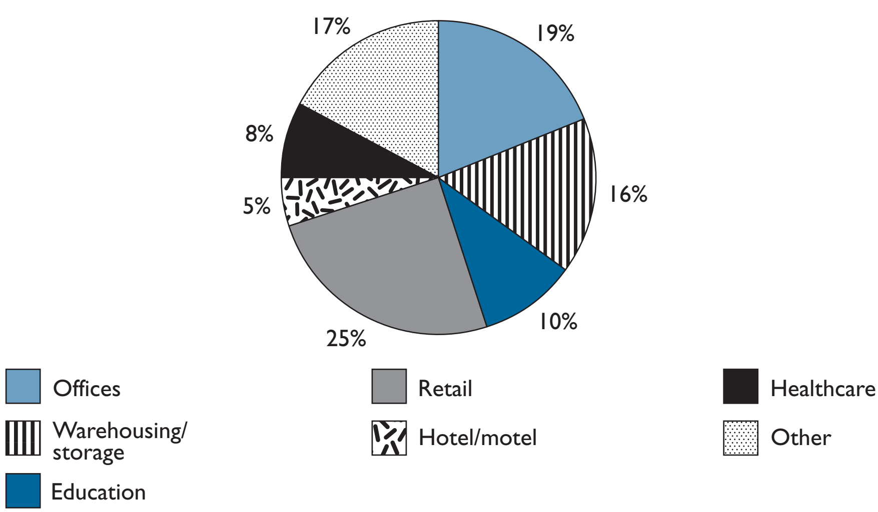
7. See pp. 141–148..
8. Includes lighting for commercial- and public-sector buildings but not street or other outdoor lighting.

There are few recent analyses of the breakdown of energy consumption in the commercial sector. A report by the IEA Centre for the Analysis and Dissemination of Demonstrated Energy Technologies (CADDET) estimates that lighting represents 45% of electricity consumption in commercial buildings, followed by 34% for office equipment, 7% for ventilation and pumping, 6% for air-conditioning, 5% for domestic use and 2% for humidifying (CADDET Energy Efficiency, 1995).

The requirement for lighting and the total lighting energy consumption varies from one type of building to another, in part because of different occupancy patterns. For example, buildings that operate 24 hours per day, seven days per week, such as hospitals, some shopping centres and hotels, have much higher lighting energy demands. The largest users are retail, offices, warehousing and educational services, which collectively account for 70% of commercial-lighting energy use (Figure 4.14).

The lighting energy intensity also shows important variation depending on the building type. The estimated global average lighting intensity in 2005 was 32.5 kWh/m² per year, but this varies from a low of 25.2 kWh/m² for

Figure 4.14 **Estimated global lighting energy consumption* by commercial-building type in 2005**



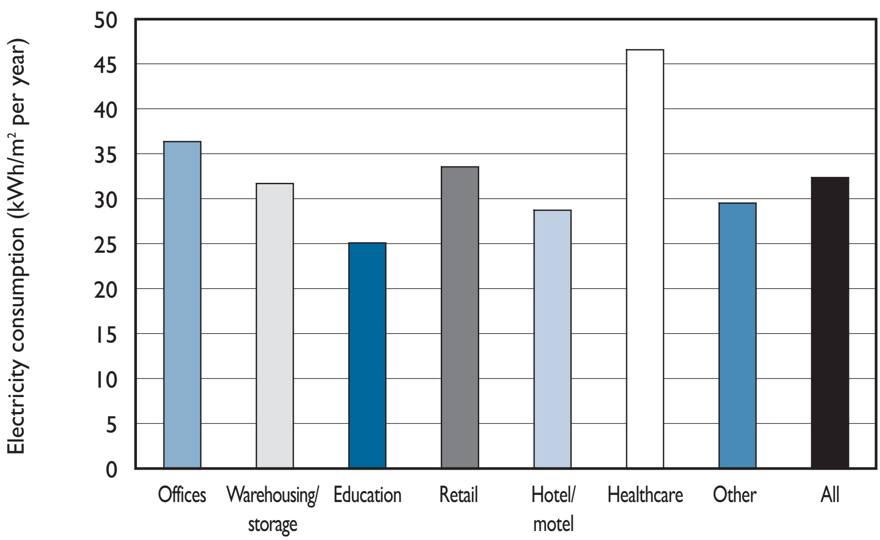
* Total = 1 133 TWh.

educational buildings to a high of 46.7 kWh/m2 for healthcare buildings (Figure 4.15). These results illustrate the importance that occupancy levels have on building lighting energy consumption.

The commercial sector demonstrates a different usage pattern for lights. While incandescent bulbs are popular, they are much less so than in the residential sector. Fluorescent lights are much more common in offices, retail outlets, schools and other facilities where there are large, open spaces for work or shopping. CFLs are gaining market share and in 1998 301 million were sold for commercial use in Western Europe, followed by 262 million in North America and 109 million in Japan (OECD/IEA, 2003).

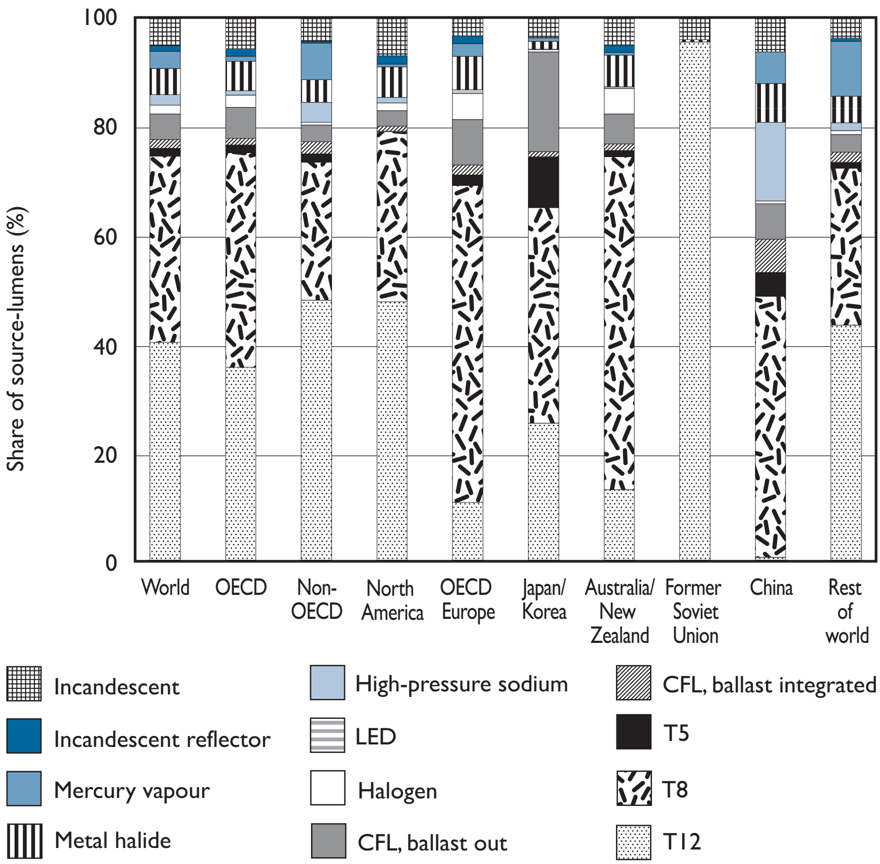
The estimated share of light emitted by each source in 2005 in the commercial sector is shown in Figure 4.16 for the world and for each modelled region. While there is considerable similarity in the mix of commercial-sector illumination provided by light source in each region, there are also important differences, resulting in significant variations in average efficacy, as discussed in the next subsection.

Figure 4.15 **Estimated global lighting energy intensity* by commercial-building type in 2005**



* Average.

Figure 4.16 Estimated regional share of light output by source in the commercial-building sector in 2005



* Total = 59.5 Plmh.
Abbreviations: CFL = compact fluorescent lamp; LED = light-emitting diode.

Commercial lighting: situational analysis

With lighting accounting for such a high share of electricity consumption in the commercial and public sectors, the energy-efficient lighting market is more developed. The purchasing of lights and lighting systems is quite different to the practice followed in the residential sector. During the construction phase, there are often lighting experts within architectural firms who design the systems. Lighting design experts are also frequently used during the renovation of buildings. Manufacturers of lights also provide advice and consulting services on the most appropriate lighting for the given function. Unlike most of the residential sector, the commercial and public sectors have a much higher percentage of fixed, installed lighting. This means that "energy efficiency" can be built in from the beginning through the appropriate types of fixtures, ballasts and controls. Unfortunately, too often the builders or developers of buildings are not their users and have no incentive to provide best-practice solutions since they do not pay for lighting energy consumption. The owner or developer is usually interested in lower initial building costs. While these practices have been an issue for decades, they continue to affect the deployment of best-practice solutions.

Commercial buildings use fluorescent lamps more than the residential sector and the type of ballast used with the fluorescent lamp and the luminaire can have a significant effect on efficiency. Pages 107–157 describe the various lighting technologies that are being used in the commercial and service sectors.

Different spaces require different lighting demand and illuminance levels. For instance, some spaces must be lit throughout the entire business day while others are needed only for certain periods. Normally, for example, corridors are illuminated constantly while offices may not be. Workspaces can benefit from both overhead ceiling lights and specific task lights. Because of the cost of lighting in the commercial sector, the use of control systems is more prominent although still mostly underdeveloped. CADDET estimates that lighting energy consumption can be reduced by 30–50% through the implementation of control systems (CADDET Energy Efficiency, 1995). Controls are often integrated into building energy management systems (BEMS), which also control heat, air-conditioning and so on. Energy consumption can also be reduced significantly through the use of daylight. In most economies there are specialised control or BEMS service companies which install and manage controls that are either specific to lighting or also have integrated control of the heating, ventilation and air-conditioning (HVAC) systems. In some cases the service is provided by an energy service company (ESCO), which provides a complete technical and financial package for lighting and other energy services and will typically share the profits from the resulting reduction in energy use.

The size of a business affects, in part, who undertakes the purchase, installation and maintenance of lighting systems. In small businesses, the owners may undertake the maintenance (purchase and replacement, in particular, but not repair) themselves. However, in medium-sized and large businesses, the installation and maintenance can be undertaken in-house through a maintenance group and in large companies the work can be undertaken by specialty lighting or maintenance companies. A survey (CIBEUS) of the use of lighting controls in the larger Canadian cities (NRC, 2002) (Table 4.4) raises some interesting issues for policy-makers. The data seem to suggest that in smaller commercial buildings very little is being done to adopt efficient lighting technology, but in larger buildings there is a much higher chance that at least one energy-saving technology will have been deployed. Unfortunately it is not possible to analyse the deployment rates on a normalised per unit area basis, but it would be consistent with findings in other countries were the small and medium-sized enterprises (SMEs) to be lagging in the adoption of efficient-lighting solutions. Whether this is because small businesses have the owner undertake most of the maintenance or whether owners perceive their lighting costs to be too small a share of total costs to bother about, is difficult to know. SMEs have been a problem for most energy-efficiency concerns, not just those related to lighting.

Table 4.4 **Use of lighting-conservation control measures in Canadian buildings in 2000**

Lighting-conservation features	Share of total floor area with lighting feature (%)
Reflectors	38.2
Energy-efficient ballast	67.2
Daylight controls	17.6
Occupancy sensors	17.0
Time clocks	40.6
Manual dimmer switches	36.0
Energy-efficient lamps	59.5
Other	12.4

Source: NRC, 2002.

In the commercial and industrial sectors, and at least in premium buildings, lighting systems are generally chosen and managed with a more careful eye to the economics, as well as with regard to the productivity and welfare impacts on the building occupants. Also unlike the residential sector, many countries apply minimum energy performance requirements for lighting in commercial buildings (pp. 345–365). Therefore, with the natural turnover of building fit-outs, worst lighting practices are often being upgraded over time. However, premium buildings such as corporate headquarters and downtown office blocks comprise a small share of the total building stock. Analysis in some IEA member countries shows that energy-efficient lighting is deployed in well under half of commercial buildings, and the figure may be lower elsewhere. Issues include: low-quality systems installed in non-premium, industrial or small retail buildings; high consumption in display lighting; the relatively poor diffusion of advanced lighting controls, sensors and other automation systems; and poor arrangements for switching (whole buildings or floors on one switch). Inefficient lighting is also a major source of internal heat load, meaning that additional energy must be expended to remove waste heat from lighting through the building's cooling and ventilation system.

The nature of the commercial-building market poses significant challenges for energy-efficient lighting. Short lease terms – notably for retail buildings – may not allow sufficient payback time on more efficient equipment. In addition, tenants may have little or no control over lighting systems, which are installed by the building owner or manager. In other cases, the electricity costs associated with lighting may be rolled up into an overall monthly leasing charge, removing any incentive for the tenant to install efficient lighting. Submetering systems that allow tenants to know the direct cost of their lighting systems are rare. Finally, commercial and industrial lighting may also suffer from the same problem observed for residential lighting: the perception that the costs are too small to worry about, combined with a lack of awareness of the high cost-effectiveness of the energy-savings alternatives.

Within the regulatory environment, key issues include the stringency of overall power density requirements (the installed lighting system's power requirements per unit area, expressed in watts per square metre, or per square foot in the United States) and the nature of general lighting requirements (which may require high and/or uniform levels of illumination, even though this may lead to over-lighting of infrequently used or "non-critical" areas of buildings and may pose a regulatory barrier to the use of daylight). Few building codes demand automation systems or optimal use of available daylight, and not all codes require zonal or individual luminaire switching. It has been demonstrated, for example, that switching or automation systems based on a "manual on, automatic off" logic are highly effective in saving energy, particularly where daylight is available and where lights are gradually dimmed rather than abruptly switched. Also, many countries have minimum energy performance requirements applying to ballasts, or to lamps, but not to whole luminaires (lamp, ballast and fitting), even though the performance of each component of this system, together with the integration of the components into the whole luminaire and the luminaire into the building, is relevant to the total energy consumption per unit of useful light output at the working plane. Furthermore, many IEA and non-IEA economies still set very few or no requirements for lamp efficacy and ballast performance.

Commercial-lighting characteristics in IEA countries

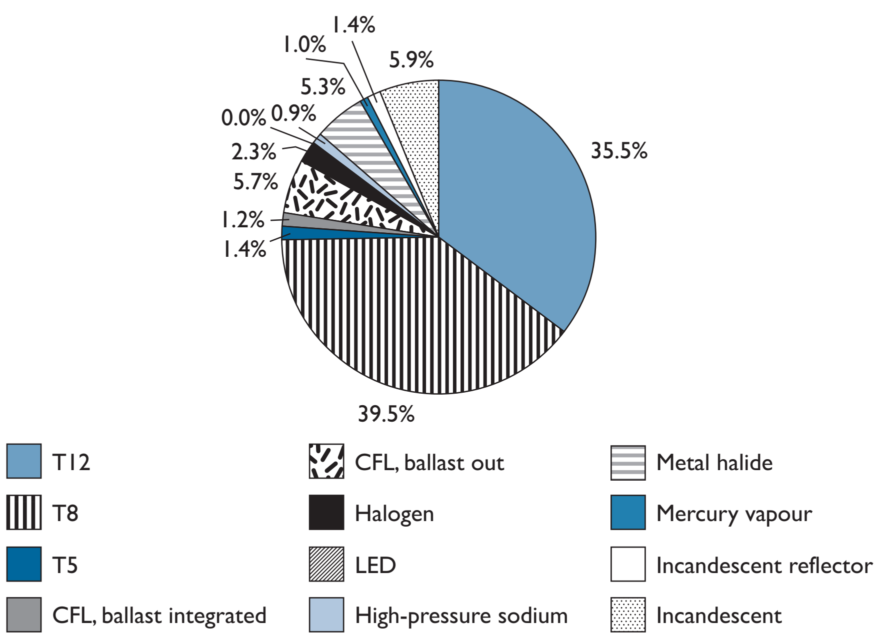
An estimated 710 TWh of electricity was used for commercial lighting in IEA countries in 2005, comprising about 63% of the world's total in this sector and 28.3% of total OECD commercial-building electricity consumption. It is projected that lighting electricity consumption in this sector is little changed since 1995, having increased by a mere 2%, largely because of ongoing efficiency improvements, which are discussed on pp. 398–406. This light is used to illuminate 17.6 billion square metres of floor area, collectively generating added value of about USD 19.4 trillion (USD 1 100 per square metre) each year. The lighting energy intensity in 2005 is estimated to be 41.1 kWh per square metre per annum, which is 27% higher than the global average. OECD lighting intensities are higher than the world average for all commercial-building types, especially for the retail sector and offices.

The cost of the light provided averages about USD 5.3 per square metre per annum or some USD 93 billion for the OECD as a whole; electricity costs contribute 60% of the total and the remaining 40% is attributed to the cost of the lighting equipment (lamps, luminaires, ballasts and controls), installation and maintenance labour. The average cost of delivered light is USD 2.5/Mlmh but local costs can vary significantly from this depending on tariffs and lighting-system efficiency. In almost all cases the highest-efficiency lighting systems have the lowest life-cycle costs; thus, raising commercial-sector lighting efficiency almost always makes sense in economic terms.

Light sources, lighting power density and efficacy

The large majority of the light delivered in the commercial sector is produced by fluorescent lamps, particularly LFLs, which account for 76.5% of the total (Figure 4.17). The share of light produced by LFLs in the commercial sector is very similar in all OECD regions; thus, the main factor explaining efficacy variations are differences in the choice of LFL technology and the associated average ballast characteristics. The remaining 23.5% of the delivered light is supplied by a mixture of incandescent, compact fluorescent and HID lamps. CFLs, of which the separate ballast and tube types predominate, account for 7%, but standard incandescent lamps including reflector lamps supply slightly more at 7.2%. HID lamps and particularly metal halide lamps also supply 7.2%, while halogen lamps account for the remaining 2.2%. These figures are very revealing because the most efficient lighting technologies, T5 LFLs, metal halide and high-pressure sodium lamps, only provide 7.7% of the delivered light. A relatively small proportion of the T8 lamps are also of the high-efficiency triphosphor variety, but the rest of the light sources have been superseded by more efficient options. As a consequence the average efficacy of commercial lighting in the OECD including ballast losses is 51 lm/W. This is twice as high as the residential sector but about 45% lower than what would be achievable from using the best fluorescent systems.

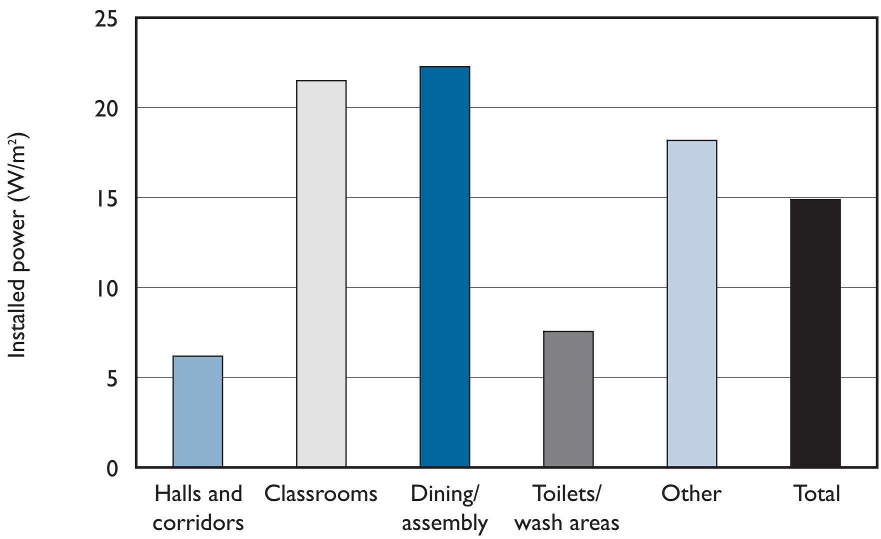
Figure 4.17 **Estimated light output by source in OECD commercial buildings in 2005**



* Total = 37.5 Plmh.
Abbreviations: CFL = compact fluorescent lamp; LED = light-emitting diode.

The consumption and make-up of the lighting systems is strongly related to the lighting demands of the type of space being illuminated. For example, Figure 4.18 shows the estimated average installed power of the lighting systems by type of floor space in the North American education sector in 2005. From this it is clear that spaces with lower illuminance requirements, such as corridors and wash areas, tend to have lower installed-lighting loads than those with higher illumination needs, such as classrooms; however, these average figures mask a wide degree of variation from site to site. Naturally there is also wide variation between different types of buildings.

Figure 4.18 **Estimated power* of installed lighting systems in North American educational buildings by type of space**



* Average, in 2005.

Table 4.5 shows the findings of a survey of lighting conducted in 1 583 commercial buildings in California in 1995. The average installed lighting-circuit power (lighting power density) was 15.8 W/m², but this varied from a low of 10.8 W/m² for warehouses to a high of 22.8 W/m² for restaurants. The average efficacy was 52 lm/W and ranged from a low of 25 lm/W for lodgings to 61 lm/W for schools. There was a pronounced spread in the distribution of installed lighting power densities within each building class. The buildings in the upper 90th percentile used 19% more power per unit area than the average and 43% more than those in the lower 90th percentile.

Table 4.5 Lighting characteristics of commercial buildings in California in 1995*

Building type	No. of premises	Total area (m^2, 1 000s)	Daily operating hours (FTE)	Average efficacy (lm/W)	Illuminance (lux)	Lighting power densities (W/m^2) Average	Lower 90th	Upper 90th	If efficacy were 85 lm/W
Small office	344	468	7.6	56	886	15.8	14.6	16.9	10.4
Large office	100	1 752	9.7	54	872	16.1	13.8	18.5	10.3
Restaurant	198	77	12.3	41	915	22.6	16.4	28.7	14.1
Retail	339	959	9.3	50	753	15.1	12.6	17.5	8.9
Grocery	104	148	17.3	60	1 104	18.4	17.0	19.8	13.0
Warehouse	114	596	7.4	59	629	10.8	8.2	13.5	7.4
School	33	150	6.6	61	1 063	17.4	15.4	19.5	12.5
Health	102	278	7.6	51	840	16.5	12.4	20.6	9.9
Lodging	30	262	18.0	26	453	17.8	14.6	20.9	7.0
Miscellaneous	219	365	8.3	46	871	18.9	14.1	23.8	10.2
Total	1 583	5 055	9.5	52	819	15.8	13.1	18.7	9.5

* Retrospective analysis of CEUS database reported in HMG, 1999c.
Abbreviation: FTE = full-time equivalent.

These data, although a decade old, reveal myriad routes by which a substantial amount of lighting energy could be saved and which are typical of this sector in the OECD. First, using more efficient lamps and control gear to raise the overall efficacy to 85 lm/W would have cut the average installed power density to just 9.5 W/m^2, a saving of 39% (see the last column in Table 4.5). The most efficient fluorescent-lighting systems can attain 95–100 lm/W, so this is far from an impractical target. Second, at a floor-area weighted-average level of 819 lux the installed illuminance in the California sample appears to be appreciably greater than (about twice as high) the Illuminating Engineers Society of North America (IESNA) recommended values (see Tables 2.4 and 2.5 in pp. 92–93). Lowering the values to match the IESNA values would have saved about 50% of the total lighting demand. Third, the number of full-time equivalent operating hours averaged 9.5 hours per day, or some 3 483 hours per year. This is the equivalent of all the lights being activated for 40% of the year. Considering typical working hours and the high coincidence of working hours with daylight, this figure suggests that a large proportion of lighting was left switched on when there are no occupants and that little use was being made of daylight to offset electric lighting.

Applying some rough rules of thumb to assess the savings potential from the deployment of best-practice lighting to this sample of buildings (assuming high-efficacy lighting, correct sizing to attain the recommended illuminance levels and proper lighting control[9]) gives an estimated savings potential of 84%. The sample discussed had an average annual lighting energy intensity of 151 kWh/m^2 per year while the best-practice case would require just 25 kWh/m^2.

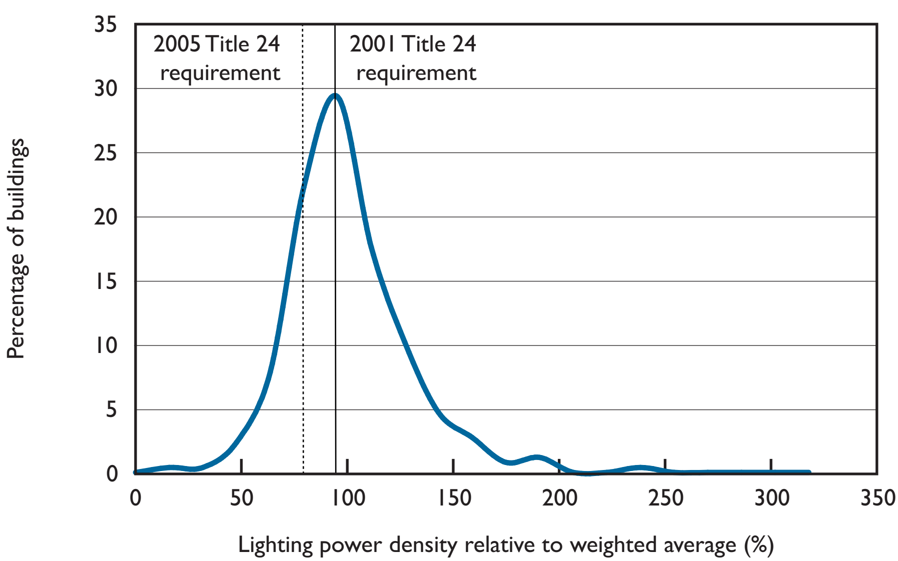
The Californian building sample figures for installed lighting power appear to be fairly typical of the United States as a whole and not unrepresentative of the OECD at large. Based on a synthesis of the available sources, and most notably the Navigant 2002 study, the average US commercial building had a lighting power density of 17.4 W/m^2 in 2000, while the figure for the average European commercial building was about 15.5 W/m^2. In Japan the estimated values are a little lower at about 13 W/m^2, although there is even less certainty for these values than in the previous two regions. Estimated values for Australia/New Zealand are slightly greater at 16.5 W/m^2, although here again there is considerable uncertainty. The regional variation in these estimates is almost certainly within the margin of error of the available data-sources and thus should be considered as indicative; however, it is based on assessments of available data. Of all the regions, the US data are comfortably the most comprehensive, but even here there are outstanding questions about the reliability of all the figures. This once again stresses the importance of gathering good end-use data for successful policy analysis and design.

Overall, it appears there is a considerable homogeneity in installed-lighting loads in OECD commercial buildings, at least at the aggregate level. However, there is great variation between otherwise similar buildings in any given sample. Figure 4.19 illustrates this point. It shows the normalised distribution of lighting power densities from a survey of 256 offices in California (HMG, 1999c). The average value is 5% higher than the requirements set in the 2001 Title 24 state building codes for new and retrofit buildings and 20% higher

9. This assumes that average full-time equivalent operating hours can be lowered to 5.2 hours per day by using lighting controls (manual switching, occupancy sensors, time switches and daylight dimming), that average lighting-system efficacy is 85 lm/W and that floor area weighted-average illuminance is 400 lux.

than the new requirements in the October 2005 revision of the code. This is to be expected because the codes are more recent than the lighting systems in the sample of buildings surveyed. What is more revealing is the large spread between the lowest and highest values. The lowest is 16% of the average and the highest 2.4 times the average, while between the two extremes there is a 15-fold difference. Similar divergence ranges are found in surveys such as this around the world. Lighting power density is a poor measure of lighting quality, but lighting energy consumption is usually roughly proportional to it,[10] thus these findings imply there is a vast difference in the energy used for lighting per unit area between different buildings with similar primary functions. However, the installed lighting power density is only one measure of the lighting-system characteristics. For example, variations in delivered light levels and system efficacy can cancel each other out to produce a similar installed lighting power density. Furthermore, there appears to be significant regional variation in the average lighting power density observed between types of buildings.

Figure 4.19 **Normalised lighting power density distribution for a sample of Californian offices**



10. This is an apparently self-evident conclusion, but in fact it need not be because there are many spaces with multiple light sources and hence it is not necessary to activate all light sources to provide some illumination.

The United States, Canada and some European countries aside, there is a dearth of good publicly available data on many of the key statistics pertaining to lighting energy use in the commercial sector. This is remarkable when one considers how much energy is used in providing this service. Regrettably, the majority of OECD countries have failed to establish and maintain reliable data-sets on this topic despite the high public-policy interest in economising lighting energy use. As a result a great many assumptions have to be made to try to characterise current practice, and a mixture of data-sources, including anecdotal ones, have been applied to make the existing estimates. With these caveats noted, the estimated average efficacy of commercial-sector lighting by region is shown in Table 4.6 for the year 2000.

Table 4.6 Estimated average lighting characteristics of commercial buildings in the OECD* in 2000

Region	Average lighting power density (W/m²)	Specific energy use (kWh/m²)	Average annual operating period (FTE; hours)	Lighting system efficacy (lm/W)	Commercial building floor area (billion m²)	Total electricity consumption (TWh/year)
Japan/Korea	12.6	33.0	2 583	62.7	1.7	54.6
Australia/NZ	16.5	31.7	1 924	43.5	0.4	12.7
North America	17.4	59.4	3 928	50.1	7.3	435.1
OECD Europe	15.5	27.7	1 781	46.1	6.7	185.8
OECD	15.6	43.1	2 867	49.6	16.1	688.2

* More data are available for the North American and European regions than for the others and hence there is greater confidence in these estimates. Data in other regions are based in part on an evaluation of lamp sales data rather than comprehensive market-characterisation studies.
Abbreviations: FTE = full-time equivalent; NZ = New Zealand.

Factors influencing efficacy

Interestingly, there is an almost identical share of LFL lighting by region across the OECD; however, differences in average efficacy occur because of variations in the relative use of CFLs, HID lighting and various incandescent light sources, and because of significant differences in the average efficacy of LFL technology and control gear used in the various regions. From this analysis it appears that the commercial lighting sector in Japan has the highest efficacy of all OECD regions, but this is not because of the use of particularly efficient LFLs, as there is still a high proportion of less efficient T12 lamps in use; rather, it is related to the very low usage of incandescent and halogen sources. The average efficacy of commercial lighting in IEA North America is lower than in Japan but slightly above that in OECD Europe for rather complex reasons, as discussed in the next subsection.

LFL efficacy and ballast performance in OECD countries

With the exception of some regulations for LFL ballasts and some national building code requirements, Europe has taken a rather *laissez-faire* attitude to commercial-lighting regulations thus far (discussed in more detail on pp. 309–365). The United States and Canada by contrast have introduced regulations at both the system and lamp levels that have obliged efficacy improvements in specific lighting product types. The rationale behind these regulatory stances is explained in part by the natural market development of LFLs in the two regions. Europe, most of Asia, Africa, the Middle East, Australia/New Zealand and Latin America operate their electricity networks at 220–240 V, 50 Hz, which naturally favours the adoption of T8 lamps at the expense of T12s. This is because in 220–250 V, 50 Hz systems T8s fit directly into older T12 fixtures and hence it is not necessary to replace the fixture when switching over to T8s. By contrast, in Japan, North America and parts of Brazil lower-voltage networks are in place and this is not possible; hence T8s have been much slower to replace T12s.

On face value this would imply that the stock of LFLs in the 220–240 V regions would have a higher average efficacy relative to the 120 V regions; however, this has arguably led to regulatory complacency in other regards whereas the opposite has been true in the 120 V regions. US, Canadian and Japanese regulations have effectively phased out the less efficient halophosphor T8s from their markets so that all remaining T8s are of the more efficient triphosphor variety. Although use of T12s is still allowed, only the most efficient varieties can still be sold and these are only slightly less efficient than the least efficient T8s. By contrast Europe has not imposed any requirements on LFL efficacy, but it has seen a natural and seamless adoption of T8 lamps because there has been no reason to continue to use T12s. The sole exception is for extra-long LFL tubes, for which T12 lamps are the only ones available because of their greater thickness and lower risk of breakage. In consequence the share taken by

T8s is much higher in Europe, Australia/New Zealand and China than in the 120 V network regions, but the average T8 efficacy is poorer than in the 120 V regions because the halophosphor T8s predominate. Until very recently a similar situation applied in Australia/New Zealand, but both these countries have now adopted LFL regulations of a similar ambition to those in place in North America.

Furthermore, North American ballast energy performance regulations are more demanding than European regulations and as a result a very large part of the North American ballast market is taken by efficient electronic ballasts. In Europe, despite a gradual phasing-in of ballast energy performance requirements that prohibit sale of the least efficient electromagnetic ballasts, the intermediate and more efficient electromagnetic ballasts dominate the market and overall ballast energy performance is not as high as in North America. The net result is that overall LFL system efficacy is not quite as high in Europe as it is in North America despite T12s, which are inherently less efficient, continuing to have a significant market share in North America.

Having remarked on this it is important to understand that at least as much of the regional difference in average commercial-sector efficacy is related to differences in efficacy between the quarter of commercial illumination that is not provided by LFLs in each region. Here it appears that North America and Australia/New Zealand have relatively high usage of incandescent lamps, while Japan has very low usage and Europe falls in between. Commercial-sector CFL usage is particularly high in Japan, quite high in Europe and less so elsewhere. Halogen lamps are most common in Europe and Australia/ New Zealand and HID lamps are most used in North America and Europe (see Figure 4.16). Overall, Japan has the highest average efficacy for the non-LFL part of commercial lighting, followed by Europe.

Operating hours, illuminance and energy use

Efficacy is only one factor affecting lighting energy consumption, however. The length of the total operating period and the average illuminance provided also have a major influence on the final consumption. Here the picture seems to be considerably different between OECD regions and far more so than for the other factors discussed. Ironically the region with the shortest average operating hours, Europe (see Table 4.6), is also the one where the weighted-average location of the population is furthest from the equator.

It is difficult to know why these differences occur, but the available sources are unambiguous regarding the main characteristics of regional hours of use. Apart from the Californian data already mentioned earlier in this section, the Navigant (2002) study found that on average US commercial buildings operated their lamps for 3 614 hours per year in 2000. The CIBEUS study implies Canadian commercial buildings are operated on average for about 4 380 hours per annum (NRC, 2002). A survey of Japanese offices found that the annual average hours of use for lighting was 3 780 hours (ECCJ, 2003a). By contrast, European surveys report annual hours of lighting use between 1 405 and 1 901 for offices (Novem, 1999; Enertech, 2005; Kofod, 2001) and between 1 247 and 1 422 hours for education establishments (Novem, 1999; Kofod, 2001). The highest hours of use appear to be for hospitals and major retailers, but overall the various European data-sources point towards an average of about 1 781 hours per year for the whole commercial-building sector, as reported in Table 4.6. Looking outside the OECD, values are in between European and other OECD levels. In Russia, lighting in commercial buildings is operated for an average of 1 900 hours per annum (Aizenberg *et al.,* 2001), while in China values of about 2 800 hours are reported (ACMR, 2004).

Some contributory factors can be raised qualitatively and may explain these differences, but it is not possible to properly quantify them. A first observation is that European employment legislation is generally more restrictive than in other OECD regions, and hours of work more tightly controlled; this will have some influence in driving down the average hours of lighting operation in some types of commercial buildings. A second factor pertains solely to offices, where open-plan designs are less common in the European office stock than other OECD regions. As discussed in pp. 141–148 the lighting in open-plan offices tends to be operated for longer than that in cellular offices, especially if the switching is not zoned. Furthermore, it is possible that a greater share of European open-plan offices operate zoned switching than elsewhere, although it has not been possible to verify this.

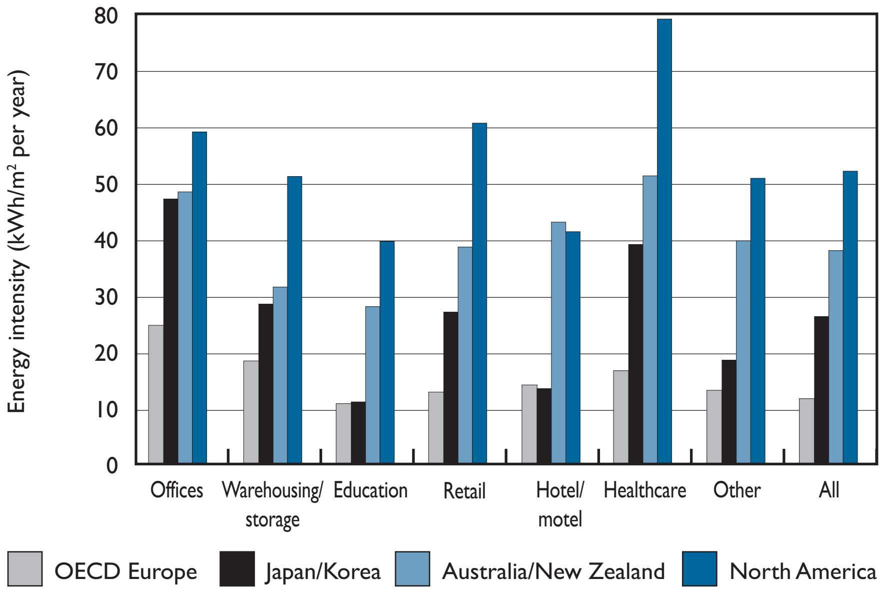
Could the use of automatic lighting controls be an explanatory factor? There is only limited information on average adoption rates of automatic lighting controls in different OECD regions, but the few available sources do not suggest that Europe has higher adoption rates than elsewhere. For example, the Canadian year 2000 survey of commercial and institutional buildings (see Table 4.4) found that about 17% of the total commercial-building floor area had occupancy sensors and daylight dimming devices and that over 40% had scheduling (time clocks) (NRC, 2002).

A Japanese survey found that 27% of office buildings had some type of lighting energy management controls (ECCJ, 2003a). No equivalent survey exists for Europe as a whole, but a survey of commercial lighting in six EU countries in 2000 (Kofod, 2001) found that 97% of buildings used manual controls, 4% scheduling (timer switches) and only 3% some kind of automatic control (occupancy sensors, daylight dimming, etc.). Even allowing for the possibility of the relative floor area coverage being higher once building area is taken into account, these figures suggest it is not likely that European buildings have higher levels of automatic lighting control than elsewhere in the OECD and that they may well be lagging. It is possible, however, that people could be more inclined to manually deactivate lights (because of cultural factors), that a greater proportion of buildings have designated staff with the responsibility of turning off lighting after working hours and that daylight utilisation may be higher. This could arise not only because of a greater proportion of older buildings, which intrinsically made better use of daylight than many modern designs, but perhaps also because of prevailing architectural practice.

Whatever the cause, the net effect is that on average European commercial buildings do not activate their lights for as long as elsewhere in the OECD and this equates to very large relative energy savings. In aggregate the data suggest that European commercial buildings operate their lights 38% less frequently than the OECD average. When these factors are combined with the efficacy and power density characteristics, European buildings use 32% less lighting electricity per unit area than the OECD average and 16% less than the country with the highest estimated average efficacy (Japan) – this despite a mix of commercial-sector lighting systems that are 23% less efficacious than in Japan.

The average estimated lighting energy intensity figures by commercial-building type and region are shown in Figure 4.20 and reveal substantial differences from one OECD region to another. The main cause of difference appears to be the length of lamp operation, but variations in efficacy and illuminance levels also play an important role.

Figure 4.20 **Estimated average commercial-building lighting energy intensities by OECD region in 2005**



United States and Canada

According to the US Lighting Market Characterization study (Navigant, 2002), which is based on a sophisticated marriage of the findings of almost 25 000 utility lighting audits and the national Commercial Building Energy Consumption Survey of 5 430 buildings, commercial buildings accounted for 391 TWh of lighting electricity consumption in the year 2001: an average of almost 84 MWh per building. Across the whole sector some 1.97 billion lamps were installed, of which 22% were incandescent/halogen, 77% fluorescent and 2% HID. The average lamp operated 9.9 hours per day and drew power of 56 W. Incandescent and halogen lighting consumed 125 TWh (32%), fluorescent lamps 220 TWh (56%) and HID lamps 46 TWh (12%). The sector comprised 4.7 million buildings with a total floor area of 6.3 billion square metres and an average lighting electricity intensity of 60.9 kWh/m^2. This produced 3.4 Mlmh of light per square metre at an efficacy of 49.5 lm/W. From this assessment the commercial sector accounts for 51% of total lighting energy use in the United States. The Navigant assessment follows on from earlier surveys that had estimated significantly lower levels of commercial-sector lighting consumption in the United States, notably 240 TWh (Vorsatz *et al.*, 1997) and 340 TWh (EIA, 1996); however, as it is more comprehensive than its predecessors and is based on a far richer set of survey data, it takes precedent.

Canadian commercial buildings consumed 43.9 TWh of electricity for lighting in 2003, which is 33% of all Canadian commercial-sector electricity consumption, at an average intensity of 80.2 kWh/m^2 (NRC, 2006b). In 1990 the commercial sector used 37.4 TWh for lighting, thus demand grew at an average of 1.3% per annum in the intervening years. The share of total Canadian commercial-building energy use taken by lighting has fluctuated between 13.4% and 15.7% since 1990. Of total commercial-building lighting consumption, 49% was in offices, 14.3% in retail organisations, 9.1% in healthcare facilities and 4.2% in warehouses. Street lighting, discussed in p. 237, consumed 7.6%.

Europe

There has been a diverse set of estimates for commercial-lighting energy use in Europe, and this continues to present a problem in properly characterising the sector. The European Climate Change Programme (ECCP) made an estimate of 135.4 TWh for the former EU15 in 1995, amounting to 28.5% of the total electricity use for the sector (ECCP, 2000); however, this was based more on a synthesis of expert opinion than on a formal survey (Waide, 2001). Blok *et al.* (1996) estimated that lighting accounts for ~38% of European commercial-sector electricity use, which would represent an EU15 commercial-lighting total of 185 TWh in 1995. A previous study (BRE, 1994) estimated commercial-sector lighting consumption in the previous EC12 countries to be 110 TWh/year, circa 1992, which translates into a lighting energy intensity of approximately 27.9 kWh/m^2. The BRE study has been a cornerstone of many EU estimates in this sector and informed Directive 2000/55/EC on ballast energy performance (see p. 317), but it was based only on scaled-up estimates from three EU countries (the United Kingdom, Germany and the Netherlands) that have since been called into question by more recent, detailed work. For example, the United Kingdom's Market Transformation Programme recently made detailed national estimates based on building survey data and a bottom-up stock model and concluded that UK commercial-sector lighting amounted to 41.9 TWh in 1994 (MTPROG, 2005a). This translates to a lighting energy intensity of

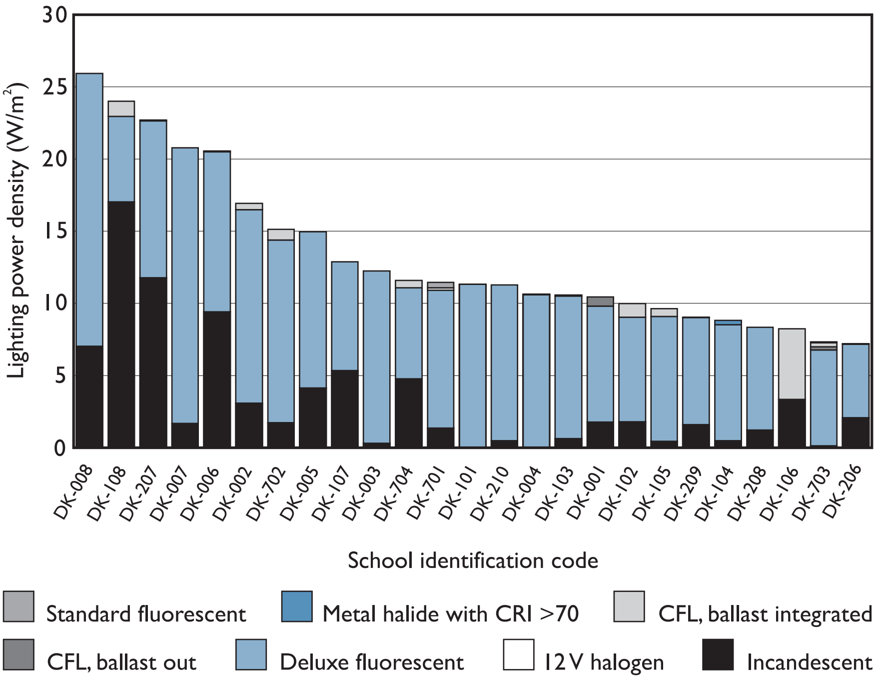
52.3 kWh/m^2, some 77% higher than estimated in the BRE study and 48% higher than the ECCP assessment for 1995.

A similar survey in the Netherlands found an average commercial-sector lighting intensity of 51.1 kWh/m^2 for the same period (van Arkel *et al.*, 1999), which is the same value as used in the ECCP assessment but 18% higher than that in the BRE study. Data from Portugal give an intensity of 14.8 kWh/m^2 (GASA FCT, 2000), which is 15% higher than estimated for the same country in the ECCP analysis and 57% higher than in the BRE study. Similarly, more anecdotal but high-quality data from end-use metering campaigns targeted at specific commercial-building types, conference papers, etc., suggest that the BRE lighting energy intensity estimates are too low and that the ECCP estimates are also somewhat low.

The situation is no less confusing when looking at lighting in individual commercial-building types. The European GreenLight Programme estimated EU15 lighting electricity consumption of 28.8 TWh for office buildings and 15.0 TWh for educational buildings (Novem, 1999). When converted into lighting energy intensities this comes to 46.3 and 29.7 kWh/m^2, respectively. However, these figures are higher than those in a survey of lighting in commercial-sector buildings for six EU countries that reports average values of 18.0 and 15.1 kWh/m^2 (Kofod, 2001). Figure 4.21 shows an example of the variation in installed lighting power densities for a sample of Danish schools from the same study. French data suggest 34 kWh/m^2 (EDF, 1996) or more recently 26.7 kWh/m^2 for offices and 44 kWh/m^2 for retail (Enertech, 2005). Intensity values for retail, as determined by the Building Research Establishment in the UK, ranged from 48 kWh/m^2 for Germany to 87 kWh/m^2 for the Netherlands (BRE, 1994). Kofod (2001) found national average values ranged from 10.3 to 83 kWh/m^2 for shop floor areas and from 39 to 450 kWh/m^2 for shop window display areas. This gave average lighting intensities of 50.2 kWh/m^2 for shop floors and 201 kWh/m^2 for display areas.

These myriad data-sources present quite a confusing picture and one that is in need of further verification and structuring. Given the large uncertainties in current EU estimates it seems more reliable to use a consistent bottom-up accounting framework to derive estimates, as has been done for the current work. This has the merit of allowing high-quality data gathered through end-use metering campaigns to be used in conjunction with

Figure 4.21 **Installed lighting power density by lamp type for a sample of Danish schools**



Source: Kofod, 2001 (reproduced with permission).
Abbreviations: CFL = compact fluorescent lamp; CRI = colour rendering index.

information on building types, areas and sub-area divisions.[11] These are combined with information on hours of use and lighting design guideline requirements to estimate total lighting energy demands from the bottom up. Such an approach has been applied here and further verified against a commercial-sector lamp stock model primed with a time series of lamp sales data to produce more consistent estimates of commercial-sector lighting energy consumption in the OECD Europe region.

The IEA analysis estimates that commercial-sector lighting in the European member states of the OECD consumed 185 TWh in 2005, a figure that is higher than the earlier values reported by the ECCP and the preceding BRE study but implies a sector average lighting intensity of 25.7 kWh/m^2.

11. A "sub-area" within a building has a homogeneous function (e.g. a corridor or an office), whereas an "area" is the building's total floor area.

Japan

The Japanese Luminaire Association (JLA) estimates that commercial buildings consumed 52.2 TWh of electricity for lighting in 2005 – 40% of total lighting consumption in Japan. This equates to a lighting energy intensity of 29.9 kWh/m² (JLA, 2005). It is not known how the JLA estimates are derived or whether there are solid, metered data to support the analysis. The difficulty experienced in the United States and Europe in obtaining reliable estimates of commercial-lighting energy use suggests that it is not a simple exercise and that considerable effort is needed to gain accurate values. The current sources imply lighting accounts for 18% of all commercial-building electricity use in Japan, a much lower share than reported in other OECD regions.

Australia

Commercial lighting in Australia was estimated to have consumed 11.4 TWh in 1998 (Ellis, 2001). As in other regions it is dominated by LFL tubes, most of which are T8 halophosphors, in line with Europe and China.

Peak power and installed-lighting loads

Were all commercial-sector lighting in the OECD to be activated simultaneously it would draw a power of about 270 GW. This is roughly two-fifths of the equivalent calculation for the residential sector; however, overall the commercial-lighting contribution to system peak power demand is probably higher than the residential-lighting peak for three reasons. First, a much greater proportion of commercial-lighting loads are likely to be operated at their peak hours than is the case in the residential sector. Second, the commercial-lighting peak occurs during working hours when other commercial loads and industrial electricity demand are high, thus for most electricity networks it will have a higher coincidence with the system peak than the domestic-lighting load. Third, the commercial-lighting peak is coincident with and amplifies the large commercial air-conditioning peak.

If it is assumed that 60% of commercial-sector luminaires are activated during the afternoon peak, the direct peak power demand of OECD commercial lighting would amount to 169 GW, not including transmission and distribution losses. The indirect influence of lighting on air-conditioning loads will add about another 50 GW to this total,[12] making a combined impact on the afternoon peak of about 219 GW. This estimate is based on fairly crude assumptions but provides a first estimate for policy discussion.

While lighting heat losses also help offset heating demand, this is less useful in the commercial sector and will produce little reduction in the overall impact of lighting in the winter peak, because commercial buildings have higher heat gains per unit area than the residential sector and hence have greater cooling needs, and because a smaller proportion of commercial-sector heating is supplied with electricity than is the case in the domestic sector.

In many regions the afternoon commercial peak overlaps the late afternoon/early evening domestic peak, and lighting contributes strongly to both. It is for this reason, in combination with high savings potentials and low costs per kilowatt-peak avoided, that utilities have traditionally focused their DSM programmes on lighting, be it commercial, residential or both.

Commercial-lighting characteristics in non-OECD countries

An estimated 422 TWh of electricity was used for commercial lighting in non-OECD countries in 2005, comprising 37% of the world total in this sector and 41% of non-OECD commercial-building electricity consumption. This provides illumination for 17.5 billion square metres of floor area at an estimated average intensity of about 24.1 kWh/m^2 and average efficacy of 52.6 lm/W. Both the floor area and the average intensity are growing much faster than in the OECD, in line with the faster average rate of growth being experienced in non-OECD countries; however, this growth is very uneven and a wide diversity of values is found.

The cost of the light provided averages about USD 3.3 per square metre per annum or some USD 57 billion for the non-OECD as a whole. As with the OECD, electricity costs contribute about 60% of the total and the remaining 40% is accounted for by the cost of the lighting equipment (lamps, luminaires, ballasts and controls), installation and maintenance labour. The average cost of delivered light is USD 2.6/Mlmh, but local costs

12. This takes account of the proportion of the OECD commercial-building stock that is air-conditioned and assumes a typical air-conditioning system heat-extraction efficiency (COP) of ~2.2 W/W.

can vary significantly from this depending on tariffs and lighting-system efficiency. In almost all cases the highest-efficiency lighting systems have the lowest life-cycle costs, thus raising commercial-sector lighting efficiency almost always makes sense in economic terms.

With some exceptions the data on commercial-lighting electricity consumption are not as good in non-OECD countries as in OECD countries, but enough is known to observe some important similarities and differences, as well as to enable regional estimates to be formulated. As in the OECD, fluorescent lamps predominate, but there are many differences from one region to another regarding the preferred linear fluorescent technology. In Thailand, for example, DSM programmes in the early 1990s effectively phased out T12 production in favour of T8s. These now dominate the Thai market, although the vast majority are the less efficient halophosphor variety. T12s appear to be have almost disappeared from the Chinese market too if the data in the All China Marketing Research survey are correct (ACMR, 2004).

By contrast, in many other regions T12s are still very commonplace and overall they occupy a large part of the non-OECD LFL market. In the Russian Federation, for example, the average LFL efficacy in the installed commercial stock is estimated to have been 65 lm/W in the year 2000 (Aizenberg et *al.*, 2001), suggesting that poor-quality T12s and low-efficiency electromagnetic ballasts were commonplace. In South Africa, commercial lighting has been switching over toward T8s from T12s, but with several years' lag compared to Europe (Henderson, 1997). In the Indian subcontinent it appears that T12s are still the dominant LFL lamp type. Given this and the poorer than average efficiency of ballasts sold in non-OECD countries, it may come as a surprise to discover that the average efficacy of lighting in commercial-sector buildings could be higher in the non-OECD regions compared to the OECD as a whole; however, this is explicable by a seemingly lower share of incandescent lamps compared with OECD buildings.

The estimated average commercial-sector lighting power density in China for 2000 was 9.7 W/m^2, which is appreciably lower than in the OECD, mostly because of lower installed light levels.[13] Across the combined commercial and industrial sectors some 1.37 billion lamps were installed in 2003, of which 25% were incandescent/halogen, 67% fluorescent and 8%

13. Perhaps 40% less than the OECD average.

HID. The average lamp operated 8.1 hours per day and drew an estimated power of 58 W. Incandescent and halogen lighting consumed 37 TWh (25%), fluorescent lamps 62 TWh (41%) and HID lamps 50 TWh (33%).[14] These values give rise to an estimated commercial-sector lighting energy intensity of 23.5 kWh/m^2, which is 60% of the OECD average despite China having slightly greater than OECD-average annual lighting-operating hours.

In Russia, however, commercial-sector usage of incandescent lighting appears to be remarkably low, as this is reported to have provided just 3.3% of the source-lumens in 2000 (Aizenberg *et al.,* 2001). Overall, in non-OECD countries it is estimated that incandescent and halogen lamps provide only 4.8% of commercial-sector lighting. This is lower than in the OECD as a whole and explains why average commercial-sector lighting efficacy is thought to be slightly higher.

Industrial sector

Globally an estimated 490 TWh of final electricity was consumed by industrial lighting[15] in 2005, amounting to about 18% of total lighting electricity consumption and just over 8.7% of total electricity consumption in the industrial sector. This produced 38.5 Plmh of light at an average source-lumen efficacy of 79 lm/W. This is higher than for any other sector except outdoor stationary lighting. The cost of the light provided averages about USD 1.33/Mlmh or some USD 51 billion globally, of which electricity costs account for 67% of the total and the remaining 33% is contributed by the cost of the lighting equipment (lamps, luminaires, ballasts and controls), installation and maintenance labour. Although local costs may vary as a result of differences in tariffs, labour and equipment costs, in almost all cases the highest-efficiency lighting systems have the lowest life-cycle costs, so raising industrial-sector lighting efficiency almost always makes sense in economic terms.

The reliability of industrial-sector lighting energy estimates is poorer than for the residential and commercial sectors because fewer data are publicly available. The most comprehensive survey of industrial-lighting energy use was provided in the Navigant study of lighting in the United States, which estimated a total US industrial-lighting energy use of 108 TWh for

14. Figures are derived from ACMR (2004).
15. Includes lighting for industrial buildings and plant but not street or other outdoor lighting.

2001, or 10.6% of industrial electricity consumption (Navigant, 2002). The Navigant figure is substantially higher than a previous estimate by Niefer and Ashton (1997), who reported 50 TWh based on an analysis of data in the US Energy Information Administration's 1991 *Manufacturing Energy Consumption Survey* (EIA, 1991). However, as the Navigant study is derived from a substantial number of real audits it has a higher credibility. In most cases industrial lighting use is dominated by fluorescent and HID lighting. In the United States, incandescent lighting consumes 2% of total industrial lighting energy, fluorescent lighting uses 67% and HID lamps account for 31%. Navigant's data suggest that US industrial buildings had a combined floor area of 1.6 billion square metres, an average lighting power density of 13.7 W/m^2 and intensity of 69 kWh/m^2 in 2001. There is almost a three-fold difference in average intensity between the various types of manufacturing-sector buildings, ranging from 37 to 107 kWh/m^2. Fluorescent lamps provide 71% of the total illumination, HIDs 29% and incandescent lamps less than 1%. On average lamps have longer duty cycles in the industrial sector than for other sectors and typically operate for 13.5 hours a day. Combining this information with the Canadian data and projecting it forward through the IEA lighting model gives an estimated industrial-lighting energy use of 110.3 TWh for the two countries in 2005 at an average efficacy of 80.4 lm/W. This compares favourably with an estimated value of 123 TWh in 2000 at a lower efficacy of 74.8 lm/W.

In Japan the JLA estimated that lighting accounts for 34.9 TWh in the industrial sector, *i.e.* about 7.8% of all industrial electricity consumption (JLA, 2005). IEA estimates, derived by analysing lamp sales time-series data to estimate stock shares by lamp type within the overall lighting-stock model, give an efficacy of 81.6 lm/W for Japanese industrial-sector lighting.

As in the United States, industrial-sector lighting in the European Union was also previously estimated to account for about 50 TWh of electricity use (BRE, 1994; European Commission, 1999); however, these estimates suffer from the same methodological flaws discussed for the commercial sector and hence are not very credible. There has been no systematic survey of industrial-sector electric lighting in the European Union and the best data available are from individual site audits and occasional national survey information. The IEA estimates that industrial lighting in OECD Europe was 100.3 TWh in 2005, amounting to ~8.7% of total industrial electricity use, in line with the global average. Despite not sharing an identical geography, this is still a significantly higher value than the previous estimate for the EU15. The sector average efficacy is projected to be 81.9 lm/W. As with other OECD regions, about 62% of industrial illumination is contributed by LFLs, 37% by HIDs and less than 1% by other sources.

In Australia, industrial lighting is estimated to have consumed about 5.76 TWh in 1998 (Ellis, 2001). If this is growing at the same speed as other lighting sectors, over 3% yearly, this implies that lighting accounts for about 7.6% of all industrial electricity use. In 2001 there were projected to be over 12 million LFLs in this sector, of which almost 9 million are halophosphor T8s, 2.2 million triphosphor T8s and 1 million T12s. LFLs were estimated to account for 55% of total industrial-lighting energy consumption. The majority of the remaining 45% is attributed to HIDs, of which 38% were mercury vapour, 34% high-pressure sodium and 28% metal halide.

Outside the OECD, industry is also a major consumer of lighting energy. In Russia, industry and agriculture combined were estimated to have consumed 56.3 TWh of electricity for lighting in 2000, of which 44 TWh was for industry alone (13.9% of total industrial electricity consumption[16]) and 12.3 TWh was for agriculture (52% of agricultural electricity consumption). The mix of light sources is dissimilar to the OECD in that 36.5% of light provision is from LFLs (mostly T12s), 56.3% from mercury-vapour HID lamps and the rest is from other HID lamps and incandescent lamps. In the agricultural sector 67% of the light is provided by mercury vapour lamps, 23% by LFLs and almost all the rest by incandescent lamps. Given the poor quality of the lamps used, the sector average efficacy is much lower than in the OECD industrial sector and averaged 61 lm/W in 2000.

In China, the industrial-sector lamp mix appears to be quite similar to that in Europe. Some differences are that the reported share of T5 lamps is even higher than in Europe and there is a slightly higher share of mercury vapour lamps (40% of all HID lamps) (ACMR, 2004). In fact there is some considerable doubt about the allocation of lamps in the Chinese industrial sector and in particular the use of low-efficacy, self-ballasted, blended mercury lamps. Some data-sources appear to be inconsistent on this issue (Nadel and Liu, 2005; ACMR, 2004).

16. Derived from Aizenberg *et al.*, 2001.

Outdoor lighting

Globally an estimated 218 TWh of final electricity was consumed by outdoor stationary lighting in 2005,[17] amounting to about 8% of total lighting electricity consumption. This produced 16.1 Plmh of light at an average source-lumen efficacy of 74 lm/W. This is higher than for any other sector except industry. The cost of light averages about USD 1.33/Mlmh, or some USD 18.7 billion globally, of which electricity costs are 79% of the total, with the remaining 21% being the cost of the lighting equipment (lamps, luminaires, ballasts and controls), installation and maintenance. Although local costs may vary as a result of differences in tariffs, labour and equipment costs, in almost all cases the highest-efficiency lighting systems have the lowest life-cycle costs, and thus raising industrial-sector lighting efficiency almost always makes sense in economic terms.

The level of outdoor lighting is strongly related to affluence and as a result OECD nations use the most: 71% of energy and 75% of the light. This is immediately evident from looking at night-time satellite photos of Earth that show cities, especially densely populated OECD regions, emitting a disproportionate amount of light as a share of their population. Globally, the lion's share of outdoor stationary lighting is taken by two applications: street/road lighting and car-park illumination, which account for 53% and 40%, respectively. Traffic signals are the next largest contributors, taking 6%. Billboards and airport lighting account for just 1% each. Both street and car-park lighting are operated throughout the entire night, especially in the OECD, and hence will generally be used for between 3 600 and 4 400 hours per year. However, modern systems using electronic ballasts can be dimmed during off-peak times and this offers the potential for significant energy savings.

Light pollution

Much as artificial lighting provides a very useful service, it has also engendered a new problem: light pollution. The light emitted by outdoor illumination devices has become so pervasive and is so poorly directed that in most of our urban environments it is no longer possible to see any

17. Includes all non-mobile outdoor lighting.

but the brightest of stars at night because of the glare from artificial light scattered back to ground from the sky vault. Light pollution is not only a waste of light energy but also diminishes our perception of the wider universe.

Pressure groups, such as the International Dark-Sky Association, have been founded to try to combat the problem, and in recent years many local and national ordinances have been issued that aim to curb light pollution. There are a variety of simple remedies involving the use of "cut-off" luminaires, which only direct light downwards (as opposed to sideways and upwards) and the proper positioning of luminaires; however, these are still seldom employed, mostly because of a lack of awareness of the issue. No government has yet prohibited the sale of outdoor luminaires on the grounds of their potential to cause light pollution, although conceivably this could be a future step.

Efficiency

Almost 62% of total outdoor light is provided by high- and low-pressure sodium lamps, 30% by mercury vapour lamps and 6% by metal halide lamps. The remaining 2% is mostly provided by halogen and incandescent lamps. Mercury vapour HID lighting is a superseded technology that has much lower efficacies and higher overall operating costs than its competitors (sodium and metal halide HID lamps); nonetheless, it continues to be widely used for outdoor public lighting because its first costs are comparatively low. Many municipalities are either unaware of the life-cycle cost and quality advantages of alternative HID technologies or have perverse cost-management incentive structures that reward lowest-cost capital procurement to the detriment of operating costs. The inability of many municipalities to finance capital investment projects is also a constraint limiting the uptake of higher-efficiency options.

In OECD regions the average efficacy of street and car-park lighting is strongly linked to the relative proportion of mercury vapour lamps compared to other HID lamps. North America has led the way in phasing out mercury vapour lamps, which now only account for a very small share of total sales in that region. Elsewhere in the OECD, including Europe, Japan and Australia/New Zealand, they continue to occupy a significant proportion of total HID lamp sales (see pp. 264–268).

Street lighting

Street and roadway lighting uses about 114 TWh of energy globally but is strongly influenced by the efficacy of the light source and ballast used, the efficiency of the luminaire, and the overall light levels provided. The IEA estimates that there are over 90 million street and roadway lamps in place in member countries. Substantial energy savings are to be had by optimising all of these, but this is rarely done in existing applications and consequently results in substantial energy waste. The importance of both the lamp and luminaire efficiency in street lighting is indicated in Table 4.7, which reports data from a European study (Eurelectric, 2004) that are generally applicable around the world.

Table 4.7 **Total efficiency of combinations of lamp and luminaire for outdoor street lighting**

	Luminous efficacy of lamp with electromagnetic ballast (lm/W)		Average luminaire efficiency (%)		Total efficiency (lm/W)
Low-pressure sodium	68–177		25		17–44
Tubular high-pressure sodium	70–150		45		32–68
Elliptical high-pressure sodium	59–124	x	30	=	18–37
High-pressure mercury	34–58		30		10–17
Metal halide	61–85		35–40		21–34
Ceramic metal halide	70–76		45		32–34

Source: Eurelectric, 2004.

High-pressure elliptical sodium lamps have markedly higher photopic efficacy than ceramic metal halide lamps, but because of their relatively poor luminaire efficiency their overall efficiency is not as good unless at high power ratings. If the improved colour rendering of the ceramic metal halide lamps and subsequent superiority under scotopic lighting conditions is taken into account (see pp. 69–70), they are a clearly superior option for the mesopic lighting conditions typical of street lighting. Both systems are far in advance of mercury vapour lamps and both have substantially lower life-cycle costs. Tubular high-pressure sodium lamps are generally superior to any of the other lamps unless whiter light and better colour rendering is required.

Street and outdoor lighting in non-OECD countries

There are only patchy data available on public lighting in non-OECD countries, but from this it is clear that the average quality and efficiency of the installed-lighting systems are often poorer than in the OECD. If in the OECD the main problem is the use of low-efficacy mercury vapour lamps, elsewhere this is often among the higher-efficacy solutions. Self-ballasted, blended mercury vapour lamps with very low efficacies (19–22 lm/W) are quite common, and in some cases incandescent lighting is still used for public illumination. Some examples are discussed below.

Brazil

A survey of street lighting in Brazil in 1995 covering cities that represent about 85–90% of the national stock found that there were 8.78 million street lights in place, consuming 7.64 TWh of electricity per year (869 kWh/year per lamp) (Geller and Leonelli, 1997). Some 81% were conventional mercury vapour lamps with an efficacy of 42–52 lm/W and only 7% were high-pressure sodium lamps (efficacy of 65–104 lm/W). The remainder were self-ballasted mercury vapour lamps (7%; efficacy 19–22 lm/W), incandescent lamps (4%; efficacy 14–17 lm/W) and fluorescent (1%; efficacy 35–61 lm/W). This mix made an average stock efficacy of 48.2 lm/W. Had this matched that of the high-pressure sodium lamps the overall consumption would have been 43% lower. First cost is the main barrier to the adoption of the more efficient systems because high-pressure sodium lamp prices were two to three times more than those of mercury vapour lamps of an equivalent light output.

China

Street lights in China were estimated to use just 3.1 TWh in 2003 (ACMR, 2004). This figure is tiny in comparison with OECD totals and may be based on some questionable assumptions; however, it is clear that street lighting has traditionally been underdeveloped in China. This situation is almost certainly changing very rapidly as a result of the exceptional growth in China's urban areas and the increase in cars and roads. Data suggest that street construction has been growing at an even faster pace than general construction in China, which is already happening at an unprecedented rate. In the two years to 2003 the total length of city streets grew 18% and the area increased by 26% to reach 3 156 km^2, equating to 9 m^2 per urban dweller (Bruce *et al.*, 2004). The length of expressways increased from just 5 000 km in 1997 to 300 000 km in 2003 (NBSC, 2004). Street and roadway lighting is most probably keeping pace with this rate of growth, or occurring even faster as older, under-lit streets become illuminated. These data are inconsistent with respect to the prevalent lighting technologies that are being deployed. Some imply that standard mercury vapour and high-pressure sodium lamps are predominant (ACMR, 2004) and others indicate that a large volume of very low efficacy, self-ballasted mercury vapour lamps are used (Nadel and Liu, 2005).

Illumination of car parks

Car parks are the other major outdoor-lighting application; IEA calculations suggest there are 55 million installations in place across the OECD alone.[18] Globally, this application is estimated to have consumed 88 TWh of electricity in 2005. This end-use is also dominated by HID lighting and includes all the lamp types already discussed.

Vehicle lighting

Amount and efficiency of vehicle lighting

The electricity used to provide lighting has long been considered a second-order issue in transportation energy use, which is true by comparison to the energy needed for motion itself. However, with a global stock in 2005 of about 750 million light-duty vehicles, including cars, light trucks and minivans, plus 50 million trucks, 14 million buses and minibuses and 230 million two- or three-wheelers, one can easily imagine that the total amount of energy used by their lighting is far from negligible. Moreover, the total lighting-related power demand of individual vehicles is rising as a result of increased expectations for comfort and safety and can be as much as 450 W for large North American trucks.[19]

18. In this context the number of installations refers to the number of light posts or columns, each of which could have one or more light sources mounted on top.
19. Without taking into account the decorative lighting a number of truck drivers add to their cabs.

Road vehicle external-lighting applications mostly provide illumination for driving and security needs. From core road-safety functions such as warning signs and stop lights, to enabling night driving and improving visibility in foggy driving conditions, there is a wide variety of different applications for lighting in road vehicles. The analysis presented here focuses on external vehicle lighting and does not investigate the characteristics of lamps used inside the vehicles because they are generally of second-order importance in energy terms; however, readers should be aware that there are cases when internal lighting accounts for a significant part of vehicle-lighting energy demand, *e.g.* in the case of buses equipped with general and individual lighting fixtures to facilitate the visual comfort of the passengers. Electricity consumption in other transportation modes (*e.g.* mass transit, passenger rail and aeroplanes) can also be important, but is not as high as for vehicles and is not addressed here.

Several factors determine the amount of lighting used by road vehicles. First the number of vehicles and the length of time they are used, second the number and output of the lamps and finally the way the lamps are used. Low-efficiency, classic incandescent lighting technology still constitutes the overwhelming proportion of existing vehicle-lighting fixtures, while the efficiency is also very low when fuel is converted into electricity in internal combustion engines equipped with an electricity-generating alternator. These factors compound to produce a poor light to energy ratio for vehicle lighting compared to grid-based electric lighting. From the analysis presented below, which is derived from a synthesis of existing national data-sources linked into an IEA global and regional vehicle fleet model, it is estimated that exterior road-vehicle lighting globally produced about 1 300 Tlmh of light in 2002 and required the equivalent of 55 billions litres of petroleum, equivalent to about 3.2% of all road vehicle energy use. In terms of international oil demand and after including the upstream energy needs of the refining industry, this accounts for 1.1 million barrels of crude oil per day.

Lighting technologies

The lamp technologies used for vehicle lighting include incandescent, halogen and xenon lamps, which are all discussed in pp. 132–134 LEDs are reviewed on pp. 445–458. Automotive lamps are chosen based on a market optimisation of a number of factors that include light level and projection characteristics, manufacturing cost, operating life, robustness, durability and aesthetic effect. Some specific factors that may need to be considered are the lamp's durability under short on/off switching cycles and its compatibility with colour filters. Incandescent lamps have a very low manufacturing cost of around USD 1 per kilolumen (excluding the cost of the lighting fixture itself, which comprises a reflector, connecting socket and glazing), but they have relatively poor lifetimes and place a relatively high strain on the battery, which may have unwanted design as well as energy consequences. While incandescent lamps are the least efficient they have almost disappeared from use in headlights and have been replaced by halogen lamps; however, the highest-efficacy option is that of xenon lamps, which use 25% of the power of a halogen lamp for the same light output. In practice these lamps are used to provide more light and thus result in energy savings of only about 36%.

In the typical configuration xenon headlamps are used on vehicles at the higher end of the market to provide higher and more stylish light output (ranging from 2 800 to 3 200 lm instead of the usual 1 200 lm of classic headlamps) and a lower power demand (35 W instead of 55 W for dipped beams and 65 W for full beam – the same fixture and bulb playing both roles). This occurs because the technology is quite complex and costly. It requires the use of an electronic ballast, but because of the doubling in light output there is a greater risk of glare to oncoming traffic and the current Euro-Asian standards for HID headlamps require the mandatory use of "automatic levelling systems" to minimise this. This requirement is also partly responsible for the additional manufacturing cost of USD 180 compared to conventional halogen headlamps. If this is passed on to consumers with usual multipliers it would amount to an incremental cost of roughly USD 360, of which about half is attributed to the inherent characteristics of the lighting technology and half to the self-levelling requirement. Xenon headlamps last much longer than halogen lamps and this yields some maintenance savings, but this is unlikely to offset the increment in purchase price. Nonetheless, it is likely that as production volumes rise the incremental costs will fall, making xenon lamps more competitive in the mass market. Incandescent lamps remain the dominant technology for all other vehicle lights with the exception of some rear-lighting applications, in which LEDs are making rapid inroads (see pp. 455–458).

Vehicle-lighting characteristics

Not surprisingly, the total electric power drawn by lighting varies from one vehicle type to another; however, it is possible to characterise typical values for OECD light-duty vehicles and trucks as shown in Tables 4.8 and 4.9, respectively.

Table 4.8 **Exterior-lighting characteristics for light-duty vehicles**

Lamp application	**Operating time***	**Lamp power (W)**		
	(hours/year)	**Incandescent**	**Xenon HIDs**	**LEDs**
Headlamps, full (high) beam	24	65	35	50
Headlamps, dipped (low beam)	115	55		40
Front turn signals	30	25		8
Front parking lamps	115	8		1.5
Rear stop lamps and turn signals	61	26		8
Rear tail lamps	115	7		2
CHMSL, exterior mount	61	18		2
CHMSL, interior mount	61	36		5
Licence plate	115	4		1
Reverse indicator	12	25		2.5
Side marker	115	3		1
Fog lamps	120	40		n/a
Daytime running lamps	341	40		31

Source: Navigant, 2003a; IEA data.
* Time of operation for a typical US use: varies from one country to another.
Abbreviations: CHMSL = centre, high-mounted stop light; HIDs = high-intensity discharge lamps; LEDs = light-emitting diodes; n/a = not available.

With the exception of two- and three-wheelers and new buses in the United States, the installed power and electricity consumption of full (high) beam and dipped (low beam) headlamps is less than that of the other external lighting fixtures combined. For light-duty vehicles, full and dipped beams account for 43% of the lighting energy use, whereas they account for 35% for trucks. The inverse relationship is true for two- and three-wheelers because they have very few lighting fixtures other than headlamps. This is also true of new buses in the United States, where a high penetration rate of LEDs in place of low-power incandescent bulbs has reduced the amount of energy used by other lamps, and accordingly

Table 4.9 Exterior-lighting characteristics for trucks

Lamp application	Operating time* (hours/year)	Wattage: Incandescent	Wattage: Xenon HIDs	Wattage: LEDs
Front clearance lamps	3 650	4.6		1.1
Front side markers	3 650	4.6		1.1
Intermediate side markers	3 650	6.1		1.1
Side turn (part of mid-marker lamp)	170	26.9		1.1
Rear side markers	3 650	4.6		0.4
Rear clearance	3 650	4.6		0.4
Rear identification	3 650	4.6		0.4
Stop lamp	170	28.4		0.4
Rear turn signal/hazard warning	170	28.4		0.4
Tail lamps (part of stop & turn lamps)	3 650	6.5		0.4
Cab roof identification lights	3 650	4.6		1.1
Cab roof clearance lights	3 650	4.6		1.1
Headlamps, full (high) beam	790	65.0	35.5**	50.0
Headlamps, dipped (low beam)	3 650	55.0		40.0
Front park	3 650	6.1		1.4
Front turn/hazard warning lamps	170	26.9		10.5
5th wheel light (upper marking)	3 650	26.9		6.8
Rear markers	3 650	6.1		1.1
Reverse indicator lamp	20	28.4		6.8
Licence plate lamp	3 650	4.6		0.7

Source: Navigant, 2003a.
* Time of operation for typical US use: varies from one country to another.
** IEA data.
Abbreviations: HIDs = high-intensity discharge lamps; LEDs = light-emitting diodes.

headlamps account for 72% of the total lighting electricity use. However, the transition to LED lighting is not as developed in other OECD or non-OECD bus markets.

Estimation of global vehicle-lighting energy use

The approach taken to estimate global lighting energy consumption matches a method developed for the US DOE (Navigant, 2003a) with an IEA bottom-up model used to account for and project global vehicle energy demand. The same model has also been used to inform the IEA's *World Energy Outlook 2004* (OECD/IEA, 2004) and support the analysis of the World Business Council for Sustainable Development (WBCSD, 2004). The original Navigant data for US vehicle-lighting consumption (Navigant, 2002) is revised for each world region and upgraded to include more recent and locally applicable sources.

Basic methodology

For cars, trucks and buses, an itemised list of lighting fixtures and their power needs is established and estimates made of their average annual usage period. A less sophisticated approach is used for minibuses and two- and three-wheelers. It is assumed that the former consume the same amount of lighting electricity per kilometre travelled as do light-duty vehicles, whereas for the latter a rough estimate of the mean power needs is derived. From these assumptions it is concluded that minibuses and two- and three-wheelers account for 0.5% and 3%, respectively, of the overall vehicle-lighting fuel use, hence the low priority given to their modelling compared with other vehicle types. The electricity used for lighting is calculated by multiplying the mean time of use of each fixture by average power needs. This is divided by IEA-derived data on average motor and alternator efficiencies to estimate the associated fuel use.[20]

A first approximation for world figures

General assumptions are used to transpose the US figures to other countries and regions regarding the time of use and the number, nature and power requirements of the fixtures. For this exercise the world is split into four regions: three OECD groups of countries (the Asia-Pacific, Europe and North America) and a fourth grouping for the non-OECD countries. Further work is needed to improve the reliability of these estimates, but at even so the current world model is sufficient to provide a first order of magnitude for the present purpose.

Situational analysis of global vehicle-lighting energy use

The move toward daytime running lights

The use of vehicle headlights during daytime is now widely acknowledged to be an important means to improve safety and is attributed with causing a 5%, or greater, decrease in crashes, injuries and fatalities (Commandeur *et al.,*

20. Engine efficiency is assumed to be 25% for light-duty vehicles and two- and three-wheelers or 35% for trucks and large buses. Alternators are assumed to have an average efficiency of 50%, except for two- and three-wheelers, for which a value of 40% is applied.

2003; CNSR, 2004). A large number of daytime crashes occur in situations where a driver, for reasons that are often not fully understood, makes an erroneous manoeuvre by overtaking or turning across the direction of oncoming traffic while a vehicle is coming in the other direction. These very serious crashes are seemingly related to a failure to identify the oncoming danger and thus are thought to be reduced by the use of daytime front lighting on vehicles. Statistical surveys of countries with experience in the daytime use of headlamps have demonstrated a clear safety benefit. Accordingly, a number of countries have taken policy action to promote greater use of daytime vehicle lighting through regulation or incentives (Box 4.2).

Box 4.2 Mandatory use of low beams during daytime for security reasons

Encouragement to use vehicle headlights during the day for road safety reasons is spreading, as either a voluntary or mandatory measure. Some countries have introduced regulations that require headlights to be on at all times: Canada, Ireland and the Scandinavian countries (Denmark, Finland, Norway, Sweden) on all roads; Hungary and Italy on rural roads only. Some countries have set an obligation to use them in the winter period only: Poland, Lithuania, the Czech Republic on all roads and Israel on rural roads only. The European Union and a number of its member states (Austria, France, Germany, the Netherlands and Spain) are considering taking mandatory action too (European Commission, 2003). The Netherlands, Austria and Switzerland recommend the use of headlights during daytime on a voluntary basis.

Beside these mandatory requirements to use dipped lights, it is also possible to apply technical specifications or standards that ensure the headlamps are automatically switched on when the engine is running; this option has been in force in Canada since 1989.

Two main technical solutions exist to provide light during the day: one is to simply use normal dipped headlamps, which means that the device has to be switched on manually; the other is for the car to be equipped with automatically activated lights. The latter option is called "daytime running lights". These lights are meant to produce a gentle luminance that assures visibility without excessive glare for oncoming traffic. The energy implications of using dedicated daytime running lights versus conventional headlamps operated on dipped beam is discussed in Box 4.3.

Box 4.3 Daytime use of dipped headlights vs daytime running lights

Traditional headlights are designed to operate simultaneously with a number of other lights, *e.g.* rear lamps, side markers, parking lamps, licence plate lights, etc. Thus their daytime use also requires all these other lights to be activated. By contrast, daytime running lights can entail any of the following configurations.

- The use of dipped headlamps that are automatically switched on with the engine, sometimes with a reduced voltage to save energy and prevent glare.
- The use of full-beam headlamps that are automatically switched on with the engine and in all cases operated at a reduced voltage to prevent glare.
- The inclusion of specific engine-activated headlights dedicated to daytime use mounted in the same headlight fixture as the other headlamps or in a separate fixture, *e.g.* lower on the front shield.

Note that the first two approaches can easily be implemented on existing cars as they only use the existing lighting facilities. For all three of the above cases manual activation of the traditional night-time headlamps overrides the daytime running lights. Furthermore, the tail lights and other night-use related lights are switched off during daytime running light operation.

The list of light-duty vehicle lighting characteristics in Table 4.8 illustrates why the automatic activation of dipped beams alone (2 x 55 W) consumes a lot less power than when they are combined with other applications that are activated together when manually operated (*i.e.* an additional 58 W, not accounting for dashboard and other internal lighting devices). In addition, daytime running lights usually use a lower voltage while operating the dipped-beam fixture, or involve specific lower-wattage lamps (2 x 40 W). In both cases half of the additional energy use is avoided.

For light-duty vehicles, the systematic daytime use of conventional dipped beams at normal voltage increases annual fuel use by 1–3%. For example, IEA calculations imply 2% for US light-duty vehicles and 3% for European cars, while other sources confirm this or provide slightly lower estimates (*e.g.* CNSR, 2004; Catania and Gagne pain 2004). The use of halogen daytime running lights in the case of mandatory daytime lighting requirements reduces the car's overall fuel consumption by 1–1.5% compared to this situation. Moving to HID lamps or LEDs in the future could save up to 2.5% (a total saving of more than 80% compared to the use of standard dipped beams and related night-time applications).

Regulatory balance

Road-safety regulations clearly have to strike a balance between safety advantages and energy and other possible drawbacks of requiring headlamps to be lit during the day, at least under specific conditions. As stated before, the trade-off can be managed in different ways and the safety improvements can be implemented in ways that minimise the additional energy burden. In Canada, for example, where it has been mandatory since 1989 both for drivers to activate the front lights during daytime (if not equipped with daytime running lights) and for car manufacturers to equip new vehicles with daytime running lights, the regulations are designed to limit the extra demand. Daytime running lights have to comply with the Society of Automotive Engineers' SAE Recommended Practice J2087 technical document, enforced through Technical Standard Document 108, paragraphs 44–53 (Transport Canada, 2005; SAE, 1991), which implies that they use a lower wattage than conventional headlights and that the tail, side and parking lights are not switched on, and hence consume about half as much electricity in use as the conventional headlights and related lighting. This Canadian policy provides a sound trade-off, allowing the implementation of a safety measure while reducing the induced additional fuel use and CO_2 emissions. The situation is different in other countries and regions, as discussed below.

In the United States, the SAE J2087 technical document also triggered an official document, Federal Motor Vehicle Safety Standard FMVSS 108, which sets the requirements for daytime running lights. However, in the United States this is a voluntary requirement and hence car manufacturers may, but do not have to, equip their new vehicles with daytime running lights. In consequence, fewer new cars on the market are so equipped.

Regulation 87 under the UN Economic Commission for Europe (ECE) 1957 Geneva agreement on vehicle standards is a similar regulation adopted by European, Asian, African and Middle Eastern countries. Its wording implies that manufacturers are allowed to introduce daytime running light-equipped cars in these countries, and in particular on the European Union's internal market; however, no standard daytime running light-equipped production models had been introduced before 2005, at least not in the European Union. More recently Audi introduced a daytime running light-equipped high-end model (the A8 12–cylinder), but in general it appears that almost all cars in Scandinavia or Ireland, where daytime headlamp use is mandatory, are running with their standard dipped beams on, which is a very energy-inefficient solution.

Limitations of vehicle fuel-economy test procedures

It is also important to note that in America, Japan and Europe, and probably in other countries as well, the fuel-economy tests for new cars do not include electrical equipment that can be switched on or off (*e.g.* air-conditioning, standard headlights and other lighting, stereos, etc.). So the use of headlights on full or dipped beam does not influence the test results, which means there is no incentive for manufacturers to provide more efficient lights to record better fuel-economy test results. In contrast, equipping cars with daytime running lights could provide such an incentive, because they are automatically switched on with the engine. In this sense lighting falls into a broader debate about how to ensure vehicle manufacturers have a sufficient incentive to improve the energy performance of all factors that affect fuel economy rather than just those which are registered in the current test procedures.

THE BUSINESS OF LIGHT: GLOBAL ILLUMINATION

Many actors are involved in supplying electric-lighting services. They include lamp, luminaire and lighting control gear manufacturers, wholesalers and retailers, lighting designers, building service contractors, electrical contractors, operation and maintenance providers, electric utilities and ESCOs. Daylight provision includes architects and builders, lighting designers, window and roof-light manufacturers, glazing companies, louvre and shading-device manufacturers, manufacturers of light pipes and fibre optic distribution systems, etc.

The global lighting-product manufacturing industry is made up of many enterprises ranging from large multinational public companies that manufacture a broad range of lighting products to small single-product firms, which may be publicly or privately owned. There are two major consumer markets, the commercial/industrial market and the residential market; however, there are many other subdivisions depending on the intended application, including indoor and outdoor lighting, stationary or portable lamps and vehicle lighting. In general, the lamp and ballast market is highly concentrated, whereas the luminaire market is very fragmented. In some instances smaller companies have created niche markets for specific products, requiring unique skills and technologies. This is true of the CFL market and of the new market for solid-state lighting, which is described in Chapter 7.

The lamp industry

Lamps are a globally traded commodity and there is a high degree of standardisation between international lighting markets. For several decades three major multinational lamp manufacturers have dominated the international lamp market: Philips, based in the Netherlands; OSRAM, based in Germany; and General Electric, based in the United States. Sylvania is another large multinational lamp manufacturer whose North American operations were merged with OSRAM's in the 1990s but is a separately owned brand elsewhere. While these companies have a strong presence in almost all global markets their strength in any one sector or region varies appreciably. Furthermore, some major national markets are dominated by local manufacturers. This is the case in Japan, where companies such as Matsushita, Toshiba, Hitachi and Mitsubishi have a very strong national presence and OSRAM is the only one of the "Big Three" to have a significant market share.

Traditionally, China has also been self-sufficient in lamp manufacture; however, in recent years there has been a significant reform of Chinese industry, which has led China to become the world's major lamp manufacturing centre in market volume terms. In the past, China had literally thousands of small local lamp producers, but over the last 15 years many of these businesses have been consolidated, markets have been opened up to foreign direct investment and a great many joint ventures with international producers have been established. The result has not only been a startling and continuing transformation of lamp manufacturing capability, but has led to a huge transfer of technology and growth in domestic lighting product quality. The "Big Three" all have manufacturing facilities in China, but they account for only a small proportion of the Chinese market.

The "Big Three"

Philips and Co. was founded in the Netherlands in 1891 and Philips Lighting is now the global market leader in general lighting and lamp production. Philips is a true multinational with 70 manufacturing facilities spread across 14 countries around the world. Its lighting business is divided into several divisions: Lamps, Luminaires, Automotive, Special Lighting & Ultra High Performance, and Lighting Electronics. Philips reports that the main growth areas in the lamps market are T5s, halogen lamps, CFLs and HIDs (especially for ceramic metal halide lamps). Its lamp sales and marketing activities are organised through three channels: Professional, OEM (Original Equipment Manufacturer) and Consumer. In 2004 it registered sales worth EUR 4.5 billion (USD 5.6 billion) and made a profit of 13% of revenue. It employs 44 000 people worldwide. Some 70% of Philips's sales are in European or North American countries, compared with only 30% for the rest of the world.

OSRAM was founded in Munich in 1929 as an affiliate of the Siemens group. In 2004 it had 53 production facilities in 19 countries and had global sales of EUR 4.2 billion (USD 5.2 billion), with a profit of 11% of revenue. It employed 36 000 people across 91 countries. Like Philips it is divided into several distinct divisions: General Lighting (51% of sales revenue), Automotive (16%), Ballasts and Luminaires (11%), Opto Semiconductors (11%), Precision Materials and Components (6%) and Display/Optics (5%). Some 78% of OSRAM's sales are in European or North American countries, compared with just 22% for the rest of the world.

General Electric was founded by Thomas Edison in the 19th century and is currently the world's second largest company. The Lighting Division, which was Edison's original product, is significantly smaller than that of Philips or OSRAM; however, with global sales valued at USD 2.55 billion in 2001, GE Lighting is a true global multinational even though its core market is focused within North America.

China and the global market

China is the largest national producer of lighting equipment in the world and is also the largest exporter. In 2003, the value of China's lighting industry was estimated to be CNY 100 billion (100 billion Yuan renminbi; USD 12.1 billion), of which exports are estimated to account for USD 5.4 billion. Exports grew by 49% from 2001 to 2003, with North America being the largest market.

In total there were between 1 300 and 2 000 active producers of light sources, 4 600 lamp and lantern manufacturers and 2 230 manufacturers of lighting-accessory equipment. The China State Statistics Bureau classifies enterprises into those above "designated size", which are businesses with annual revenues in excess of RMB 5 million (USD 600 000), and those below this threshold. Some 1 443 of all lighting manufacturing companies were above "designated size" in 2003, including 350 light-source manufacturers, and these had sales of RMB 52.9 billion (USD 6.4 billion), of which 30% was for light sources, 50% fixtures and 20% for accessories. The interests of the Chinese lighting manufacturers are represented by the industry association, CALI (China Association of Lighting Industry).

The industry has been undergoing a process of concentration and rationalisation that is forcing unprofitable producers out of the sector. In 2003 almost one-third of the smaller producers had either shifted production to other products or gone into bankruptcy. The remaining producers are growing, however, such that the top nine Chinese lighting manufacturers had sales revenues of between 370 million and just over RMB 1 billion in 2003 (Table 4.10). The top six companies include three businesses that are joint ventures or directly owned by the "Big Three" global lighting companies. The Chinese lighting industry is estimated to have employed 343 000 people in 2003, including almost 120 000 in lamp manufacturing.

Table 4.10 The top nine Chinese lighting-product manufacturing enterprises in 2003

Enterprise	Sales revenue (RMB, millions)
Zhejiang Yankon Group Co., Ltd	1 058
Foshan Electrical and Lighting Co., Ltd	1 014
OSRAM Foshan Lighting Co., Ltd	734
Philips & Yaming Lighting Co., Ltd	584
Penglai Debao New Light Source Lamps Co. Ltd	582
GE Lighting Co. Ltd	524
Lisheng Electric Light Source (Xiamen) Co. Ltd	450
Zhongyu Electrical Product (Shenzhen) Co., Ltd	422
Shanghai Zhenxin Electronic Engineering Co., Ltd	377

Source: ACMR, 2004.
Abbreviation: RMB = Yuan renminbi.

Europe

When viewed as a region, the European Union is the world's largest producer of lighting equipment in terms of value, although China probably now surpasses it in terms of volume. The European lighting manufacturing industry has annual revenues of about EUR 13 billion (USD 16.2 billion), of which EUR 5 billion (USD 6.2 billion) is from lamp manufacture (ELC, 2005) and EUR 8 billion (USD 10 billion) from luminaires, ballasts and associated electrotechnical equipment (CELMA, 2005). Lamp manufacturers are represented by the European Lamp Companies Federation (ELC), which includes among its members Philips Lighting, OSRAM, GE Lighting, Aura Lighting Group, BLV, Leuci, Narva and Sylvania Lighting International (SLI). The European activity of these companies employs roughly 50 000 people, produces annual revenue of EUR 5 billion (USD 6.2 billion) and supplies about 90% of the lamps sold on the European market. Manufacturers of luminaires and electrotechnical components for luminaires are represented by a European federation of national industry associations called CELMA. The 16 national member associations of CELMA represent some 1 200 companies in 11 European countries. These producers, which include many SMEs, directly employ some 100 000 people and generate EUR 8 billion (USD 10.0 billion) annually. CELMA claims to supply more than 90% of luminaires and associated electrotechnical components for the EU market.

North America

According to statistics from the US Census Bureau the US electric lamp industry comprised 80 enterprises, employed 11 473 people and had an annual turnover of USD 2.62 billion in 2002. In addition there were 12 manufacturers of fluorescent lamp ballasts who employed 2 443 people and had an annual turnover of USD 0.83 billion, and two manufacturers of HID ballasts. As in other markets the luminaire industry is bigger in terms of value and employment than lamp and ballast manufacture. In 2002 there were 473 companies (543 in 1997) manufacturing lighting fixtures for the residential sector, with annual revenues of USD 2.2 billion (USD 2.3 billion in 1997) and 15 700 employees (17 700 in 1997). There were 321 companies (326 in 1997) manufacturing lighting fixtures for the commercial and industrial sectors, with annual revenues of USD 3.9 billion (USD 4.1 billion in 1997) and 19 700 employees (23 100 in 1997) (USCB, 2005). The size of lamp and luminaire manufacture in the United States in both volume and value terms appears to have declined since 1997, presumably because of greater competition from low-cost imports.

Lamp, luminaire and control gear manufacturers in North America are represented through their industry association, the National Electrical Manufacturers Association (NEMA), which is the largest trade association in the United States for companies that manufacture products for the electro-industry. Its member companies fall into one or more of eight NEMA divisions, each made up of sections whose companies manufacture the same or related products. Some 41 manufacturers of lighting equipment are members of NEMA. The value of shipments from NEMA lighting companies was USD 8.3 billion in 2001, of which lamps accounted for 29% (USD 2.4 billion), fixtures 39%, ballasts 11% and outdoor lighting 22%. Almost all this product was sold within North America.

Japan

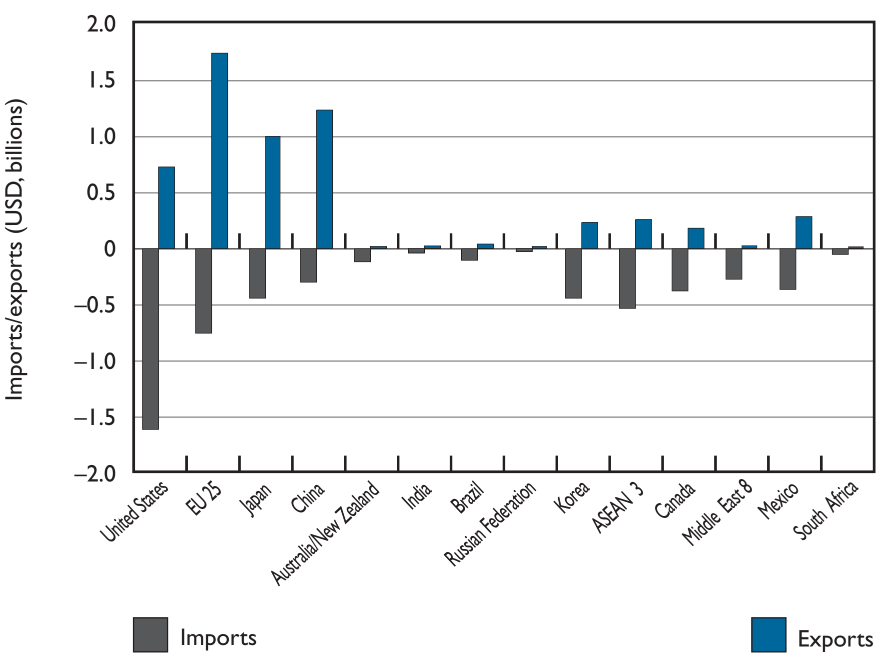
The Japanese lighting industry is represented by two associations: the Japanese Electric Lamp Manufacturers Association (JELMA) and the Japanese Luminaire Association (JLA). JELMA comprises 102 members, including Toshiba, Matsushita Electric Industries, Toshiba Lighting & Technology, Hitachi Lighting, Mitsubishi Electric, OSRAM, NEC Lighting, Koito Manufacturing, Stanley Electric, Ushio Inc., Iwasaki Electric Nichia Corp., Toyoda Gosei Co., Fuji Electric Lamp Industrial and Hakuyo Electric Lamp. In 2003 JELMA members had sales worth JPY 418 billion (USD 3.9 billion).

Global trade in lamps and lighting products

The European Union, China and Japan are the major exporters of lighting equipment according to data from the United Nations Commodity Trade Statistics Database (UN Comtrade, 2005). The global trade in individual lamps (light-bulbs) was probably of the order of USD 6 billion in 2003, but a large volume and value of lamps pre-integrated into fixtures were also traded. Europe was the largest exporter in value terms, with almost 30% of the global lamp market. Exports from China accounted for ~21%, Japan 17% and the United States 13%. There was strong growth in exports from China, which grew by 30% compared to 2002, and to a lesser extent from the European Union, with growth of 17% (Figure 4.22).

The United States was the largest importer, accounting for roughly 29%, followed by the European Union with 14% of the market, three ASEAN

Figure 4.22 **Global trade in electric lamps in 2003**



Source: UN Comtrade, 2005.

countries (specifically Malaysia, Singapore and Thailand) with 10%, Korea and Japan with 8% each and Canada with 7%.

The global trade in ballasts (those not already integrated into fixtures) is worth in excess of USD 1 billion, with Europe and China being the leading exporters and the United States and Europe the leading importers.

But these figures only capture a relatively small share of the global lamp and ballast trade as a great many lamps and ballasts that are traded are integrated into a luminaire or larger finished product (such as vehicles).

The growing importance of China

The main trend in the international lamp trade is the growing market share of Chinese products. China's lamp exports grew in value by 35% from 2003 to 2004 to reach USD 1.43 billion. Fluorescent lamps increased sales by 42% compared to the previous year, to account for over half of China's lighting-product exports. CFLs accounted for two-thirds of total fluorescent lamp export value. There are estimated to be more than 1 000 CFL manufacturers in China and they are thought to account for about 70% of the global CFL market in volume terms. The boom in fluorescent lamp exports is driven largely by a global trend toward energy-efficient light sources and CFLs in particular. But other Chinese exports of other lighting products have also grown strongly: halogen and incandescent lamp exports grew by 27% to USD 197 million and USD 236 million, respectively. The main export markets for Chinese lighting products are North America, Asia, Europe, South America and the Middle East. In 2002, products worth some USD 1.64 billion, more than one-third of the total export value, were sold in the United States.

The lighting market

Global market value and trends

According to a market forecast from the Freedonia Group, the global demand for lighting fixtures is expected to increase by 6.2% each year from 2004 up to and including 2008 and reach a value of USD 85 billion (Freedonia, 2004). On this basis the fixture market in 2003 was worth USD 63 billion. The global lamp market was estimated to be worth USD 14 billion in 1999 (OSRAM, 2000), while the value of the global automotive-lighting market was estimated to be USD 9.2 billion in 2001

(Koito, 2001). A synthesis of this information together gives an estimated global lighting market with a value of roughly USD 83.4 billion circa 2001, of which fixtures accounted for USD 58.8 billion, lamps approximately USD 15.4 billion and vehicle lights USD 9.2 billion.

According to the Freedonia forecasts there will be a greater rate of growth in the global lighting-fixture market up to 2008 than occurred in 1998–2003, as a result of increased manufacturing and construction activity triggered by global economic growth, continuous urbanisation and the expansion of electricity grids in rural areas. Not surprisingly, the rate of growth is projected to be highest in the developing areas of Asia-Pacific, Eastern Europe, Africa, the Middle East and Latin America. The highest growth rates, at 7.7% per annum, are expected in the Asia-Pacific region because of the rapid industrialisation of countries such as China and India. Demand for lighting fixtures in North America and Western Europe is projected to grow by 5.9% and 4.0% per annum, respectively, which is well above the 1.5% and 2.9% growth rates registered over the period of 1998 to 2003.

Freedonia anticipates that more technologically advanced and energy-efficient products will be the trend, particularly in economically advanced markets with stringent regulations. Non-portable lighting fixtures, which accounted for almost three-quarters of overall lighting-fixture demand in 2003, will remain the dominant line.

Lamp sales by volume[21]

Incandescent lamps

Incandescent lamps, especially GLS lamps, are the most commonly sold lamp in the world and dominate retail lamp sales orientated toward the residential sector in most countries. Open-source statistics on their sales volume are rather hard to come by and so comprehensive international sales data are somewhat sparse. It has been estimated that in 1997 there were about 10 billion GLS lamps sold internationally (Borg, 1997b), but sales of other standard incandescent lamps are also significant. These include decorative lamps and reflector lamps and can account for up to 17% of incandescent lamp sales by volume. In this study a great many different sources have been

21. Sales data reported in this section are from a large variety of sources, including: ACMR, 2004; Borg, 1997b; BRE, 1994; CALI, 2005; CELMA, 2005; ELC, 2005; Ellis, 2001, 2003; Itron, 2005; G. Januzzi (personal communication, 2005); JELMA, 2004; MTPROG, 2005; Nadel and Liu, 2005; Navigant, 2002; PWC, 2001; Ramaswamy 2004; Turiel *et al.*, 2000; UN Comtrade, 2005; USCB, 2005; USDOE, 2003, 2004; Vorsatz *et al.*, 1997.

Table 4.11 **Estimated* global lamp sales in 2003**

Lamp type	World		OECD		Non-OECD	
	Lamp sales (millions)	Share by volume (%)	Lamp sales (millions)	Share by volume (%)	Lamp sales (millions)	Share by volume (%)
Incandescent	13 152	72.4	5 375	69.7	7 777	74.3
Halogen	839	4.6	372	4.8	467	4.5
T5	184	1.0	103	1.3	82	0.8
T8 LFL	1 589	8.7	749	9.7	840	8.0
T12 LFL	1 085	6.0	520	6.7	566	5.4
CFL	1 111	6.1	499	6.5	612	5.9
High-pressure sodium	68	0.4	33	0.4	35	0.3
Metal halide	70	0.4	44	0.6	26	0.2
Mercury vapour	79	0.4	23	0.3	56	0.5
Total	**18 177**		**7 716**		**10 462**	

* Synthesis derived from multiple sources for general lighting applications.
Abbreviations: CFL = compact fluorescent lamp; LFL = linear fluorescent lamp.

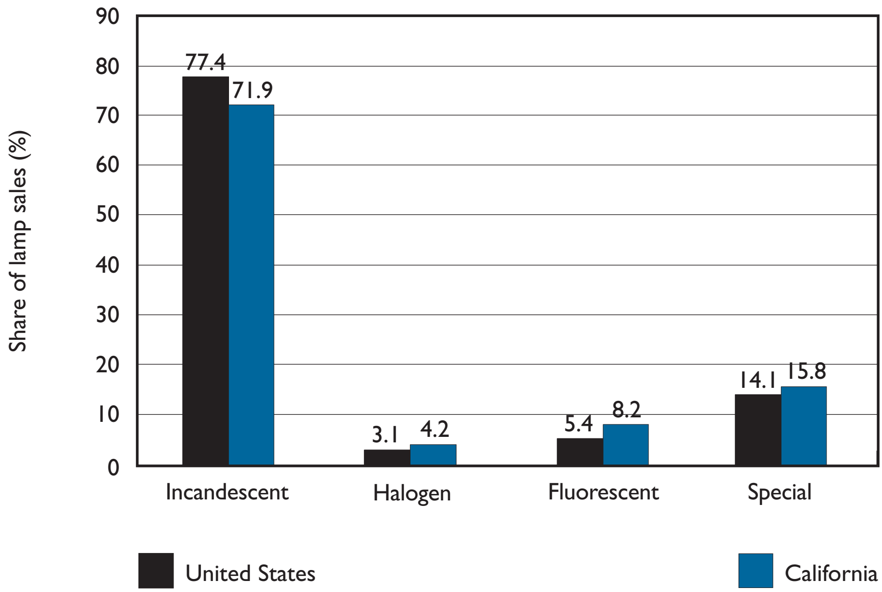
synthesised to produce estimates of global lamp sales by country and lamp type (Table 4.11). From this it is estimated that more than 13 billion incandescent lamps for general lighting applications were sold globally in 2003, with 41% in the OECD and 59% in non-OECD countries.

The United States and China are the largest markets for incandescent lamps, with combined residential and non-residential sales probably in excess of 2.5 billion lamps per year in each market. Sales in the rest of Asia and the countries of the Former Soviet Union are about 3.2 billion and in Europe about 1.8 billion. In all countries the residential sector is the dominant market for incandescent lamps. Figure 4.23 shows data on lamp sales in the US residential retail sector in 2000 accounting for slightly more than 80% of total residential sales. It shows the degree to which incandescent lamps dominate the residential lamp market and is indicative of patterns seen in most but not all other economies.

Halogen lamps

The continued popularity of incandescent lamps is related to their very low initial cost, warm colour, excellent colour-rendering index (CRI) and

Figure 4.23 Residential lamp sales by lamp type in the United States and California in 2000



Source: RER, 2001.

instant brightness. It is also related to a long-standing consumer familiarity that is not matched by any other lamp type in most lighting markets. However, in some lighting markets, such as Japan and the Philippines, incandescent lamps are not the dominant lighting technology in any user sector, while in others they face competition from halogen lamps and CFLs.

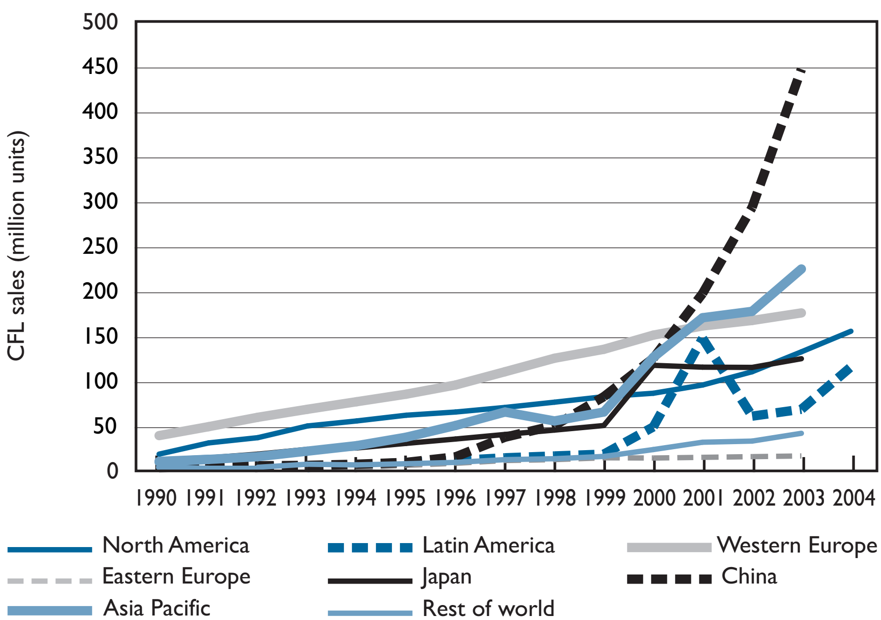
Halogen lamps are popular in most economies but have much lower sales volumes than standard incandescent lamps. Europe and China have the largest markets, with annual sales of almost 220 million lamps in each, but Japan is the country where halogen lamps have the largest proportion of total incandescent lamp sales (almost 30%) because other incandescent lamp sales are so low. In Europe the share is 12% and in China it is 8.5%. Halogen lamps are less popular in the United States, where they took roughly 3.4% of residential retail lamp sales in 2000, and although their market share is thought to be growing it is still lower than that seen in other OECD regions.

CFLs

Since their introduction onto the mass lighting market at the beginning of the 1980s, CFL sales have slowly increased as a proportion of the total lamp market, but at an accelerating pace. A synthesis of recent market data conducted for this study suggests that global CFL sales have increased strongly in recent years and attained 1.1 billion units in 2003. This is a highly important development for lighting efficiency as CFLs are competing directly with standard incandescent lamps and have a far higher efficacy. Europe remained the largest market for CFLs from the moment they were first launched until 2001, but thereafter China has become the largest market, with sales of 355 million CFLs in 2003 (Figure 4.24).

The market share by volume occupied by CFLs varies considerably from one region to another and seems to follow no obvious relationship with

Figure 4.24 **Estimated* global CFL sales by region in 1990–2004**

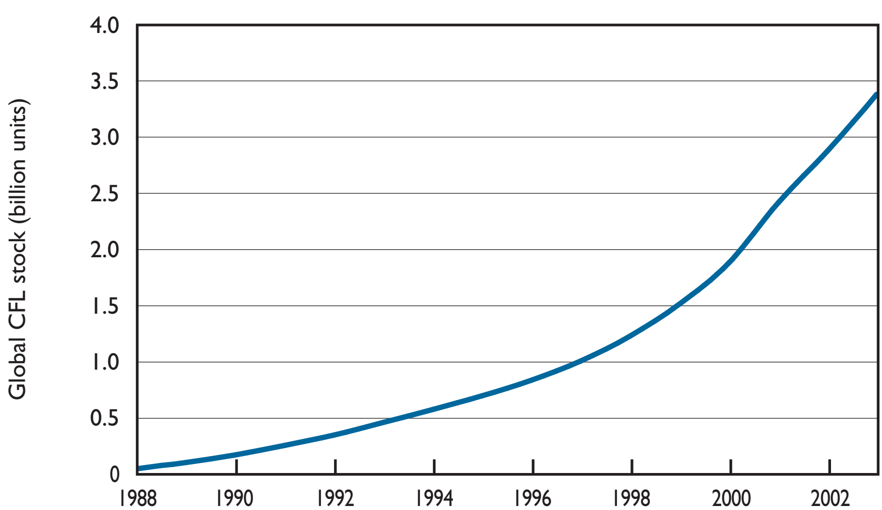


*Various sources.
Abbreviation: CFL = compact fluorescent lamp.

consumer spending power or affluence. In the United States the CFL share of medium screw-based lamps has steadily increased from less than 1% in 1998 to 2.5% in 2004 (Itron, 2005). In Europe CFL sales comprise about 10% of incandescent lamp sales, but in Japan CFL sales slightly exceed those of GLS lamps. Despite their relatively high price many less developed countries have highly developed CFL markets. CFL sales reached almost 14% of incandescent lamp sales in China in 2003 and 17% of those in Brazil in 2002. Depending on the quality of technology used, a CFL will last 3 to 20 times as long as an incandescent lamp, thus each lamp sold is equivalent to the sale of several incandescent lamps in terms of the light it delivers from any fixture. Based on typical lamp-life assumptions it is estimated that as of 2003 there were almost 3.5 billion CFLs being used around the world (Figure 4.25), which is somewhere between 12% and 20% of the global incandescent lamp stock at that time.

The changing fortunes of CFL sales result from a number of factors. When CFLs were first introduced they were expensive (more than 30 times that of an incandescent lamp), had quality issues (flicker, long start and warm-up times, bluish light) and would only fit into some existing lamp fixtures.

Figure 4.25 **Estimated* global CFL stock**



Abbreviation: CFL = compact fluorescent lamp.

Furthermore their advantages of low life-cycle cost and long lifespan were little understood. This mixture of high price, mixed quality and low awareness hindered their adoption in residential markets but was less of a barrier in commercial- and industrial-lighting markets, where awareness of overall economy is higher and installations are more likely to be installed and serviced by lighting professionals. The commercial- and industrial-lighting markets rapidly favoured pin-based CFLs rather than ballast-integrated models because the ballast lasts longer than the tube, which allows for greater overall economy, and because more efficient luminaires could be designed for the pin-based lamps. Accordingly pin-based CFLs accounted for almost 60% of all CFL sales in 1990; however, as the residential CFL market has grown their share has fallen and was about 40% in 1999 and may have been less than one-third in 2003.

The rise in residential CFL sales has occurred because of much more competitive prices, improved CFL performance compared with incandescent lamps, a growing number of applications for CFLs, which can now be used in almost all the same sockets as incandescent lamps, and a growing, though still low, understanding of the energy, lifetime and life-cycle cost benefits.

LFLs

LFLs have high sales in all economies but occupy a larger proportion of total lamp sales in some than in others. While LFLs dominate the commercial-lighting market in all countries, they also dominate the residential-lighting market in some, such as Japan and the Philippines. They account for 66% of all lamp sales by volume in Japan, about 24% in India, 21% in Australia, 16% in Europe, 12% in China, 7% in Russia and 4% in the United States.

There are also significant variations in the share of total LFL sales by type. In Europe, China, Australia and many other countries, such as Thailand, T8s dominate LFL sales, but in all these markets the less efficient halophosphor T8s have a much larger market share than the more efficient triphosphor lamps. In Europe, for example, T8s accounted for 77% of all LFL sales in 2003 and T12s only 6% (purely for very long tubes), but triphosphor tubes accounted for 36% of the T8 market and halophosphor tubes for 64%. In countries using lower voltages, such as the United States, Japan and parts of Brazil, it is not possible to install T8s into T12 fixtures and as a result the older and less efficient T12 lamp technology has retained a significant share of the LFL market. In the United States, T8 sales had grown to about 50% of the LFL market in 2004 and T12 sales had declined to 45%. Of the T12s about 75% were of the so-called "energy saving" variety, which are 34 W lamps for the most common 1 200 mm length.[22] Minimum energy performance regulations prohibit the sale of halophosphor T8 lamps on the US market, hence about 80% of T8 sales in 2004 were for standard triphosphor lamps and the remainder for the so-called "super" T8s. But in many non-OECD countries on 220–240 V electricity networks, including Russia and India, low-quality T12s still dominate the LFL market despite it being possible to directly substitute T8s into existing T12 fixtures.

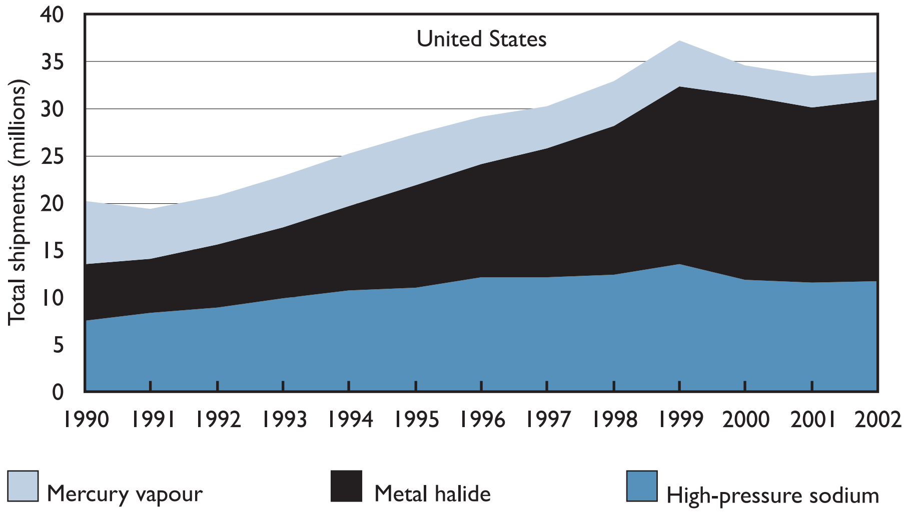
Despite T5s having to be installed in specific fixtures, the market has started to gain momentum in many countries and now accounts for significant sales in some of them. In most OECD countries T5s accounted for 4–5% of LFL sales in 2003, but in Japan they had 10%; however, this is not as high a share as in China, where they accounted for 13% of LFL sales. This can be explained by the relative share of new-fixture sales in the different countries. In rapidly developing economies, such as China, there is more new construction and hence T5s have a larger opportunity to capture market share.

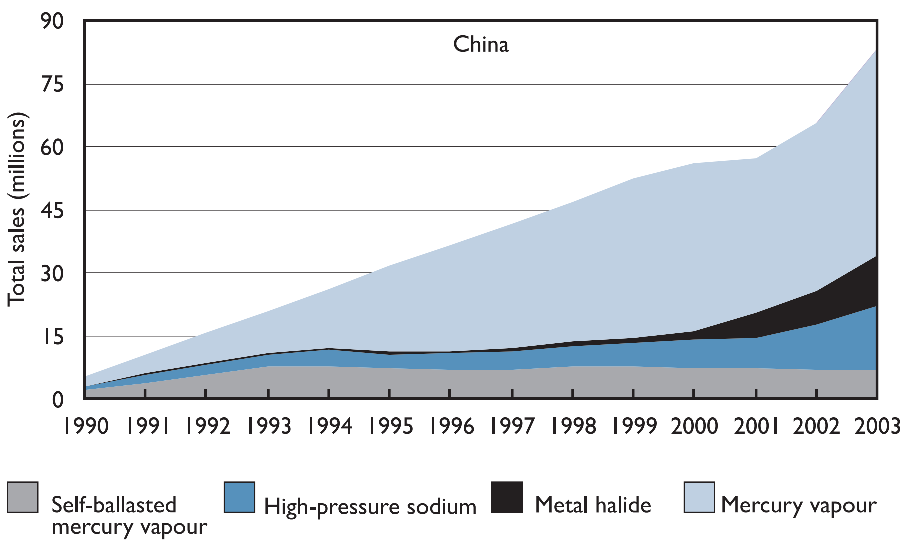
HID lamps

HIDs account for a very small share (0.8–1.7%) of lamp sales volumes in all countries, but because of their high efficacy, high average power and lifetimes they account for a disproportionately high degree of the delivered light. The relative size of the HID market is generally larger in OECD countries than the non-OECD ones, mostly because of higher levels of street and roadway lighting. The average efficiency of HID lamps varies considerably between national markets depending on the relative share of low-efficacy mercury vapour lamps compared to the high-efficacy metal halide and high-pressure sodium lamps. Among OECD countries, Japan has the highest share of mercury vapour lamp sales at 42% of all HID lamps, in Europe they account for 30%, in Australia 18% and the United States only 8%. In non-OECD countries, mercury vapour lamps account for about 93% of HID sales in Russia and a more modest 61% in China. The higher share of mercury vapour lamp sales in non-OECD countries is to be expected given their relatively low first cost, but their continuing high share of HID sales in all countries, including those in the OECD, is a major source of energy inefficiency. Figure 4.26 shows sales volumes of HID lamps in the United States and China.

22. S. Nadel, Executive Director, American Council for an Energy-Efficient Economy, personal communication, 2005.

Figure 4.26 **HID lamp sales in 1990–2002/3 in the United States and China**





Source: Nadel and Liu, 2005.
Abbreviation: HID = high-intensity discharge.

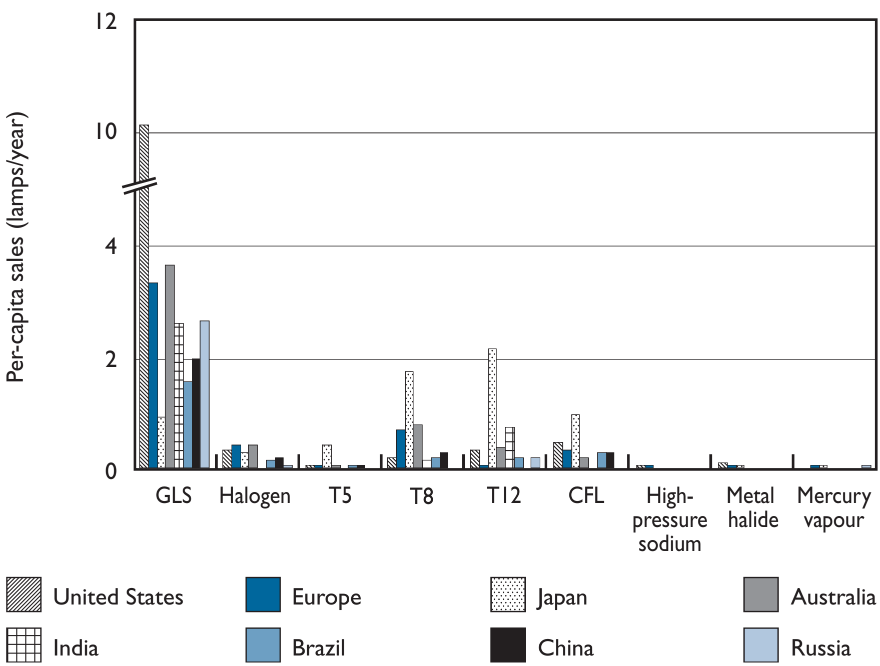
Regional summaries

The estimated sales of lamps by type is given for eight key regions or countries in Figures 4.27–4.29. The data presented in these figures are drawn from multiple sources of varying comprehensiveness and reliability and hence should be viewed as indicative rather than authoritative. The estimates are most reliable for Japan and Europe and least reliable for the non-OECD countries.

THE POTENTIAL FOR ENERGY SAVINGS

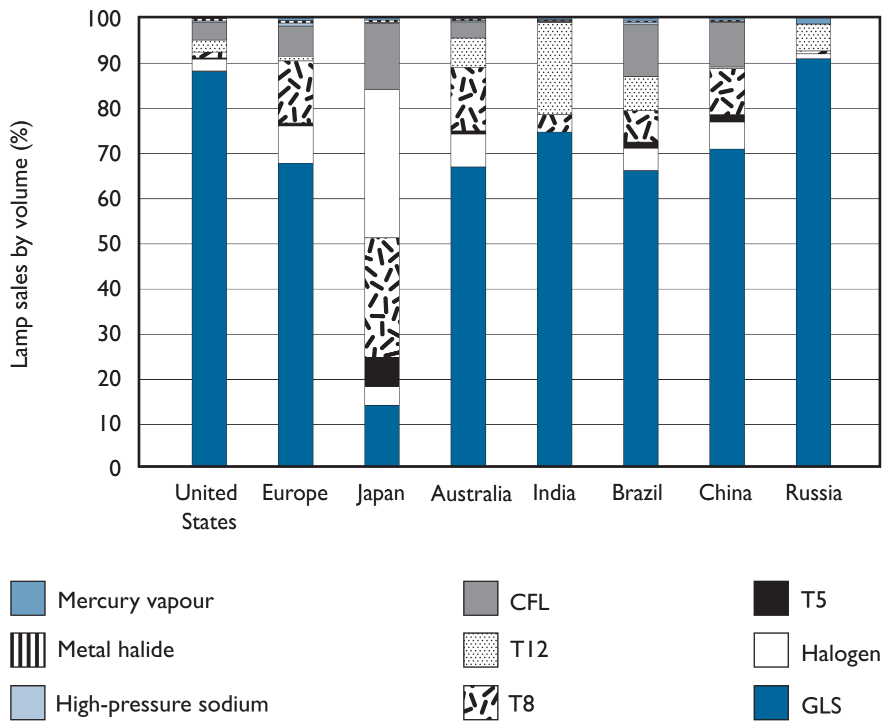
Changes in policies and programmes will take place only if there is significant potential for cost-effective energy-efficiency improvements;

Figure 4.27 **Estimated annual per-capita lamp sales by country or region***



* Data are for 2003, except for Australia and Russia, which are for 2000.
Abbreviations: CFL = compact fluorescent lamp; GLS = general lighting service.

Figure 4.28 Estimated share of lamp sales by volume, by country or region*

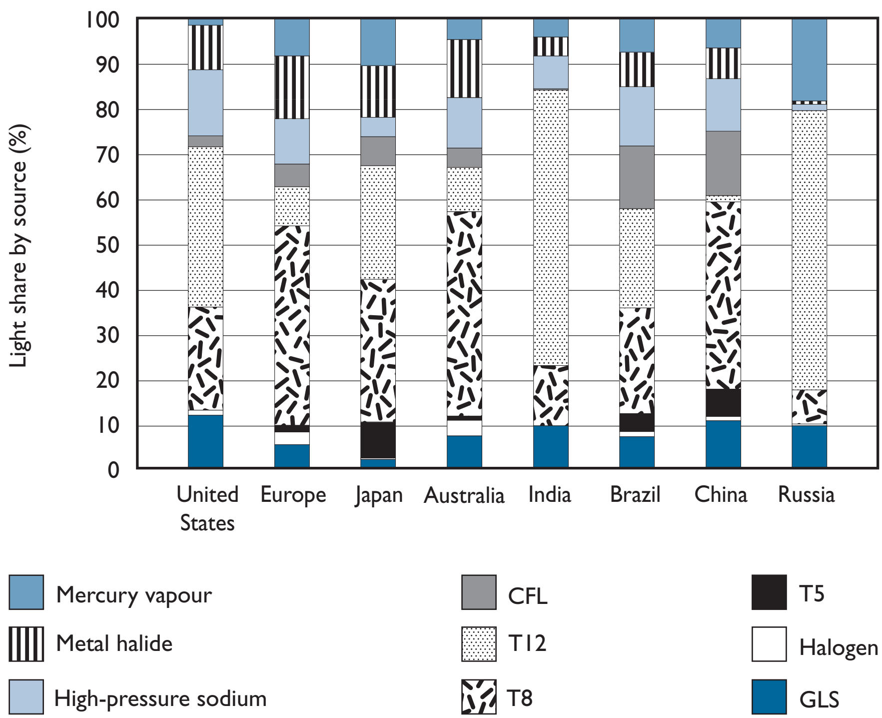


* Data are for 2003, except for Australia and Russia, which are for 2000.
Abbreviations: CFL = compact fluorescent lamp; GLS = general lighting service.

however, what is meant by the term "potential" must be clarified. This issue has been discussed in several IEA publications and it is useful to summarise the main categories of potential as follows (OECD/IEA, 1997).

- "Market potential" is the saving that can be expected in practice. It reflects what is seen to be technically and financially viable by individual and organisation end-users.
- "Economic potential" is the saving that can be achieved by optimising costs and making the best overall use of resources. It reflects the viewpoint of individual and organisation end-users.

Figure 4.29 **Estimated share of light sales by lamp type, by country or region***



* Data are for 2003, except for Australia and Russia, which are for 2000.
Abbreviations: CFL = compact fluorescent lamp; GLS = general lighting service.

- "Social potential" is the saving that can be achieved at a net positive economic benefit to society as a whole. In this situation multiple economic actors are included and externalities are taken into consideration.
- "Technical potential" is the saving achievable with the maximum energy-efficiency improvement available at a given time, regardless of cost considerations.

The rest of this section considers examples and analyses of each of these potentials as derived from the literature.

What technology opportunities are available?

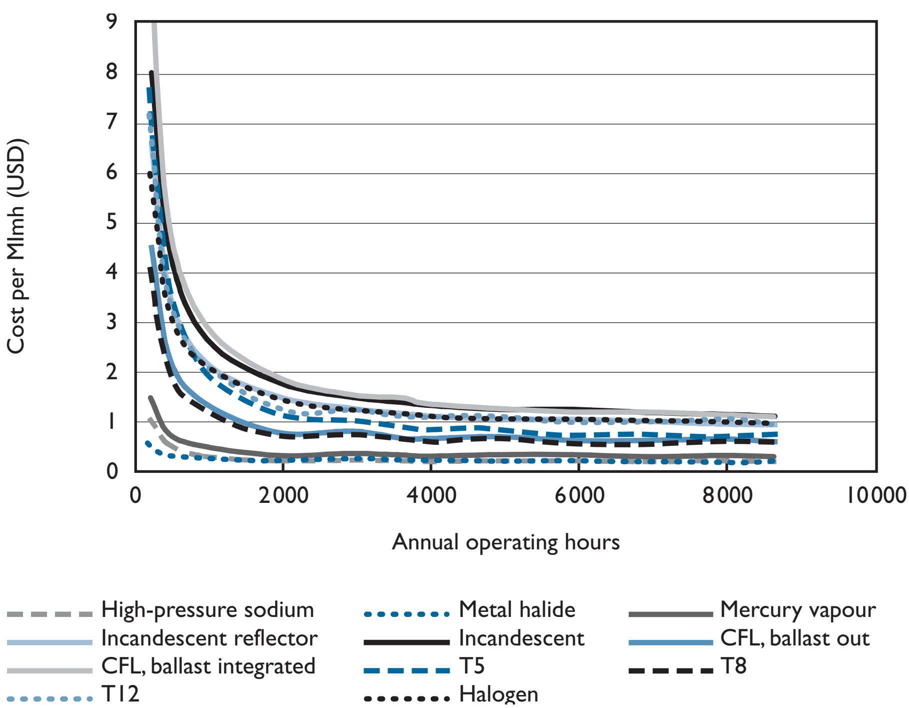
It is clear from the description of lighting technologies in Chapter 3 and the discussion of lighting markets in this chapter that there is a wide range of potential means of achieving energy savings in lighting. A relatively comprehensive list of energy-saving technology options is given in Section 8.2.3. These embrace the use of more efficacious lamps, more efficient ballasts, better luminaires, improved controls, greater use of daylight and better overall lighting design.

The economics of more efficient lighting choices

Once a given technical specification for a lamp is selected in terms of its start-up time, brightness and chromatic characteristics, the main determinant for its selection in many applications is its economic viability. This includes the costs of purchasing the lamp, luminaire, ballast and other control gear as well as the labour installation costs for all of these. In addition, life-cycle cost assessment requires full consideration of equipment replacement costs (based on the required frequency of replacement, purchase price and replacement labour costs), maintenance costs and energy costs. For example, in the commercial sector a lighting system might have a serviceable life of 20 years before a major refurbishment is undertaken. In that time the luminaires might be bought once, the lamps could be replaced three times (assuming T8 lamps with a useful life of 21 000 hours and an average annual operating period of 2 500 hours) and the ballast might need to be replaced either once or not at all (assuming it has 50 000 hours of useful life). Thus the total cost of the lighting equipment and labour would include the equipment costs for one luminaire, one (or two) ballasts, six lamps (assuming two lamps per luminaire) plus the cost of the initial installation and the subsequent replacements and maintenance costs.

In the current IEA analysis the costs of lighting include estimates of all the above as well as information about local energy tariffs taken from the *World Energy Outlook 2004* (OECD/IEA, 2004). Various sources have been used to derive equipment costs, including local lighting-industry sources, commercial websites and recent analytical references (USDOE, 2003; Navigant, 2003b). The methodological framework applied was based upon that in US DOE lighting life-cycle cost analyses used for energy-efficiency standards assessments of HID lamps (USDOE, 2003) and LFL ballasts (Turiel, *et al.*, 2000). The same spreadsheets used in these analyses were adapted for the current assessment and applied to derive life-cycle costs for all major lamp types in each region using local labour, equipment and energy costs. Because typical lighting systems have a finite lifetime regardless of how often they are used (e.g. the 20 years mentioned for the commercial sector, or longer in other environments), their costs per lumen-hour provided are sensitive to their average hours of use. Figure 4.30 shows some representative commercial-sector cost functions for the major lamp types based upon the above sources, from which it is clear that the per lumen-hour capital equipment costs diminish rapidly as average annual operating periods increase from 250 to 2 000 hours, but thereafter they tend to stabilise.

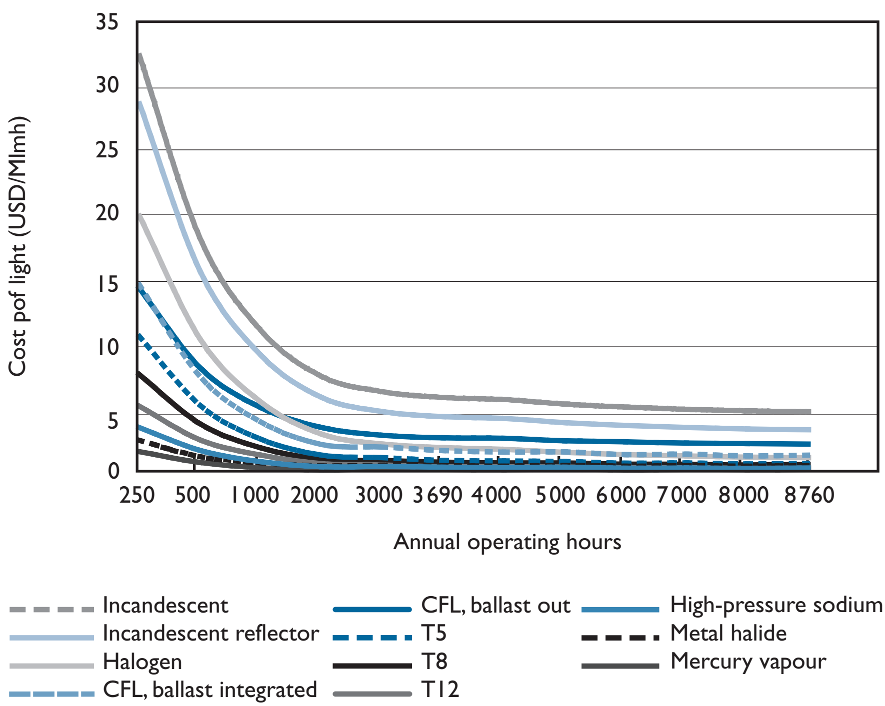
Figure 4.30 **Estimated equipment and labour costs vs. annual operating hours for providing 1 Mlmh of light, by light source***



* Assuming 0% real discount rate. Costs and operating hours are averages.
Abbreviations: CFL = compact fluorescent lamp; Mlmh = megalumen-hours.

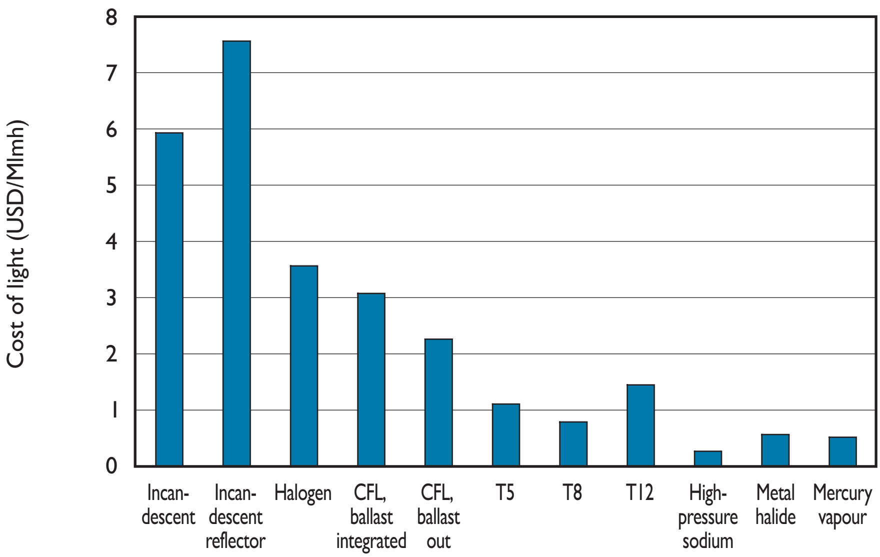
If the energy costs are included (Figure 4.31), the order of cost-effectiveness of the lamps changes dramatically such that the incandescent sources are shown to be far less cost-effective than the others. In general, the higher the efficacy of the lamp the more cost-effective it is for operating periods in excess of 500 hours per annum when energy costs are considered. Figure 4.32 shows the relative cost of the major light sources assuming a typical OECD commercial-building environment and tariff and an average annual operating period of 2 500 hours, and clearly shows the link between cost-effectiveness and efficacy.

Figure 4.31 **Estimated total costs vs. average annual operating hours for providing 1 Mlmh of light, by light source***



Source: ECODROME, 1998 (reproduced with permission).
Abbreviation: CFLs = compact fluorescent lamps.

Figure 4.32 **Estimated total costs by light source operated for 2 500 hours/year to provide 1 Mlmh of light**



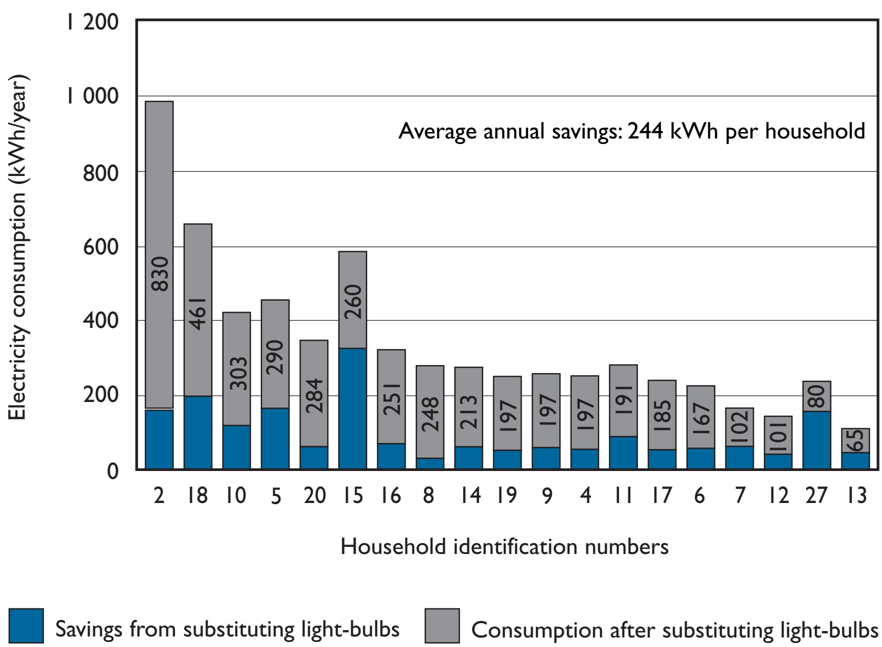
* Assuming 0% real discount rate. Costs (energy, equipment and labour) are averages.
Abbreviations: CFL = compact fluorescent lamp; Mlmh = megalumen-hours.

Lighting energy-savings potentials in the residential sector

In most countries the largest energy-savings potential for residential lighting is to be gained by replacing incandescent lamps with fluorescent lighting, particularly CFLs. A real-life example of what can be achieved is given in Figure 4.33, which shows the results from an end-use metering campaign conducted in a small sample of French households (ECODROME, 1998). The annual consumption for lighting averaged 431 kWh per household in the first year of metering. In the second year the majority of incandescent lamps were replaced with CFLs, which reduced the total consumption for lighting over the second year by an average of 74% (340 kWh per household).

In practice, converting all household incandescent lamps to CFLs will be difficult programmatically and technically, not least because many

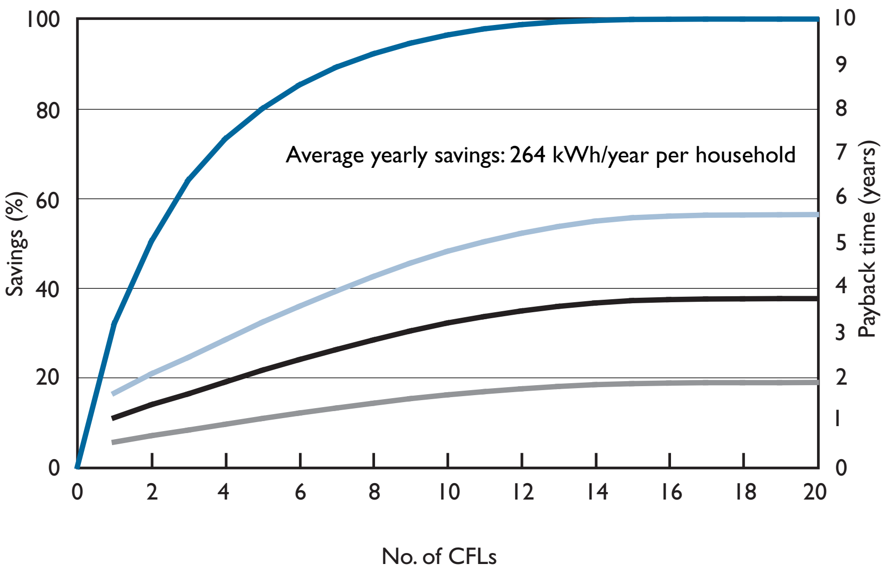
Figure 4.33 **Annual lighting electricity consumption in a sample of French households before and after replacing incandescent lamps with CFLs**



Source: ECODROME, 1998 (reproduced with permission).

fixtures are poorly suited to CFLs. Thus the question arises as to what proportion of lamps would need to be replaced to make a significant reduction in residential-lighting energy usage. The EURECO project examined this issue and found, as other analyses have done, that most of the savings can be attained with a relatively small number of CFLs per household provided that they replace the most commonly used incandescent lamps (EURECO, 2002). For example, Figure 4.34 shows the diminishing returns from replacing incandescent lamps with CFLs in a sample of Italian households, based on the results of an end-use metering campaign (EURECO, 2002). If the lamps are replaced in order of use (most-used first), replacing six lamps will produce about 85% of

Figure 4.34 **Savings and simple payback times vs. the number of incandescent lamps replaced with CFLs in a sample of Italian households**



Savings

Price of 1 kWh: EUR 0.1033

Payback time

Price of one CFL: EUR 15
Price of one CFL: EUR 10
Price of one CFL: EUR 5

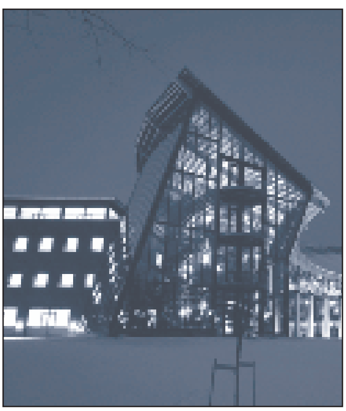
* Assuming 0% real discount rate. Costs (energy, equipment and labour) and operating hours are averages.

the total potential energy savings of 264 kWh per year; replacing the remaining 10 lamps will only give rise to another 15% savings. If the price of CFLs is EUR 10 each the payback time to the end-user will be 2.4 years at the tariff of EUR 0.1033/kWh, but if the price falls to half this level the payback period is also halved. This example demonstrates the value of targeting the lamps to be replaced.

Lighting energy savings in non-residential case studies

There are myriad examples of lighting energy savings from specific projects around the world, either in the form of new, efficient designs compared to standard practice or through direct savings following the retrofit of an existing site. The European GreenLight Programme, described on pp. 366–368 has stimulated over 1 000 such retrofits; some typical examples are shown below.

Project: Statoil Research Centre, Norway



Measure:
- Installation of occupancy-linked controls in offices and laboratories

Results:
- Lighting electricity savings: 219 000 kWh/year
- Energy cost savings: EUR 13 375/year
- Payback time: 2.5 years
- Internal rate of return = 40%

Project: Gas Natural Headquarters, Spain

Measures:
- Replaced incandescent fixtures with luminaires for CFLs (halls)
- Changed halophosphate fluorescent low-efficiency magnetic ballasts and poor-efficiency luminaires with triphosphor lamps, electronic ballasts and parabolic troffers (offices)
- Replaced general manual switch with localised switches

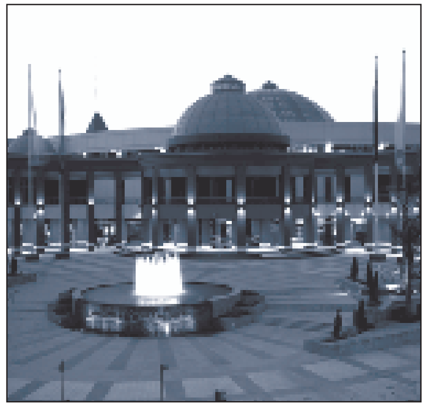
Results:
- Improved visual conditions
- Lighting electricity savings: 533 028 kWh/year
- Reduction in electricity use: 60%
- Energy cost savings: EUR 27 230/year
- Payback time: 3.5 years (halls) to 8 years (offices)

Project: Beerse Metaalwerken NV, Belgium

Measures:
- Replaced high-pressure mercury fixtures with luminaires for 26 mm fluorescent tubes
- Daylight-responsive control
- Replaced 38 mm fluorescent tubes with 26 mm fluorescent tubes
- Lamps geared by electronic ballasts

Results:
- Better lighting quality
- Lighting electricity savings: 24 919 kWh/year
- Reduction in electricity use: 38%
- Total running-cost savings: EUR 7 133/year
- Internal rate of return: 20%

Project: Colombo Shopping Centre, Portugal



Measures:
- Substituting magnetic ballasts with electronic ones

Results:
- Lighting savings: 400 838 kWh/year
- Reduction in electricity use: 12%
- Energy cost savings: EUR 23 814/year
- Internal rate of return: 20%

The common factor in these and the other examples is the high cost-effectiveness of the savings even when accounting for the incremental cost of a retrofit (which involves premature retirement of lighting capital), as opposed to implementing a new, efficient installation (which does not). Payback periods typically vary between 1 and 11 years, depending on the project, and internal rates of return of 20% on investments are usual. This provides circumstantial evidence to support the notion that the use of more efficient lighting is generally cost-effective in almost all circumstances. Although the European GreenLight Programme documents such examples for a wide range of projects that only cover

Project: City of Sassari, Italy

Measure:
- Installed a centralised dimming system

Results:
- Easier maintenance
- Lighting savings: 2 412 620 kWh/year
- Reduction in electricity use: 30%
- Energy cost savings: EUR 224 374/year
- Payback time: 2.3 years
- Internal rate of return: 33%

Project: Upgrade of LFL installation in Neukauf Merz Supermarket, Germany

Measures:
- Substituting magnetic ballasts with electronic ones

Results:
- Lighting savings: 400 838 kWh/year
- Reduction in electricity use: 12%
- Energy cost savings: EUR 23 814/year
- Internal rate of return: 20%

European buildings, savings with a similar order of magnitude have been found in lighting retrofit projects around the world. It is the attractive nature of such investments that has drawn utility and government energy-efficiency programmes to this sector more than all others, as discussed in Chapter 5.

Previous savings estimates

Global and generic savings estimates

There are few systematic and quantitative studies estimating the global or even the IEA countries' lighting savings potential. One recent study, commissioned for the IEA, estimated the global lighting energy-savings potential to be 30–50% of total lighting energy use (Mills, 2002). The savings potential within the residential sector (including fuel-based lighting) was estimated at 40–60% and within the commercial sector at 25–40%. In the case of the commercial sector these savings were intended to represent a hypothetical policy pathway that included a combination of modest standards and aggressive voluntary programmes promoting cost-effective lighting-efficiency improvements with today's technologies. Mills estimated the pure technical savings potential to be considerably larger if market barriers and policy limitations are ignored. Furthermore, the estimates took no account of the very large differences in recommended illuminance levels across IEA countries (see pp. 85–93) or the potential for savings from the use of daylight. If these are taken into account much larger savings potentials can be derived, *e.g.* 64% of energy for lighting in Swedish commercial buildings (Nutek, 1995), or an estimate of 50–80% energy savings in global office buildings from the use of daylight (Bodart and De Herde, 2002). The savings in this latter study result not only from decreasing artificial-light energy consumption, but also from decreasing waste heat of lamps.

In the work leading up to this analysis Mills reviewed previous lighting energy-savings potential literature and found very few studies that examined this issue within IEA member countries. Many assessments looked at specific policy options (*e.g.* the impact of ballast standards [Webber and Slater, 1994]) or technologies in specific sectors such as CFLs in the European residential sector (Palmer and Boardman, 1998). There were differences depending on the type of potential being examined. Some looked at pure technical savings potential while others examined potentials bounded by market, policy and economic constraints. These differences naturally make it difficult to make direct comparisons between studies. In Mills's survey only three studies (Atkinson, *et al.*, 1992; Swisher *et al.*, 1994; Vorsatz *et al.*, 1997) used detailed supply-curve analysis to cost and rank technology options, and these only applied to the United States and Sweden. Only two studies (Sezgen *et al.*, 1994; Nutek, 1995) explored the impact of lighting on heating and cooling loads in addition to direct energy demand, and only three examined lighting-related carbon emissions (Atkinson *et al.*, 1992; Granda, 1997; Palmer and Boardman, 1998). Finally, most scenarios analysed were unclear with respect to the reference scenario from which the more efficient scenarios were developed, although this was not the case for one US and three Swedish studies (Atkinson *et al.,* 1992; Bodlund *et al.,* 1989; Swisher *et al.*, 1994; Nutek, 1995).

A few recent analyses estimated the savings potential of more efficient lighting in specific sectors and regions. The IEA applied the least life-cycle cost (LLCC) analysis method to estimate residential energy savings in the IEA member countries (OECD/IEA, 2003). Under a scenario that imagined the outcome were LLCC lighting systems to be installed under normal lighting-replacement cycles from 2005 onwards (the Least Life-Cycle Cost from 2005 [LLCC from 2005] scenario), residential-lighting electricity consumption was projected to decrease by 54% over the period 2005–2010. In the LLCC from 2005 scenario, 80% of all incandescent lamps, which are used for one hour or more a day, are substituted with CFLs between 2004 and 2007. The corollary of this is an assumption that some 20% of existing luminaires that would otherwise contain incandescent lamps used for one hour or more per day are not suitable for CFLs. The net impact of this substitution is to lower the average unit energy consumption per lamp socket from 49.7 kWh/year to 24.3 kWh/year in North American households and from 26.2 kWh/year to 10.8 kWh/year in European households. In consequence, savings in residential lighting among IEA member economies would exceed 200 TWh in 2020, which is larger than the savings projected for any other residential electrical end use.

In offices and schools, an EU SAVE project reported that substantial energy savings are possible from upgrading to current typical or best-practice lighting technologies (Novem, 1999). The average lighting stock gradually improves as newer, more efficient installations replace old, inefficient ones; however, much of the existing stock remains unchanged. Upgrading this unchanged part of the current office-lighting stock to the standard for typical new installations would give a saving between 20% and 47% of the current energy used for lighting, depending on the country considered. This would give a 34% (9.8 TWh) saving across EU offices as a whole. Upgrading to current best practice would raise this saving to around 55% (16 TWh) for the European Union, with variations between 45% and 68% depending on the country. The potential savings in schools are somewhat lower. A saving across the European Union of 30% (4.5 TWh) would result from upgrading all existing lighting to typical current practice. If the lighting were upgraded to best practice, a saving of 54% (8 TWh) would be realised.

In the commercial sector in the United States, one study found that the proportions of potential cost-effective energy savings were highest for incandescent-using building types: 35% of energy could be conserved in lodging facilities, 33% in restaurants and 41% in miscellaneous building types (which includes public assembly) by the year 2010 (Vorsatz *et al.*, 1997).

In a separate study on solid-state lighting, analysis in the United States estimates that by 2025 solid-state lighting could reduce the global amount of electricity used for lighting by 35%. Most of the electricity comes from burning fossil fuel, hence the reduction in energy consumption results in reduced carbon emissions at the level of hundreds of millions of tonnes a year. The cumulative savings potential in the United States alone over 2000–2020 could amount to 760 GW of electrical energy, eliminating 258 million tonnes of carbon emission, alleviating the need for 133 new power stations (1 000 MW each), and leading to cumulative financial savings of USD 115 billion (1998-dollars) (OIDA, 2002a; Kendal and Scholand, 2001). The potential for solid-state lighting is reviewed in Chapter 7.

Recent national lighting energy-savings estimates

Japan

The Japanese Luminaire Association has produced past and future estimates of Japanese lighting energy consumption under certain scenarios (JLA, 2005). The reference case is indicated in Table 4.12.

The savings from implementing various energy-savings measures were also projected to 2010 under two scenarios:

a) implementation of the existing "Top Runner" energy-efficiency requirements (described on pp. 309–345).

Table 4.12 **Estimated lighting energy consumption in Japan were no energy-savings policy measures to be implemented**

Year	Total energy use* (TWh)	Commercial sector (TWh)	Residential sector (TWh)	Industrial sector (TWh)
1990	100.8	39.3 (39%)	31.2 (31%)	30.2 (30%)
1997	114.1	45.6 (40%)	38.0 (33%)	30.5 (27%)
2000**	120.0	48.0 (40%)	40.0 (33%)	32.0 (27%)
2005**	130.6	52.2 (40%)	43.5 (33%)	34.9 (27%)
2010**	142.0	56.8 (40%)	47.3 (33%)	37.9 (27%)

Source: JLA, 2005.
* Electricity use for lighting.
** Without additional energy-efficiency policies or measures in lighting. Growth rate of energy demand used in this prediction is 1.7%.

Table 4.13 Energy and CO_2 savings* from current and potential policy measures for energy-efficient lighting

Policies and measures**	Estimated 2000 (achieved)	Average luminaire 2005 (target)	Total efficiency 2010 (target)
2.1 Top Runner programme on fluorescent lights	3.1 (1.12)***	14.5 (5.23)	32.0 (11.5)
2.2 Introduction of CCFLs to "emergency exit" lamps	0.3 (0.10)	1.1 (0.40)	1.7 (0.62)
2.3 Introduction of lighting control systems to commercial sector	1.0 (0.37)	3.7 (1.3)	6.5 (2.3)
2.4 Replacement of incandescent lamps with CFLs	0.36 (0.13)	2.0 (0.71)	4.5 (1.6)
2.5 Introduction of efficiency-improved incandescent lamps	0.58 (0.21)	1.1 (0.38)	0.89 (0.32)
2.6 Introduction of high-efficiency HID lamps to street lighting	0 (0)	1.7 (0.61)	2.3 (0.83)
Total energy savings	**5.4 TWh** **(1.93 Mt-CO_2)**	**24 TWh** **(8.64 Mt-CO_2)**	**48 TWh** **(17.2 Mt-CO_2)**
Energy saving rate (total energy savings/energy use†) (%)	4.5	18.4	33.7
Lighting Energy Consumption Index (compared to 1990)	113.7	105.8	93.4

Source: JLA, 2005.
* Energy savings are given in TWh; CO_2 savings (in brackets) are given in Mt-CO_2.
** Details are provided in Chapter 5.
*** CO_2 emission reduction (Mt-CO_2/TWh = 0.36).
† See Table 4.12.
Abbreviations: CCFLs = cold-cathode fluorescent lamps; CFLs = compact fluorescent lamps; HID = high-intensity discharge; Mt-CO_2 = million tonnes of CO_2.

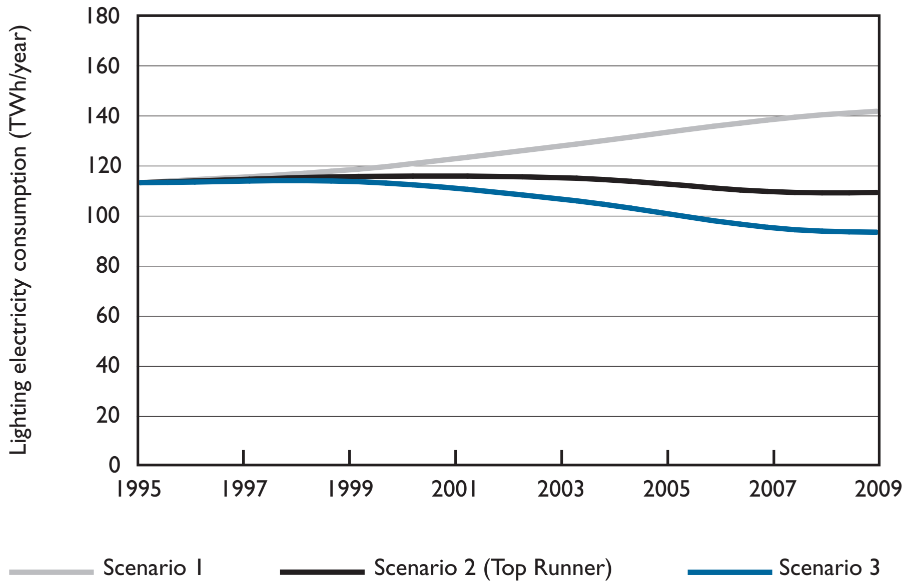
b) as in "a" but with additional energy-savings measures as described in Table 4.13.

The projected impacts of these measures are also given in Table 4.13 and Figure 4.35.

The specific technical features of the additional measures considered in the third scenario ("b" in the preceding list) are as follows.

- Introduction of cold-cathode fluorescent lamps (CCFL) to "emergency exit" signs.
  - 19 W savings per lamp (reducing energy consumption from 28 W for the current type to 9 W for the CCFL).

Figure 4.35 **Japanese lighting energy consumption scenarios for 1995–2010**



Source: JLA, 2005.

- CCFL market share (sales): 56% in 2000, 97% in 2005, 100% in 2010.
- Stock share: 13% in 2000, 48% in 2005, 68% in 2010.

■ Introduction of efficient lighting-control systems into the commercial-building sector.

- Energy-savings potential of 30–65% in office and shop buildings.
- This measure is the main target in the 2005 revision of the Japanese Energy Conservation Law.

■ Replacement of incandescent lamps with CFLs.

- Assumes 60% of incandescent lamps will be replaced with CFLs.
- Also assumes use of higher-efficiency CFLs, leading to energy savings of 15–20% per CFL.

- Introduction of more efficient incandescent lamps.
- Introduction of high-efficiency HID lamps for street lighting, assuming:
  - Replacement of mercury vapour lamps with high-pressured sodium lamps in street lighting.
  - Use of improved reflectors that also cut the upward light waste from street lights.
  - Possible street-light stock composition in 2010 of 30% mercury lamps, 55% metal halide lamps and 15% high-pressure sodium lamps.

According to these estimates, if the JLA measures are fully implemented total lighting consumption in Japan would be reduced by 34% by 2010 and 48 TWh of electricity consumption would be saved. This is in spite of Japan being a country with historically low usage of incandescent lighting and already having the highest average lighting-system efficacy among OECD countries. Nor do any of the above measures consider the possibility of energy savings from adjusting recommended illuminance levels to be in line with other OECD country norms or from making greater use of daylight, both of which are still attractive opportunities.

United Kingdom

The UK government conducts regular appraisals of energy-savings opportunities in specific end-use sectors through its Market Transformation Programme (MTPROG, 2005b). Recent assessments have examined lighting savings potentials in the residential, commercial, industrial and public lighting sectors. Table 4.14 shows how commercial-sector lighting energy consumption is projected to evolve from 1994 to 2020 were there to be no market changes (Zero Line scenario) and the forecast impact of the current policy measures and market changes that make the new Reference Line scenario. From this it is clear that the existing mix of autonomous market changes and policy measures are on course to reduce total consumption by 11 TWh in 2020 (18.5%) and that within this some 3.9 TWh are a result of the EU Ballasts Directive described on pp. 309–345, 6.4 TWh are from the 2002 revision to the UK commercial-building codes, and 0.5 TWh are a result of autonomous market developments, *i.e.* 95% of the improvements are related to policy measures and 5% to autonomous market changes.

Table 4.14 Projected commercial-sector lighting energy consumption in the UK and forecast savings from existing policies

Year	Zero Line Scenario (TWh)	Energy savings due to market trends or policy measures					Reference Line Scenario (TWh)
		T12–T8 conversion (TWh)	HF sales to 2002 (TWh)	EU ballast Directive (TWh)	Lightswitch* 2000–2002 (TWh)	Total from building regulations 2002 (TWh)	
1994	41.42	0	0	0	0	0	41.42
2000	46.56	0.36	0.1	0	0	0	46.10
2005	51.54	0.36	0.14	0.53	0.2	1.35	49.15
2010	54.32	0.36	0.14	2.53	0.2	3.03	48.06
2015	56.91	0.36	0.14	3.91	0.2	4.72	47.58
2020	59.50	0.36	0.14	3.91	0.2	6.40	48.48

Source: MTPROG, 2005a.
* Run by the Energy Saving Trust.
Abbreviation: HF = high frequency.

It is further projected that the adoption of the "Earliest Best Practice" scenario would reduce consumption of electricity for lighting in the commercial sector to 30 TWh in 2010 and about 24 TWh in 2020, constituting savings of 38% and 50%, respectively, compared with the Reference Line scenario. The main additional measures considered in this scenario are: increased use of lighting controls (accounting for 43% of total additional savings); substituting incandescent lamps with CFLs (17% of savings); replacing halophosphor LFLs with triphosphor LFLs (14% of savings); upgrading luminaires (14% of savings); and replacing halogen lamps with new technologies such as compact ceramic metal halide lamps (12% of savings).

The Market Transformation Programme estimates that consumption in the residential sector is set to rise from about 18 TWh in 2005 to 19 TWh in 2010 under the Reference Line scenario. Adoption of Earliest Best Practice would reduce this to just 9.5 TWh in 2010, mainly through the greater usage of CFLs. This savings potential of 53% is very close to that estimated in the IEA's *Cool Appliances* publication for the same sector across IEA member countries (OECD/IEA, 2003).

China

China has been experiencing an unprecedented economic boom over the last 18 years that among other factors saw lighting energy consumption grow by about 15% per annum throughout much of the 1990s, while total national energy consumption was growing by an average of only 5% yearly. According to one estimate (Liu *et al.*, 2005), over the decade from 1988 to 1998 estimated national energy consumption for lighting grew from 44 TWh to 152 TWh per year. The China Greenlights programme has estimated that there is a technical potential to reduce lighting energy consumption by 40% just through the use of more efficient lighting technologies – particularly through greater use of CFLs in place of incandescent lamps, use of advanced fluorescent tubes and ballasts, and the replacement of older blended and mercury vapour lamps with more efficient high-pressure sodium and metal halide lamps and ballasts.

Australia

The Greenlight Australia programme estimates that lighting was responsible for 7% of industrial-, 33% of commercial- and 10% of residential-sector greenhouse gas emissions in 2001, contributing an estimated total of 25 Mt of CO_2 in 2002. Lighting consumed about 26 TWh of electricity in Australia in 2002 but this is projected to rise to 40 TWh by 2015 if no new policy measures are implemented (AGO, 2004a). Under the provisions of the Greenlight Australia programme it is expected that growth will be held to 32 TWh in 2015, which constitutes savings of 20% by 2015. These are expected savings through the implementation of a suite of policy measures, as discussed on pp. 312–316 and hence are less than the techno-economic savings potentials estimated for the same time frame.

BARRIERS TO ENERGY-EFFICIENT LIGHTING

Acknowledging cost-effective potential and realising all of it are quite different propositions. Undoubtedly, some part of the potential will be realised through normal market forces, but an important share will be hampered by factors that make the market function less effectively; in turn, this presents a rationale for policy intervention. The following section presents the major categories of market barriers that are hindering the cost-effective potential of energy-efficient lighting from being achieved. It is through a thorough analysis of the barriers that policy makers can target their initiatives to effectively overcome them and achieve their required goals.

Common barriers

Lack of information

When consumers do not have adequate information, they miss out on cost-effective opportunities. Energy-efficient lighting and lighting systems cover a wide spectrum of technologies and it is difficult for consumers, and even for distributors and installers, to learn about all their attributes, including quality. For example, the European GreenLight Programme surveyed private-sector participants to determine why they had not already installed energy-efficient lighting systems – lack of information and awareness of the cost-effective savings potential was one of the most common responses (JRC, 2001). Some areas that require better information include the importance of overall electricity costs attributable to lighting, what total savings are possible from using control systems, the payback from switching to more efficient lighting systems, the lighting-quality benefits that better lighting can provide and the indirect energy impacts of energy-efficient lighting, including the decreased need for air-conditioning.

Luminaires provide a good example of the consequences of inadequate information. The majority of luminaires in homes across Europe and the United States are designed for and use incandescent bulbs and are therefore not necessarily suitable for use with CFLs. Because of differences between the two technologies, there are a number of factors that need to be taken into account when using CFLs in existing fixtures, such as orientation of the bulb and light distribution. Most individual consumers will be unaware of these technical issues and, given the present retail structure and lack of informed retail staff, they are unlikely to find out about them. Misapplication of the technology, by using CFLs in inappropriate fixtures, may well have put people off using CFLs in the past because of the resulting poor light quality or shortened bulb life. It should also be emphasised that installing more efficient luminaires or fixtures which are suitable for CFL technologies and/or even LFLs holds a much larger potential for energy reduction.

Sources of information about energy-efficient lighting include distributors, builders/installers, utilities and governments, often via newspapers, the internet and points of sale. The credibility and reliability of information is essential but difficult to guarantee. Energy labels, such as those of the

European Union or ENERGY STAR (pp. 309–345), are important in establishing credibility. Information for professionals (builders, architects, researchers, etc.) can also be obtained through various information clearinghouses such as the IEA's CADDET or the Energy Efficiency and Renewable Energy Clearinghouse of the US DOE.

How information is presented to the consumer is important. It should be specific, simple, straightforward and available close to the time of making decisions (such as at the point of purchase).

Lack of time

Most users of lighting systems are time-constrained and have to weigh up the benefits of optimising their information and decision-making about lighting systems with many other competing demands on their time. Given the need to prioritise many will choose to invest their efforts in other directions and live with the consequences of potentially poorly informed decisions about lighting. Policy makers need to recognise this in order to understand the appropriate mix of measures they might take. The less time that is required to be invested in understanding and adopting an energy-efficient lighting solution the more chance of achieving a higher adoption rate. An analysis of this factor can favour measures that remove the work from the consumer by ensuring that efficient solutions are widely available in the marketplace through retailer and industry incentives or mandatory regulations.

Lack of confidence

Traditionally there has been scepticism about predictions of the benefits of any new technology, and this holds equally true for energy-efficient lighting. Many consumers are concerned that new lamps and systems will lack performance and reliability. In some cases, early equipment was substandard and bad reports quickly travelled from consumer to consumer.

Consumers are understandably wary of any new products, not just energy-using equipment. They often look for guarantees or assurances that the products they buy will achieve the promised results, especially when they have paid a high initial cost compared to prices for other, less efficient products. Building managers are often reluctant to invest in new technologies unless they have been well demonstrated. Demonstration projects, grant programmes and a variety of other measures have been used to gain experience to show that the equipment lives up to its promises.

Confidence is an ongoing concern when any new technology comes to the marketplace, and solutions depend in part on the maturity of the market. The public often look for independent advice, and this may mean governments need to develop measures accordingly. Often the best approach is government working in partnership with industry or utilities to gain the trust of consumers. Involvement of consumer groups also helps immeasurably.

Incremental capital equipment costs

Energy-efficient lighting is often more expensive at the point of purchase. The purchase cost of CFLs, for example, is significantly greater than that of incandescent lamps, even though their price has decreased significantly in recent years, both following enhanced market competition and because of promotions by large department stores and government or utility campaigns. However, even though CFLs are more expensive than incandescent lamps, their lifetime costs are much lower. The degree to which initial cost increments are a market barrier to a technology when life-cycle costs are lower is often related to the calibre of consumer information and the issue of confidence, as discussed in the subsections above. If the full range of benefits is known (e.g. reduced operating costs, improved comfort, lower air-conditioning needs and higher lighting quality), then the higher initial costs become less of a barrier. However, conveying this information is difficult to do in a comprehensive manner and thus there have been several initiatives to transform the market, through government or utility purchase actions. More information is available on pp. 365–380. Third-party financing is also an option to help overcome initial capital financing barriers.

State of technology development

There are concerns that many of the energy-efficient technologies cannot immediately replace existing lamps. The most obvious case is that of CFLs and incandescent bulbs. Among some end-users CFLs are perceived as bulky, unattractive, expensive, undimmable, providing poor lighting quality and slow start-up. Often they do not fit into existing lamp fixtures. The new generation of CFLs has improved the situation and some models can be dimmed. There is a problem with design because the most energy-efficient lamps are not always perceived as attractive and as versatile as incandescent bulbs or low-power halogens.

Inertia

Consumers normally opt to avoid changing habits or actions, especially when conditions such as energy prices are stable. However, within companies as well as among individuals – even given rapid economic changes, as has been evident in transition countries in Central and Eastern Europe – there is often a reluctance to move from known practice, even if purchasing energy-efficient lighting makes financial sense.

Inadequate incentives through the design and supply chain

Many decisions about lighting technologies are taken by suppliers and planners who are not the final users of the technologies. These often lack economic incentives to offer the most energy-efficient options to their customers. For example, in many situations engineers and architects are unlikely to be rewarded for investing additional time and effort in the design of a more efficient lighting installation. In a similar vein contractors will often seek to install the lowest-cost, fastest solution that satisfies the minimum conditions of the contract. If high-efficiency lighting systems are not explicitly specified it is unlikely that they will be provided under these conditions.

Separation of capital expenditure and operating expenditure

Often, those using energy or making capital decisions about lighting equipment are not the ones who pay directly for the system's energy use and hence lack an incentive to minimise operating costs. When a developer or landlord is constructing or retrofitting a building they may have every incentive to lower initial costs, *e.g.* by installing less efficient lighting systems. The tenant or purchaser of the building is then obliged to pay for the higher operating and maintenance costs. This problem is compounded because service costs are either seldom known to would-be purchasers and tenants in advance or are a second-order consideration in the decision to rent or purchase a property, and hence there is little market pressure to optimise their performance. Even within the same organisation it is commonplace for the management of capital expenditure to be separated from that of operating expenditure, which frequently results in the capital expenditure manager seeking to minimise costs in isolation of their implications for the operational costs.

Although some commercial customers purchase lamps through the typical residential "consumer channels", large commercial and government consumers typically purchase lamps directly from distributors. While purchase price plays the primary role in the lamp decisions made in the consumer market, larger commercial customers are more inclined to consider additional factors such as light quality and the costs of energy and lamp maintenance in their purchase decisions. A report found the decision-making process for commercial lighting in the United States to be highly complex and to involve at least 11 groups of people (Conway, 1991). The three most influential groups of decision-makers were found to be the building owners, lighting designers and building managers.

The "owner/user" or "landlord/tenant" discrepancy has commonly caused "principal agent" problems for improving the energy efficiency of rented buildings. Because landlords and commercial builders are responsible for an important component of lighting purchase decisions, they play an important role in determining diffusion rates. However, the final consumer generally pays for the energy costs resulting from these decisions. Landlords and builders are more likely on average to be able to take advantage of scale economies in information collection and purchasing, but the problem is that they may not find it profitable to invest in energy efficiency because the benefits of saving electricity generally do not accrue to them. Building practices and the organisation of markets for building space obviously vary to a great extent across countries. Figure 4.36 shows the links between market actors who influence the efficiency of installed-lighting systems.

Energy subsidies

The specific problem and opportunity that energy subsidies pose to energy-efficient lighting is discussed in Box 4.4.

Matching policy interventions to barriers

Chapter 5 gives actual examples of the type of policies that can be implemented to address the barriers identified above to help bring about the list of technology objectives listed on pp. 484–487. The Greenlight Australia programme recently undertook an exercise in matching

Box 4.4 Subsidies: a disincentive to invest in efficient lighting

Many countries, especially in non-OECD countries, subsidise electricity tariffs for domestic consumers for reasons of wealth distribution and social welfare. As a rule, subsidies to energy services are ineffective, economically inefficient and contrary to good environmental practice; however, they may be justified in some cases in order to combat poverty.

According to the *World Energy Outlook 2005* (OECD/IEA, 2005), electricity prices in the Middle Eastern and North African (MENA) countries are far below OECD prices and often do not even cover the long-run marginal cost of supply*. This is because electricity is considered to be a service that the government provides to its citizens and subsidies are a way to distribute oil rent in resource-rich countries. Fossil fuels may be abundant in this region, but fully cost-reflective electricity prices are unlikely to be much lower than in OECD countries, because a large part of the electricity price is related to the investment cost. Although operating costs are low in MENA countries (mainly because fuel – accounted for at prices below the opportunity cost – is cheap), charges related to generation, transmission and distribution infrastructure should be close to those of the OECD. For example, distribution-network charges in Europe range between USD 0.03 and 0.05 per kilowatt-hour in most areas. These charges are not reflected in electricity prices in most countries in the MENA region.

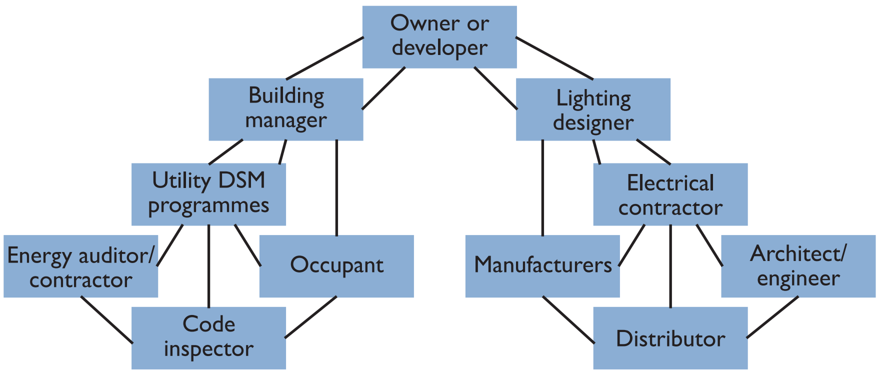
What does this mean for energy-efficient lighting? Providing subsidies to consume electricity obviously lowers the incentive for the end-user to invest in efficient technology, and this will tend to drive up the overall cost of the energy service. It is difficult to imagine market forces operating effectively to stimulate the adoption of energy-efficient lighting when energy prices are artificially suppressed. This is especially so because the application of subsidies encourages profligate consumption and disregard for energy costs, and thus dampens the price signal. Furthermore, this is in a market environment that is already unduly preoccupied with initial costs as opposed to the discounted cost of the energy service over time. As a result, the economic benefit to the state of adopting energy-efficient solutions can be even higher in countries with subsidised energy prices than in those without. This is because the adoption of efficient technology helps to offset the cost of servicing the subsidy and is usually a far cheaper option at the margin. For example, in the case of energy-efficient lighting, the marginal cost of investing in efficient (as opposed to standard) lighting is a fraction of a US cent and hence is much lower than the cost of building and maintaining the electricity network. At this low cost it will be profitable to the end-user even in the unfavourable circumstances where electricity is subsidised; however, its deployment is even more profitable to the state providing the subsidy.

Of course this finding is not confined to MENA countries as many other economies also subsidise electricity consumption. Furthermore, according to a new joint study by the IEA and OECD, many developing countries apply higher import duties on efficient fluorescent lighting than they do on inefficient incandescent lighting, which creates a further disincentive to the adoption of efficient-lighting solutions (OECD/IEA, 2006). Yet according to IEA estimates in the *World Energy Outlook 2004* (OECD/IEA, 2004) developing countries as a whole need to secure about USD 5 trillion in financing for power generation, transmission and distribution from now until 2030. This should serve as a powerful incentive to improve management of all investment portfolios, including the demand side. As efficient lighting is among the most cost-effective options available, it should be an objective of state efforts to reduce the cost of servicing their subsidies.

* The World Energy Outlook 2006 will include a special study on high energy prices and subsidies.

potential policy interventions to barriers to help identify the most appropriate and effective lighting programmes. Table 4.15 indicates how this programme has matched up technical opportunities with policy interventions for overcoming market barriers in order to prioritise a selection of measures that form a comprehensive strategy to improve lighting efficiency in Australia. Each technology opportunity is listed in the

Figure 4.36 Relationships between actors influencing the efficiency of installed lighting



Source: Conway, 1991 (reproduced with permission).
Abbreviation: DSM = demand-side management.

first column of the table, followed by its potential to reduce greenhouse gas emissions, the main barriers to be addressed and the potential intervention measure. The ranking of the potential to reduce greenhouse gas emissions for each technology measure should be viewed in the context of the Australian market, and while a similar ranking is likely to apply in most IEA economies it will not be true of all of them. Similarly, the technology options listed also depend on the specifics of the previous market and technology adoption history in Australia.

Table 4.15 Barriers and suitable policy interventions for efficient lighting (Greenlight Australia programme)

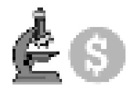
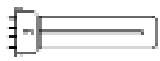
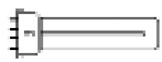
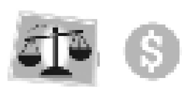
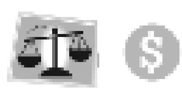
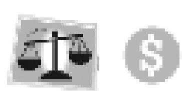
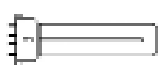
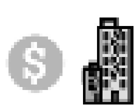
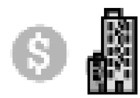
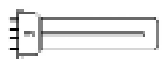
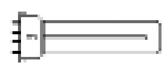
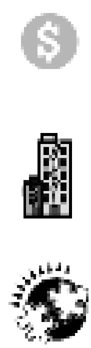
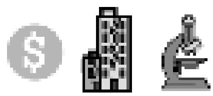
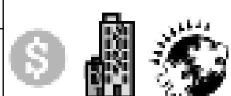
Technology opportunity	Potential to reduce emissions	Key barriers: * "Why is it not happening?"	Possible programmes
GLS lamps			
(A) Increase the market penetration of efficient GLS lamps	High		• MEPS for GLS lamps • Comparative lamp labelling • Bulk procurement of low-power GLS lamps
(B) Substitute GLS lamps with CFLs	High		
Incandescent reflector (ICR)			
(C) Substitute ICR lamps with CFLs	Low		
(D) Substitute ICR lamps with halogen reflector lamps	Low		• MEPS for reflector lamps • Comparative lamp labelling
Tungsten halogen			
(E) Increase the market penetration of efficient tungsten halogen lamps	High		• MEPS for tungsten halogen lamps • Comparative lamp labelling
(F) Increase the market penetration of efficient tungsten halogen transformers	High		• MEPS for tungsten halogen transformers • Comparative transformer labelling
(G) Increase the market penetration of efficient luminaires (for non-reflector halogen lamps)	Low		• MEPS for luminaires • Comparative luminaire labelling
(H) Substitute halogen lamps with CFLs	High		
Linear fluorescent			
(I) Increase the market penetration of efficient triphosphor lamps	High		• MEPS for LFLs • Comparative lamp labelling

Table 4.15 (continued)

Technology opportunity	Potential to reduce emissions	Key barriers:* "Why is it not happening?"	Possible programmes
(J) Increase the market penetration of efficient magnetic and electronic ballasts	Medium		• MEPS for linear fluorescent ballasts • Comparative ballast labelling
(K) Increase the market penetration of efficient luminaires	High		• MEPS for luminaires • Comparative luminaire labelling
CFLs			
(L) Increase the market penetration of efficient CFLs	Low		
(M) Increase the market penetration of dedicated CFL luminaires	High		• Bulk procurement of dedicated CFL luminaires
(N) Increase the market penetration of CFLs with superior non-energy attributes	Medium		
HID lamps			
(O) Increase the market penetration of efficient HID lamps	High		• MEPS for HID lamps • Comparative lamp labelling or mandatory information disclosure
(P) Increase the market penetration of efficient HID ballasts	Medium		• MEPS for HID ballasts • Comparative ballast labelling or mandatory information disclosure
(Q) Increase the market penetration of reliable photoelectric cells	Low		• MEPS for photoelectric cells
(R) Increase the market penetration of efficient HID luminaires	High		• Holistic MEPS for lamp/ballast/luminaire packages
(S) Substitute inefficient HID lamps for triphosphor fluorescent lamps and CFLs	High		• Bulk procurement of appropriate triphosphor & CFL products • Holistic MEPS for lamp/ballast/luminaire packages

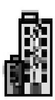
(continued over).

Table 4.15 (continued)

Technology opportunity	**Potential to reduce emissions**	**Key barriers:* "Why is it not happening?"**	**Possible programmes**
LEDs			
(T) Substitute incandescent traffic signal lamps with LEDs	High		• MEPS for traffic signals and exit-sign applications • Bulk procurement of LEDs and fittings
(U) Substitute incandescent and fluorescent exit signs with LEDs	Medium		
Lighting controls & lighting design			
(V) Spread intelligent lighting controls	High		• MEPS for new lighting installations • Education and training for specifiers
(W) Improve lighting design	High		

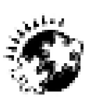
* Key:

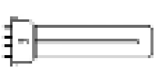

Customers do not consider life-cycle costs


"Split incentives" – the equipment purchaser does not pay its running cost


Consumers have no method of comparing efficiency between products


Lack of availability of suitable products in Australia


Disaggregated market with many stakeholders


CFLs are an appropriate solution for improving efficiency in many lighting applications. For simplicity, this symbol summarises the barriers to CFL uptake and the solutions for overcoming these barriers.
The barriers to CFL purchase are price, lack of consideration for life-cycle costs and poor performance of some CFLs. The solutions to this include MEPS for CFLs, endorsement labelling for CFLs, and comparative lamp labelling.

Source: AGO, 2004b (reproduced with permission).
Abbreviations: CFL = compact fluorescent lamp; GLS = general lighting service; HIDs = high-intensity discharge lamps; LEDs = light-emitting diodes; MEPS = minimum energy performance standards.

BLAZING THE TRAIL: POLICIES AND PROGRAMMES FOR ENERGY-EFFICIENT LIGHTING

Key messages

- Policies and measures to promote energy-efficient lighting exist in each OECD country and many non-OECD countries.
- However, they differ in nature, ambition and scope across individual countries and markets as well as across end uses.
- Information labels, MEPS and voluntary programmes are the most popular measures applying to lighting components and are typically implemented at national and regional levels.
- Building codes are increasingly being applied to new-build and retrofit lighting systems.
- Financial incentives, market transformation and promotion campaigns are mostly implemented at sub-national – state/provincial and local – levels, with utilities often playing a leading role.
- Creating a favourable environment for energy service companies can play an important role in the deployment of efficient lighting.

MEASURE FOR MEASURE: AN INTRODUCTION

Lighting is an obvious target for government energy-efficiency programmes because (i) there is a high cost-effective savings potential from the use of more efficient equipment and practices, (ii) there are significant market barriers that prevent end-users from making cost-optimised decisions and (iii) there is a rapid turnover of energy-using capital, meaning that rapid energy savings can accrue. Within 20 years the large majority of lighting systems in place even in mature economies will be new and hence implementing policies that target the new and replacement stock only could produce a large impact over that time frame.

Policies and programmes that address efficient lighting are generally targeted at the energy performance of specific lighting components, at the performance of entire lighting systems or at general transformation of the lighting market. This chapter reports on the application of these policies by type and summarises international experience to date. It begins with an introduction to the types of policies that have been deployed to date.

Government policies and programmes: common types

IEA member countries generally have well-developed energy-efficiency strategies and a wide range of policy measures to address their energy-efficiency objectives. Measures to promote energy-efficient lighting are usually integrated into other policy measures, although there are many examples of specific actions to deal with energy-efficient lighting. The main policy measures deployed include: minimum energy efficiency standards, energy labels, building codes, market-transformation programmes, financial incentives, procurement programmes and competitions, and voluntary agreements. It is useful to review the main categories of measures before country initiatives are discussed.

Minimum energy performance standards

Minimum energy performance standards (MEPS) are regulatory measures that stipulate minimum efficiency levels or maximum energy-use levels acceptable for products sold in a particular country or region. Targets are similar but commonly refer to a voluntary agreement established between industry and government. In some cases voluntary targets are used to forewarn industry and other market actors of future mandatory requirements. Targets can also be applied in a mandatory manner if they incorporate a fleet-average efficiency specification that a manufacturer's or importer's products must attain. In this case it is not necessary for all products from a given supplier to meet a minimum performance threshold providing the offer or sales-weighted average does. In some countries, the minimum efficiency levels in MEPS and targets are determined from what is technically and economically feasible. In others, they are negotiated incremental improvements based on the energy-performance characteristics of existing products. Although MEPS are applied to all products of a similar type on a given market, targets are sometimes only negotiated between government and a group of key market actors and hence may have less than total market coverage. While MEPS must have a legal basis, targets do not require one.

In general MEPS and targets are used to raise the efficiency of specific lighting components, (*e.g.* compact fluorescent lamps [CFLs], or linear fluorescent lamp [LFL] ballasts) and have not so far been set to apply horizontally across lighting product classes. This is a significant limitation, especially in the case of lighting, because the largest efficacy improvements occur when switching from a low-efficacy source to a higher-efficacy source and thus mostly involves using an alternative lamp type. For example, there might be a 10% efficacy gain from applying MEPS that phase out the least efficient incandescent lamps, but switching from an incandescent lamp to a CFL could improve the efficacy by 400%. In a similar vein, much larger gains are to be had from switching from mercury vapour lamps to high-pressure sodium, metal halide or ceramic metal halide lamps than from prohibiting the sale of the least efficient mercury vapour lamps. In theory, were lamp suppliers providing all major lamp types, which is commonly the case, government could impose fleet-average lamp efficacy requirements on market suppliers, set for each group of interchangeable lamps (*e.g.* general lighting service [GLS] lamps and CFLs; T5, T8 and T12 LFLs; mercury vapour, metal halide, ceramic metal halide and high-pressure sodium lamps), but this would be administratively challenging and a bold step for a government to undertake. In theory governments could also opt to phase out the least efficient lighting sources, namely standard incandescent lamps. Although some administrations are known to have considered such a step, none has implemented it thus far.

Energy labels, ratings and certification schemes

Energy labels show equipment energy use or efficiency as defined using a common performance metric and testing methodology. They alert and inform consumers to the energy use, energy costs and environmental consequences of their purchase decisions. They are also used to underpin other programmes, such as MEPS, procurement activities and financial incentives. There are three major types of label. *Comparison labels* indicate the energy efficiency of a particular model relative to similar models on the market and are usually, though not always, mandatory. *Endorsement labels* (or quality marks), affixed only on models meeting or exceeding a certain efficiency level, indicate models of superior energy efficiency.

They show the top of the market (in efficiency terms) explicitly. Endorsement labels, by definition, are voluntary. *Ecolabels* invariably indicate multiple environmental parameters – such as noise, water use and energy use – associated with the manufacture, use and disposal of products. Energy labels are usually designed to be displayed physically at the point of sale, but where distance selling occurs (such as through internet sales, catalogues or advertising) specifying the label performance is still an option and may be mandatory depending on the legal nature of the scheme. Furthermore, many products (especially those destined for the non-residential sector) are sold directly to installers and are never put in a showroom for display to eventual end-users. In this case energy-efficiency performance-based ratings can be applied and may even mimic the design of a commonly used label applied to displayed products. The label rating will be given in product directories and promotional materials, rather than on the equipment itself, so that at least installers are informed of the energy-performance characteristics of the equipment. In some cases certification labels or marks are applied to indicate that the product energy performance has been certified by a reputable third party and in some cases to attest that it meets a minimum energy performance and quality specification. Certification schemes are usually administered by government or industry associations, but non-governmental organisations (NGOs) have also operated such schemes. Many endorsement labelling schemes include a certification function.

Building codes

Building codes addressing energy performance traditionally focused on space heating above all other energy end uses, but lighting is either the largest or one of the largest uses of primary energy in commercial-sector buildings; this has led to many regulators in OECD countries to broaden the focus of their codes in recent years to include lighting. This is either done explicitly or indirectly depending on the approach taken. In the explicit form minimum lighting energy performance specifications are set, whereas with the indirect approach whole-building energy-performance specifications that encompass lighting are set. In an increasing number of cases both approaches are adopted. Explicit lighting requirements can take numerous forms. They will typically specify maximum permissible lighting power density levels, defined as the installed lighting power requirement per unit area (W/m^2 or W/ft^2).

The thresholds applied will usually be established following consideration of the lighting requirements for the space concerned and hence will be set according to the specific purpose of the illuminated space. Regulations may specify fixed average values for a whole building depending on the building purpose, or for each type of space within the building, or they may do both and give the lighting installer the option of choosing which requirement they will comply with. In some cases the lighting power thresholds are specified in terms of watts per lux (W/lux), which ensures there is no unintended incentive to lower illuminance levels but complicates compliance and may increase the risk of over-lighting. The advantage of using building codes to ensure a minimum lighting energy performance is attained is that they do not dictate the choice of lighting system that a designer should choose but merely specify a minimum system performance. Furthermore they avoid a weakness of MEPS, and to a lesser extent labels, which is that they only apply within a product category and hence do not encourage the adoption of inherently superior technologies for a given application. Building-code lighting requirements indirectly address all aspects of a lighting system's performance and its integration into the built environment, including lamp efficacy, luminaire losses and light distribution, ballast efficiency and room reflectivity levels needed to attain a given illuminance and coefficient of utilisation (CU). Building codes also often specify fenestration requirements, usually with the aim of preventing excessive solar gains but sometimes with an objective to encourage the use of daylight. Some set obligations or incentives to use skylights, light wells, clerestories and light shelves. The most advanced codes now include requirements or incentives (through compliance credits) to deploy lighting controls such as adequate switching, user dimming and direct control, occupancy sensors, motion sensors (for exterior lighting) and automatic daylight-responsive dimming.

Applicability of the codes also varies, with some addressing lighting explicitly for new commercial buildings only, while others apply to all building types (including housing) and may also apply to major retrofits. In the few cases where lighting energy performance requirements are specified for new residences, simpler approaches that require either a certain percentage of fixtures to use efficient light sources or the average efficacy of lighting systems to surpass a minimum threshold have been utilised. In the case where there are no explicit lighting requirements but lighting energy performance is included as part of a whole-building energy-performance requirement, the building designer can choose the degree of emphasis they wish to place on lighting energy efficiency in order to meet the general requirements. This is a purer approach than setting explicit lighting requirements but carries the risk that some buildings subject to code will continue to use costly, inefficient lighting – probably through a lack of awareness of or attention to the savings options – while still attaining the overall minimum energy performance goal by extra effort in an alternative direction.

Building energy performance certification

Market disclosure of building energy performance is becoming increasingly common in OECD countries, either through mandatory energy-performance certificates or through voluntary rating schemes. This instrument is intended to help overcome user information barriers. Where these schemes operate they invariably follow a whole-building energy performance rating approach and hence include lighting within the energy-performance evaluation. Lighting efficiency can thus have a major impact on the overall rating in cases where it is a large proportion of the load, such as tends to be the case for most commercial buildings. In some cases the certificates are based on actual metered loads, while in others they rely on calculated performance levels. In the latter case they will use similar or identical methodological approaches to those applied in building codes. In the more proactive cases these certificates can guide certificate users with respect to how they can improve the energy efficiency of their properties; if structured appropriately, this would present a natural opportunity to provide guidance on the means to improve the efficiency of the lighting system. Building energy performance certificates usually apply a rating system that shows how efficient the building is in relation to other similar buildings, or buildings in general.

Financial and fiscal incentives

A variety of programmes offer financial incentives to consumers to purchase energy-efficient equipment and in some cases retire older equipment, with the intention of mitigating the first-cost barrier to more efficient lighting. The most common incentive is the rebate, which acts as a sort of financial endorsement of a product's energy-efficiency attributes. Financial-incentive programmes were particularly popular in the 1980s and 1990s, being offered as part of demand-side management (DSM) initiatives implemented by utilities and local, state and provincial authorities. With utility deregulation in the late 1990s these programmes became less common, but in recent years they have had a renaissance as market regulators have increasingly sought ways to better integrate the demand side into competitive electricity markets. Furthermore they are now being implemented over a broader range of countries and in more diverse forms. Many European, Asian and the traditional North American jurisdictions are now implementing such measures and are being joined by some in South America, Africa and the Indian subcontinent. Financial incentives to encourage the adoption of efficient equipment are also sometimes provided by the state in the form of direct point of sale rebates, credits or soft loans. Fiscal incentives in the form of tax deductions are also increasingly being applied to encourage the preferential adoption of energy-efficient equipment. The same is true of fiscal and financial incentives to encourage building energy performance, and in some cases lighting energy performance explicitly, to achieve levels beyond building-code minimum regulatory requirements.

Procurement programmes and competitions

Several large organisations (such as government departments, military housing agencies, low-income housing authorities, homeowner associations and major corporations) operate procurement programmes that seek to increase the efficiency of the equipment installed in their properties and premises. The large quantity of equipment purchased through these channels lowers the information-gathering and -processing costs for each product specification compared with those of individual market actors, which helps to reduce the importance of the information and time barriers to efficient lighting (see p. 287). Moreover, these organisations can obtain attractive borrowing terms and large price discounts through bulk procurement and competitive bidding, further increasing the financial attractiveness of energy-efficient lighting. The procurement specifications are greatly simplified if they take advantage of existing endorsement- and/or energy certification-label requirements. Furthermore, if a whole lighting system is being installed it is useful for the procurers to be able to specify established high-performance benchmarks, when these have been developed, within the terms of reference of a building energy certification scheme. Both these examples illustrate the positive synergies that often exist between different policy instruments that target efficient lighting and which help to leverage the overall policy impact. Going a step further, these organisations sometimes conduct technology-procurement competitions, which explicitly use their high collective purchasing power to influence manufacturers to develop and market more efficient lighting products than would otherwise have been the case.

Information, awareness raising and capacity building

Information and promotional activities – such as energy cost estimation guides, product directories and awareness-raising campaigns – are the most basic methods used to encourage lighting energy efficiency. They help raise the profile of energy efficiency in consumers' purchasing decisions and give manufacturers the incentive to produce more efficient products. Although they can be used alone, they are frequently (and most usefully) coupled with other policies such as labels, procurement competitions and financial incentives. Furthermore, in the case of lighting there is a constant need to supply professionals engaged in the field with good-quality information regarding the design, installation, commissioning, operation and maintenance of high-performance efficient lighting. This is often in the form of professional guidelines that specify – among other parameters – recommended illuminance levels and other lighting-quality factors; they may also give considerable guidance on the selection and installation of the lighting system, its integration with daylight, the specification of room reflectance levels, etc. To be most effective it is important for information programmes to be complemented by direct education and training activities, both of which are highly valuable tools for promoting energy-efficient lighting. If policy instruments such as building codes and lighting design guidelines are to be effective it is essential that key market actors such as designers and installers are familiar with the requirements, their obligations and the means of putting them into effect. Such training is often provided by professional bodies, but in most economies there is a shortfall in relation to the need; hence, this is an area where government can provide useful support, both in the development of training material and in organising and or funding its delivery. Capacity building goes beyond just training market actors, however, because it is important that actors have an incentive to acquire such skills. There are many ways this can be addressed, but government also has a role to play in specifying the degree of qualifications a designer or installer of lighting systems needs before they can legally ply their trade.

Market-transformation programmes

Market-transformation programmes combine many of the policy instruments discussed above to provide a comprehensive package to bring about more efficient lighting. They are more comprehensive than traditional DSM programmes in that they aim to positively influence the market for energy efficiency on a voluntary basis through a mixture of information, proactive engagement, capacity building and incentives. In this sense, as well as providing incentives to end-users they offer a coordination point for all actors involved in the procurement, specification and installation of lighting. They take many forms and use different techniques to engage market actors, including offering technical support and capacity building, but are also highly complementary to policy measures such as equipment labelling, building certification and utility or government incentive schemes. In general, market-transformation programmes aim to identify and address all the key barriers to the speedier adoption of energy-efficient technologies and practices and will often evolve over time as the understanding of those barriers and the best means of addressing them improves. They therefore need to engage in continuous, or regular, process and impact evaluation to be sure that they are targeting resources effectively.

Voluntary and long-term agreements and auditing

Voluntary agreements describe a wide range of actions for industry and commerce and sometimes the public sector. They can include covenants, negotiated agreements, self-regulation, codes of conduct and eco-contracts. A voluntary agreement is defined as an agreement between government and industry (or others) to facilitate action with a desirable social outcome; it is encouraged by the government and is undertaken by the participant based on the participant's self-interest. Almost all IEA member countries have a number of voluntary agreements, which often have the objectives of reducing energy intensity and/or lowering greenhouse gas emissions. Many IEA governments have also entered into long-term agreements with major industries, commerce and other large energy users that specify energy or greenhouse gas reduction targets. Like a pure voluntary agreement, these are negotiated on a voluntary basis but may become a mandatory obligation once the targets are agreed. Alternatively, there is usually a financial or fiscal penalty for failure to meet the target. For example, in many cases governments have coupled negotiation of the long-term agreement with the introduction of an energy, carbon or eco-tax such that if an industry commits itself to meet an agreed target they become exempt from the full weight of the tax. These agreements usually cover all the energy consumption or greenhouse gas emissions of the sectors concerned, but there is no reason in principle why provisions addressing the adoption of efficient lighting could not be explicitly included in the conditions of the agreements. In general, government is somewhat handicapped in negotiating such agreements because of an inherent asymmetry of information between government and industry regarding the nature of industrial processes and the economic options for their improvement. However, this is not the case with lighting, for which technical options are well known and high-performance benchmarks are relatively straightforward to establish. As lighting accounts for almost 9% of global industrial electricity use, it presents a significant cost-effective savings potential, as discussed on pp. 234–236. Voluntary agreements and long-term agreements can also be negotiated within tiers of government, with different ministries, regional governments and local government sectors agreeing to meet pre-specified energy-efficiency or greenhouse gas targets. Similarly, commercial organisations are increasingly establishing internal energy and greenhouse gas performance benchmarks. Progress towards these targets are now sometimes reported under corporate-responsibility commitments. Government can not only encourage the adoption of such practices but can also facilitate them by helping the private sector identify what appropriate performance targets should be, assisting with identifying competent contractors and auditing outcomes. Once again lighting is an obvious target within this process because it accounts for such a high proportion of commercial-building electricity use.

Utility obligation schemes

A number of countries, notably some European ones, have begun to place obligations on utilities to either implement energy-efficiency measures or suffer a penalty. These involve more than just setting energy-savings targets and fixing non-compliance penalties – they also include establishing compliance pathways. In some cases the energy-saving routes to be used are prescribed, while in others they are left open; however, in both situations there is a need for the regulator to certify that the savings have been achieved, and this involves agreeing on the means of determining the savings impacts of the utility-sponsored energy-savings interventions. In some cases, once the savings have been certified the regulator issues a corresponding quantity of savings certificates, known as "white certificates" to the utility, who is then free to trade on an open market with other utilities subject to the same obligations. The savings targets given to each utility are generally proportional to their energy sales, but allowing utilities to trade their obligations enables specialisation to develop within the market place. Accordingly, a utility may find that it is cheaper to buy its obligations from the market than to initiate its own savings schemes because the market has found more cost-effective means of delivering the savings than the utility has been able to identify. These white-certificate schemes are thus often very similar to carbon cap-and-trade schemes but place the obligation on improving energy efficiency rather than reducing carbon. Lighting energy-efficiency improvement is one of the most obvious objectives to select in such schemes; and in some jurisdictions specific lighting energy-savings targets have been fixed.

ESCOs and third-party finance

Energy service companies (ESCOs) assist their customers to reduce energy costs and then share the value of the benefits with them to mutual advantage. The ESCO typically provides the technical know-how, labour and financial means to effect the energy savings and thus obviates the knowledge, capacity and finance barriers to energy efficiency that may be suffered by their clients. In general the ESCO and client enter into what is known as a performance contract, wherein the ESCO agrees to perform some blend of the following services (Novem, 1999):

- Conduct a feasibility study and an energy audit of a potential municipal, commercial or industrial client's facilities.
- Identify cost-effective energy-savings opportunities.
- Draw up a financial plan for the project (to be financed by the ESCO, the client, or a third party).
- Implement these energy-conservation measures at no initial cost to the customer.
- Maintain the energy-savings investment for the life of the contract.
- Provide training for the client if requested.
- Monitor the savings.
- Guarantee energy savings, which are used to pay back the initial investment.

When the energy service contract expires, the client may continue to benefit from the ongoing reduced energy costs and thus gain an additional benefit. ESCOs thus present a "win–win" situation in terms of energy, economy and the environment. Because energy-efficient lighting presents such an attractive energy-savings opportunity, many ESCOs make this a major focus of their activity.The health of the ESCO market is thus a good indicator of the extent to which the private sector is providing high-quality and efficient lighting services.

In practice; however, ESCOs face many obstacles that government can help to overcome. First and foremost there is a difficulty with the business model, which relies on selling a counterfactual benefit that is very difficult to unambiguously prove and thus requires a high degree of trust. Many potential clients are suspicious that the energy savings proposed may not be real and fear that the performance contract might be selling them a fictitious benefit. This is all the more challenging when the baseline against which savings are to be evaluated is discussed: businesses have dynamic energy needs and it is rare to find a static environment where the energy-usage situation before and after can be unambiguously compared.

Government can offer help to overcome these concerns by: (i) promoting the ESCO model to the private sector, (ii) helping to build trust in the nature of the changes effected, perhaps by certifying ESCO practitioners and establishing common performance benchmarks, (iii) developing and endorsing standardised performance contracts, and (iv) ensuring the legal and financial framework is supportive of ESCO activity.

Government may also assist in leveraging more competitive financing for ESCOs and may even provide attractive loans to help boost the market. Alternatively, government may subsidise the costs of the initial audits in order to lower the magnitude of loss-leaders encountered by the ESCO industry. Finally, government can support technical capacity-building in the ESCO sector to ensure the most current skills are in place and to boost uptake of the most efficient technical solutions.

The remainder of this chapter reviews all such measures as they have been applied to lighting to date, beginning with an overview of equipment standards and labelling schemes.

POLICIES TO IMPROVE LIGHTING-COMPONENT EFFICIENCY

Since as early as the 1970s, and at a greater rate since the mid-1990s, governments around the world have implemented a mixture of energy-performance standards and energy-labelling requirements for various lighting components. The large majority of these measures have been targeted at lamps and ballasts; thus far there have been very few explicit performance requirements imposed for other components used in lighting systems, such as luminaires and controls.

Table 5.1 lists the status of mandatory MEPS, energy labels and efficiency targets applied to lighting-system components (lamps, ballasts, luminaires, controls and specific lighting-related systems and components) in key economies, with a focus on the OECD countries. The table reveals two facets. First, there are many regulations in place to encourage or require either the disclosure of the energy performance of lighting-system components or the attainment of specific energy-performance levels. Second, there are still many gaps in comparison with the full range of potential measures. The large majority of lighting components are not subject to MEPS, comparison energy labels or voluntary labels. Ballasts for fluorescent lamps and LFLs are the products that are most commonly subject to MEPS, but even here some major economies have no measures in place. The energy performance of standard incandescent lamps is only regulated in Korea and California. There are very few provisions for high-intensity discharge (HID) lamps, with no OECD country applying MEPS or mandatory labels and only China having any mandatory requirements. Despite the popularity of MEPS for fluorescent lamp ballasts, very few countries have any requirements for HID ballasts. Twelve economies impose MEPS for CFLs, but some major economies still do not. Halogen lamps are subject to very few requirements, despite a potential to replace standard tungsten halogen lamps with infrared halogen lamps with a significantly higher efficiency. Furthermore, most jurisdictions continue to permit the sale of extremely inefficient halogen torchières, although California has effectively prohibited their sale by banning the use of high-wattage lamps in torchière luminaires. Nor are there any MEPS or labels for low-voltage halogen transformers, although this is under discussion in Australia. Luminaires are subject to very few requirements despite the large variation in luminaire energy performance, and only California has

Table 5.1 Use of labels, standards and targets for lighting and related equipment

	Comparison label												Endorsement label												Standards											
	Australia	California	Canada	China	EU	HK, China	Japan	Korea	NZ	Norway	Switzerland	USA	Australia	California	Canada	China	EU	HK, China	Japan	Korea	NZ	Norway	Switzerland	USA	Australia	California	Canada	China	EU	HK, Chaina	Japan	Korea	NZ	Norway	Switzerland	USA
Lamps					M					M	M																									
GLS lamps			R		M			M		M	M	R														M						M				U
Incandescent reflector lamps			R		M					M	M	R														M	M									M
Halogen lamps					M					M	M																			M						
CFLs, self-ballasted			R	C	M		M	M		M	M	R			V	V	V	V		V		V		V	U	M	M	M			F	M				M
CFLs, separate ballast							M									V	V			V		V		V				M			F					
LFLs			R	C	M		M	M		M	M	R				V				V					M	M	M	M		M	F	M	M			M
Circular fluorescent lamps							M	M																								M				
Other fluorescent lamps					M		M			M	M															M	M				F					M
HID lamps																									U		U	U		M	U					U
Mercury vapour lamps																																				U
High-pressure sodium lamps				C												V												M								U
Metal halide lamps																				V								U								U
Ballasts/transformers for:																																				
LFLs					C			M		C	C	M			V	V				V	V			V	M	M	M	M	M		F	M	M	M		M
CFLs, self-ballasted																																				
CFLs, separate ballast					C					C	C									V					M			M	M							
Halogen																									U											
Mercury vapour																									U	P										P
Metal halide																				V					U			U								
High-pressure sodium																V									U			M								

Table 5.1 (continued)

	Comparison label												Endorsement label												Standards											
	Australia	**California**	**Canada**	**China**	**EU**	**HK, China**	**Japan**	**Korea**	**NZ**	**Norway**	**Switzerland**	**USA**	**Australia**	**California**	**Canada**	**China**	**EU**	**HK, China**	**Japan**	**Korea**	**NZ**	**Norway**	**Switzerland**	**USA**	**Australia**	**California**	**Canada**	**China**	**EU**	**HK, Chaina**	**Japan**	**Korea**	**NZ**	**Norway**	**Switzerland**	**USA**
Luminaires																	V							V												
Reflectors for LFL lamps																				V																
Reflectors for HID lamps																				V																
Residential																								V												
Metal halide																										M										
Outdoor																										M										
Torchières (mainly halogen)																										M										M
Under-cabinet luminaires																										M										
Specific applications																																				
Exit signs																								V		M										M
Traffic signals																				V				V		M										M
Street lights																											M									
Outdoor lighting																										M										
Ceiling fan lights																										M										M
Lighting controls																				V																
Windows																				V				V												
Homes																								V												
Non-residential buildings					M																			V												
Backlighting applications																																				
Monitors													V	V		V	V	V	V	V		V	V	V							F	M			V	
Televisions							M								V	V			V	V	V	V		V			M	V		M	F					

* As of end 2005.

Abbreviations: C = mandatory energy-efficiency classification; CFLs = compact fluorescent lamps; EU = European Union; F = fleet average efficiency requirement; GLS = general lighting service; HID = high-intensity discharge; HK, China = Hong Kong, China; LFLs = linear fluorescent lamps; M = mandatory; NZ = New Zealand; P = mandatory pending implementation; R = mandatory informative requirements but short of a full energy label giving information on efficiency; U = under development; USA = United States; V = voluntary.

imposed any luminaire performance requirements. Similarly, very few jurisdictions impose energy-performance requirements on the key outdoor lighting applications of street lighting, car parks and traffic signals.

Nonetheless, MEPS, labels, certification schemes and targets for lighting products have grown dramatically in popularity in recent years (Figure 5.1), and those that have been implemented appear to have been extraordinarily cost-effective. The fact that there are so many outstanding gaps in the regulatory performance and voluntary-disclosure instruments suggests that there is still plenty of scope for additional policy attention. The details of the specific measures implemented to date will now be reviewed for key economies.

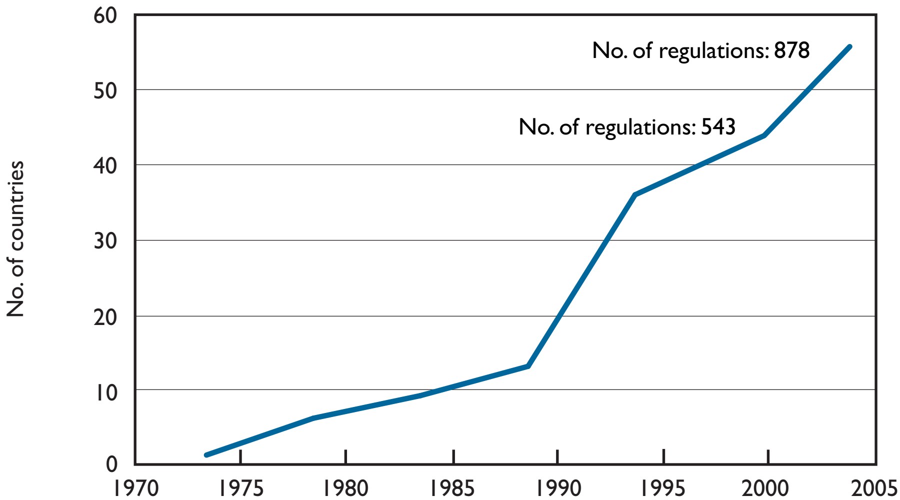
Australia and New Zealand

Australia

Australia implemented MEPS for LFL ballasts in March 2003 and for LFLs in October 2004. The provisions for ballast MEPS are set out in the Joint Australian/New Zealand Standard AS/NZS 4783.2:2002 but are essentially harmonised with the European Union's MEPS, which are discussed on pp. 317–319. They apply to (i) ferromagnetic and electronic ballasts used with LFLs that are rated from 15 W to 70 W, and which are themselves rated for 50 Hz and 230–250V supply and (ii) to ballasts supplied as separate components or as part of a luminaire. As in Europe, regulated ballasts are also required to carry an energy-efficiency marking using an energy efficiency index (EEI). AS/NZS 4783.2:2002 further requires that ballasts within the scope of MEPS must be designed to comply with the relevant performance requirements of IEC 60921 for ferromagnetic ballasts and IEC 60929 for electronic ballasts. The effect of these MEPS will be to eliminate the less efficient ferromagnetic ballasts from the Australian market; classes C and B2, however, they do not go as far as requiring electronic ballasts to be used. The regulatory impact assessment conducted for the measure estimates that the MEPS will have net present-value economic benefits of AUD 416 million calculated at a 10% discount rate and that the benefit:cost ratio will be 4.1 (GWA, 2001). It is also projected to avoid 0.63 Mt of CO_2 per annum in the 2010–12 time frame.

The provisions for LFL MEPS are set out in the Joint Australian/New Zealand Standard AS/NZS 4782.2:2004. Part 1 of the same standard

Figure 5.1 **Evolution of the number of countries with equipment standards and labelling regulations, including those addressing lighting**



Source: Weil, 2004.

specifies the test methods for luminous efficacy. The MEPS apply to LFLs ranging from 550 mm to 1 500 mm in length (inclusive) and having a nominal lamp power of 16 W or more. The minimum efficacy requirements, shown in Table 5.2, are essentially harmonised with those applied for LFLs in the United States and Canada but are adapted for Australian power supply and test conditions. They include requirements for a minimum colour rendering index (CRI). The effect of these MEPS will be to eliminate the less efficient halophosphor T8 lamps and small residual proportion of T12 lamps from the Australian market. Evaluating their impacts is slightly more complex than for ballasts because directly substituting a triphosphor T8 lamp for a halophosphor T8 lamp produces no energy savings but merely increases light output; however, over the longer term the use of higher-efficacy triphosphor lamps allows less lamps to be used to illuminate a given area, so benefits accrue at the rate at which new and retrofit light fixtures are installed. Estimated carbon savings are between 0.5 and 3.1 Mt depending on the assumptions, yet despite the large spread in this range they are always cost-effective to the end-user (Ellis, 2003).

Table 5.2 Minimum efficacy requirements for LFLs in Australia

	Nominal lamp length* (L) (mm)			
	550 ≤ L <700	**700 ≤ L <1 150**	**1 150 ≤ L <1 350**	**1 350 ≤ L <1 500**
Lamp typical power** (W)	16–24	17–40	28–50	35–80
Initial efficacy	≥6.0	≥74.0	≥80.0	≥85.0
Maintained efficacy***	≥57.5	≥61.0	≥70.0	≥70.0
Minimum CRI	69	69	69	69

Source: AGO, 2006.
* Mandatory.
** Informative.
*** Efficacy at 70% of the rated lamp life.
Abbreviations: CRI = colour rendering index; LFLs = linear fluorescent lamps.

Assessment

At present there are no other labelling or MEPS regulations applying to lighting equipment sold in Australia, but the Australian government has initiated a proactive market-transformation programme, Greenlight Australia, which sets out to improve the efficiency of lighting via a variety of means and has an aim of reducing lighting energy consumption by 15–25% over the period 2005–15 (AGO, 2004a). Under the terms of this programme a wide range of new policy measures are being developed or are under active consideration. The initially proposed measures are set out in Table 5.3.

Following discussion with stakeholders, the Australian regulatory authorities have now set about developing MEPS for:

- Low-voltage halogen transformers.
- CFLs.
- Halogen and reflector lamps.
- Luminaires.
- HID lamps.
- HID ballasts (AGO, 2005).

Moreover, a holistic energy-performance standard is being developed for lighting on main roads, taking into account the lamp, ballast, luminaire, control system and overall design of each installation.

Table 5.3 Initially proposed lighting efficiency policy measures, Greenlight Australia programme

Programme reference no. and title		Priority	Timetable for programme commencement					
			2005	2006	2007	2008	2009	2010
MEPS programmes								
1	MEPS and comparative labelling for tungsten halogen transformers	1						
2	MEPS for new lighting installations	1						
3	MEPS and labelling for luminaires	1						
4	Holistic MEPS for public amenity lighting	1						
5	Endorsement labelling and MEPS for CFLs	2						
6	MEPS for tungsten halogen lamps	2						
7	MEPS for HID lamps (high-pressure sodium)	2						
8	MEPS for HID ballasts	2						
9	MEPS for LFLs	2						
10	MEPS and comparative labelling for linear fluorescent ballasts	2						
11	MEPS or bulk procurement for traffic signals and exit signs	2						
17	MEPS for photoelectric cells	4						
18	MEPS for GLS lamps	5						
19	MEPS for incandescent reflector lamps	5						
Non-MEPS programmes								
12	Education and training for specifiers	2						
13	Comparative lamp labelling	3						
14	Bulk procurement of dedicated CFL luminaires	3						
15	Bulk procurement of triphosphor and CFL street-lighting packages	3						
16	Bulk procurement of efficient GLS lamps	4						

Source: AGO, 2004b.
Abbreviations: CFLs = compact fluorescent lamps; GLS = general service lamps; HID = high-intensity discharge; LFLs = linear fluorescent lamps; MEPS = minimum energy performance standards.

Among these measures the proposals regarding luminaires and road lighting are the most innovative. In the case of luminaires the Australian authorities concede that it is not yet viable to develop MEPS for residential products, but they have targeted commercial and industrial luminaires. A performance measure has already been developed by Lighting Council Australia for LFL luminaires, and it is reported that this could be extended to cover CFL and HID luminaires too. Finally, Australia is developing an enforcement protocol to strengthen testing and compliance testing arrangements for lighting products and has established an online database of efficient products known as Energy Allstars.[1] Once implemented these initiatives are likely to make a considerable impact in lighting energy consumption in Australia and will give the country one of the most comprehensive set of lighting equipment policy portfolios.

New Zealand

New Zealand has MEPS for LFL ballasts and LFLs. The requirements for ballasts are harmonised with Australia's, but those for LFLs are not. New Zealand introduced its LFL MEPS in July 2002, before Australia did, and although LFLs are tested to the same standard in both countries the New Zealand MEPS requirements are slightly more stringent than the Australian equivalents (Table 5.4).

The MEPS for LFLs were projected to give present-value benefits of NZD 11 million and costs of NZD 8.4 million, with a benefit:cost ratio of 1.32. New Zealand is also a stakeholder in the Greenlight Australia programme and hence may adopt some of the same measures as Australia is developing in this regard.

Table 5.4 **Minimum efficacy requirements for LFLs in New Zealand**

Class		Nominal lamp length (mm)			
		550–600	**850–900**	**1 150–1 200**	**1 450–1 500**
Q	Initial efficacy	≥70.0	≥74.0	≥85.0	≥85.0
R	Initial efficacy	≤70	<74	<85	≥85
	Maintained efficacy*	≥57.5	≥61.0	≥70.0	≥70.0

Source: EECA, 2005.
* Efficacy at 70% of the rated lamp life.
Abbreviation: LFLs = linear fluorescent lamps.

1. Available at www.energyallstars.gov.au.

OECD Europe

European Union

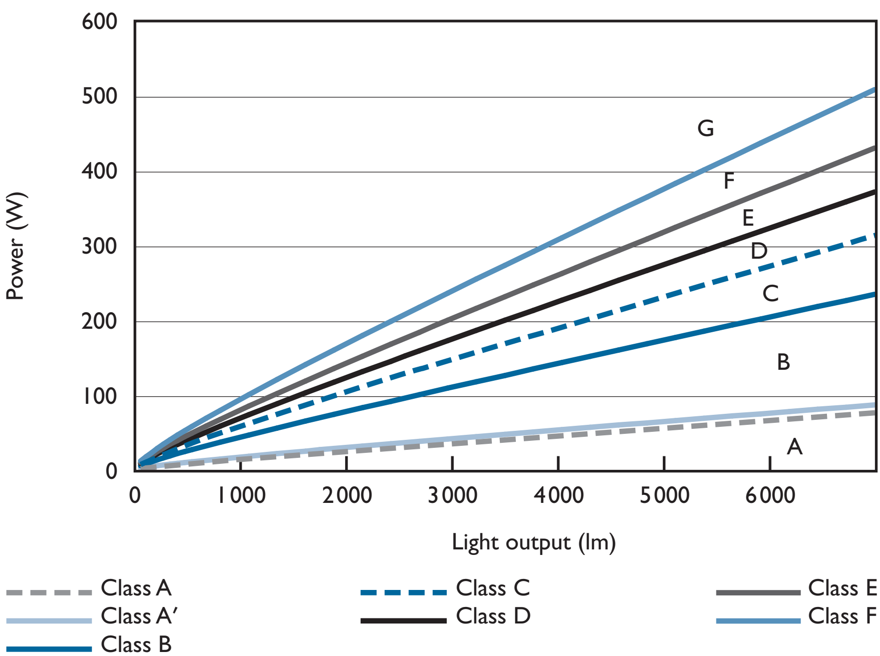
Thus far the European Union has introduced two mandatory regulations addressing lighting equipment: MEPS for ballasts, and energy labelling for household lamps.

Directive 2000/55/EC of the European Parliament and of the Council set the minimum energy efficiency standards for fluorescent lighting ballasts on the EU market, based on energy-efficiency indices used to devise seven performance classes (A1, A2, A3, B1, B2, C, D) as specified in European Standard EN 50294. Under this scheme the A1 class is the most efficient and corresponds to the performance characteristics of dimmable electronic ballasts; A2 corresponds to low-loss electronic ballasts; A3 to standard electronic ballasts; B1 to low-loss electromagnetic ballasts; and B2, C and D represent progressively less efficient electromagnetic ballasts. The least-efficient ballasts (class D) were prohibited from 21 May 2002, while class C ballasts were phased out on 21 November 2005. Although further changes were due to be assessed at the end of 2005, the Directive does not go as far as the comparable Australian and New Zealand regulation in phasing out the B2 ballast class nor is it as advanced as the corresponding North American regulations and incentive programmes. These latter have succeeded in converting the majority of the North American ballast market to electronic ballasts, while in Europe less than one-quarter of new ballast sales were for electronic ballasts in 2004 (see pp. 391–392).

The European Commission estimated in the proposal for the ballast Directive (COM(1999) 296 final) that the savings impact would be 1 TWh per year by 2005, 5 TWh by 2010 and 12 TWh by 2020, when all existing ballasts would have been replaced, *i.e.* some 10% of total electricity consumption from fluorescent lighting in the European Union in 2020.

The most innovative and still unique aspect of EU policy on lighting is the introduction of mandatory energy labelling for household lamps under Directive 98/11/EC, which came into effect in 1998 (Plate 5.2). This policy requires all lamps sold to the domestic-lighting market to carry an energy label that is similar to the A to G energy label used for household appliances. It is unique because it is the only international policy instrument that applies a common grading scale across different lamp types, *i.e.* all household lamps, regardless of type, are assessed and graded using the same energy-efficiency metric. In other countries lamp labelling is only applied within product classes, *i.e.* CFLs may have one efficiency rating system and incandescent lamps another. Under the EU scheme, CFLs are typically rated as class A or B, halogen lamps as class C or D and incandescent lamps E, F or G. Figure 5.3 shows the relationship between the different classes based on the lamp input power and light output levels, where the A threshold is the level that CFLs without an integrated ballast must attain to be rated class A, and the A′ threshold is that which ballast-integrated CFLs and all other lamps need to reach to be rated class A. The Directive does not apply to reflector lamps or lamps with a flux beyond 6 500 lm (lumens). Because the label was initially designed to work under ten different languages, it uses a simplified information format wherein the word "Energy" is spelt out in all ten languages at the top of the label, and the light output, rated power and rated lifespan are given at the bottom of the label. The label is printed in monochrome or colour on the lamp packaging.

Figure 5.3 **Thresholds applied in the EU household lamp label**



Source: European Directive 98/11/EC.

Assessment

Thus far the European Union has implemented only two MEPS and labelling measures for lamps. There has been no formal evaluation of either instrument, although a comparison with other markets of the efficiency of ballasts sold reveals that the EU market is not as efficient as in North America and has some way to go to catch up in terms of sales of electronic ballasts. This suggests that the EU policy measures are not as ambitious. The impact of the lamp label is harder to ascertain. In terms of market share, sales of CFLs are stronger in the EU than in North America, Australia and New Zealand, and sales of incandescent lamps are slightly lower. Furthermore, CFL sales continue to grow, while incandescent sales have been static or declined in recent years; however, these trends were at least partially apparent prior to the label's introduction so it is not clear how effective the label has been in influencing consumer lamp choices (PWC, 2001). The EU appliance label has been highly effective in transforming appliance markets, so it may well be that there is a positive impact in the household lamp sector too.

This aside, the European Union has been slower in introducing lighting MEPS and labels than other OECD regions. There are currently no instruments encouraging the adoption of triphosphor T8 or T5 lamps and there are no measures addressing the efficiency of HID lamps and ballasts. Nor are incandescent reflectors, standard incandescent lamps, halogen spotlights, halogen torchières, low-voltage halogen transformers, CFLs, exit signs, traffic signals, street lights or luminaires subject to any MEPS. The recent adoption of the far-reaching EU Directive 2005/32/EC on the eco-design of energy-using products could change this. It empowers the European Commission to negotiate voluntary industrial agreements or impose MEPS for a broad range of energy-using equipment, including lighting products, based upon an assessment of their life-cycle ecological impacts. For most products, energy consumed during use is generally the key determinant; in the case of lamps, the European Lamp Companies Federation (ELC) estimates that this can amount to up to 99% of the total environmental impact (ELC, 2005). A pilot-study has already been undertaken for street lighting and the ELC has been highly proactive in seeking ways to work with the Commission and member states to improve lighting efficacy. Europe has led the way in international environmental legislation and the recently implemented Directives 2002/96/EC (on waste of electrical and electronic equipment [W3E]) and

2002/95/EC (on the restriction of the use of certain hazardous substances in electrical and electronic equipment [RoHS]) have imposed challenging requirements (i) to reduce mercury content in lamps and (ii) for manufacturers to take back and safely dispose of discharge lamps at the end of life, both of which add costs onto the more efficient discharge lamps. Low-efficacy incandescent lamps do not contain mercury and hence are not subject to the same end-of life constraints, so there may be a need to redress the balance if an unintended incentive to use less efficient incandescent technology is not to result.

The European Climate Change Programme (ECCP) has an objective of saving emissions of 24 Mt of CO_2 per annum through the use of efficient lighting during the Kyoto implementation window of 2010–12. The measures under discussion include MEPS for certain less efficient lamps or the luminaires that take them, public procurement, fiscal incentives and market-transformation programmes. There will need to be swift, comprehensive and ambitious policy action if these savings are to materialise by 2012.

Switzerland

Switzerland has a specific target for growth in electricity consumption between 2001 and 2010 (not more than 5%), and energy-efficient lighting is an obvious area of attention for information, energy campaigns, marketing, consultancy and quality management. In 2002 Switzerland formally adopted the EU energy-labelling scheme for household appliances, including the label applying to household lamps. Switzerland has also initiated the "Top Ten" programme discussed on p. 322.

Norway, Iceland, Liechtenstein and the EU Accession States

Norway, Iceland and Liechtenstein have formally adopted the EU energy-labelling and MEPS regulations, including those that apply to ballasts and lamps. The EU Accession States of Bulgaria and Romania have also adopted these regulations, while those states with aspirations to join the EU, including Croatia and Turkey, are believed to be considering their adoption. Turkey has already implemented the EU energy label for domestic refrigerators, for example. Outside this grouping, Israel, Russia and the Republic of South Africa have all adopted at least part of the EU energy-labelling regulations, although it is not known if these include household lamps and ballasts.

European CFL quality-labelling efforts

The European Union, the United Kingdom and Denmark all operate CFL-performance certification schemes. The objective of these schemes is to ensure that consumers are able to distinguish and attain high-quality CFLs and thereby mitigate the risks of consumer dissatisfaction and disillusionment with the technology. In addition the European Union's voluntary eco-labelling scheme also specifies requirements for CFLs.

In 1999 the European Commission launched the European CFL Quality Charter, which is a voluntary programme that aims to promote high-quality CFLs in the European market (JRC, 2005). For a CFL to be eligible for participation it must attain the following performance requirements: an EU lamp label class A rating, or B if the CFL is fitted with an external casing. For example, for GLS look-alike lamps:

- The luminous flux must be at least 88% of the initial flux after 2 000 hours of use.
- The CRI must be at least 80.
- 60% of stabilised light output must be reached within 60 seconds.
- Lamp life must be at least 6 000 hours.
- The lamp must be able to endure at least as many ignitions under test conditions as the rated lamp life expectancy in hours.

It also includes a requirement for customers to be given a two-year guarantee against lamp failure. The Eco label requirements are more stringent in that they require a minimum lifetime of 10 000 hours, 70 or 80% lumen maintenance at 9 000 or 10 000 hours depending on the lamp type, and extensive switch test durability.

The UK CFL-performance certification scheme is operated by the Energy Savings Trust (EST), which maintains a list of recommended CFLs that are eligible to carry the "energy saving recommended" logo (Figure 5.4). These must also meet high performance standards for efficacy, CRI, power factor and warm-up time that are similar to the Quality Charter requirements. The EST adds additional requirements regarding the colour correlated temperature (CCT), which must be between 2 650 and 2 800 K, and also sets precise lumen-maintenance

Figure 5.4 **The UK Energy Saving Recommended endorsement label**

specifications, but it does not include a two-year guarantee requirement. Over 100 CFLs on the UK market currently meet the requirements. CFLs must meet EST specifications to be eligible for inclusion in the UK Energy Efficiency Commitment scheme discussed on pp. 373–375.

The Danish Electricity Saving Trust (DEST) launched its CFL energy-label campaign in 2000. To be eligible for the label CFLs need to attain an EU class A rating but otherwise are subject to requirements similar to those of the EST scheme.

The "Top Ten" initiative

Pioneered in Switzerland and now encompassing ten European countries with an expectation of widening global membership, including China, the "Top Ten" concept is a publicly accessible database listing the ten most energy-efficient products available in each national market. Each participating country operates an independent certification process for eligible product groups. The role of these groups is to keep the website product lists continuously up to date and to confirm through third-party testing that the energy performance of candidate products merits their inclusion in the top ten. Manufacturers who believe their products should be in the lists are able to submit an application on line and make arrangements to have their products tested according to the certification process. In addition, there are a variety of promotional activities that encourage consumers to visit the website, large procurers to take advantage of it and product suppliers to participate.

This is a new concept that is rapidly gaining popularity, and many of the lists include lighting products. In Switzerland the site was visited by more than one-seventh of the population in 2005 and the city of Zurich has begun to make use of it for equipment-procurement purposes.[2]

Japan

Japan first implemented efficiency standards for fluorescent lamps in 1993 in which the government called for an improvement in energy efficiency by 2000 of 3–7% compared to the level of 1992. In 1999 revision of the Energy Conservation Law led to the adoption of the wide-ranging Top Runner Program. This programme currently imposes fleet-average minimum energy efficiency requirements for 19 energy-using product types including passenger cars, trucks, air-conditioners, refrigerators, televisions and fluorescent lights. In the latter case, fleet-average efficacy targets have been set for 12 individual fluorescent lamp technologies (Table 5.5). For each manufacturer or importer the weighted-average efficiency of all units shipped within a category must meet the standard or they risk being fined and publicly named. In order to establish the ambition of the standard a statistical analysis of the efficacy of fluorescent lamps on the Japanese market was conducted, and the future standard was then set at the efficacy level of the most efficient product (Figure 5.5).

Overall the part of the Top Runner Program that addresses appliances and lighting is projected to save 9.7 Mt of carbon by 2010–12, representing 15% of Japan's overall savings target of 56.5 Mt of carbon under the Kyoto Protocol. The Top Runner Program for fluorescent lights was expected to increase average new lamp efficacy by 16.7% by the target fiscal year of 2005 compared with the average in 1997 (Murakoshi *et al.*, 2005). Plans are now under way to strengthen and broaden the Top Runner requirements. The Japanese Luminaire Association (JLA, 2005) projects that 85% of fluorescent luminaires in the commercial sector will be switched to high-efficiency types (*i.e.* high-frequency and inverter-based electronic ballasts) by 2010, leading to savings of 15% in 2005 and 30% in 2010 compared with the situation in 1997. In the residential sector, 97% of fluorescent luminaires will be of a high-efficiency type, resulting in savings of 18% in 2005 and 36% in 2010 compared to 1997; for desk lamps using fluorescent lights, 95% will be of a high-efficiency type by 2010, leading to 7% savings compared to 1997.

2. Available at www.topten.info.

Table 5.5 Japan's Top Runner requirements for fluorescent lamps

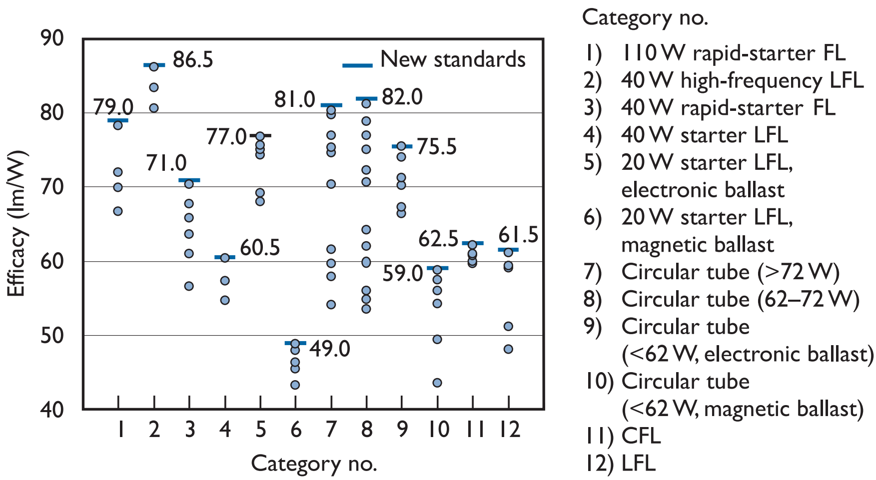
Category no.	Definition	Efficacy target
1	Equipment using 110 W rapid-start fluorescent lamp*	79.0
2	Equipment using dedicated 40 W fluorescent lamp for high-frequency lighting**	86.5
3	Equipment using 40 W rapid-start fluorescent lamp***	71.0
4	Equipment using 40 W starter fluorescent lamp	60.5
5	Electronic ballast type using 20 W starter fluorescent lamp	77.0
6	Magnetic ballast type using 20 W starter fluorescent lamp	49.0
7	Equipment using circular fluorescent lamps with size category† of over 72	81.0
8	Equipment using circular fluorescent lamps with size category of over 62 and up to 72	82.0
9	Electronic ballast type among equipment using circular fluorescent lamps with size category of 62 or less	75.5
10	Magnetic ballast type among equipment using circular fluorescent lamps with size category of over 62	59.0
11	Desk-top lamp using CFLs	62.5
12	Desk-top lamp using fluorescent lamps	61.5

Source: ECCJ, 2003b.
* Equipment using 110 W rapid-start fluorescent lamps includes 96 W CFLs and 105 W CFLs for high-frequency lighting.
** Equipment using dedicated 40 W fluorescent lamps for high-frequency lighting includes equipment using dedicated 65 W fluorescent lamps for high-frequency lighting.
*** Equipment using 40 W rapid-start fluorescent lamps includes 36 W and 55 W CFLs, plus equipment using dedicated 32 W, 42 W and 45 W CFLs for high-frequency lighting.
† Size category refers to the size category specified in the appendix Table 1 of Japanese Industrial Standard JIS C 7601. For circular dedicated fluorescent lamps for high-frequency lighting, the value should be the rated wattage value. However, for high-output fluorescent lamps, the value should be the lamp power value generated when the high-output fluorescent lamp is lit.
Abbreviation: CFL = compact fluorescent lamp.

Labelling

Energy labelling became mandatory under the revised Energy Conservation Law of 5 June 1998. Fluorescent lamps now carry an energy label of the form shown in Plate 5.6, such that when a product has met or exceeded the Top Runner threshold it is colour-coded green, but when it is of a lower efficiency than the Top Runner fleet-average threshold it is colour-coded orange. The label also expresses the product's efficiency as a percentage of the Top Runner target such that values above 100% have surpassed the target and values below are yet to attain it. In addition to the product label, Japan has begun to implement an innovative retailer-

Figure 5.5 Japan's Top Runner efficacy requirements for fluorescent lamps



Source: Murakoshi *et al.*, 2005.
Abbreviations: CFL = compact fluorescent lamp; FL = fluorescent lamp; LFL = linear fluorescent lamp.

labelling scheme, wherein retailers who stock predominantly high-efficiency equipment are eligible for an endorsement label that can be mounted as a plaque on the store entrance and used in promotional materials.

Assessment

Japan has moved swiftly to introduce meaningful efficiency regulations for fluorescent lighting products and is set to attain some significant improvements (see pp. 280–283). Japan already benefits from a very low share of incandescent lighting and hence has the highest-efficacy lighting of all OECD countries; however, there are still important gaps in the current policy measures that would bring about greater savings. Most notably Japan has no policy measures for HID lamps yet has a high proportion of low-efficacy mercury vapour lamp sales. Fluorescent lamp ballast efficiency requirements are yet to be formalised, and there are no measures for HID ballasts. As elsewhere there are large savings opportunities with the use of better luminaires, therefore these could also be a suitable target for future product requirements. Of lesser importance, but still relevant, is the lack of Top Runner requirements or labels for halogen lamps and incandescent lamps and of specific measures for applications such as traffic signals, exit signs and street lights, although many of these are under discussion (pp. 280–283).

The nature of the current Top Runner requirements for fluorescent lamps is also intriguing as efficacy thresholds are nominally based on the discrete rated wattage of the lamp rather than its light output or size, as is common elsewhere. This reflects a tradition common in many economies of marketing lamps based on their wattage rather than their light output. In western OECD countries this has tended to occur more for the incandescent lamp market than the fluorescent lamp market as the latter is most commonly used in the commercial sector, where lamp specification is more sophisticated. Yet, in Japan, fluorescent lighting also dominates the residential sector. Hence, simplified marketing has probably evolved such that consumers are familiar with the notion of a 40 W tube or a 20 W tube and seek this nominal power when procuring new lamps. It is unclear from the literature whether attainment of the higher Top Runner efficacy targets results in manufacturers maintaining the light output of a nominal 40 W or 20 W lamp based on pre-1997 light output levels and hence reducing the actual power requirements of the lamps, or whether the actual power remains at the nominal levels and the light output is increased. The energy savings that materialise are likely to be significantly less in the latter case, especially in the residential sector, because higher light output is unlikely to lead to a corresponding reduction in the number of lamps used to illuminate a given area; rather, it is more likely to lead to greater illumination.

Korea

The Korea Energy Management Corporation (KEMCO), a non-profit government agency, supervises the implementation of the Korean energy-efficiency standards and labelling programme, which was established in 1992. Its target is to eliminate inefficient designs from the market and help consumers choose more energy-efficient appliances. This programme covers nine items, including incandescent bulbs (October 1992), fluorescent lamps (October 1992), ballasts for fluorescent lamps (July 1994) and self-ballasted lamps such as ballast-integrated CFLs (July 1999). The programme applies to both domestic and imported products. To date, South Korea is the only national authority to have implemented MEPS for standard incandescent lamps (GLS incandescent lamps). These MEPS do not prohibit the sale of incandescent lamps but they do prevent the sale of the least efficient varieties.

Korea has pioneered a unique way of introducing and revising MEPS. For each product subject to MEPS a higher target efficiency level is also specified, and in some cases a date by which the target should be attained is specified. In these cases the target serves as notification of a future MEPS requirement. Korea's MEPS and target thresholds for incandescent lamps, fluorescent lamps and CFLs, respectively, are shown in Tables 5.6–5.8. The incandescent lamp requirements are specified separately for lamps designed to operate at 110 V and 220 V, respectively, with requirements for the latter being less stringent by roughly 16%. The 220 V MEPS are roughly equivalent to phasing out the EU lamp-label classes F and G, whereas meeting the target value would also add most of the class E lamps. The standard is therefore quite demanding for 220 V incandescent lamps. Mandatory energy labelling has also been introduced for all these products, using an efficiency grading scale operating from 1 (most efficient) to 5 (least efficient) (Plate 5.7). The grades are set at equal intervals between the MEPS and target efficiency thresholds.

When manufacturers, importers and suppliers fail to meet the MEPS, the Ministry of Commerce, Industry and Energy can prevent them from selling the product concerned, in accordance with the Law on the Rationalised Use of Energy.

Table 5.6 **Korea's MEPS and target requirements for incandescent lamps***

Type	Lamp wattage (W)	Minimum lumens per watt**	Target lumens per watt***
110 V	30	10.0	12.8
	60	13.0	15.0
	100	14.2	16.5
220 V	30	8.0	10.0
	60	10.8	13.0
	100	12.5	14.6

Source: KIER, 1997.
* Effective date 1 January 1996.
** As of 1 January 1997.
*** By the end of 1998.
Abbreviation: MEPS = minimum energy performance standards.

Table 5.7 Korea's MEPS and target requirements for fluorescent lamps*

Lamp type		Lamp wattage (W)	Minimum lumens per watt**	Target lumens per watt***
Tubular (*i.e.* linear)	T10	20	55.0	76.0
		40	66.0	98.0
	T8	32	73.0	95.0
Circular		32	52.8	68.0
		40	58.0	76.0

Source: KEMCO, 2005a.
* Effective date 1 July 1999.
** As of 1 January 2000.
*** By the end of June 2002.
Abbreviation: MEPS = minimum energy performance standards.

Table 5.8 Korea's MEPS and target requirements for CFLs*

Nominal lamp wattage (W)	Minimum lumens per watt **	Target lumens per watt ***
<10	42.0	48.3
10–15	48.0	55.2
>15	58.0	66.7

Source: EES, 1999.
* Effective date 1 July 1999.
** As of 1 January 2000.
*** By the end of June 2002.
Abbreviations: CFL = compact fluorescent lamp; MEPS = minimum energy performance standards.

Energy certification labelling

In addition to the MEPS and mandatory labels implemented for the products mentioned above, KEMCO has developed a voluntary energy certification label known as the "Energy Boy" (Plate 5.8), which indicates that products carrying the label are energy efficient and their performance has been certified by KEMCO.

Of 31 product types that are currently certified, some 13 concern lighting applications, as follows:

- 26 mm, 32 W fluorescent lamps.
- Ballasts for 26 mm, 32 W fluorescent lamps.

- CFLs.
- Reflectors for fluorescent lamps.
- Sensor lighting equipment.
- Windows.
- 16 mm fluorescent lamps and ballasts.
- Electronic ballasts for metal halide lamps.
- Electronic ballasts for natrium lamps.
- Light-emitting diode (LED) traffic lights.
- Metal halide lamps.
- Reflectors for HID lamps.
- Ballasts for non-ballast-integrated compact fluorescent lamps.

Assessment

Korea has one of the more established and comprehensive MEPS and labelling programmes addressing lighting equipment in the OECD, with the first MEPS coming into effect in 1996 (incandescent lamps) and the most recent in 2000 (CFLs). In particular, Korea's energy-labelling certification scheme has one of the broadest coverages of any such schemes and is alone in addressing light sensors, reflectors and metal halide lamps.

The IEA is not aware of an explicit evaluation of the impact of these policy measures, so the effects are unknown; however, the MEPS levels are reasonably ambitious by comparison with international best practice and so it is highly likely that they are making cost-effective energy savings. This is still probable despite Korea's traditionally low electricity tariffs, which fall between those found in Australia and New Zealand. All the main lighting products are addressed by some kind of policy instrument, but as with other economies there remain important gaps, most notably MEPS for HID lamps and ballasts. Other gaps include: MEPS for traffic lights, exit signs and street lamps; energy ratings for luminaires; and MEPS and/or labels for halogen lamps, torchières, low-voltage transformers and incandescent reflector lamps.

Similar comments can be made about Korea's MEPS requirements for fluorescent lamps as for Japan, in that the efficacy requirements are stipulated by discrete power rating rather than by light output or size. This is particularly pertinent for T8 lamps, which only have an obligation at a 32 W rating and not at the internationally common 18 and 54 W classes. It is possible then that different ratings are not currently subject to any efficacy requirement.

The impact of Korea's incandescent lamp standard would be very interesting to establish as it is unique among such measures. In theory, setting such MEPS may have increased incandescent lamp efficacy by about 20%, but if Korean consumers purchase the lamps based on their wattage ratings (*e.g.* 40, 60, 75, 100 and 150 W), as is reported to be the case in many other parts of the world, they may simply have taken the advantage in terms of higher illumination rather than fewer lamps. This concern is believed to have deterred many other regulators from setting incandescent lamp MEPS; however, if the market has gravitated toward lower-power lamps as a result of their higher efficacy and light output levels then genuine energy savings would have occurred.

North America

Canada

With the passing of the Energy Efficiency Act in 1992 the Canadian federal government was granted authority to develop, implement and enforce MEPS for energy-using products. The first such MEPS were issued in 1995 and Canada now applies MEPS for fluorescent lamps, incandescent reflector lamps and ballasts. These MEPS are harmonised with the equivalent US regulations (see p. 322), as are the associated lamp labelling regulations. In addition, both countries operate a voluntary performance requirement for CFLs and both apply the ENERGY STAR label in their territory (see p. 336). Canada also has an extra CFL endorsement label operated by Environment Canada.

United States

MEPS and labels for lamps were first introduced at the federal level in the United States with the passing of the Energy Policy Act (EPAct) of 1992. Subsequent to its passage MEPS were introduced for LFLs (1994/5) and incandescent reflector lamps (1995) (US Code of Federal Regulations

10CFR430). In addition, labels were implemented for all the above products as well as for incandescent lamps and CFLs (US Code of Federal Regulations 16CFR305). The October 2005 Energy Policy Act introduced additional MEPS for exit signs, traffic signals, torchières, pedestrian walkway modules and medium screw CFLs, effective from 1 January 2006. It also prohibited the manufacture or import of mercury vapour ballasts from 1 January 2008.

Specifically, the provisions apply to:

- Incandescent non-reflector lamps, rated between 30 W and 199 W and with an E26 medium screw base.
- Incandescent reflector lamps, with an R bulb shape, a PAR bulb shape similar to R or PAR that is neither ER nor BR, as described in ANSI C79.1, and rated between 40 W and 205 W.
- Fluorescent lamps, including the four main categories of fluorescent lamps (4 ft and 2 ft U tube, 8 ft slimline and 8 ft high output), excluding coloured, cold-temperature, reprographic and certain other special-purpose lamps.
- CFLs, specifically those that are integrally ballasted fluorescent lamps with a medium screw base and a rated input voltage of 115–130 V and are designed as a direct replacement for a GLS incandescent lamp.

US and Canadian MEPS for fluorescent and incandescent reflector lamps are shown in Tables 5.9 and 5.10.

The 1992 EPAct did not establish provisions for HID lamps or pin-based CFLs, but it did require the Secretary of the Department of Energy to make a determination of the HID lamps for which "energy conservation standards would be technologically feasible and economically justified and would result in significant energy savings".

MEPS for ballasts

Following the introduction of MEPS for fluorescent lamp ballasts in California in 1982 and the progressive adoption of state-level MEPS over the following years, a federal standard for fluorescent ballasts was added to the National Appliance Energy Conservation Act (NAECA) in 1988 and became effective in January 1990. The regulations are based upon the

Table 5.9 US and Canadian MEPS for fluorescent lamps

Lamp type	Nominal lamp wattage (W)	Minimum CRI	Minimum average lamp efficacy	Effective date
4 ft medium bi-pin	>35	69	75.0	1 November 1995
	≤35	45	75.0	1 November 1995
2 ft U-tube	>35	69	68.0	1 November 1995
	≤35	45	64.0	1 November 1995
8 ft slimline	>65	69	80.0	1 May 1994
	≤65	45	80.0	1 May 1994
8 ft high output	>100	69	80.0	1 May 1994

Source: Derived from Ellis, 2003.
Abbreviations: CRI = colour rendering index; ft = feet; MEPS = minimum energy performance standards.

Table 5.10 US and Canadian MEPS for incandescent reflector lamps

Lamp power (W)	Minimum average lamp efficacy (lm/W)
40–50	10.5
51–66	11.0
67–85	12.5
86–115	14.0
116–155	14.5
156–205	15.0

Source: Derived from Ellis, 2003.
Abbreviation: MEPS = minimum energy performance standards.

Ballast Efficacy Factor (BEF) in order to allow meaningful comparison between different ballasts operating the same type and number of fluorescent lamps. The MEPS had the effect of prohibiting the use of high-loss magnetic ballasts so that only more energy-efficient magnetic ballasts and electronic ballasts could meet the BEF requirements. The MEPS were revised in 2000 with effect from 2005 and essentially require fluorescent lamp ballasts for F40 and F96 lamps to be electronic. Table 5.11 shows the MEPS applying to replacement ballasts, which are defined as ballasts that are manufactured on or before 30 June 2010 and designed to replace an existing ballast in a previously installed luminaire, and are marked “for replacement use only”. Table 5.12 shows MEPS applying to new (non-replacement) ballasts.

Table 5.11 US and Canadian MEPS for replacement fluorescent lamp ballasts

Application for operation of specified lamp	Ballast input voltage (V)	Total nominal lamp wattage (W)	Minimum ballast efficacy factor
One F40T12	120 or 277	40	1.805
Two F40T12	120	80	1.060
	277	80	1.050
Two F96T12	120 or 277	150	0.570
Two F96T12HO	120 or 277	220	0.390

Source: USDOE, 2000.
Abbreviation: MEPS = minimum energy performance standards.

Table 5.12 US and Canadian MEPS for non-replacement fluorescent lamp ballasts

Application for operation of specified lamp	Ballast input voltage (V)	Total nominal lamp wattage (W)	Minimum ballast efficacy factor
One F40T12	120 or 277	40	2.29
Two F40T12	120 or 277	80	1.17
Two F96T12	120 or 277	150	0.63
Two F96T12HO	120 or 277	220	0.39

Source: USDOE, 2000.
Abbreviation: MEPS = minimum energy performance standards.

Exceptions apply for fluorescent lamp ballasts that (i) are designed for dimming to 50% or less of maximum output, (ii) are designed for use with two F96T12HO lamps at ambient temperatures of –20 °F (–28.9 °C) or less and for use in an outdoor sign, or (iii) have a power factor of less than 0.90 and are designed and labelled for use in residential buildings only.

Luminaire standards

The 1992 EPAct called for a voluntary national testing and information programme for luminaires. A programme has been created jointly by a stakeholders' working group called the National Lighting Collaborative. Members include the National Electrical Manufacturers Association (NEMA), the American Lighting Association and other interested parties. The working group introduced a new tool for comparing luminaires, the luminaire efficacy rating (LER), which is based on NEMA's LE 5 standard for fluorescent luminaires. NEMA has since released several lighting performance testing standards relevant to luminaires.

Impacts of MEPS

At the time of their introduction the North American reflector lamp MEPS had the effect of removing from sale almost all common incandescent reflector (R and PAR) lamps rated 75 W or above. These incandescent reflector lamps are used mainly in the residential and commercial sectors for interior or exterior accent lighting applications and still have significant sales in North American and European markets (*e.g.* 13% of the European total incandescent lamp market by volume in 2003). Their efficacies are equivalent to those of GLS incandescent lamps and thus are not as high as those of tungsten-halogen or fluorescent light sources. Consequently the North American MEPS are believed to have helped stimulate a market for alternative technologies, including halogen reflector lamps, krypton-filled reflector lamps, elliptical reflector (ER) lamps and compact fluorescent reflector lamps.

The US and Canadian MEPS for tubular fluorescent lamps practically prohibit the use of halophosphor coatings in 38 mm (T12) lamps and standard T8 lamps in favour of higher-efficacy triphosphor coatings, which are needed to attain the specified efficacy thresholds for lamps with standard light-output ratings. Reduced-wattage lamps with standard phosphors can also meet the EPAct requirements. At the time of their introduction Lawrence Berkley National Laboratory (LBNL) estimated that the net present value (NPV) of the lamp standards in the 1992 EPAct were worth USD 56 billion to the United States (in 1990-dollars, discounted at 7% real discount rate and limited to 1996–2030). The combined impact of the 1990 MEPS for ballast and water heater MEPS was estimated to be even higher, at USD 66 billion (1990-dollars, discounted at 7% real discount rate and limited to 1996–2030) (McMahon, 1995), of which the large majority was because of the ballast MEPS. The US DOE estimates the 2005 update to ballasts MEPS will avoid between 1.2 and 2.3 Quads[3] of primary energy, avoid the emissions of 11–19 Mt of carbon and produce NPV savings of USD 2.4–3.9 billion (1997-dollars, discounted at 7% real discount rate and limited to 2003–30) (Berringer, 2003).

3. A quadrillion Btu, or 1 Quad, is 1.06 exajoules.

Table 5.13 **Estimated savings from US lighting-related MEPS**

MEPS (year of passage)	Electricity savings (TWh/year)			Primary energy savings (Quads/year)*			Peak load reductions (GW)			Carbon reductions (Mt carbon/year)			Net benefit (USD, billions)**
	2000	2010	2020	2000	2010	2020	2000	2010	2020	2000	2010	2020	
Ballasts (1988)	18.0	22.8	25.2	0.21	0.27	0.29	5.7	7.1	7.9	4.4	5.0	5.0	8.9
Ballasts update (2000)	0.0	6.2	13.7	0.0	0.06	0.13	0.0	1.8	3.0	0.0	1.3	2.7	2.6
EPAct – lamps, motors (1992)	42.0	110.3	121.9	0.59	1.51	1.67	10.1	26.2	28.9	11.8	27.5	27.9	84.2
Total of above	60.0	139.3	160.8	0.80	1.84	2.09	15.8	35.1	39.8	16.2	33.8	35.6	95.7
Total all product MEPS	88.0	253.1	341.0	1.24	3.26	4.23	20.8	65.9	120.4	24.7	61.0	74.5	186.0
Lighting share (%)	68	55	47	65	56	49	76	53	33	66	55	48	51
Lighting savings, share of all US use (%)	1.7	3.6	3.7	0.9	1.6	1.7	2.1	4.0	4.2	1.1	1.9	1.8	

Source: Nadel *et al.*, 2005.
* One Quad is a quadrillion British Thermal Units, or 1.06 exajoules.
** Calculated from 2000 to 2030.
Abbreviation: MEPS = minimum energy performance standards.

A more recent assessment of the total savings accruing from all these measures is given in Table 5.13, which projects that lighting-related MEPS will save 3.7% of all US electricity consumption in 2020 and reduce total peak load by 4.2%. From this it appears that lighting MEPS supply about 50% of the savings from all equipment MEPS in the United States. It is likely that similar savings shares will apply in Canada.

Labelling

The 1992 EPAct also set out mandatory lamp-labelling requirements for all the lamp types previously mentioned. In each case the label must be displayed on the lamp packaging and include information on the lamp rated voltage, light output (based on average initial lumens), rated power and lamp life. The EPAct also encouraged the adoption of a voluntary luminaire testing and rating programme.

Green Lights/ENERGY STAR

In 1991 the US Environmental Protection Agency (EPA) introduced the Green Lights Program and in 1995 integrated it into the ENERGY STAR programme, which is now jointly operated by the EPA and US DOE. The Green Lights Program chose to focus on commercial lighting as it was believed the greatest savings potential could be achieved there. It operated as a voluntary public/private partnership that encouraged building owners and operators to adopt energy-efficiency of products and services. In return for technical assistance and public recognition, Green Lights partners voluntarily committed themselves to the installation of high-efficiency lighting products wherever they could be demonstrated to deliver a minimum financial return.

The ENERGY STAR programme also established voluntary endorsement labelling (Plate 5.9) for exit signs (1996), residential lamp fixtures (1997), televisions and windows (1998) and CFLs (1999). ENERGY STAR further sets performance specifications for LFLs, fluorescent ballasts, industrial HID luminaires and fluorescent luminaires. The ENERGY STAR efficiency recommendations proposed for these technologies are harmonised with the recommended levels used in the Federal Energy Management Program (FEMP) (pp. 379–380).

A comprehensive evaluation of the Green Lights Program estimated that it was responsible for annual savings of over 5.6 million tonnes of carbon equivalent in 2000 (Horowitz, 2001). The potential benefit from the full adoption of ENERGY STAR over the following ten years was estimated to be 30–35 Mt of carbon equivalent per year in terms of greenhouse gas reductions.

In 2003 ENERGY STAR-endorsed residential light fittings had captured 4% of the market and were estimated to be saving enough energy to light 2 million homes and avoid the emissions of 580 000 automobiles. Endorsed commercial fixtures had about 11% of the market share, traffic signals about 14%, televisions almost 50% and exit signs over 90% (USEPA, 2003).

2005 EPAct updates

The 2005 EPAct issued MEPS for the following lamps and fixtures:

- Medium screw-based CFLs produced after 1 January 2006 must meet ENERGY STAR requirements from August 2001; these cover efficacy, lumen maintenance, rapid-cycle stress test, lamp life, CRI, power factor and warm-up time.
- Illuminated exit signs manufactured after 1 January 2006 must meet ENERGY STAR version 2.0 requirements.
- Traffic signals manufactured after 1 January 2006 must meet ENERGY STAR version 1.1 requirements.
- Torchières manufactured after 1 January 2006 must not consume more than 190 W or be capable of operating with a lamp rated at >190 W.
- Mercury vapour ballasts cannot be manufactured or imported from 1 January 2008.
- Ceiling fan light kits manufactured after 1 January 2006 must be fitted with a light that is (a) a self-ballasted CFL meeting ENERGY STAR version 3.0 requirements, or (b) a pin-based CFL meeting ENERGY STAR Residential Light Fixture Version 4.0 requirements.

These are wide-ranging provisions that bring many of the federal regulations in line with Californian requirements and with the potential to save a large amount of energy. One set of estimates made before the implementation of the 2005 EPAct is shown in Table 5.14. Furthermore the DOE has subsequently issued a final rule to codify 15 new appliance standards prescribed by the 2005 EPAct. Under the new schedule released by DOE in January 2006, lighting MEPS for HID lamps are expected to be issued in June 2010, lighting MEPS for GLS incandescent lamps and revised standards for incandescent reflector lamps and fluorescent lamps by June 2009, and revised MEPS for fluorescent lamp ballasts by June 2011.

Assessment

The United States and Canada have the most established and comprehensive lighting MEPS programme in the OECD, with provisions now either covering or pending for all the main lamp types. These measures are helping to save a great deal of energy with very cost-effective rates of return for end-users

Table 5.14 Estimates of US national savings from implementing additional lighting MEPS*

	Assumed effective date	Electricity savings in 2020 (TWh)	Electricity savings in 2030 (TWh)	Cumulatve primary energy savings to 2030 (Quads**)	NPV savings to 2030 (USD, billions)	Benefit:cost ratio
Ceiling fan lights	2007	18.9	18.9	3.4	13.0	18.3
Exit signs	2007	1.7	2.9	0.4	1.4	11.9
Metal halide lamp fixtures	2008	9.0	14.4	1.9	7.3	10.8
Reflector lamps	2007	3.9	3.9	0.9	2.6	4.1
Torchières	2007	11.8	11.8	2.3	8.4	10.0
Traffic signals	2007	1.3	1.3	0.3	0.6	3.2
Total		**46.6**	**53.2**	**9.2**	**33.3**	

Source: Nadel *et al.*, 2005.
* All were either passed or planned in the October 2005 EPAct.
** One Quad is a quadrillion British Thermal Units, or 1.06 exajoules.
Abbreviations: MEPS = minimum energy performance standards; NPV = net present value.

and society as a whole. These requirements have helped to make the lighting products sold on the North American market the most efficient in the OECD for fluorescent lamp ballasts, HID lamps, traffic signals and exit signs and among the most efficient for fluorescent lamps. North America is also taking the lead in phasing out inefficient halogen torchières that are still commonplace in many other markets. The North American market is not the most energy-efficient when the blend of lighting products is viewed as a whole, however, largely because of a high dependence on incandescent lamps, which is shared with most other OECD regions. This illustrates the limitations of MEPS and labelling applied within product classes, in that they cannot influence the broader mix across products. Nonetheless there is still some scope to strengthen North American lighting MEPS as at present there are no requirements for ballasts designated for use with metal halide or high-pressure sodium lamps, nor for halogen lamps or low-voltage halogen transformers. Furthermore there is only voluntary performance rating of commercial- and industrial-sector luminaires and there are no provisions for high-pressure sodium or metal halide lamp performance foreseen until 2010. Labelling has also had mixed success in North America. The EPAct lamp-labelling requirements do not include reporting of lamp efficacy, nor is a comparative performance rating scale employed, so it is likely that consumers will not find it easy to compare efficiencies across lamp products. By contrast the ENERGY STAR label is well known and respected and evaluations have shown that it has had a significant positive impact.

Mexico

Mexico implemented MEPS for CFLs in 1997 (Table 5.15) and also applies MEPS related to commercial buildings and exterior lighting (see p. 363). Mexico's MEPS for CFLs have more stringent efficacy requirements than the Canadian and US voluntary requirements that preceded the adoption of the 2005 US EPAct MEPS for CFLs and exclude the least efficient electromagnetic ballasts from the market.

Table 5.15 **Mexican MEPS for CFLs**

Designation	Nominal power* (W)	Base	Bulb	Minimum efficacy (lm/W)
5W/5T4/T/G23/PH	5	G23	T4	38.0
7W/5T4/T/G23/PH	7	G23	T4	50.0
9W/6T4/T/G23/PH	9	G23	T4	55.0
13W/T4/T/GX23/PH	13	GX23	T4	52.5
9W/4T4/Q/G23-2/PH	9	G23-2	T4	51.0
13W/5T4/Q/GX232/PH	13	G23-2	T4	52.0
18W/7T4/Q/G24/PH	18	G24d-2	T4	60.5
26W/8T4/Q/G24/PH	26	G24d-3	T4	61.5

Source: NOM-017-ENER-1997.
* Nominal power is specified to identify lamps.
Abbreviations: CFLs = compact fluorescent lamp; MEPS = minimum energy performance standards.

Moreover, the Fideicomiso para el Ahorro de Energía Eléctrica (FIDE; Electrical Energy Saving Trust) administers a voluntary endorsement label for CFLs that has participating products from leading manufacturers and which has been used as a determinant for inclusion in Mexico's successful CFL programmes.

California

California has played an important role in fostering the adoption of lighting efficiency standards in the United States and has often taken the lead in advance of federal requirements. Aside from being subject to all the prevailing federal regulations California has also introduced MEPS for incandescent lamps, traffic-signal modules and lamps, emergency illuminated exit signs, torchières, metal halide luminaires and under-cabinet luminaires.

To date California is the only jurisdiction aside from Korea to have implemented mandatory or voluntary efficiency standards for GLS incandescent lamps. Legislation prohibiting the sale of less efficient GLS incandescent lamps was due to come into effect on 1 January 2006 (CEC, 2004). These MEPS impose minimum efficacy levels as a function of the rated lamp power (Table 5.16 and Figure 5.10). These MEPS seem to be roughly equivalent to Korea's target value for incandescent lamps operated at 110 V and hence are quite challenging. It remains to be seen what their impact will be and the remarks on this topic in the assessment of Korea on pp. 329–330 also hold true for California.

California's torchière MEPS, which came into effect in March 2003, prohibit the sale of torchières that consume more than 190 W and hence effectively outlaw all but the lowest-power halogen torchières. The US ENERGY STAR programme has had considerable success in promoting the development of alternative, efficient CFL and LFL torchières and these will be able to fill the gap created by the requirements. Moreover the states of Connecticut and Maryland also implemented comparable legislation (Nadel *et al.,* 2005); US federal requirements are now identical.

The metal halide luminaire MEPS outlaw the use of the older, less efficient probe-start metal halide lamps in new HID luminaires manufactured on or after 1 January 2006. The MEPS only apply to luminaires in which the lamp is orientated within 15° of vertical.

California's exit sign and traffic signal MEPS entered into force in March 2003 and effectively require the use of LEDs (see Chapter 7). Connecticut and Maryland implemented similar requirements and these measures are now also adopted at the US federal level under the terms of the 2005 EPAct. California's under-cabinet luminaire MEPS entered into force in January 2006 and obliges the use of high-efficiency ballasts.

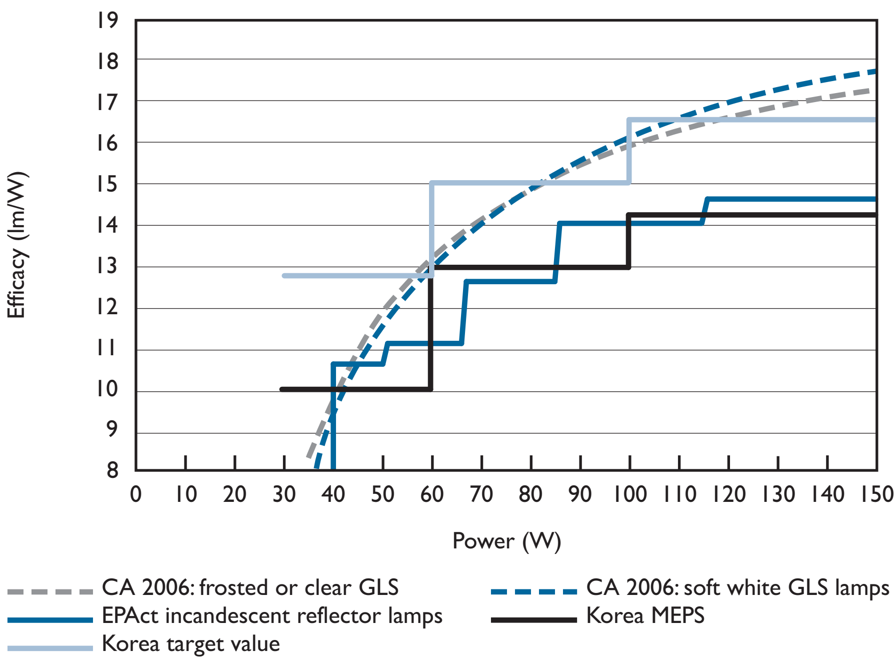
The projected cost-effectiveness of these regulations is striking. In the case of the torchières the benefit:cost ratio is 2500:1, *i.e.* to produce savings of 6 TWh with a value of USD 780 billion, a cost of only USD

Table 5.16 Californian MEPS for GLS incandescent lamps*

Type of lamp	Maximum power use (W)
Frosted or clear	0.050 x light output (lumens) + 21
Soft white	0.048 x light output (lumens) + 23

Source: CEC, 2004.
* From 1 January 2006. These MEPS do not apply to vibration service lamps or full- or enhanced-spectrum lamps.
Abbreviations: GLS = general lighting service; MEPS = minimum energy performance standards.

Figure 5.10 MEPS for incandescent lamps*



Source: CEC, 2005.
* Californian MEPS for GLS lamps from 2006; US EPAct MEPS for reflector lamps; Korean MEPS and target values for 110 V lamps.
Abbreviations: CA = California; GLS = general lighting service; MEPS = minimum energy performance standards.

312 million and a simple payback to end-users of only 0.4 years. For exit signs the benefit to cost ratio is 2031:1 for electricity savings of 0.5 TWh and a simple payback to end-users of 0.6 years. For traffic signals the savings are projected to be 2.1 TWh with a benefit to cost ratio of 275:1 and a simple payback period of 4.1 years (CEC, 2004).

China

China first issued MEPS for appliances and equipment in 1989 and has progressively been broadening and strengthening the requirements ever since. Lighting MEPS have been implemented since June 2003 for:

- Ballasts for tubular fluorescent lamps.
- Double-capped fluorescent lamps for general lighting service (LFLs).
- Single-capped fluorescent lamps (CFLs).
- Self-ballasted fluorescent lamps for general lighting service (CFLs).
- High-pressure sodium lamps.
- Magnetic ballasts for high-pressure sodium lamps.
- Metal halide lamps (under development).
- Ballasts for metal halide lamps (under development).

These MEPS are quite sophisticated in that when they enter into force they include a voluntary higher-performance requirement, which corresponds to the threshold needed to be eligible for receipt of the energy-conservation certification label (see the next subsection); however, these requirements become the new MEPS at a specified future date. This combination of MEPS and so-called "reach standards" sends clear signals to the market about where product efficiency will need to be in a few years' time and allows manufacturers time to prepare new product lines. The MEPS requirements for LFLs and self-ballasted CFLs are shown in Tables 5.17 and 5.18.

Energy endorsement label

China operates an extensive endorsement labelling scheme under the management of the China Certification Center for Energy Conservation Products (CECP) (Figure 5.11). The scheme sets performance criteria for efficient products, including lighting, and certifies performance levels of eligible products via a third-party testing and certification process. Lighting products that are addressed include high-pressure sodium lamp ballasts, tubular fluorescent lamp ballasts, two-end fluorescent lamps and self-ballasting fluorescent lamps (CFLs). In addition, certification labelling requirements are being developed for HID lamps and LEDs. Indirect lighting

Table 5.17 Chinese MEPS for double-capped fluorescent lamps*

Rating (W)	Initial luminous efficacy (lm/W)					
	Energy-efficiency grades (colour temperature: RR, RZ)		Energy-efficiency grades (colour temperature: RL, RB)		Energy-efficiency grades (colour temperature: RN, RD)	
	Certification	Minimum	Certification	Minimum	Certification	Minimum
14–21	53	44	62	51	64	53
22–35	57	53	68	62	70	64
36–65	67	55	74	60	77	63

Source: Chinese standard GB 19043-2003.
* Applicable from June 2003.
Abbreviation: MEPS = minimum energy performance standards.

Table 5.18 Chinese MEPS for self-ballasted CFLs

Rating (W)	Initial luminous efficacy (lm/W)			
	Energy-efficiency grades (colour temperature: >4 400)		Energy-efficiency grades (colour temperature: <4 400)	
	Certification	Minimum	Certification	Minimum
5–8	46	36	50	40
9–14	54	44	58	48
15–24	61	51	65	55
25–60	67	57	70	60

Source: Chinese standard GB 19044-2003.
Abbreviation: CFLs = compact fluorescent lamps; MEPS = minimum energy performance standards.

Figure 5.11 China's endorsement label

applications include windows and televisions. As of 2004 about 1 500 energy-efficiency products from 150 manufacturers received the CECP certificate (Caifeng *et al.*, 2004). China has also recently implemented a mandatory energy-information label for refrigerators and air-conditioners that rates product performance from 1 (more efficient) to 5 (less efficient); so far this has not yet been applied to lighting products, but it may be in the future.

Impacts and assessment

It has been estimated that the MEPS for fluorescent lamp ballasts and LFLs alone will save over 27 TWh of electricity in 2010 and over 59 TWh in 2020, giving a NPV of more than CNY 49 billion (49 billion Yuan renminbi) (CNIS, 2004).

Other non-OECD countries

Beyond the countries mentioned above, energy labelling for CFLs has been implemented in: Brazil; Columbia; Hong Kong, China the Philippines; Chinese Taipei; and Thailand. These all have voluntary endorsement labels with the exception of the Philippines, whose label has been mandatory since November 2005. The Philippines label indicates light output, power consumption, efficacy and average life. In Brazil, two voluntary labels are applied, one that is harmonised with the EU A to G household lamp label and another that is a pure endorsement mark. Thailand also applies a voluntary information label that rates efficiency on a scale from 1 to 5, where 5 is the most efficient (Plate 5.12). Thailand and Brazil both apply similar labels to LFLs, but Thailand also uses the same basic design for LFL ballasts. Singapore has also implemented a voluntary energy label for ballasts. Brazil also applies a voluntary label to fluorescent lamp ballasts, sodium vapour lamp ballasts and sodium vapour lamps; the ballast label design is quite different from the others.

An evaluation of the impact of the Thai labelling scheme found that for two products over the time frame 1994–2000 government spent USD 0.2 per capita, which stimulated investments worth USD 2.4 per capita and produced savings of USD 3.5 per capita. The savings amounted to 1.3% of national electricity usage and avoided 1.4% of peak power, producing cumulative net benefits of USD 56 million and avoiding the emission of 0.9 Mt of CO_2. The scheme is managed by the Electricity Generation Authority of Thailand (EGAT) and financed through a multi-million dollar DSM fund, which allowed a considerable budget to be used to promote the label.

In other initiatives the member countries of ASEAN have been developing a harmonised endorsement label for fluorescent lamp ballasts. Malaysia, Taiwan and the Philippines have all implemented MEPS for ballasts and Thailand has been reported to be considering this option (Weil, 2004; Ellis, 2003). Peru has developed technical performance specifications for CFLs, but no label or MEPS as yet. Hong Kong, China, implemented an endorsement label for fluorescent lamps in 1998. Sri Lanka applies a voluntary 1- to 3-star rating label for ballasts and LFLs and India is reported to be developing requirements for fluorescent lamp ballasts. Taiwan, the Philippines and Malaysia all have ballast MEPS. Singapore, Thailand and Brazil have voluntary ballast labels (Weil, 2004).

ENERGY-PERFORMANCE BUILDING CODES AND CERTIFICATION POLICIES

Legislation such as building codes can affect design and purchase decisions regarding lighting systems. In some cases, homeowners may be influenced by the codes; more often, the codes provide guidelines or requirements for the people who are responsible for designing and installing lighting systems in new commercial and residential buildings (such as developers, contractors and lighting designers). Building codes present one of the principal means of influencing the efficiency of lighting installations and hence provide a means of overcoming the weakness of MEPS and labels because they apply at the lighting-system level rather than the component level.

United States

Building energy codes in the United States are generally established at the state level. Since the 1970s, guidelines for lighting have been included in national voluntary building energy standards, but since 1989 numerous states have established mandatory energy performance standards applying to lighting systems installed in commercial and to a lesser extent residential buildings. When the 1992 EPAct was enacted in October 1992, regulations affecting lighting energy efficiency became much more comprehensive. In addition to the MEPS and labelling provisions mentioned on pp. 330–337, the provisions of the EPAct include a requirement to develop and maintain model national building codes; these have subsequently been established with specific provisions for lighting energy performance. The model building codes are endorsed through EPAct but individual states have the freedom as to whether to adopt their provisions, and hence in practice a wide range of codes apply. The model codes differ depending on whether they apply to commercial buildings or residential buildings, as is now discussed.

Codes for commercial buildings

Model codes have been established at the national level, but these are usually modified to meet specific needs within each state. State energy codes for commercial buildings are generally based on either the Model Energy Code (MEC) – which is published and maintained (since 1998) by the International Code Council (ICC) as the *International Energy Conservation Code (IECC)* – or on the American Society for Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) 90.1 codes.

ASHRAE and the Illuminating Engineering Society of North America (IESNA) developed the voluntary building code for lighting in commercial buildings in the United States. Since the 1989 version of this code there has been a lighting section which specifies maximum "lighting power density" (LPD) limits, in units of watts per square foot, to limit the connected lighting load in a building or space type. The most recent version is entitled ASHRAE/IESNA 90.1-2004, which supersedes the earlier 90.1-2001, -1999 and -1989 versions. In addition to the ASHRAE codes, US states also employ codes developed by the IEC. The most recent version of the *IECC* is dated 2004 and supersedes the earlier 2000/2001 and 2003 versions. In consequence the 50 states apply building codes to varying degrees and of varying vintages based on either the ASHRAE or IEC model codes. Once again California is unique as it has developed its own code, known as Title 24. A survey of the status of US building codes in August 2005 conducted by the IEA and derived from information contained in the Building Codes Assistance Project[4] found that:

- 11 states covering about 11.8% of the US population had no state-wide codes.
- A further four states covering 5.3% of the population were using ASHRAE 90.1-1989.
- 15 states covering 37.4% of the population were applying either ASHRAE 90.1-1999 or *2000 IECC*.

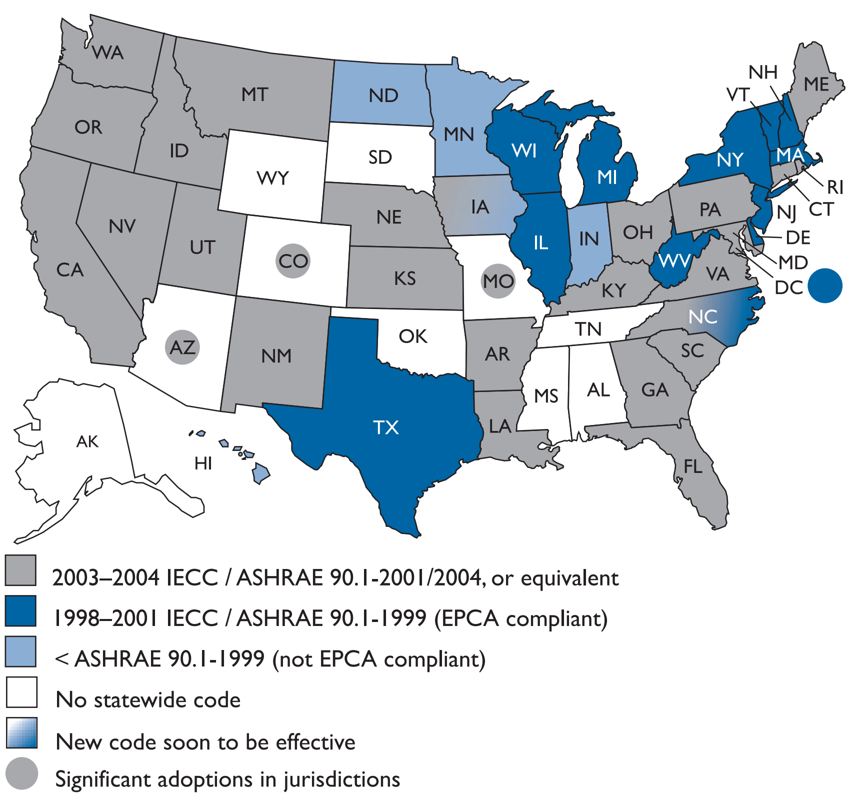
4. Available at www.bcap-energy.org.

- 19 states covering the remaining 44.6% of the population were applying ASHRAE 90.1-2001 or 90.1-2004, *2003 IECC* or, in the case of California, Title 24 codes.

The first two groupings either had no codes or were using outdated codes and hence were not compliant with the provisions of the 1992 EPAct. The remaining states were compliant (Figure 5.13).

In the case of lighting these distinctions are important because the stringency and comprehensiveness of the lighting regulations has advanced over time in both the ASHRAE and IEC codes such that the

Figure 5.13 **Status of US commercial building code adoption in 2005**



Source: BCAP, 2006.

potential impacts of the codes vary significantly. For example the *2003 IECC* code contains almost identical LPD limits as in the most advanced ASHRAE 90.1-2004 code, but for earlier versions of both codes the LPD limits are appreciably weaker. Ever since the 1989 edition, the ASHRAE 90.1 codes have given installers a choice in how they comply with LPD requirements: they can either adopt a simplified method known as the "building-area" approach under which LPD limits are set for the whole building and compliance is established by dividing the total installed lighting power by the total building floor area; or they can opt to apply LPD thresholds for each common functional area of the building. This latter method is known as the "space-by-space" method. It can be more complex to apply but allows more freedom in the event that the design is atypical of the primary building type in terms of its share of high-illuminance floor areas. The maximum permissible LPDs for the building-area approach are set by building type. At one extreme a building for family dining has a LPD limit of 17.2 W/m^2 under the latest ASHRAE 90.1-2004 code, while at the other extreme a warehouse has a limit of 8.6 W/m^2 (Table 5.19). When the average value of the building area based LPD is calculated, it is 12.1 W/m^2 for the 2004 version, whereas it is 16.3 W/m^2 under the 1999 version, *i.e.* 35% higher. The LPD limits in the ASHRAE 90.1-1989 code are about 13% higher again than the 1999 code, so overall there has been a very significant tightening of requirements since the maximum LPD thresholds were first introduced in the 1989 code. The main factors that have allowed these reductions are: (a) a move toward lower recommended illuminance levels and clearer uniformity requirements in line with IESNA recommendations; (b) the higher efficacy of more recent commercial-lighting equipment, in part driven by MEPS and labelling measures but also including higher-performance luminaires; (c) greater understanding of lighting design and superior lighting design techniques; (d) a rising appreciation of the value of task lighting.

Compliance with lighting codes

There appear to have been few studies into compliance with light provisions under the US building codes, but the results of one such investigation were reported in a conference paper in 2004 (Richman *et al.*, 2004). The study looked at compliance data gathered across several states with the LPD provisions of ASHRAE 90.1-1989. Some of the states had implemented the code at the time the audited buildings were constructed and some had not. The sample comprised offices, dining establishments, schools. Some 33 buildings were constructed in states applying the ASHRAE 90.1-1989 code

Table 5.19 **Sample of building-area LPD requirements under ASHRAE 90.1-2004**

Building type	Maximum LPD requirement	
	W/ft²	W/m²
Automotive facility	0.9	9.7
Court house	1.2	12.9
Dining: family	1.6	17.2
Hospital	1.2	12.9
Hotel	1.0	10.8
Manufacturing facility	1.3	14.0
Motel	1.0	10.8
Multi-family	0.7	7.5
Office	1.0	10.8
Parking garage	0.3	3.2
Retail	1.5	16.1
School/university	1.2	12.9
Warehouse	0.8	8.6
Workshop	1.4	15.1

Abbreviations: ft = feet; LPD = lighting power density.

and 31 were in states applying no codes. On average the LPDs in the sample of buildings in the states with codes were 4% lower than the mandated threshold. Among these, 23 buildings met the code with average levels being 36% lower, while 10 buildings did not meet the code and on average had LPD levels 69% higher than allowed. Intriguingly the situation was similar but slightly better in the states that did not have any codes. The average LPD of all the buildings was 11% lower than the ASHRAE 90.1-1989 limits. Of this sample of buildings some 22 had LPDs that would have met the ASHRAE 90.1-1989 provisions and on average exceeded them by 34%, while some 9 buildings failed to meet the provisions by an average of 47% above the code LPD requirements. This information can be interpreted in numerous ways but certainly highlights the importance of compliance. If those buildings that did not met code had done so, the average LPD for the entire building sample would have been 25% below code and lighting energy consumption would be roughly 21% lower overall. These findings are typical of international investigations into building energy code compliance and suggest that policy makers need to make compliance a much higher priority if they are to reap the full potential benefits of modern building energy codes.

Impacts of lighting power density provisions in US codes

An IEA analysis of the impact of the current US building-code lighting provisions estimates that with full code compliance in the states that have adopted building lighting codes to date, average installed LPDs would be 19% lower than pre-code (1990) levels by 2010; they would then fall to 40% less than 1990 values by 2030. These improvements are purely as a result of meeting the code requirements, *i.e.* they are assessed in isolation of other policy measures. This analysis is based on a sophisticated modelling assessment that takes account of: the time-dynamic nature of the adopted codes; the stringency and scope of applicability of the provisions in each code; the relative weighting of building floor areas in the commercial-building sector; the likely rate of introduction of new buildings and turnover rates of lighting systems in existing buildings; and the probable pre-code LPD levels based on the information in the US Lighting Market Characterization study (Navigant, 2002). It is also quite probable that most of this benefit would be gained even with current compliance levels, but there is considerable uncertainty about this and thus it cannot be relied upon.

The scale of the potential policy-driven LPD impacts is substantial and generally lighting energy consumption would be expected to scale proportionately to the changes in the stock average LPD levels. If US commercial-building lighting energy use were to remain static at the 2001 figures identified in the US Lighting Market Characterization study (Navigant, 2002), the full compliance improvement in commercial-building LPD by 2030 would translate into annual electricity savings of 141 TWh compared to the situation were there to be no improvement in the 2001 stock-average LPD levels.

Measures influencing lighting use

LPD levels are only one facet influencing lighting energy use. Other facets concern the control of lighting and the demand for artificial light, which is influenced by daylight availability and the design illuminance levels. The most recent versions of the ASHRAE and IEC codes have placed far greater emphasis on these areas than previously and this also holds the potential for significant energy savings.

2003 IECC stipulates that lighting controls are required for each area enclosed by ceiling-height partitions and that the switch locations must be in view of the lights and have a clear on/off indication. Each such area must have light-reduction controls and automatic lighting shut-off (scheduling) unless regulated by the use of occupancy sensors. Exceptions apply to some spaces such as emergency-egress corridors. For manually controlled areas it should also be possible to dim the lighting by at least 50% by way of either dimmers or bi-level switching. Automatic switching or photocell controls shall be provided for all exterior lighting not intended for 24 hour operation (USDOE, 2005a).

Provisions for exterior lighting

The ASHRAE 90.1-2004 code includes LPD requirements for exterior-lighting energy performance, which is not addressed in the previous model codes although it has been proposed for the IEC code of 2006. The previous ASHRAE code stipulated a minimum mean external lighting efficacy of 60 lm/W, while the current *2004 IECC* stipulates 45 lm/W. The new LPD requirements are assessed assuming the use of metal halide lamps and following creation of multiple lighting-solution models for parking areas, walkways/plazas, building entries/exits, canopies, façade lighting and outdoor sales. This has given rise to a recommended LPD limit of 1.6 W/m^2 for outside parking areas, for example (Richman, 2005).

California now requires outdoor lamps to have an efficacy of >60 W for all but a handful of exceptions. In addition, automatic controls (either photosensors or astronomical time switches) are required to turn off outdoor lighting during the day and during other periods when it is not needed. This requirement applies to all permanent outdoor light fixtures except a designated list of applications that require daytime illumination. For illumination of exterior façades, car parks, garages and outdoor-sales areas, controls that reduce power by at least 50% are mandated so that lighting can be dimmed during low-usage periods. In an effort to limit light trespass and pollution, "cut-off" luminaires (see pp. 237–238) are required for a large range of outdoor lighting fixtures rated at or above 175 W. California has introduced LPD limits for a range of exterior illumination applications, including car parks, that are substantially lower than the ASHRAE recommendations; performance provisions have also been set for indoor and outdoor display signage (CEC, 2003).

Ontario in Canada is also reported to have set energy-performance standards for street lighting.

Applicability of codes

Another highly important development in the US lighting building-code provisions is an expansion in their coverage to apply not only to lighting installed in new buildings but also to major retrofits of lighting systems in existing buildings. As these retrofits typically occur every 20 years this presents a much greater opportunity to influence the efficiency of the lighting systems being installed in the building stock as a whole than was previously the case.

Measures to encourage the use of daylight

There is much that can be done through building codes to promote the use of daylight as an energy-saving and high-quality lighting option. Recently, for example, California revised its building standards to include several aspects on energy-efficient lighting. Skylights are required in "big box" non-residential buildings, with controls to turn off electric lighting when natural daylight is available.

Residential buildings

California currently has the most stringent North American building-code requirements applying to new residential buildings. These demand state-of-the-art fluorescent lighting to be installed in all permanent fixtures and are effected by specifying a certain amount of "energy-efficient lighting" to be installed (CEC, 2005). The 2001 Title 24 codes defined "energy-efficient lighting" as having an efficacy of >40 lm/W, but the 2005 version defines it as >40 lm/W for lamps rated less than 15 W, >50 lm/W for 15–40 W, and >60lm/W for >40 W. This effectively requires at least high-efficiency CFLs, but can also include reasonable-efficacy, small LFL options. Ballasts for lamps rated over 15 W must be of a high-efficiency electronic type. Switching requirements are set so that low-efficacy lighting must be controlled independently of high-efficacy lighting. The requirements for high-efficacy lighting are as follows:

- Kitchens – at least 50% of the installed wattage must have high efficacy.
- Bathrooms, garages, utility and laundry rooms – all hard-wired lighting must have high efficacy or be controlled by an occupancy sensor.
- All other rooms – all hardwired lighting must have high efficacy or be controlled by a manual-on occupancy sensor or dimmer.

Government buildings

Specific energy codes apply to federal buildings, separated into those for commercial federal buildings (Federal Commercial Building Energy Standard; FEDCOM) and residential federal buildings (e.g. housing for the military). The US DOE has been developing more advanced requirements for these codes than usually apply elsewhere. Lighting systems in federal buildings are specified to meet the conditions of the Federal Energy Management Programme (see pp. 379–380).

Building energy performance certification

The ENERGY STAR programme operates voluntary energy performance certification schemes for new and existing residential and commercial buildings. The latter scheme relies on an assessment of utility bills for existing buildings and awards the ENERGY STAR certificate if the building is in the upper percentiles of energy performance compared with peer buildings. The US Green Building Council applies its Leadership in Energy and Environmental Design (LEED) rating and award for energy-efficient and low environmental impact commercial buildings. Some cities now require LEED certification for new building developments in their jurisdiction.

Assessment

North America has pioneered the use of building codes to limit lighting energy consumption. The most recent codes have either been adopted or are under consideration by most US and Canadian states and if fully implemented will progressively save a substantial amount of lighting in commercial buildings. Less is being done in the residential sector, although there are noteworthy examples in the Californian codes and some other states, as well as successful market building initiatives such as the Residential Energy Services Network (RESNET[5]) and its ENERGY STAR homes. More widespread adoption of residential lighting fixture efficacy requirements and outdoor lighting ordinances could help to make substantial improvements in lighting efficiency in both sectors. Code compliance and fully harmonised and broadly based building energy certification schemes are also areas that may be worthy of increased attention. The former is traditionally neglected in relation to need in most economies, while the latter can be an important vector to promote building energy efficiency.

5. Available at w.w.w.natresnet.org.

Europe

As is true of the wider international community, the existing building codes in place in Europe vary considerably in their scope, methodology and rigour. An extensive review was conducted through the ENPER-TEBUC project, which established the degree of commonality and divergence existing in European building codes at that time (ENPER-TEBUC, 2003). To a large extent this exercise serves as a microcosm of the broader international picture, where exactly the same types of differences are found. Table 5.20 summarises the energy flows that were considered in the European building code energy-performance calculation procedures. Despite being one of the main contributors to building primary energy use, lighting was treated in only 6 of the 18 countries' codes. For countries without provision for lighting there would be no reward in terms of compliance with the overall building energy performance requirements from using efficient-lighting solutions and hence no incentive through the code to optimise lighting performance. This is surprising considering that:

i) Efficient lighting is one of the most cost-effective means of reducing building energy use.

ii) Efficient lighting is one of the most rapidly implementable means of reducing building energy use.

iii) Lighting energy performance is comparatively simple to verify for compliance purposes (whereas insulation performance, for example, is not).

iv) Lighting systems are replaced more frequently than the building fabric and hence lighting energy performance codes for existing buildings present a faster route to low-energy buildings than fabric-related performance measures.

Energy Performance in Buildings Directive

The ENPER-TEBUC review of codes was triggered by the passage of the European Union's Energy Performance in Buildings Directive (EPBD) (2002/91/EC) in 1992. This Directive entered into force in January 2003 and gave EU member states until January 2006 to implement regulations that:

Table 5.20 **Energy flows covered in European building-code calculation procedures pre-2003**

	Netherlands	Fl. Belgium	France	Germany	Italy	Greece	Lithuania	Sweden	Switzerland	UK	Austria	Czech Rep.	Denmark	Finland	Ireland	Norway	Portugal	Russia
Transmission	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Ventilation	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Internal and solar gains	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Heating system	X	X	X	X	X	X	X	X	X	X	X							
Lighting	X	X	X			X		X	X	X								
RE, thermal	X	X	X	X	X													
RE, electric	X	X																

Source: ENPER-TEBUC, 2003 (reproduced with permission).
Abbreviations: Fl. = Flanders; RE = renewable energy; Rep. = Republic; UK = United Kingdom.

- Incorporate mandatory minimum energy efficiency requirements for both new buildings and the renovation of large existing buildings.
- Apply mandatory energy performance certification of all buildings above 2000 m^2 in surface area.
- Display the energy performance of public buildings.
- Use a comprehensive method to calculate the energy performance of buildings; the method is to incorporate all factors that influence energy consumption, including lighting, and should be suitable for all building types (homes, offices, schools, etc.).
- Require regular inspection and assessment of boilers/heating and cooling installations.

This Directive is a major step forward in promoting energy-efficiency requirements in both new and existing buildings but allows a large degree of subsidiarity (freedom for national interpretation of measures) in the methodology to be applied, stringency and enforcement mechanisms.

The requirement to move toward a whole-building energy-performance assessment is a new departure for most EU states. To facilitate this action

Table 5.21 Draft European standards for lighting energy performance in buildings developed under the auspices of CEN

Draft standard or work item no.	Work item	Responsible technical committee
prEN 15193-1:2005 (E)	Energy performance of buildings – energy requirements for lighting (including daylight)	TC 169 WG9
TC 156 WI 00156100:2005 (E)	How to specify criteria for the internal quality environment, (thermal, lighting, indoor air)	TC156 WG7

Abbreviation: CEN = Comité Européen Normalisation (European Committee for Standardization).

the European Commission has been developing a comprehensive set of calculation methods that allow building energy performance to be assessed. It includes 31 different methodological standards, of which two address lighting (Table 5.21).

The inclusion of these methods ensures that lighting is one of the factors influencing the rating of the overall building energy performance. Hence, in future there will be an incentive to use efficient lighting installations to meet mandatory performance requirements in all new buildings and in the retrofit of large buildings. Lighting performance will also be one of the factors contributing to the building energy performance certificate ratings and so again there will be an incentive to use efficient lighting in order to improve the performance rating for buildings with a surface area above 2 000 m^2.

Review of EU lighting energy performance regulations prior to the EPBD

The ENPER-TEBUC 2002/3 review of the factors included in building-code energy-performance calculations found that seven countries (Austria, Germany, Italy, Spain [although one provision was under preparation], Sweden, Switzerland and the former Yugoslavia) had no provisions addressing lighting in their codes. Denmark applied a detailed mandatory standard for lighting in workplaces that asked for, but did not require, efficient lighting, including lighting controls by building zone. The standard contained no numerical requirements for energy efficiency, although other voluntary Danish standards did recommend maximum LPD levels in watts per square metre. Six other countries were found to apply default values for lighting in their building energy calculation procedures. These were

Finland, Ireland (optional calculation for dwellings only), Lithuania, Norway, Portugal and the Netherlands (for residential buildings). Typically these default values would depend on the type of building being considered; however, in each of the six national procedures there was no incentive to use more efficient lighting because the procedures did not allow the use of efficient lighting to offset energy use elsewhere.

Four countries (Flanders-Belgium from 1 January 2004, France, Greece [the requirement was a draft standard at that time] and the Netherlands) used a detailed calculation procedure for lighting that was included in their overall building energy performance requirement. Each calculation procedure estimated the overall average energy or power consumption for the lighting in the building in units of primary energy for Flanders-Belgium, France and the Netherlands and in watts per square metre for Greece. The use of efficient lighting would thus contribute to attaining the minimum building energy performance requirement in each case. Each method required the building to be divided into zones dependent on the use of the zone, the type of lighting system installed or whether the zone was day-lit. The estimated lighting energy use is derived for each zone by multiplying the installed lighting load by the zone area, the estimated hours of use, and by coefficients that depend on the availability of daylight and the type of control system used. Varying degrees of simplification were used that would influence the incentive to optimise parts of the lighting system. In Greece, all ballasts were assumed to increase the circuit wattage by a factor of 1.2, so there would be no incentive to minimise the circuit power via efficient ballasts, whereas in France the ballast and lamp loads would be counted. The Flanders regulations included the consumption of light sensors and ballasts in the overall circuit power.

Treatment of daylight also varied in sophistication such that the Dutch, French and Belgian codes applied a simple day-lit zone allowance, although the French codes allowed adjustment for climate. The Belgian codes included an option that allowed thorough daylight factors to be calculated, while the Greek codes required this. As is common in building codes, default assumptions were allowed that could be used if the values were unknown or if the developer did not wish to do the calculation; however, these defaults would assume higher than typical energy usage to encourage designers and developers to consider efficient lighting and assess its performance. To avoid giving a perverse incentive for lighting systems to be under-installed (*i.e.* not providing sufficient light for the task in order to comply with the lower energy requirements) at the time of assessment, the French method compared the building performance against that of a hypothetical reference building providing the same illuminance. In terms of their scope the Flanders-Belgian method only applied to non-residential buildings and the Greek codes applied to all building types but used a simplified method for residences.

The EPBD has acted as a major catalyst to European building codes and there have been many changes since the ENPER-TEBUC review. For example, Germany has issued a new building energy performance code that complies with all the provisions of the Directive and hence includes lighting within an overall calculation procedure. The new German code, along with most of the other new European national building codes, rates building energy performance using primary energy, which reflects the losses in the production of final energy and gives a higher importance to electrical end-uses, such as lighting, than if final energy were the indicator. Some countries, most notably the United Kingdom, are using CO_2 emissions as their performance indicator, although this often results in a weighting that is similar to when primary energy is used, providing renewable energy sources are given a bonus in the primary energy calculation. Germany is not alone in updating its codes and making existing provisions more ambitious. Denmark, France and the United Kingdom have done, or are doing, the same with increases in minimum energy performance stringency of about 25%. Many other EU and EU accession states are doing likewise.

The regulations applying in France and the United Kingdom are different to those in most other European states because they not only include lighting in the assessment of the overall building energy performance, but also set specific performance limits for lighting, as is the case in the ASHRAE and IEC requirements in North America. These are now discussed.

France

The Réglementation Thermique 2000 (RT2000) specifies minimum lighting energy performance requirements for new buildings and new extensions to existing buildings (J Officiel, 2000). The regulation specifies multiple compliance routes, thus the user can respect whole-building LPD requirements, space-by-space LPD levels or lighting flux limits as follows:

- Spaces of less than 30 m^2: 4 W/m^2 per 100 lux.
- Spaces of more than 30 m^2: 3 W/m^2 per 100 lux.

The whole-building LPD limits are 16 W/m^2 for offices, commercial establishments, educational establishments and hospitals, 12 W/m^2 for hotels, restaurants and other locales, and 10 W/m^2 for warehouses. In general these requirements are not as stringent as the most recent US codes, although they do include a provision specifying that when automatic lighting controls are used they should not activate lighting when natural daylight is sufficient. Another provision specifies separate control of spaces that have access to daylight. A revision to the RT2000 codes is currently under way and a draft of the proposed RT2005 codes has been circulated for consultation. The draft includes more stringent requirements: lighting flux limits of no more than 2.5 W/m^2 per 100 lux; whole-building LPD limits of 12 W/m^2 for commercial establishments, offices, educational establishments, hospitals, hotels, restaurants and other locales; and 10 W/m^2 for warehouses (DGUHC, 2005). These provisions are much closer in ambition to the most stringent US requirements.

United Kingdom

Within the United Kingdom, building regulations require that lighting systems in non-domestic buildings are energy efficient. In older versions of the Part L2 building code (Conservation of Fuel and Power) the requirement was for the general lighting in a building to have an average lamp and ballast efficacy (total lamp output divided by circuit-watts) of 50 lm/W or more and for suitable lighting controls to be fitted. Portable lighting, display lighting, external lighting and some forms of emergency lighting were exempt. In the 2002 edition the requirement was altered so that for office, industrial and storage areas compliance would be attained through lighting with an average initial efficacy of not less than 45 luminaire-lumens per circuit-watt as averaged over the whole area of these spaces in the building. The average luminaire-lumens per circuit-watt is calculated by (source-lumens x LOR) summed for all luminaires in the relevant areas of the building, divided by the total circuit-watts for all the luminaires, where lamp-lumens equals the sum of the average initial (100 hour) lumen output of all the lamps in the luminaire and LOR equals the light output ratio of the luminaire, *i.e.* the ratio of the total light output under stated practical conditions to that of the lamp or lamps contained in the luminaire under reference conditions. In general the apparent lower-efficacy requirement is more than offset by incorporating the luminaire losses into the calculation. This provision has not been extended to other building areas, in part because of uncertainty that luminaires with the appropriate photometric data are available. In general these requirements translate into a minimum general lighting efficiency of no more than 3.75 W/m^2 per100 lux, while all other lighting (except display lighting) has an efficacy of not less than 50 lamp-lumens per circuit-watt (ODPM, 2005).

The most recent 2006 version of these codes comes into line with the EPBD provisions and moves toward a whole-building energy-performance rating (ODPM, 2006). It uses a web-based calculation tool to determine if a building complies with the overall performance requirement (expressed in terms of CO_2 emissions per unit area by comparison with the value from a hypothetical reference building). The calculation rewards the use of daylight and lighting controls as well as the use of efficient-lighting systems beyond the minimum requirements. In this way there is a direct performance benefit from using efficient-lighting options combined with minimum performance measures, which ensure lighting performance is not overlooked. These provisions also apply for lighting in building refurbishments.

The UK 2002 L1 regulations applying to domestic buildings required new homes to be fitted with at least three internal, fixed light fixtures and one external, fixed fixture with an efficacy of >40 lm/W. Alternatively the external fitting could use automatic lighting controls. The 2006 regulations specify that compliance with codes can be attained by installing at least one fixed luminaire that only takes one efficient lamp (>40 lm/W efficacy) per 25 m^2 of floor space as well as one such fixture per four fixed fittings. For external lighting the specification is that either lamp circuit power does not exceed 150 W per light fitting and the lighting automatically switches off when there is enough daylight and when it is not required at night, or the lighting fittings have sockets that can only be used with lamps with an efficacy >40 lm per circuit-watt. These provisions also apply to lighting in building refurbishments. Moreover, the overall residential building energy performance standard is based on a target CO_2 emissions rate for heating, hot water and lighting, but the overall stringency of the minimum energy performance requirement has increased by 25% compared with the 2002 code and thus will provide an additional incentive to use efficient lighting fixtures in new homes (ODPM, 2005).

Building energy performance certification

The provision for mandatory building energy performance certification is among the most novel and important measures in the EPBD. In many member states the assessment methodology to be used is harmonised with that applied to new buildings and comprises an asset-based rating, *i.e.* an assessment of the building design and construction. In others the approach used is to derive building energy performance from metered energy-consumption data, which is akin to the approach applied by the US ENERGY STAR buildings rating system for commercial buildings. Some have contemplated using both approaches with the intention of allowing their results to be compared. The idea here is that if the actual metered performance rating is worse than the asset rating it implies that immediate savings may be attained by better operation and management of the building energy systems. In Germany the new energy performance certificate, known as the "Energy Passport", has already been issued; like many of the certificates it uses a label format that resembles the EU appliance label, except in this case it extends the scale from A (more efficient) to I (less efficient) as compared with the A to G used in the appliance label. The rating is based on primary energy per square metre such that an A-rated building uses less than 80 kWh/m^2 per year, while an I rated building uses more than 401 kWh/m^2 per year (Plate 5.14).

The label informs the user that the ratings I to F apply to typical older buildings, while those for D to A are typical of new buildings. The building owner must show the certificate to new tenants or owners whenever there is to be a change of occupancy. The certificate informs people not only of what the rated performance is but also of the best set of options for improving the building's performance.

In fact there is considerable experience with building energy performance certification in some European states. Denmark, the United Kingdom, the Netherlands, the Russian Federation and Austria all introduced schemes in the 1990s.

Assessment

Europe is moving from an era when lighting was under-represented in building energy codes to one where it is fully considered as part of the energy performance assessment mix. Moreover, the requirement to have mandatory building energy certification will make energy performance much more visible in the market and this will focus greater attention on all areas of building energy use, including lighting. Despite some minor setbacks these measures are being implemented at a rapid pace, which shows a serious intent among policy makers to move things forward. The inclusion of benefits for daylighting measures in the model energy performance calculations will also provide an additional spur to the use of natural light as an energy-savings measure. There are still many areas where the existing provisions could be strengthened, however. Member states could consider following the example of France and the United Kingdom in setting minimum requirements for lighting as an additional guarantee that cost-effective lighting measures will not be forgotten. The ambition of these measures might look to those of their counterparts in North America to ensure that they are suitably comprehensive and that their compliance is sufficiently easy to check. They might wish to consider greater provisions for outdoor lighting, lighting controls and the strengthening of provisions for display lighting, for example. In particular, the United Kingdom's requirements specifying high-efficiency, fixed lighting fixtures for households are worthy of attention as are the efforts to bring commercial- and industrial-sector luminaire performance into the evaluation. Evaluations of compliance with building energy code provisions in numerous European states have shown that compliance rates are often poor and in some states they are reported to be worsening. Although the IEA is unaware of any evaluation of compliance with lighting-code provisions in Europe, it is not improbable that results similar to those reported for the United States could be expected. This suggests that attention will need to be focused on compliance once the new provisions have been adopted and this will probably also require much greater attention to capacity building among all the involved market actors. Knowledge of and the ability to attain compliance through efficient-lighting options will need specific attention if a large part of the potential is to be mined.

Other OECD and non-OECD countries

Many countries in the rest of the OECD are not believed to have implemented requirements for lighting energy performance in their building codes and some do not have mandatory building energy performance codes. The requirements that are known of are detailed in the following sections.

Australia

In March 1999, following wide consultation, the federal government and the building industry reached agreement on a comprehensive strategy aimed at making Australian buildings more energy efficient by incorporating a single standard for minimum performance requirements into the Building Code of Australia (BCA). Work began on developments to define an acceptable minimum level of energy efficiency for new buildings throughout Australia to eliminate worst practice within the industry. Energy-efficiency provisions for housing, including lighting, were due to be incorporated into the BCA on 1 January 2003, with provisions for commercial and public buildings introduced in 2004. The requirements for lighting address multi-family dwellings and commercial buildings. For the multi-family dwellings, minimum efficacy specifications for bathroom fixtures, maximum LPD levels for common areas and accommodation areas, and concessions for use of intelligent light controls are included. The requirements for the commercial sector include LPD limits for interior spaces, mandatory time switching or occupancy sensors for large areas, minimum efficacy and sensing requirements for exterior lighting, and concessions for intelligent light controls.

Australia is also developing efficient-lighting requirements for main roads under the auspices of Project Greenlight Australia (AGO, 2005).

Mexico

Mexico applies building code standards for the energy performance of lighting in commercial buildings (NOM-007-ENER-1995) and exterior lighting (NOM-013-ENER-1996). The commercial-building requirements are LPD limits expressed in watts per square metre. The exterior-lighting standard requires the efficacy to be greater than 22 lm/W for exterior lighting of building fronts, parks, gardens and numerous other outdoor places and hence effectively prohibits the use of incandescent lighting for these applications. Lighting of pavements, bus stops, plazas and main squares must have an efficacy of >40 lm/W and hence prohibits self-ballasted mercury vapour lamps but not separately ballasted mercury vapour lamps.

Japan

Japan has model building energy codes that are applied on a voluntary basis but does not yet mandate performance requirements. For many years the government has promoted the use of building energy management systems that usually include some form of intelligent lighting control through the form of incentives. This was a major focus of the 2005 revision of the national Energy Conservation Law.

China

Building energy performance requirements for lighting, standard number GB 50034-2004, were adopted by the Ministry of Construction on 24 June 2004 and came into effect on 1 December 2004. This sets illuminance requirements and maximum LPD thresholds that have been estimated to be about 20% looser than the average Title 24 requirements for California.[6] The standards sets LPD limits for all buildings and roadways. In the case of households the limit is 7 W/m² and for roadways it varies between 0.4 and 0.8 W/m². An example of the requirement for office buildings is given in Table 5.22.

Table 5.22 **Maximum LPD thresholds permitted in Chinese standard GB 50034-2004 for office buildings**

Room or place	LPD (W/m²)		Illuminance (lux)
	Current	Target	
Normal office	11	9	300
Luxurious office, technical drawing	18	15	500
Meeting room	11	9	300
Business room	13	11	300
Filing, copying, circulating room	11	9	300
Archive room	8	7	200

Abbreviation: LPD = lighting power density.

The impacts of full compliance with these standards are difficult to gauge. However, China constructs roughly 600 million square metres of commercial buildings annually, so each watt per unit area of avoided power demand translates into the avoidance of 600 MW in direct power requirements for each year of construction. If China avoids just 1 W of load per unit area as a result of these standards and construction continues at 600 million square metres per annum, direct power reductions after 20 years will be 12 GW. Furthermore, in the Chinese context each watt of lighting load adds 0.3–0.5 W of air-conditioning

6. D. Goldstein, Director, Natural Resources Defense Council, United States, personal communication, 2005.

power demand. Overall it is estimated that full compliance with the lighting codes could save up to 150 GW of power demand within 20 years and up to 116 Mt of CO_2 emissions per annum; however, for these savings to materialise the code will have to be strictly adhered to and that presents a formidable challenge for the Chinese administration.

REVIEW OF OTHER ENERGY-EFFICIENCY PROGRAMMES INFLUENCING LIGHTING

Market-transformation programmes

Many countries have implemented broad-based market-transformation programmes that are often termed "green lights" programmes after the first such initiative operated in the United States. These are described in the next section, followed by a description of other market-transformation initiatives.

Government-sponsored green lights programmes

US Green Lights/ENERGY STAR

The US Environmental Protection Agency (EPA) introduced the Green Lights Program in 1991; since 1996 it has been integrated into the ENERGY STAR programme. The Green Lights Program focused mainly on commercial lighting as this was where the greatest savings potential could be attained. It set out to achieve this through the establishment of voluntary public/private partnerships with building owners and operators to encourage them to adopt energy-efficient products in return for technical assistance and public recognition. As a result Green Lights participants committed themselves to installing cost-effective high-efficiency lighting products, including electronic fluorescent ballasts, high-efficacy fluorescent lamps, CFLs, non-incandescent exit signs and automatic lighting controls. The programme also sought to reduce over-lighting by encouraging the removal of unneeded lamps in over-lit spaces. To become a Green Lights Partner, building owners signed a Memorandum of Understanding through which they committed themselves to make energy-efficient lighting upgrades for 90% of the upgradeable floor area. The programme offered no financial incentives, but over the period 1991–2000 more than 2 000 organisations participated as partners and some 1 000 lighting suppliers became programme Allies.

One of its major successes concerned the transformation of the fluorescent lamp ballast market. With the support of Green Lights and various utility programmes, 305 million electronic ballast were shipped in the United States from 1986 to 2000, of which 74% is estimated to be attributable to the public programmes. A detailed evaluation has estimated that the impact of the Green Lights Program on ballast efficiency was responsible for annual savings in the year 2000 of over 5.6 Mt of carbon equivalent (Horowitz, 2001). A further 6.4 Mt of carbon savings is attributable to utility energy-efficiency programmes. In all, both sets of measures were estimated to save over 59 TWh of electricity. A further 1.2 Mt of carbon were projected to be saved as a result of the FEMP actions on ballasts (see pp. 377–378).

European GreenLight Programme

Inspired by the US Green Lights Program, the European GreenLight Programme was launched in February 2000. The EU GreenLight Programme is a voluntary pollution-prevention initiative encouraging non-residential electricity consumers (public and private), referred to as Partners, to commit to installing energy-efficient lighting technologies in their facilities when it is profitable and lighting quality is maintained or improved. The objective of this programme is to reduce the energy consumption from indoor and outdoor lighting throughout Europe, and thus reduce greenhouse gas emissions, while saving consumers money and improving the quality of visual conditions.

Specifically, Partners commit to the following.

- For existing spaces: either upgrade at least 50% of all the eligible spaces owned or on long-term leases or reduce the total aggregate lighting electricity consumption by at least 30%. Eligible spaces are those where lighting upgrades are profitable.

- For new spaces: choose new installations so that there is no alternative installation that would maintain or improve the lighting quality provided by the chosen installation or consume less electricity and represent a supplementary investment that would be profitable.

- Complete the upgrades within five years of joining the programme, send a progress report every year and appoint a Corporate Manager responsible for assuring the programme's execution.

If a Partner cannot meet minimal space requirements or reductions in total lighting energy, they may drop out of the programme without any prejudice to rejoin when their situation changes.

While the Commission does not provide funds for lighting upgrades (because they pay for themselves with energy savings), it provides support to its Partners in the form of information resources and public recognition (plaques on buildings, advertisements, exclusive use of the logo, awards, etc.). The Commission has been assisted in the implementation of GreenLight by the national or regional energy agencies (or similar organisations) of 26 European countries, who have had a fundamental role in promoting GreenLight at national and regional level.

Since its launch, several hundred public and private Partners have now joined the GreenLight programme and implemented a wide range of cost-effective savings measures. Lighting in over 1 000 buildings has now been upgraded through the programme, and this experience offers a very large set of examples of efficient-lighting solutions as applied in diverse built-environment sectors (schools, offices, airports, supermarkets, etc.); some examples of completed projects are given on pp. 275–277. The number of Partners increased by more than 12-fold between 2001 and the end of 2005. These positive results prompted most national energy agencies to catalyse and spread further the programme's implementation.

Several programmatic lessons have been learned throughout the GreenLight process. At the marketing stage energy savings alone often do not constitute a sufficient reason for companies to join GreenLight. Public recognition benefits have proved to be effective additional arguments to convince them, including the fact that participation in the programme allows them to be seen as environmental "champions". It is reported that arguments related to indirect productivity increases would also be decisive if they could be scientifically demonstrated (see pp. 74–83).

During the upgrading process, GreenLight Partners need a user-friendly lighting audit procedure which allows rapid identification of the spaces that could be upgraded and of the cost-effective measures that could be applied. Complex material does not get used, especially because the final decisions are often taken at a high level and the information presented to the senior management has to be simple and based on economic terms. To aid this there appears to be a need to develop further rules of thumb, simple lighting-quality assessment procedures and lighting energy performance benchmarks for spaces other than offices. This latter includes average and best-practice lighting power density (W/m^2) and lighting energy intensity (kWh/m^2) figures.

Finally, the main issue identified during monitoring of Partner energy-savings progress throughout the GreenLight programme is the need to provide Partners with an extremely simple form to report on their achievements. The current form is limited to one page per facility and contains a short description of the baseline and the post-installation lighting conditions.

Greenlight Australia

In recent years, extensive discussions concerning energy efficiency between the Australian government and the lighting industry resulted in agreement on MEPS for fluorescent lighting ballasts. They also identified the desirability of a voluntary programme specifically aimed at providing public information on the benefits of energy-efficient lighting. The Australian Greenhouse Office (AGO) assisted the lighting industry to develop a voluntary scheme to improve lighting efficiency (AGO, 2006). In 1999 the Australian Lighting Industry Forum proposed an Australian Greenhouse Lighting Challenge programme. The AGO subsequently joined with industry to manage a consultancy to identify the appropriate scope for a lighting energy-efficiency programme, which gave rise to the Greenlight Australia project. This programme is now helping to develop and implement most of Australia's lighting energy-efficiency initiatives mentioned elsewhere in this chapter.

China Greenlights programme

The USD 28 million China Greenlights programme was developed by the National Development and Reform Commission with assistance through a Global Environmental Facility grant managed by the United Nations Development Programme. It has successfully helped develop energy-efficiency policies and awareness measures concerning lighting in China. The primary goals of the project are:

- "To reduce lighting energy use in China in 2010 by 10% relative to a constant efficiency scenario.
- To increase exports of efficient quality lighting products, aiding the Chinese economy and helping to reduce energy use and GHG [greenhouse gas] emissions worldwide." (CGIN, 2003, p. 2).

The programme seeks to achieve these goals by targeting key market actors to bring about a transformation to more energy-efficient products through a mixture of technology push (increasing the supply of quality energy-efficient lighting products) and demand pull (creating the information and awareness environment that will stimulate demand for the improved product offering). Most of the Chinese lighting energy-efficiency policy measures mentioned in this chapter were developed under the auspices of the China Greenlights programme.

The Green Energy Family Movement

The Green Energy Family (GEF) Movement was initiated by KEMCO in 1995 to contribute to addressing global environment problems by enhancing energy efficiency through the diffusion of energy-efficient facilities. GEF is a partnership movement to engage the voluntary participation of citizens, companies, NGOs and the press in CO_2 reduction and energy savings. Any entity willing to participate in GEF programmes must submit an application to the GEF centre and establish a voluntary agreement to pursue the goal of the particular GEF programme. Currently, the GEF movement consists of four programmes, including the Green Lighting Program, which began in 1996. The Green Lighting Program aims to replace 90% of conventional lighting facilities with high-efficiency bulbs. It aims to eliminate 20% of electricity use for lighting, which accounts for 18% of total electricity consumption.

Other government market-transformation initiatives

Danish Electricity Savings Trust lighting programmes

The Danish Electricity Saving Trust (DEST) was established in 1996 to promote electricity savings in households and the public sector in accordance with socio-economic and environmental considerations. With an annual budget of about DKK 90 million, funded through a special tax on electricity bills, this independent agency promotes the conversion of electrically heated houses to less intensive energy forms and also promotes energy-efficient appliances and equipment. In the last two years DEST established a highly innovative online website where the electricity consumption of buildings can be reported in real time.[7] The data can be gathered easily without the need to install additional metering equipment because almost all Danish buildings using over 100 MWh of electricity per year already have real-time metering installed. This is to allow the electricity consumption data to be reported to the power-network operators via power-line carrier technology so that the operators can manage the network more efficiently. In Denmark it has been legally established that these data belong to the building owners and that they have the right to access it for free. DEST has made arrangements with public-building owners, but also with the private sector to encourage them to report their data to the DEST website. The website manages and presents the data in a user-friendly manner so that any historic and current load profile can be accessed and viewed on demand. This creates an excellent resource for actors engaged in demand management because it allows rapid identification of savings potentials and enables performance benchmarking. In cases where buildings operate submetering for lighting, the load profiles can be readily analysed to identify savings opportunities as well as the impacts from installing energy-savings measures. The site is now available in English and DEST is actively encouraging managers of buildings outside of Denmark to also enter their real-time building electricity consumption data into the site.

Norway's street-lighting programme

Norway's national energy agency, Enova SF, has one main programme, Energy End Use, which includes a component on the retrofitting of street lights and is aimed at the owners of large facilities and outdoor lighting infrastructure where changes to the existing light fixtures are being considered.

European Union

Energy-efficient lighting is promoted in the 1998 Communication on Energy Efficiency, which was followed by an Action Plan in 2000.[8] In addition, the European Climate Change Programme, established in 2000

7. Available at http://se-elforbrug.sparel.dk.
8. COM (1998)246 final, 29.04.1998, and COM (2000)247 final, 26.04.2000, respectively.

to identify the most environmentally and cost-effective measures to help the European Union meet its Kyoto Protocol obligations, gave considerable emphasis to energy efficiency and set savings objectives for lighting by 2020. The 2001 report identified a large range of carbon savings potentials from energy-efficiency measures in 2010–12. Some of these potentials directly or indirectly concern lighting (for example, 7 Mt of carbon from an agreement with lamp manufacturers to increase sales of CFLs), but others have an indirect involvement (for example, 15–24 Mt of C from technology procurement, 40–55 Mt of C from a directive on energy services and 35–45 Mt of C from the Energy Performance in Buildings Directive (ECCP, 2001).

Other explicit lighting-efficiency measures taken apart from the initiatives mentioned on pp. 317–320 and pp. 354–358 include design competitions and the European GreenLight Programme.

European Design Competition

To complement the GreenLight Programme, and to promote the use of energy-efficient lighting in the domestic sector, the European Commission established the European Design Competition "Lights of the Future" in 1999 (EDC, 2003). This competition is held every second year, with the next being held in 2006, and it has grown into one of the key awards for professional designers, design students and luminaires manufacturers. The competition aims to encourage and promote energy-efficient, dedicated lighting fixtures that are of innovative, highly attractive and decorative designs for the residential and office market.

At the first competition in 2000, the main target was to produce innovative and attractive design solutions for residential lighting fixtures dedicated to pin-based CFLs. In the second competition in 2002, the range of eligible lighting technologies was extended to include other high-efficiency lamps, such as metal halide lamps, induction lamps, cold-cathode fluorescent lamps (backlighting for large liquid crystal display monitors and televisions) and LEDs. A European-wide marketing and promotion campaign for the award winning models has followed each competition.

EU lighting studies

Lessons learnt from previous national campaigns were discussed in the DELight study (Palmer and Boardman, 1998), a project funded by the

European Union's SAVE programme. DELight investigated the potential for using CFLs in existing luminaires from both technical and aesthetic perspectives. One of the main findings of the study was that 70% of the 150 million households in the European Union still did not own a single CFL. The 45 million homes that did use CFLs, however, owned an average of around three per household. A telephone survey undertaken as part of the DELight project highlighted one of the major barriers to the penetration of these households without CFLs: namely, the lack of knowledge and awareness of the characteristics and performance of CFLs. People found it difficult to imagine the advantages of using CFLs in their homes without first-hand experience. Providing people with opportunities to test CFLs or see them in use in lighting displays in shops might help to bridge the gap between knowledge and experience, build a positive image of CFLs and encourage their wider use.

Householders without CFLs often cite the lack of suitable luminaires as a reason why they do not own any energy-efficient lamps. However, the detailed survey (of 24 households in each of the three partner countries) revealed that CFLs could have been immediately installed in 42–46% of the existing luminaires designed for incandescent lamps, or about eight luminaires per household, without any modification to the luminaires. The risk remains, however, that the homeowner will switch back to an incandescent lamp the day the CFL fails. There is therefore is a need to promote luminaires dedicated to efficient lighting in order to achieve long-term savings. Accordingly, any energy policy aimed at furthering the adoption of efficient domestic lighting should contain the following two key strategies:

- Aim to install a CFL in every home so that households can experience the advantages of this type of lighting.
- Design policies that help increase the proportion of household luminaires dedicated to more energy-efficient light sources, such as pin-based CFLs.

US Next Generation Lighting Initiative/solid-state lighting

Because of the potential energy, environmental and national security benefits, there is increasing national interest in creating a partnership of industry, universities and national laboratories aimed at accelerating the development of solid-state lighting (LEDs and organic LEDs [OLEDs]) science and technology. The US government is now strongly supporting the R&D, and this programme receives funding from Congress, the Department of Energy and the National Science Foundation.

It is estimated that by 2025 solid-state lighting could reduce the global amount of electricity used for lighting by 35%. Most of the consumed electricity is produced by burning fossil fuels; hence, a reduction in energy consumption would reduce CO_2 emissions at the level of hundreds of millions tonnes a year. The cumulative savings potential in the United States alone over the period 2000–20 could amount to 17.6 exajoules of primary energy, eliminate 258 Mt of carbon emissions, alleviate the need for 133 new power stations (1 000 MW each), and lead to cumulative financial savings of USD 115 billion (1998-dollars) (see pp. 461–462).

US National Lighting Fixture Design Competition

Following the success of the European Design Competition's "Lights of the Future", the US launched the similar National Lighting Fixture Design Competition "Lighting for Tomorrow" over a period of two years. The main purpose of "Lighting for Tomorrow" is to increase the market presence of energy-efficient lighting fixtures for the home (LFT, 2006).

Utility programmes

Since the 1970s there have been numerous utility-led initiatives to promote lighting energy efficiency. Current schemes can be broadly classified as either utility obligation schemes, which are increasingly favoured in Europe, or demand-side management schemes, which have a broader geographical coverage. Both are described in the next section.

Utility obligation programmes

UK Energy Efficiency Commitment

Following the formation of the Energy Saving Trust (EST) in 1994, the United Kingdom has operated a number of programmes for energy-efficient lighting that have been sponsored by either regional electricity companies or generating utilities. The Energy Efficiency Standards of Performance programmes (SOP1, SOP2 and SOP3) operated from 1994 to 2002; these were replaced by the first phase of the Energy Efficiency Commitment scheme EEC1, which ran from 2002 to 2005. The latter scheme operated through an energy-efficiency obligation placed upon generators under the Utilities Act 2000, the costs of which could then be passed on to the electricity pool and hence would ultimately be paid for by end-users. Utilities are set obligatory energy-savings targets for the residential sector and are given four compliance pathways to reach their targets through the installation of CFLs, efficient appliances, insulation or gas-condensing boilers. In EEC1 about 50% of the measures were required to be targeted at "fuel poor" households. All energy suppliers with customer bases of 50 000 or more were obliged to take part, with specific targets being judged in accordance with their customer base. The total savings required equated to 64 TWh of fuel-weighted benefits and it was expected that this commitment would cost energy suppliers somewhere in the region of GBP 165 million annually. The results of the programmes have become progressively more significant such that for the EEC1 programme some 39.5 million high-quality, certified CFLs were supplied in the three years 2002/03/04 to the residential market. This is three times the baseline scenario of 12.5 million lamps and is believed to have doubled UK CFL ownership to over two per household. About 25% of the total energy savings of 64 TWh from EEC1 are estimated to derive from CFLs.

The EEC1 terms were not only comfortably met but were reported to be highly cost-effective. As a result, the second stage, EEC2, is operating from 2005 to 2008 and is expected to be followed by a third stage, EEC3, from 2008 to 2011. For the time frame 1 April 2005 to 1 April 2006 there is a target to supply 7 million CFLs through major retailers, 6 million directly to the energy-poor and 1 million through smaller independent retailers (Verdun, 2005).

Utility savings targets are proportional to their energy production. There is discussion about broadening the terms of reference of the programme to also include measures aimed at commercial sector customers.

In addition, the EST and the UK Lighting Association have begun to operate the Domestic Energy Efficient Luminaire Scheme to address the traditional low efficacy of domestic luminaires (*i.e.* table lamps, standing lamps or other portable luminaires aimed at the domestic market). The scheme gives a GBP 5 subsidy supplied through EEC2 to luminaire manufacturers that produce and sell CFL-dedicated luminaires, *i.e.* ones that can take only pin-based CFLs. The luminaires must use high-efficiency 50 kHz ballasts with a minimum life of 25 000 hours and the CFLs are certified through the EST certification scheme. By using pin-based CFLs there can be no switching back to incandescent light sources once the first CFL tube fails. The first-year target is to sell 1 million luminaires: 400 000 were sold in the first seven months (Verdun, 2005).

Work is also under way to establish a whole-building lighting programme to target small and medium-sized enterprises such as hotels, restaurants, nursing homes, etc. The scheme will receive funding through the UK Carbon Trust and be operated with support from the Lighting Association.

Other European white-certificate programmes

Italy, France, Denmark and the Netherlands are all developing or have initiated utility white-certificate programmes that could be an important vector for lighting energy-efficiency activities.

Brazil

In response to a nationwide electricity shortfall over the period 2000–02 the Brazilian government and utilities launched aggressive campaigns to encourage the public to use CFLs in place of incandescent lamps. Details of the programmes applied vary by region, but the utilities and government provided subsidies for CFLs to encourage higher use and also ran major marketing efforts. Funding was supplied in part via a utility obligation issued by the regulator, Agência Nacional de Energia Elétrica (ANEEL; Brazilian Electricity Regulatory Agency), in 1998 that requires utilities to invest a minimum of 1% of their net annual revenues in energy-efficiency and R&D programmes. This is known as the "1% obligation". The cause and effect of the Brazilian programmes is not clear, but the growing sales of CFLs provides strong evidence for their impacts. Imports of CFLs rose from 33 million lamps in 2000, to 102 million in 2001 before falling back to 42 million in 2002 as the electricity crisis eased; they then climbed back to over 80 million in 2004.[9] Over the period 2000–04 CFL shipments were roughly one-fifth of those for incandescent lamps. Assuming an average lifetime of 5 000 hours they would now account for about half of the installed screw-based lamp stock in Brazil.

Prior to the electricity crisis, the average annual percentage growth in electricity demand in 1990–2000 was 4.2%. Demand dropped sharply by 6.2% in 2001 because of the power shortage, which lasted until 2002, but then grew by 5.4% in 2002–03, indicating a revival in economic activity

9. G. Januzzi, Associate Professor, State University of Campinas, São Paulo, Brazil, personal communication, 2005.

after the crisis. It seems probable that the huge growth in CFL imports during the shortage and continued high use since has helped to shave a substantial portion of the residential-lighting load off the evening peak and thereby helped Brazil to weather the electricity shortfall crisis.

Utility DSM programmes

There have been hundreds and maybe thousands of utility-sponsored programmes to promote lighting energy efficiency, most of them occurring in North America or Europe but increasingly in other regions too. Analysis of the INDEEP database developed by the IEA Implementing Agreement on Demand Side Management (SenterNovem, 2004) found that lighting programmes accounted for almost one-third of all utility DSM initiatives. Many of these programmes have been highly successful in cost-efficiency terms. In physical terms the programmes generally aim to encourage the end-user to install efficient lighting such as high-frequency ballasts, superior luminaires, occupancy sensors, high-efficacy lamps, etc. The utility programmes use a mixture of information, promotions and incentives to encourage participation. Incentives include rebates, financing through loans or leasing, tariff reductions, bulk purchasing, direct installation and gifts. Of these, rebates and financing methods are the most common. Both aim to overcome the first-cost obstacle to efficient lighting but also to use the financial incentive as a means of engaging in a dialogue with the customer. The range of techniques applied will vary depending on whether the target is in the commercial, industrial or residential sector.

Between the late 1980s and 1996 US utilities had invested over USD 9 billion in DSM programmes, with many of these addressing lighting. A detailed study of 20 utility commercial- and industrial-sector lighting DSM programmes conducted in the United States over this period found that they had a levelised total resource cost of USD 4 per megawatt-hour (Eto *et al.*, 1996). The cost estimate includes administration costs, the incentives paid and the costs incurred by customers. It also uses conservative accounting to estimate the degree of "free riders" (customers who benefit from the programme but were going to implement the energy-saving measure in any case) to be sure that programme impacts are not overestimated. This cost was significantly lower than the supply-side options and hence highly attractive from a societal perspective. While similar benefits have been recorded in the majority of evaluations of other utility lighting DSM initiatives, some – mostly earlier – programmes were not as successful as hoped for a variety of reasons.

Canada

Several Canadian utilities are giving away CFLs as part of their DSM activities. For example, in late 2003, BC Hydro ordered a large quantity of CFLs to give out to its customers. Each Lower Mainland customer received a voucher for two free CFLs. Residents of Vancouver Island and the Gulf Islands received a CAD 5 (5 Canadian dollars) rebate on an ENERGY STAR-labelled CFL in October and November 2003. NRCan, through its home energy audit programme, EnerGuide for Houses, is providing a free CFL to each homeowner undertaking an audit.

Thailand

In 1991, the Thai government implemented a five-year master plan for DSM in the power sector, to be operated by the state utility EGAT. The most effective measures have concerned lighting and include the High Efficiency Fluorescent Tube or "Thin Tube" programme. Through the efforts of the programme, which involved a very strong promotional campaign together with voluntary labelling, Thai lamp manufacturers agreed to discontinue production of the less efficient T12 tubes (40 W and 20 W) and moved their entire production over to thinner-tube T8 lamps (36 W and 18 W). As of 2001 this and two smaller lighting initiatives had saved 629 MW of power demand, 2 374 GWh of electricity consumption and 1.78 tonnes of CO_2 emissions, over four times the programme targets. The cost to EGAT of the measures was USD 1.3 per megawatt-hour, about one-quarter of their marginal electricity production and distribution costs (EGAT, 2001).

Other instruments

A variety of other instruments are also used to promote lighting energy efficiency, including procurement programmes, energy service companies offering technical expertise and third-party finance, tax incentives, financial incentives, and information and awareness campaigns. Examples of all of these are described in the next section.

Procurement programmes

US Federal Energy Management Program

A US Executive Order requires federal agencies to purchase efficient equipment (*i.e.* within the top 25%). The US Federal Energy Management

Program (FEMP) helps to support this objective by defining product-procurement specifications based on their energy efficiency and cost-effectiveness. Among the range of products addressed, FEMP specifies energy-performance targets for lighting components and lighting systems. Specific recommendations have been developed for luminaires, fluorescent lamps, fluorescent ballasts, exit signs and lighting controls, which are sometimes harmonised with ENERGY STAR criteria. The luminaire requirements were established after the 1992 EPAct included an objective of supplying public-sector information on luminaire performance.

The resulting luminaire efficiency ratio values developed by the National Electrical Manufacturers Association (NEMA) have subsequently been adopted in FEMP public procurement guidelines. FEMP works with the federal supply agencies of the General Services Administration (GSA) and Defense Logistics Agency (DLA) to clearly identify supplied products meeting the recommended efficiency levels. In their catalogues and online systems, GSA and DLA use an "EE" symbol or the ENERGY STAR label to identify those products that meet or exceed the energy-efficiency criteria for government purchasing.

The two largest construction agencies within the federal government (Army Corps and Navy) have incorporated the recommended efficiency levels for some products, including lighting, in their design guidelines.

Danish "A-club"

For public organisations such as public housing associations and state and municipal institutions, DEST set up the "A-club" (the A representing, at the time, the most efficient equipment under the EU labelling scheme). Under this scheme, bulk purchasing of energy-efficient equipment is undertaken to lower costs. There are over 150 members of the A-club, covering more than 250 000 households. DEST also sets procurement guidelines and sets up framework contracts for reducing the price of equipment. This is aided by a website, newsletters, demonstrations and subsidies. DEST also runs promotional campaigns to market more energy efficient products and demonstration projects such as energy-efficient lighting and ventilation systems in schools. The lighting specifications require that when incandescent lamps are replaced, they must be replaced by approved CFLs (pp. 321–322).

Sweden

Since 1990, the Swedish National Energy Administration (STEM), formerly the Swedish National Board for Industrial and Technical Development (NUTEK), has been operating an innovative technology-procurement programme. The programme focuses on using innovative technology procurement, demonstration activities, and market-introduction strategies to increase the market shares of new, improved energy-efficient technologies. In the area of lighting, these include lighting technologies and applications for homes, offices, schools, industry, hospitals and outdoor installations. These schemes focus on dedicated fixtures and started from high-frequency electronic ballasts resulting in rapid growth of the market for improved, high-frequency lighting systems.

Vietnam

As part of a World Bank-supported national DSM programme, the Vietnamese utility Electricity Vietnam successfully procured 1.5 million high-quality CFLs in 2005 through a competitive bidding process for use in a residential-lighting programme. The price:quality ratio was reported as being extremely good value and thereby demonstrated the value of the chosen bulk-procurement method (du Pont *et al.* 2005).

US technology procurement

As the world's largest volume-buyer of energy-related products, the federal government can reduce energy consumption and achieve enormous cost savings by purchasing energy-efficient products. As a part of the DOE FEMP, the Buying Energy Efficient Products Program helps federal purchasers identify these types of highly efficient products. Federal buyers are directed by Federal Acquisition Regulation (FAR) Part 23 and Executive Orders 13123 and 13221 to purchase products that are ENERGY STAR-labelled or products that are designated to be in the upper 25% of energy efficiency in their class. In the list of product energy-efficiency recommendations, there are various energy-efficient lighting products, including fluorescent tube lamps, fluorescent ballasts, industrial HID luminaires, downlighter luminaires, fluorescent luminaires, CFLs, lighting controls, exit signs. The Federal Lighting Guide, issued in June 1998, also instructs Federal Energy Managers to procure energy-efficient lighting products.

Recently, the Pacific Northwest National Laboratory, on behalf of the DOE, has begun implementing technology procurement for recessed downlighters (also known as recessed cans). Recessed downlighters are by far the most popular type of residential lighting fixture, with estimates of 150 million recessed cans currently installed in the United States. Virtually all of the fixtures use incandescent lighting. The project started in 2001, and new products are in field tests, which will be followed by practical promotional programmes.

Another recent procurement programme focuses on CFL reflector lamps, which are typically used in recessed downlighters and track lights and are very popular in new homes. Annual sales of these lamps are estimated at 120–140 million, but availability of CFL reflector lamps is very limited. To increase market acceptance of these lamps, the DOE is working with the Northwest Energy Efficiency Alliance on a technology-procurement project. This procurement will seek to introduce CFL reflector lamps that fit into current fixtures, deliver adequate light, are available at affordable prices and meet ENERGY STAR specifications.

ESCOs

A review of ESCO activity in the United States (Goldman *et al.*, 2000) concluded that they were responsible for approximately 4 960 projects, of which 87% were concerned with lighting. This demonstrates the value that ESCOs can bring as vectors for energy-efficient lighting. Horowitz estimated that these ESCO lighting-related activities may have produced savings of 1.2 Mt of C in 2000 (Horowitz, 2001).

Korea

The Korean government has helped to establish and continues to support the ESCO sector in Korea. Support comes in the form of government promotional activities and the provision of low-interest loans that are reported to have produced a steady increase in ESCO investment. Various forms of financial support aimed at lightening the ESCO debt burdens are offered, such as mortgages, credit loans and factoring programmes as well as working capital loans for small and medium-sized ESCOs. Moreover the Korean government provides tax credits for energy users who install energy-saving facilities. ESCO customers may qualify for tax credits according to the provisions of the Exceptional Taxation Limitation Law. The number of ESCOs rose from 3 to 159 by 2004.

Their major business focuses are high-efficiency lighting, waste heat recovery, heating and cooling systems, and process improvement (KEMCO, 2005b).

Tax incentives

US EPAct efficient-building incentives

The 2005 US EPAct includes a provision that offers a tax deduction of up to USD 1.80 per square foot (USD 19.4 per square metre) for building owners who invest in energy-efficient building systems as part of new construction or refurbishment of energy-efficient property. This latter is defined to be commercial-building property that is certified as requiring combined annual energy and power costs that are at least 50% less than those of a building satisfying the ASHRAE 90.1-2001 standard. If a building does not meet all these requirements, but one system (such as the lighting) does then it is eligible for a partial deduction of up to USD 0.6 per square foot. The Interim Rules for Lighting Systems set a lighting-system energy-savings target corresponding to an LPD that is 25–40% lower than the ASHRAE 90.1 requirements, where a 25%-lower LPD qualifies for a deduction of USD 0.3 per square foot and a 40%-lower LPD qualifies for a deduction of USD 0.6. This is considered to be sufficient to stimulate considerable interest from the property-development sector.

UK Enhanced Capital Allowance Scheme

This scheme provides tax relief for enterprises that invest in efficient lighting and other energy-efficient equipment. Energy-efficiency performance benchmarks have been defined for lamps, lamp circuits and luminaires. Qualifying lighting technologies include electronic self-ballasted CFLs, triphosphor T8 lamps and certain combinations of light fitting, lamp and lamp control gear.

Other financial incentive efforts

Japanese support for BEMS and HEMS

The Ministry of Economy, Trade and Industry (METI) provides subsidies through the New Energy and Industrial Technology Development Organization (NEDO), a semi-governmental organisation affiliated with METI, to introduce Home Energy Management Systems (HEMS) and Building Energy Management Systems (BEMS) (NEDO, 2003). These systems help manage the energy consumption of appliances such as lighting, air-conditioning and hot-water supply by using information-technology control systems. These enable automatic management of several appliances at the same time, which in turn leads to energy savings.

UK Lightswitch Programme

The UK EST implemented Lightswitch, a programme to provide rebates for lighting controls to small and medium-sized enterprises. The programme has now terminated but is estimated to produce savings of 0.2 TWh per year from 2002 to 2020 (MTPROG, 2006). In 1999–2000, rebates amounted to about GBP 600 000.

Information and awareness programmes

US lighting technology roadmap

In 2000, the US DOE issued "Vision 2020: The Lighting Technology", which outlines the DOE's lighting technology roadmap. The roadmap describes a view of where the lighting industry is today, a vision of where its stakeholders want to go tomorrow, and strategies on how to get there. It provides guidance to both government and industry on the direction of future activities. It offers a framework for greater collaboration across the industry in creating new market opportunities and innovative technologies, and provides guidance for the DOE and other agencies in planning their activities and in forming R&D partnerships with industry. Although the roadmap did not include detailed implementation approaches for each technology, it clarified the technology development strategies and their priorities on short-, medium- and long-term bases.

Japan

To provide customers with information about energy conservation, "Energy Conservation Performance Catalogues" are issued in both summer and winter. These guides are distributed through retailers and contain the latest lists of energy-efficient lighting fixtures and advice on how to use them. They are also available on the Internet homepage of the Energy Conservation Centre, Japan (ECCJ), the agency responsible for disseminating information on energy conservation (ECCJ, 2003b).

The ECCJ also offers awards for energy-efficient appliances, equipment, materials and systems in residential, commercial and transport (automobile) sectors once a year. This design competition targets the deployment of energy-efficient technologies. Some of its awards include design improvements for fluorescent circular tubes, CFLs, ceramic metal halide lamps, new types of street lighting and automatic lighting-control systems.

Canada

Information on energy-efficient lighting is available for most sectors through the information programme of the Office of Energy Efficiency. For example, information on lighting for industry is provided through the EnerGuide for Industry website.[10]

The US "Change a Light, Change the World" campaign

Under this programme the US EPA worked with manufacturers, retailers, state governments and utilities to make it easier to find and buy energy-efficient lighting. Local, regional and national promotions were implemented and included special offers and rebates from major retail chains and regional utility companies for the acquisition of efficient CFLs, fixtures and ceiling fans with lighting. Nationwide promotions and in-store lighting workshops were held through a national home improvement chain. These included local events where customers could exchange older technology halogen floor lamps for discounts on more energy-efficient ones. The objectives of this programme were to stimulate demand for ENERGY STAR-qualified lighting products and strengthen awareness of the ENERGY STAR programme. The 2002 campaign was considered a success, with more than 140 partners participating, including well-known manufacturers and retailers. Utilities from around the country also teamed up with state governments and mayors to host community-based lighting events that set the stage for longer-term community-wide changes to energy efficiency. These included bulb giveaways and replacing light fixtures in governors' residences and other public buildings.

International initiatives

There have been a number of international initiatives to promote energy-efficient lighting. The following are a few initiatives that affect IEA member countries.

10. Available at http://oee.nrcan.gc.ca/egi.

Efficient Lighting Initiative

The Efficient Lighting Initiative (ELI) began as a three-year programme designed by the International Finance Corporation (IFC) and funded by GEF to accelerate the penetration of energy-efficient lighting technologies into emerging markets (ELI, 2006). Of the seven countries participating in the project, two – the Czech Republic and Hungary – are IEA member countries. The focus in these two countries has been on market transformation with the use of outsourcing through ESCOs. The project includes lighting in the residential and commercial sectors as well as street lighting.

IAEEL

The International Association for Energy-Efficient Lighting (IAEEL) is a global contact network and an information resource for high-quality, energy-efficient lighting. However, *IAEEL Newsletter* No. 1–2, published in 2000, was the last issue – for now, the IAEEL has no financial means to publish new issues. Various national energy agencies had supported the *IAEEL Newsletter* up to early 2001. Although the website is still a useful archive of material on energy-efficient lighting, there are not believed to be any imminent plans to revive the newsletter.

IEA Implementing Agreements

An important part of the IEA programme involves collaboration in the research, development and demonstration of new energy technologies to reduce excessive reliance on imported oil, increase long-term energy security and reduce greenhouse gas emissions. Collaborative programmes in the various energy-technology areas are conducted under Implementing Agreements, which are signed by contracting parties (government agencies or entities designated by them). There are currently 42 Implementing Agreements covering fossil-fuel technologies, renewable-energy technologies, efficient energy end use technologies, nuclear fusion science and technology, and energy technology information centres.

The Solar Heating and Cooling Programme was one of the first IEA Implementing Agreements to be established. Since 1977, its 21 members have been collaborating to advance active solar, passive solar and photovoltaic technologies and their application in buildings. In that programme, the Task 31 "Daylighting Buildings in the 21st Century" commenced in 2001.

Another Implementing Agreement, the Energy Conservation in Buildings and Community Systems (ECBCS) programme, has also recently proposed new lighting technology projects.

CADDET

CADDET, the Centre for Analysis and Dissemination of Demonstrated Energy Technologies, is an international information network that helps managers, engineers, architects and researchers find out about renewable energy and energy-saving technologies that have worked in other countries.

Its objective is to enhance the exchange of information on new, cost-effective technologies that have been demonstrated in applications such as industry, buildings, transport, utilities and agriculture. The information is not only collected and disseminated to a very wide audience, it is also analysed to provide a better understanding of the benefits of the technologies.

Along with GREENTIE (Greenhouse Gas Technology Information Exchange), CADDET is part of an IEA Implementing Agreement known as EETIC (Energy and Environmental Technologies Information Centres). CADDET was established in 1988 to promote the international exchange of information on energy-efficient technologies. In 1993, the Agreement was expanded into two Annexes – CADDET Energy Efficiency and CADDET Renewable Energy. In 1996, GREENTIE was added as a third Annex to the Agreement, complementing the CADDET project information with details of suppliers of greenhouse gas mitigating technologies and services. One of the technology areas covered by CADDET is energy-efficient lighting.

International CFL Harmonization Initiative

This initiative was launched at a special session hosted by Australia at the Right Lights 6 conference in Shanghai in May 2005, with an objective of pursuing plans for the international harmonisation of CFL test and performance standards. The initiative is supported by Australia, China, ELI, the United States, the European Union and several major manufacturers.

MEPS and endorsement labels for CFLs exist in many other countries (Table 5.23) and there is considerable interest in the harmonisation of CFL standards between the major markets in order to improve quality, lower compliance costs and reduce manufacturer costs and hence CFL prices.

Table 5.23 Summary of international CFL MEPS and labelling schemes

Economy	MEPS	Label	
		Compare	Approve
Argentina		**M**[1,2]	V
Australia	**M**[3]		V
Brazil			V
Bulgaria		UC[2]	UC[2]
Canada	**M**[4]		V[4]
China	**M**	UC	V
Columbia	**M**[1]	**M**[5]	
Costa Rica	V	**M**	
Croatia		UC[2]	UC[2]
EU25		**M**	V
Ghana	UC		
Hong Kong, China			V
Iceland		**M**[2]	V[2]
Indonesia	UC		
Israel	**M**	V	
Japan	**M**[6]	**M**	
Korea	**M**	**M**	V
Liechtenstein		**M**[2]	V[2]
Malaysia	**M**[7]	UC	
Mexico	**M**[4]		V
New Zealand	**M**[5]		V
Norway		**M**[2]	V[2]
Peru		UC	V
Philippines		**M**	V
Russia		UC[1,2]	
Singapore			V
South Africa		UC[2]	V
Sri Lanka		V	
Switzerland		V[2]	
Chinese Taipei	**M**		V
Thailand	UC	V	V
Tunisia	UC	UC	
United States	**M**		V
Vietnam	UC	UC	

Source: IEA and OECD Secretariats, based on various sources.
1. Framework legislation is passed but the implementing legislation is believed to still be under consideration.
2. Harmonised with the European Union.
3. Harmonised between Australia and New Zealand.
4. Partially or fully harmonised with the United States.
5. Partially harmonised with the European Union.
6. Japan requires the sales-weighted average efficiency of any supplier's appliances to exceed a prescribed efficiency threshold – these requirements are mandatory but fines for non-compliance are very low and therefore they are sometimes described as voluntary targets; nonetheless, being named and shamed for non-compliance is likely to have severe consequences in the Japanese marketplace and hence is thought to be an adequate deterrent by Japanese regulators.
7. For ballasts used with fluorescent lamps only.
Abbreviations: CFL = compact fluorescent lamp; M = mandatory; MEPS = minimum energy performance standards; V = voluntary; UC = under consideration.

Policies to encourage better use of daylight

Countries and regional jurisdictions have typically implemented the following measures to encourage savings potential from the use of daylight:

- Implemented daylight-saving time (DST) and sometimes double DST.
- Given credit for daylight measures in building codes.
- Supported R&D and dissemination of daylighting practices and technologies.
- Labelling and certification of windows.

Thus far, to our knowledge, no jurisdiction has implemented regulations imposing minimum daylight usage requirements nor have any countries required measurement and disclosure via a label, certificate or some other device, of building daylight utilisation factors.

Daylight-saving time

The use of daylight-saving time is one of the oldest and most established means of reducing lighting energy consumption. Germany was the first country to introduce it in the first part of the 20th century. Since then almost all OECD economies and many others have introduced provisions for daylight-saving time, largely for energy-savings and public-amenity purposes. There are still opportunities to save energy by optimising daylight savings. By way of example, the 2005 US EPAct extended daylight-saving time by a month in order to save energy. Nonetheless there are several major economies that still do not operate DST. These include India and China. The Indian Bureau of Energy Efficiency has recently made an assessment of the savings potentials from implementing DST and is considering measures for its introduction.

LIGHT'S LABOUR'S FOUND: THE IMPACT OF CURRENT AND FUTURE POLICIES

Key messages

- Energy-efficiency policies implemented from 1990 onwards saved 12.6% of lighting energy use around the world in 2005.
- In general, lighting energy-efficiency policies and programmes are very cost-effective and deliver CO_2 savings at negative net cost.
- However, most lighting energy is used by inefficient technologies and will continue to be in 2030 unless policies are strengthened.
- Over 38% of future global lighting energy use could be saved cost-effectively, with almost equal relative cost-effective savings potentials in OECD and non-OECD countries.
- Realising this potential would save USD 2.6 trillion and more than 16.6 gigatonnes of CO_2 emissions to 2030. The average net cost of CO_2 abatement is negative, at USD –156 per tonne.
- Some 3.2% of vehicle fuel consumption is used to provide lighting; this will grow strongly if new regulations require the daytime operation of headlights but do not also require the use of dedicated "daytime running lights" in new vehicles.

BEACONS OF HOPE

The role of government in stimulating the adoption of efficient lighting has long been recognised and has led to an extensive history of lighting energy-efficiency policies and programmes. There have certainly been hundreds and probably thousands of different initiatives implemented since the first energy crisis of the early 1970s, and this has also coincided with a substantial improvement in average lighting-system efficacies. In 1960 the average lighting system had an efficacy of about 18 lumens/watt (lm/W), whereas by 2005 this had risen to roughly 48 lm/W. The rate of improvement appears to have been relatively constant from 1960 to 1985 at about 2.8% per year, but from 1985 onwards it slowed to 1.3% per year. This decline in the rate of efficiency improvement mirrors those seen in other end-uses and sectors and may imply that efforts to conserve energy slowed as adjusted real energy prices fell back in the mid-1980s. The current environment of higher energy prices and concerns about energy security and climate change may provide a stimulus to reverse this tendency.

This chapter gives an appraisal of the magnitude of impacts resulting from these policy measures and provides an estimate of the potential for future cost-effective savings that would result from the wholesale adoption of lighting systems that minimise life-cycle costs for the end-user. The former establishes that historic and existing policies have had a large impact and are on course to produce even larger energy savings in the future. The latter, while not a policy scenario *per se*, allows policy makers to understand the scale of benefits that could accrue through the adoption of firmer policy settings.

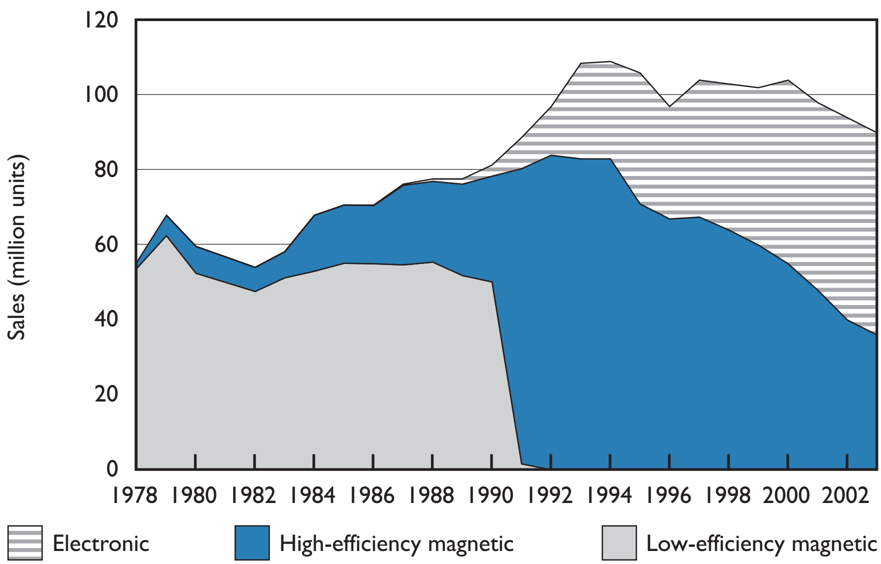
IMPACT OF CURRENT POLICIES

Estimating consequences of current policies

It is important for policy makers to know how much energy has been conserved through current programmes and how much energy could be conserved were the ambition of those programmes increased. The evaluation of savings attributable to current policy measures is not a perfect science as it depends upon a number of assumptions. The only data that can be gathered with a high degree of confidence comprise information on how much energy is being used by each lighting end-use, and even here there has often not been sufficient research conducted to provide unequivocal estimates for all end-uses, sectors and regions.

The estimation of how much energy would have been used had current policy measures not been implemented is necessarily less precise, although there is plenty of evidence to demonstrate the magnitude of the impacts of specific lighting-efficiency policy measures. The change in efficiency of ballasts offered for sale in the United States before and after the introduction of minimum energy performance standards (MEPS) provides a good example of this. Figure 6.1 shows how sales of low-efficiency magnetic ballasts completely ceased following the implementation of MEPS that precluded them from sale in 1990.

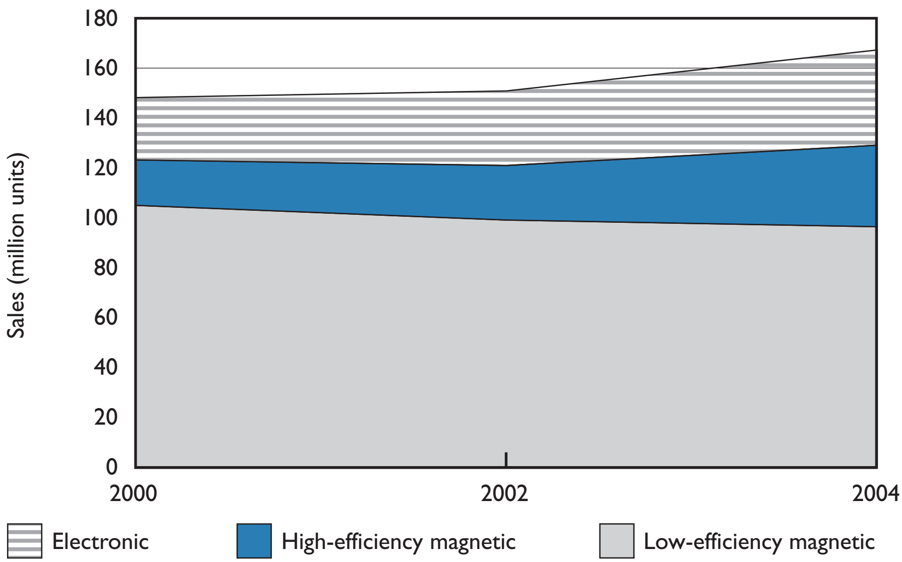
Figure 6.1 **Linear fluorescent lamp ballast sales by type in the United States**



Source: USCB, 2003, 2004.

The same graph also shows the growing market share being captured by electronic ballasts at the expense of even the relatively efficient remaining magnetic ballasts, stimulated in large part by ENERGY STAR and utility-sponsored energy-efficiency programmes. A simple comparison with equivalent data for the European market (Figure 6.2), shows that up until 2004, standard-efficiency magnetic ballasts were dominating sales in the European Union, where they were not due to be phased out through MEPS until October 2005. Furthermore, in the absence of strong incentive programmes, electronic-ballast sales were considerably less advanced by comparison with the United States.

Figure 6.2 **Linear fluorescent lamp ballast sales by type in the European Union**



Source: CELMA, 2005.

Generally, an evaluation of a policy's impacts will assume that previous efficiency trends would have continued unchanged had no policy measures been introduced and that all other aspects of a product's sale and use would be the same as occurred with the policy in place *(i.e.* that the equipment retirement rates, sales volumes, capacities, features and characteristics of use would have been the same as those that did occur). Applying these assumptions for each lighting electrical end-use in the lighting-equipment energy stock model described on pp. 169–171 has enabled estimates of the savings attributable to the policies enacted in OECD countries from 1990 onwards to be established. However, useful retrospective policy analysis may also be helpful to project the impacts forward in time to estimate where future residential electricity consumption is heading and to calculate the continuing impacts of current policies. This is especially true for the evaluation of lighting-efficiency measures which only apply to the efficiency of new equipment sales, because depending on the lighting system and usage sector, it takes between 10 and 20 years for half of the existing luminaire stock to be replaced and between 0.5 and 7.5 years for half the lamps to be replaced.

Assumptions and data for the Current Policies and No Policies scenarios

To assess the impact of current policies, two detailed lighting electricity consumption end-use scenarios have been produced for each of the seven regions treated in the bottom-up lighting model: the No Policies and Current Policies scenarios. The sole difference between the No Policies and Current Policies scenarios is that the former has a slower rate of efficiency improvement, based on the best estimate of the efficiency progressions by end-use that would have occurred had none of the current policies been implemented from 1990 onwards.

The results of the Current Policies scenario are estimates of the historic lighting energy consumption up to 2005 and are projections beyond that date. The same end-use stock model used to organise the historical energy data up to the year 2005 is primed with the historical energy and efficiency data for each lighting electrical end-use. These are then projected into the future based upon reasonable assumptions regarding future demand for individual energy services (which is driven by underlying trends in the key drivers of: commercial building floor area by building type, household numbers and floor area, illumination levels and gross domestic product [GDP], roadway length and area and industrial activity). All these are assumed to progress smoothly from the historical levels and where possible are harmonised with the equivalent projections given in the IEA's *World Energy Outlook 2004* (OECD/IEA, 2004). Consideration of probable future changes in lighting-equipment efficiency levels are directly influenced by current energy-efficiency policies whenever these exist. It is often possible to make informed estimates of the impact of policies that have already been enacted, especially when these result in step changes in the efficiency of products available on the market (the US MEPS and North American and European building-code provisions are good examples of these) and when sufficient market data have been gathered to enable the magnitude of the step change to be recorded. The Current Policies scenario assumes that existing programmes are maintained into the future but that their ambition is not altered in any way. The efficiency levels of lighting end-use equipment used in the No Policies scenario are drawn from published sources whenever these exist (*i.e.* either they are drawn from the results of post-implementation evaluations or they are derived from published estimates of the impact of programmes made in the process of developing the policy). Otherwise they are drawn from estimates made from the analysis of lighting-equipment efficiency time series before and after the introduction of a policy. In some cases the available data are comparatively rich (for many lighting end-uses in Australia, North America and some European countries), but in others fewer data are available.

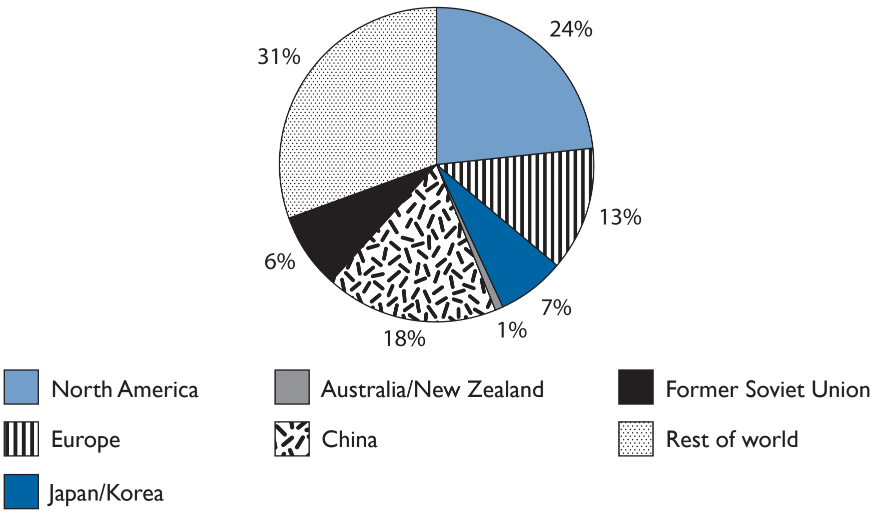
Past and future demand for light

The primary driver of lighting energy use is the demand for light, expressed in terms of source-lumens per unit time (lumen-hours). As mentioned previously, the provision of light is a poor measure of the quality of the lighting service because most source-lumens emitted do not make a useful contribution to aiding vision. There are large losses in luminaires and room surfaces, while many source-lumens also illuminate unoccupied spaces or are unneeded because of over-illumination, especially in day-lit spaces.

Over the last decade, global demand for artificial light grew at an average rate of 2.4% per annum. Growth was slower in IEA countries (at 1.8% each year), than in the rest of the world, where it averaged 3.6%. Growth rates in IEA countries are lower than in previous decades and for the first time in history may be indicative of the beginnings of demand saturation. Nonetheless, the overall growth in demand is expected to continue for the foreseeable future, driven by new construction, rising average illumination levels in non-OECD countries, ongoing electrification and a trend towards more outdoor lighting.

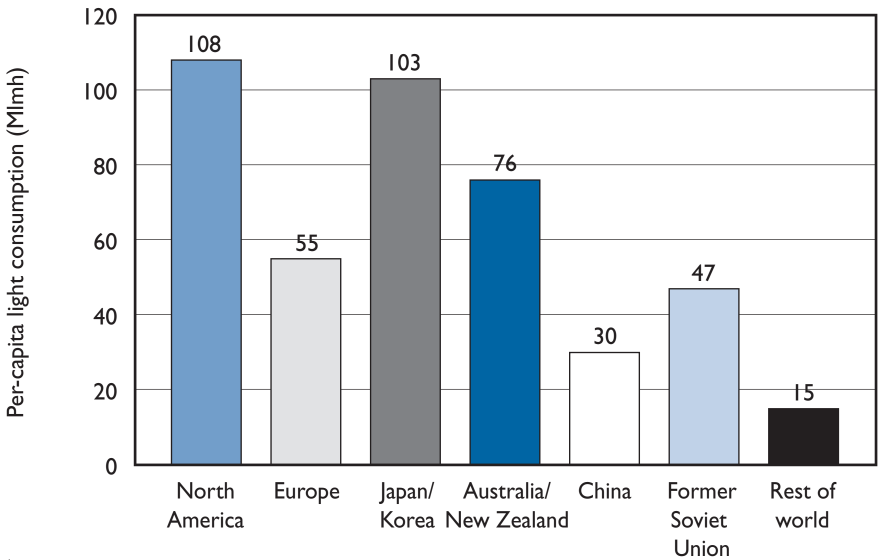
With current socio-economic patterns and policies, the global demand for grid-based electric light is forecast to attain 239 petalumen-hours (Plmh) by 2030 (Figure 6.3), representing an average annual growth rate over the next two and a half decades of 2.4%; some 79% over the whole period. Overall this leads to the global average annual consumption of electric light increasing from 21 megalumen-hours (Mlmh) per capita in 2005 to 30 Mlmh in 2030. In 2030 the use of this light remains unevenly distributed, but there is greater equality than in 2005. An average North American uses 108 Mlmh of electric light annually (compared with 101 Mlmh in 2005), while the average use in the Rest of the World region increases from 8 to 15 Mlmh (or from 13 to 20 Mlmh for those who have access to the electricity network) (Figure 6.4).

Figure 6.3 **Regional share of electric-light consumption* in 2030 under the Current Policies scenario**



* Total = 239 Plmh, source-lumens.

Figure 6.4 **Per-capita consumption of electric light* in 2030 under the Current Policies scenario**

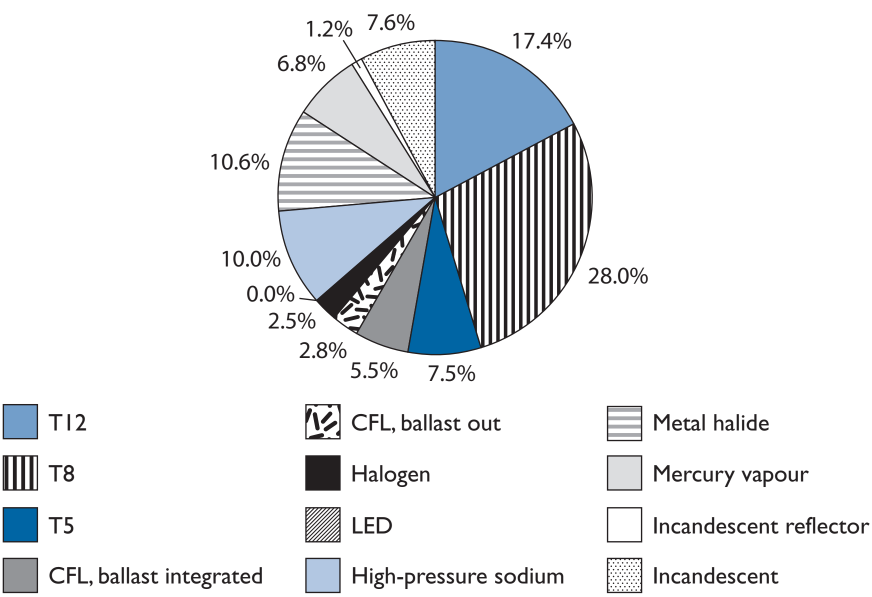


* Source-lumens.

Light production by lamp technology under the Current Policies scenario

The share of light produced by each light source in 2030 has been estimated by region and sector. Global aggregate results are shown in Figure 6.5. Incandescent sources (incandescent, reflector and halogen lamps) provided some 27.1 Plmh of light (11.3% of the total), high-intensity discharge (HID) sources provided 65.5 Plmh (27.4%) and fluorescent sources 146.1 Plmh (61.3%). From these data it is also clear that inefficient light sources, particularly incandescent lamps, mercury vapour lamps and T12 linear fluorescent lamps (LFLs), are still projected to provide a large part of the global lighting service (35.6% of source-lumens). Overall the relatively higher share of light provided by incandescent sources compared to the situation in 2005 is related to the faster rate of growth of residential lighting than the other sectors. In this scenario it is also assumed that solid-state lighting (see Chapter 7) makes

Figure 6.5 **Global average share of electric-light production* by lamp type in 2030 under the Current Policies scenario**



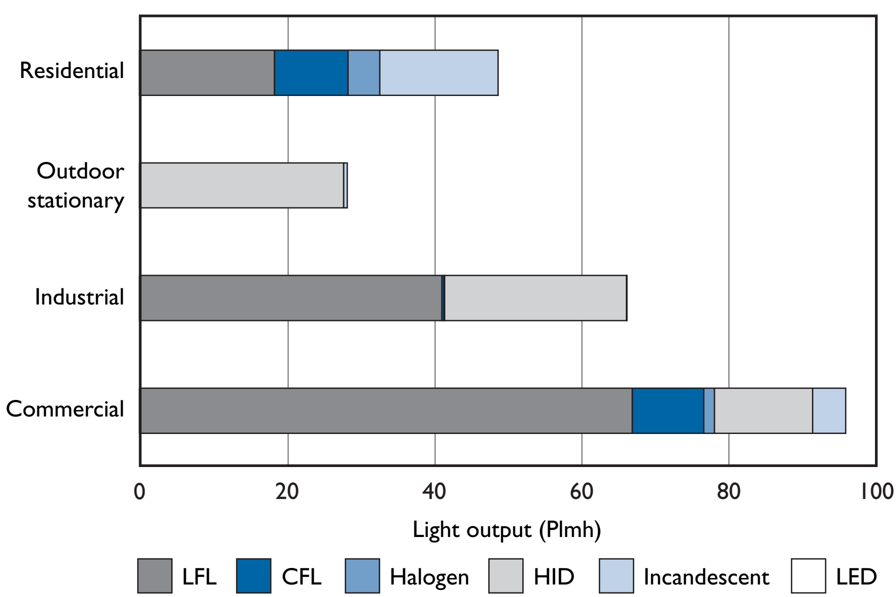
* Total = 239 Plmh, source-lumens.
Abbreviations: CFL = compact fluorescent lamp; LED = light-emitting diode.

only a very small contribution to total lighting-energy services. Given recent progress with this technology this may well be overly conservative, but as the future status of the technology is still unclear it would be imprudent to assume that it will make a major contribution at this stage.

Light production by sector under the Current Policies scenario

Figure 6.6 shows the estimated global aggregate share of light produced by major light-source type in each sector in 2030. The residential sector consumes some 49 Plmh of light (20% of the total), the commercial and public building sector sources 96 Plmh (40%), the industrial sector uses 66 Plmh (28%), and the outdoor stationary sector, which comprises street, roadway, security, outdoor signage and car-park lighting, consumes 28 Plmh (12%). These figures ignore the much smaller amount of light produced by vehicle lighting and off-grid residential fuel-based lighting.

Figure 6.6 Global average share of electric-light production* by lamp type and end-use sector in 2030 under the Current Policies scenario

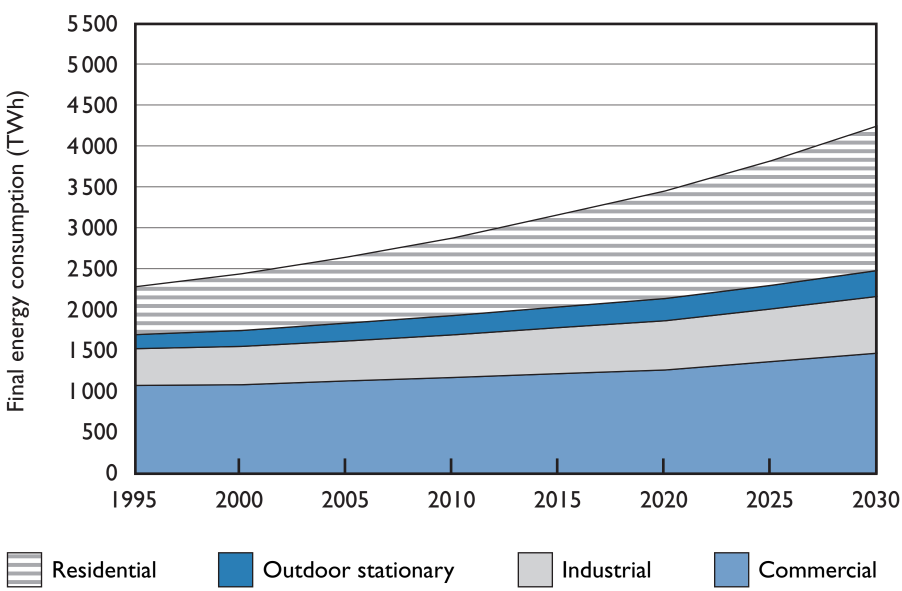


* Total = 239 Plmh, source-lumens.
Abbreviations: CFL = compact fluorescent lamp; HID = high-density discharge; LED = light-emitting diode; LFL = linear fluorescent lamp.

Projected energy trends and impacts of current policies

As demand for artificial light grows, so does the energy consumption required to supply it; however, thanks to numerous efficiency improvements, this is happening at a far slower rate. Over the last decade global electricity consumption for lighting applications grew at 1.5% per annum, less than three-quarters of the rate of growth in demand for light. Over the next 25 years global electricity consumption for lighting, with current socio-economic trends and policies, is projected to rise to 4 253 TWh: an increase of 60% at an average rate of 1.9% per annum. By 2030 some 1 470 TWh will be used for commercial lighting, 1 769 TWh for residential lighting, 695 TWh for industrial lighting and 319 TWh for outdoor stationary lighting (Figure 6.7). This growth is driven in strong part by the growing use of lighting in residential buildings in non-OECD countries, and with a continuation of current policies it is forecast that residential lighting will overtake commercial-sector lighting in importance by 2020.

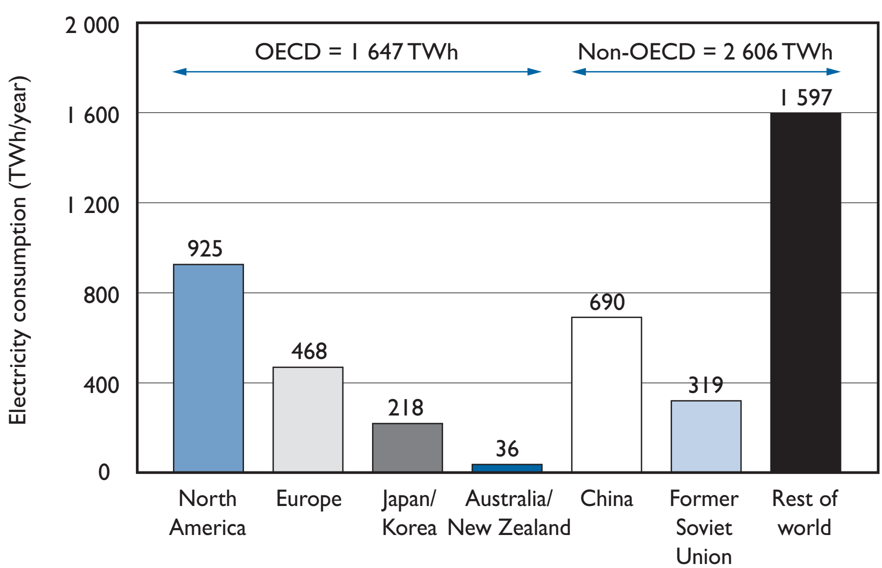
Figure 6.7 **Global lighting electricity consumption by end-use sector in 1995–2030 under the Current Policies scenario**



This projected growth is the aggregate result of many, sometimes divergent, trends. Average consumption of source-lumens per unit floor area of tertiary buildings in IEA countries is set to fall, for example, as measures that improve the efficiency of lumen delivery and reduce lumen wastage continue to take effect. In the residential sector, current policy measures are less pervasive and efficiency of lighting systems is improving less rapidly. In this sector the primary drivers of global lighting energy demand are both economic growth and population growth, as shown in part in Figure 4.12.

The OECD countries accounted for about 57% of total electric lighting demand in 2005 and the non-OECD countries for just 43%; however, as the fastest rates of economic growth are occurring outside the OECD, the share taken by OECD countries is declining and by 2030 non-OECD countries are expected to account for 61% of global lighting electricity demand (Figure 6.8).

Figure 6.8 **Regional share of stationary-lighting electricity consumption* in 2030 under the Current Policies scenario**



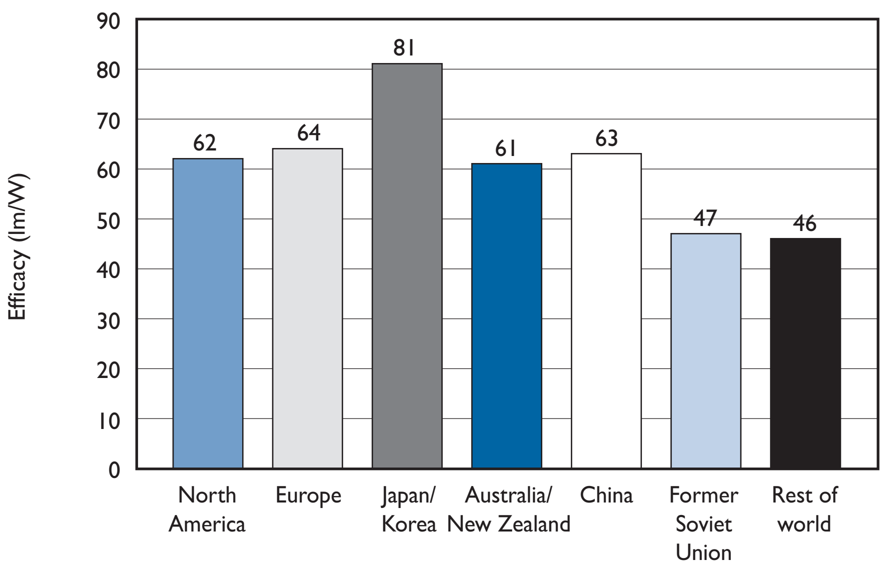
* Total = 4 253 TWh.

Efficacy trends

Despite this increasing energy consumption, the average efficacy of lighting continues to improve under the Current Policies scenario. In 2005 the global average efficacy of lighting is 50.2 lm/W, but by 2030 this has improved by 12% to 56.1 lm/W, in spite of the residential sector contributing a larger share of the total, with the global average efficacy of lighting in this sector being just 23.7 lm/W in 2005 and only slightly better at 27.5 lm/W in 2030. In the commercial sector, global average efficacy improves from 52.3 lm/W in 2005 to 65.2 lm/W in 2030. In the industrial sector, global average efficacy improves from 78.6 lm/W in 2005 to 95.2 in 2030. In the outdoor stationary sector the global average efficacy rises from 74.0 lm/W in 2005 to 88.3 lm/W in 2030.

The efficacy trends by region are such that most of the OECD and China attain an average lighting-system efficacy between 61 and 64 lm/W by 2030. Japan and Korea have the highest efficacy level at 81 lm/W, and the Former Soviet Union and the Rest of the World are further behind, at about 47 lm/W (Figure 6.9).

Figure 6.9 **Average lighting-system efficacy by region in 2030 under the Current Policies scenario**



Impact of current policies

Impacts on efficacy

On average, global lighting-system efficacy levels were 10.1% higher in 2005 than would have been the case were no policies to have been introduced since 1990. By the year 2020 they are projected to be 15.4% higher under the Current Policies scenario than under the No Policies scenario and to remain at that level until 2030. The greatest average improvement is in the commercial-building sector, where lamp efficacies are estimated to have been 12.8% higher in 2005 as a result of current policies and are on course to attain an improvement of 21.5% by 2020. In the industrial sector, average lighting-system efficacy in 2005 under the Current Policies scenario is 9.0% higher than in the No Policies scenario and is 17.7% higher in 2020. In the residential sector, average lighting-system efficacy in 2005 is 8.8% higher under the Current Policies scenario than under the No Policies scenario and is 12.4% higher in 2020. Finally, for the outdoor stationary lighting sector, average efficacy under the Current Policies scenario is only 4.1% higher than in the No Policies scenario in 2005 and just 4.0% higher in 2020.

On average, OECD countries have had greater policy-induced improvements in relative lighting-system efficacy levels than non-OECD regions, largely as a result of broader and more sustained policy measures. On the aggregate level there is little difference in the projected improvements between OECD regions, with Japan and Korea having an estimated efficacy improvement of 14% in 2005, North America and Europe 13% and Australia and New Zealand 9%. However, larger differences are seen when the time dynamics of savings are compared and the savings between sectors are analysed. North America had very proactive policies in the early 1990s and hence was experiencing slightly larger efficacy gains in 1995 (16%) than in 2005 (13%). The other OECD regions started later in initiating their policies and hence were only experiencing policy-induced efficacy gains of 4–6% in 1995. Intriguingly, it is projected that continuation of the policies implemented as of 2005 is going to result in very similar relative efficacy gains by OECD region in 2020: these are projected to be 27% in North America, 25% in Europe and Australia and New Zealand, and 24% in Japan and Korea. It should also be stressed that there are significant margins of error in these estimated improvements and the determinations are based on numerous compounded assumptions, which are mostly derived from past evaluations. Overall there is greater confidence in the North American projections than for the other regions because of the greater confidence in the initial market characterisation, as discussed on pp. 170–171, and the prevalence of policy measures with relatively clear outcomes, such as MEPS with fixed cut-off points.

Outside the OECD the picture is more varied. Some countries, such as China, Brazil and Thailand, have been quite proactive in their lighting-efficiency policies. Others, such as India, have just implemented some measures or have some in the planning stage. Many, such as Russia, have not implemented any measures in recent years and hence have no policy-induced efficacy improvements. As a result, in China current policies are projected to improve average efficacy levels by 12% in 2020, while in the Rest of the World region the improvement is projected to be 9% on average. Not surprisingly there are even greater uncertainties about these estimates because data are more sparse and of a more variable quality. There are also great uncertainties about the impacts of some of the policy measures that have been implemented, because of their nature and implementation. In China, for example, the recently implemented commercial-sector building codes impose lighting power density limits but also specify recommended illumination levels. The latter are higher than historically found in Chinese buildings but may still be lower than those which would have been installed in new buildings had they remained unregulated, thus there is no clear baseline from which to gauge their impacts. The same is true with respect to probable compliance with the lighting codes, which has been a problem in all regions and has historically been low in China for general building energy codes. Therefore in such circumstances a view has been taken about probable results without significant additional efforts to strengthen outcomes; however, the actual impacts could vary appreciably around these estimates depending upon implementation.

Impacts on use

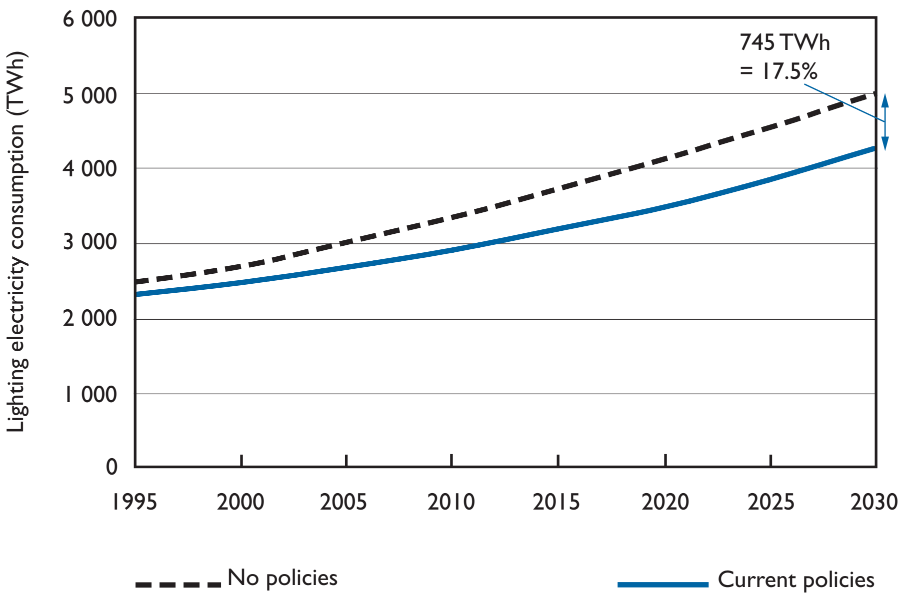
Until recently, addressing the demand for artificial light has been little targeted in most OECD regions through national-level policies. Those measures that have been implemented in the public domain have tended to be either through building codes operating at state level and are very recent (*e.g.* the latest rounds of the ASHRAE 90.1-2004 and IECC 2003/4 codes and the UK building codes to encourage better lighting control in the commercial-building sector, and the 2005 Californian Title 24 codes to encourage better control of outdoor stationary lighting) or are done in a more oblique way through the encouragement of better building energy management. The latter was and is a focus of Japan's Energy Conservation Law and there has clearly been success in European states in encouraging building managers to use time scheduling and other manual lighting-control methods to reduce excess lighting use. Evaluating the impact of these measures is harder to do than evaluating the efficacy improvements alone because time-series data on hours of use are not generally available, therefore the IEA scenarios have not always been able to capture these impacts. However, these may be the most important savings of all, as the hours of use constitute the single largest cause of differences in lighting energy consumption between OECD regions.

Impacts on energy consumption

With the Current Policies scenario, global energy consumption for electric grid-based lighting is projected to rise from 2 651 TWh in 2005 to 4 253 TWh in 2030; however, had these policies not been implemented, lighting energy consumption would have been 334 TWh (12.6%) higher in 2005 and 745 TWh higher in 2030 (17.5%) (Figure 6.10). For reasons of simplicity these values only include direct lighting-energy savings and do not incorporate any additional savings resulting from avoided air-conditioning loads, or losses related to a need for additional heat; however, for reasons explained on pp. 179–180 this is a deeply conservative consumption on a global basis as avoided air-conditioning loads are likely to significantly exceed additional heating requirements in primary energy terms.

The greatest relative savings of 18.6% are projected to occur in 2020 as current policies make their maximum impact on the lighting stock and before natural market progressions begin to catch up again. In general, lighting energy policies exercise a rapid transition in lighting equipment, but many of the most telling policies have only just been implemented and will take some time to influence the majority of the current stock.

Figure 6.10 **Global lighting electricity consumption in 1995–2030 under the No Policies and Current Policies scenarios**



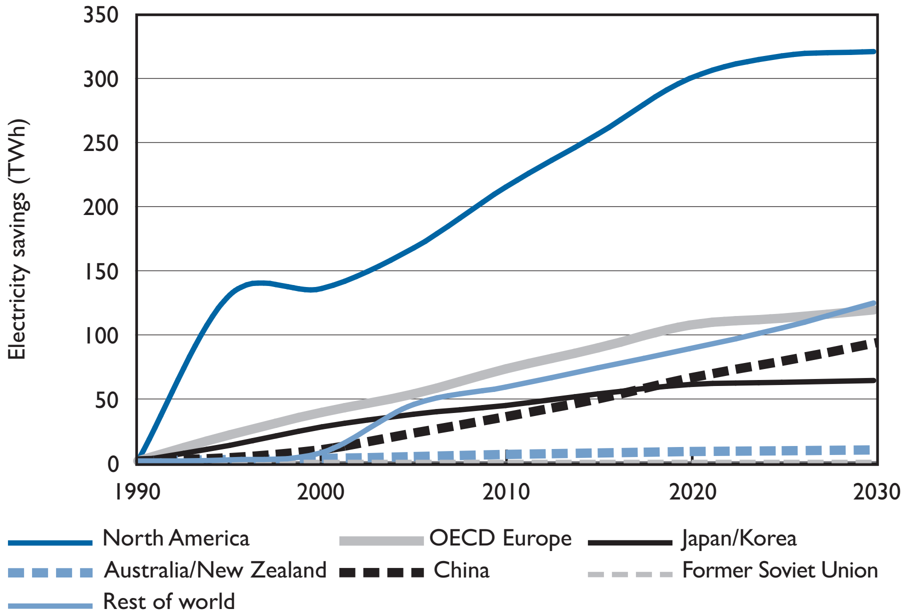
In cumulative terms current policies saved almost 8% of lighting electricity consumption by 2005 (2 960 TWh) and 1 700 Mt of CO_2 emissions; they are also forecast to save another 14 500 TWh and 8 500 Mt of CO_2 (17% of the total) from 2006 to 2030 without being strengthened. These savings are truly impressive and should provide considerable encouragement to policy makers to continue to develop and strengthen policies within this sector.

Electricity savings by region

The largest total savings have occurred in OECD North America, where some 171.1 TWh of lighting electricity was saved in 2005 and 307.5 TWh is projected to be saved by 2020, assuming a continuation of current policies (Figure 6.11).

These savings are achieved despite OECD North America having by far the highest per-capita lighting electricity consumption across the OECD regions. In percentage terms, these values correspond to savings of 19.8% in 2005 and 35.6% in 2020. The policies enacted in OECD Europe since 1990

Figure 6.11 **Lighting electricity savings by region in 1990–2030 under the Current Policies scenario compared with the No Policies scenario**



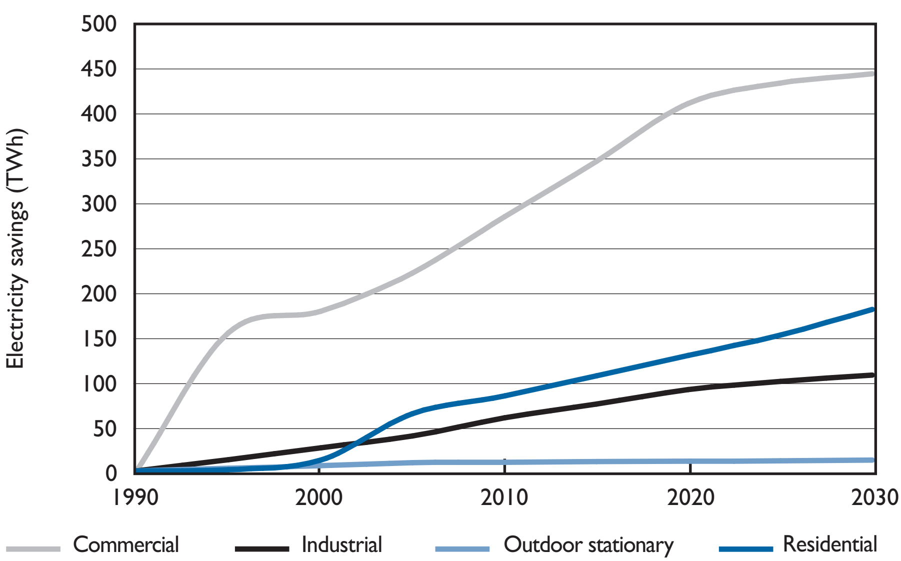
(including EU and national policies) are estimated to produce electricity savings of 53.9 TWh in 2005 and 109.2 TWh by 2020. In percentage terms, this corresponds to savings of 13.1% in 2005 and 24.9% in 2020. These values, which are slightly lower than those in North America, reflect the slower start and less comprehensive enactment of lighting-efficiency policies in OECD Europe in the decade to 2005. In Japan, the pace of policy initiation was slower in the early 1990s but accelerated from the mid-1990s onwards. Savings of 37.7 TWh are estimated for 2005, rising to 61.6 TWh in 2020. In percentage terms, these savings are the joint most impressive across the OECD, with values of 19.4% in 2005 and 29.7% in 2020; however, as a result of some important data limitations there is greater uncertainty in these projections compared with those for the other regions. In Australia and New Zealand the implementation of lighting energy-efficiency programmes is a relatively recent occurrence but current policy discussion is quite ambitious. Consequently, savings of 11.2% (3.5 TWh) are estimated for 2005 and savings of 22.2% (7.6 TWh) are forecast for 2020.

Electricity savings by sector

The largest energy savings attributable to current policies have been achieved in the commercial sector. These totalled 225 TWh in 2005 (Figure 6.12), comprising 66% of all lighting energy savings and 19.6% of lighting energy use. The policies that have produced these savings include a mixture of building codes, MEPS for lamps and control gear, and market-transformation programmes. By 2020, energy savings in the commercial sector are set to reach 412 TWh, but those within the residential sector are projected to grow to 129 TWh (20% of the total savings) even if current policies are not strengthened in the future.

Current policies are also producing large savings in industrial-sector lighting energy use (amounting to 39 TWh, some 8% of the sector's total lighting electricity use in 2005) but have had a smaller impact on outdoor stationary lighting, largely because MEPS for HID lamps have not yet been implemented.

Figure 6.12 **Global lighting electricity savings by end-use sector under the Current Policies scenario compared with the No Policies scenario**



Costs and benefits of current policies

The costs of implementing the current set of lighting-efficiency policy measures are generally far lower than the value of the benefits. The costs associated with energy labelling, MEPS, voluntary agreements, building codes and market-transformation programmes include the administrative cost of designing and implementing the policy measures, the cost to manufacture more efficient equipment as passed down the supply chain to the final consumer, and any promotional and training costs carried by other interested parties such as manufacturers, retailers and installers. The benefits include reduced operating costs and the lower environmental impacts of the lighting equipment (e.g. lower indirect CO_2 emissions) associated with the net increase in lighting-equipment efficiency. Surprisingly, when viewed over the product life cycle the more efficient lighting equipment can be slightly less expensive in terms of its pure capital acquisition and labour costs than the less efficient lighting equipment because (i) it often lasts longer and hence has longer replacement cycles and (ii) it often has lower maintenance costs.

Estimating costs and benefits

The methodology used to estimate lighting capital and labour costs is described on pp. 269–272 and is applied in the scenarios to project lighting-equipment, labour and energy costs over time. The assumed future estimated electricity tariffs and CO_2 emission factors are harmonised with the IEA's *World Energy Outlook 2004* Reference Scenario projections to 2030 by region and sector (OECD/IEA, 2004). Even ignoring the benefits accruing from lower energy costs, on average the more efficient lighting considered in the Current Policies scenario saves the end-user USD 0.006 per kilowatt-hour of electricity avoided compared with the No Policies scenario because of lower net maintenance and capital-equipment costs.

Table 6.1 shows the estimated reduction in energy bills and estimated savings in equipment purchase and labour costs from 1990 to 2030 attributable to the electric lighting energy-efficiency policies that were already in place in countries around the world circa 2005. The net-cost savings shown in the table are the sum of the two costs. Also indicated are the annual and cumulative reductions in indirect CO_2 emissions attributable to the policies enacted. These estimates show that

Table 6.1 Energy-cost savings, equipment purchase-cost changes and carbon emission reductions under the Current Policies scenario compared with the No Policies scenario

Year	Energy-cost savings (USD, billions)		Equipment purchase- and installation-cost changes (USD, billions)		Net-cost saving (USD, billions)		CO_2 reductions		
	Annual	Cumulative from 1990	Annual	Cumulative from 1990	Annual	Cumulative from 1990	Annual ($Mt\text{-}CO_2$)	Share of lighting total (%)	Cumulative ($Mt\text{-}CO_2$)
1995	13	32	–1.1	–2.9	14	35	98	7.5	246
2000	18	111	–2.2	–11.9	20	123	129	9.1	830
2005	28	230	–2.4	–23.6	30	253	194	12.7	1 672
2010	36	394	–2.7	–36.7	39	431	257	15.3	2 831
2015	45	602	–3.4	–52.2	48	654	317	17.1	4 296
2020	54	853	–3.9	–70.8	58	924	382	18.6	6 076
2025	59	1 136	–3.8	–89.9	63	1 226	418	18.2	8 096
2030	63	1 442	–3.4	–107.5	66	1 550	449	17.5	10 281

Abbreviation: $Mt\text{-}CO_2$ = million tonnes of CO_2.

cumulatively 2 831 Mt of CO_2 emissions are expected to be avoided globally from 1990 to 2010 as a result of current lighting-efficiency policies and that far from being incurred at a higher net cost to consumers and society, these policies are anticipated to save end-users some USD 431 billion in net costs over the same period. If the time frame is extended to 2030 some 10 281 Mt of cumulative CO_2 emissions are expected to be avoided for a net saving of USD 1 550 billion.

Energy-efficiency policy measures, especially those aimed at the lighting, stand apart from other CO_2-abatement policy measures, such as fuel-switching, because they are still in the domain where they can be achieved at a large net financial benefit to society even without the value of pollution externality costs being taken into account. The cost savings indicated in Table 6.1 give an insight into the imperfect nature of the lighting-equipment market as far as energy performance is concerned. Such large net-cost savings are attainable through enacting equipment-efficiency policy measures because, in their absence, a variety of barriers exist that prevent the true economic value of energy-efficiency investments being apparent to, or obtainable by, lighting-equipment purchasers. The estimates in Table 6.1 suggest that each tonne of CO_2 saved to 2010 through current policies will be attained at a net-cost saving of USD 152, *i.e.* the net cost of CO_2 abatement is USD –152 per tonne of CO_2.

The costs of CO_2 abatement are attractive in all the end-use sectors. For the commercial sector the cumulative abatement costs to 2010 amount to USD –154 per tonne of CO_2, for the residential sector USD –172, for the industrial sector USD –129 and for the outdoor stationary sector USD –129.

IMPACT OF FUTURE POLICIES: AIMING FOR LLCC EFFICIENCY LEVELS FROM 2008

As comparatively reliable data on the relationship between life-cycle cost and efficiency are available for the majority of lighting electrical end-uses in the major economies, a high-efficiency scenario has been produced wherein it is generally assumed that all electrical lighting equipment sold from 2008 onwards attains the least life-cycle cost (LLCC) efficiency level for each service type and in each economy.

The scenario is confined to the consideration of technical options that would raise the efficiency of electric lighting end-uses in a cost-effective manner for the average consumer/end-user without lowering the lighting service provided. In determining the efficiency level associated with the LLCC, there is no constraint imposed on the maximum length of the payback period for higher-efficiency equipment, *i.e.* it is only necessary for the LLCC efficiency level to produce the lowest total cost of designing, purchasing, installing and operating the lighting system discounted over its normal lifetime.

For reasons of simplicity, the Least Life-Cycle Cost from 2008 (LLCC from 2008) scenario only treats the direct energy impacts of lighting choices and does not include an assessment of the indirect impact of lighting on air-conditioning and heating loads. Nor are the economic assessments based on minimising the marginal costs of peak power; rather they aim to minimise the life-cycle cost for the end-user and hence apply the average electricity tariff applying in each end-use sector and region in line with the assumptions in the *World Energy Outlook 2004* (OECD/IEA, 2004). For reasons of simplicity this is time-averaged for all sectors except street lighting, where typical night-time tariffs are applied. These modelling necessities are also conservative in the sense that they will tend to cause the efficiency level associated with the LLCC to be underestimated and will also tend to underestimate the cost-effectiveness of efficient lighting options. In practice the latter issue is a more serious problem because the economics of most lighting systems are such that it is cost-effective to use the most efficient lighting choice available even if time-averaged tariffs are applied and avoided space-conditioning costs are ignored.

Assumptions for the LLCC from 2008 scenario

The details of the assumptions underpinning the scenario are explained below for the different types of equipment considered.

Key technology assumptions

Under the LLCC from 2008 scenario more efficient lighting technologies are only considered to be viable alternatives to traditional choices if they provide the same, better or sufficiently acceptable lighting quality for the application considered. This means that in the majority of cases when the operating hours exceed an economic threshold it is assumed that:

- Compact fluorescent lamps (CFLs) replace standard incandescent lamps, but only for the proportion of sockets that are suited to CFL use and with only high-quality CFLs being considered.
- High-efficiency high-pressure sodium and/or metal halide lamps replace mercury vapour lamps.
- T12s and halophosphor T8 LFLs are replaced by triphosphor T8s and T5s.
- High-efficiency electronic ballasts replace magnetic ballasts.
- Halogen torchières are phased out.
- For all other lamp types it is assumed that only the most efficient varieties are applied in the future whenever this is cost-effective to the end user.

These changes only occur in line with natural installation and replacement cycles for lamps, ballasts and fixtures; in other words there is no premature replacement of existing capital equipment. This limits the rate at which T5s can be applied, for example, because it is assumed that they cannot be retrofitted into existing T8 and T12 fixtures; rather, they are only an option as existing luminaires are replaced or completely new installations are added. This assumption is rather conservative because adaptor kits are available and may be an appropriate solution in some cases, although there is always a risk that the optics of an existing T8 luminaire will not be well adapted to receive a T5. In fact there are many cases where premature replacement of the existing lighting equipment would be cost-effective, but these are more complex to model and hence are not considered here.

In addition to these measures, two other technology options are included in the LLCC from 2008 scenario:

- A proportion of halogen lamps are replaced by light-emitting diodes (LEDs) (from the medium term onwards).
- Lighting controls (presence sensors, daylight dimming, etc.) are installed in spaces where the energy cost is over USD 2.5 per square metre of floor area per annum.

LEDs are discussed in Chapter 7 and are a very promising, potentially high-efficiency option for numerous lighting applications in the future. In this scenario only very modest inroads are assumed for this technology in the future because its full prospects and viable range of applications are still not fully clear. Because of the strong directional nature of existing LED illumination it is conservatively assumed that this technology can only compete with similar light sources for general illumination purposes in the future and hence a small proportion of halogen lighting is replaced by more efficient LED lighting from 2015 onwards in the LLCC from 2008 scenario. This is probably underplaying the potential for progress with solid-state lighting, but as this progress cannot be assumed it is not included in the current scenario. In a similar vein the scenario is also conservative because it does not assume any major technology development in either other new forms of lighting or existing lighting technologies, even though some degree of progress is probable. In this sense it is a frozen technology scenario and explores what can be done with today's technologies. The same is true for lighting controls, for which no assumptions are made regarding improved technology or lower costs from greater deployment. In fact the price differential for controls and efficient lighting technologies would be expected to decrease were their volumes greatly increased, as is assumed in this scenario; however, because the degree of reduction is uncertain, static prices and performances are assumed for modelling purposes. The cut-off point for the application of automatic lighting controls, *i.e.* for spaces with energy costs greater than USD 2.5 per square metre, is derived from sources in the literature that assert that the use of such controls is almost always cost-effective in such circumstances.

Future demand for light

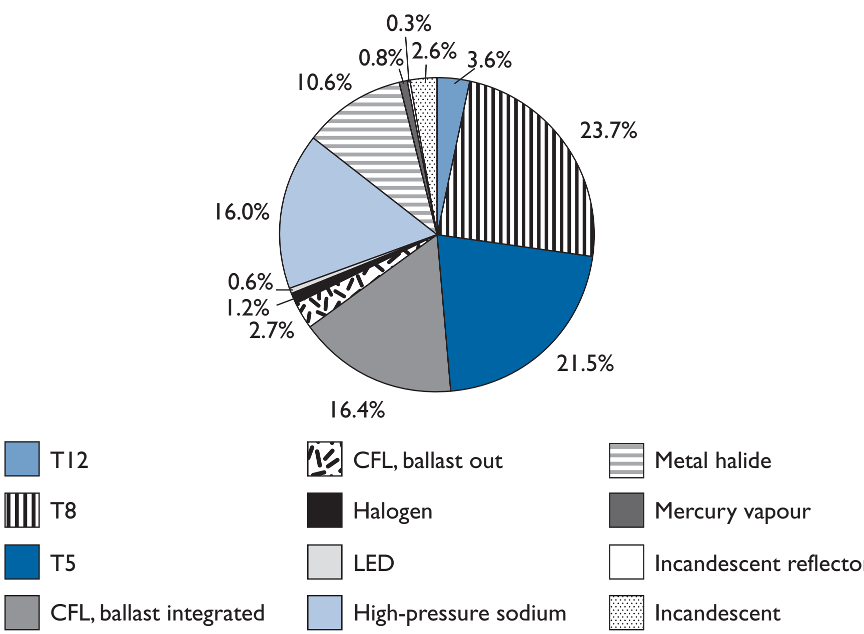
Under the LLCC from 2008 scenario the global demand for grid-based electric light is forecast to attain 205 Plmh by 2030, which is 34 Plmh lower than in the Current Policies scenario and 38 Plmh lower than in the No Policies scenario. The reduction results entirely from the use of lighting controls, which are gradually applied in high-usage areas of commercial and industrial buildings from 2008 onwards. A moderate degree of off-peak dimming and greater use of motion sensors is also applied in outdoor stationary lighting. The analysis of current recommended illuminance levels on pp. 84–98 suggests that there is a substantial savings opportunity in those countries that currently recommend illuminance levels beyond their peers were they to reduce their recommendations; however, savings from this option are not considered here.

The use of lighting controls results in the global annual average per-capita consumption of light falling from 30 Mlmh in 2030 under the Current Policies scenario to 25 Mlmh under the LLCC from 2008 scenario. Not surprisingly, the largest reductions occur in the regions that consume the most light, so in OECD North America annual average per-capita levels fall from 108 to 88 Mlmh and in Japan/Korea they fall from 105 to 93 Mlmh.

Light production by lamp technology under the LLCC from 2008 scenario

The global average share of light produced by each light source in 2030 under the LLCC from 2008 scenario is shown in Figure 6.13. Incandescent sources (incandescent, incandescent reflector and halogen lamps) provide 4.1% of the total light, compared to 11.3% in the Current Policies scenario. HID sources provide 27.4%, which is the same as in the Current Policies scenario; however, among these the less efficient mercury vapour lamps provide only 0.8% of the total light, compared to 6.8% under the Current Policies scenario. Linear fluorescent sources provide 48.8% of the total light, compared to 52.9% under the Current Policies scenario, but within this the share taken by T5s increases to 21.5%, compared to 7.5% under the Current Policies scenario, while the share taken by the less efficient T12s falls to just 3.6% from 17.5% under the Current Policies scenario. The share taken by T8s is slightly lower at 23.7%, compared to 28% under the Current Policies scenario; however, almost all these lamps are of the high-efficiency triphosphor variety, whereas in the Current Policies scenario the less efficient halophosphor types still command a leading share. The other major change concerns the use of CFLs. These provide 19.1% of delivered light in the LLCC from 2008 scenario for 2030 but just 8.4% under the Current Policies scenario. In both cases the less efficient ballast-integrated type is assumed to predominate, but it has an even greater dominance in the LLCC from 2008 scenario because a far greater use of CFLs in the residential sector is assumed (the separate tube and ballast type dominates commercial-sector applications in both scenarios). Finally, 0.7% of all light in 2030 is assumed to be supplied by

Figure 6.13 Global average share of electric-light production* by lamp type in 2030 under the LLCC from 2008 scenario



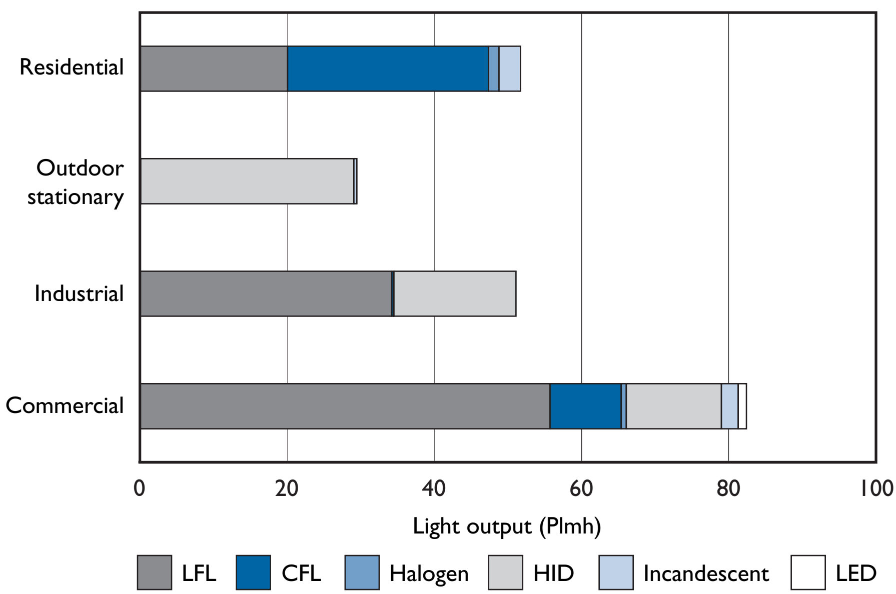
* Total = 205 Plmh, source-lumens.
Abbreviations: CFL = compact fluorescent lamp; LED = light-emitting diode.

LED sources at the expense of halogen spotlights, for which the share declines to 1.2% from 2.5% under the Current Policies scenario. It is also assumed that a small proportion of halogen lighting that is not of the spot variety can be replaced by other light sources, e.g. halogen torchières are replaced by CFL or LFL torchières under the LLCC from 2008 scenario.

Light production by sector under the LLCC from 2008 scenario

Figure 6.14 shows the estimated global aggregate share of light produced by major light source type in each sector in 2030 under the LLCC from 2008 scenario. The residential sector consumes some 49 Plmh of light (24% of the total), the commercial and public building sector consumes 81 Plmh (40%), the industrial sector 49 Plmh (24%), and the outdoor stationary sector, which comprises street, roadway, security, outdoor

Figure 6.14 Global average share of electric-light production* by lamp type and end-use sector in 2030 under the LLCC from 2008 scenario



* Total = 205 Plmh, source-lumens.
Abbreviations: CFL = compact fluorescent lamp; HID = high-density discharge; LED = light-emitting diode; LFL = linear fluorescent lamp.

signage and car-park lighting, uses 26 Plmh (13.0%). These figures ignore the much smaller amount of light produced by vehicle lighting and off-grid residential fuel-based lighting.

Projected energy trends and impacts of the LLCC from 2008 scenario

Impacts on efficacy

The LLCC from 2008 scenario produces very appreciable efficacy gains compared with the Current Policies scenario. In 2015 the global average efficacy of lighting is 71.7 lm/W, compared with 54.3 lm/W under the Current Policies scenario, and by 2030 the average has risen to 78.8 lm/W, compared to 56.1 lm/W. This is a gain of 32% in 2015 and 40.5% in 2030. The relatively rapid rise in the differential shows how quickly lighting systems could be improved from a technical perspective and illustrates one feature of why lighting remains an attractive policy target whenever quick energy savings are needed. The largest relative improvement is in the residential sector: global average electric lighting efficacy rises to 42.2 lm/W in 2020, compared with just 26.2 lm/W under the Current Policies scenario. This is an increase in relative efficacy of 61%. This result is explained by the large proportion of incandescent lamps substituted by CFLs in the residential sector and by the use of improved linear fluorescent lighting and high-quality and high-efficiency CFLs. The next largest gain is in the outdoor stationary sector, where relative efficacy levels are 42.2% higher under the LLCC from 2008 scenario compared with the Current Policies scenario in 2020. These substantial savings illustrate the value of rapidly phasing out low-efficacy mercury vapour and blended mercury vapour lamps. Lesser but still important contributions arise from the use of new, high-efficacy electronic ballasts and the preferential use of more efficient high-pressure sodium lamps or ceramic metal halide lamps. The latter have not only a high efficacy, but also a high colour rendering index (CRI) and colour stability and thus are particularly appropriate for mesopic lighting conditions or for lighting where a high CRI is required.

The commercial-building sector sees average efficacy gains of 39.3% in 2020, with global average efficacy levels rising from 63.8 to 88.9 lm/W. These gains arise from a multitude of sources, including less use of incandescent lighting, higher-efficacy LFLs, better ballasts, and substitution of halogen lighting with LEDs and ceramic metal halide lamps.

The smallest improvements are seen in the industrial sector, where average lighting-system efficacy rises by 15.1% in 2020. Less use of mercury vapour lighting and more efficient LFLs and HID sources are the origin of these gains. The smaller improvement compared with other sectors reflects the fact that industrial-sector lighting already tends to use higher-efficacy light sources, although the improvements are still significant.

Under the LLCC from 2008 scenario there are fewer regional differences in average efficacy by 2030; however, Japan and Korea still have the highest efficacy levels because they use less incandescent lighting than elsewhere. The OECD average lighting system efficacy, across all end-use sectors, is 87.8 lm/W, while the non-OECD average is 72.2 lm/W. The difference is explained primarily by the higher proportion of residential lighting compared with other higher-efficacy sectors in the non-OECD countries.

Impacts on use

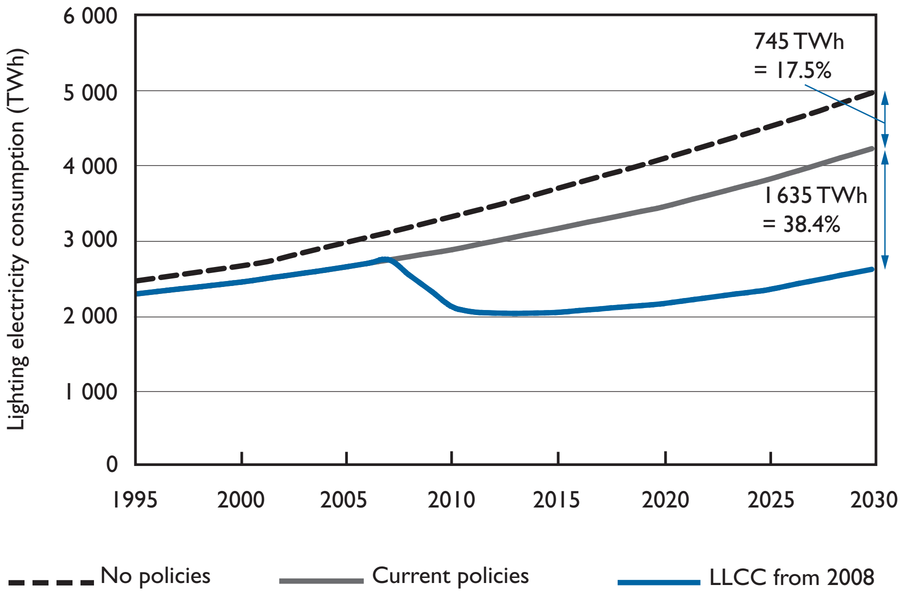
Under the LLCC from 2008 scenario the greater use of lighting controls reduces average lighting operating hours by 14.2% across all sectors, but the largest savings are a reduction of 14.9% in the commercial sector and 26.7% in the industrial sector compared to the Current Policies scenario in 2030. The outdoor stationary sector also experiences an 8.7% reduction in the hours of use by 2030.

Impacts on energy consumption and CO_2 emissions

Under the LLCC from 2008 scenario, grid-based lighting electricity consumption is projected to drop from 2 651 TWh in 2005 to 2 013 TWh in 2015, and then rise to 2 618 TWh in 2030. Compared with the Current Policies scenario this constitutes a saving of 35.9% in 2015 and 38.4% in 2030 (Figure 6.15). Compared to the Current Policies case the OECD countries save 633 TWh in 2030 under the LLCC from 2008 scenario, as opposed to 1 002 TWh in the non-OECD countries; however, the relative savings are almost identical, at 38.4%, in both regional groupings (Figure 6.16).

In cumulative terms the LLCC from 2008 scenario saves 28.6% of lighting electricity consumption by 2015 (6 807 TWh) compared to the Current Policies scenario and 35.3% (27 988 TWh) by 2030. These highly impressive energy savings result from the mixture of efficacy

Figure 6.15 **Global lighting electricity consumption in 1995–2030 under the No Policies, Current Policies and LLCC from 2008 scenarios**

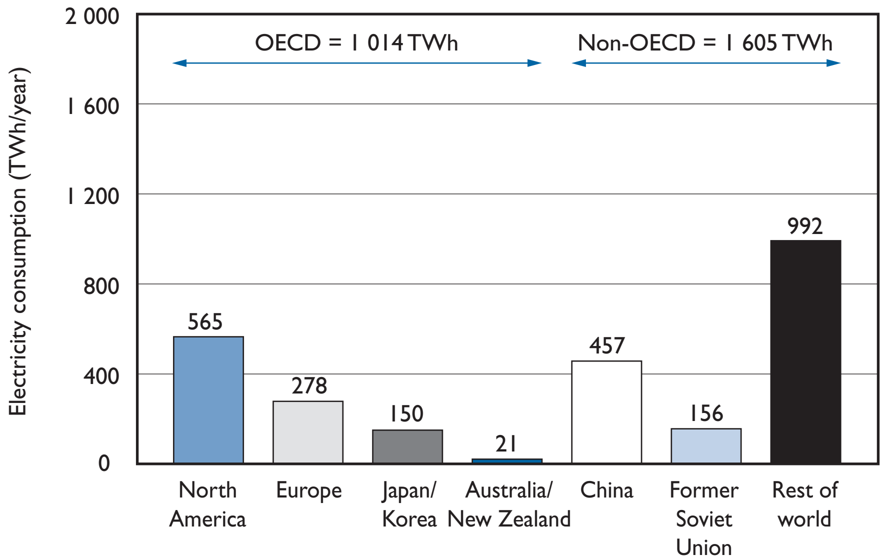


improvements and reductions in hours of use discussed in the preceding paragraphs. There is no reduction in the lighting service provided and in many cases lighting quality will be improved through the use of superior HID and fluorescent technology. These savings are about 1.8 times larger again than what is projected to be achieved with the Current Policies scenario compared to the No Policies scenario over the same period.

Electricity savings by region

The largest total savings are projected to occur in the Rest of the World region, where some 605 TWh are saved by 2030 under the LLCC from 2008 scenario compared with current policies. This is followed by savings of 360 TWh in North America, 233 TWh in China, 191 TWh in Europe, 163 TWh in the Former Soviet Union, 63 TWh in Japan and Korea, and 15 TWh in Australia and New Zealand (Figure 6.17).

Figure 6.16 **Regional share of lighting electricity consumption* in 2030 under the LLCC from 2008 scenario**



* Total = 2 618 TWh.

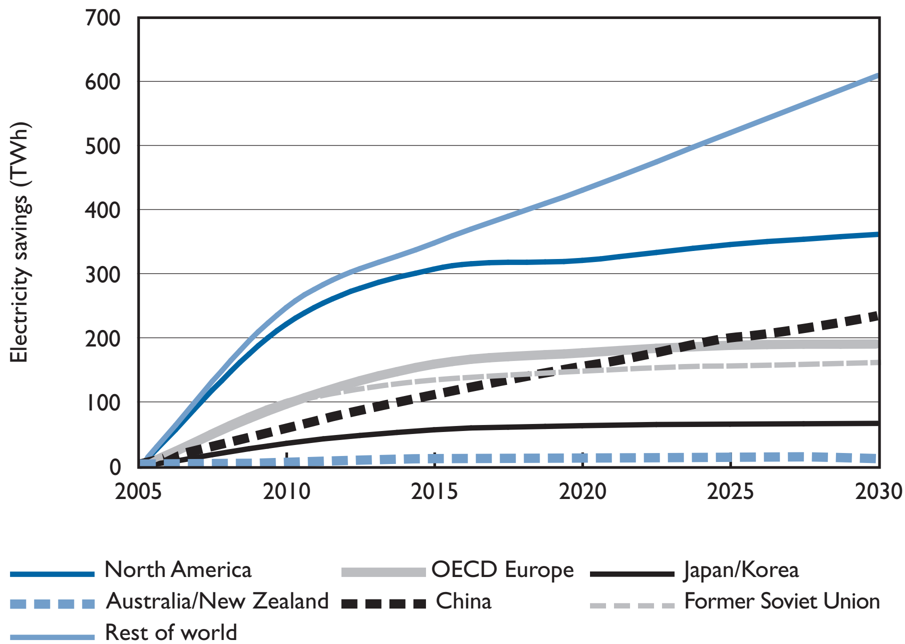
Electricity savings by sector

Ultimately the largest energy savings from the LLCC from 2008 scenario compared to current policies are in the commercial sector. By 2030, savings in the commercial sector are set to reach 661 TWh (40.4% of the total), but those from the residential sector are almost as large at 610 TWh (37% of the total savings). Savings in the industrial sector amount to 250 TWh (15.3% of the total) and those in the outdoor stationary sector reach 114 TWh (7.0% of the total) (Figure 6.18).

Costs and benefits of the LLCC from 2008 scenario

By definition the measures implemented in the LLCC from 2008 scenario are cost-effective to end-users as the scenario seeks to minimise the discounted life-cycle cost of lighting. The global costs of lighting equipment (including controls) and maintenance are slightly higher under the LLCC from 2008 scenario than under the Current Policies scenario and on average amount to USD 0.003 per kilowatt-hour of avoided electricity.

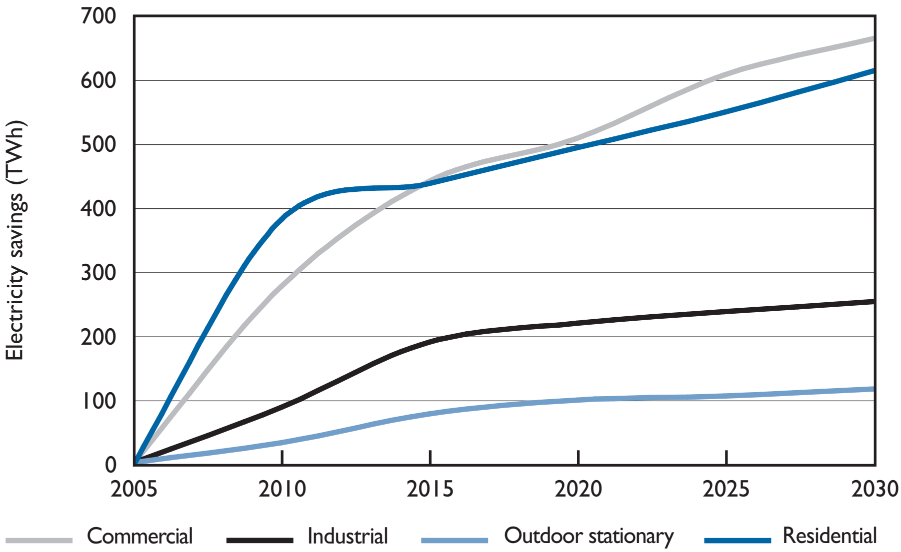
Figure 6.17 **Lighting electricity savings by region under the LLCC from 2008 scenario compared with the Current Policies scenario**



This increment is mostly related to the additional cost of the automatic lighting controls. However, the increment is a small fraction of the average electricity tariff and so the global-average net cost of lighting electricity saved under the LLCC from 2008 scenario is strongly negative, at USD –0.093 per kilowatt-hour avoided.

Table 6.2 shows the estimated reduction in energy bills and estimated savings in equipment purchase and labour costs from 2005 to 2030 attributable to the LLCC from 2008 scenario. The net-cost savings shown in the table are the sum of the two costs. Also indicated are the annual and cumulative reductions in indirect CO_2 emissions attributable to the policies enacted. These estimates show that cumulatively 3 721 Mt of CO_2 emissions are expected to be avoided globally from 2008 to 2015 as a result of the LLCC lighting measures and that far from being incurred at a higher net cost to consumers and society, these measures are

Figure 6.18 **Global lighting electricity savings by end-use sector under the LLCC from 2008 scenario compared to the Current Policies scenario**



anticipated to save end-users some USD 615 billion in net costs over the same period. If the time frame is extended to 2030 some 16 160 Mt of cumulative CO_2 emissions are expected to be avoided for a net saving of USD 2 594 billion.

The estimates in Table 6.2 suggest that each tonne of CO_2 saved to 2015 by LLCC lighting measures is attained at a net-cost saving of USD 148, *i.e.* the net cost of CO_2 abatement is USD –148 per tonne of CO_2 and each tonne saved to 2030 is at a net cost of USD –156. Figure 6.19 shows how the total savings resulting from the LLCC lighting measures accumulate after 2008 compared with the Current Policies scenario (the $y = 0$ line). Also shown are the extra costs incurred under the No Policies scenario compared with the Current Policies scenario.

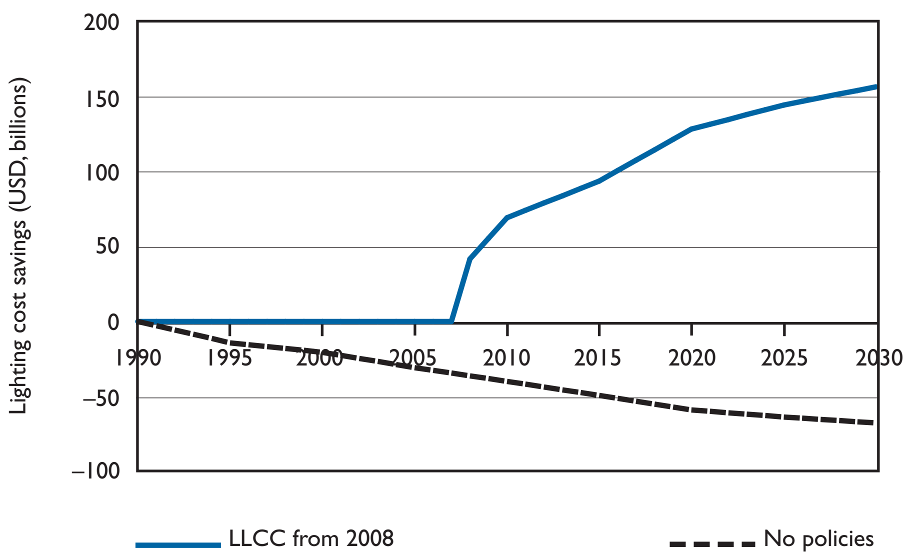
Once again the costs of CO_2 abatement are attractive in all the end-use sectors. For the commercial sector the cumulative abatement costs to 2030 amount to USD –106 per tonne of CO_2, for the residential sector they are USD –205, for the industrial sector they are USD –164 and for the outdoor stationary sector they are USD –154.

Table 6.2 Energy-cost savings, equipment purchase-cost changes and carbon emission reductions under the LLCC from 2008 scenario compared with the Current Policies scenario

Year	Energy-cost savings (USD, billions)		Equipment purchase- and installation-cost changes (USD, billions)		Net-cost saving (USD, billions)		CO_2 reductions		
	Annual	Cumulative from 1990	Annual	Cumulative from 1990	Annual	Cumulative from 1990	Annual ($Mt\text{-}CO_2$)	Share of lighting total (%)	Cumulative ($Mt\text{-}CO_2$)
2010	78	237	11	32	68	205	438	26.1	885
2015	107	716	16	101	92	615	654	35.1	3 721
2020	122	1 298	–3	122	126	1 176	763	37.1	7 319
2025	138	1 957	–3	106	141	1 852	879	38.3	11 483
2030	151	2 688	–2	93	153	2 594	973	37.8	16 160

Abbreviation: $Mt\text{-}CO_2$ = million tonnes of CO_2.

Figure 6.19 Global lighting-cost savings under the LLCC from 2008 and No Policies scenarios compared to the Current Policies scenario



The high potential for energy savings in lighting reflects the fact that although there are already many cost-effective energy-efficient lighting technologies available on the market, they are currently underutilised. The estimated savings potentials presented above are based on today's artificial-lighting technology and today's average prices; however, new lighting technologies that are under development promise higher levels of efficiency and could further increase the cost-effective savings potentials to 2030. Furthermore, the above estimates take no account of the cost-effective potential to increase daylight utilisation beyond the selective use of automatic dimming systems in spaces that already have access to daylight. Finally, the calculations take no account of the reduction in parasitic lighting-induced energy loads such as air-conditioning, nor the typical high peak-power coincidence factor of many lighting loads that increases the value of lighting electricity savings compared to average electricity loads. Were all these factors to be taken fully into consideration the cost-effective savings potential could be substantially greater.

PROJECTED TRENDS IN VEHICLE LIGHTING

The trends in transport activities in the 15 years to come will drive the demand for vehicle lighting, together with the potential for future penetration of efficient technologies and the evolution of voluntary or regulatory use of lighting. Pages 245–248 describe the potential changes that may occur as a result of different responses to the safety benefits of operating front vehicle lighting during the daytime; the choices made may have a significant impact on future vehicle-lighting energy-use trends. An analysis was conducted in order to assess the trends and possibilities depending on regulatory and technology choices. The core model is the same as that applied by the IEA in the *Mobility 2030* report (WBCSD, 2004) and as used in the IEA's *World Energy Outlook 2004* (OECD/IEA, 2004) but is adapted as described on pp. 245–248 to include an appraisal of lighting energy demands. Trends in travel demand used in the scenarios described on pp. 423-424 are also harmonised with those from the IEA model used in the *World Energy Outlook 2004* and in the WBCSD *Mobility 2030* report. A continuous rise in numbers of vehicle stocks, passenger-kilometres travelled and tonnes of freight-kilometres travelled are assumed. Over the next 15 years, vehicle activity expressed in terms of vehicle kilometres is projected to rise by 40% worldwide for light-duty vehicles and by 60% for heavy trucks, for example. This highlights the importance of the sector for the future demand of oil, in a world where the price of oil, the security of supply, the environmental impact and the long-term depletion of resources are increasingly a concern.

Vehicle-lighting fuel-use scenarios

Future vehicle-lighting energy consumption will be driven by both behavioural and technological aspects. In order to assess the potential future outcomes, four scenarios have been established that combine two technology visions (*i.e.* low or high penetration rates for a mix of LED and xenon lamps in 2020) and two visions of the future use of light-duty vehicle headlamps for road-safety reasons that depend on the future regulatory environment. The four scenarios are defined as follows.

1. The Reference ("REF") scenario is a business as usual scenario that assumes a slow adoption rate of higher-efficiency vehicle-lighting technologies (that is (i) a low share of high-efficacy xenon HID and LED lamps, (ii) typical xenon HID lamps continue to require 35 W yet deliver twice the light output of typical halogen headlights [see pp. 242–243], and (iii) the improvement in LED efficacy is relatively low compared with the third and fourth scenarios below).

2. The Security ("SEC") scenario is similar to the REF scenario except that light-duty vehicles and minibuses are progressively subject to a mandatory requirement to use either dipped beams or daytime-running lights during daytime. This requirement is introduced in a linear progression from the countries already having such requirements in 2002 to all countries by 2020. Daytime-running lights are not compulsory for new cars and the rate of daytime-running light penetration remains the same throughout the 2002–20 period.

3. An energy-efficient technologies scenario (denoted "REF+EET") applies the same assumptions regarding lighting use and traffic as in the REF scenario; however, all the new models on the market adopt 18 W[1] xenon HID headlamps and/or very efficient (future) LEDs for all applications.

1. This assumes that it is possible to produce 18 W xenon HID lamps that have the same light output as a standard halogen headlamp of today but require one-quarter of the power; this compares to the typical 35 W xenon HID lamp available today, which provides twice the light but requires half the power of a standard halogen headlamp.

4. An alternative energy-efficient technology scenario (denoted "SEC+EET") that applies the same technology assumptions as in the third scenario above and the same elevated road-safety provisions as introduced in the SEC scenario.

Under the REF scenario, global lighting energy consumption for road vehicles is projected to increase by 10% in 2010 and 20% in 2020 compared to 2002. This is despite the anticipated limited progress in vehicle-lighting efficiency. Fuel consumption for lighting reaches 61 billion litres of petroleum-equivalent in 2010 and some 67 billion litres in 2020 (Figure 6.20). In 2002 vehicle lighting-related emissions (including the associated upstream energy-industry transformation emissions) were nearly 140 million tonnes (Mt) of CO_2, which is equal to the total greenhouse gas emissions of Belgium. Under the REF scenario this figure rises to nearly 155 Mt of CO_2 in 2010 and 170 Mt of CO_2 in 2020.

The SEC scenario results in much higher consumption, namely 70 billion litres of petroleum-equivalent (+15%) in 2010 at a time when the regulation for daytime use of dipped beams would be half implemented, and 91 billion litres (+36%) in 2020, when it is fully implemented. This results in incremental CO_2 emissions of 20 Mt of CO_2 in 2010 and 75 Mt of CO_2 in 2020 compared with the REF scenario.

Implementing energy-efficient technologies reduces energy consumption and CO_2 emissions dramatically. Under the REF+EET scenario, 27% less energy is consumed in 2010 and 70% less in 2020 compared with the REF scenario, while under the SEC+EET scenario 34% less energy is consumed in 2010 and 73% less in 2020 compared with the SEC scenario.

In 2020 the reduction in greenhouse gas emissions is 120 Mt of CO_2 for the REF+EET scenario compared with the REF scenario, and 165 Mt of CO_2 for the SEC+EET scenario compared with the SEC scenario.

In terms of policy trade-offs, implementing energy-efficient lighting technologies – namely, LED and xenon HID technologies and making daytime-running lights mandatory in new cars – would more than offset the additional energy use required from making the daytime use of dipped headlights obligatory. In fact, as early as 2010 both the consumption of fuel and CO_2 emissions in the SEC+EET scenario are much lower (–25%) than in the REF scenario.

Figure 6.20 **World vehicle lighting-related fuel use under four scenarios**

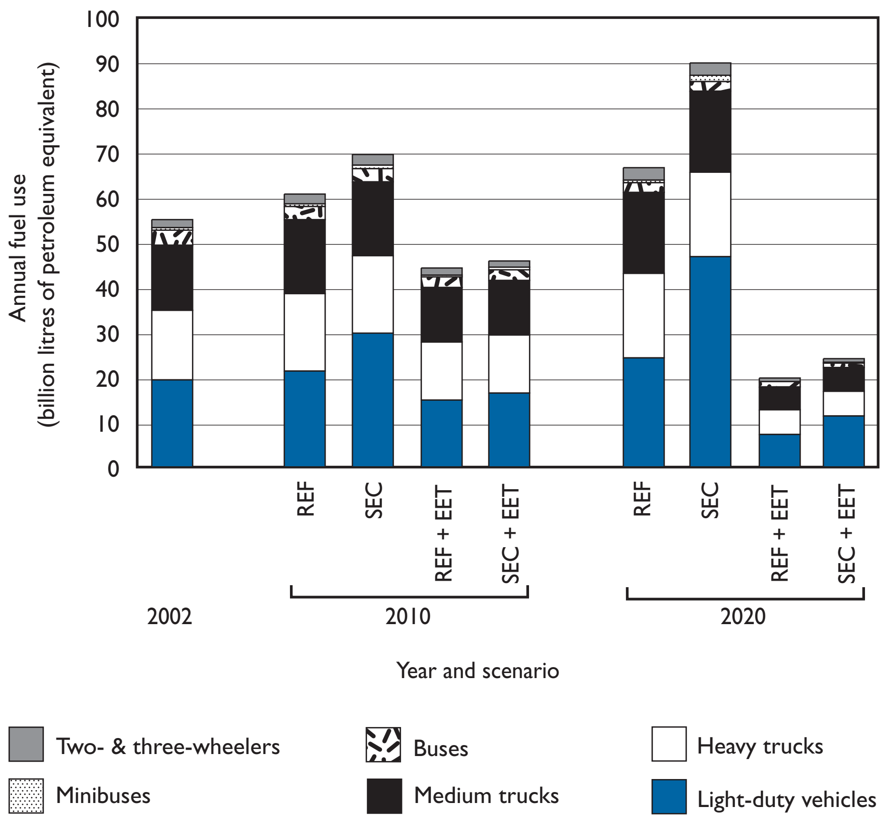
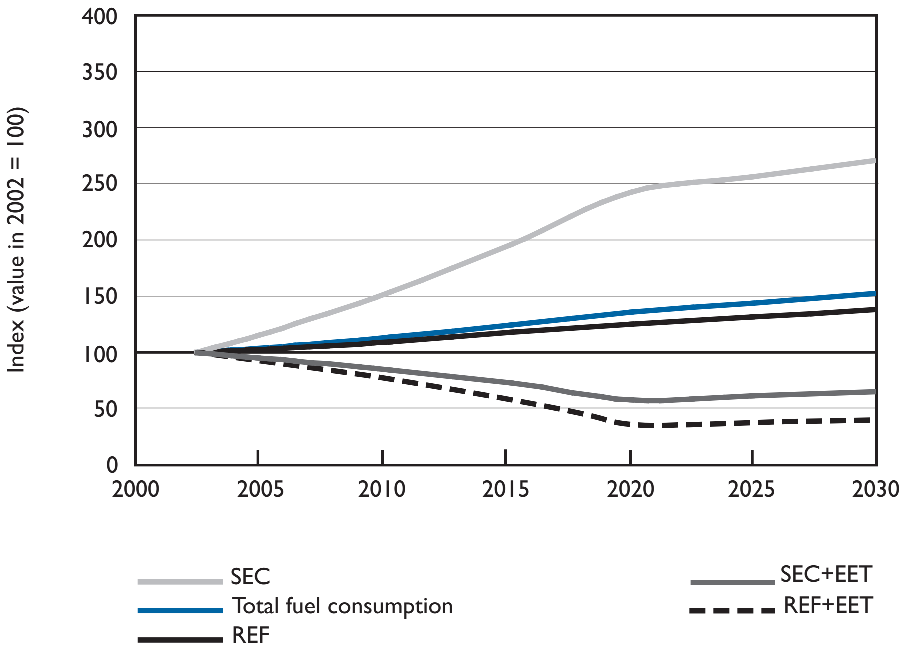


Figure 6.21 shows the relative changes in vehicle-lighting energy consumption under the four scenarios and contrasts them with the projected trends in light-duty vehicle traffic and fuel use. Lighting-related fuel use in the REF scenario rises steadily (+25% in 2020) but at a slower rate than both total world light-duty vehicle traffic (+50% in 2020) and total light-duty vehicle fuel use (+35% in 2020). This indicates that energy-efficiency improvements in light-duty vehicle lighting are projected to occur more rapidly than the improvements in overall light-duty vehicle fuel economy projected in the *World Energy Outlook 2004* Reference Scenario (OECD/IEA, 2004).

Figure 6.21 **Relative trends in world light-duty vehicle lighting-related fuel use under four scenarios**



The SEC scenario is characterised by a much higher pace of growth in lighting fuel use for light-duty vehicles. In 2010, with the assumed introduction of mandatory daytime headlamp use, there is a 50% increase in vehicle-lighting fuel use, compared to about 10% under the REF scenario. In 2020, fuel consumption is forecast to be 140% higher once global adoption of daytime lights is fully implemented.

In contrast, lighting-related fuel consumption is not so different between the two energy-efficient technology scenarios (REF+EET and SEC+EET). In both cases lighting-related fuel consumption is not only much lower than in the REF and SEC scenarios (–70% and –53%, respectively), but is also lower than in 2002 (–62% and –41%, respectively). In the SEC+EET scenario, lighting fuel use for light-duty vehicles around the world is less than one-quarter of what it would be in the SEC scenario. This is not only because of the higher performance of the lighting sources used, but also because of the use of daytime-running lights instead of mandatory use of standard dipped beams.

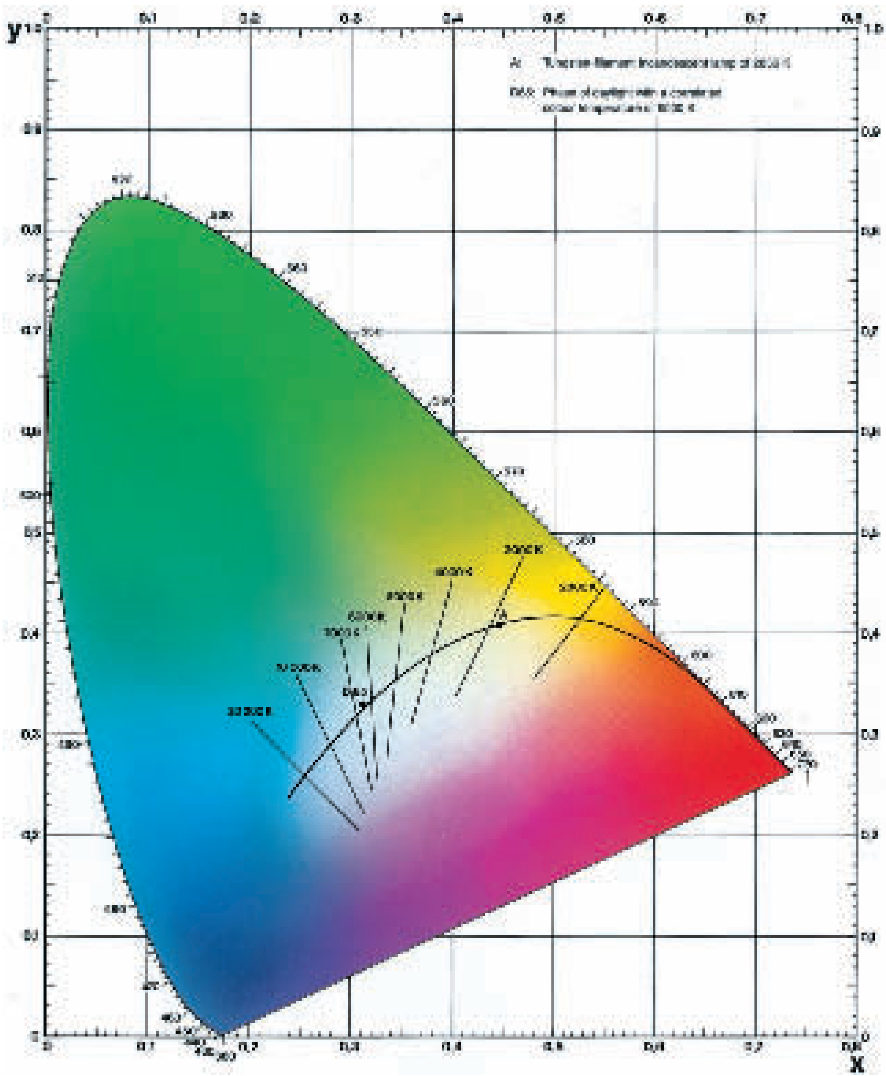
CONCLUSIONS

The scenarios presented draw contrasted perspectives for the short- and medium-term future of road vehicle exterior-lighting fuel use. These are not cost-optimised scenarios and the higher-efficiency lighting choices for vehicles have more ambiguous cost performance than is the case for efficient grid-based lighting technologies. However, provisional life-cycle cost analyses indicate that efficient lighting technologies currently under development are likely to have acceptable cost performance – at least for a large number of the vehicle-lighting applications – and yield major energy savings.

Of course, none of these scenarios can pretend to represent an exact picture of the future – none of them take marketing or economic considerations into account. Furthermore, road-safety policy issues can have an overwhelming impact on lighting-related fuel consumption, and it is of course impossible to foresee which countries will decide to move to mandatory lighting use during the daytime. It is probable that some will, but it is not clear which and decisions for large countries or regions could change the picture dramatically. It is also probable that energy-efficient and cost-effective technologies will be underemployed in relation to their cost-effective potential because of market barriers of different types (*e.g.* lack of consumer awareness and information, insufficient investment in new product development, products not being available on the market, inconsistent decision-making regarding investments and running costs, etc.). This has happened in the past and may do so here too, unless, for example, manufacturers take advantage of xenon HID and LED technologies for marketing-differentiation purposes rather than only to distinguish high-end models.

Nevertheless, this analysis suggests that through the application of efficient lighting technology, a very large amount of fuel could be saved: up to 1.2 million barrels per day in 2020, which is the difference in fuel consumption between the SEC and SEC+EET scenarios. By comparison, IEA action during the Katrina hurricane in 2005 involved the release of 2 million barrels per day over a 60-day period and has been acknowledged as a very efficient measure to prevent additional increases in oil prices in a situation that was already tight. Nonetheless, full realisation of the vehicle-lighting energy-efficiency potential identified in the REF+EET and SEC+EET scenarios would clearly require new public policies. Many options are available, ranging from awareness campaigns, voluntary agreements and incentives, to direct regulation and mandatory standards. Furthermore, the widespread application of efficient vehicle-lighting technology is likely to yield such efficiency benefits that the increased energy consumption associated with a move toward more stringent road-safety regulations regarding daytime vehicle lighting would be more than offset provided the design of such regulations properly stipulates a requirement for dedicated daytime-running lights for new vehicles.

Plate 3.3 CIE chromaticity diagram



Source: Courtesy of Philips Lighting.
Abbreviation: CIE = Commission Internationale de l'Éclairage (International Lighting Committee).

Plate 5.2 The EU household lamp label

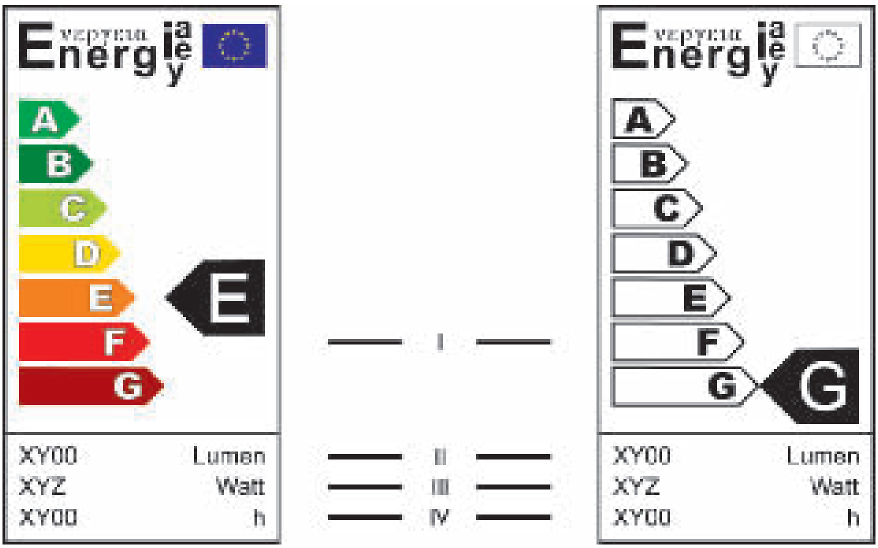


Plate 5.6 The Japanese energy label

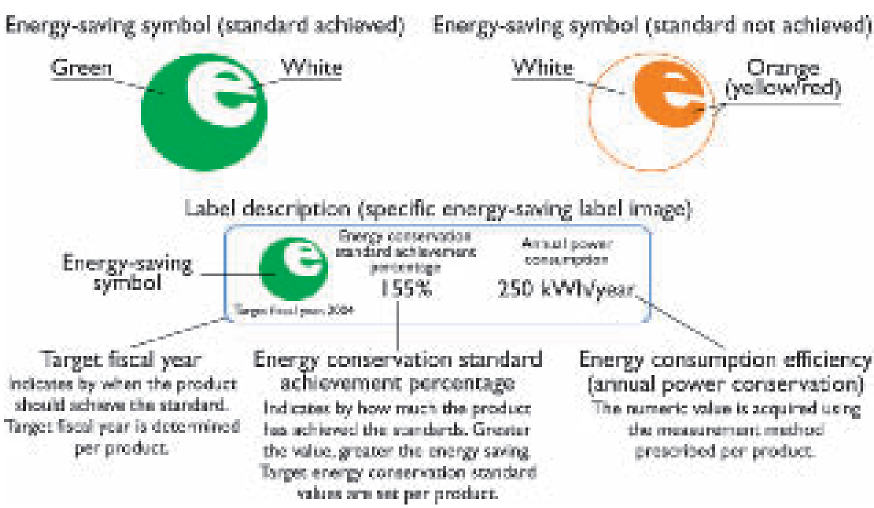


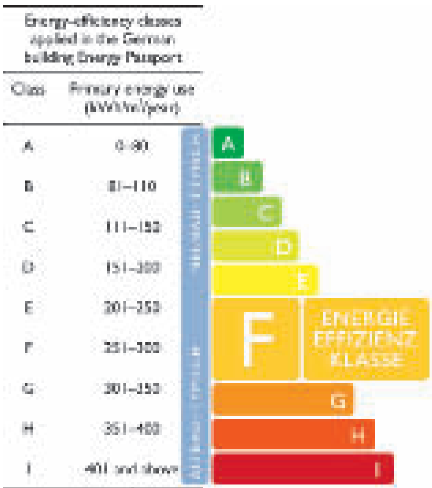
Plate 5.7 **The Korean mandatory energy label**

Plate 5.8 **Korea's Energy Boy certification label**

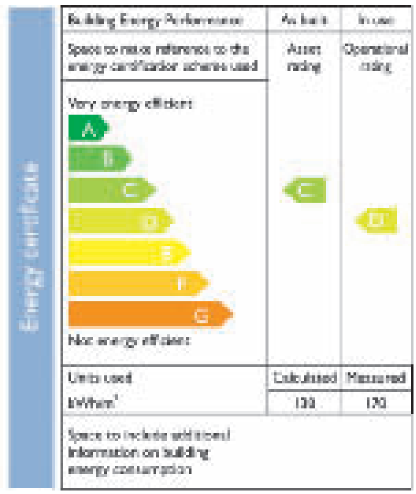
Plate 5.9 **The ENERGY STAR endorsement label**

Plate 5.12 **The Thai energy label**

Plate 5.14 Germany's building Energy Passport and a notional dual-rating building energy certificate



Energy-efficiency classes applied in the German building Energy Passport.



Concept for a dual-asset and operational-based building energy certificate.

Source: Dena, 2006 (left); CEN, pr EN 15217 (right).

O'LED WHERE ART THOU? EMERGING SOLID-STATE LIGHTING TECHNOLOGIES AND OPPORTUNITIES

Key messages

- The efficacy of LEDs has been improving rapidly and has doubled roughly every two years since the 1960s.
- Commercially available LEDs now have higher efficacy levels than incandescent and halogen lighting and are beginning to rival the efficacy levels of fluorescent sources.
- LEDs already offer important cost (over their lifetime) and energy-efficiency advantages for some niche lighting markets and, in particular, for exit signs, traffic signals, computer monitors, LCD televisions, mobile phone displays, commercial signage, some vehicle lighting and festive lights (e.g. Christmas lights). The wholesale use of LEDs in these applications would save up to a 100 TWh of electricity globally compared with current practice.
- LEDs enjoy a very long lifetime and high durability, which makes them competitive for applications with high maintenance costs, but in most general illumination applications they are still (as of the end of 2005) too costly to be competitive.
- If jointly established US government and industry targets are attained, it is projected that solid-state lighting could decrease US lighting energy consumption by 29% by 2025.
- Newly developed handheld solar-charged solid-state lighting devices can provide affordable reading lights for off-grid households that are currently reliant on inefficient fuel-based lighting.
- Government has an important role to play in supporting the development of common performance measurement standards and stimulating RD&D for solid-state lighting.

THE STATE OF THE ART

Solid-state lighting (SSL) in the form of light-emitting diodes (LEDs) was first applied commercially in the 1960s, but only in recent years has it matured sufficiently that people are now considering it as a potentially serious contender for general lighting applications. The light output of early LED devices was very low and the efficacy extremely poor; however, in the intervening four decades LED efficacy has been doubling every two years and in recent years surpassed that of incandescent light sources. Furthermore, the US DOE and manufacturers of SSL devices have set a target of 160 lumens/watt (lm/W) by 2015, which would be more than ten times as efficient as incandescent lamps and two and a half times more than compact fluorescent lamps (CFLs). Not since fluorescent lighting was first popularised in the 1940s, giving rise to what the lighting industry referred to as the "age of abundance" because of the huge increase in lighting it stimulated, has there been so much excitement about a new lighting technology. But will SSL live up to expectations, and what are the implications for lighting energy consumption if it does? Are we on the edge of a new age of abundance where extra efficiency gains allow another explosion in artificial-lighting levels, or will highly efficient SSL hale a new "age of economy" where the total amount of energy used to provide lighting will finally decline?

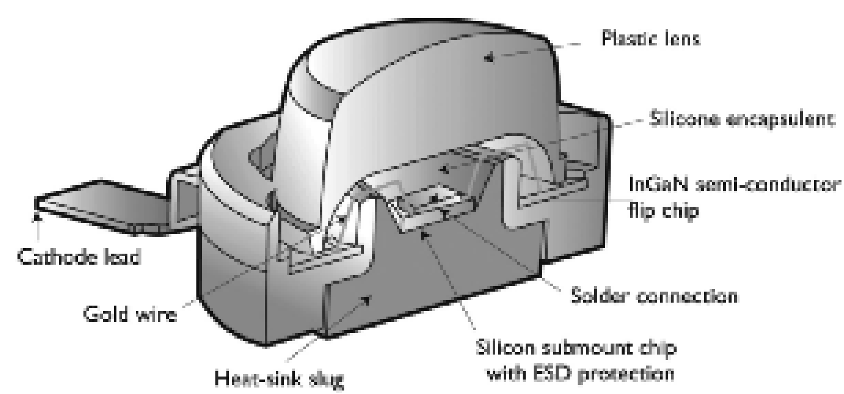
This chapter reports on the state of the technology and its potential and examines the issues that may determine whether SSL will herald a new revolution in lighting.

Physical principles and performance characteristics

Physical principles and types of LED

LEDs are the primary SSL technology (Figure 7.1). Unlike computer chips, which are based on doped silicon, LED semi-conductors are crystals comprised of combinations of typically two or three inorganic elements, such as gallium phosphide (GaP) or gallium indium nitride (GaInN). When an electric field is applied to the material, negatively charged electrons and positively charged holes (positively charged electron vacancies) are produced and exist at different energy levels separated by a "band gap". When these subsequently recombine the released band-gap energy is converted into a photon of light with a frequency, and hence colour, that is equivalent to the band-gap energy. This results in the emission of light in a very narrow spectrum. Because the light is narrow band, SSL is capable of much higher light-emission efficiencies than are incandescent light sources. By contrast, light from LEDs is monochromatic, which means that intermediate processing is needed if white light is to be produced.

Figure 7.1 **Composition of a modern LED**



Source: Courtesy of Lumileds Lighting LLC.
Abbreviations: ESD = electrostatic discharge; LED = light-emitting diode.

The history of SSL

Electrically stimulated light emission from inorganic semi-conductors was first witnessed in 1907 by Henry Joseph Round, who produced yellow light from silicon carbide. Unfortunately, research was discontinued because the light yields were extremely low, and it was not until 1962 that a team from General Electric demonstrated the first LED. Six years later LEDs were first commercialised in the form of gallium arsenide phosphide (GaAsP) chips used as red-light indicator lamps and electronic displays by Monsanto and Hewlett-Packard, respectively. Further advances arose with the development of new combinations of materials. Gallium aluminium arsenate phosphide (GaAlAsP) enabled the first generation of very bright red, yellow and green LEDs to be produced in the 1980s. A combination of indium gallium aluminium phosphide (InGaAlP) was subsequently used to produce ultra-bright red, orange, yellow and green LEDs. Blue LEDs of an equivalent brightness were developed in the mid-1990s using gallium nitride (GaN), and shortly afterwards high-intensity green and blue indium gallium nitride (InGaN) LEDs were demonstrated.

When LEDs were first introduced as indicator lights in the 1960s they were only available in red, had an efficacy of 0.01 lm/W and emitted tiny levels of light. The efficacy of LEDs has been doubling roughly every two years ever since, following an improvement progression that is known as Haitz's Law. Comparing progress in LED efficacy is not straightforward because smaller LEDs with low light outputs have a higher efficacy than larger, brighter LEDs. Furthermore, LED efficacy depends on the colour of light emitted. In 2005 the efficacy of so-called "large-area" LEDs drawing 350 MA of current and 1 W in power had reached: 16 lm/W for blue LEDs, 53 lm/W for green, 42 lm/W for amber, 42 lm/W for red and 45 lm/W for white. Much higher values of up to 100 lm/W have been achieved for small (20 mA) white LEDs and amber devices (see Box 7.1).

This progress has enabled significant penetration of monochrome coloured lighting applications such as traffic signals and exit signs, but LEDs now dominate several other lighting applications and are making headway in new ones, as described on pp. 448–460. The secret to this and the cause of mounting excitement is the development of increasingly viable white-light emitting diodes (WLEDs).

There are three methods currently deployed to produce WLEDs. Most use GaN or InGaN LEDs to produce blue or ultraviolet light which is subsequently converted into white light by the application of down-shifting phosphors in a manner similar to that of discharge lamps. The blue LED devices use a yellow phosphor to produce a broad emission spectrum centred on yellow that is then mixed with some of the original blue light to produce the white spectrum. In contrast, the ultraviolet-light approach uses a mixture of phosphors to emit light across the visible spectrum. An alternative approach is to use combinations of red, green and blue LEDs in an array and to control their relative intensity to produce the required blended white-light characteristics. Each

Box 7.1 Solid-state lighting performance milestones

- 1968: Indicator lamps with an efficacy of about 0.1 lm/W appear in the first usable LED products: digital displays by Hewlett-Packard.
- Early 1970s: LED displays dominate the market for digital calculators; other display applications for character sizes from 5 to 15 mm emerge.
- Mid-1970s: The physics of LED light generation is well understood, and efficiency improves to 1 lm/W. GaAsP (gallium arsenic phosphide) and GaP devices provide colours ranging from red to yellow-green. A single green GaP LED coupled with light piping illuminates the entire dial plate of the "Princess" telephone.
- Mid-1980s: OLEDs appear; LED applications in automobiles begin, first as indicator lights on the dashboard.
- Early 1990s: The dawn of cool white light, potentially available by combining light from GaAlInP (gallium aluminium indium phosphide, red, orange, and yellow) and GaInN (green and blue) sources. Both materials produce records for LED efficacy by the year 2000: 100 lm/W in the red/orange range, and around 50 lm/W in the green range. The current source of white LED light is blue GaInN light emitters coated with a yellow phosphor.
- Mid-1990s: a new class of organics, polymer OLEDs, is developed. Power LEDs emerge for automobile tail lights. The power increase results from both improved efficiency and higher drive currents.

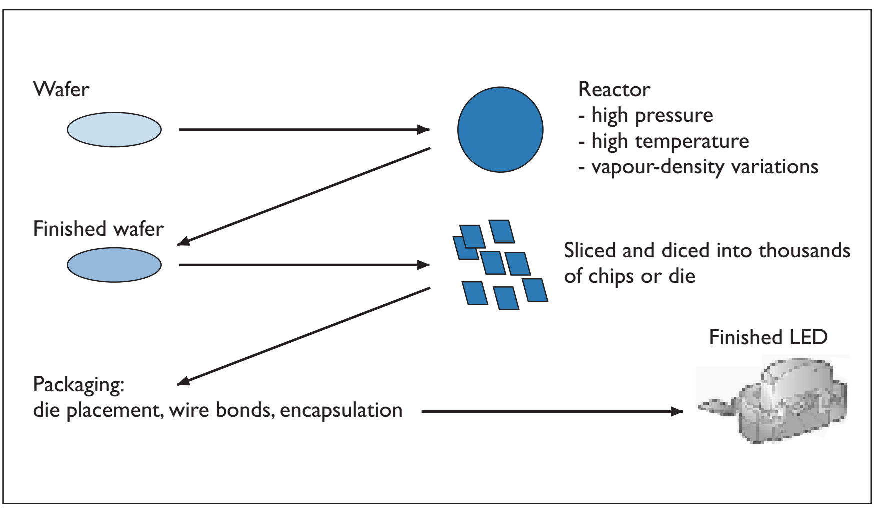
Source: Bergh, 2003.

technique has advantages and drawbacks, but the technologies are still evolving rapidly and it is not yet clear which approach is most promising, although the use of blue LEDs with yellow phosphors is the most common WLED solution currently on the market.

At the time of writing (at the end of 2005) the efficacy of LEDs and WLEDs is superior to that of incandescent light sources, but not as high as that of either fluorescent or high-intensity discharge (HID) sources. The highest light-output levels from a single WLED is 120 lm (equivalent to that of a 12 W incandescent lamp), but higher levels can be attained by using LEDs in arrays. Both efficacy and light-output records continue to be established at a dizzying rate, in approximate accordance with Haitz's Law.

LED manufacturers have forecast that WLEDs, now commercially available at 20 to 40 lm/W, will ultimately meet and exceed the efficacy of other white-light sources, achieving a goal of between 150 and 200 lm/W. In principle, there are no known reasons why this cannot be achieved, and the technology is progressing to overcome barriers that currently limit the performance of these devices; however, the barriers are still very significant and it is not yet clear how viable LEDs will ultimately become as white-light sources. Figure 7.2 illustrates the steps that are followed in manufacturing an LED.

Figure 7.2 **Steps to making an LED**



Source: Courtesy of Lumileds Lighting LLC.
Abbreviation: LED = light-emitting diode.

White light, white heat: current LED performance characteristics

So how does the performance of LEDs and WLEDs compare with conventional light sources and what issues would need to be resolved for them to make inroads into the general illumination market? Efficacy is only one of many important performance characteristics of a light source that determine its viability for any given application. Light output, longevity, light distribution, dimensions, chromaticity, control, stability, environmental impact, durability and cost are all major factors that have to be considered before the full balance sheet can be assessed. In the case of LEDs their current characteristics are summarised against each of these metrics below.

Light output and efficacy

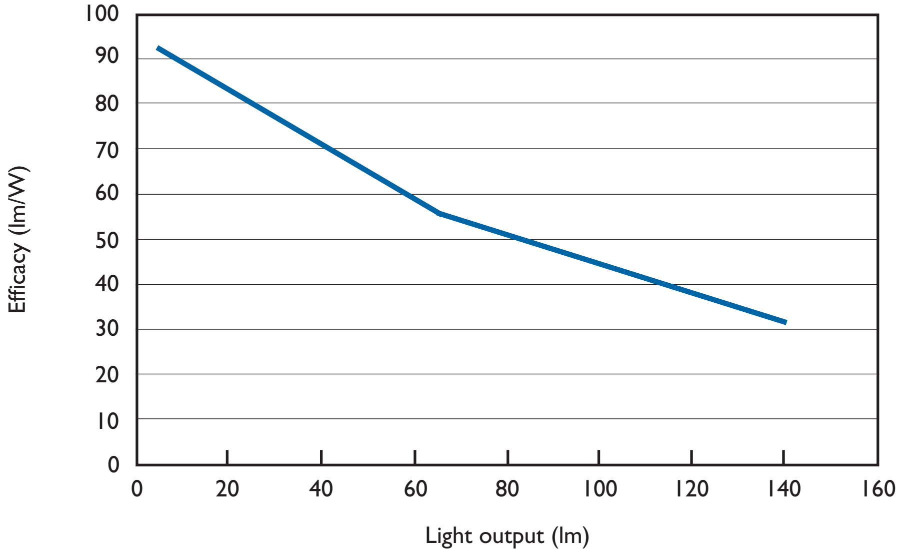
Compared with competing light sources, the light output of individual LEDs is still either very low or low; for example, for WLEDs it varies from 2 to 142 lm. The dimmer LEDs often have better efficacy levels, *e.g.* in October 2004 Cree's "XThin XT-27" 300 µm extra-thin chips had an efficacy of 92 lm/W for an output of 5.8 lm, but their brighter counterparts, the "XB900" (900 mm^2) chips, have an efficacy of 57 or 34 lm/W for a light output of 67 to 142 lm (Figure 7.3). More recently Cree demonstrated its "Xlamp" WLED, which has a reported light output of 86 lm at an efficacy of 70 lm/W (Figure 7.4).

In principle, ten of these devices would produce the same amount of light as a standard 60 W incandescent lamp for close to 12 W, which is roughly equivalent to the performance of a good CFL. At the smaller scale Cree have demonstrated 5 mm diameter WLEDs with an efficacy of 100 lm/W, although the light output is very small. In early 2005 Citizen Electronics demonstrated a WLED device with a light output of 245 lm and an efficacy of 70 lm/W. This device comes in a package containing twenty-four 0.3 mm^2 standard-sized chips with overall dimensions of 40 x 4 x 0.75 mm.

Thermal management

The heat generated by all light sources needs to be managed to avoid fire risk and damage to the luminaire. In the case of conventional incandescent or fluorescent lamps the heat produced is emitted as infrared light, or is

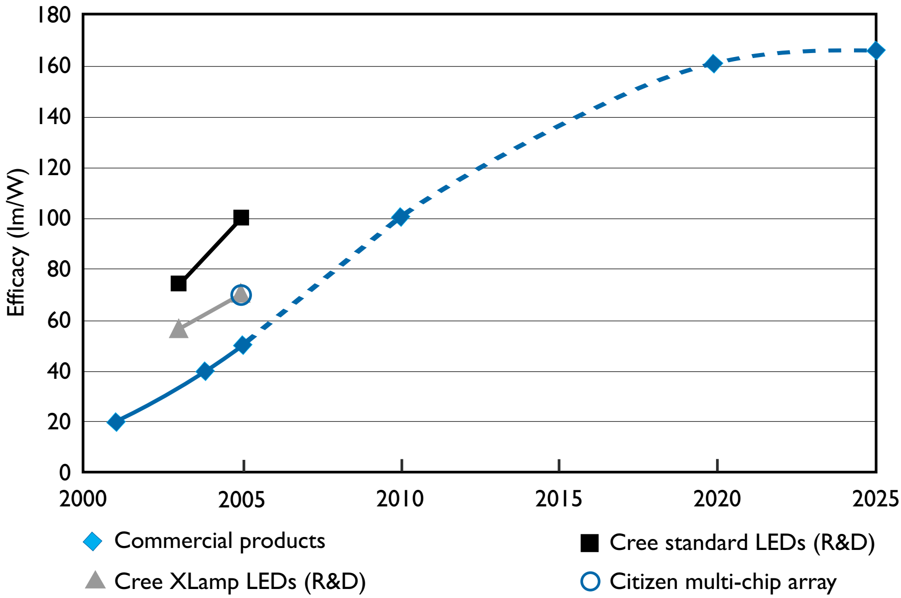
Figure 7.3 **Reported light output vs. efficacy for Cree WLEDs circa October 2004**



Source: Whitaker and Stevenson, 2004.
Abbreviation: WLED = white-light emitting diode.

produced in or conducted to the bulb wall. This means that the heat is distributed away from the light emitter and hence can be managed. With current average commercial efficacy levels of 25 to 35 lm/W for WLEDs, approximately 25% to 35% of the input energy is converted to light, while the rest creates heat. This is from five to seven times better than achieved by an incandescent lamp and furthermore the light emitted is near to the visible part of the spectrum and hence contains very little infrared heat. As a result, illuminated objects are not significantly heated by LED light and in principle the optical surface of the LED should be cool enough to touch. This enhances safety and convenience for the end-user. However, the remaining 65% to 75% of energy drawn by the LED produces heat within the semi-conductor and, unlike for fluorescent or incandescent sources, this heat is concentrated in the emitting device and cannot be easily conducted, radiated or convected away through a bulb wall. If the heat is not dissipated the semi-conductor will overheat. In the worst case

Figure 7.4 **Recent historic and projected future efficacy improvements for WLEDs circa October 2005**



Source: LEDs Magazine, 2005a (reproduced with permission).
Abbreviation: LED = light-emitting diode; WLED = white-light emitting diode.

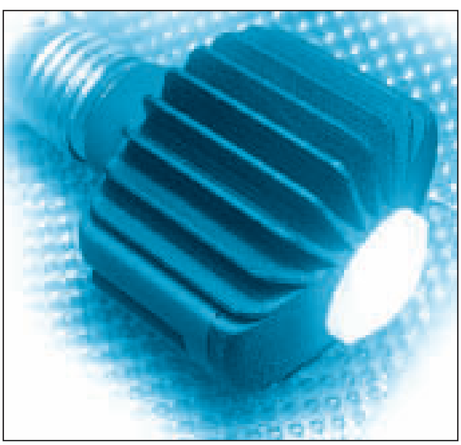
this will cause the device to fail, but more commonly it would shift emission wavelength, lower lumen output and reduce the product's lifetime. As a result, great attention is needed in the design and mounting of LED chips so that this heat can be safely dispersed via conduction through the LED base: one design solution is shown in Figure 7.5.

Clearly the degree of heat dissipation required increases as total light output rises, but declines with rising system efficacy. Accordingly the size of heat exchanger required will diminish as LED efficiency improves; however, at present general illumination WLED devices require substantial heat exchangers, and this has important implications for the cost, size and stability of the device. In some applications there is an argument for using many smaller LEDs with higher efficiency rather than a small number of high-power devices that generate more heat, although the latter produce more light per unit area.

Longevity

An undoubted major advantage of LEDs is their very long lifespan, which can be in excess of 50 000 hours, although there is more uncertainty about how long they will work well. LEDs will last for a very long time without a catastrophic failure because there is no filament or cathode to burn out. Instead of suddenly ceasing to emit light their performance will gradually degrade over time. High-quality LEDs are predicted to deliver more than 60% of the initial light intensity after 50 000 continuous operating hours and to continue working for up to 100 000 hours (some 100 times longer than a standard incandescent lamp). With such long operational lifespans it is impractical to measure the rated life of LEDs in the same way as for conventional lamps. Rather, the few tests that have been done have focused on the rate of performance degradation over time (Figure 7.6). Not surprisingly, LED lifetime and performance degradation is sensitive to heat and this is a key reason why such efforts must be made to remove heat from the device.

Figure 7.5 **LED white-light lamp* with built-in heat exchanger**

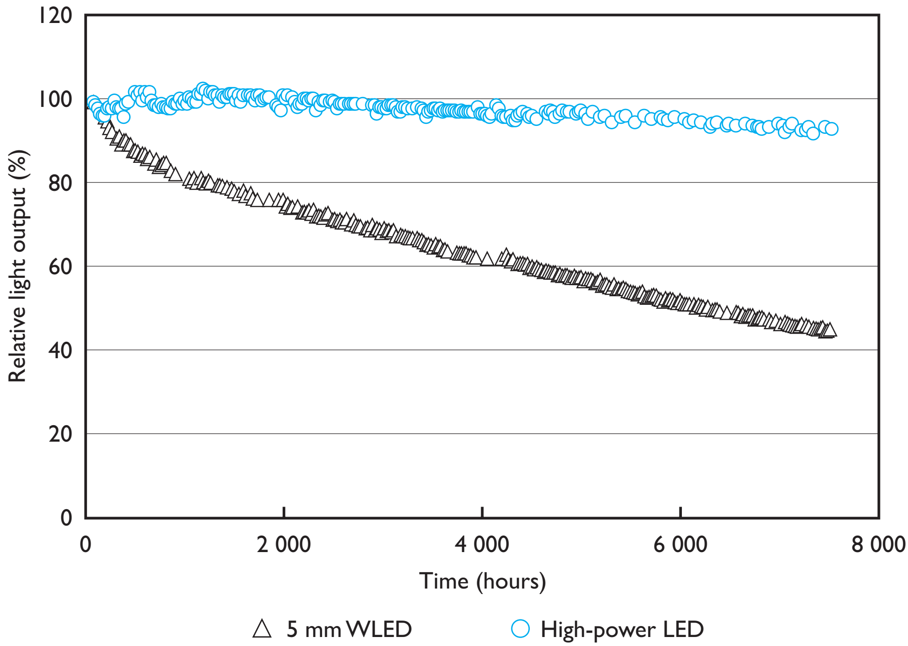


Source: LEDs Magazine, 2005a (reproduced with permission).
* Marl's Aztec LED Light Engine, which contains a 5 W Lamina source.
Abbreviation: LED = light-emitting diode.

Light distribution

LEDs are effectively point sources of light – this appears to be a bane or a boon depending on the lighting application. On the positive side, LEDs produce luminosity via a direct electricity to light conversion process that gives a strong forward directional orientation to the emitted photons and enables them to be precisely targeted to where they are required. The LED housing includes a reflector cup and an epoxy lens, the characteristics of which determine the photometry of the LED source and allow LEDs to deliver light to any specified viewing angle up to 180°. Conventional light sources emit light in all directions and require

Figure 7.6 **Light output over operating life of LEDs**



Source: LRC, 2002 (adapted, and reproduced with permission).
Abbreviations: LED = light-emitting diode; WLED = white-light emitting diode.

redirection with secondary optics, or reflectors, which results in lumen leakage and energy waste. In some applications, such as vehicle headlamps and displays on handheld equipment such as mobile phones and personal digital assistants (PDAs), etc., the ability to tightly control light distribution can avoid glare or unwanted stray light. However, in some regards this strong directional aspect of LEDs may be a limitation. Closely focused directionality is suitable for task lighting but may be less well suited to general illumination, for which a more uniform illumination on all surfaces is required. Furthermore, strongly directional light sources are more prone to glare and problems of excessive contrast for general illumination purposes.

For applications other than general illumination, transparent (plastic or glass) waveguides can be used to distribute concentrated LED light to the required location. This is done for backlighting of liquid crystal display (LCD) screens for telephones, computer monitors, televisions and PDAs, for example.

Dimensions

LEDs can be embedded within structural elements and objects, housed in flat panels set in tiny recesses or mounted in thin tracks. This is possible because each LED is extremely compact, giving them a high configuration versatility that allows them to be set in different patterns according to a designer's wishes. LEDs may be assembled into larger units of varying size and shape that in principle allow almost any part of a building or its furnishing to become a light fixture. In practice, however, this versatility is constrained by the amount of light required and the size of the heat sink and power supply needed. If light levels can be low designers can already employ LEDs in compact or distributed light fixtures in manners that are not possible or practicable with conventional light sources. However, if higher illumination levels are needed, the number of LEDs required multiplies and the size of the overall device escalates accordingly.

Chromaticity

LEDs have some significant chromatic advantages and a major weakness compared with traditional electric lamps. An obvious advantage is the broad choice of colours they provide without recourse to a filter, which would lower system efficacy. LEDs are currently available in red, orange, amber, green, yellow, cyan, violet, blue and white, and there are also bicolour, tricolour and red/green/blue (RGB) LEDs. This broad spectrum of pure colours allows LEDs to be integrated into multicolour-producing packages and gives lighting designers new options for coloured illumination. The use of RGB LED combinations, which provide users with the largest choice of colours, is made possible because the light intensity of each individual LED can be uniquely controlled. This allows millions of colours to be created without requiring diffusing filters that other light sources need to give a homogeneous appearance to the light source.

But what are the chromatic characteristics of WLEDs? Blue or ultraviolet-based WLEDs can produce correlated colour temperatures (CCTs) of 2 700 to 6 500 K and have colour rendering indexes (CRIs) of 70 to 85. These CRI ranges are comparable to those produced by CFLs, while the CCT ranges are broader than for incandescent lamps and equivalent to those achievable with fluorescent lamps. More critically, however, the chromaticity coordinates from any LED batch are relatively unpredictable, leading to two consequences. First, there needs to be a post-processing of LED chips to sort them into matched-colour "bins", which is not only costly but also leads to wastage of WLEDs that are in less-desired chromatic categories. Failure to bin LEDs into matched chromatic categories produces an unpleasing disjointed illumination because the human eye is very sensitive to chromatic differences. This is less important for multicoloured architectural illumination than it is for general-purpose white-light illumination, but it is a significant obstacle for current generations of WLED. Second, whatever the acceptability of the CCT and however well colour-matched a batch of WLEDs may be, it is relatively difficult to produce them with *x,y* chromaticity coordinates positioned on the black body locus that corresponds to the diurnal and seasonal progression of natural daylight. Almost all other light sources are designed to emit light that is on this locus at some point in order to produce light that looks "natural".

Operation, control and stability

LEDs offer many advantages for control and operation. They produce an instant light with power that is directly proportional to the strength of electric field applied across the LED, so problems that are common with other light sources are avoided, such that there is no warm-up time or flicker, there is full linear dimmability (0% to 100%) with no loss of efficacy or any colour shifts (changes in CRI or CCT), and there is no reduction in service life. The instant-on characteristic of LEDs makes them well suited to security lighting, emergency lighting and signalling. This feature combined with the ready ability to individually control each LED in an array via a microcontroller allows mixed dynamic lighting control such as is utilised by RGB technology using light-mixing consoles. This kind of controllability allows an enormous variety of lighting effects to be produced, including dynamic and multicoloured architectural and mood lighting, water-feature illumination, entertainment lighting, signage, etc. LEDs also function very well in cold conditions and will function happily at temperatures as low as –40 °C and thus are extremely well suited to many outdoor applications. However, LEDs may be less well suited some applications as their efficacy diminishes at higher temperatures, when adequate thermal management becomes critical.

Another important feature of LEDs is that they are low-voltage direct-current (DC) light sources. This makes them easy to integrate into mainstream electronics systems and products that are powered by a DC power supply but require voltage conversion for mains-based alternating-current (AC) applications. While single LEDs draw 0.5 to 5 W of power they require an electromotive force (EMF) of 2 to 4 V DC; however, this increases proportionally with the number of LEDs connected in series, so when an array of LEDs is formed, a higher voltage is required. For mains-powered applications, standard DC LEDs use an AC/DC voltage converter that produces stable output even if there are fluctuations in the input power. These "drivers" may be constant-voltage types (*e.g.* 10 V, 12 V) or constant-current types (*e.g.* 350 mA, 700 mA) and are able to power LED arrays or single LEDs depending on the application requirements. More recently, Korean manufacturers have produced AC-powered LEDs (SSI, 2005), which eliminate the cost of a power supply and are claimed to use 80% less power than equivalent incandescent lighting and last for 50 000 to 100 000 hours; however, AC LEDs are currently not as widely used as the DC variety.

Durability

Compared to traditional light sources, LEDs are rugged and shock-resistant, which makes them well suited for transportation applications such as cars, trains, ships and aircraft. It also means they can more readily be positioned in places where safety concerns may discriminate against conventional light sources, such as locations that are in reach of children.

Environmental suitability and health impacts

LEDs have some important environmental advantages compared to conventional light sources. They are made from non-toxic materials and are recyclable. Fluorescent and some HID sources contain mercury and can emit some ultraviolet light, which can damage materials, fade colours and cause tissue damage. Furthermore, in principle it is possible to programme combinations of LEDs to mimic the spectral shifts of daylight without containing harmful ultraviolet light, and this has given LEDs a role in display lighting in museums and galleries where light quality and preservation of artefacts is important. In the longer term the lighting community has speculated whether LEDs may allow the first viable artificial-light sources that can mimic natural daylight for general illumination purposes, with associated benefits such as the prevention of seasonal affective disorder (SAD) and health and productivity benefits through better matching of artificial light to circadian rhythms.

Cost

Whatever the current technical strengths and limitations of LEDs, the final determinant of their suitability for any given application is their cost. For most applications this is currently far too high, although they have become economically viable for a growing range of important niche markets. The first costs of LEDs are very high relative to standard illumination devices. If a typical incandescent light bulb costs about USD 1 per kilolumen, standard WLEDs currently cost about 100 times as much. If the cost of ownership is considered, LEDs begin to look much more attractive. Their very long lifetimes would allow them to almost compete with incandescent sources on bulb costs alone were a zero-rated discount rate applied, and if the cost of bulb-replacement labour is included they become even more attractive. When their increasingly superior efficacy and lower operating costs are taken into account they begin to look more viable still, although as experience with CFLs has shown the reality of general illumination markets (especially for residential applications, where incandescent lamps dominate) is that product market penetration is highly sensitive to first cost and much less so to ongoing costs. It is thought that costs need to come down by at least an order of magnitude if WLEDs are to become competitive for general lighting purposes; ideally, WLEDs would attain a cost of USD 2 per kilolumen or lower.

Some of the high first cost of WLEDs is associated with their relative novelty and ongoing rapid development. Despite the long history of LEDs it is only in the last few years that they have begun to reach a performance level where they might be suitable for general illumination applications; expenditure on R&D is still high, product market life short (because of rapid obsolescence) and production costs high. Costs should fall progressively as the technology matures, production is standardised and scaled up, and as manufacturers improve their production facilities.

Although LEDs are not yet competitive for general indoor illumination purposes they are already the best option for a number of important niche markets, where their characteristics of long life, durability, compactness and chromatic versatility give them a competitive edge. These applications are highlighted in the next section.

SSL applications

LEDs currently have high market shares in compact portable DC lighting applications, such as backlighting of LCD displays in mobile phones, PDAs and personal music players, coloured-light applications such as traffic signals, exit signs, other signage and architectural lighting, and in high maintenance cost applications such as the illumination of monuments and bridges. Increasingly, they are also entering the automobile and large LCD screen markets. In the coloured-light applications LEDs can produce the required colour without efficacy loss from colour filtering and can produce a wide range of dynamic colours, instantaneously, reliably and efficiently. In the mobile electronics market, LEDs benefit from being more compact and efficient than the preceding electroluminescent technologies, while in the external signage and difficult-maintenance applications they benefit from high durability, reliability and long life, which lowers their maintenance costs and gives them an overall service-cost advantage compared to alternatives. In this section some of the main current and potential near term applications are reviewed and assessed from an energy-efficiency perspective.

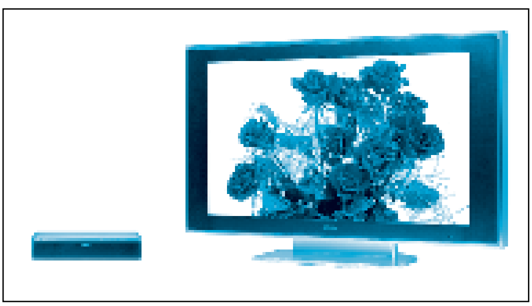
Backlighting of mobile electronic devices

In recent years WLEDs based on blue LEDs using a yellow phosphor have completely taken over certain popular backlighting applications found in mobile consumer electronics, including mobile phone keypads, PDAs and digital cameras. Prior to the arrival of WLEDs these applications were supplied by electroluminescent backlight, but WLEDs have much superior performance, cost and durability qualities and so have rapidly dominated these applications. Mobile phones now comprise the single largest market for LEDs (see p. 460). In 2004 about 670 million mobile phone handsets were shipped globally, of which 75% had full-colour displays using WLED backlighting. Many also had secondary displays and there is a rapidly growing number of camera phones, many of which use WLED flashes.

Backlighting of LCDs for televisions and computers

LCDs are used in a variety of applications but are making increasing inroads into the computer monitor market and the flat-screen television market (Figure 7.7). Traditionally LCD screens have been backlit with a cold-cathode fluorescent lamp (CCFL), which is a very thin fluorescent tube (see p. 123), but LEDs offer some important advantages compared with CCFLs. First, the colour range of conventional LCD monitors is not as good as that of cathode ray tube (CRT) screens and this has held back their development; however, backlighting with LEDs offers an extremely vivid array of colours. Second, less power is required to backlight with LEDs than with CCFLs, even if the efficacy levels of the light source are not yet as good. The reason for this is that the use of LEDs does not require light to be directed edgeways into a transparent medium, which incurs substantial transmission losses; rather, the light is directed forward from the LED into the LCD screen, with far lower losses. Third, in some markets (most notably the European Union as a result of the Waste Electrical and Electronic Equipment Directive [WEEE, 2002]) manufacturers are required to recycle old products and dispose of them safely. If the product contains mercury, as do CCFLs, the cost of disposal is much higher; this gives a competitive edge to LEDs. The only disadvantage for LEDs is their higher cost, which has been 2 to 3 times that of CCFLs.

Figure 7.7 LED backlit television screen



Source: Hough, 2005 (reproduced with permission).
Abbreviations: LCD = liquid crystal display; LED = light-emitting diode.

The potential uptake of LEDs in LCD television screens has been analysed within the UK Market Transformation Programme (Graves *et al.*, 2005). It is estimated that if LEDs attain their future efficacy targets (see pp. 461–465) they will save an average of 23 W per LCD television. If a television is operated for an average of 4.5 hours a day this amounts to 38 kWh of savings per television each year. Global television sales have been in excess of 150 million units per annum over the last two years, which implies an eventual global stock of above 1.5 billion televisions if sales continue at this level and if each television is kept for an average of ten years before being disposed of. LCD-based flat-screen televisions had over 10% of the global television market by volume in 2005 (Display, 2005) and are likely to dominate all except the large-size classes in the future as production volumes increase, costs decline and technology standards improve. Thus LED backlighting has the potential to save approximately 35 TWh in global television electricity consumption by 2030 if the LED performance targets on pp. 461–465 are attained.[1] In fact in the longer run larger televisions are more likely to use organic LEDs (OLEDs) if this technology matures (see pp. 473–474).

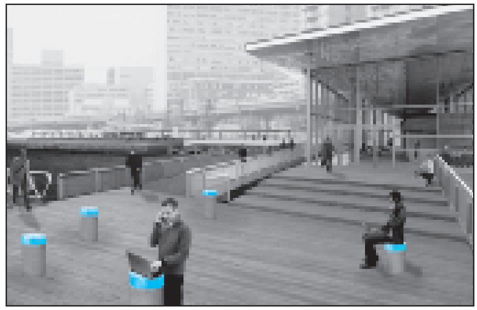
There is an even larger potential market for LEDs in backlighting of computer monitor screens. Computer monitor screens already exclusively use LCD technology in laptop computers and this is becoming increasingly popular for standalone computer monitors too. As with televisions, conventional LCD computer monitors are backlit by CCFLs, and LEDs potentially have exactly the same advantages for this purpose as they do for television screens. It is estimated that on average using an LCD computer monitor backlit with high-efficacy LEDs will save 7 W per screen compared to traditional CCFLs, and much more compared to CRT technology. The global computer market is already greater than 200 million units a year, so the potential energy savings from LED backlit screens is significant.

Architectural and mood lighting

The colour, resilience and easy control of LEDs is making them popular for the growing architectural and mood-lighting applications. LEDs are increasingly being used for exterior accent lighting of buildings and structures for aesthetic purposes. A growing number of projects have been installed to illuminate bridges, building façades and outlines, shop windows, and monuments, fountains and lakes with coloured light during the night. These sometimes use dynamic lighting displays to change the colour of the illumination. In the case of the Eiffel Tower in Paris, for example, WLEDs are used to provide an efficient and low-cost, spectacular sparkling effect during the evenings, albeit with non-varying colour. LEDs used for architectural purposes can also be solar-powered, as shown in Figure 7.8.

1. Assumes 23 W savings per LCD television backlit with LEDs, 4.5 hours of use per day; and that LCD televisions account for 60% of the global television stock of 1.5 billion units in 2030.

Figure 7.8 **Solar-powered LEDs used as architectural lighting in bollards***

Source: Kennedy, 2005 (reproduced with permission).
* Design by Kennedy and Violich Architecture Ltd for East River Ferry Landings, Manhattan, New York.
Abbreviation: LEDs = light-emitting diodes.

Traffic signals

Globally, traffic signals probably use about 15 TWh of electricity each year, yet traditional systems are very inefficient because they employ low-efficacy incandescent lamps in combination with coloured filters that further reduce efficacy. For example, the red light filter used for the stop light in a traffic signal only allows 10% of the light output to pass, which causes the system efficacy to fall to less than 2 lm/W and requires a high-power lamp to be used (14 W for a 30.5 cm diameter lamp). The use of red LEDs improves the source efficacy several fold and avoids all filter losses, which enables total power to be cut to only 11 W. This saves almost USD 80 per year per lamp in energy costs. Similar efficacy improvements arise from using LEDs for green traffic lights, while using amber LEDs reduces power demand by at least a factor of seven compared with incandescent sources. While the efficacy improvement from the use of commercially available WLEDs compared to incandescent sources has not been as high as in the case of coloured LEDs, in practice their use can save significant amounts of energy because of their point-source characteristics. For example, in the United States incandescent lamps that are used to provide backlighting of white-light "walking man" pedestrian signals can be replaced with low-power WLEDs arranged in an outline formation, which reduces the total power needed for the signal by a factor of 17. In the United States it is estimated that fully LED-based traffic signals only require about 11% of the energy of equivalent conventional incandescent traffic signals. Furthermore, the economics of using LEDs is even more favourable in this application because of the significant savings in lamp replacement and maintenance costs.

Overall, it is estimated that about 30% of US traffic signals had been converted to LEDs by 2002, largely as a result of national market-transformation programmes such as the US Environmental Protection Agency (EPA) and Department of Energy (DOE) ENERGY STAR programme, and the US Consortium for Energy Efficiency (CEE) Energy-Efficient Traffic Signal Initiative. This conversion to LEDs was estimated to be saving 1.48 TWh of final electricity demand in 2003. If all US traffic signals are converted to LEDs the potential savings are estimated to be 4.5 TWh per annum (Navigant, 2003a).

Similar transformations of the traffic-signal market are taking place around the world, although they have often required leadership from informed municipal authorities before they have happened. While LEDs are gaining a large part of the new traffic-signal market, inefficient incandescent lamps are still the prevalent technology in existing installations despite very favourable economics for early replacement with LED-based systems. However, were LED-based systems to replace all existing incandescent systems, the global traffic-signal electricity consumption would probably be cut to around 12 TWh/year. Box 7.2 gives a real example of the benefits of LED-based traffic signals.

Billboards, hoardings and advertising signs

A considerable amount of lighting energy is used for external signage, especially for commercial advertising to announce a business establishment, backlighting of billboards, advertisements, etc. Traditionally, these signs have been illuminated via incandescent, fluorescent and neon lamps usually deployed as backlighting, although occasionally with the lamp forming the sign itself. LED lights have begun to make inroads into this market, especially at the expense of neon lighting, because of their favourable colour, stability, light distribution, size, longevity, durability and efficacy properties. A survey in the United States found that in 2002 almost half of commercial signage companies offered LED-based signage in their product range and that LED signs made up just over 6% of shipments (Navigant, 2003a). Total US shipments of commercial signs were in excess of 1 million units a year, of which about 41% used neon or an equivalent inert gas to provide coloured

Box 7.2 Case study: LEDs in traffic lights in Stockholm

- Like many other cities, Stockholm was aware of the promise of newer, LED-based traffic signal technology. However, Stockholm is among the world's most northerly capitals. In winter, its climate can be ferocious, with temperatures in the –20° C range for weeks at a time. To compound the challenge, Stockholm is a seaport, adding humidity and salt to the factors that any new system has to deal with. Catastrophic failure of any part of the traffic control system in this urban centre of close to one million inhabitants would have serious consequences. Given these conditions, could a reliable LED-based system really save the city money in the long run?

- After six months of *in situ* testing of traffic control systems and signal heads from several manufacturers, the answer was a resounding "Yes"! The potential savings in energy and maintenance were confirmed, as were product reliability claims. Stockholm then completely committed itself to LED-based technologies, with two of the leading manufacturers chosen as principal suppliers. Since the end of 2000 Stockholm has fully converted its traffic control systems to LEDs.

- The result has been a reduction in energy use of around 85%. By exchanging incandescent bulbs in traffic lights for diodes, the energy used was reduced by 5 800 MWh/year, which is far more than was expected (4 200 MWh/year). The average energy used per traffic light sank from 70 W to around 6 W.

Source: CADDET Energy Efficiency, 2002b.

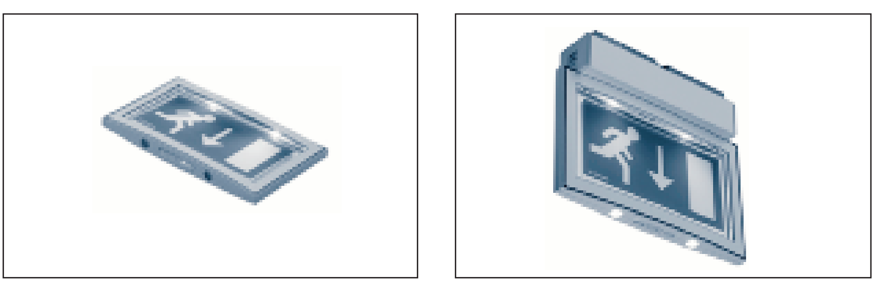
lighting. The same study estimates that switching from neon or equivalent lighting to LEDs will reduce average power consumption by almost two-thirds. The national stock of illuminated commercial signs is estimated to total almost 14 million units, of which about 5.7 million are neon or equivalent. These are operated on average for over 3 200 hours per year and consume more than 10 TWh of electricity. Replacing the neon signs with

LEDs would save about 6.6 TWh per annum. As with traffic signals, standard commercial logic should begin to favour the adoption of LED signage because of its high reliability, low maintenance costs, greater versatility and control, and low energy cost, but there is certainly a knowledge transfer and first-cost barrier to overcome and many markets are likely to make only a slow transition to LED lighting unless actively encouraged.

Exit signs and emergency lighting

Exit signs, especially those using red lettering as found in North America, formed one of the first large illumination applications for LEDs. In OECD countries, exit signs are required by law in all commercial and institutional buildings and must operate continuously. In the United States, for example, there is estimated to be over 33 million continuously illuminated exit signs (Navigant, 2003a) and until recently these were backlit using incandescent or occasionally fluorescent lamps. In 1985, LED-based exit signs became commercially available and, thanks to vigorous market-transformation programmes such as the ENERGY STAR initiative, by 2002 they had succeeded in capturing 80% of the installed market and 91% of sales. An average US incandescent exit sign draws 32 W, compared to 17 W for a CFL-lit sign and 6 W for a sign using LEDs. If these signs were fully lit with incandescent lamps they would use 9.3 TWh per year, compared to 1.7 TWh per year when fully lit by LEDs. In 2002, exit signs in the United States were estimated to be using just 2.6 TWh, which constituted a saving of 6.7 TWh (Navigant, 2003a). Once first cost, maintenance cost and energy costs were taken into account the average cost saving per sign from using LEDs was estimated at USD 315 over a ten-year period.

Figure 7.9 **Common illuminated exit signs***



Source: Courtesy of Van Lien Emergency Lighting.
*The standard wall-mounted type (left) and the recessed ceiling-mounted type (right) are common signs in Europe.

In Europe and many other parts of the world, the savings potential from conversion to LED exit and emergency-egress signs is not as high because the colouring used is green and white and the default light source is generally a relatively efficient CCFL (see p. 123). Nonetheless, LEDs still offer important energy-savings advantages because of their superior light distribution. A great many exit signs hang vertically and show an illuminated figure running toward an illuminated open door that can be viewed from either direction (Figure 7.9).

The illumination is provided by directing light into the edge of a translucent sign; this involves far less light loss when using LEDs compared to an omnidirectional source such as a CCFL. Furthermore, the DC current and low power requirement of LEDs allows a much smaller emergency back-up battery to be used, saving costs and energy.

Vehicle lighting

Vehicle lighting was one of the first markets for LEDs and continues to be one of their largest near-term opportunities. Depending on the application, LEDs offer the potential of higher light output, longer lifetime, lower power consumption, greater styling opportunities and better safety. Against this they are still more costly than traditional vehicle-lighting technologies and have not yet been granted regulatory approval for all vehicle-lighting applications in all jurisdictions.

LEDs first began to be used in cars for centred, high-mounted stop lights (CHMSLs), also known as the "third brake light", and for brake and indicator lights in buses and trucks in the mid-1980s. The early use of LEDs for these roles arose in part from the general advantages they offer and from the more rapid efficacy advances of red LEDs compared with other colours. LEDs have been favoured for these applications because of their long lifetimes, low power demand, instant activation and compact size characteristics. Vehicle lighting is now one of the largest and fastest-growing markets for LEDs (Navigant, 2003a). Some market analysts have predicted that LEDs will soon dominate the rear-lighting applications for cars, including reverse lights and licence-plate illumination, and will increasingly be used in the interior for dome lights, reading lamps and dashboard illumination.

In 2003, 21.5% of new North American vehicles used LEDs in CHMSLs, and this is expected to increase to 55% by 2010. LEDs are also used in rear combination lamps (RCLs); they accounted for only 1% of RCLs in new vehicles in 2001, but they are expected to reach more than 10% by 2010 (Frost & Sullivan, 2004). Despite the advantages of LEDs in terms of safety and maintenance costs for such applications, they are still more costly. For example, LED-based RCLs cost approximately USD 50 in 2003, compared to USD 13.80 for incandescent RCLs.

LED headlamps and other forward-lighting applications

WLEDs are increasingly being considered for forward vehicle lighting (see Box 7.3) because they have the following advantages compared to halogen or xenon lamps.

Box 7.3 The Hella LED headlamp

The prototype LED headlamp developed by Hella and Stanley Electric.

Hella from France, with its partner Stanley Electric from Japan, has demonstrated a prototype LED headlamp. The lamp comprises a number of LED arrays equipped with specially designed Cartoval lenses, which are oval-shaped lenses produced on the basis of a Cartesian mathematical equation. Five of the lens modules are arranged adjacent to each other in the upper part of the headlamp and are used to produce the dipped beam (see figure). The full beam is produced from two vertically mounted side-positioned modules. Each module comprises a four-chip WLED array. The new headlamp is purposely designed so that new, higher-output LED arrays can be used as they become commercially available. It is hoped that these lamps will be able to produce the same light output as a xenon headlamp by 2008.

Source: LEDs Magazine, 2005b (reproduced with permission).

- Their service life exceeds the life of the vehicle, thereby avoiding maintenance costs.
- They offer space savings: this is already the case for signal functions and will become the case in the medium term for dipped and full-beam lighting once efficacy levels improve.
- They have greater styling options because they produce no infrared radiation and thus can be placed directly behind a plastic optical component. The light sources are also more compact and hence can be arranged in a wide variety of ways.
- They have a superior chromaticity because their light colour is near to daylight, which is more comfortable for the driver, especially with respect to the main headlamps.
- They allow the use of intelligent light functions such as dynamic bending lights because the light from LEDs can be instantly controlled and dimmed to any level.

Finally, they also offer important potential energy savings. For example, a low-beam daytime running light can consume more than 150 W; however, it is possible to create a daytime running light from three 1 W LEDs drawing just 5 W once the power consumed by the control driver is taken into account. Despite these advantages LEDs are only just being applied in forward-lighting applications, largely because the technology of WLEDs has only just matured enough to be considered and because of the higher cost. In the last two years a number of headlamp prototypes have been produced using LEDs, inspired by the design benefits they offer. Thus far these prototypes have managed to achieve the same luminous flux as xenon lamps for low-beam applications (about 1 000 lm), but the high-beam LED headlights have not yet quite attained xenon lamp flux levels. Although they have already reached the light levels of traditional halogen headlamps they are less likely to compete with these because of their higher price, which currently puts them into competition with other high-end sources.

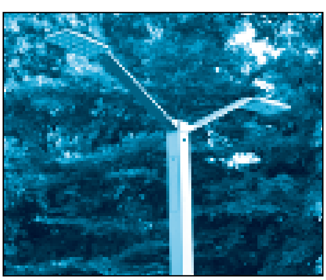
The regulatory environment has been another barrier to be addressed. LEDs have been approved for headlamp main-lighting functions in North America according to the Society of Automotive Engineers (SAE) standards that are applied there, but not yet in regions using the Economic Commission for Europe (ECE) regulations (Europe and Asia), although this is expected by 2008. However, LEDs have already been fully approved for signalling functions in headlamps (*i.e.* for direction indicators, position lights and daytime running lights) in both jurisdictions. The Audi A8 W12 has been using WLEDs in combined position and daytime running light headlamps since 2003.

Overall the high cost of LED-based systems is seen as the main barrier to their future adoption in this sector. According to one market analysis, WLED headlamps will be about twice as expensive as xenon HID headlamps, which in turn will be about twice as expensive as halogen headlamps by 2012 (Frost & Sullivan, 2004).

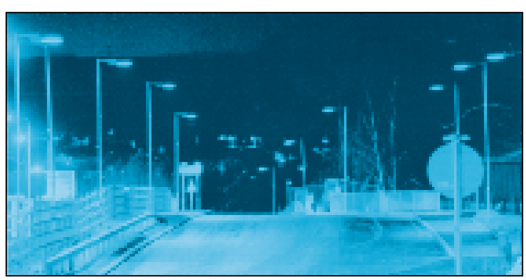
Street lamps and outdoor lighting

WLEDs are not yet as efficient as high-pressure sodium or metal halide street lights, although they do offer some potential advantages that might make them attractive for street-lighting applications in the future (Figure 7.10). Very long lifespans minimise maintenance costs, tight light distribution allows light pollution to be minimised, and full dimmability and instant on/off capacity allows much easier time-of-use and presence control, which has significant energy-savings potential. LED road lighting may also be viable in combination with renewable photovoltaic (PV)-generated electricity for off-grid applications. Another potential advantage of LED street lighting is a far higher CRI and CCT than is possible with traditional street-lighting sources such as high- and low-pressure sodium vapour lamps. However, WLEDs would have to attain the efficacy levels discussed in pp. 461–465 if SSL is really to become an attractive option for street lighting.

Figure 7.10 **LED street-light projects**



In July 2005, Philips installed warm-white LED street lights in the Dutch town of Ede. The luminaires contain six 3 W white and twelve 1 W amber LEDs.

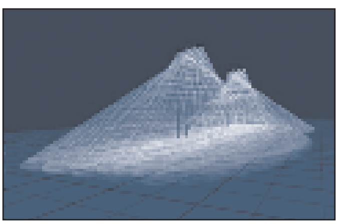


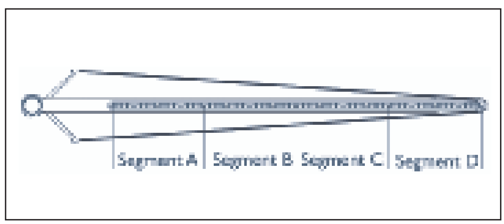
In 2003, 30 LED street lights were installed in Coryton, a suburb of Cardiff, Wales, by Mooncell. The luminaires contain thirty-six 1 W LEDs mounted on 6 m poles.

Source: LEDs Magazine, 2005c (reproduced with permission).
Abbreviation: LED = light-emitting diode.

In 2004 the city of New York launched an international design competition for a new street light. The winning design, which will be used to illuminate streets, walkways and parks, uses WLEDs combined with high-performance lensing optics set in a small, slim and oval-shaped profile that provides both the structural support and heat sink for the LED packages (Figure 7.11). Using LEDs enabled the luminaire dimensions to be reduced and produces a very different appearance from a conventional "cobra head"-shaped street lamp. Each luminaire contains four linear segments containing a 16-LED package. In turn, each of these packages has an optical lens with an integrated film diffuser to provide the desired light-distribution pattern. The segmented structure is intentional to allow modular upgrades using fewer but brighter LEDs to be installed as they become available (Whitaker, 2004b).

Figure 7.11 **The New York 2004 LED street-light competition winner***





Source: Whitaker, 2004b (reproduced with permission).
* Left: the pattern of light distribution. Right: the design of the street light, showing the four segments that each contain16 LEDs.
Abbreviation: LED = light-emitting diode.

Christmas lights

In many countries there are high-volume markets for festive illumination lamps such as are used for Christmas trees and similar lighting. These lamps typically operate for only a small part of the year but have traditionally used low-efficacy, small incandescent light sources. In the United States an estimated 34 million Christmas trees are sold annually, and festive lights are also used for external illumination purposes. LED versions of these lights are now commercially available and use one-tenth of the power of the incandescent lamps they replace. They also have other benefits, including much higher reliability and durability and greater safety to touch. It is estimated that in total, some 37 billion festive lamps are used each year in the United States, with an average wattage of 0.4 W per lamp and average total operating period of 150 hours per year. This gives rise to an estimated annual consumption of 2.2 TWh. A systematic switch to LED lights would cut this to 0.2 TWh (Navigant, 2003a).

The LED market

LEDs now comprise a substantial market, with an estimated global value of USD 4.0 billion in 2005, up 48% over a two-year period. About 50% of these revenues were from applications using InGaN-based devices, comprising blue, green and white LEDs. Market forecasts have projected that revenues will grow to USD 8.4 billion in 2010. This growth is projected because of the development of new applications, including headlights and large-area LCD backlights, even though chip prices from the largest revenue segment, backlighting of mobile appliances (mobile phones, PDAs, etc., accounting for 58% of LED sales revenues in 2004), have started to erode as a result of greater competition.

Mobile appliances account for the largest part of the LED market, contributing USD 2.15 billion of sales in 2004, some three times higher than in 2002. Signage and automotive lighting each represented 13% of high-brightness LED sales, with a value of USD 500 million in 2004. General lighting represented only 5% of the total LED market, with a value of about USD 185 million, of which most sales were for coloured-light applications but include small, handheld applications such as torches and reading lamps (LEDs Magazine, 2005d). It has been projected that signs will account for 34% of sales in 2010 and illumination 13%.

The SSL industry

Japan's Nichea is the largest LED manufacturer and had sales revenues of USD 1.2 billion in 2004. The "Big Three" lighting companies are also important players in the emerging LEDs business. OSRAM'S Opto Semiconductors division had revenues of USD 570 in 2004, while Philips Lighting's Lumileds business had revenues of USD 324 million from August 2004 to July 2005, with an operating profit of USD 83 million. General Electric's GELcore SSL business had revenues of USD 70 million in 2004, with most coming from the sale of traffic lights, signage and display products. Other major manufacturers include Cree (with annual revenue of USD 322 million to the end of June 2005), Toyoda Gosei (a Toyota affiliate that is reported to expect sales from

LED products of USD 225 million for 2005), Seoul Semiconductor and Cotco. While LED manufacturing specialists such as Cree and Nichia are focused on producing LEDs and their packages, the traditional lighting companies such as OSRAM and Philips appear to be developing vertically integrated businesses that combine in-house chip fabrication with LED packaging, module manufacturing and system integration.

THE "GREAT WHITE HOPE"

Energy savings, technology targets and investment

The existing LED and WLED markets and their associated niche energy savings are discussed on pp. 448–460, but the real challenge for LEDs is to replace inefficient light sources, such as halogen lamps and general lighting service (GLS) incandescent lamps in the general illumination market. But what performance levels will need to be reached if WLEDs are to attain their potential, and what can be reasonably expected? The most advanced strategic studies looking into this question so far have been conducted in the United States. In 2002 the US DOE and US-based Optoelectronics Industry Development Association (OIDA) published two sets of technology roadmaps for SSL (OIDA, 2002b, 2002c) for LEDs and OLEDs, respectively (see pp. 473–474 for discussion of OLEDs). These documents set out joint government and SSL industry price and performance benchmarks and the dates by which they hope to achieve them, as summarised in Tables 7.1 and 7.2. Some of the 2007 targets already appear to be in reach, although the degree to which this is fully the case is open to some interpretation.

If SSL attains its full promise, considerable energy savings would be in reach, but the extent of energy savings that could be expected is dependent on the size of existing lighting markets that would be replaced by SSL and the incremental efficiency improvement that would be expected. This topic was addressed by an investigation into the energy-savings potential from SSL commissioned by the US DOE (Navigant, 2003b), which found that if SSL achieves key price and performance targets it could save 3.5 quadrillion Btus (3.5 Quads[2]) of primary energy demand by 2025 in the United States alone. This is to be achieved by displacing a large proportion of incandescent and fluorescent lighting with high-efficiency, low-cost WLEDs that would:

2. A quadrillion Btu, or 1 Quad, is 1.06 exajoules.

Table 7.1 Technology-roadmap price and performance improvements for LEDs

	2002	2007	2012	2020
Luminous efficacy (lm/W)	25	75	150	200
Lifetime (hours)	20 000	>20 000	>100 000	>100 000
Flux (lumens per lamp)	25	200	1 000	1 500
Lumen cost (USD/kilolumen)	200	20	<5	<2
Colour rendering index	75	80	>80	>80
Lighting markets penetrated	Low flux	Incandescent	Fluorescent	All

Source: OIDA, 2002b.
Abbreviation: LED = light-emitting diode.

Table 7.2 Technology-roadmap price and performance improvements for OLEDs

	2002	2007	2012	2020
Luminous efficacy (lm/W)	10	50	150	200
Lifetime (hours)	300	5 000	10 000	20 000
Flux (lumens per device)	10	3 000	6 000	12 000
Lumen cost (USD/kilolumen)	>200	~50	5	<1

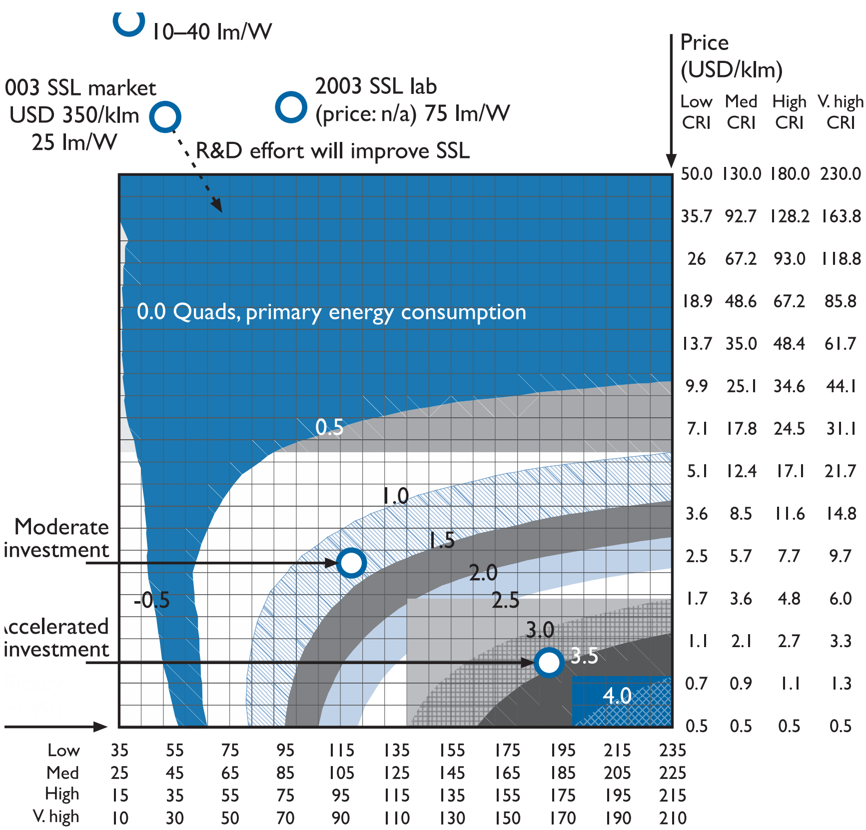
Source: OIDA, 2002c.
Abbreviation: OLED = organic light-emitting diode.

- Decrease national lighting energy consumption by 29%.
- Produce cumulative electricity savings from 2005 to 2025 worth USD 125 billion to end-users.
- Defer the need for more than forty 1 000 MW power plants, thereby contributing to a cleaner environment and a more reliable electrical transmission and distribution system.
- Produce a SSL market worth USD 10 billion per annum.

Furthermore these savings would be expected to grow beyond 2025 as SSL takes a progressively larger share of the market. However, these savings will only occur if the core technology targets are attained and these are contingent on the level of investment secured. The precise relationship between projected US energy savings from SSL (specifically WLEDs) and the two key technology targets (efficacy and price) estimated in this study are shown in Figure 7.12.

This figure shows the energy savings expected in 2025 if SSL (particularly WLEDs) were to attain given price and efficacy targets, which vary depending on four "CRI bins": a low CRI is <40, medium 40 to 75, high 76 to 90 and very high >90. The analysis assumes that it is harder to attain a good efficacy and price for WLEDs with a high CRI than with a lower CRI and further assumes that the CRI bin is a key factor determining the suitability of the light source as a substitute.

Figure 7.12 **Projected US primary energy savings in 2020 for SSL**



Source: Navigant, 2003b.
* Savings are for combinations of price and efficacy levels.
Abbreviations: CRI = colour rendering index; klm = kilolumen; n/a = not available; Quad = quadrillion British Thermal Units; SSL = solid-state lighting; V. High = very high; WLEDs = white-light emitting diodes.

It also assumes that SSL development will follow a classic technology S development curve where the pace of improvement in performance and product cost is highest when the product is first in the process of being mass produced. Inspection of the figure shows the relative importance of improving efficacy and price for energy savings to be attained. The three dots in the upper left-hand corner of the figure show the performance characteristics of WLED technology in the commercial market in 2003 (USD 350 per kilolumen and 25 lm/W) and the best device manufactured in the laboratory in 2003 (no price, 75 lm/W). If price improvements occur without efficacy gains it is even possible to reach negative energy savings (in the lower left portion of the figure); however, this now seems a remote possibility because WLED efficacy levels have already improved since this graph was produced. Of greater concern would be that low price and high efficacy levels might not be simultaneously achieved, in which case WLEDs would not bring about a significant positive transformation of the general illumination market.

The Navigant study attempts to estimate how accelerating R&D with government support might be expected to increase the speed and certainty of the US DOE/OIDA targets being met and to tie this to the resulting energy savings in 2025. The figure of 3.5 Quads in savings by 2025 is the savings projected from an accelerated R&D scenario, which assumes that USD 100 million is invested in R&D each year from 2005 to 2025. Table 7.3 reports the expected WLED (the main SSL technology) performance benchmarks that would be reached in 2025 under this scenario, as well as a moderate R&D investment and a reference case scenario (with no government R&D investment).

While the United States may have conducted the most definitive analyses of savings potentials through LEDs, this is not the only country to have investigated their potential. A similar analysis has been conducted in South Korea, where it has been estimated that the adoption of AC-LED technology could enable Korea to save up to 60 TWh per year by 2010 (SSI, 2005). For the United Kingdom it has been estimated that WLEDs could save up to 39.2 TWh of general lighting electricity demand by 2020 were they to attain the performance specifications projected in the Navigant Accelerated Investment scenario and were they to become popular among end-users (Graves *et al.*, 2005).

Table 7.3 Description of the SSL market scenarios and maximum S-curve values

Scenario	General	Discussion	CRI bin	Efficacy limit* (lm/W)	Price limit* (USD/klm)	Life limit* (hours)
Reference	All SSL penetration is set to zero	Considers the energy consumption of the lighting market if SSL did not exist, and conventional lighting improves according to the conventional technology improvement scenario selected. This scenario establishes a baseline against which to compare the energy consumption of the other three scenarios.	n/a	n/a	n/a	n/a
Moderate Investment	A national investment of USD ~ 50 million per year	Government and industry cooperate on R&D investment in SSL, though this level of investment is insufficient to catalyse development of the technology necessary to significantly conserve energy. The rate of SSL technology advancement lags behind that of the Accelerated Investment scenario. Medium-CRI LED technology may achieve 93 lm/W and USD 4.3/klm by 2025.	Low Med High V. high	160 95 81 70	1.9 4.1 5.4 6.8	80 000 75 000 70 000 65 000
Accelerated		A national	In an accelerated technology scenario,Low			229
1.2	100 000					
Investment	investment of USD ~ 100 million per year	government and industry cooperate on R&D to improve technology performance (efficiency and life) and reduce costs. In this scenario, the medium-CRI LED technology achieves 181 lm/W and USD 2.5/klm by 2025.	Med High V. high	183 164 145	2.4 3.1 3.9	100 000 100 000 100 000

Source: Navigant, 2003b.
*These values represent the S-curve maximum achievable price and performance anticipated for each scenario. These limits represent 100% of the SSL technology goal, which may not be attained before the end of the analysis period (*i.e.* SSL technology performance improves beyond 2025).
Abbreviations: CRI = colour rendering index; klm = kilolumen; n/a = not available; SSL = solid-state lighting; V. High = very high.

Quantum dots: a leap in the light?

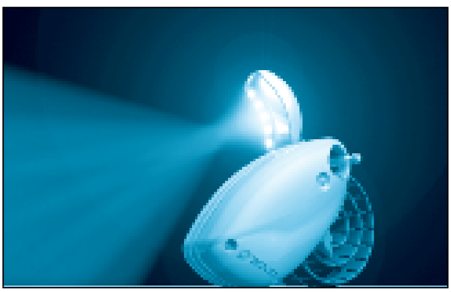
White-light spectrum conversion efficiency and light distribution are two key factors that need to be addressed for SSL to move forward; however, a very recent finding offers promise for both. An accidental discovery in 2005 seems to herald an alternative means of generating broad-spectrum white light from LEDs rather than the three established methods outlined on pp. 434–??? Tiny nanocrystals, which are just a few atoms wide and colloquially known as "quantum dots", have been found to emit broad-spectrum white light when stimulated with a narrow-spectrum light source. If the quantum dots are mixed into a polyurethane sealant and painted over a blue-light LED, a white-light lamp is formed that has an efficacy twice as high as that of an incandescent lamp, lasts 50 times as long and can be designed to emit light in all directions.

Another potentially important advantage is that it should be possible to fashion quantum dots into an electroluminescent source (*i.e.* a light source powered directly by electricity), because they can be used with a wider selection of binding compounds without affecting their emissions characteristics (Bowers *et al.,* 2005). In principle, SSL using quantum dots should be simpler and less expensive to manufacturer than current WLEDs. There are drawbacks of course – the crystals used are made of cadmium selenide (CdSe) and cadmium has been banned from product manufacture in many countries on grounds of its environmental risks. The favourable properties of the CdSe nanocrystals are that they exhibit broad-band emission (420 to 710 nm) covering most of the visible spectrum while not suffering from self-absorption. This is a direct result of the extremely narrow size distribution and unusually large Stokes shift (40 to 50 nm). It is still far too soon to know whether other quantum dots can be manufactured with similar properties. Furthermore, as currently applied, quantum dots simply hold out the potential to behave like a higher-efficiency and higher-performance phosphor and thus will only ever produce a light source with an efficiency that is limited by the efficiency of the stimulating light source (blue LED in the above example).

LEDs for fuel lighting: a fast track to clean development?

A typical household in the developing world without access to the electricity grid and reliant on fuel-based lighting will spend USD 77 per year for their lighting service and will only receive 44 klmh (kilolumen-hours) of light per person (Mills, 2005a) – some 16 times less light than the average person in a grid-connected household – and for as little as one-thousandth of the efficiency. This service cost and lighting level corresponds to three paraffin (kerosene)-fuelled hurricane lamps burning for an average of four hours per lamp per day for each family of four people. Replacing these lamps with a stand-alone solar-PV-powered lighting system using 5 W CFLs could supply the same amount of light for an amortised cost of USD 30 a year, or if the same number of lamps were used it would supply more than five times as much light for about USD 158 a year. The cost of a solar-PV-powered system is less than half that of an equivalent fuel-based lighting system in the long run, but only for equivalence in illumination level, not for equivalence in the number and distribution of light sources. To conserve the number of light sources would require increasing costs, albeit for a much higher total lighting service level.

Figure 7.13 **Handheld solar-PV-powered WLED lighting system***



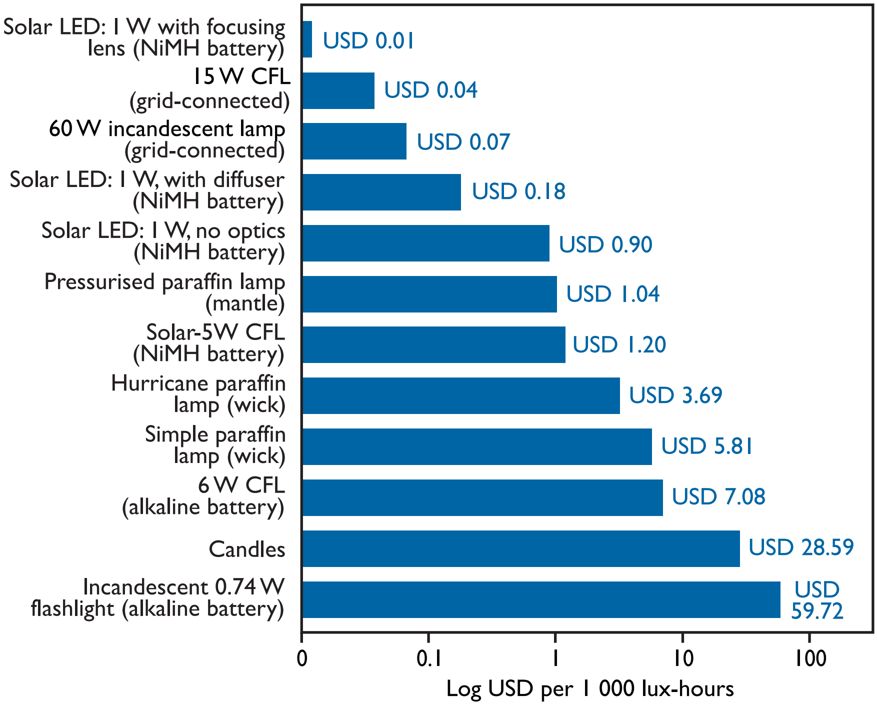
Source: Courtesy of Evan Mills.
* Solio compact solar-powered charger with WLED peripheral attached, developed by Better Energy Systems, UK.
Abbreviations: PV = photovoltaic; WLED = white-light emitting diode.

The advent of WLEDs changes all this. LEDs only draw 1 W but give out as much light as a hurricane lamp (about 40 lm); furthermore, their light distribution is far more effective for task lighting on a horizontal plane, which means the lighting they provide for tasks such as reading is far superior to that of hurricane lamps (Figure 7.13).

The cost of a stand-alone solar-PV-powered 1 W LED system with three AA-sized NiMH batteries is about USD 25. It will last for 50 000 hours (about 37 years at normal usage rates) and incurs about USD 2.2 a year in battery replacement costs (Mills, 2005b). When all costs are amortised over three years the cost of light from such a system is around USD 0.12 per kilolumen-hour, which is about 70% of the cost of the solar-PV-powered CFL system (USD 0.17 per kilolumen-hour) and less than one-quarter of the cost of light from the hurricane lamp (USD 0.52 per kilolumen-hour). Importantly, however, the first costs of such lighting systems are only one-third of those for the solar-PV-powered system and a three-lamp system would cost the same as a year's light with hurricane lamps (Figure 7.14).

Moreover, solar-PV-based LED lighting has other advantages compared to the alternatives. Its very low power demand and DC power supply mean that the entire solar-PV lighting system can be both highly compact and very robust. It requires a PV panel that is only the size of a paperback to charge

Figure 7.14 Cost of fuel-based lighting and solar-PV-powered LED lighting



Total cost of illumination services. Costs include equipment purchase price amortised over 3 years, fuel, electricity, wicks, mantles, replacement lamps and batteries. Performance characteristics of light sources vary: values shown reflect common equipment configuration and include dirt-depreciation factors for fuel lanterns and standard service-depreciation factors for electric light per the Illuminating Engineering Society of North America. Assumptions are 4 hours per day operation over a 1-year period in each case, USD 0.1/kWh electricity price, USD 0.5/litre fuel price. An average of 11 litres of lighting fuel per household per month is estimated; observed values vary from 2 to 20 litres.

Source: Mills, 2005a (reproduced with permission of Science Magazine).
Abbreviations: LED = light-emitting diode; NiMH = nickel metal hydride; PV = photovoltaic.

the WLED batteries, and the whole system has no moving or fragile parts and hence very little that is likely to fail. Furthermore, while the efficacy of the CFL-based lighting system is similar to that of the WLED system, its light is omnidirectional and thus provides far less useful illumination on the working plane. A 1 W WLED can provide between 40 and 600 lux on the task area, depending on the optics it is fitted with, while a 5 W CFL will provide only about 30 lux. This makes LEDs a far better and economical lighting source for specific tasks such as reading, with clear implications for education and development.

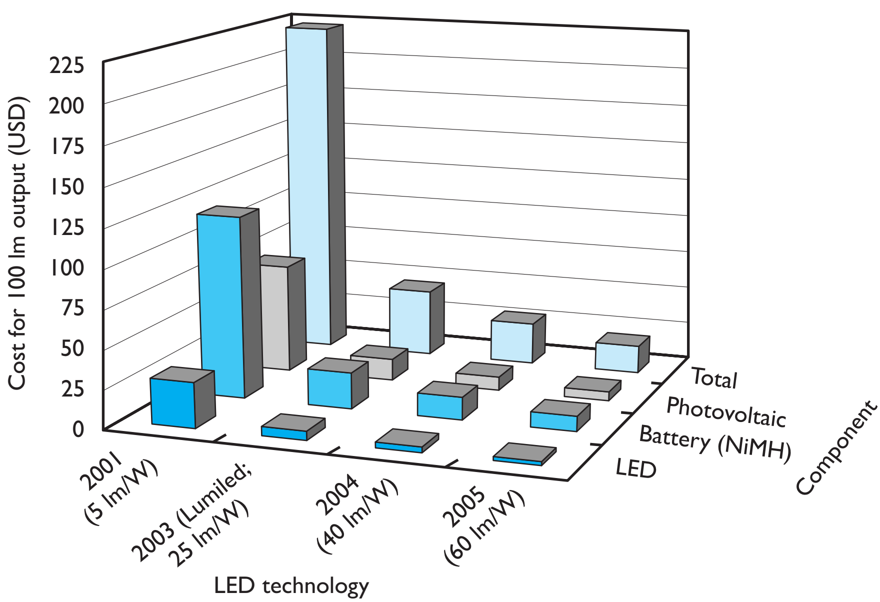
So what would be the consequences were half of the world's fuel-based lighting to be replaced with solar-PV-powered WLED lighting systems over the next 15 years? To do so would require the installation of 40 million solar-PV-powered WLED systems each year at a capital cost of roughly USD 1 billion per annum and assumed additional programme delivery costs of USD 0.1 billion. But these costs incrementally avoid the need for fuel-based lighting costs of USD 1.2 billion each year, so that net-cost savings worth USD 117 billion have accrued at the end of 15 years. This is equivalent to giving each household an extra USD 600 of disposable income spread over the same time frame.

Yet the real benefit from the end-user's perspective is the improvement in lighting service, education and health benefits that would ensue. The task illumination from the same overall number of lamps per family would be more than eight times greater than that supplied by hurricane lamps and families would have enough illumination to read at night. If families ultimately chose to convert the cost savings into more light they could choose to double the number of lamps they use or double their output and still pay less for their lighting service. On a macro-scale this would reduce global oil demand by 0.65 million barrels per day and avoid 100 Mt of CO_2 emissions per annum. Were the full costs of paying for the lighting systems to be borne entirely by third parties (*i.e.* were offered as pure development assistance) it would amount to a cost of avoided CO_2 of USD 22 per tonne. However, if net costs are considered (*i.e.* one takes account of the avoided fuel-based lighting costs) the CO_2-abatement cost becomes strongly negative, at USD – 216 per tonne. Most importantly, by 2020 the number of people still reliant on fuel-based lighting would be 530 million, rather than the 1 330 million projected under current development trajectories.

Despite the clear advantages of renewably powered SSL compared with fuel-based lighting and other off-grid sources, the transition to off-grid SSL will not occur rapidly without substantial support. The technology will need to be demonstrated to each target group if they are to consider adopting it. Since first costs are still beyond the means of most potential users, financing mechanisms would need to be established to minimise the size of the initial investment. Nonetheless, this technology holds out the potential to bring effective task lighting to off-grid households at less than one-tenth of the cost of other options, a the same time curbing CO_2 emissions and improving indoor air quality. This has major development implications and is worthy of serious consideration for targeted development assistance. The costs have also declined dramatically as the efficacy of WLEDs has improved over the last few years (Figure 7.15), and this trend is likely to continue into the future.

Furthermore, the service-delivery mechanisms pioneered for solar-PV-powered fluorescent lighting systems are readily adaptable to the solar-PV-powered WLED systems and include leasing schemes, micro-credit and solar cooperatives that can all help mitigate the first-cost barrier while creating a sustainable and affordable lighting service. Such delivery mechanisms could be readily applied to solar-PV-powered WLED systems but would be easier to establish and maintain because of the inherent cost, durability and simplicity advantages of WLEDs.

Figure 7.15 **Effect of improving WLED efficiency on PV and battery sizing and overall system cost***



Source: Mills, 2005b (reproduced with permission).
* Standardised to 50 lm output.
Abbreviations: LED = light-emitting diode; NiMH = nickel metal halide; PV = photovoltaic; WLED = white-light emitting diode.

Why it might not happen: the barriers to be overcome

Much as SSL has generated a great deal of excitement, it has also produced a certain scepticism that has led increasingly to calls for key practical issues to be addressed in order for the true value of the technology to be gauged. The main barriers continue to be cost and brightness, where the former is too high (especially for the initial costs) and the latter is still too low. As mentioned on pp. 461–465 significant improvements have occurred and more are expected in both areas, but these are not the limit of the barriers that LED lighting faces.

The chief cause of immediate concern holding back the practical application of LEDs is the lack of standardisation within the industry and the associated failure of manufacturers to provide information about LEDs in ways that can be compared with traditional light sources. Work is under way through the Commission Internationale de l'Eclairage (CIE; International Lighting Committee) to set out a common basis for making photometric measurements of LEDs, and this will help meet the needs of lighting designers once it is complete. Other issues needing attention are:

- The acceptable degree of spread in LED chromaticity characteristics.
- How LED lifetime and performance depreciation should be measured and defined.
- The way LED system energy performance is defined in relation to thermal management and LED-driver energy needs.

The difficulty encountered in being able to precisely control WLED chromaticity is still causing problems with the quality of WLED lighting. Manufacturers have responded to this by binning their products according to their CCT, but devices with identical CCTs can still appear tinted depending on their position relative to the black body locus. Leading manufacturers are now using more sophisticated binning processes based on regions of the CIE chromaticity diagram (see Plate 3.3), where colours are generally perceived to be the same; however, the bins are still large enough for differences to be distinguishable between WLEDs in the same bin (Whitaker, 2004a). Furthermore, colour matching is most problematic if a repeat shipment is required at a later date or if replacements are needed.

Claims regarding LED lifetime have become quite contentious and several different conventions have evolved regarding how it should be measured and specified. Manufacturers generally do not present measured life data because there is currently no standard test procedure and life tests are costly and time-consuming to conduct. LEDs rarely fail completely, so any lifetime definition needs to be based upon the degradation of performance over time. Current informal conventions have defined LED lifetime in terms of the time taken for lumen output to decline to 50% or 70% of its initial value, for example, but these do not compare directly with the lifetime convention applied to fluorescent lighting, which is the time elapsed before light output falls to 80% of its initial value. A collaborative group of LED and fixture manufacturers, systems end-users and government agencies organised by the US Lighting Research Center (LRC), known as the Alliance for Solid-State Illumination Systems and Technologies (ASSIST), has recently issued recommendations on how LED lifetime should be rated (Taylor, 2005). ASSIST proposes that initial lumens are determined after a 6 000-hour seasoning period and for end of useful life ratings to be given in terms of lumen depreciation at either 70% (for general lighting) or 50% (for decorative lighting) of the 6 000-hour value. These recommendations do not preclude the time to reach a lumen depreciation of 80% also being reported and used for group relamping purposes. The ASSIST recommendations also specify a maximum permissible colour shift of a four-step MacAdam ellipse. In practice, however, LED lifetime has only a limited meaning when tested independently of the luminaire because LED performance degradation is highly dependent on the quality of thermal management achieved, and this is dependent on how the LEDs are integrated into any given luminaire.

Another practical issue to be considered is how to account for maintenance costs. While LEDs will continue to operate for much longer than other light sources and hence will need much less frequent replacement or maintenance than other sources, they still need cleaning maintenance to prevent their practical performance being far lower than specified.

While LED efficacy figures are routinely reported based on the pure source efficacy, as with other lamp types it is much more difficult at present to get reliable data on the system efficacy, e.g. the energy requirements once the power used by the LED controller (driver) and the heat removal system are taken into account. The drivers are the equivalent of ballasts and while they do not consume much energy, it is still several percent of the system total. The energy that may be needed for heat removal is obviously much more difficult to determine and will be highly location- and luminaire-specific.

Overall there is a legitimate concern that if the quality control of LED products is not adequately addressed at an early stage they will develop a poor reputation, which will significantly retard market development. In the past, the lighting industry has been beset by the same kind of problem with other innovative products such as CFLs, T5s and fibre-optic lighting, and in each case the market has either taken longer to develop than hoped for or has barely developed at all. At present, LEDs are also suffering from another difficulty inherent to rapidly evolving technology – the rate of technical development is so fast that any current generation of LEDs is immediately obsolete by the time it has been fitted in a given application. This means there are inherent risks for lighting designers and original equipment manufacturers (OEMs) who are considering investing time and effort in developing products based on a specific LED platform. The production runs are likely to be so short before the LED chips are outdated that they may struggle to make a return on their investment.

OLED WHERE ART THOU?

SSL is not limited to LEDs – organic semi-conductors are also being developed and may ultimately hold even greater promise. While inorganic semi-conductors (*i.e.* LEDs) are much more developed, their organic counterparts, OLEDs, offer the potential for an even broader transformation of lighting in the future. OLEDs are fabricated from chains of carbon and hydrogen atoms and hence use more readily available and cheaper materials than LEDs. First developed in the mid-1980s they have been the subject of a significant research effort since. The main reason is that OLEDs offer the potential of fabricating full-colour, low-voltage light sources in the form of thin flexible sheets that can be used in flat-panel displays and as area illumination. In theory OLEDs could be manufactured using a continuous "roll-to-roll" process, allowing large sheets of OLEDs to be prepared at a very low cost. It is speculated that these sheets could replace or be integrated into wall finishes such as wallpaper or ceiling coatings and used to provide uniform general-purpose illumination. The same material could be woven into a fabric and used as a curtain in daylight or a light source at night (Bergh, 2003).

OLEDs are quite similar to LEDs, but they are made of amorphous materials while LEDs are comprised of discrete crystals. An OLED is comprised of one or more organic layers, of which one is transparent, sandwiched between two electrodes. Applying a voltage across the device causes electrons and holes to be injected into the organic layer(s) in the same manner as with an LED. When these carriers recombine at a luminescent centre they release a photon. The colour of the emitted light is influenced by modifying the chemical structure of the organic materials as well as by the details of the device. OLEDs that emit light (including white light) across the whole visible spectrum have been developed.

OLEDs and LEDs face similar barriers linked to their cost and performance benchmarks, but as with LEDs there has been substantial improvement in OLED performance over the last decade. The OIDA targets set out in Table 7.2 provide a good indication of where the industry hopes OLED performance will be in the next 15 years. The efficacy of OLEDs has improved by more than two orders of magnitude over the last decade, while the operating lifetime at display brightness levels has progressed from less than 1 hour to over 10 000 hours in the same period. OLEDs have already been used in some mobile phones and are expected to be used for flat-screen televisions in the next decade (Bergh, 2003; Graves *et al.*, 2005). Nonetheless the performance of OLEDs is not yet good enough for them to be considered for general illumination applications.

The market value of OLEDs has been projected to reach USD 615 million in 2005, based on the shipment of 60 million units, and is projected to have a compound annual growth rate of 34% to reach USD 2.9 billion by 2011. While OLEDs are mostly being used as alternatives to LCDs in mobile phones, recent developments suggest they will be used increasingly in large screens, especially computers. Samsung Electronics presented the first single-sheet, 40-inch (102.5 cm) active matrix OLED panel in 2005, paving the way for large-size OLED televisions with a total thickness of only 3 cm or less (LEDs Magazine, 2005e). Nonetheless, it is expected that it will take more than five years before this leads to commercially available products.

LIFTING THE LED WAIT: POLICIES AND PROGRAMMES TO ACCELERATE SSL

Government and industry have not been slow to recognise the possibilities heralded by SSL, and many regions have established cooperative development programmes to speed up the development of the technology.

International R&D programmes for SSL

United States

In the United States the DOE has been supporting the US SSL industry via its Solid-State Lighting programme (USDOE, 2005b), which has funded many projects related to LEDs and OLEDs. This programme and the support it offers have been significantly strengthened in the Energy Policy Act of 2005 (EPAct, 2005), which authorises the formation of a public–private partnership called the Next Generation Lighting Initiative Alliance (NGLIA) and entitles it to receive up to USD 50 million in annual funding for the fiscal years 2007 to 2009 (up from the current level of USD 11 million) in order to support the development of energy-saving SSL. Currently some USD 19.3 million of funding is being requested for funding in federal year 2007. The act also includes a provision for an extended authorisation to continue the USD 50 million annual funding through the fiscal years 2010 to 2013. In addition to the DOE, NGLIA (which is hosted by the National Electrical Manufacturers Association [NEMA]) includes all the major actors in the US SSL industry, such as Corning Inc., Cree Inc., Eastman Kodak Company, General Electric Company, GELcore LLC, LumiLeds Lighting LLC, OSRAM Opto Semiconductors Inc. and Philips Electronics North America Corporation.

Europe

European efforts are increasingly focusing on stimulating OLEDs. In October 2004, 24 European organisations established the Organic LEDs for Lighting Applications (OLLA) project with funding of EUR 12 million over a 54-month period. According to the project manager of OLLA, Peter Visser (Philips Lighting), the objective of this project is "to gather and focus the European expertise in OLEDs to jointly accomplish everything necessary for the light sources of the 21st century" (LEDs Magazine, 2005e). More explicitly the OLLA project has set a principal goal of developing a white OLED prototype for general illumination by 2008. This is to be a 30 x 30 cm light source with a brightness of 1 000 candela per square metre (cd/m^2), efficacy of 50 lm/W, lifetime of 10 000 hours and a CRI exceeding 70. Beyond this target the OLLA members aim to produce higher-efficacy light sources, with colour tenability, innovative packaging and control, on flexible substrates. European industry has also established the European Photonics Industry Consortium (EPIC) to support the development of SSL.

Asia

Asian governments and industry are also investing heavily in SSL, especially in Japan, Korea, Taiwan and China.

Japan

One of the first national R&D programmes for LEDs was initiated in Japan in 1998 as the Light for the 21st Century project. This initiative was jointly established by the Japan Research and Development Center for Metals (JRCM) and the New Energy and Industrial Technology Development Organization (NEDO), a semi-governmental organisation affiliated with Japan's Ministry of Economy, Trade and Industry. It brought together 13 member companies and universities with a target to produce SSL with a quantum efficiency of 40%. The project finished in 2002, by which time it had received total funding of JPY 6 000 million (USD 55 million). Following this, the Japan LED Association (JLEDS) was formed in June of 2004 to promote and support technology development and standardisation for LED lighting. In the same year a new government-backed five-year initiative was launched in Japan to develop LED medical and therapeutic equipment, with first-year funding of JPY 500 million (USD 4.6 million) and similar funding levels expected in each of the following four years (Sandia, 2005).

Korea

Korea Photonics Technology Institute (KOPTI) has been working on developing LEDs and supporting domestic SSL industry. It is also reported that Korea is funding a high-performance R&D initiative for LEDs by about USD 20 million per year, aiming to produce an 80 lm/W WLED by 2008 (Sandia, 2005).

Chinese Taipei

Chinese Taipei established the Semiconductor Lighting Industrial Association (SLIA) in October 2002 and in 2003 launched a project to develop next-generation lighting technologies involving a consortium of 11 companies. This initiative was funded with ~TWD 383 million (383 million new Taiwan dollars) up to 2005 and had a goal of achieving commercialised LEDs with an efficacy of 50 lm/W and laboratory prototypes with an efficacy of 100 lm/W. The National Science Council (NSC) has also supported an additional project aimed at producing highly efficient LEDs, with two years' funding for TWD 12 million (Sandia, 2005).

China

In 2004 the Chinese government launched its National Solid-State Lighting Program, which it is hoped will save 100 TWh of electricity annually by 2015 – more than the output of the Three Gorges dam. It is anticipated that this will be achieved through the development of solid-state general-lighting devices with efficacies of 150 lm/W that will displace 40% of all incandescent lighting (Whitaker, 2005). The programme, which is supported by the Ministry of Science and Technology, has funding of CNY 140 million (140 million Yuan renminbi; USD 17 million) and involves more than 50 enterprises and 15 research organisations.

Into the light: some recommendations

In general it seems clear that industry and government are mobilising at the regional level to try to accelerate the development of SSL and presumably also to benefit from the large potential markets it might create. Overall these programmes aim to bring together the main actors in SSL to pool resources and accelerate product development. They rely upon tightening cooperation between industry, academia and diverse institutions to accelerate innovation and product development, foster awareness and develop the professional skills base. Important as the existing efforts are, they are still small in relation to the potential rewards, and furthermore they are multipolar in their orientation. Greater international cooperation could bring even faster rewards and would help hasten the day that SSL is a serious energy-saving candidate for general illumination.

Furthermore, government can do much to foster the positive development of SSL through targeted programmes. The positive experience of government-sponsored programmes to promote highly cost-effective energy-saving niche applications, such as exit signs and traffic signals in the United States, for example, demonstrate what can be achieved. National government has a large role in informing local government and the private sector about energy-savings potentials when they arise and in encouraging their rapid adoption. Government also has a very important role in accelerating the development and adoption of common technical and performance standards, e.g. for lifetime, photometry, efficacy rating and chromaticity reporting.

Goverments also need to act promptly to establish regulatory requirements for the use of innovative efficient lighting technologies where safety issues are concerned, as in the case of vehicle lighting, for example.

Finally, governments need to closely monitor the status of innovative lighting technologies to better understand when they create new opportunities to raise the bar of existing policy settings. For example, if flat-screen technology continues to develop at the rate that it has, there may be a point where government decides that CRT screens have become obsolete and should be regulated out of certain markets because of their comparatively high energy consumption. A similar logic might favour setting performance requirements that practically oblige the use of higher-efficiency LEDs or OLEDs in flat screens in place of CCFLs or other less efficient backlighting options. If LEDs and OLEDs ever reach a point where they surpass all the performance characteristics of less efficient traditional lighting technologies and their life-cycle economics are favourable, there might be a strong argument to regulate, or otherwise lead, the market toward the higher-efficiency technology. In each case this requires policy makers to be aware of all important, energy-using lighting applications and to monitor the status of the lighting technologies that can be applied to them.

THE AGE OF ENLIGHTENMENT: FUTURE STRATEGIES FOR ENERGY-EFFICIENT LIGHTING

Key messages

- Designing effective energy-efficient lighting policies requires a comprehensive set of measures to be implemented to bring about each desired cost-effective technology or practice in every lighting end-use application.
- The highest cost-effective savings opportunities arise from reducing the use of incandescent lamps, mercury vapour lamps, low-efficacy fluorescent lamps, low-efficiency luminaires and low-efficiency ballasts, increasing the use of energy-saving automatic lighting controls, and avoiding poor lighting design and installation practice.
- Enhancing the appropriate utilisation of daylight by increasing professional awareness, design capabilities and market incentives will also improve lighting efficiency over the longer term.
- Adopting and fully enforcing comprehensive MEPS and building codes will significantly raise lighting efficiency by avoiding poor practice.
- The major objective of reducing reliance on incandescent lamps requires the adoption of measures such as financial and/or fiscal incentives to reduce the price difference between high-quality CFLs and incandescent lamps, and measures to stimulate more CFL-friendly luminaire design.
- Procurement programmes, awareness campaigns, market-transformation initiatives, energy labelling, RD&D and third-party financing can all make important contributions.
- Increasing policy ambition, effort and resources across all areas should be the highest priority.

AT THE END OF THE TUNNEL

This study has looked at energy-efficient lighting from the point of view of market characteristics, technologies, the magnitude of the cost-effective savings potential, the reasons why the potential is not being achieved, and the initiatives (whether by governments or others) that aim to achieve it. This cost-effective potential remains stubbornly high, so its realisation is a challenge. When there is only one compact fluorescent lamp (CFL) per average IEA household and incandescent lamps continue to command such an overwhelmingly large share of the residential lighting market, when less than one-third of all commercial buildings in Canada state they have some type of energy-efficient lighting, when mercury vapour lamps are still routinely used for outdoor lighting, when recommended lighting levels remain so divergent, when the use of lighting controls remains marginal, and when buildings continue to be designed in ways that fail to make good use of daylight, then there are some fundamental challenges remaining.

As shown in Chapter 5, there are many government, industry and utility initiatives promoting greater energy efficiency in lighting, and where these exist they are generally delivering cost-effective energy savings. However, the analysis on pp. 409–422 shows that these efforts still fall far short of delivering the majority of cost-effective savings potentials available through current technology and that a great deal more remains to be done. The want of better results is not because of a lack of effort, or effective effort, by those who have been charged to deliver these savings. However, it does pose the question of whether energy-efficient lighting is receiving sufficient policy attention and sufficient resources. Given that lighting represents about 19% of global electricity demand and there is a potential to reduce demand by almost 40% for a cost of conserved electricity of only USD 0.002 per kilowatt-hour, it surely merits greater attention. When the average net CO_2-abatement cost for efficient lighting is strongly negative (USD –158 per tonne) and the magnitude of potential savings is so large (7.2 gigatonnes of CO_2 to 2030) it becomes an even more attractive arena for invigorated policy activity. And if one considers the potential for efficient lighting to increase the security of supply by offsetting peak demand and slowing or reversing growth in demand (especially in summer-peaking localities through an additional reduction in air-conditioning load), it becomes a yet more attractive proposition.

But no country is currently taking full advantage of these opportunities and some have scarcely begun. The reasons are multiple but include: (i) a lack of awareness within government of the scale of opportunity presented by efficient lighting; (ii) a lack of familiarity and capacity within government regarding the design and administration of such policies and programmes; (iii) a traditional orientation of energy ministries towards supply-side issues, where both industry and energy flows are more concentrated; (iv) in some cases a lack of clear mandate to tackle such subjects; (v) a diffusion of responsibility for energy-demand issues among different ministries and layers of government; and (vi) an overall lack of resources for innovative government-sponsored activity no matter how competitive the internal rates of return may be from a societal perspective. Energy-efficient lighting, like other highly promising energy-efficiency opportunities, has to make its way within current institutional frameworks and financial constraints, but these may also need to evolve and ease if a large proportion of the current savings potentials are to be realised.

But a well-designed, proactive, adequately mandated and resourced long-term approach can make a major difference. Before considering what policy elements should be included in a comprehensive strategy, it is useful to clearly set out the policy objectives and to quickly review some of the major lessons that have been learned from past years of experience.

POLICY OBJECTIVES

In general terms the broad objective of energy-efficient lighting policy is to provide high-quality, economic, energy-efficient lighting that will improve energy security and economic competitiveness while minimising the negative environmental impacts from greenhouse gases and other pollutants associated with providing the lighting service. The first step to achieving these goals is to clearly identify the procedural, situational, technology and development objectives that such a policy will strive to attain. While some of these objectives have been effectively addressed in some economies, most have not, and no economy has yet fulfilled the majority of them. Accordingly, the objectives are now listed to assist policy makers in defining a comprehensive matrix of measures to stimulate energy-efficient lighting.

Procedural objectives

- Optimised light-level guidelines that provide a good lighting service for the lowest amount of delivered light.
- Greater adherence to guidelines in practice.

As discussed on pp. 84–98, recommended light levels set the requirements for how much light should be delivered to specific surfaces but, as also mentioned, current recommendations are widely divergent from one economy to another. Despite some convergence towards lower recommended task-lighting levels compared with recommended levels in the 1980s, not all economies have brought their recommendations in line with the more recent research findings. Given the high importance of these recommendations in driving energy demand, it is essential that lighting authorities avoid recommending unnecessarily high illuminance levels if there is negligible advantage in terms of visual acceptance and performance from doing so. It is important to consider not just the task illuminance levels but also the requirements for uniformity and ambient lighting – the higher the latter two parameters are the more light has to be provided.

The second concern is the degree of adherence to the recommended levels in practice. Many OECD economies have taken no measures to determine the degree of compliance with recommended light levels, but those few that have find it is poor. Without practical sanction for non-compliance this result is to be expected and very few jurisdictions have taken any action to deter non-compliance with lighting guidelines. The current *laissez-faire* approach reflects the relatively low priority that has historically been given to lighting energy-performance matters but is inconsistent with the desire to achieve energy security, economic efficiency and environmental protection and hence is ripe for review.

Situational objectives

- Increased awareness of the importance of high-quality low-energy lighting.
- Increased capacity among practitioners to design and deliver high-quality low-energy lighting.
- Appropriate use of daylight-saving time.

No action will be taken to improve lighting energy efficiency if awareness of the topic is minimal among key stakeholders. If lighting designers and installers feel that minimising lighting energy use will bring no commercial rewards to them, they will not exercise any effort to achieve it. Similarly, commissioners of lighting systems need to be made aware of the potential to achieve high-performance low-energy lighting if they are to consider writing it into their specifications and purposely checking to see if it is delivered. In the absence of such knowledge their investment decisions will be based purely on first cost and speed of delivery. Similarly, despite 25 years of commercially available CFLs there is still enormous confusion among end-users, especially in the residential sector, of their relative merits. While many consumers will know they are more efficient than standard incandescent lamps, few realise quite how big the difference is or how much they are likely to save overall by paying the higher price of a CFL. Furthermore, even fewer will know that CFLs can provide not only light of the same hue (correlated colour temperature; CCT) as incandescent lamps but also a wider range of hues if desired. Labelling schemes can help, but they need additional support through greater and sustained awareness-building if consumers are to become more conscious of the advantages of the more efficient technologies. Similar concerns apply to the awareness of other higher-efficiency lighting options; this awareness remains quite low even in the more informed commercial, municipal and industrial sectors.

Insufficient technical capacity among practitioners is also a barrier to energy-efficient lighting. Most installers of lighting systems are electrical contractors without in-depth training in lighting design and performance issues. Many designers similarly lack information and experience in energy-efficient design practices. This limitation greatly reduces the probability of deployment of efficient lighting solutions in mainstream installations.

Daylight-saving time has been deployed in some countries since the early 20th century and is now in use in all OECD countries; however, some non-OECD countries still do not operate daylight-saving time and many of the OECD countries that do have not fully optimised daylight availability to working hours. This means there is still an opportunity for further lighting energy savings by seasonal adjustments in standard time settings. The recent research on the human benefits of daylight discussed on pp. 68–84 implies this may well have health and productivity benefits too.

Technology objectives

This list of technology objectives sets out outcomes that would greatly increase lighting energy performance without any loss of lighting quality. Furthermore, most of the items in the list are cost-effective in almost all circumstances for new installations and many are for retrofits of existing installations. All of the items except the last are concerned with the greater deployment of existing and widely available lighting technologies. This means they are not contingent on the development of new technology, just the greater dissemination and application of existing good technology and practice. Full deployment of these technologies would lead to greater savings than those estimated in the Least Life-Cycle Cost from 2008 scenario presented in Chapter 6. This scenario only assumes wide deployment of efficient active lighting systems, but (conservatively) does not assume increased deployment of daylighting technologies, better luminaires or the development of new, more efficient lighting technologies.

Phasing-out of inefficient incandescent lamps

- Replacement of incandescent lamps with lamps of an efficacy matching or exceeding that of CFLs.
- Replacement of standard halogen lamps with lighting of an efficacy at least as high as that of infrared halogen lamps and potentially better, e.g. ceramic metal halide lamps or new, white-light emitting diode (WLED) lamps.
- Replacement of halogen uplighters with more efficient alternatives (e.g. linear fluorescent lamps [LFLs], CFLs or ceramic metal halide uplighters).
- Replacement of low-efficiency halogen transformers with higher-efficiency transformers or alternative lighting solutions.
- Replacement of incandescent lamps in important niche markets such as:
  - Interior and exterior incandescent vehicle lights, with light-emitting diodes (LEDs) and/or xenon lamps.
  - Incandescent traffic lights, with LEDs.
  - Halogen display lighting, with ceramic metal halide lamps or, potentially, WLEDs.

- Incandescent ceiling fan lights, with CFLs.
- Incandescent Christmas and other festive lights, with LEDs.
- Incandescent reflector lamps, with CFL reflectors or higher-efficacy infrared halogen reflector lamps.
- Incandescent lamps and inappropriate fluorescent lamps, with LEDs with a high system efficacy in emergency-lighting applications such as exit signs.

- Ensure any remaining incandescent lamps are as efficient as could reasonably be expected within their product and power class.

Higher-efficiency high-intensity discharge lamps

- Replacement of mercury vapour lamps with higher-efficiency alternatives (*e.g.* high-pressure sodium or metal halide lamps).
- Replacement of probe-start metal halide lamps with higher-efficiency alternatives (*e.g.* pulse-start metal halide lamps).
- Ensure high-pressure sodium and metal halide lamps permitted on the market have adequate efficacy levels and are matched to good ballasts and lighting controls.

Higher-efficiency fluorescent lamps

- Removal of low-efficacy and poor-quality CFLs from the market.
- Removal of low-efficacy and poor-quality LFLs from the market (phase out T12s, halophosphor T8s and other less common low-efficacy LFLs in favour of alternative higher-efficacy LFLs that are at least as efficient as triphosphor T8s).

Higher-efficiency luminaires

- Higher luminaire efficiency levels (luminaire output ratios [LORs] should be greater than a minimum threshold, *e.g.* 70%, for all but special cases; minimum LOR levels could be defined by luminaire class).
- The photometric performance of all luminaires should be measured and available according to standard test procedures; if the latter are not yet developed for specific luminaire or lamp combinations they need to be established.

- Outdoor luminaires should generally be of a cut-off variety[1] to avoid light trespass and minimise light pollution unless there is a strong aesthetic argument to the contrary.

Higher-efficiency and more versatile ballasts

- Higher-efficiency ballasts should be used for fluorescent lamps, consistent with reasonable-quality high-frequency electronic ballasts or better.
- Fluorescent ballasts used in day-lit spaces should incorporate illuminance sensors and automatic dimming.
- For high-intensity discharge (HID) lamps there is a need to define standard ballast efficiency and performance metrics before measures can be taken to remove the least efficient ballasts from the market and encourage the use of the highest-efficiency options.

Routine use of efficient lighting controls

- Individuals should have independent control of their lighting needs in the workspace, ideally with dimming.
- Spaces with access to daylight should have daylight dimming sensors to automatically control artificial lighting so that design light levels are not exceeded by the combined use of daylight and artificial light.
- Manual-on/auto-off occupancy sensors should be used to ensure that spaces are not lit when unoccupied.
- Timer systems should be deployed to ensure lighting systems are off, unless intentionally overridden, when premises are generally unoccupied.
- Outdoor security lighting should be activated by motion sensors on a timer delay.
- There should be greater use of dimming and presence detection for street and roadway lighting.

1. A "cut-off luminaire" cuts off light emissions at high angles.

Greater use of daylighting technologies

- Spaces directly beneath a roof should be equipped with light wells and skylights: this is especially true for high-bay spaces typically found in large retail outlets, factories and many classrooms and educational establishments.

- The more intelligent use of windows with appropriate shading and diffusing devices such that the maximum ratio of daylight without glare to unwanted solar gains or thermal losses is attained.

Greater use of sophisticated lighting design

- Better lighting design to achieve the best-quality lowest-energy lighting; this is increasingly viable because of the growing capabilities and user-friendliness of lighting design software.

- Higher coefficients of utilisation for illuminated workspaces to be achieved by more routine use of light-coloured, diffusely reflective ceilings and walls.

Stimulation of new, higher-efficacy lighting technologies

- Development of higher-efficiency lighting: high-efficacy solid-state lighting, advanced daylight distribution systems, improved controls and better optics all offer the potential for a significantly higher-efficiency lighting service in the future and merit increased R&D and technology deployment activity.

Development objectives

- Replacement of fuel-based lighting by superior stand-alone lighting technologies in regions that are unlikely to be connected to the electricity system in the near future.

The analysis on pp. 466–470 shows how fuel-based lighting could be replaced by robust solar-powered solid-state lighting technology that provides more light than existing fuel-based lamps at a lower overall cost and with much lower CO_2 emissions. Given the huge social, health and economic handicap that reliance on fuel-based lighting places upon families without grid-based electricity, there is a clear win–win development potential to be gained from the structured support and promotion of solid-state lighting alternatives.

Summary of policy objectives

This list of objectives makes it apparent that achieving energy-efficient lighting will require a matrix of policies and measures to be implemented if all cost-effective opportunities are to be addressed. Many governments and private organisations will prioritise among such a list and choose to focus on areas that are of greatest concern to them; however, every objective mentioned above constitutes an important cost-effective opportunity to save energy, and hence there is a strong case for governments to aspire to develop a comprehensive portfolio to eventually address all these opportunities. Doing so implies a much greater level of activity than has been historically directed at this topic and has significant resource implications; however, if the policies are properly designed and implemented, the commitment of greater resources to bring about energy-efficient lighting will constitute a very sound investment from a societal perspective.

LESSONS LEARNED FROM CURRENT AND PAST EFFORTS

As shown in Chapter 5, IEA member countries are actively promoting energy-efficient lighting, sometimes through lighting-specific programmes and sometimes integrated within broader energy-efficiency programmes. Reviewing those programmes, a number of conclusions can be made, as follows.

Consumers are not unwise…

…but they may be time-constrained and unaware of specific lighting technologies. There must be a reason why consumers routinely leave lights on and continue to buy inefficient lighting technologies such as incandescent lamps and mercury vapour lamps. In part the answer can be found in tradition, awareness and time constraints. Important as lighting is to the global economy, inefficient lighting is easily affordable for the majority of inhabitants of OECD countries. It is perhaps not a coincidence that some of the highest levels of CFL lighting use are seen in emerging economies such as Brazil and China. In these countries wealth levels are high enough to enable investment in energy-saving technology and people are sufficiently service-cost conscious to be prepared to do it. In OECD economies, where energy bills typically account for a small percentage of total expenditure and lighting accounts for a smaller proportion again, consumers are less likely to give it much attention. Unless they are expressly motivated by concerns about the environment or a dislike of waste, many will disregard relatively low-impact, personal economic decisions as being unworthy of the effort their optimisation may require.

Furthermore, we live in an age of rapidly expanding demands on our attention and an ever-wider range of activities and subjects in which we could choose to participate. This causes information fatigue and leads to heavy filtering of new demands on our attention, resulting in any single item of information being less influential than it might have been in the past.

Given these factors why should consumers focus on making lighting more efficient when they have so many other more pressing demands on their time to consider? In fact there is good reason because a key advantage of efficient lighting is that it can save precious time by avoiding the need for such frequent lamp replacement. But these advantages are still not well known and most people will tend to stay with the technologies with which they are familiar unless there is an overwhelming reason to change.

There is much misunderstanding

There is still much misunderstanding about the efficiency of various lighting options, about life-cycle costs, lifespan, lighting quality, etc., and the resulting lack of clarity leads to poor outcomes. Very few people who commission lighting systems are aware of the wide disparity in performance that exists between different lighting solutions and hence lighting is often viewed as a commodity for which price and speed of installation are the only market drivers. If those implementers and products that provide a superior service are to be rewarded in the market they need to be able to show customers the additional value they offer.

Governments can play a very helpful role in this through the following means. They can provide standardised performance metrics, perhaps developed jointly with industry but with final approval by government. They can help educate the public (especially those who commission lighting systems or rent commercial premises) about the range of performance outcomes and what to look for in lighting installations. They can help train and endorse lighting professionals and approved contractors. They can implement rules and incentives that encourage the adoption of efficient lighting. Perhaps most importantly, they can implement measures that make lighting energy performance visible to the market. They can also identify specific market failures and imperfections and design policies to address them. The main advantage of governments engaging in these areas is that they have both the authority and independence that the private sector lacks.

To avoid poorly adapted standardised lighting solutions in the commercial and public sectors, many governments recommend that building developers and other system commissioners use design experts to customise the solution. While design experts are important and useful, they are seldom used in smaller-scale projects for reasons of cost; thus small and medium-sized enterprises tend to be faced with a bewildering array of options and are usually reliant on the advice of less well-qualified electrical contractors. If standards are to be raised governments need to work with installers and their associations to disseminate good practice and to create greater reward for professionals with better qualifications in energy-efficient lighting.

Energy-efficient lighting is available but not always obvious

There are enough energy-efficient lighting options currently available to make a significant change in lighting energy consumption. This is gratifying for the policy maker because it means not having to wait for the research community and industry to come up with new solutions in the short term. In recent years, there have been many improvements to issues of size, colour rendering and cost, and improvements continue to be made. New, specifically designed luminaires are also increasingly available. Although they exist and are available, however, they are not always well marketed and displayed. Many stores opt for focusing on traditional incandescent lighting or on halogens, which have captured the interest of consumers but still have significant efficiency concerns. Lighting consultants and designers for commercial and institutional buildings need to be kept abreast of latest energy-efficient developments and designs. Better marketing of energy-efficient options could have a significant impact.

There is a need for CFLs-for-incandescent substitution programmes

Historically CFLs have made the greatest inroads into the use of the incandescent lamp when:

- The price differential of CFLs compared to incandescent lamps has been minimised by direct subsidy or soft-financing.
- There has been a proactive promotional campaign.
- The quality of CFLs has been ensured.
- There has been pressure on the energy system, such as a power crisis.

The last factor has been shown to aid consumer awareness of energy conservation and hence preparedness to consider alternative lighting solutions but is obviously not a desirable condition. Of the other factors, not all are required for successful growth in CFL market share, but the market advances most rapidly when all are in place. The key factors appear to be minimising the price differential while ensuring product quality is maintained. If product quality is not policed the market rapidly becomes "poisoned" by inferior products that give the technology a poor reputation and prevent good CFLs from attaining the market share they deserve. Consumers will not take the risk of purchasing a relatively expensive lamp if they think it might flicker, fail long before its claimed lifespan, produce significantly dimmer light over its lifespan, have a poor colour rendering index (CRI) and CCT, and take a long time to warm up. Successful CFL promotional initiatives such as the UK's Energy Efficiency Commitment programme have offered strong subsidies for products that pass stringent quality criteria established through third-party testing. In more cost-conscious markets, leasing of approved CFLs through utility- or government-run programmes has been shown to be effective in removing the first-cost barrier while ensuring quality is maintained.

Substitution of halogen spotlights

Unfortunately, for residential consumers the main energy-efficient option is the CFL. There are currently few alternatives for the increasingly ubiquitous low-voltage halogen, which is often perceived to be efficient but in many cases is no better than the incandescent lamp. However, WLEDs may soon offer an alternative and if this eventuates, government may wish to intervene to accelerate a transformation towards them.

All barriers need to be addressed

Perhaps the most common cause of failure or underachievement in market-transformation efforts is the implementation of measures that address some but not all market barriers. Most barriers to efficient lighting operate in series rather than parallel to each other, which means that there can only be a positive outcome if all the barriers are addressed. For example, a CFL subsidy that lowers the first cost of CFLs will remove the price barrier to CFL purchase but will not in itself lead to market transformation unless consumers (i) are also aware of the energy saving, economic and lifespan advantages of CFLs, (ii) are aware that low-price CFLs are available and know how to get them without having to go to much trouble to do so (having the subsidy does not of itself ensure people know about it), and (iii) are happy that the CFLs are suitable to fit into their existing luminaires and are happy with the quality of the light they produce.

Policy makers must therefore always think of why market actors might not engage in their programmes as well as why they should and need to plan strategies to negate resistance and inertia as well as to provide positive incentives to engagement. Thus effective policy development considers all the perspectives and factors influencing market engagement and designs instruments to address the key barriers until a positive tipping point is passed. It is best if this can be done from the outset, which requires sufficient market research and analysis to be conducted in order to have high confidence in the policy design. However, it is usually not possible to foresee all factors in advance, so policy implementation needs to build in a monitoring and evaluation feedback process to: (a) document and evaluate impacts, and (b) analyse the effectiveness of implementation so that unexpected difficulties can be fixed through ongoing refinement. These tenets seem obvious, but it is surprising how many critical yet redeemable failures are not identified until too late, if ever, because of inadequate provision for monitoring and evaluation following a measure's implementation. Part of the problem is a lack of rigour in policy development (induced by a sometimes unrelenting need to produce quick and easy results) that stems from ever-changing pressures in the process of government. Energy-efficiency policies need time to be implemented, mature and become effective, and in democracies driven by the rhythms of the electoral cycle the luxury of time to demonstrate results is often not available. It is therefore greatly beneficial if there is broad bipartisan support for government engagement in efficiency activities that can allow initiatives to continue over suitably long periods even if there is a change in administration.

Depending on the programme or policy it may also be appropriate to trial-test implementation via a pilot programme. If there are significant uncertainties in the likely response, this can help to identify and confirm the best strategy before committing to a full-scale initiative.

Available data are usually poor

With some notable exceptions, in most countries many of the core building blocks needed to design and administer an effective set of policies to promote efficient lighting are still missing. In particular, most data available on lighting energy consumption are poor, and market data and analysis at the national and regional levels are often anecdotal. In general there is large and sometimes huge uncertainty about average real illuminance levels, the distribution of lighting power density values, the mix of installed lamp technologies, the quality of luminaires and coefficients of utilisation, average annual operating hours, market volumes and values for lighting technologies and services, and the total annual energy use for lighting in specific sectors and overall.

Most governments have simply not invested sufficient time and resources into characterising their lighting markets so that energy-saving opportunities can be properly identified and policy impacts verified. While this problem bedevils energy-efficiency policy in general and is not confined to lighting, the resulting level of uncertainty would be unacceptable on the energy supply side. No energy market could operate if the amount of power feeding into the grid from specific types of generation plant were unknown by ±50%, but this is precisely the situation that applies to knowledge about lighting energy demand. The establishment of regular surveys and metering campaigns to provide data to be fed into demand-side models can remedy this situation and allow reliable information to be established, but it requires resources and commitment in order to happen. The remarkable Danish website (see pp. 369–370) that exploits existing EU mandatory metering requirements for large end-users to pool real-time electricity-demand data (and often explicit lighting-circuit data as a submetering channel) for large public buildings shows how easily and cheaply good-quality data can be established if there is a little creativity and willingness to gather it. It also allows the advantages of advanced lighting systems to be seen in real time, which can be an invaluable tool for an energy service company (ESCO), for example, that wants to demonstrate that the energy savings it can produce are based on real phenomena and are not a contrivance.

Luminaire quality remains a concern

There is a lack of standardisation in defining luminaire quality, and regulators have largely failed to impose performance metrics on the market. Considering how critical the luminaire characteristics are to the overall system energy efficiency, this is a major concern. With a factor of two difference in the amount of light that escapes from commercially available luminaires there is much that can be done on a technical level to improve the situation. However, most countries have left the market to its own devices despite a general ignorance among end-users of the differences in performance of the products on offer. The reluctance of regulators to become involved is understandable. The luminaire industry is much more fragmented than the lamp industry and there are many small-scale producers. There is a strong and almost indefinable set of aesthetic factors that influence luminaire choice and there is a natural reluctance to impinge on the creative process. However, this characterisation is only partially true. The vast majority of luminaires used in the workplace, where most light is consumed, follow standardised designs that lend themselves to direct within-type comparison. Standardised photometric tests are available which allow the LOR and light distribution properties to be compared in a meaningful way that would allow luminaire efficiency to be graded and rated. There is thus a large untapped scope to intervene and impose a comparative performance system that would allow energy performance to be visible in the luminaire market.

Leadership is vital

Governments should take the lead but they cannot operate alone. There is a need to have all stakeholders active in promoting energy-efficient lighting, particularly the electricity distribution companies and lighting industry. For governments, it is not primarily a matter of providing more funds, although this certainly helps, but of providing a better policy and legislative framework that allows all market actors to participate. Governments can also lead by example, using government facilities for demonstration programmes or for showing how energy-efficient lighting retrofits actually can save money and energy. Governments are also necessary for monitoring progress and for regularly analysing market conditions to see if initiatives are effective.

A long-term commitment is necessary

Progress can be made in the short term, but not usually to a great extent. The design of policies and programmes is needed to signal a long-term commitment to improving the energy efficiency of lighting. This can include a combination of short- and long-term measures (e.g. some awareness campaigns can last weeks or months), but they have to be seen as part of a long-term approach.

Developing countries can also practice energy-efficient lighting

Some of the most advanced and successful energy-efficient lighting programmes have been implemented in less developed countries. Major and successful CFL substitution programmes have been implemented in Brazil, Mexico, Peru, South Africa, Guadeloupe and Martinique, while China has become the world's largest CFL market. T5s have higher penetration rates in China than in most OECD countries, as do electronic ballasts. Thailand successfully converted its entire LFL market from T12s to T8s in a matter of years. The Philippines has run some highly successful lamp-quality programmes. Vietnam recently completed the largest and lowest-cost bulk procurement of quality-assured CFLs. These experiences show that running successful efficient-lighting initiatives is more a matter of political priority and organisation than access to innate developed-economy advantages. Having said this it is also true that huge opportunities to reduce expenditure on electricity networks are currently being missed in developing countries through a failure to focus on energy-efficiency issues and lighting in particular. A recent study by the IEA and OECD has identified that import duties for higher-efficacy fluorescent lighting are often higher than those for low-efficacy incandescent lighting in developing countries (OECD/IEA, 2006), which creates a perverse incentive to consume more electricity.

Performance benchmarks are required

The difficulty with simple component-based measures is that while they may raise the average efficiency of individual components they do not provide any guarantee that the components will be used in an integrated design that lowers lighting energy consumption. More efficient lamps and ballasts could be used in poor luminaires such that total lighting energy demand remains high. Alternatively they could be used in an efficient luminaire in a room with dark surfaces so that the efficiency gains are lost in providing higher illuminance to maintain a desired set of luminance levels. Or they might be used to provide more illuminance but not result in lower energy demand if no effort is made to ensure the system is sized to provide the same level of light as the less efficient system it replaced. All of these outcomes are possible unless steps are taken to also ensure that lighting-system performance is improved.

Lighting power density

But what system-performance benchmarks are appropriate and how should they be specified? The most common are limits on the maximum allowable installed lighting power density expressed in units of watts per unit area (square metre or foot). Such limits are set in all the US building code derivatives. An alternative approach is to set limits on lighting power density per hundred lux, which is favoured in the United Kingdom and France. This latter approach has the merit that the limit can be the same regardless of the illumination level required and thus is more generally applicable across a wider variety of spaces. It also avoids creating an unwanted incentive to attain low-energy lighting at the expense of following illuminance specifications. However, these advantages have to be weighed against the additional complexity of compliance verification, which requires both the power density of the lighting system to be determined and the illuminance that it provides to be measured. Some codes such as California's Title 24 have returned to using simple lighting power density requirements because they consider its advantages in ease of compliance testing to outweigh the other considerations.[2]

The rigour of thresholds expressed in existing codes is discussed on pp. 345–365, but while these provide a benchmark for the maximum acceptable lighting power density limits they are not adequate as benchmarks of good lighting performance. Numerous field studies and direct design experiments have shown that good electric lighting systems will attain appreciably lower lighting power density limits than are specified as maximum acceptable values in current building codes. In the

2. D. Goldstein, Director, Natural Resources Defense Council, United States, personal communication, 2005.

case of offices, for example, good-quality lighting that maintains required illuminance and luminance levels without glare has been achieved with lighting systems using as little as 5 W/m^2 without recourse to daylighting (Motiva, 1999). Good-quality office lighting with installed lighting power densities of 5 to 7 W/m^2 have been reported in many other sources too, although it is also clear that open-plan offices may have higher requirements than cellular offices (Novem, 1999).[3] Field studies have found even lower values in existing buildings, but these may well have been achieved at the expense of lighting quality (Kofod, 2001).

Given these findings it appears that good office lighting should be able to maintain high lighting quality without requiring an installed lighting power density of greater than 8 W/m^2. This transposes to a threshold of roughly 1.6 W/m^2 per 100 lux. If this figure is generally transposable across building types it implies that a typical office building (including circulation spaces, reception areas, meeting rooms, archive rooms, printing/photocopying spaces and offices) would need an average whole-building installed lighting power density of 3.9 W/m^2 to be illuminated to Illuminating Engineering Society of North America (IESNA) recommended levels. This is some 64% less than the most stringent current requirements in North American building codes.[4] This confirms that there is a large difference between minimum and best practice and implies there is further scope to both tighten existing minimum mandatory requirements and implement new non-regulatory policy measures to encourage more routine application of best practice.

Energy consumption per unit area benchmarks

The real benchmark of a lighting system's performance is not its installed lighting power density but its annual energy intensity, expressed as annual energy consumption per unit area. Such a metric takes account of how effective the lighting-control system is and how well daylight is exploited, in addition to all the factors influencing the installed power density. The problem with using metrics expressed in these terms for policy purposes is that in practice it is difficult to normalise lighting-system performance to take account of the occupancy of the building and behaviour of its occupants. All other things being equal, a building with high occupancy

3. M. Fontoynont, Director, Laboratoire Sciences de l'Habitat, Département Génie Civil et Bâtiment, ENTPE, Vaulx-en-Velin Cedex, France, personal communication, 2005.
4. An even higher saving is implied against European building code requirements in place in 2005.

rates will use more lighting energy than one with a lower occupancy because the lighting systems will be required to operate for longer periods of time. While it is possible to further normalise the metric by dividing the lighting energy intensity by the number of occupants and number of working hours (when known), this adds complexity and still provides an incomplete normalisation because, for instance, it does not take account of the overlap of working hours with the hours of daylight. Furthermore, the ability of a design to exploit daylight may be constrained by the site location. As a result, while the ultimate objective of lighting energy-efficiency policy may be to lower lighting energy intensity, it is difficult to meaningfully compare intensity benchmarks to be able to say what is good practice for a specific building. Nonetheless, were enough high-quality data samples to be available it would be possible to define good lighting energy intensity practice in statistical terms.

Vertical and horizontal policy measures "shave off the bottom" and "pull up the top"

A myriad of policy measures have been implemented to encourage energy-efficient lighting, and most have had some degree of success although without yet succeeding in transforming the whole lighting market toward least life-cycle cost (LLCC) options. In general these policies can be divided into regulatory measures, with the goal of removing the least efficient technologies and practices from the market, and other types of instruments and incentives that aim to encourage good practice.

Regulatory measures and the need for meaningful enforcement

As governments across the OECD have become more convinced of the existence of market barriers in this sector, there is increasing willingness to contemplate regulatory approaches, which have become increasingly common over the last decade. Regulatory measures may be characterised as those that apply horizontally at the system level (such as building codes that specify a minimum level of system energy performance) and those that apply vertically at the component level (such as by specifying a minimum energy performance level for a given type of lamp). Some nuances of this approach are to specify minimum fleet average requirements, as is the case in Japan's Top Runner programme, and to forewarn industry of future mandatory requirements by complementing existing mandatory performance thresholds with more ambitious voluntary targets, as is the case in Korea. In the case of building codes, these are divided into (a) those that explicitly specify lighting energy limits as either maximum lighting power density limits or maximum lighting power density per unit of illuminance, and (b) those that specify whole-building energy-performance requirements for which attention to lighting is just one of many potential routes to compliance. Combination codes are also possible by which both whole-building energy limits and lighting energy performance limits are set. This approach is relatively new but is likely to be effective because while it allows efficient lighting measures to contribute to whole-building performance targets, it sets a minimum lighting performance benchmark that focuses attention on the lighting installation (which is often a subcontractor's responsibility) and informs building developers or fitters of the degree to which the lighting is contributing to the overall performance target.

In addition to setting minimum energy performance requirements, regulatory measures are used that require some types of energy performance information to be measured and communicated, as is the case for mandatory energy labels for lamps or for some luminaire photometric measurements. Many countries, especially all EU countries as a result of the requirements of the Energy Performance in Buildings Directive (European Commission, 2002), are also requiring building energy performance to be measured, certified and displayed to end-users. Thus far these measures have focused on the whole-building energy performance where all end-uses are combined; however, it could make good sense to have a subsection explicitly displaying the lighting energy performance as either metered or audited values, because this allows users to ascertain how readily they can economise through retrofitting the lighting and simultaneously puts the work of lighting electrical contractors more firmly in the spotlight.

The main advantage of regulation compared with other measures is its higher certainty of outcome. Providing there is adequate monitoring and enforcement, a regulation will ensure that prescribed low-efficiency products are excluded from the market, thereby guaranteeing an energy-efficiency improvement. This certainty of outcome leads to a corollary advantage in terms of cost-effectiveness because regulations are generally cheap to establish and maintain compared to the value of the energy savings they induce. In practice though there have been many failures in how regulations have been implemented that have greatly reduced their impact. Many economies have conducted little or no market surveillance to ensure that there is compliance with requirements and when regulatory breaches have been identified there has often been a lack of willingness to prosecute offenders. This situation has been serious for component requirements, where some areas such as claimed product lifespan and luminous flux have been particularly laxly enforced, but is even worse for system energy performance requirements. While the very few compliance studies conducted have found routine breaches of building code lighting energy performance requirements, and in some cases have found no better compliance levels in regions with codes than those without, the authors of this study have been unable to identify a single case where a building contractor was sanctioned because of the installation of lighting systems that did not comply with building energy codes. If there is no practical sanction for non-compliance, regulations will have no greater impact than the issuance of guidelines; that is to say that they may well produce some positive results, but that their impacts will be far less than the intention.

There is a need then to set regulatory requirements that oblige reasonable system and component performance, ensure common and reliable metrics are used to establish this, ensure energy performance (especially comparative to comparable systems) is communicated to the market and are adequately enforced. To do this comprehensively implies a much more vigorous level of government activity than has been seen to date.

Regulations within or across product classes?

Thus far regulators have been cautious about considering lighting minimum energy performance standards (MEPS) that apply across lighting technologies. With the exception of LFLs, all the existing MEPS for lamps within OECD countries only apply to the specific lamp technology considered. Thus MEPs have been set for CFLs, incandescent lamps, certain classes of reflector lamp, LFLs, etc., but they have not been set across main lamp technologies. This is sensible when there is a key advantage for each technology such that there is no alternative technology that can compete to provide the same service; however, this is not always the case. In the residential sector, CFLs and incandescent lamps compete to provide the same service: the only service uniquely provided by the latter is a very high CRI.[5] Among HIDs there is competition between all three main technologies such that high-pressure sodium and mercury halide lamps both have some technical advantages that are unique to them, but mercury vapour lamps have no such distinction. In display lighting applications, ceramic metal halides compete with halogens, and both can provide the same lighting service. Thus while it is still inappropriate to impose minimum efficacy limits applying across all lighting types, there is broader scope than has hitherto been exercised to apply efficacy thresholds across lamp technology types. The obvious potential targets are:

- MEPS across LFL types.
- MEPS across HID types.
- MEPS to phase out incandescent lamps.

MEPS for LFLs

Some countries, such as the United States, Canada, New Zealand and Australia, currently apply MEPS across LFL types, but others still apply them to specific LFL types or have not yet established them at all. It is obviously easier to set MEPS when there is a higher-efficiency alternative that could slot directly into the existing fixture, as is the case when triphosphor T8 lamps are substituted for halophosphor T8 lamps, for example. It is less simple when fixtures would also have to be replaced, as applies when T12s are replaced by T8s or T5s in 120 V electricity networks, or when T8s are replaced by T5s anywhere. However, this does not preclude MEPS being used to force such a market change, especially if a sufficiently long lead time is permitted to allow fixture replacement cycles to run their course, e.g. it could be made illegal to sell T12 fixtures long before it is made illegal to sell the lamps.

MEPS for HID lamps

There are actually remarkably few countries applying MEPS to HID lamps, with China being one of the few to have done so and California being the only OECD jurisdiction. This is remarkable because the savings potential is significant both within product classes and across them. There is now

5. High-quality CFLs have high CRIs but will always have slightly lower values than incandescent lamps; see the discussion of this issue on pp. 101–107.

no good reason why low-efficacy HIDs, such as mercury vapour lamps, should not be prohibited, because there are higher-efficacy alternatives available which are better from all service-performance perspectives and that can fit directly into existing luminaires. There is also considerable savings potential to be had by setting MEPS within the remaining HID product classes.

MEPS to prohibit standard incandescent lamps

Many regulators have considered prohibiting standard incandescent lamps, but so far none has done it; however, the degree of regulatory courage required to take this step is not as great as it once would have been. First, in many OECD countries there is now likely to be support or little opposition from industry for such a measure because margins are so low on incandescent lamps that manufacturers are struggling to make profit from the business. The main alternative technology, that of CFLs, is more profitable and all OECD lamp manufacturers produce both. Second, the cost of CFLs has declined significantly so the price shock to consumers would be less of a hurdle, while previous technology-performance barriers such as CFLs not fitting into existing fixtures, incompatible CCTs, low CRIs, flicker and long warm-up times have been addressed.

Interestingly, it may well be a non-OECD country that is the first to take this step. Regulators in some non-OECD Asian and African countries are known to have been seriously considering this option. It could also be the case that standard incandescent lamps might first be regulated out of certain sectors, *e.g.* building codes could preclude the use of any lamp with an efficacy of less than say 25 lm/W in commercial and industrial buildings. This would preclude the use of normal incandescent lamps but also prohibit the use of standard halogen lamps in favour of more efficient infrared halogens.

"Pulling up the top"

The main weakness of regulatory measures is that they generally only limit the use of poor components and poor practice: they do not encourage the uptake of good or advanced practice, *i.e.* they do not "pull up" the most efficient end of the distribution. The exceptions to this are some types of labelling and certification schemes that may be mandatory and hence regulated but may make both low and high performance visible to the market. Regulatory measures will also generally only apply to new installations and hence do not directly influence the existing stock of lighting systems. If accelerated retrofit measures are desired, other policy measures have to be applied. The outcome of these measures is less certain than for regulatory actions, but nonetheless many have proved their worth and have been shown to be cost-effective in their own right. These measures include:

- Energy performance disclosure and labelling.
- Fiscal and financial incentives.
- Co-operative procurement.
- Technology procurement.
- Education and training.
- Awareness building and promotional campaigns.
- Voluntary agreements and corporate commitments.

These measures are discussed on pp. 504–520, and some of their strengths and limitations are summarised there.

Measures are needed to increase the use of daylight

Maximising the use of daylight, when properly done, has been found to be popular among building occupants, beneficial for human health and worker productivity and to greatly lower electric lighting energy requirements. Yet reaping the large available harvest through policy actions is much more challenging. With the exception of daylight-saving time, experience with policy measures to encourage daylight use in existing and new buildings is still in its infancy. Some building codes are now encouraging or requiring the use of daylight sensor and dimmer controls that enable available daylight to automatically offset electric-lighting requirements. Some are now demanding or encouraging the use of light wells and skylights in certain situations. The new European Energy Performance in Buildings regulations (European Commission, 2002) will encourage buildings that exploit daylight intelligently by enabling better ratings through either an asset[6] or a metered energy rating of building

6. An "asset" rating evaluates the energy performance of the building based on an analysis of the building characteristics as constructed and will use some set of algorithms to estimate its energy performance. "Operational" ratings determine its performance based on the metered energy bill.

energy performance in the form of building energy certificates (although lighting energy consumption is obviously mixed in with all other sources of energy consumption in such ratings). Regulations are yet to go so far as to require an array of daylighting features in new building designs or to set minimum daylight availability factors for interior spaces, although this is a conceivable development. There remains, however, great potential to educate practitioners, especially building and lighting designers, about how best to exploit and integrate daylight.

More work is needed to achieve the cost-effective potential

The cost-effective potential for energy-efficient lighting will only be "chipped away at" unless there is a comprehensive approach by all stakeholders. Chapter 5 documents the initiatives in IEA member countries and yet the large cost-effective savings potentials revealed through the analysis presented on pp. 409–422 show they are not yet sufficient. It is therefore apparent that more ambitious and comprehensive policy portfolios are required if this substantial savings resource is to be tapped. The potential elements of such a portfolio are discussed in the following section.

PROGRAMMES FOR THE FUTURE

The policy maker faces a quandary concerning what more, if anything, is needed to further promote energy-efficient lighting. There is a quandary because the energy-efficient lighting market is developing and some would question whether there is a need to do more. Yet policy makers can be in no doubt that the cost-effective potential remains high and the rate of deployment of energy-efficient lighting in many countries remains stubbornly low.

Experience has shown that no area of energy demand can be left alone, expecting to achieve the cost-effective potential. What government action should be is debatable, dependent on the state of market development nationally and the overall energy-efficiency objectives.

Some realignment of government programmes related to energy-efficient lighting is needed, with greater emphasis on government–industry partnerships and utility/ESCO programmes and obligations, and finally more international co-operation and collaboration. But most importantly, greater policy attention and effort is needed to make inroads into the cost-effective savings potentials presented by energy-efficient lighting.

Government programmes

In reviewing and revising government programmes, the following should be considered.

Minimum energy performance requirements for lighting systems

There is clearly value in introducing explicit lighting energy performance requirements into building codes. These can be implemented in a complementary manner to broader building energy performance requirements and can be applied in a dual approach where a developer can comply either by satisfying a prescribed maximum installed lighting power level for an entire building (the value would depend on the total area of the building and the type of building), or by satisfying prescribed space-specific maximum installed power level requirements for each type of space within the building (*e.g.* for corridors, storage areas, offices, reception areas, meeting rooms, dining areas, etc.). The requirements could be set in terms of just installed power levels or installed power levels per unit of luminous flux, as discussed on pp. 488–504. An important distinction is whether the requirements are set to apply to only new construction (in which case their influence on the building stock as a whole will be quite limited over the medium term) or whether they will also apply to major retrofits (*e.g.* where a substantial part of the lighting in the building is due to be retrofit). In the latter case the impact of the codes will be felt much earlier, at least in the commercial sector, where lighting retrofits occur about every 10 to 15 years in most OECD countries. Another critical issue for lighting building codes is the treatment of lighting controls. The most up-to-date codes in use internationally have either required or rewarded the use of lighting controls in the formulation of minimum requirements.

While non-residential buildings are the most obvious focus for such requirements, minimum lighting energy performance measures can also be specified in building codes for residential buildings. For example, the recent UK and Australian building codes require a number of the major lighting fixtures in new residential properties to be fitted with CFLs.

In the United Kingdom, dedicated CFL fixtures are specified so that incandescent lamps cannot be fitted afterwards without retrofitting the luminaire. California has also imposed requirements on the efficacy of light fittings in new housing.

For those countries that do implement lighting energy performance requirements in their building codes there is a critical need for code compliance to be monitored and enforced.

MEPS for components

MEPS have been shown to work for lamps, ballasts and luminaires, particularly as shown by the experience in the United States at both federal and state levels. The existing MEPS should be analysed to see how they could be strengthened to achieve even greater savings. Regions or countries with limited MEPS should consider expanding them beyond ballasts, while those without any MEPS should consider introducing them. While most MEPS target lighting products predominantly used in the commercial, public and industrial sectors, consideration should be given to their expanded use in the residential sector, where to date they have had limited application. Explicit possibilities for MEPs include the following.

MEPS for LFLs

While many OECD countries have already established MEPS for the main types of LFLs, many (most notably the European Union) have not. There is considerable scope in both OECD and non-OECD countries to remove inefficient LFL technologies such as T12 lamps and halophosphor T8 lamps by the application and strengthening of LFL MEPS. Furthermore, in those countries applying MEPS, many of the less common classes of LFL are exempt, including circular lamps, short-length LFLs, etc. These lamps may also warrant attention.

MEPS for luminaires

Thus far only California has implemented MEPS for luminaires, despite the very large range in luminaire energy performance that is found on every market. The key to introducing luminaire MEPS appears to be the identification of common categories so that within-class performance can be established. This is certainly possible for luminaires aimed at commercial, industrial and street lighting but has scarcely been attempted thus far. MEPS could be applied just for the luminaire but might make more sense if integrated into a system requirement for the luminaire/lamp/ballast package. Such requirements could be developed for LFL-, CFL- and HID-based luminaire packages. The residential market is more complex because the luminaires are more individualised and aesthetics are a primary factor, but even here it is possible in principle to design minimum requirements for specific categories of luminaire (table lamp, floor lamp, pendant lamp, etc.). In addition to pure energy concerns, MEPS for outdoor luminaires are also worthy of consideration to ensure that light is directed where it is needed and light pollution is avoided through a requirement for cut-off luminaires, for example.

MEPS for fluorescent lamp ballasts

All OECD countries now have MEPS for linear fluorescent ballasts, but in most cases there is potential to increase the minimum requirement to at least the level of standard electronic ballasts. This would be a highly viable policy option for those non-OECD countries that do not yet impose MEPS for LFL ballasts.

MEPS for CFLs

Policy makers concerned about poor-quality CFLs discouraging the adoption of good CFLs in the primary residential lighting market may wish to implement MEPs that include quality as well as efficacy requirements. These could specify minimum requirements for warm-up time, lifetime, lumen maintenance, power factor and colour rendering as well as efficacy. If environmental concerns are also included the mercury content might also be regulated (as could apply to LFLs). The stringency of MEPS set would need to consider the potential for undesired impacts on the price and availability of CFLs and strike an appropriate balance.

MEPS for tungsten halogen transformers

There is a wide variation in the performance of low-voltage transformers used for tungsten halogen lamps, whose losses range from 5% to 25% at full load depending on type and can be even higher at part load. This implies there is considerable potential to regulate the least efficient transformers from the market. No country has yet done this although it is under consideration in Australia (AGO, 2004a).

MEPS for tungsten halogen lamps

In many countries the market for low-voltage tungsten halogen lamps is of a significant size and growing rapidly. The infrared variety have a much higher efficacy than the non-infrared variety and hence there is a potential to introduce MEPS that phase out the latter; however, this may have to be tied to a transformer policy for the low-voltage units because many existing halogen transformers require full load to operate properly and hence there could be difficulties in the replacement market. The same constraints do not apply to mains-operated halogen lamps.

By contrast there is a strong argument on energy and safety grounds to phase out the highly inefficient halogen uplighters (torchières) in favour of their fluorescent alternatives.

MEPS for HID lamps

As there are no advantages for mercury vapour lamps except lower first cost in some cases (but significantly higher life-cycle cost), there is a strong argument in favour of their prohibition through MEPS; however, MEPS for HID lamps could also be designed to preclude poorer-efficacy high-pressure sodium and other less efficacious HID lamps. In the latter case this might entail setting MEPS that phase out probe-start metal halide lamps.

MEPS for HID ballasts

No country yet has MEPS for HID ballasts, but there is a wide range in HID ballast performance and considerable scope for improvement. When designing such regulations it may be important to consider the dependencies that can exist between types of lamps and available ballasts as such dependencies may imply that permitted ballast losses should be higher in some cases than in others.

MEPS for incandescent lamps

Despite an appreciable difference in the efficacy of equivalent incandescent lamps, thus far many countries have decided not to introduce MEPS that allow only the relatively less inefficient models onto the market. This is driven by a thought that the route to follow is not to try to maximise the efficacy of an inherently inefficient technology, but to encourage the use of more efficient fluorescent technology in its stead.

However, the two goals are not exclusive, especially if the regulator is not prepared to consider setting MEPS that ban all incandescent lamps. Setting MEPS that only allow higher-efficacy incandescent lamps onto the market will tend to increase the average price of incandescent lamps and lower the price differential between them and CFLs. However, expectations regarding the impact of incandescent lamp MEPS should not be exaggerated. As incandescent lamps are almost invariably marketed according to their wattage rather than their light output, the resulting efficacy improvements per lamp are likely to translate into higher light levels rather than energy savings. The same argument is likely to apply in the case of MEPS for incandescent reflector lamps, but less so for halogen-based reflector lamps, for which the lamp power ratings (wattage values) are less resonant in their marketing.

MEPS for traffic signals and exit signs

Traffic signals and exit signs using incandescent lamps can no longer be justified given the far higher efficiency LED alternatives that exist. There is a strong argument in favour of countries following Canada's lead and adopting MEPS that preclude the use of incandescent lamps in new products.

MEPS for street lighting

In order to speed local authority transition over to higher-efficacy public lighting it may be appropriate to consider imposing MEPS for street lighting as a system. This could incorporate all the aspects that affect street-lighting energy use (lamp, ballast, luminaire, lighting-control system and system design) through the form of a system-based energy limit applying to all new road-lighting installations. The requirement could be expressed in terms of maximum permissible power limits per linear distance for a given road category on the condition that specified minimum illuminance levels are attained.

In many countries thermal photoelectric cells are used to regulate street lighting, but these are liable to failure and drift, which causes the lights to be wrongly illuminated during daylight hours as a fail-safe measure (AGO, 2004a). Newer-generation photoelectric cells avoid this problem and thus offer an energy-saving opportunity that could be appropriate for MEPS either independently or within the broad-based scheme outlined in the preceding paragraph.

Energy labels

Energy labelling, whether mandatory or voluntary, is an important means of providing consumers with appropriate information at the point of sale. However, since lamp packages are small, labels are not as obvious as they are on a refrigerator, for example. Nonetheless, labelling is an essential vehicle to making energy performance visible to the market. More emphasis must be given to bringing the energy-efficiency message more directly to the consumer and a label is obviously one means of doing this. However, the impact of a label can be strengthened through additional actions designed to bolster its weight in the sales argument, such as the training of sales staff and the use of in-store explanatory leaflets. Labelling needs to be combined with awareness campaigns, including making available literature that is not normally present in stores. Other innovative approaches can also be helpful, such as educating schoolchildren about the purpose and use of the labels.

Energy labels also need to better highlight the inefficiencies of incandescent bulbs or low-voltage halogens. While it may be deemed premature to remove them from the market, their energy-efficiency characteristics can be better displayed.

Explicit potential targets for energy labels include all the components mentioned in the section on MEPS above, but with the following observations.

- Endorsement or mandatory comparative energy labelling can be applied.
- It is desirable for the same performance metric to be used for labelling as is used for MEPS and for the MEPS and labelling revision process to be coordinated to maximise the joint market-transformation impact.
- Regulators should be aware that in the case where fundamentally different lamp technologies compete with one another a decision must be taken on whether to design a label that is common across the diverse technologies or only applies within each technology class (the former allows direct energy performance comparison across types while the latter allows greater comparison within types, so the most appropriate choice depends on how likely the label is to influence a decision to move from one lamp type to another compared to choosing a relatively efficient lamp within type: a dual or hybrid

approach is also conceivable). Independently of the direct point of sale market-transformation impact that a label may have, it could also be a means of increasing general knowledge of lamp energy performance and quality if designed to communicate basic performance information.

- It is often argued that lamps which are aimed at the non-residential sector are not in need of labelling because they are bought in bulk by professional customers who can read the performance information they require in the product catalogues; however, policy makers should not underestimate the value that requiring the display of performance heuristics in a catalogue can have on professional lighting markets. If lighting catalogues and internet sites were to indicate the energy rating of the lamp using a simple heuristic device (such as a derivative of the EU's A-to-G scheme, for example) it would allow relatively efficient lamps to be immediately apparent and could facilitate the communication of the added value from selecting efficient lighting through the supply chain.

As with MEPS, performance claims made on labels need to be policed if they are to be credible. There have been frequent and increasing accusations of substandard lighting products being sold on OECD markets and there is a growing concern about the validity of claims made on lamp labels. The recent rise in the number of counterfeit brands, even on OECD markets, is another (yet related) cause for concern. Regulatory authorities need to monitor and enforce their regulations if they are to be respected, and additional resources may need to be allocated to this task.

Financial and fiscal incentives

There is limited use of financial incentives to promote energy-efficient lighting. There is the possibility of subsidising CFLs, and this has taken place, at least as part of awareness "give-aways". Some countries support energy audits and a criterion for support could be that the lighting systems are included in the audit. Consideration could be given to allowing energy-efficient lighting systems to be eligible for some type of accelerated depreciation for business tax deduction calculations. In particular this would be true for building retrofits as opposed to new construction.

Financial support for municipal street lighting that deploys the most energy-efficient options should be considered.

Procurement programmes

Technology and bulk-procurement programmes have been popular and effective. These could be expanded for lighting technologies and could be particularly effective for public-sector procurement programmes. Encouraging business to establish internal bulk-procurement programmes for efficient lighting technology is another useful avenue to be pursued. This can be encouraged just through contact and awareness building or by more direct incentives such as free audits and financial or regulatory incentives (*e.g.* being able to reduce carbon or eco-tax obligations through implementation of practical energy-efficiency measures such as energy-efficient lighting).

Good candidates for bulk-procurement programmes are high-quality CFLs and dedicated CFL luminaires, LED traffic signals and exit signs, lighting controls, efficient street lights, etc. Good candidates for technology procurement activities are high-efficacy LED and organic LED (OLED) applications, specific types of high-efficacy luminaires, superior fluorescent lamps and optimised next-generation lighting controls.

Information and awareness raising

There are many possibilities for expanding information and awareness programmes. National and regional awareness campaigns are beneficial and can be expanded by running them on a regular basis and by increasing the number of partners participating in the programme. Campaigns can also be organised at the local level.

Campaigns can be directed specifically at the commercial, public and industrial sectors as well. These can be organised through business associations, utilities or directly appointed governmental agencies. Companies, through their intranet, can have awareness campaigns within their own organisations.

As discussed above, support material and training for energy-labelling programmes can be expanded. Utilities and lighting manufacturers can participate. Design competitions should be expanded, particularly since there is a need for more specific luminaires for energy-efficient lighting options.

Demonstrations, which are a form of information, are particularly important in the commercial and public sectors where building managers need to have a more immediate and visual expression of results. Demonstrations can be of lamps, luminaires and control systems. They can include a thorough examination of costs and the full range of benefits. They can also show how integrated energy-management systems can include lighting into the overall system.

Education programmes for schoolchildren will have long-term benefits at fairly low cost. A better understanding of life-cycle costs, of the environmental costs and benefits and of the full range of benefits is very important. Energy-efficient lighting should be explained as part of the solution for addressing global climate change.

Voluntary agreements

Most IEA member countries use voluntary agreements. They are mainly used for the industrial, commercial and municipal areas. Normally these agreements set targets based on cost-effective potential. The agreements usually have combined energy and environmental benefits. The participation in voluntary agreements often leads to lower taxes or some other form of benefit. These voluntary agreements would not normally exclude lighting, but nor do they give them great prominence. Voluntary agreements should be reviewed as to whether they are adequately addressing energy-efficient lighting, and the necessary revisions should be made if they are not.

Outdoor-lighting ordinances

There has been a strong growth in the number of municipalities and local authorities issuing outdoor-lighting ordinances over the last decade. The objective of these ordinances is essentially to reduce or limit light pollution and light trespass while reducing outdoor-lighting energy use. The methods applied are diverse but involve setting constraints on some mixture of: the amount of outdoor lighting that can be used; the hours of use; and the angle of light emission, orientation, control and efficacy of outdoor luminaires. There is clearly a role for central government to encourage, facilitate and coordinate such initiatives.

Government–industry partnerships

Initiatives often work best when developed and implemented in partnership with the lighting industry (manufacturers and retailers). To date, there has been good collaboration between government and industry. This should continue and be expanded. Areas where there can be significant benefits include general awareness campaigns, information support for energy-labelling programmes, technology procurement actions, R&D and demonstrations. Partnerships can include more than lighting manufacturers (lamps and luminaires) and retailers. They can also include consumer and environmental groups, the media and local governments.

Capacity building among lighting specifiers and installers

Improving knowledge about energy-efficient lighting among those who specify and install lighting systems should be a high priority if a significant improvement in lighting energy efficiency is to occur. Government can take the lead in conjunction with industry in organising training and training materials for lighting specifiers and installers.

Utility and energy-service programmes

Electricity distribution companies have a unique role because they have direct access to consumers of all end-use sectors. Utilities have been involved since the late 1970s, either through obligation or voluntarily, in promoting energy efficiency through demand-side management (DSM) activities. Depending on the IEA member country, these efforts have waxed and waned, in part because of the move towards deregulation and greater supply-side competition. There were thoughts that greater competition among utilities might encourage them to embrace DSM activities because promoting energy efficiency would be seen as a service that could distinguish one company from another; however, this has not occurred to the point where it can be depended upon. The move towards mandated DSM is coming back in many IEA member countries. This, in part, is occurring to correct some deficiencies in the liberalisation process. Energy-efficient lighting is an important area for DSM activities. Where possible in the residential sector, it should focus on more than just CFLs. For the commercial and public sectors, it should focus on best practice.

Third-party financing

As incremental first costs are a key barrier to energy-efficient lighting, the provision of third-party financing through ESCOs or other financing facilities is a proven means of funding energy-efficiency projects in the commercial, public and industrial sectors as well as for street lighting. While ESCOs have been active for more than two decades, there is still considerable scope for growth in most IEA member countries. Lighting is a natural area for such financing because, following a detailed audit that provides baseline data and identifies potential savings, lighting systems can easily be installed and monitored. In the course of the contract negotiations, the end-user would stipulate the lighting hours and the lighting intensity expected and a formula may be agreed to take account of variations.

The Energy Charter (2003) report on third-party financing makes an important distinction between energy performance contracting and traditional contracting:

"Performance contracting through an energy service company transfers the technology and management risks away from the end-user to the energy service company. A fundamental difference between traditional contracting (detailed technical specification, price offers) and performance contracting is that traditional contracting is price driven. The emphasis in traditional contracting is on achieving the lowest price for a known specification. In performance contracting, the emphasis, by contrast, is on results, i.e. *on the outputs rather than the inputs."*

Another key difference between performance contracting and traditional contracting is the provision of the package of services from a single supplier (the ESCO) as opposed to contracting the engineering design from one company, supply and commissioning from another, and/or maintenance from a third.

International co-operation

There is significant scope for further international co-operation at different levels: among governments through international organisations such as the IEA (including through its implementing agreements), through international financial institutions, in partnership with industry and industry associations including utility associations, through voluntary programmes such as ENERGY STAR (which has spread beyond the United States to many IEA member countries) and through non-governmental bodies. There is also an important role for international development agencies and multilateral development banks to encourage and support initiatives that promote energy-efficient lighting in developing countries.

Some examples of existing international co-operative efforts worthy of mention include the Efficient Lighting Initiative (ELI), the European GreenLight Programme and the International CFL Harmonization Initiative, which are all discussed in Chapter 5.

The IEA Implementing Agreements have already conducted important research work on daylighting through the Energy Conservation in Buildings and Community Systems (ECBCS) and Solar Heating and Cooling (SHC) Task 21 and 31 activities, and ECBCS is currently engaged in research on energy-efficient lighting through its Annex 45 activity. Part of the mandate of the latter Annex encompasses a review of lighting building code specifications, which is highly relevant for policy makers. However, more international collaborative work is still needed on policy-specific areas if policy development is to be optimised. There is a need for much better lighting end-use data and for an international data repository, for example, which would enable lighting energy use to be better quantified and performance indicators established.

Finally...

Governments and industry need to find the right balance to pull it all together, combining good policy and good marketing. Lighting is vital for the lifestyles and work practices enjoyed in IEA countries. Technologies are evolving, markets are growing. The design of programmes that reflect the dynamic character of the marketplace is necessary.

Drawing consumers towards a more energy-efficient approach is not impossible because there are many benefits to the individual and the country. Somehow the consumer needs to better understand the benefits and the options. That takes good market analysis and a better understanding of consumer needs and consumer behaviour in all sectors. It is clearly within the reach of both OECD and non-OECD governments to do better. Reaching more of that potential brings so many benefits to both energy-policy and environmental-policy goals. And new programmes are not high cost. They should fit well within the resources of existing strategies.

Keeping the lights on is so important in our modern societies, but it is equally important and wholly consistent to ensure that those lights are as energy-efficient and cost-efficient as possible.

Explicit policy recommendations

The fulfilment of such policy objectives requires the adoption of specific policy measures, which in turn may require the establishment of a mixture of implementation programmes and regulatory measures.

It is recommended that countries consider the following.

1. Adoption of mandatory energy performance requirements for lighting systems in all lighting end-uses.

MEPS may be developed for residential, commercial/industrial and outdoor applications, whereas today such requirements usually only cover the commercial/industrial sector. Wherever possible, requirements should be performance-based and not prescriptive with respect to certain technologies. Performance requirements are needed at the level of both whole lighting systems and system components (lamps, ballasts and luminaires/fittings, since these are often "mixed and matched"), and should be based on realistic test procedures. Performance requirements should target the LLCC for the lighting system, using (shadow) energy prices adjusted to reflect the value of associated greenhouse gas emissions. They also need to take into account: (i) an appropriate mix of peak and off-peak electricity prices (reflecting the incidence of lighting demand in peak system demand, and the duration of peak system costs; and (ii) the indirect parasitic energy implications of lighting (higher air-conditioning loads, but lower space-heating loads). Performance requirements should be updated regularly (at 3- to 5-year intervals) to reflect changes in life-cycle costs.

2. Adoption of mandatory building codes, or other regulations, that set maximum lighting power density limits for all building types.

Performance requirements are necessary at the level of whole buildings (*i.e.* lighting applications), since even with highly efficient components, lighting applications can be inefficient, *e.g.* through excessive lighting density. In the majority of IEA countries specific lighting requirements are either not yet in place or only apply to indoor lighting of newly constructed non-residential buildings. Policy makers should consider the establishment of requirements where none exist, the broadening of current requirements to encompass all building types including residential buildings and major retrofits of existing buildings, and the establishment of requirements for outdoor lighting.

3. Building codes requiring lighting-control systems that allow separate switching and regulation for each room or work area, rather than whole floors or buildings.

Inadequate deployment of switching and controls for lighting systems is an important source of energy inefficiency. Increasingly, controls are able to regulate luminaire output as a function of daylight availability, occupation of the illuminated space and/or time of day. Such controls should be encouraged, or required, when cost-effective on a life-cycle-cost basis.

4. Strengthening of the enforcement of existing regulatory requirements, particularly building codes.

While all IEA countries have energy provisions in their building codes and many have implemented or are developing lighting provisions, the enforcement of these provisions appears to be seriously neglected and reported compliance levels remain low. Countries are urged to pay much greater attention to this issue as its neglect is currently seriously undermining the effectiveness of public policy objectives.

5. Adoption of whole-building energy-performance codes and building energy-performance certification.

IEA member states are increasingly adopting building codes that assess whole-building energy performance as opposed to just prescribing performance limits for specific components. This is to be encouraged as it enables all aspects of building energy performance to be taken into account, including lighting, on an equal basis. Many IEA countries are also adopting building energy performance certification and disclosure labelling, which enables market actors to see the energy efficiency of the building stock and take more rational market decisions accordingly. This practice is encouraged but it is also proposed that the certificates might be designed to report lighting energy both within the whole-building rating and as a separate element. The latter will allow short- to medium-term tenants (especially in the tertiary-building sector) to consider the viability of lighting-system upgrades independently of more costly fabric and heating, ventilation and air-conditioning-based measures.

6. Comprehensive labelling of lamps, fittings and whole systems, backed by effective point-of-sale and reference information.

Mandatory comparative energy-performance labels should be carried by all lamps and all lamp fittings/systems (where the lamp and fitting are sold together as one unit, or where the fitting only allows one type of lamp to be used). In this case, the fitting should be labelled "As sold", *i.e.* tested with the lamp actually fitted for sale. Where this is not possible, a generic warning label could be considered, *e.g.* "Warning: this light fitting is not suitable for low-energy lamps". "Low-energy lamps" would be defined with reference to the performance standards referred to in the first recommendation above. Point-of-sale information and reference materials should be provided to explain the meaning of labels and to assist consumer research. Today, labelling is often voluntary, covers only a portion of the lamps on the market and generally does not apply to fittings.

7. Market-transformation initiatives to overcome market barriers for energy-efficient lighting technologies.

Such initiatives may be technology-neutral (*e.g.* provide assistance for the commercialisation of lamps that achieve a certain performance level) or technology-specific, targeted to overcoming specific barriers unique to one technology (such as the relative bulk of CFLs). There are numerous successful examples of such programmes from the US ENERGY STAR and Green Buildings initiatives to the China Greenlights programme and the United Kingdom's Energy Efficiency Obligation. It is recommended that all countries consider such initiatives and that those which already have them consider extending their ambition.

8. Governmental removal of barriers to the efficient operation of energy service providers.

Energy service providers, such as ESCOs, comprise an important delivery mechanism for energy efficient lighting, particularly for the business sector. However, ESCOs have generally suffered as a result of the liberalisation of electricity markets, which has reduced the market presence of efficient-lighting options. Market regulators may wish to review the extent to which demand-side service options are able to compete fairly under current regulatory frameworks and to consider implementing policies to address any problems identified. Some recently implemented approaches with great promise include systems benefits charging, energy-efficiency obligations and white certificate schemes (see Chapter 5).

9. Governmental support of public-interest R&D into new lighting sources and applications.

Some countries provide significant support for R&D efforts designed to bring to the market new lighting concepts and technologies. Given the limitations of some existing energy-efficient lighting technologies, ongoing support is required to deliver broadly acceptable and energy-efficient lighting solutions. Where such research is "near to market", public–private partnerships may be an important delivery mechanism.

10. Donor and development agencies and multilateral banks should work with developing countries to promote solid-state off-grid lighting.

The plight of the 1.6 billion people using fuel-based lighting could be significantly improved were they to have access to affordable and superior-quality lighting. Recent advances with WLEDs have dramatically improved the cost-effectiveness, durability, longevity and overall viability of standalone photovoltaic-powered lighting systems. It is recommended that an international development effort be considered to accelerate the spread of this technology to those in most need of it.

It is recommended that policy makers establish comprehensive policy portfolios such as these at the earliest opportunity and, most importantly, identify and commit appropriate resources for their successful implementation.

It is further recommended that policy makers conduct a full market-characterisation survey and develop baseline and policy targets (if this has not already been done) so that the ambition and expected effectiveness of the policy portfolio can be realistically gauged while allowing strengthening of the policy mix if required.

GLOSSARY

accent lighting: highlighting of displayed merchandise or the features of a shop or building.

albedo: the proportion of light or radiation reflected by a surface.

ambient lighting: lighting that produces general illumination throughout an area.

average illuminance: the illuminance (lux) averaged over an area.

ballast: a device that provides the circuit conditions necessary to start and operate electric discharge (fluorescent and high-intensity discharge) lamps.

ballast factor: the fractional flux of a lamp(s) operated on a ballast compared to the flux when operated on a reference ballast specified for rating lamp-lumens.

billion: 1×10^9, *i.e.* 1 000 000 000.

British thermal unit (Btu): unit of energy equivalent to 1.055 joules.

candela (cd): the SI unit of luminous intensity. One candela is one lumen per steradian. Formerly "candle".

ceramic metal halide lamp: a type of metal halide high-intensity discharge lamp containing ceramic.

chromaticity: the dominant or complementary wavelength and purity aspects of the colour taken together, or the aspects specified by chromaticity coordinates of the colour taken together.

clerestory: an upper row of windows or (raised) glazed section of a roof.

coefficient of performance (COP): the cooling power of an air-conditioning system (measured in watts) divided by the input electrical power (measured in watts).

coefficient of utilisation (CU): the ratio of the luminous flux (lumens) from a luminaire received on the working plane to the luminous flux emitted by the luminaire's lamps alone.

cold-cathode fluorescent lamp (CCFL): a very thin low-pressure fluorescent lamp that creates a discharge current by ionic bombardment of the cathode rather than via thermionic emission, which is the technique used by standard fluorescent lamps. CCFLs are used for exit signs and backlighting of monitors. Neon fluorescent lamps are also a type of CCFL.

colour rendering: general expression for the effect of a light source on the colour appearance of objects in comparison with their colour appearance under a reference light source.

colour rendering index (CRI): a measure of the degree of colour shift an object undergoes when illuminated by the light source, as compared with the colour of the same object when illuminated by a reference source of the same colour temperature.

compact fluorescent lamp (CFL): a fluorescent lamp with bent tubes to reduce the size of the lamp. A CFL is constructed either with an integrated ballast, in which case it is designed to be directly interchangeable with a general lighting service lamp, or in a modular form where the ballast is supplied independently of the fluorescent tube.

contrast: the difference between the brightness of an object and that of its immediate background.

correlated colour temperature (CCT): a measure to describe the quality of a light source by expressing the colour appearance correlated with the black body locus. CCTs of 4 000 K or higher appear as white and cool, while CCTs of less than 3 000 K have a warm colour appearance.

cut-off luminaire: a luminaire designed to limit light pollution by ensuring the cut-off angle at which light can be viewed from the luminaire (*i.e.* the angle between the vertical axis [nadir] and the first line of sight when the bare source is no longer visible) is not greater than 90°.

daylight factor: the ratio of the illuminance received at a point indoors from a sky with a known luminance distribution (usually an overcast sky) to the horizontal illuminance outdoors from an unobstructed hemisphere of the same sky. The ratio is expressed as a percentage. Direct sunlight is excluded from both values of illuminance.

daylight-saving time: also known as "summer time"; the practice of advancing local time by a certain period (most commonly one hour) during the summer months in order to maximise the coincidence of the hours when people are awake with the availability of daylight. Applying daylight-saving time saves energy because it reduces the need for artificial lighting.

daytime running lights: dedicated headlamps designed for use during the day, with the purpose of increasing the visibility of a vehicle to oncoming traffic. They are usually operated independently of other lights, such as rear lamps, side markers, parking lamps, licence plate lights, etc., and are often of reduced power compared to full-beam headlamps. They thus require less energy during operation than conventional full-beam headlamps.

delamp: the process of removing lamps from a lighting installation, usually to bring the light levels into line with recommended values or in response to some other change to the lighting system.

demand-side management (DSM): the methods used to manage energy demand, including energy efficiency, load management, fuel substitution and load building.

dichroic: showing two colours, especially for doubly refracting crystals.

diffuser: a device to redirect or scatter the light from a source, primarily by the process of diffuse transmission.

diffuse ratio: the ratio of the flux leaving a surface or medium by diffuse reflection to the incident flux.

diffuse reflection: the process by which incident flux is redirected over a range of angles.

diode: a semi-conductor device that allows current to flow only in one direction and has two terminals.

direct lighting: lighting by luminaires that distribute 90–100% of the emitted light downwards.

downlighter: a small, direct-lighting unit that directs the light downward and can be recessed, surface-mounted or suspended.

efficacy: also known as the "luminous efficacy of a light source"; the ratio of light from a lamp (measured in source-lumens) to the electrical power (watts) consumed, expressed in lumens per watt (lm/W). System efficacy includes the ballast losses.

emissivity: the ratio of energy radiated by a material to energy radiated by a black body at the same temperature. It is a measure of a material's ability to absorb and radiate energy.

fluorescence: the property of absorbing light of short (invisible) wavelength and emitting light of longer (visible) wavelength.

flux: see "luminous flux".

footcandle (fc): the unit of illuminance when the foot (30 cm) is taken as the unit of length. It is the illuminance on a surface of one square foot in area on which there is uniformly distributed flux of one lumen, or the illuminance produced on a surface, all points of which are at a distance of one foot from a directionally uniform point source of one candela (1 fc = 10.76 lux).

general lighting service (GLS) lamp: always used to refer to a standard incandescent light-bulb.

glare: the discomfort or sensation produced by luminance within the visual field that is significantly greater than the luminance to which the eyes are adapted.

halogen lamp: a class of incandescent lamps containing a halogen gas that recycles tungsten (which would normally be deposited onto the bulb wall during lamp operation) back onto the filament surface.

high bay: a term used to refer to lighting in industrial or certain commercial building environments where lamps are mounted at high heights.

high-intensity discharge (HID) lamp: an electric discharge lamp in which the light-producing arc is stabilised by wall temperature and the arc tube has a bulb-wall loading in excess of 3 W per square centimetre. HID lamps include mercury vapour, metal halide and high-pressure sodium light sources.

high-pressure sodium lamp: a type of high-intensity discharge lamp that contains pressurised sodium vapour.

illuminance: the amount of light (strictly, the luminous flux) incident on a surface/plane per unit area; measured in units of lux (lm/m^2).

incandescence: the emission of light through being heated, *i.e.* glowing.

indirect component: the portion of the luminous flux from a luminaire arriving at the working plane after being reflected by room surfaces.

indirect lighting: lighting by luminaires that distribute 90–100% of the emitted light upwards.

kilolumen-hour (klmh): 1 x 10^3 lumen-hours; a quantity of light.

LED driver: a device to power and control a light-emitting diode.

lens: a glass or plastic element used in luminaires to change the direction and control the distribution of light rays.

light: radiant energy that is capable of exciting the retina and producing a visual sensation. The visible portion of the electromagnetic spectrum extends from about 380 nm to 770 nm.

light-emitting diode (LED): a semi-conductor device that emits light when a current is passed through it.

light shelf: a classic daylighting system known to the Egyptian Pharaohs that is designed to provide shade and reflect light on its top surface and to shield direct glare from the sky. A light shelf is generally a horizontal or nearly horizontal baffle positioned inside and/or outside a window façade. The light shelf can be an integral part of the façade or mounted on the building.

light trespass: a situation that occurs when light from a source is emitted into areas where the light is unwanted.

light well: a skylight with relatively deep walls that diffusely reflect daylight and thereby minimise glare and maximise light distribution in the space below.

linear fluorescent lamp (LFL): a straight fluorescent lamp.

louvre: a series of baffles used to shield a source from view at certain angles or to absorb unwanted light. The baffles are usually arranged in a geometric pattern.

low-pressure sodium lamp: a type of discharge lamp that contains low-pressure sodium vapour.

lumen (lm): SI unit of luminous flux. Radiometrically, it is determined from the radiant power. Photometrically, it is the luminous flux emitted within a unit solid angle (one steradian) by a point-source with a uniform luminous intensity of one candela.

lumen-package: a term used to indicate the amount of light, measured in lumens, that a lamp emits.

luminaire: a complete lighting unit consisting of a lamp (or lamps), or ballasts where applicable, together with the parts designed to distribute the light, position and protect lamps and connect them to the power supply.

luminaire efficiency: also known as the "luminaire output ratio" (LOR); the ratio of luminous flux (lumens) emitted by a luminaire to that emitted by the lamp or lamps used therein.

luminaire output ratio (LOR): also known as the "luminaire efficiency"; the ratio of luminous flux (lumens) emitted by a luminaire to that emitted by the lamp or lamps used therein.

luminance: the luminous flux emitted in a given direction divided by the product of the projected area of the source element perpendicular to the direction and the solid angle containing that direction, *i.e.* luminous intensity per unit area; measured in units of candela per square metre (cd/m^2). In effect it is the physical measure of the subjective sensation of brightness.

luminous efficacy: the quotient of the total luminous flux emitted by the total lamp power input; expressed in lumens per watt (lm/W).

luminous flux: the quantity of radiant flux that expresses its capacity to produce visual sensation; measured in units of lumens (lm).

luminous intensity: the luminous flux emitted in a very narrow cone containing the given direction divided by the solid angle of the cone, *i.e.* luminous flux per unit solid angle; measured in units of candela (cd).

lux (lx): the SI unit of illuminance; one lux is one lumen per square metre (lm/m^2).

MacAdam ellipse: the standard deviation in the chromaticity coordinates for colour matches made between two small visual fields, with the reference field being at the centre of the ellipse. The lighting industry generally considers the colour characteristics of two lamps to be "matched" if they are within a range of four MacAdam ellipses of each other on the CIE chromaticity chart (see Plate 3.3).

megalumen-hour (Mlmh): 1×10^6 lumen-hours; a quantity of light.

megatonne (Mt): 1×10^6 tonnes; a quantity of weight.

mercury vapour lamp: a type of high-intensity discharge lamp that contains mercury vapour.

metal halide lamp: a type of high-intensity discharge mercury vapour lamp that contains metal halides.

Mt of CO_2 emissions: megatonne of CO_2 emissions (*i.e.* 1×10^6 tonnes of CO_2). Not to be confused with Mt of C (which is 1×10^6 tonnes of carbon and is converted to Mt of CO_2 through multiplying by 3.46).

nit: the SI unit of luminance, expressed as candela per square metre (cd/m^2).

organic light-emitting diode (OLED): a semiconductor device made from an organic compound (*i.e.* one that contains carbon) and which emits light when a current is passed through it.

petalumen-hour (plmh): 1×10^{15} lumen-hours, a quantity of light.

photopic: related to daytime illumination levels in which the eye is adapted to light and vision is supported by the cone photoreceptors.

point-source: an idealised light source that emits light from a point rather than from the surface of a solid form.

power factor (PF): ratio of the real power to the apparent power in a circuit, where the real power is the capacity of a circuit to perform work in a particular time and the apparent power is the product of the voltage and current in the circuit; the apparent power will be greater than or equal to the real power.

Quad: shortened form of "quadrillion Btu" (US form of peta, *i.e.* 1×10^{15}) and used in US English to denote 1×10^{15} British thermal units (Btu) of primary energy; 1 Quad of primary energy is equal to 1.055 exajoules, *i.e.* 1×10^{18} joules.

quality of light: pertains to the distribution of luminance in a visual environment. The term is used in a positive sense and implies that all luminances contribute favourably to visual performance, visual comfort, ease of seeing, safety and aesthetics for the specific visual tasks involved.

rapid-start fluorescent lamp: a fluorescent lamp designed for operation with a ballast that provides a low-voltage winding for preheating the electrodes and initiating the arc without a starting switch or the application of high voltage.

reflectance: the ratio of the luminous flux reflected from a surface to the luminous flux incident upon it.

reflection: characteristic of a surface to return (bounce back) light or energy. Various surfaces will reflect light in different ways, *i.e.* specular or diffuse surfaces.

reflector: a device used to redirect the luminous flux from a source by the process of reflection. See “retroreflector”.

regular (specular) reflectance: the ratio of the flux leaving a surface or medium by regular (specular) reflection to the incident flux. See “regular (specular) reflection”.

regular (specular) reflection: the process by which incident flux is redirected at the specular angle.

retroreflector (reflex-reflector): a device designed to reflect light in a direction close to that at which it is incident, whatever the angle of incidence.

scotopic: related to night-time illumination levels in which the eye is adapted to dark and vision is supported by the rod photoreceptors.

semi-indirect lighting: lighting by luminaires distributing 60–90% of their emitted light upwards and the balance downwards.

SOI lamp: indium-oxide low-pressure sodium lamp emitting light of a greenish hue.

solid-state lighting (SSL): lighting from solid-state devices such as light-emitting diodes and organic light-emitting diodes.

source-lumens: lumens emitted by a light source, *i.e.* from a lamp as opposed to a luminaire.

SOX-E: high-efficacy, low-pressure sodium lamp emitting light of a reddish hue.

SOX lamp: standard tin-oxide low-pressure sodium lamp emitting light of a yellow/orange hue.

specular surface: shiny or glossy surface (including mirrors and polished metal) that reflects incident light.

steradian: the SI unit of solid angle, equal to the angle at the centre of a sphere subtended by a part of the surface equal in area to the square of the radius.

suspended or pendant-mounted luminaire: any luminaire that is suspended from a ceiling by a support or supports.

task lighting: lighting directed to a specific surface or area that provides illumination for visual tasks.

teralumen-hour (Tlmh): 1×10^{12} lumen-hours; a quantity of light.

thermionic: of or related to electrons emitted from a substance at very high temperature.

torchière: a tall pedestal (standing) lamp that throws light upwards, also known as a torchère or uplighter.

translucent: allows light to pass through without being transparent, scattering or diffusing light so that objects cannot be seen through the material.

troffer: recessed lighting unit, usually long and installed with the opening flush with the ceiling. The term is derived from "trough" and "coffer".

uplighter: see "torchière".

veiling reflections: luminous reflections from specular or semi-matt surfaces that physically change the contrast of the visual task and therefore change the stimulus presented to the visual system.

visual acuity: a measure of the ability to resolve the detail of a target with a fixed luminous contrast.

visual comfort probability (VCP): the rating of a lighting system expressed as a percentage of people who, when viewing from a specified location and in a specified direction, will be expected to find it acceptable in terms of discomfort glare. Visual comfort probability is related to discomfort glare rating.

working plane: the plane at which work is usually done and on which illuminance is specified and measured. Unless otherwise indicated, this is assumed to be a horizontal plane 76 cm (30 inches) above the floor.

ABBREVIATIONS AND ACRONYMS

AC	alternating current
AGO	Australian Greenhouse Office
ANEEL	Agência Nacional de Energia Elétrica (Brazilian Electricity Regulatory Agency)
ANSI	American National Standards Institute
ASEAN	Association of Southeast Asian Nations
ASHRAE	American Society for Heating, Refrigeration and Air-Conditioning Engineers
ASSIST	Alliance for Solid-State Illumination Systems and Technologies
ATLAS	Action for Training in Land Use and Sustainability (European Union)
BCA	Building Code of Australia
BEF	ballast efficacy factor
BEMS	building energy management system
BRE	Building Research Establishment (United Kingdom)
Btu	British thermal unit
C	carbon
CADDET	Centre for the Analysis and Dissemination of Demonstrated Energy Technologies
CALI	China Association of Lighting Industry
CCFL	cold-cathode fluorescent lamp
CCT	correlated colour temperature
cd	candela
CDM	clean development mechanism, a flexible mechanism under the Kyoto Protocol
CdSe	cadmium selenide
CEC	California Energy Commission (United States)
CECP	China Certification Center for Energy Conservation Products
CEE	Consortium for Energy Efficiency (United States)

CELMA	Federation of National Manufacturers Associations for Luminaires and Electrotechnical Components for Luminaires in the European Union
CEN	Comité Européen de Normalisation (European Committee for Standardization)
CENELEC	European Committee for Electrotechnical Standardization
CFL	compact fluorescent lamp
CHMSL	centred, high-mounted stop light
CIBSE	Chartered Institute of Building Service Engineers (UK)
CIE	Commission Internationale de l'Eclairage (International Lighting Committee)
CNIS	China National Institute of Standardisation
CNSR	Conseil National de la Sécurité Routière (France)
CNY	Yuan renminbi (China)
CO_2	carbon dioxide
COP	coefficient of performance
CRI	colour rendering index
CRT	cathode ray tube
CU	coefficient of utilisation
DC	direct current
Dena	Deutsche Energie-Agentur (German Energy Agency)
DEST	Danish Electricity Saving Trust
DIY	"do-it-yourself"
DKK	Danish kroner
DLA	Defense Logistics Agency (United States)
DOE	Department of Energy (United States)
DSM	demand-side management
DST	daylight-saving time
EC	European Commission
ECBCS	Energy Conservation in Buildings and Community Systems (IEA Implementing Agreement)
ECCJ	Energy Conservation Centre (Japan)

ECCP	European Climate Change Programme
ECE	Economic Commission for Europe
EEI	energy-efficiency index
EETIC	Energy and Environmental Technologies Information Centres
EGAT	Electricity Generation Authority of Thailand
EIA	Energy Information Administration (United States)
ELC	European Lamp Companies Federation
ELI	Efficient Lighting Initiative
EM	electromagnetic
EMF	electromotive force
ENTPE	Ecole Nationale des Travaux Publics de L'Etat (France)
EPA	Environmental Protection Agency (United States)
EPAct	Energy Policy Act (United States)
EPBD	Energy Performance of Buildings Directive (European Union)
EPIC	European Photonics Industry Consortium
ESCO	energy service company
EST	Energy Savings Trust (United Kingdom)
EU	European Union
EUR	euros
FEDCOM	Federal Commercial Building Energy Standard (United States)
FEMP	Federal Energy Management Program (United States)
FIDE	Fideicomiso para el Ahorro de Energía Eléctrica (Electrical Energy Saving Trust) (Mexico)
FSU	Former Soviet Union
GaAlAsP	gallium aluminium arsenate phosphide
GaAlInP	gallium aluminium indium phosphide
GaAsP	gallium arsenic phosphide
GaInN	gallium indium nitride
GaN	gallium nitride

GaP	gallium phosphide
GBP	British pounds (sterling)
GDP	gross domestic product
GEEA	Group for Energy Efficient Appliances
GLS	general lighting service
GREENTIE	Greenhouse Gas Technology Information Exchange
GSA	General Services Administration (United States)
GW	gigawatt (1 watt x 10^9)
GWh	gigawatt-hour (1 watt-hour x 10^9)
HID	high-intensity discharge
HVAC	heating, ventilation and air-conditioning
IAEEL	International Association for Energy-Efficient Lighting
ICC	International Code Council (United States)
ICT	information and communication technology
IEA	International Energy Agency
IES	Illuminating Engineering Society
IESNA	Illuminating Engineering Society of North America
IFC	International Finance Corporation
InGaAIP	indium gallium aluminium phosphide
InGaN	indium gallium nitride
IRR	internal rate of return
JELMA	Japanese Electric Lamp Manufacturers Association
JIES	Japanese Illumination Engineering Society
JIS	Japanese Industrial Standard
JLA	Japanese Luminaire Association
JLEDS	Japan LED Association
JRC	Joint Research Council (European Union)
JRCM	Japan Research and Development Center for Metals
K	kelvin
KEMCO	Korea Energy Management Corporation
KIER	Korea Institute of Energy Research

klmh	kilolumen-hours
KOPTI	Korea Photonics Technology Institute
kW	kilowatt (1 watt x 10^3)
kWh	kilowatt-hour
LBNL	Lawrence Berkley National Laboratory (United States)
LCC	life-cycle cost
LCD	liquid crystal display
LED	light-emitting diode
LEED	Leadership in Energy and Environmental Design (United States)
LER	luminaire efficacy rating
LFL	linear fluorescent lamp
LLCC	least life-cycle cost
lm	lumen
lm/W	lumens/watt
LOR	luminaire output ratio
LPD	lighting power density
LRC	Lighting Research Center (United States)
mA	milliamp
MEC	Model Energy Code (United States)
MEPS	minimum energy performance standard
METI	Ministry of Economy, Trade and Industry (Japan)
Mlmh	megalumen-hours
Mt	megatonne (1 million tonnes)
Mtoe	million tonnes of oil equivalent
MTPROG	Market Transformation Programme (United Kingdom)
MW	megawatt (1 watt x 10^6)
NAECA	National Appliance Energy Conservation Act (United States)
NAM	United States and Canada
NEDO	New Energy and Industrial Technology Development Organization (Japan)

NEMA	National Electrical Manufacturers Association (United States)
NGLI	Next Generation Lighting Initiative (United States)
NGLIA	Next Generation Lighting Initiative Alliance (United States)
NGO	non-governmental organisation
NPV	net present value
NRC	Natural Resources Canada
NSC	National Science Council (Chinese Taipei)
NUTEK	National Board for Industrial and Technical Development (Sweden)
OECD	Organisation for Economic Co-operation and Development
OEM	original equipment manufacturer
OIDA	Optoelectronics Industry Development Association (United States)
OLED	organic light-emitting diode
OLLA	Organic LEDs for Lighting Applications
PDA	personal digital assistant
PF ratio	power factor ratio
Plmh	petalumen-hours
PV	photovoltaic
R&D	research & development
RCL	rear combination lamp
RD&D	research, design and development
RESNET	Residential Energy Services Network (United States)
SAD	seasonal affective disorder
SAE	Society of Automotive Engineers (United States)
SHC	Solar Heating and Cooling (IEA Implementing Agreement)
SLIA	Semiconductor Lighting Industrial Association (Chinese Taipei)
SOI	indium oxide low-pressure sodium lamp

SOX	standard tin oxide low-pressure sodium lamp
sr	steradian
SSL	solid-state lighting
STEM	Swedish National Energy Administration
TWh	terawatt-hours (1 watt-hour x 10^{12})
UNDP	United Nations Development Programme
USD	US dollars
WBCSD	World Business Council for Sustainable Development
WEEE	Waste Electrical and Electronic Equipment Directive
WEO	World Energy Outlook of the IEA
Wh	watt-hour
WLED	white-light emitting diode

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