



INTERNATIONAL ENERGY AGENCY

ENERGY TECHNOLOGY TRANSITIONS FOR INDUSTRY

Please note that this PDF is subject to specific restrictions that limit its use and distribution. The terms and conditions are available online at www.iea.org/about/copyright.asp

Strategies for the Next Industrial Revolution



ENERGY TECHNOLOGY TRANSITIONS FOR INDUSTRY

Strategies for the Next Industrial Revolution

Industry accounts for one-third of global energy use and almost 40% of worldwide CO₂ emissions. Achieving substantial emissions reduction in the future will require urgent action from industry. What are the likely future trends in energy use and CO₂ emissions from industry? What impact could the application of best available technologies have on these trends? Which new technologies are needed if these sectors are to fully play their role in a more secure and sustainable energy future?

Energy Technology Transitions for Industry addresses these questions through detailed sectoral and regional analyses, building on the insights of crucial IEA findings, such as *Energy Technology Perspectives 2008: Scenarios and Strategies to 2050*. It contains new indicators and methodologies as well as scenario results for the following sectors: iron and steel, cement, chemicals, pulp and paper and aluminium sectors. The report discusses the prospects for new low-carbon technologies and outlines potential technology transition paths for the most important industrial sectors.

This publication is one of three new end-use studies, together with transport and buildings, which look at the role of technologies and policies in transforming the way energy is used in these sectors.

(61 2009 22 1 P1)
978-92-64-06858-2 €100



9 789264 068582



INTERNATIONAL ENERGY AGENCY

ENERGY TECHNOLOGY TRANSITIONS FOR INDUSTRY

**Strategies for
the Next Industrial
Revolution**

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.

It carries out a comprehensive programme of energy co-operation among twenty-eight of the thirty OECD member countries. The basic aims of the IEA are:

- To maintain and improve systems for coping with oil supply disruptions.
- To promote rational energy policies in a global context through co-operative relations with non-member countries, industry and international organisations.
- To operate a permanent information system on international oil markets.
- To provide data on other aspects of international energy markets.
 - To improve the world's energy supply and demand structure by developing alternative energy sources and increasing the efficiency of energy use.
 - To promote international collaboration on energy technology.
 - To assist in the integration of environmental and energy policies, including relating to climate change.

IEA member countries:

Australia
Austria
Belgium
Canada
Czech Republic
Denmark
Finland
France
Germany
Greece
Hungary
Ireland
Italy
Japan
Korea (Republic of)
Luxembourg
Netherlands
New Zealand
Norway
Poland
Portugal
Slovak Republic
Spain
Sweden
Switzerland
Turkey
United Kingdom
United States

The European Commission also participates in the work of the IEA.

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

The OECD is a unique forum where the governments of thirty democracies work together to address the economic, social and environmental challenges of globalisation. The OECD is also at the forefront of efforts to understand and to help governments respond to new developments and concerns, such as corporate governance, the information economy and the challenges of an ageing population. The Organisation provides a setting where governments can compare policy experiences, seek answers to common problems, identify good practice and work to co-ordinate domestic and international policies.

© OECD/IEA, 2009

International Energy Agency (IEA)

9 rue de la Fédération, 75739 Paris Cedex 15, France

Please note that this publication is subject to specific restrictions that limit its use and distribution. The terms and conditions are available online at www.iea.org/about/copyright.asp

FOREWORD

Nearly one-third of global energy demand and almost 40% of worldwide CO₂ emissions are attributable to industrial activities. The bulk of these emissions are related to the large primary materials industries, such as chemicals and petrochemicals, iron and steel, cement, pulp and paper, and aluminium. If we are to combat climate change successfully, industry will need to transform the way it uses energy and radically reduce its CO₂ emissions. This publication identifies both the current and future technologies that can achieve these outcomes, as well as the policies that are needed to ensure their widespread use.

The first priority should be to more widely disseminate current best practice. Our analysis shows that if today's best available technologies were deployed globally, industrial energy use could be reduced by 20 to 30%. This would be a good start. Yet such savings will be nowhere near sufficient to offset the anticipated growth in demand for industrial materials, which in most sectors will double or triple over the next 40 years. CO₂ emissions will therefore continue to rise unless a wide range of new technologies are commercialised. Industry and governments will need to work together to research, develop, demonstrate and deploy the promising new technologies that have already been identified, and also to find and advance novel processes that will allow for the CO₂-free production of common industrial materials in the longer term.

Bringing about this technology transition will not be easy. It will require both a step change in policy implementation by governments and unprecedented investment in best practices and new technologies by industry. Engaging developing countries and their industries in this transition will also be vital, since most of the future growth in industrial production, and therefore CO₂ emissions, will happen in countries outside of the OECD region.

A number of regional and international industrial associations are already examining how their members might rise to the challenge posed by climate change. I welcome these efforts and reaffirm that the IEA is looking to play its part. For instance, we have been asked by the G8 to develop roadmaps for the most important low-carbon technologies. As part of this activity we are working with the Cement Sustainability Initiative of the World Business Council for Sustainable Development to develop a cement sector roadmap. We would welcome the opportunity to replicate this activity with other sectors and to help show the way to the next industrial revolution.

This publication has been produced under my authority as Executive Director of the IEA. The views expressed do not necessarily reflect the views or policies of individual IEA member countries.

Nobuo Tanaka

Executive Director

ACKNOWLEDGEMENTS

This publication was prepared by the International Energy Agency's Directorate of Sustainable Energy Policy and Technology (SPT), with support from the Energy Statistics Division (ESD). Pieter Boot, Director of SPT until March 2009, provided invaluable leadership and inspiration during the project. Peter Taylor, Head of the Energy Technology Policy Division, offered important guidance and input.

Cecilia Tam was the project leader and had overall responsibility for the design and development of the study. The other main authors were Richard Baron, Dolf Gielen, Michael Taylor, Peter Taylor and Nathalie Trudeau from the IEA, and Martin Patel and Deger Saygin of Utrecht University. Important contributions were provided by Pierpaolo Cazzola, Michel Francoeur, Lew Fulton, Tom Kerr, Julia Reinaud and Kanako Tanaka. The work also benefited from the expertise of many other IEA colleagues, in particular Barbara Buchner, Jean-Yves Garnier, Dagmar Graczyk, Nigel Jollands and Jonathan Sinton.

Gillian Balitrand, Annette Hardcastle and Sandra Martin helped to prepare the manuscript. The editors were Rob Wright and Viviane Consoli. Production assistance was provided by the IEA Communication and Information Office: Jane Barbieri, Madeleine Barry, Muriel Custodio, Delphine Grandrieux and Bertrand Sadin. Rebecca Gaghen and Sylvie Stephan added significantly to the material presented.

Special thanks go to Neil Hirst, formerly Director of the IEA Office of Energy Technology and R&D and then Director for Global Energy Dialogue, for his encouragement, support and suggestions.

The work was guided by the IEA Committee on Energy Research and Technology. The inputs and suggestions from the members of this committee and other IEA government officials are gratefully acknowledged.

A large number of reviewers provided valuable feedback and input to the analysis presented. These include:

Giuseppe Astarita, Federchimica, Italy; Mark Atkinson, American Iron and Steel Institute, United States ; Peter Axegard, STFI-Packforsk AB, Sweden; Chris Bayliss, International Aluminium Institute, United Kingdom; Thore Berntsson, Industrial Energy-Related Technology Systems Implementing Agreement, Sweden; Christopher Beauman, EBRD, United Kingdom; Peter Botschek, European Chemical Industry Council, Belgium; Tom Browne, Paprican, Canada; Anthony de Carvalho, OECD, France; Ian Christmas, World Steel Association, Belgium; Yuan-sheng Cui, Institute of Technical Information for the Building Materials Industry, China; John Davison, IEA Greenhouse Gas R&D Programme, United Kingdom; Gerhard Endemann, Stahlinstitut VDEh, Germany; Stuart Evans, Novacem, United Kingdom; Linda Gaines, Argonne National Laboratory, United States; Mike Gaines, IEA Greenhouse Gas R&D Programme; John Gale, IEA Greenhouse Gas R&D Programme; Eamon Geraghty, CRH, Ireland; Thomas Graedel, Yale University, United States; Herman Halozan, Chair EUWP, Austria; Jake Handelsmann, American Forest & Paper Association, United States; Andy O'Hare, Portland Cement Association, United States; Russell Heinen, SRI Consulting, United States; Volker Hoening, VDZ,

Germany; Toshio Hosoya, Japan Cement Association, Japan; Stephen Hsu, Advanced Materials for Transportation Implementing Agreement, United States; Tomoya Ichimura, METI, Japan; Yoshito Izumi, Taiheyo Cement Corporation, Japan; Mitsuru Kaihori, Japan Paper Association, Japan; Larry Kavanagh, American Iron and Steel Institute, United States; Bernhard Kohl, Eurofer, Belgium; Kazuaki Komoto, METI, Japan; René Kleign, Leiden University, Netherlands; Ron Knapp, International Aluminium Institute, United Kingdom; Paul Lansbergen, Forest Products Association of Canada, Canada; Claude Lorea, Cembureau, Belgium; Hans-Bodo Luengen, Stahlinstitut VDEh, Germany; Vagner Maringolo, Cembureau, Belgium; Rob van der Meer, Heidelberg Cement, Belgium; Marco Mensink, Confederation of European Paper Industries, Belgium; Nobuaki Mita, Japan Petrochemical Industry Association, Japan; Hamid Mohamed, National Resources Canada, Canada; Shigeru Moriyama, Japan Soda Industry Association, Japan; Ben Muirhead, International Fertilizer Industry Association, France; Naokazu Nakano, Japan Iron and Steel Institute, Japan; Hiraku NiheiHi Chun Park, Inha University, Korea; Lynn Price, Lawrence Berkeley National Laboratory, United States; Frank Roberto, ExxonMobil, United States; Dan Santini, Argonne National Laboratory, United States; Vianney Schyns, Utility Support Group, the Netherlands; Stanley Santos, IEA Greenhouse Gas R&D Programme, United Kingdom; Arseen Seys, Eurochlor, Belgium; Bert Stuij, SenterNovem, the Netherlands; Tongbo Sui, China Building Materials Academy, China; Kevin Swift, American Chemical Council, United States; Jukka Tissari, FAO, Italy; Caroline Twigg, World Business Council for Sustainable Development, Switzerland; Robert Vance, Nuclear Energy Agency, France; Patrick Verhagen, Holcim, Belgium; Michael Walls, American Chemical Council, United States; Hiroshi Watanabe, METI, Japan; Wolfgang Weber, BASF, Germany; Angela Weigel, European Chemical Industry Council, Belgium; Keith Wilson, Potash Corporation, Canada; Ernst Worrell, Ecofys, the Netherlands; Fumio Yamashita, METI, Japan.

The IEA gratefully acknowledges financial and in-kind support for this work from the governments of Australia, the Netherlands and Japan.

The individuals and organisations that contributed to this study are not responsible for any opinions or judgements contained in this study. Any errors and omissions are solely the responsibility of the IEA.

Comments and questions are welcome and should be addressed to:

Cecilia Tam

Directorate of Sustainable Energy Policy and Technology
International Energy Agency
9, rue de la Fédération
75739 Paris Cedex 15
France

Email: cecilia.tam@iea.org

TABLE OF CONTENTS

Industry overview	1
Iron and steel	2
Cement	3
Chemicals and petrochemicals	4
Pulp and paper	5
Aluminium	6
Cross-cutting options	7
Impacts on materials demand	8
Policy implications	9
Annex A: Regional detail of industry analysis	A
Annex B: Energy and CO ₂ indicators	B
Annex C: Framework assumptions	C
Annex D: Definitions, abbreviations, acronyms and units	D
Annex E: References	E

	Foreword	3
	Acknowledgements	5
	Table of contents	7
	List of figures	13
	List of tables.	19
	Executive summary.	23
Chapter 1	Industry Overview	29
	Introduction	30
	Energy and CO₂ savings potential with best available technologies.	31
	Industry scenarios	32
	Demand projections for industry	33
	Industrial energy use	34
	Electricity use in industry	35
	CO₂ Emissions in industry	36
	Technologies for reducing direct CO ₂ emissions	38
	Regional implications	41
	Investment costs in industry	43
	RDD&D needs.	45
	Policy implications	46
Chapter 2	Iron and Steel	49
	Introduction	50
	Trends in energy efficiency and CO₂ emissions	51
	Best available technology and technical savings potential.	52
	R&D programmes	56
	Scenario analysis	57
	Cost of CO ₂ reductions in the iron and steel sector	63

	New technology options.	65
	New coal-based processes	65
	Smelting reduction processes	65
	Coal-based direct reduced iron (DRI)	66
	Fuel switching	67
	Gas-based DRI	67
	Use of charcoal	68
	Use of waste plastic	69
	Electricity-based steel-making	69
	Use of hydrogen	70
	CO ₂ capture and storage	70
	Material flows and material flow optimisation.	72
	Materials use and efficiency	73
	Conclusion: transition pathway for the iron and steel sector . . .	74
Chapter 3	Cement	77
	Introduction.	78
	Cement production process and technologies.	78
	Trends in energy efficiency and CO₂ emissions.	81
	Technology and fuel consumption in cement production	82
	Alternative fuel use in cement production	83
	CO ₂ emissions from cement production	85
	Best available technology and technical savings potential. . .	86
	R&D programmes.	90
	Scenario analysis.	90
	Costs of CO ₂ reduction in the cement sector	97
	New technology options.	98
	CO ₂ capture and storage	99
	Oxyfuel technology as part of CO ₂ capture and storage	99
	Post-combustion technologies: absorption	100
	CCS abatement costs in cement kilns	101
	New low-carbon cements	101
	Conclusion: transition pathway for the cement sector.	103

Chapter 4	Chemicals and petrochemicals	105
	
	Introduction	106
	Trends in energy efficiency and CO₂ emissions	107
	Best available technology and technical savings potential .	115
	Process integration and process intensification at site level	117
	Combined heat and power (CHP)	117
	Recycling and energy recovery	117
	Age of capital stock and transition to BPT	118
	Scenario analysis	119
	Costs of CO ₂ reduction in the chemical and petrochemical sector	125
	New technology options	125
	New olefin production technologies	125
	Other catalytic processes with improvement potential	127
	Membranes and other separation technologies	128
	Future process intensification potentials	129
	Bio-based chemicals and plastics	129
	CO ₂ capture and storage in the chemical and petrochemical sector	130
	Material flows and material flow optimisation	130
	Conclusion: transition pathway for the chemical and petrochemical sector	132
Chapter 5	Pulp and paper	135
	
	Introduction	136
	Pulp and paper processes	137
	Recovered paper	138
	Trends in energy efficiency and CO₂ emissions	138
	Energy efficiency index methodology	138
	Data issues	141
	Best available technology and technical savings potentials .	143
	Age of the capital stock and transition to BAT	145
	Scenario analysis	146
	Costs of CO ₂ reduction in the pulp and paper sector	151

	New technology options.	152
	Black liquor gasification	152
	Lignin production from black liquor	153
	Biomass gasification with synfuels production	153
	Biorefinery concepts	153
	CO ₂ capture and storage (CCS)	154
	Paper-drying technologies	155
	Material flows and demand analysis	155
	Conclusion: transition pathway for the pulp and paper sector .	158
Chapter 6	Aluminium	161
	Introduction	162
	Trends in energy efficiency and GHG emissions.	163
	Mining	164
	Alumina refining	164
	Anode production	166
	Smelting	166
	Recycled production	169
	Best available technology and technical savings potentials .	169
	Scenario analysis	171
	Costs of CO ₂ reductions in the aluminium sector	175
	New technology options.	176
	Improvements to the Hall-Héroult cell	176
	Wetted drained cathodes	177
	Inert anodes	177
	Alternative technologies	177
	Carbothermic reduction	177
	Kaolinite reduction	178
	Carbon capture and storage	178
	Aluminium markets.	178
	Conclusion: transition pathway for the aluminium sector . .	179
Chapter 7	Cross-cutting options	183
	Introduction	184

	Biomass and biomass-waste use	185
	Systems optimisation	191
	Electric motor-driven systems	191
	Steam systems	193
	Combined heat and power (CHP)	195
	CHP technologies	196
	CHP applications	196
	CHP barriers and policy solutions	197
	Carbon capture and storage (CCS)	198
	Recycling	204
	Use of recycled aluminium	204
	Use of scrap iron and steel	206
	Use of recovered paper	207
	Use of recycled plastic	207
	Municipal solid waste and by-products	208
	Reducing other GHG emissions.	209
Chapter 8	Impacts on materials demand	211
	Introduction	212
	Power sector	213
	Materials needs for PV technologies	217
	Transport sector	219
	Base year (2005) estimates	220
	Future scenarios	222
	Vehicle sales and total materials use by scenario	224
	Building sector	229
Chapter 9	Policy implications	235
	Introduction	236
	Energy efficiency policies	236
	Research, development and demonstration.	240
	Priority near-term RD&D targets for the development of lower-carbon technologies	241
	Public-private partnerships	242

	Emissions trading	244
	The impacts of ETSs on competitiveness and carbon leakage	247
	Options to reducing carbon leakage	249
	Sectoral approaches	250
	Implementing sectoral approaches	253
	Coverage and data availability	254
	Domestic implementation issues	255
	Carbon leakage	255
	Challenges on the demand side	255
	Sectoral approaches: the logical next step for international action?	257
	Conclusions	257
Annex	A Regional detail of industry analysis	259
Annex	B Energy and CO₂ indicators	271
Annex	C Framework assumptions	283
Annex	D Definitions, abbreviations, acronyms and units	289
Annex	E References	305

LIST OF FIGURES

Executive Summary and

Chapter 1 Industry Overview

ES.1	Technologies for reducing direct CO ₂ emissions from industry, 2006 to 2050	25
1.1	Direct CO ₂ emissions in industry by sector and by region, 2006	30
1.2	Materials production under the low-demand case, 2006, 2030 and 2050	33
1.3	Final energy use in industry	34
1.4	Electricity use by sector, as a share of final energy use under the Baseline and BLUE scenarios, 2006 and 2050	35
1.5	Total industry emissions in Baseline and BLUE scenarios, 2006 and 2050	36
1.6	Total industrial energy use and CO ₂ emissions in the BLUE low 2050 scenario	37
1.7	Contribution to total direct and indirect emissions reduction under the BLUE scenarios compared to Baseline scenarios	37
1.8	CO ₂ intensity of electricity production by scenario	38

1.9	Technologies for reducing direct CO ₂ emissions in industry, 2006 to 2050	39
1.10	Direct energy and process CO ₂ emissions in industry by sector	40
1.11	Direct CO ₂ emissions in industry by region under the Baseline low-demand and BLUE low-demand scenarios, 2006 to 2050	41
1.12	Share of direct CO ₂ emissions in industry by region under the BLUE low-demand scenario, 2006 and 2050	42
1.13	Abatement cost curves for industry	44

Chapter 2 Iron and Steel

2.1	Energy savings potential in 2006, based on best available technology	54
2.2	Regional crude steel production, 2006 to 2050	59
2.3	CO ₂ emissions by scenario, 2006 and 2050	59
2.4	Final energy consumption by scenario, 2006 and 2050	60
2.5	Iron and steel direct CO ₂ intensity index in the Baseline and BLUE scenarios, 2006 to 2050	61
2.6	Direct CO ₂ emissions reductions below the Baseline scenario, 2006 to 2050	62
2.7	Direct CO ₂ emissions by region and by scenario, 2006 and 2050	62
2.8	Steel scrap availability and recycling rate, BLUE low scenario, 1970 to 2050	72

Chapter 3 Cement

3.1	Share of cement kiln technology by region, 1990 to 2006	82
3.2	Thermal energy consumption per tonne of clinker by country, including alternative fuels, 1990 to 2006	83
3.3	Alternative fuel use in clinker production in Europe, 1990 to 2006 (percentage of total thermal fuel use)	85
3.4	Thermal fuel CO ₂ emissions per tonne of cement by country, 1990 to 2006	86
3.5	Energy savings potential based on best available technology in 2006	87
3.6	CO ₂ savings potential based on best available technology in 2006	88
3.7	Distribution of thermal fuel consumption for clinker production in Europe and North America, 2006	89
3.8	Cement consumption by sector in the United States and India	91
3.9	Regional cement production 2006 to 2050	93
3.10	Final energy consumption by scenario, 2006 and 2050	94
3.11	CO ₂ emissions by scenario, 2006 and 2050	95

3.12	CO ₂ emissions reductions below the Baseline, 2006 to 2050	96
3.13	Direct CO ₂ emissions by region and by scenario, 2006 and 2050	97

Chapter 4 Chemicals and Petrochemicals

4.1	Regional breakdown of final energy savings potential by means of BPT and other measures related to the chemical and petrochemical sector, 2006	116
4.2	Estimated development of HVC production capacity in OECD and non-OECD countries in the BLUE scenarios, 2006 to 2050	119
4.3	Regional HVC, ammonia and methanol production and total consumption between 2006 and 2050 in the BLUE scenarios	122
4.4	Final energy consumption by scenario, 2006 and 2050	123
4.5	CO ₂ emissions by scenario, 2006 and 2050	123
4.6	Direct CO ₂ emissions by region and by scenario, 2006 and 2050	124
4.7	CO ₂ emission reductions below the Baseline scenario, 2006 to 2050	125
4.8	Estimated plastics flows to end-sectors and final products in the global economy, 2006	131

Chapter 5 Pulp and Paper

5.1	Global paper and pulp production, 1990 and 2006	136
5.2	Heat efficiency potentials	140
5.3	Energy savings potentials in 2006, based on best available technology	143
5.4	Age distribution of pulp mills	145
5.5	Age distribution of paper mills	146
5.6	Regional paper and paperboard production, 2006 to 2050	147
5.7	Energy use by fuel and region in 2006 and 2050 by scenario	148
5.8	CO ₂ emissions by scenario, 2006 and 2050	149
5.9	CO ₂ emission reductions below Baseline scenario, 2006 to 2050	150
5.10	Direct CO ₂ emissions by region and by scenario, 2006 and 2050	150
5.11	Material and product flows for a biorefinery	154
5.12	Wood products flow	156
5.13	Wood production by category, 1990 and 2006	157
5.14	Biomass use by application in 2006 and BLUE 2050	157

Chapter 6 Aluminium

6.1	Global aluminium flows, 2007	163
6.2	Regional average energy use of metallurgical alumina production	165

6.3	Smelter technology mix, 1990 to 2007	166
6.4	Regional specific power consumption in aluminium smelting	167
6.5	Average PFC emissions per tonne of aluminium	168
6.6	Sources of electricity production for aluminium smelting by region	168
6.7	Share of scrap in aluminium production, 1950 to 2010	169
6.8	Energy savings potentials in 2006, based on best available technology	170
6.9	Primary aluminium production in Baseline Scenarios, 2006 to 2050	172
6.10	Final energy consumption by scenario, 2006 and 2050	173
6.11	CO ₂ emissions by scenario, 2006 and 2050	174
6.12	Direct CO ₂ emission reductions below Baseline scenario, 2006 to 2050	174
6.13	CO ₂ emissions by region and by scenario, 2006 to 2050	175
6.14	Global end-use markets for aluminium, 2006	179

Chapter 7 Cross-Cutting Options

7.1	Use of biomass and waste in the industrial sector	186
7.2	Use of biomass in the industrial sector by region	187
7.3	Technical biomass resource potentials by region in 2050	188
7.4	The world's forests	188
7.5	Final consumption of biomass and waste by region in 2006	189
7.6	CHP share of total national power production	195
7.7	Reductions in industry direct CO ₂ emissions in the BLUE scenarios against the Baseline scenarios, 2050	199
7.8	Breakdown of industrial CO ₂ emissions reductions from CCS by sector, 2050	200
7.9	Regional breakdown of CCS in the industry sector in the BLUE scenarios	200
7.10	Share of CCS by sector in the BLUE Map scenario	201
7.11	Map of sedimentary basins and their storage potential	203
7.12	Share of recycled materials by industry	204
7.13	Use of aluminium scrap by region in the BLUE low scenario, 2050	205
7.14	Use of iron and steel scrap by region in the BLUE low scenario, 2050	206
7.15	Use of recovered paper by region	207
7.16	Methane emissions from solid waste management	210

Chapter 8 Impacts on Materials

8.1	Installed power capacity by technology in the Baseline scenario, 2010 to 2050	213
-----	---	-----

8.2	Installed power capacity by technology in the BLUE Map scenario, 2010 to 2050	214
8.3	Cumulative steel, cement and copper consumption in the Baseline and BLUE Map scenarios, 2010 to 2050	216
8.4	Cumulative plastics, aluminium, fibreglass and uranium consumption in Baseline and BLUE Map scenarios, 2010 to 2050	217
8.5	Estimated cumulative material needs (2010 to 2050) for PV technologies in the BLUE Map scenario assuming single technologies and a mix of technologies	218
8.6	Estimated annual peak material demand in 2010 to 2050 compared to 2008 production for a mix of technologies and for a single technology	219
8.7	Material composition and weight of North American and European gasoline and diesel LDVs, 2005	221
8.8	Average vehicle weight by region, 2005	222
8.9	(a) – (d): Baseline materials projections by vehicle type	223
8.10	Light-duty vehicle sales by technology/fuel, Baseline to 2050	225
8.11	Light-duty vehicle sales by technology/fuel, ETP BLUE Map to 2050	225
8.12	Cumulative demand over time, Baseline scenario	226
8.13	Cumulative demand over time, BLUE Map scenario	226
8.14	Baseline and BLUE Map use of materials base with recycling	228
8.15	Existing, new build and refurbished residential building stock by scenario in the OECD	231
8.16	Cumulative materials use in the OECD residential sector in the Baseline and BLUE Map scenarios, 2005 to 2050	232
8.17	Share of cumulative additional materials demand in the BLUE low-demand scenario by source, 2005 to 2050	233

Chapter 9 Policy Implications

9.1	Energy efficiency policies and measures for industry	238
9.2	Near-term technology development priorities and CO ₂ mitigation for industrial energy technologies	241
9.3	Beyond offsets: an illustration of sectoral no-lose targets	252

Annex A Regional detail of industry analysis

A.1	Total industrial CO ₂ emissions in China in Baseline and BLUE scenarios, 2006 and 2050	259
A.2	Industrial energy use and CO ₂ emissions in China in the BLUE low scenario, 2050	260
A.3	Total industrial CO ₂ emissions in India in Baseline and BLUE scenarios, 2006 and 2050	261

A.4	Industrial energy use and CO ₂ emissions in India in the BLUE low scenario, 2050	261
A.5	Total industrial CO ₂ emissions in OECD Europe in the Baseline and BLUE scenarios, 2006 and 2050	262
A.6	Industrial energy use and CO ₂ emissions in OECD Europe in the BLUE low scenario, 2050	262
A.7	Total industrial CO ₂ emissions in OECD North America in the Baseline and BLUE scenarios, 2006 and 2050	263
A.8	Industrial energy use and CO ₂ emissions in OECD North America in the BLUE low scenario, 2050	264
A.9	Total industrial CO ₂ emissions in OECD Pacific in Baseline and BLUE scenarios, 2006 and 2050	264
A.10	Industrial energy use and CO ₂ emissions in OECD Pacific in the BLUE low scenario, 2050	265
A.11	Total industrial CO ₂ emissions in other developing Asia in the Baseline and BLUE scenarios, 2006 and 2050	266
A.12	Industrial energy use and CO ₂ emissions in other developing Asia in the BLUE low scenario, 2050	266
A.13	Total industrial CO ₂ emissions in Africa and the Middle East in Baseline and BLUE scenarios, 2006 and 2050	267
A.14	Industrial energy use and CO ₂ emissions in Africa and the Middle East in the BLUE low scenario, 2050	257
A.15	Total industrial CO ₂ emissions in economies in transition in the Baseline and BLUE scenarios, 2006 and 2050	268
A.16	Industrial energy use and CO ₂ emissions in economies in transition in the BLUE low scenario, 2050	269
A.17	Total industrial CO ₂ emissions in Latin America in the Baseline and BLUE scenarios, 2006 and 2050	269
A.18	Industrial energy use and CO ₂ emissions in Latin America in the BLUE low scenario, 2050	270
Annex	B Energy and CO₂ indicators	
B.1	Allocation issues for CHP	274
Annex	C Framework Assumptions	
C.1	World GDP by region in 2006 and 2050 (based on purchasing power parities)	284
C.2	Per capita GDP in 2006 and 2050 (based on purchasing power parities)	285

LIST OF TABLES

Chapter 1 Industry Overview

1.1	Potential savings from adoption of best available technologies in industry	31
1.2	Percentage of direct emissions reductions by sector in BLUE low- and high-demand scenarios, 2050	40
1.3	Direct CO ₂ reductions in industry by region under the Baseline and BLUE low-demand scenarios to 2050	42
1.4	Investment needs in industry under the Baseline and BLUE scenarios, 2050	44
1.5	Technology requirements in industry	45

Chapter 2 Iron and Steel

2.1	Global steel production, 2006	53
2.2	Crude steel demand projections for the low- and high-demand cases, 2006 to 2050	58
2.3	Economics of fuel switching and reduction options	63
2.4	Investment needs for iron- and steel-making, 2010 to 2050	64
2.5	Energy use for gas-based DRI production	68

Chapter 3 Cement

3.1	Heat consumption of different cement kiln technologies	80
3.2	Typical composition of different cement types	80
3.3	Global cement production, 2006	81
3.4	Cement demand scenario projections	92
3.5	Availability of clinker substitutes in the BLUE scenario, 2005 and 2050	94
3.6	Estimated availability of selected alternative fuels, 2005 and 2050	95
3.7	Estimated cumulative additional investment needs in the BLUE scenarios, 2005 to 2050	98

Chapter 4 Chemicals and Petrochemicals

4.1	BPT values on the specific energy consumption for the production of key chemicals	110
4.2	Energy improvement potential by BPT in the global chemical and petrochemical sector, 2006	114
4.3	Worldwide energy saving potential by means of BPT and other measures related to the chemical and petrochemical sector, 2006	116
4.4	Per capita low- and high-demand scenario consumption projections of HVC, ammonia and methanol for 2005, 2015, 2030 and 2050	120

4.5	Comparison of conventional olefin production by steam cracking with new processes	126
4.6	Overview of estimated CCS costs in the chemical and petrochemical sector	130
Chapter 5	Pulp and Paper	
5.1	Best available technology	139
5.2	Analysis of reported biomass use in 2006	142
5.3	Energy efficiency technologies energy savings, cost and CO ₂ reductions	144
5.4	Low and high demand paper and paperboard demand projections for 2005, 2015, 2030 and 2050	146
5.5	Investment needs for pulp and paper making, 2010 to 2050	151
Chapter 6	Aluminium	
6.1	Global primary aluminium production, 2007	162
6.2	Primary energy use in the aluminium industry by process step	164
6.3	Per capita and total aluminium demand by region	171
6.4	Cost of aluminium smelter upgrade options	176
Chapter 7	Cross-Cutting Options	
7.1	Biomass and waste usage in the industrial sector and potential	190
7.2	Cost estimates for emerging motor technologies	193
7.3	Steam system efficiency measures	194
7.4	CHP applications	197
7.5	Regional capture potential and industrial capture in the BLUE scenarios, 2050	202
Chapter 8	Impacts on Materials	
8.1	Average material use by technology	215
8.2	Specialty material needs for various PV technologies	217
8.3	Material composition of European light-duty vehicles, 2005	221
8.4	Production and reserves of various materials	228
8.5	Indicative range of materials used in residential dwellings, OECD	229
8.6	Dwelling stock and retirement rates in selected EU countries, 1980 to 2002/03	230
Chapter 9	Policy Implications	
9.1	Summary of reviewed policies	239
9.2	Key technology priorities for industry RD&D	240

9.3	Overview of existing and considered emissions trading systems	245
9.4	Carbon leakage estimates for different manufacturing sectors	248
9.5	Measures to address carbon leakage	250
Annex	B Energy and CO₂ indicators	
	
B.1	Summary of indicators available for each sector	278
Annex	C Framework Assumptions	
	
C.1	Population projections, 2006 to 2050	283
C.2	GDP projections, 2006 to 2050 (based on purchasing power parities)	285
C.3	Oil, gas and coal price projections for the Baseline scenarios (in USD 2007 price per unit)	286

EXECUTIVE SUMMARY

Overview

Industry accounts for approximately one-third of global final energy use and almost 40% of total energy-related CO₂ emissions. Over recent decades, industrial energy efficiency has improved and CO₂ intensity has declined substantially in many sectors. However, this progress has been more than offset by growing industrial production worldwide. As a result, total industrial energy consumption and CO₂ emissions have continued to rise. Projections of future energy use and emissions show that without decisive action, these trends will continue. This path is not sustainable. Making substantial cuts in industrial CO₂ emissions will require the widespread adoption of current best available technology (BAT), and the development and deployment of a range of new technologies. This technology transition is urgent; industrial emissions must peak in the coming decade if the worse impacts of climate change are to be avoided. Furthermore, such emissions reductions will only be possible if all the regions of the world contribute. Action in OECD countries alone, which represent 33% of current global industrial CO₂ emissions, will not be sufficient to make the necessary reductions. Industrial production will continue to grow most strongly in non-OECD countries so that by 2050, in the absence of any further action, they will account for 80% of global industrial CO₂ emissions.

Industry exhibits a number of characteristics that set it apart from other end-use sectors and these need to be taken into account when designing energy and climate policies for the sector. First, while significant energy efficiency potentials remain, they are smaller than in the building or transport sectors. Policies should therefore promote realistic levels of energy efficiency improvement and CO₂ abatement and ensure, where possible, flexibility in the way these can be achieved. Secondly, many industries compete in global or regional markets, and so the introduction of policies that impose a cost on CO₂ emissions in some regions, but not others, risks damaging competitiveness and may lead to carbon leakage – in other words, industries relocating to regions with lesser carbon restrictions. While there is little, if any, evidence of such effects to date, this may become a significant problem if CO₂ prices rise substantially in the future. Thirdly, many industrial sectors have the knowledge, technology access and financing possibilities to reduce their own CO₂ emissions if governments provide a stable policy framework that will create clear, predictable, long-term economic incentives for the use of new efficient and low-carbon technologies.

Given these considerations, a global system of emissions trading may eventually be a crucial policy instrument for promoting CO₂ abatement in industry. However, a worldwide carbon market is unlikely to emerge immediately and so, in the short- to medium-term, international agreements covering some of the main energy-intensive sectors might be a practical first step in stimulating the deployment of new technologies, while addressing concerns about competitiveness and carbon leakage. Meanwhile, national energy efficiency and CO₂ policies, including standards, incentives and regulatory reform (including the removal of energy price subsidies), which address specific sectors or particular barriers, will continue to be

necessary. Gaining public acceptance for certain new technologies may also be important to their widespread deployment.

To complement policies that generate market pull, many new technologies will need government support while in the research, development and demonstration (RD&D) phases before they become commercially viable. There is an urgent need for a major acceleration of RD&D in breakthrough technologies that have the potential to significantly change industrial energy use or greenhouse gas (GHG) emissions. Support for demonstration projects will be particularly important. This will require greater international collaboration and will need to include mechanisms to facilitate the transfer and deployment of low-carbon technologies in developing countries.

Technologies for the next industrial revolution

The introduction of current and new technologies can deliver significant reductions in CO₂ emissions from industry. In the BLUE scenarios, in which global energy-related CO₂ emissions are halved from current levels by 2050, direct CO₂ emissions in industry fall by 21% compared with today. In 2050 this represents a CO₂ reduction from Baseline scenario emissions of 7.5 Gt to 8.5 Gt. This reduction exceeds total present CO₂ emissions of North America. Because of different rates of industrial growth in the future, not all regions of the world will be able to cut industrial emissions by the same amount. This study indicates that emissions in OECD countries will need to fall by between 50% and 61% compared to today's level, whereas in China and the economies in transition reductions of between 31% and 34% will be necessary. In other emerging economies emissions grow between 19% and 90%, as this is where future growth in production is expected to rise the fastest.

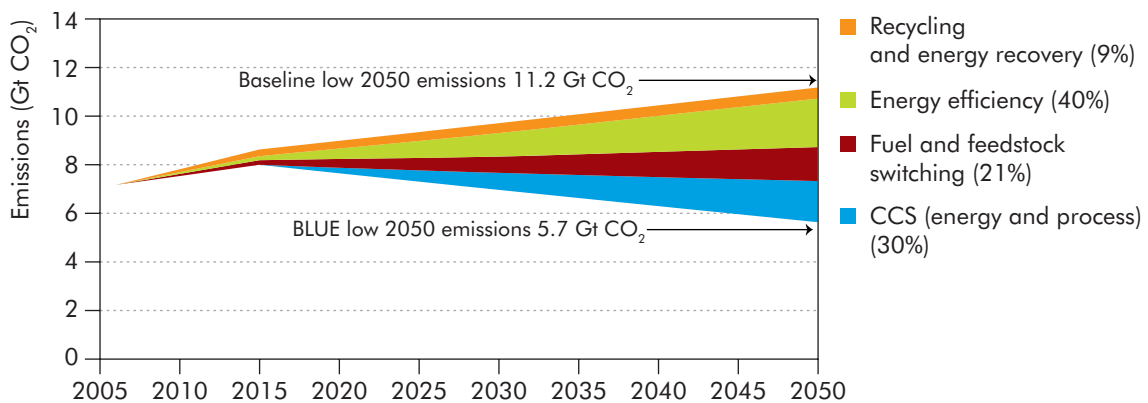
The majority of the technological options to reduce industrial CO₂ emissions will cost between USD 50 and USD 100 per tonne CO₂, but some options with a cost of up to USD 200 per tonne CO₂ will be needed. Deploying these technologies will require increased investments. Global investments in industry under the BLUE scenarios are 20% higher than in the Baseline scenarios, an increase of between USD 2 trillion and USD 2.5 trillion between now and 2050. This is only around 6% of the total investment cost needed across all sectors to halve global CO₂ emissions.

The implementation of current BAT could reduce industrial energy use by up to between 20% and 30% and should be a priority in the short-term. But this will be nowhere near enough to achieve absolute reductions in CO₂ emission levels, as production is expected to double or triple in many sectors. Continued improvements in energy efficiency offer the largest and least expensive way of achieving CO₂ savings over the period to 2050 (Figure ES.1). Energy efficiency gains will need to increase to 1.3% per year, double the rate seen in the Baseline scenarios. This will require the development of new energy-efficient technologies. New low-carbon fuels and technologies will also be needed, with a smaller but important contribution from increased recycling and energy recovery. The use of biomass and electricity as CO₂-free energy carriers will be significant. While the technologies required are often sector-specific, the development and deployment of carbon capture and storage (CCS) will be critical for achieving deep emissions reductions, particularly in the iron and steel and cement sectors. The options outlined in this

publication will not be sufficient to maintain significant CO₂ reduction into the second half of this century and new carbon-free production processes will have to be developed and deployed.

Technology development is fraught with uncertainties. Some of the technologies identified may never come to fruition, but future research may also deliver new technologies or breakthroughs that are not currently foreseen. A portfolio approach can help to deal with this uncertainty.

Figure ES.1 ▶ Technologies for reducing direct CO₂ emissions from industry, 2006 to 2050



Key point

Direct emissions in industry can be significantly reduced through a combination of energy efficiency, fuel and feedstock switching, recycling and energy recovery, and CCS.

Sectoral results

CO₂ emissions reductions will be needed across the whole of industry. But action is particularly crucial in the five most energy-intensive sectors: iron and steel, cement, chemicals and petrochemicals, pulp and paper, and aluminium. Together, these sectors currently account for 75% of total direct CO₂ emissions from industry, with contributions as follows: iron and steel 29%, cement 25%, chemicals and petrochemicals 17%, pulp and paper 3% and aluminium 1%.

Iron and steel

The global deployment of current best available technologies (BAT) could deliver energy savings of about 20% of today's consumption. Given the limited efficiency potential inherent in existing technologies, new technologies such as smelt reduction will be needed. Fuel switching can also help to reduce emissions. A switch from blast furnaces to gas-based direct reduced iron (DRI) could halve emissions, depending

on the availability of cheap stranded gas. Biomass (charcoal), plastic waste and CO₂-free electricity also offer interesting opportunities. CCS is an important option that would allow the sector to achieve deep reductions in emissions in the future. Large-scale CO₂ capture pilot projects at iron and steel plants must be urgently developed in order to better understand the cost and performance of different CO₂ capture methods.

Cement

Reducing CO₂ emissions in the cement sector is very challenging owing to high process emissions related to the production of clinker, the main component in cement. Process CO₂ emissions alone are equal to approximately 1.2 Gt per year. Improving energy efficiency at existing plants, investing in BAT for new plants, and increasing the use of alternative fuels and clinker substitutes could reduce current energy use by 21%, but this will not be enough to achieve net emissions reductions in the future. New technologies should be developed and implemented, particularly in the application of CCS to cement production. CCS can reduce emissions in the sector by up to 1.0 Gt CO₂ in 2050. Urgent action is needed to support the development and demonstration of CCS for cement production. In the very long-term, new CO₂-free processes will need to be developed.

Chemicals and petrochemicals

The full application of best practice technologies (BPT) in chemical processes could achieve energy savings of 5.2 EJ/year or approximately 15%. Additional measures such as process intensification and process integration, the greater use of combined heat and power (CHP), and life-cycle optimisation by recycling and energy recovery from post-consumer plastic waste could save an additional 5 EJ of final energy. However, there are important barriers which constrain the exploitation of this theoretical potential. To achieve future CO₂ emissions reductions in the sector, a range of new technologies must be developed and successfully applied. These include novel olefin production processes such as the wider use of catalysis, membranes and other new separation processes, process intensification, and the development of bio-based chemicals and plastics. In addition, CCS for ammonia, ethylene and large-scale CHP applications will need to be developed. A life-cycle approach can be especially valuable in this sector as most carbon is stored in products.

Pulp and paper

Significant potentials exist in many countries to increase energy efficiency and reduce CO₂ emissions in the pulp and paper sector. A transition to current BAT could save up to 25% of energy used today. Reducing emissions in the sector will require additional improvements in efficiency, fuel switching to biomass, and the increased use of CHP. Promising new technologies such as black liquor gasification, lignin removal, biomass gasification and CCS will also be needed to achieve significant emissions reductions.

Aluminium

Most of the energy consumed in the aluminium industry is in the form of electricity used for smelting. The impact of implementing BAT is limited, offering the potential to reduce energy use by up to 12% compared with current levels. Important options include reducing heat losses in refineries and improving process controls, and reducing heat losses and the electricity used in smelters. In the longer-term, moving towards the use of zero-carbon electricity in smelters is the single largest opportunity for long-term CO₂ emissions reduction. New technologies such as wetted cathodes and inert anodes or carbothermic reduction also offer reduction opportunities, if they can be successfully commercialised.

Cross-cutting options

There are important cross-cutting technologies and options for reducing CO₂ emissions from a range of sectors, of which fuel switching to biomass and CCS are the two most significant and thus deserve particular attention for technology development. Other options include efficient motor and steam systems, CHP, and increased use of recycled materials.

Fuel switching, particularly to make greater use of biomass and biomass waste, offers significant opportunities for CO₂ emissions reductions in industry. However, iron and steel, pulp and paper, cement and chemicals will have to compete with the power, building and transport sectors for limited biomass resources. Such competition will put significant pressure on the price of biomass and could create economic barriers that could limit its potential use in industry. The development and use of high-yield crops, water management, soil management and land-use policies, together with an effective assessment of ecological sustainability, all need to be taken into account and closely co-ordinated to ensure the sustainability of biomass use.

Carbon capture technologies will need to be developed and implemented widely across different industrial sectors to realise their full emissions reduction potential. Approximately 30% of industry's CO₂ reductions in the BLUE scenarios are attributable to CCS. Significant investments are needed to support the development and demonstration of CCS in iron and steel, cement, ammonia and pulp and paper production. Major financial, economic, legal and regulatory barriers will have to be overcome before CCS can be widely deployed. Governments need to take a leading role in overcoming these barriers, particularly in relation to CO₂ transportation and storage, but industry should also begin to ramp up investments in CO₂-capture technologies and pilot projects. Large-scale demonstration of capture technology in industry is urgently needed and should be undertaken simultaneously with the demonstration projects planned for the power sector. CO₂ infrastructure and storage issues need to be considered, and this will perhaps result in synergies with the power sector.

Impacts on the demand for materials

The transformation of the global energy economy that is needed to achieve significant CO₂ reductions will have mixed impacts on the demand for materials. The effect on the overall demand for most major commodities will be small, although constraints on the availability of certain specialty materials could reduce the penetration levels of some low-carbon technologies. High levels of recycling will be required to keep up with material input requirements, particularly in transport. Decarbonisation of the power sector will require large increases in material inputs, but the overall impact on global demand for major commodities will be limited as the current share of total material use in the power sector is relatively small. A transition to low-carbon transport technologies, especially in the case of electric vehicles, could deplete known lithium resources. In the building sector, only a modest increase in the most important building materials will be required.

Implementing the technology transition

Achieving significant CO₂ reductions in industry will require both a step change in policy implementation by governments and unprecedented investment in best practice and new technologies by industry. A prerequisite for such actions is a clear understanding of the current energy and CO₂ emissions performance of industry. While the IEA indicator analysis presented in this report can help provide much of the information that is required, it is currently hampered by a combination of methodological difficulties and a lack of detailed and accurate data for some industries and countries. Private-sector led initiatives have started to address some of the gaps through the development of common methodologies and joint data gathering. However, further international cooperative efforts involving both governments and industry are needed to gather comprehensive and reliable industry-level energy and emissions data. International standards could play an important role in such an endeavour.

Roadmaps that show what is needed to take technologies from their current status through to full commercialisation are a further useful tool to help governments and the private sector take the right action. These roadmaps should include all the technical, policy, legal, financial, market and organisational requirements that are necessary to deliver an earlier uptake of more efficient and low carbon technologies into the market. For example, the International Energy Agency is collaborating with the World Business Council for Sustainable Development (WBCSD) and its Cement Sustainability Initiative to develop an international roadmap for the cement sector. This approach should be considered for other industrial sectors as well.

Chapter 1 INDUSTRY OVERVIEW

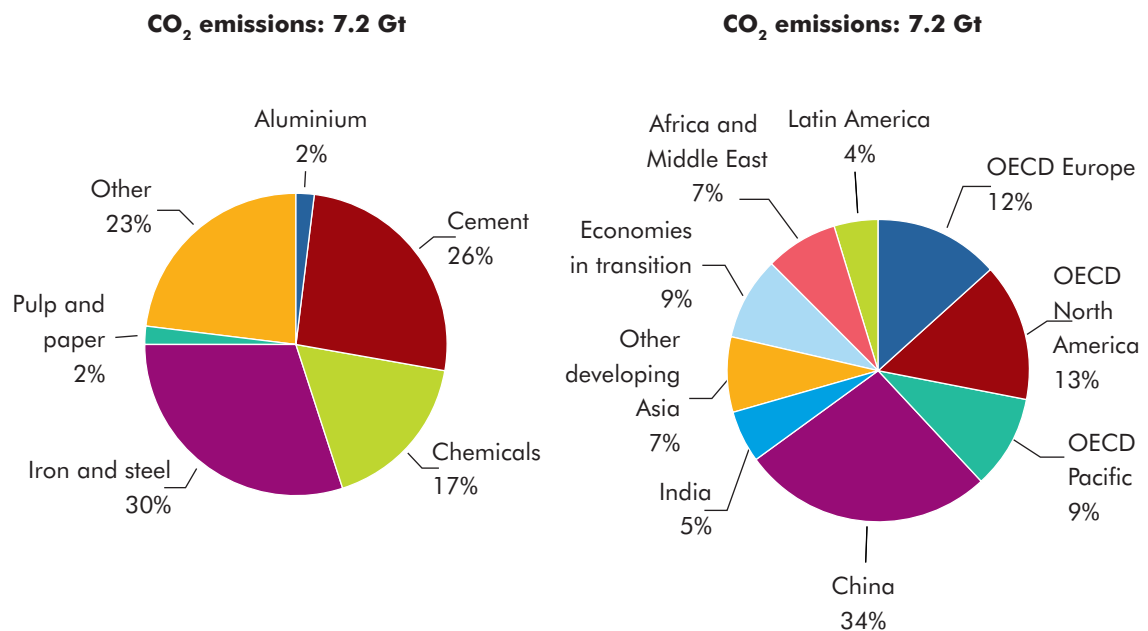
Key Findings

- ▶ Energy efficiency in industry has improved significantly in the last decade, but additional improvements are still possible through the implementation of best available technologies (BAT).
- ▶ In the IEA scenario analysis, achieving a global reduction in carbon dioxide (CO₂) emissions by half by 2050 will require industry to reduce its direct emissions in 2050 by 21% compared to today's levels.
- ▶ Energy efficiency measures offer some of the least-cost options in industry. Implementation of BAT could reduce current emissions by 12% to 23%. But efficiency measures alone will not be enough to offset strong demand growth. New technologies, such as carbon capture and storage (CCS), smelt reduction, separation membranes and black liquor gasification will be needed if net emissions are to be reduced.
- ▶ Indirect CO₂ emissions from the use of electricity currently represent 32% of total industry emissions. These emissions could be nearly eliminated by 2050 with the near-decarbonisation of electricity generation.
- ▶ CCS represents the most important new technology option for reducing direct emissions in industry, with the potential to save 1.7 to 2.4 Gt CO₂ in 2050. Without CCS, emissions in 2050 could only be brought back to current levels. Urgent action is needed to develop and demonstrate CCS applications in industry. Demonstration of capture technologies in industry should be undertaken simultaneously with projects in the power sector.
- ▶ Fuel and feedstock substitution with biomass and waste represents another important option. But there will be significant competition for limited biomass resources from other sectors that will lead to increased costs and possibly make industrial applications less attractive.
- ▶ The additional investment needs for industry are estimated at between USD 2 trillion and USD 2.5 trillion or approximately 20% above investment needs under the Baseline scenarios. The bulk of the reduction in industry can be achieved with an incentive of between USD 50 and USD 100/t CO₂, but realising the full potential will require incentives of up to USD 200/t CO₂.
- ▶ Greater investment by both government and industry is needed to research, develop, demonstrate and deploy a wide range of promising new technologies and also to identify and advance novel processes which allow for CO₂-free production of materials in the longer-term.
- ▶ Clear, stable, long-term policies that put a price on CO₂ emissions will be necessary if industry is to implement the technology transition needed to produce deep emissions reductions. A global system of emissions trading may eventually be a crucial policy instrument, but in the short-to medium-term, international agreements covering particular energy-intensive sectors may be a practical first step. Government intervention will also be needed in the form of standards, incentives and regulatory reforms.

Introduction

Industry accounts for one-third of all the energy used globally and for almost 40% of worldwide CO₂ emissions. In 2006, total final energy use in industry amounted to 120 exajoules (EJ). Direct emissions¹ of CO₂ in the sector amounted to 7.2 gigatonnes (Gt) (Figure 1.1). Indirect emissions² amounted to 3.4 Gt CO₂. Reducing CO₂ emissions from industry must be an essential part of a global action to prevent dangerous climate change.

Figure 1.1 ► Direct CO₂ emissions in industry by sector and by region, 2006



Source: IEA data.

Key point

Iron and steel, cement, chemicals and petrochemicals account for almost three-quarters of emissions in industry.

Chapters 2 to 6 present an extensive analysis of the CO₂ reduction opportunities for the five most energy-intensive industry sectors, namely iron and steel, cement, chemicals and petrochemicals, pulp and paper, and aluminium. Each chapter includes a review of recent trends based on the latest IEA industry indicators and a regional analysis of the potential of existing and new technologies to increase energy efficiency and reduce CO₂ emissions. Each chapter also outlines a potential energy technology transition pathway. Chapter 7 summarises the potential for improving energy efficiency and reducing CO₂

1. Fuel combustion and process-related emissions from within the industry sector.
2. Emissions from the power generation sector due to electricity use in industry.

emissions through a range of cross-cutting industrial practices. Chapter 8 analyses the impacts that a significant energy technology transition will have on a range of materials. Chapter 9 discusses the policy implications and the framework needed to support deep cuts in industrial emissions.

Energy and CO₂ savings potential with best available technologies

Significant energy and CO₂ savings in industry are possible through the implementation of currently available BAT. Table 1.1 shows the results for the five most energy-intensive sectors. More detail can be found in each of the five sector chapters. In summary, it is estimated that the application of BAT could reduce final energy use by between 13% and 29% in different sectors. Total estimated savings for the five sectors analysed is 14 EJ per year, equivalent to 12% of energy use in industry in 2006 and 4% of global energy consumption in that same year. In terms of CO₂ savings, the sector potentials vary from 12% to 23%, in total equivalent to 1.3 Gt CO₂. This equates to a reduction of 12% of total industry emissions and 4% of global emissions in 2006.

It will not be possible to achieve these savings immediately. The rate of implementation of BAT in practice depends on a number of factors, including capital stock turnover, relative energy costs, raw material availability, rates of return on investment, and regulation. Energy subsidies, for example, undermine the role of markets in driving greater energy efficiency. Governments should remove them.

Table 1.1 ► Potential savings from adoption of best available technologies in industry

	Energy savings potential (EJ/yr)	Share of current energy use	CO ₂ savings potential (Mt CO ₂ /yr)	Share of current emissions
Chemicals	5.2	15%	300	20%
Iron and steel	4.7	20%	350	14%
Cement	2.5	29%	450	23%
Pulp and paper	1.4	20%	80	20%
Aluminium	0.4	13%	45	12%
Total	14.2		1 225	
Potential as share of industrial energy and CO₂ emissions	13%		12%	
Potential as share of total energy use and CO₂ emissions	4%		4%	

Source: IEA estimates.

Industry scenarios

Worldwide implementation of BAT is just the first step if industry is to make deep cuts in CO₂ emissions. To analyse the longer-term potential for new technologies to reduce CO₂ emissions, a detailed modelling framework is used that examines different scenarios to the year 2050.

The scenarios are updated versions of those described in *Energy Technology Perspectives 2008*, hereafter referred to as *ETP 2008* (IEA, 2008a). The Baseline scenarios reflect developments that are expected on the basis of the energy and climate policies that have been implemented or are planned. It is consistent with the Reference Scenario for the period 2005 to 2030 described in the *World Energy Outlook 2008*, hereafter referred to as *WEO 2008* (IEA, 2008b). The *WEO 2008* trends have been extrapolated for the period 2030 to 2050 using the *Energy Technology Perspectives* model. The pattern of economic growth changes after 2030 as population growth slows and developing countries' economies begin to mature.

The BLUE scenarios examine the implications of a policy objective to halve global energy-related CO₂ emissions in 2050 compared with today's level. The outcomes implicit in the BLUE scenarios are consistent with a global rise in temperatures of 2°C to 3°C, but only if the reduction in energy-related CO₂ emissions is combined with deep cuts in other greenhouse gas (GHG) emissions. The BLUE scenarios are coherent with the 450 parts per million (ppm) scenario of the *WEO 2008*. Annex C presents more details on the framework assumptions for the scenarios.

The BLUE scenarios enable the exploration of the technological options that will need to be exploited if global CO₂ emissions are to be halved by 2050. This does not mean that industry will necessarily need to halve its emissions. Reaching the global CO₂ emissions objective in the most cost-effective way will require each economic sector to make a contribution based on its costs of abatement. Some sectors may therefore reduce emissions by less than 50%, while others will reduce them by more.

Given the recent global economic crisis and uncertainties about projecting long-term growth in consumption, a low-demand and a high-demand case have been developed for each industry. The high-demand case is consistent with *WEO 2008* and *ETP 2008*. In the five sectors covered in this analysis, the difference between the low- and high-demand cases to 2050 varies by between 15% and 40%. As both the BLUE low- and high-demand scenarios are driven by the same level of CO₂ emissions in 2050, greater reductions in emission levels are needed in the high-demand scenario than in the low-demand one. As a result, costs are also higher in the high-demand scenario.

The scenarios take an optimistic view of technology development and assume that technologies are adopted as they become cost-competitive. The analysis does not assess the likelihood of these assumptions being fulfilled, but it is clear that deep CO₂ reductions can only be achieved if the whole world plays its part.

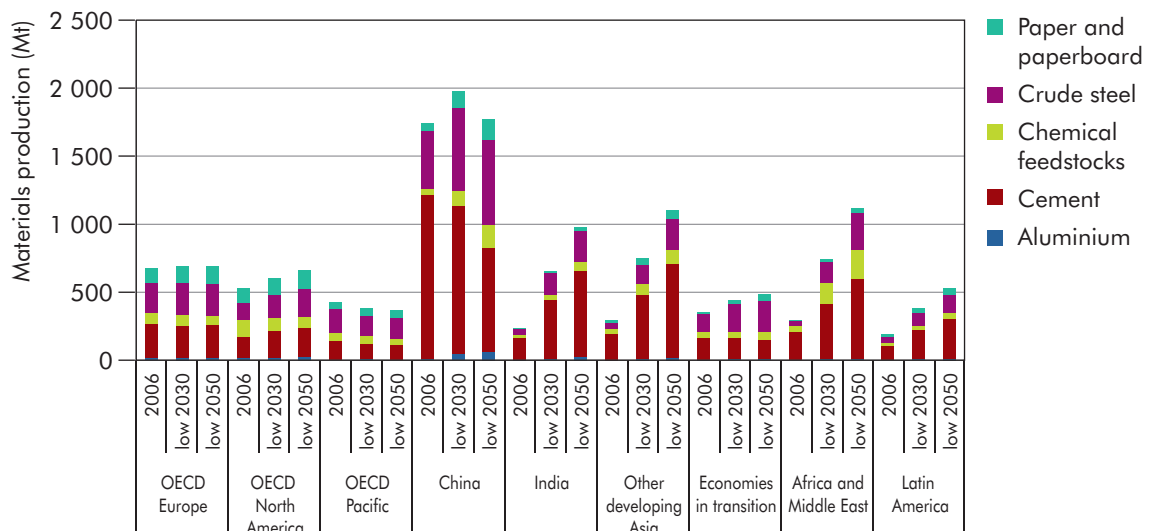
These scenarios are not predictions. They are internally consistent analyses of the least-cost pathways that may be available to meet energy policy objectives, given

a certain set of optimistic technology assumptions. This work can help illustrate the options that policy makers will need to consider in identifying technology portfolios and flexible strategies that may deliver the outcomes they are seeking.

Demand projections for industry

Growth in industrial production since 1990 has been dominated by China, India and other developing Asian countries (ODA). Together, these countries accounted for over 80% of the increase in industrial production over this period. Today China is the largest producer of ammonia, cement, iron and steel, methanol and many other products. In OECD countries, industrial production since 1990 has increased only modestly. The IEA scenario analysis assumes that in the next 20 years, as industrial development matures, there will be another significant change in industrial production growth (Figure 1.2). Production in China will flatten or, in cement production, decline. But in India, ODA, and Africa and the Middle East, industrial development will accelerate. Industrial production in these three regions is expected, in the low-demand scenario, to increase compared to 2006 by over 250% by 2030 and by almost 400% by 2050. OECD countries are expected to show relatively flat demand or only modest increases as consumption levels for materials in these countries are already mature and population growth is expected to be relatively flat or declining.

Figure 1.2 ▶ Materials production under the low-demand case, 2006, 2030 and 2050



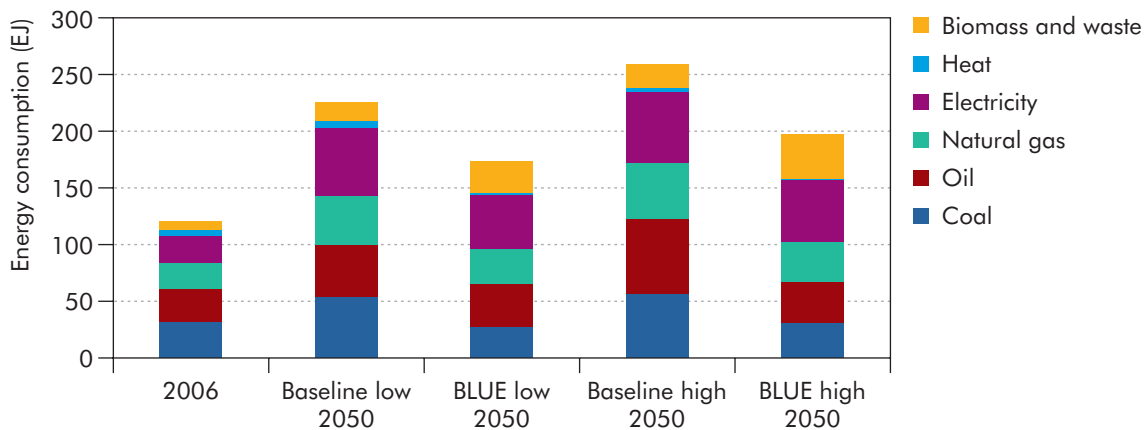
Key point

Growth in industrial production will be strongest in India, ODA and Africa and the Middle East.

Industrial energy use

In the Baseline low-demand scenario, total final energy use is estimated almost to double from 120 EJ in 2006 to 225 EJ in 2050 and to more than double in the Baseline high-demand scenario to 260 EJ. Fossil fuels currently constitute 70% of the total final energy used in industry. In all scenarios, fossil fuel use will continue to dominate (Figure 1.3). But its share of final energy use will decline to 55% in the BLUE low-demand scenario and 52% in the BLUE high-demand equivalent. The remaining energy and feedstock will come from biomass and electricity. Coal currently accounts for over a quarter of total final energy use. In the BLUE scenarios, where a significant reduction in the CO₂ intensity of industry is needed, coal's share of final energy use falls to 16% by 2050.

Figure 1.3 ► Final energy use in industry



Key point

The share of fossil fuels will decline significantly in the BLUE scenarios, offset by higher biomass and electricity use.

In the Baseline scenarios, the share of biomass and waste use remains similar to current levels but, will increase sharply in the BLUE scenarios, rising from a share of 7% of fuel use in 2006 to 14% in the low-demand scenario and to 18% in the high-demand scenario by 2050. The switch from fossil fuels to biomass will largely contribute to lower CO₂ emissions in all sectors except in aluminium production where electricity provides most energy. Greater biomass use in combination with CCS will also enable net emissions reductions over its life cycle as CO₂ from the atmosphere, initially captured in biomass, is sequestered. Industrial applications will have to compete with power generation for the available biomass. Significant improvements will be needed in agricultural yields if costs are to be contained and the negative impacts of land-use change are to be minimised.

In the BLUE scenarios, higher levels of energy efficiency will significantly reduce energy intensity, but total final energy use will still rise by 43% by 2050 in the BLUE low-demand scenario and by 63% by 2050 in the BLUE high-demand scenario compared

to 2006. This will be driven by strong production growth. The use of CCS in the BLUE scenarios to reduce CO₂ emissions increases energy consumption, offsetting some of the savings from higher energy efficiency that would otherwise be projected.

Electricity use in industry

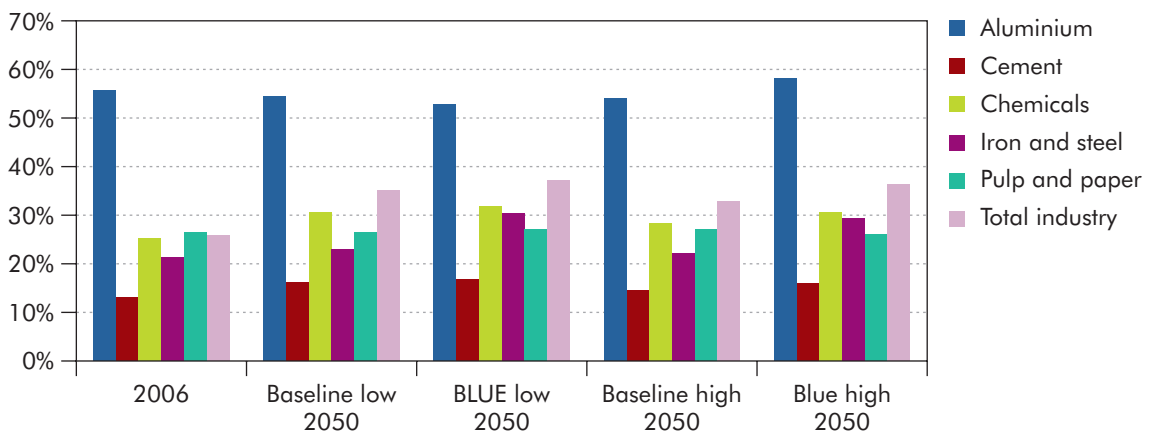
1

Electricity currently constitutes just over one-quarter of the total final energy used in industry. This share is expected to rise to around one-third in 2050 in all Baseline and BLUE scenarios because of the greater share of electricity-using processes. For example, more scrap is used in the production of iron and steel, and paper recycling rates increase.

The intensity of electricity use varies widely between sectors: for example it varies from 13% of total final energy in the cement sector to 56% in the aluminium sector. In the Baseline scenarios, electricity use as a proportion of total final energy is expected to rise in 2050 to between 16% and 54% in different industry sectors and to 35% for industry as a whole. In the BLUE scenarios, this share will increase slightly to between 17% and 58% for the individual sectors and to 37% for industry as a whole.

The high share of electricity use in industry means that measures taken in the power sector will have a significant impact on industry's total emissions. The location of industrial applications near to low-carbon power generation sources can also help to reduce the CO₂ emissions associated with the sector. The pulp and paper sector in particular is well placed to take advantage of promising new biomass and waste technologies that would allow the sector to become a net supplier of energy. As the power sector increasingly decarbonises over time, research may create new opportunities for industry to reduce its CO₂ intensity through electrification, stimulated by the introduction of appropriate carbon reduction incentives.

Figure 1.4 ► Electricity use by sector, as a share of final energy use under the Baseline and BLUE scenarios, 2006 and 2050



Key point

The share of electricity use in industry will rise.

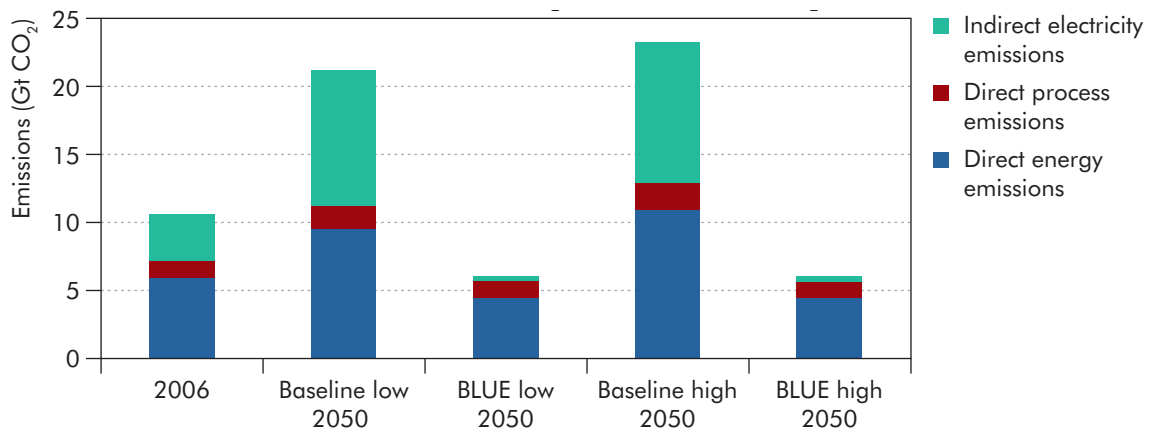
CO₂ emissions in industry

In the Baseline scenarios, total (direct and indirect) emissions from industry in 2050 rise by 100% in the low-demand scenario and by 120% in the high-demand scenario, reaching 21.2 Gt and 23.3 Gt respectively. In the BLUE scenarios, total emissions would be 42% lower in 2050 than in 2006. In these scenarios in 2050, compared to the Baseline scenarios, emissions would be 71% lower in the low-demand scenario and 74% lower in the high-demand scenario.

Of these, direct process and energy CO₂ emissions from industry itself are expected to reach 11.2 Gt or 12.9 Gt in the Baseline low- and high-demand scenarios in 2050. In the BLUE scenarios, direct CO₂ emissions fall from 7.2 Gt in 2006 to 5.7 Gt in 2050. This is a 21% reduction in 2050, compared to 2006 levels.

Indirect CO₂ emissions from electricity use represent the largest increase between 2006 and 2050 in the Baseline scenarios, rising from 3.4 Gt in 2006 to 10.0 Gt or 10.4 Gt in 2050. In the BLUE scenarios, as the power sector reaches near-decarbonisation, indirect CO₂ emissions show the largest decline, falling by 2050 to as little as 0.4 Gt in both BLUE scenarios.

Figure 1.5 ► Total industry emissions in Baseline and BLUE scenarios, 2006 and 2050



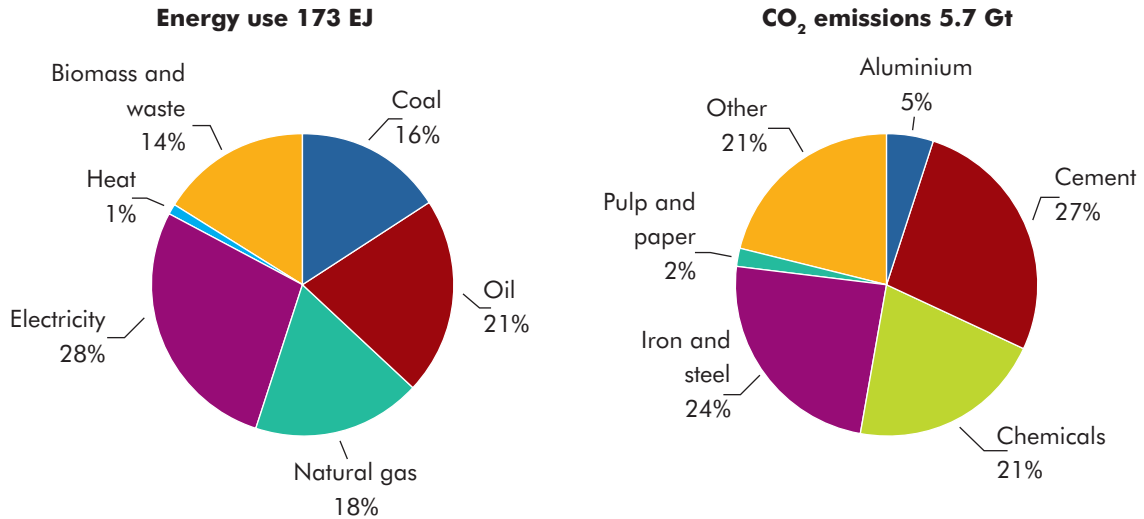
Key point

Direct CO₂ emissions in industry will fall by 21% under the BLUE scenarios compared to 2006 levels.

In the BLUE low-demand scenario, the share of total CO₂ emissions from the chemical and petrochemical sector rises from 17% in 2006 to 21% in 2050 (Figure 1.6). The iron and steel sector, which is currently the largest emitter, also shows the largest potential for reduction. The cement sector, which is currently the second-largest emitter becomes the largest, accounting for 27% of total direct industrial emissions in 2050.

As shown in Figure 1.7, the decarbonisation of the power sector accounts for half of all the reductions in total emissions by 2050 in both BLUE scenarios. Energy efficiency (including electricity demand reductions) makes the next largest contribution, of 29% and 25% of total reductions in the BLUE low- and high-demand scenarios respectively. The fitting of CCS to industrial applications, which accounts for 11% and 14% of the total direct and indirect emissions reductions in the BLUE low- and high-demand scenarios respectively, will also be needed.

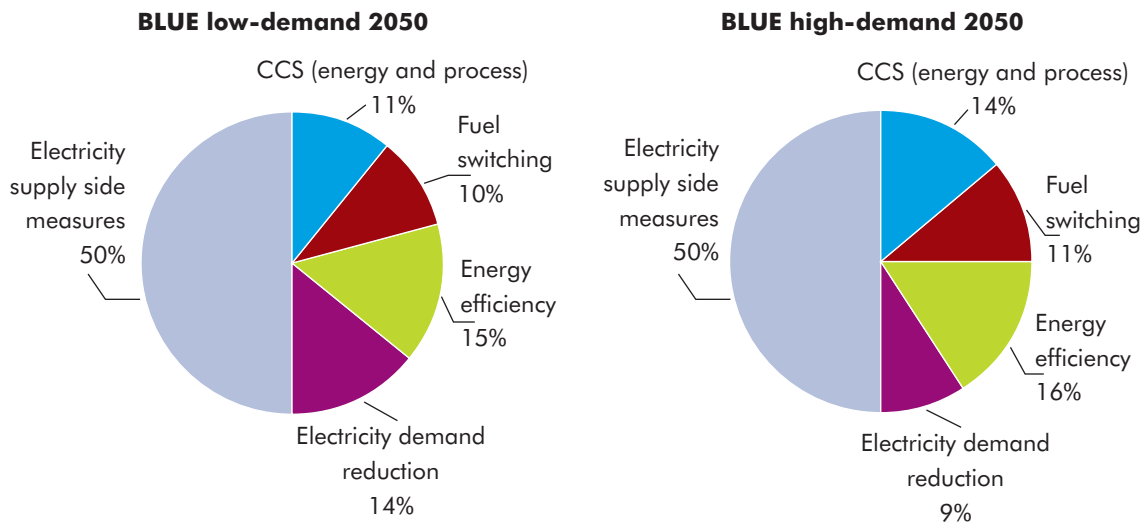
Figure 1.6 ► Total industrial energy use and CO₂ emissions in the BLUE low 2050 scenario



Key point

Fossil fuels will still account for the major part of energy use in industry in the BLUE low-demand scenario.

Figure 1.7 ► Contribution to total direct and indirect emissions reduction under the BLUE scenarios compared to Baseline scenarios

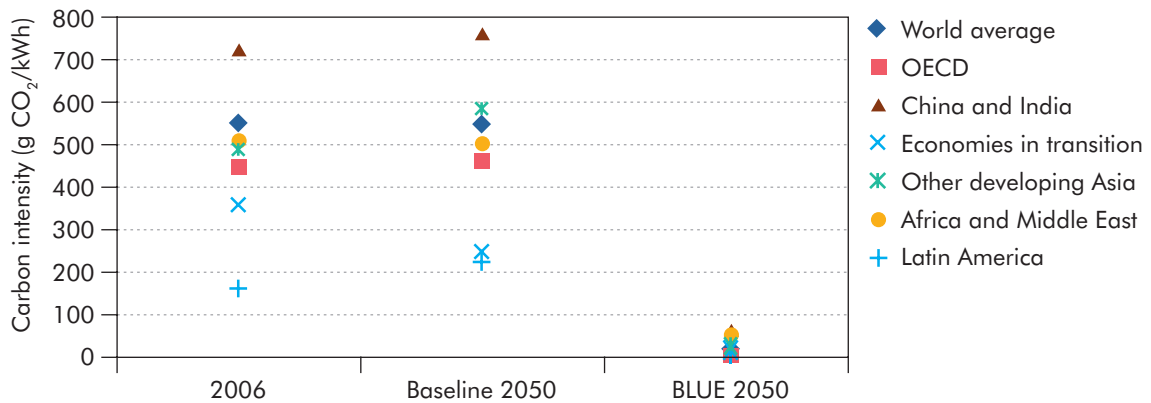


Key point

Measures in the electricity sector account for the largest reduction in total direct and indirect emissions in industry.

The difference in the carbon intensity of electricity production between regions also narrows (Figure 1.8). In OECD countries, the carbon intensity of electricity production falls from 467 g CO₂/kWh in 2006 to less than 10 g CO₂/kWh by 2030 and to just 2 g CO₂/kWh by 2050. Although all regions will show significant improvements in carbon intensity by 2030, non-OECD countries (with the exception of Latin America, which already has very low carbon intensity thanks to the dominance of hydropower) are not expected to reach near decarbonised levels until 2050.

Figure 1.8 ► CO₂ intensity of electricity production by scenario



Key point

The power sector will reach levels of near decarbonisation in the BLUE scenario by 2050.

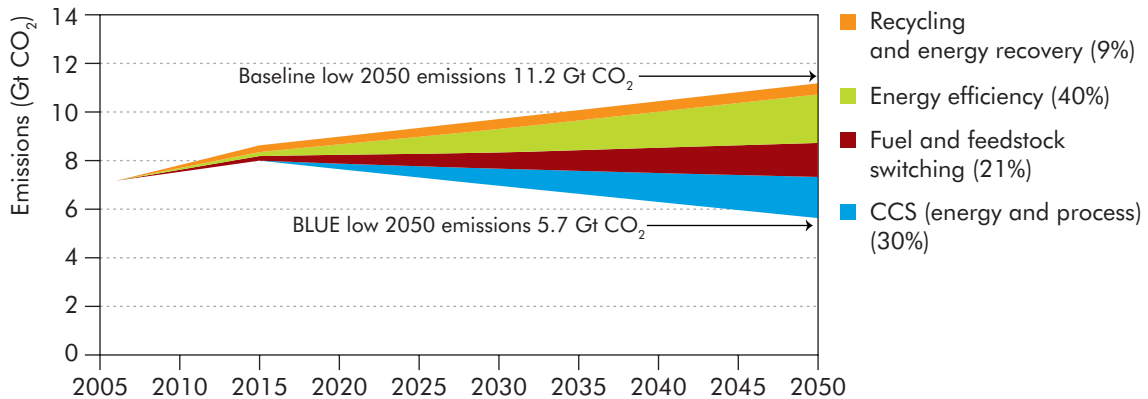
Technologies for reducing direct CO₂ emissions

Reduction of direct CO₂ emissions in industry can be achieved through the deployment of existing BAT and through the development and deployment of new technologies that can deliver improved energy efficiency, enable fuel and feedstock switching, greater levels of recycling, and capture and store CO₂. Many new technologies which can support these outcomes, such as smelt reduction, new separation membranes, black liquor and biomass gasification and advanced cogeneration, are currently being developed, demonstrated and adopted by industry.

Additional research, development and demonstration (RD&D) is needed to develop breakthrough process technologies that allow for the CO₂-free production of materials, and to advance understanding of system approaches such as the optimisation of life-cycles through recycling and using more efficient materials. These longer-term options will be needed in the second half of this century to ensure sustainability of industrial processes to the end of the century and beyond.

Figure 1.9 shows the technologies that are used to reduce direct CO₂ emissions in industry from 11.2 Gt in 2050 under the Baseline low-demand scenario to 5.7 Gt in the BLUE low-demand scenario. A similar result is also found for the BLUE high-demand scenario.

Figure 1.9 ► Technologies for reducing direct CO₂ emissions in industry, 2006 to 2050



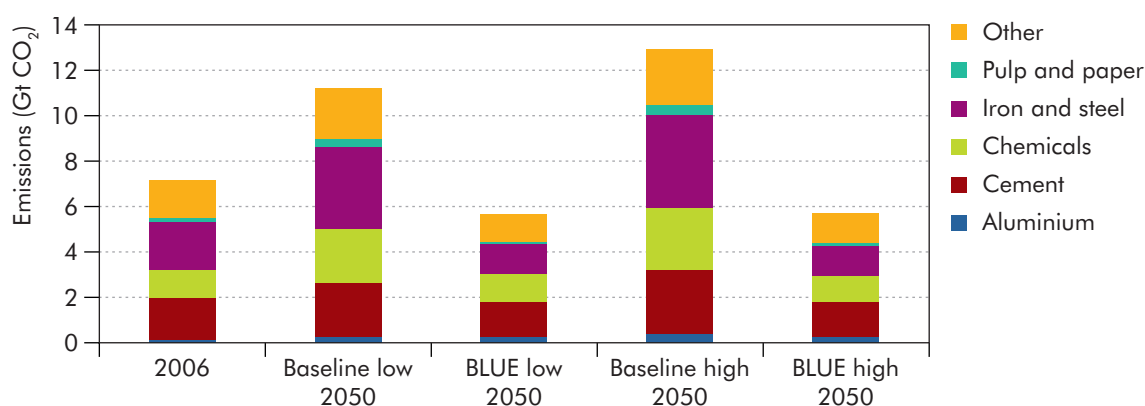
Key point

Direct emissions in industry can be significantly reduced through a combination of energy efficiency, fuel and feedstock switching, recycling and energy recovery, and CCS.

The largest contribution to direct emissions reductions comes from energy efficiency. This accounts for 40% and 38% of the total reductions in 2050 in the BLUE low- and high-demand scenarios respectively. CCS plays a significant role in reducing emissions in the iron and steel, cement, chemical and pulp and paper sectors in 2050. It accounts for 30% and 34% in the BLUE low- and high-demand scenarios respectively of industry's total direct emissions reduction. But to achieve this outcome, both industry and government need to take steps to ensure that the technology is demonstrated and deployed by 2020 to 2025. Government-funded programmes that already plan to demonstrate CCS in power generation should be extended also to enable the demonstration of this technology in industry. Fuel and feedstock switching account for 21% of the total reduction, recycling and energy recovery for 9% and 7% respectively in low- and high-demand scenarios.

Thus, increased energy efficiency, combined with fuel and feedstock switching, and recycling and energy recovery, enable industry to bring back CO₂ emissions to current levels, but to achieve more significant emissions reductions in the sector, CCS will have to be widely implemented.

Figure 1.10 shows industrial direct CO₂ emissions by sector in the Baseline and BLUE scenarios. The iron and steel, cement, and chemical and petrochemical sectors represent over 70% of current direct emissions in industry. Process emissions in cement production and in iron and steel production are particularly high.

Figure 1.10 ► Direct energy and process CO₂ emissions in industry by sector**Key point**

All sectors will need to significantly reduce emissions.

Industry can significantly reduce emissions by 2050 only if all industrial sectors make a contribution. Table 1.2 shows the projected direct emissions reductions by sector in the BLUE low- and high-demand scenarios compared to 2006 and to the Baseline low- and high-demand scenarios in 2050. As the scenario analysis assumes that least-cost options are used first, the different contributions required from each sector reflect the relative costs of the options for reducing emissions in each sector.

Table 1.2 ► Direct emissions reductions by sector in BLUE low- and high-demand scenarios, 2050

Reference	2006 (%)	2006 (%)	Baseline low 2050 (%)	Baseline high 2050 (%)
Iron and steel	-37	-38	-62	-67
Cement	-18	-18	-34	-45
Chemicals and petrochemicals	0	-4	-50	-58
Pulp and paper	-47	-46	-71	-77
Aluminium	122	121	-8	-32
Total	-21	-21	-49	-56

Note: Iron and steel includes coke ovens and blast furnaces.

Source: IEA data.

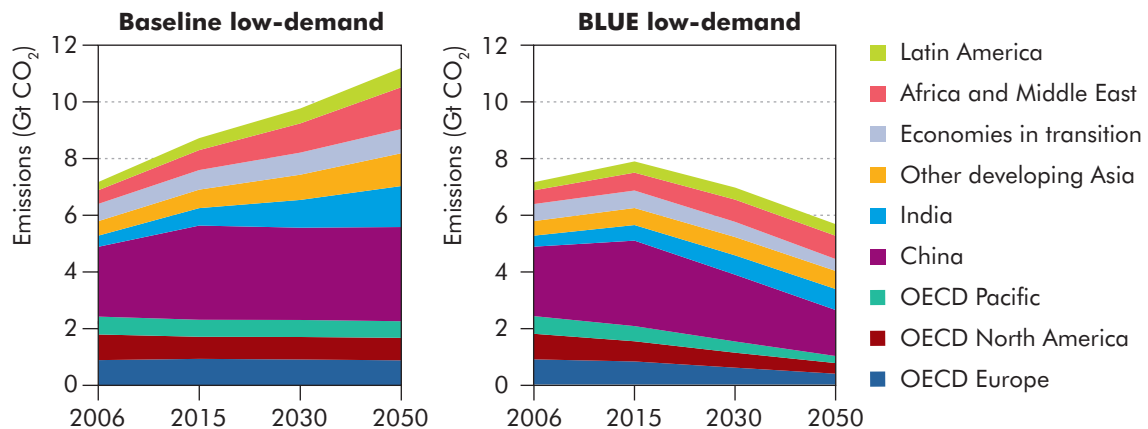
The contribution needed in the BLUE low-demand scenario to reach a 21% reduction in direct emissions in 2050 below 2006 levels varies by industry sector. The aluminium sector shows an increase in direct emissions of 122%, offset by significant indirect emissions reductions from decarbonisation of the power sector, while the iron and steel sector decreases its direct emissions by 37%. Compared to the Baseline scenarios, total direct emissions fall in the BLUE low- and high-demand scenarios in 2050 in all five sectors. This reduction ranges from between 8% and 32% in the aluminium sector to between 71% and 77% for the pulp and paper sector.

Regional implications

A significant reduction in CO₂ emissions in industry will only be possible if all regions contribute. Actions in OECD countries alone, where emissions today represent 33% of total direct industrial emissions, would not be enough. Industrial production growth will continue to be strongest in non-OECD countries, with over 80% of total industrial emissions in 2050 expected in developing countries under the Baseline scenarios as compared to 65% today (Figure 1.11). As Table 1.3 shows, direct industry emissions in 2050 can only be reduced by 21% compared to today's levels if all regions significantly reduce future emissions growth below the level expected in the Baseline scenario. In the BLUE low-demand scenario, all regions need to show a sharp decrease in emissions in 2050, ranging from 38% to 57% lower than in the Baseline low-demand scenario.

In the Baseline scenarios, regional emissions grow fastest in India, ODA and in Africa and the Middle East where current levels of industrial development are significantly below current global levels and where industrial production is expected to grow at the fastest rates. China's emissions will continue to rise rapidly in the next 20 years but then rise only moderately as the country's consumption of the most CO₂-intensive products, such as cement and iron and steel, begins to level off after 2030.

Figure 1.11 ► Direct CO₂ emissions in industry by region under the Baseline low-demand and BLUE low-demand scenarios, 2006 to 2050



Key point

In the BLUE low-demand scenario, all regions will need to significantly reduce future emissions.

In the Baseline low-demand scenario, emissions are expected to continue rising in all regions to 2050. By contrast, in the BLUE low-demand scenario, emissions are expected to peak in 2015 to 2020 and then to begin to decline as more efficient and cleaner technology is introduced. The largest contributor to the emissions reduction in the BLUE scenarios is expected to be China given its dominant position in industry today. Direct emissions from industry in China fall from 2.5 Gt in 2006 to 1.7 Gt in 2050 in the BLUE low-demand scenario as greater levels of energy efficiency are achieved and as CCS technology is deployed in industry. This would be 1.7 Gt lower (–51%) than in the Baseline low-demand scenario for 2050.

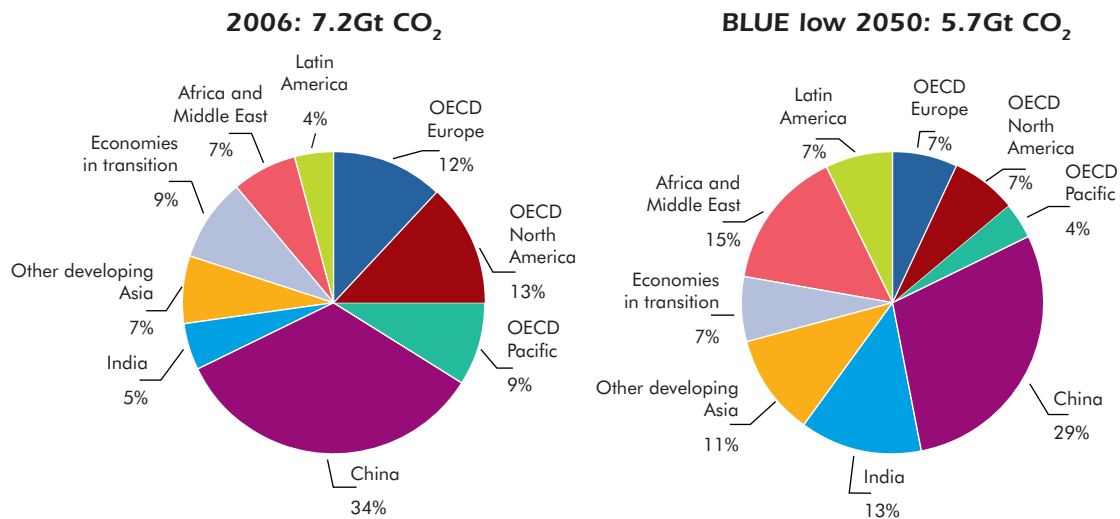
Table 1.3 ► Direct CO₂ reductions in industry by region under the Baseline and BLUE low-demand scenarios to 2050

	2006 Mt CO ₂	Baseline low 2050 Mt CO ₂	BLUE low 2050 Mt CO ₂	Reduction BLUE 2050 vs 2006	Reduction BLUE 2050 vs baseline 2050
China	2 460	3 326	1 635	-34%	-51%
India	390	1 444	739	90%	-49%
OECD Europe	890	883	386	-56%	-57%
OECD North America	905	924	454	-50%	-51%
OECD Pacific	633	581	247	-61%	-57%
Economies in transition	606	853	416	-31%	-51%
Other developing Asia	517	1 158	644	24%	-44%
Africa and Middle East	485	1 470	825	70%	-44%
Latin America	284	554	339	19%	-38%
Total	7 170	11 196	5 637	-21%	-49%

Source: IEA data and estimates.

As shown in Figure 1.12, emissions from OECD countries will decrease in the BLUE low-demand scenario, falling by more than half from 2.4 Gt in 2006 to 1.1 Gt in the BLUE low-demand scenario in 2050. With lower rates of production growth than China's, the OECD will contribute fewer reductions than China in all the scenarios for 2050. It is important that OECD countries take the lead in terms of technology deployment and diffusion. But measures in the OECD alone will not be sufficient to reduce global emissions from industry.

Figure 1.12 ► Share of direct CO₂ emissions in industry by region under the BLUE low-demand scenario, 2006 and 2050



Key point

The share of emissions in the BLUE low-demand scenario to 2050 will show the largest reductions in China and all OECD regions.

As domestic consumption feeds demand, India's industrial CO₂ emissions will grow the most of all countries in the Baseline scenarios. In the BLUE low-demand scenario, India's emissions would rise at a slower rate, but will still almost double from today's levels of 0.4 Gt CO₂ to 0.7 Gt CO₂ in 2050. High energy prices for industry in India have helped the country develop a relatively energy-efficient industrial sector in the last two decades. Nevertheless, significant efficiency potentials still exist in the country's older, often smaller and inefficient plants. It will be important for India to implement BAT where possible in order to limit the environmental impacts of growth in industrial production.

Industrial production in ODA and in Africa and the Middle East is also expected to grow strongly. With combined emissions of 2.6 Gt in 2050 in the Baseline low-demand scenario, these two regions will account for 24% of total global industry emissions, surpassing total OECD industry emissions of 2.4 Gt. In the BLUE low-demand scenario, the two regions' share of emissions is expected to rise to 26% in 2050. This would be 44% lower than in the Baseline low-demand scenario, and 47% higher than in 2006. The higher share of emissions in the BLUE low-demand scenario for 2050 is due to lower levels of CCS penetration than in other regions.

Detailed regional results can be found in Annex A.

Investment costs in industry

In the BLUE scenarios, investment needs by 2050 are estimated to be between USD 2 trillion and USD 2.5 trillion higher than in the Baseline scenarios, with most investment being needed in the cement, iron and steel, and chemical sectors (Table 1.4). These sectors account for the largest share of emissions in industry. Total additional investments in industry represent just 6% of the total investment costs needed across all sectors to halve global CO₂ emissions. With the exception of cement, where investment needs in the BLUE scenarios are more than 50% higher than in the Baseline scenarios, investments in the other sectors are estimated to be 10% to 15% higher than under the Baseline scenarios. The investment in new technologies will yield significant savings in fossil fuel consumption, but lead to increased biofuel and feedstock costs. Many of the energy efficiency investments are already competitive based on life-cycle costs insofar as, under current market prices, cumulative undiscounted fuel savings (excluding electricity) of an estimated USD 4 trillion to USD 5 trillion would be expected to result from these investments. These do not include the extra costs for a near-decarbonised power sector under the BLUE scenarios.

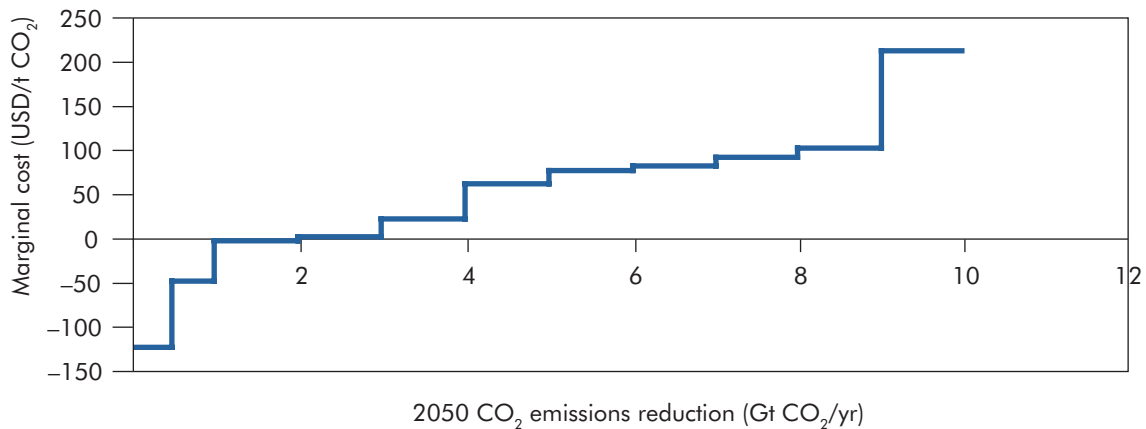
Industry measures to save energy and emissions have different marginal abatement costs (Figure 1.13). Many energy efficiency options, for example, are cost-effective on a life cycle basis provided they are introduced during the regular capital stock turnover cycle. For the most part, these options have negative or low marginal costs as the additional investment costs are offset by fuel savings.

Table 1.4 ► Investment needs in industry under the Baseline and BLUE scenarios, 2050

USD billion	Total investment needs 2010-2050 Baseline 2050	Total investment needs 2010-2050 BLUE 2050	Additional investments
Iron and steel	2 000 – 2 300	2 300 – 2 700	300 – 400
Cement	760 – 970	1 200 – 1 640	440 – 670
Chemicals and petrochemicals	4 100 – 4 700	4 500 – 5 200	400 – 500
Pulp and paper	1 220 – 1 350	1 340 – 1 490	120 – 140
Aluminium	660 – 910	720 – 1 000	60 – 90
Total industry			2 000 – 2 500

Source: IEA estimates.

Figure 1.13 ► Abatement cost curves for industry



Note: Includes reductions in direct energy and process emissions and indirect emissions from reduced electricity use.

Key point

The bulk of industrial emissions reductions can be achieved with a cost of USD 50 to USD 100/t CO₂, but options of up to USD 200/t CO₂ will be needed to achieve the full reduction potential.

The industrial use of CCS is generally more expensive than CCS for coal-fired power plants, but it is essential for deep emissions reductions in industries such as cement and iron and steel. CCS in industry falls within the range of USD 50 to USD 100/t CO₂ saved. Other more expensive options (up to USD 200/t CO₂ saved) include higher levels of recycling and fuel and feedstock substitution, including switching to biomass feedstock in the chemical and iron and steel sectors.

RDD&D needs

Reducing emissions in industry will require the application of current BAT, together with the development and deployment of promising new technologies which will significantly reduce energy use and CO₂ emissions. A list of the most promising new technologies in each sector can be found in Table 1.5.

The current financial crisis, a weaker economic outlook and falls in commodity prices have significantly changed the investment profile for all sectors. New projects have been delayed or cancelled because of a lack of affordable funding and uncertainty about future demand. Government support of promising new technologies will be needed through increased RDD&D. New technology development is risky and can fail. Government R&D planning should incorporate these risks when programmes are developed. In the very long-term, additional RD&D will also be needed to develop CO₂-free processes for industry that will not need to rely on the capture and storage of CO₂.

Table 1.5 ► Technology requirements in industry

Iron and steel	Cement	Chemicals	Pulp and paper	Aluminium
Application of current best available technologies				
Including CHP, efficient motor and steam systems, waste heat recovery and recycling				
Fuel and feedstock switching				
DRI, charcoal and waste plastics injection	Alternative fuels, clinker substitutes	Biomass feedstocks	Increased biomass	
New technologies				
Smelt reduction		Membranes	Lignin removal	Wetted drained cathodes
Electrification (MOE)		New olefin processes	Black liquor gasification	Inert anodes
Hydrogen		Process intensification	Biomass gasification	Carbothermic reduction
CCS for blast furnaces	CCS post-combustion	CCS for ammonia	CCS for black liquor gasification	
CCS for DRI	CCS oxyfuel	CCS for large scale CHP		
CCS for smelt reduction	CCS pre-combustion	CCS for ethylene		

Box 1.1 ► **Technology roadmaps**

Roadmaps show what is needed to take technologies from their current status through to full commercialisation. In response to a request from the G8 leaders at their summit in Hokkaido in 2008, the IEA is leading efforts to develop roadmaps for the most important low-carbon technologies on both the demand side and the supply side. Effective roadmaps will require the engagement of all key stakeholders, including the private sector and developing countries.

The goal of roadmaps is to advance the understanding of what is needed to secure the global development and uptake of key technologies needed for deep emissions reductions. They will enable governments, investors and industry to identify the steps that they need to take to implement measures that will achieve the required technology development and uptake.

Each roadmap will identify the major barriers to be removed, opportunities, and policy measures for each group of stakeholders (policy makers, industry and financial partners) to accelerate RDD&D efforts for specific clean technologies at both national and international levels. The approach will use existing experience of technology roadmaps as a basis for further development of a process aimed at creating stronger international collaboration/co-operation and public-private partnerships for clean energy technologies.

International sector roadmaps in industry can contribute to advance technology transfer and enable countries to better understand the energy efficiency and CO₂ reduction potentials of existing and new technology options, as well as identify policy and financial needs to bring about a technology transition in the sector. A roadmap for the cement sector is currently under way and being developed by the IEA in collaboration with the World Business Council for Sustainable Development's (WBCSD) Cement Sustainability Initiative. Similar approaches should also be considered for other sectors in industry.

Policy implications

The CO₂ mitigation options outlined in this publication will require substantial investments in new technologies. This will only come about if it is supported by clear, long-term policies that put a price on CO₂ emissions. Government intervention will also be needed in the form of standards, incentives and regulatory reforms if the potential offered by current technologies is to be realised and if new low-carbon options for industry, such as CCS, are to be brought to fruition. Significant financial, regulatory and public acceptance barriers will have to be overcome.

Unlike in the power sector, where the higher costs of decarbonisation can often be passed on to the end-user through tariff increases, the price of commodities is set by the global market. A global carbon price will eventually be needed so that international commodity prices properly reflect the high cost of reducing CO₂ emissions. The low price of carbon today will not stimulate the investments needed for an energy technology transition in industry. Current emissions trading systems are not sufficient to bring about the transitions needed in industry. The CO₂

incentive will need to rise to approximately USD 100/t CO₂ by 2030 and then up to USD 200/t CO₂ if all of the reduction potentials outlined in the scenario analysis are to be realised.

A global system of emissions trading may eventually be a crucial policy instrument to achieve this outcome. However, in the short- to medium-term, international agreements among major economies covering some of the main energy-intensive sectors might be a practical first step in stimulating the development of new technologies, while addressing concerns about competitiveness and carbon leakage. Public-private partnerships could also play an important role in stimulating investment in low-carbon technologies. Technology development is uncertain and hence very risky. Governments need to play a role in mitigating some of the policy and economic risks that, especially in the early stages, industry may be unwilling to take.

As most of the future growth in industry production will take place in regions outside the OECD, policy measures should also include mechanisms that will facilitate the diffusion of low-carbon technologies into developing countries. Greater international collaboration will be needed to promote the diffusion of BAT. Factors such as energy subsidies, the unavailability of low-cost financing for capital stock replacement, energy efficiency retrofits, and the lack of skilled labour risk acting as barriers to the wider implementation of more efficient and low-carbon technologies.

Chapter 2 IRON AND STEEL

Key Findings

- ▶ Global steel production has been growing at an unprecedented rate in the last decade, largely driven by developments in China. This growth has slowed recently, but the IEA projects a resumption of strong growth with crude steel demand increasing by 85% to 122% between 2006 and 2050.
- ▶ The energy efficiency potential, based on today's best available technologies, is about 20%. Replacement of small-scale blast furnaces is the single most important opportunity. Better recovery and use of residual gases and waste heat is also important. Given the limited efficiency potential inherent in existing best technologies, other technological improvements will be needed to reduce carbon dioxide (CO₂) emissions more significantly.
- ▶ With the projected demand growth in the coming decades, the need for the production of steel from ore, the most energy-intensive and CO₂-emitting production method, will increase under the Baseline scenarios from around 840 Mt in 2006 to between 1 440 Mt and 1 740 Mt in 2050. In the BLUE scenarios, increased use of scrap will limit production from ore to between 1 060 Mt and 1 290 Mt.
- ▶ In order to halve global CO₂ emissions from today's level by 2050, the iron and steel sector would have to reduce its direct CO₂ emissions by about 38%. Given expected demand growth, this requires direct CO₂ intensity (t CO₂/t crude steel) to be reduced by a factor of almost four. The cost of achieving this will be significant: options with a cost of up to USD 200/t CO₂ will be needed.
- ▶ New energy-efficient technologies are being developed and demonstrated. When fully developed, these technologies are expected to reduce coal use for hot metal making by 8% to 15% compared with current levels. They could also allow for 40% to 70% of CO₂ emissions to be captured without major process adjustments, but with additional process steps.
- ▶ Fuel switching can help to reduce emissions. A switch from blast furnaces to gas-based direct reduced iron (DRI), a solid iron product, and the increased use of biomass (charcoal), plastic waste and CO₂-free electricity also offer interesting opportunities.
- ▶ Carbon capture and storage (CCS) will be an important future option for reducing emissions in the iron and steel sector. But this technology is not yet commercially available. There is an urgent need to demonstrate CCS on a commercial scale for various iron and steel processes.
- ▶ Total additional investments in the iron and steel sector in the BLUE scenarios would amount to between USD 300 billion and USD 400 billion by 2050, about 17% higher than the levels of investment implicit in the Baseline scenarios. But these additional investments will be lowered by savings in fossil fuel costs.

Introduction

World steel production amounted to 1 250 Mt in 2006 and 1 344 Mt in 2007. World steel-making capacity was 1 563 Mt in 2007 (OECD, 2008). While production was nearly constant between 1975 and 2000, it grew by 58% between 2000 and 2007. The main growth during this period occurred in China. Chinese production amounted to 489 Mt in 2007, around 36% of world production. China now produces four times as much as the second-largest producing country, Japan. A rapid restructuring of the industry is taking place, with larger multinational companies. ArcelorMittal, the largest steel producer, had an 8.7% market share in 2007. The second-largest company, Nippon Steel, is less than one-third the size of ArcelorMittal.

Rapid expansion of production capacity has had generally positive effects on the energy efficiency of the industry. Additional capacity has reduced the average age of the capital stock. New plants tend to be more energy-efficient than old plants, although not all new plants apply the best available technology. In addition, energy efficiency equipment has been retrofitted to existing furnaces, and ambitious efficiency policies have resulted in the early closure of inefficient plants, notably in China.

But in parallel, recycling as a proportion of total steel production has declined since 2000. In 2007, 480 Mt of steel scrap was recycled. This was around 36% of the amount of crude steel production, down from 47% in 2000. The decline in scrap use is primarily attributable to the rapid growth in China of the use of blast furnace/basic oxygen furnace (BF/BOF) technologies, rather than scrap-intensive electric arc furnaces (EAF), as well as the increasing amount of steel in products still in use and the loss of steel metal during processing.

The amount of scrap available is limited. As a result, more primary steel production has had to be produced from ore to meet the rapid rise in demand for steel. In 2007, 984 Mt of steel was produced from ore and 65 Mt from DRI. Because primary steel production is much more energy-intensive than the recycling of steel scrap, the rising share of primary materials production has resulted in higher energy use per tonne of steel product.

The product mix has been changing as well. For example, in 2007, 28 Mt of stainless steel was produced, an increase of about 90% over 2000 (ISSF, 2008) compared to 58% growth in steel overall. Stainless steel contains a high proportion of alloys. The energy used to produce these alloys is not significant worldwide, but has a significant impact in high-volume stainless steel producing countries such as South Africa and Russia.

Crude steel is converted into a mix of hot and cold rolled products, including wire, reinforcement bars, and hot and cold rolled sheet. In some cases a metal or paint coating is applied. The energy needed per tonne of product depends on the nature of the final product, but is small compared to that involved in making crude steel.

Coke is a major feedstock for blast furnaces. Coke is produced in coke ovens using high-quality coking coal. It is then used in iron-making blast furnaces. Coke is typically 60% to 75% more expensive than the coking coal feedstock. In modern

blast furnaces, 300 kg of coke produced from half a tonne of coking coal is needed to produce one tonne of hot metal (IEA, 2007).

High coking coal and coke prices create a major incentive to minimise coke consumption through efficiency measures and by switching to other types of feedstock. As coal injection on blast furnaces has reached its limit in the short-term, other solutions are being investigated. In Japan, plastic waste is added to the coke-making process. Smelting reduction processes that use steam coal and therefore avoid the need to make coke are currently moving from the demonstration stage to commercialisation. Steam coal and gas-based DRI production has also been expanding at a rapid rate in the last 20 years although blast furnace has remained the dominant technology overall.

Trends in energy efficiency and CO₂ emissions

Two important international initiatives are under way to improve the quality of the available data on the efficiency and CO₂ intensity of iron and steel-making. The first takes place under the umbrella of the World Steel Association¹ (Worldsteel). Worldsteel is an organisation with company members, which cover about 85% of global steel production. Membership is high in all countries with the exception of China where direct company membership accounts for 25% to 30%, and the China Iron and Steel Association, member of Worldsteel, accounts for 70%. The second initiative is the Asia-Pacific Partnership on Clean Development and Climate (APP). This is a co-operation programme, with government and industry participation from Australia, Canada, China, India, Japan, Korea and the United States. Improving the quality of data from China, Russia and Ukraine is critical to the work of both initiatives.

Worldsteel has embarked on a project that aims to collect CO₂ emission data for all steel plants. As an interim target, the initiative was seeking to collect CO₂ intensity data from some 400 steel plants, accounting for over 50% of the Worldsteel membership tonnage. These data and the country averages are not publicly available.

The APP collects energy efficiency data at plant level. Its data collection is well advanced and data for 50 integrated plants and 30 EAFs had been collected by April 2008 (APP, 2008). The goal is to extend the coverage to all plants in the member countries and to make data available for country averages. The APP data for integrated plants, excluding a small number of extreme outliers, suggest a range of energy intensity between 20 GJ/t and 35 GJ/t of steel produced. The data suggest a correlation between size and efficiency, with a difference of 6 GJ/t between smaller (less than 1.5 Mt per year) and larger (more than 8 Mt per year) blast furnaces.

1. The World Steel Association was formerly known as the International Iron and Steel Institute (IISI).

Box 2.1 ► **Energy efficiency gains in BRIC* countries through structural change**

Capacity growth is slowing in China. In 2007, the State Development and Planning Commission signed Letters of Commitment with 28 provincial and municipal governments, which are expected to result in 77.76 Mt of outdated steel-making capacity and 89.17 Mt of outdated iron-making capacity closing by 2010. These will be replaced by new, modern, larger-scale plants, resulting in an expected increase in the efficiency of use of raw materials. By November 2007, 15.21 Mt of steel-making capacity and 29.4 Mt of iron-making capacity had been closed. According to the China's Steel Industry Revival Plan, published in February 2009, the Chinese government plans to eliminate an additional 72 Mt of outdated iron-making capacity and 25 Mt of steel-making capacity by 2011 to reduce oversupply and eliminate the most inefficient and environmentally harmful plants.

In response to increasing steel demand from the construction and energy industries, many Russian steel makers had until recently planned capacity expansions, including several mini-mill projects to replace outdated open-hearth furnaces. Investment projects were aimed at reducing energy needs and costs in steel smelting. But with many steel companies now facing difficulties in raising funds because of the global financial crisis, some companies have delayed or significantly reduced their investment plans.

Steel-making capacity in Brazil is expected to rise from 41.5 Mt to 50.7 Mt in 2010. Several foreign companies and local mills are planning to construct new steel-making facilities to take advantage of access to the region's iron ore resources and comparatively good market prospects. However, some investment projects have been postponed or cancelled as a result of the steel market recession.

Steel-making capacity in India is expected to increase from 56.1 Mt in 2007 to 78.5 Mt in 2010. Very significant expansion has been planned to keep pace with forecast demand. The Ministry of Steel has announced the implementation of plans for a capacity increase of 243 Mt per year, involving investment of around INR 51 500 billion, according to some news sources. However, many new steel mill projects have encountered strong local resistance, resulting in some steel makers deciding to shelve their projects.

* BRIC: Brazil, Russia, India, China.

Best available technology and technical savings potential

The iron and steel sector is the second-largest industrial user of energy, consuming 24 EJ in 2006, and the largest industrial source of CO₂ emissions. The four most important producers (China, Japan, the United States and Russia) account for 57% of total world steel production (Table 2.1).

Steel is produced through a dozen or so processing steps, laid out in various configurations depending on product mix, available raw materials, energy supply and investment capital. There are three principal modern processing routes:

- BF/BOF, based on 70% to 100% ore and the remainder scrap for the iron input;
- scrap/EAF method, based on scrap for the iron input; and
- DRI/EAF method based on iron ore and often scrap for the iron input.

The scrap/EAF route is much less energy-intensive (4 GJ to 6 GJ per tonne) than the BF/BOF route (13 GJ to 14 GJ per tonne), because there is no need to reduce iron ore to iron, and it removes the need for the ore preparation, coke-making and iron-making steps. Significant energy savings can be made by switching from BF/BOF processes to scrap/EAF in some countries. However, as scrap supply is determined by the amount of steel reaching the end of its useful life, there is a limit to the proportion of total steel output that can be produced by the scrap/EAF route.

Table 2.1 ▶ Global steel production, 2006

	Production (Mt/year)	Production share (%)	Cumulative production share (%)	BOF steel (%)	EAF steel* (%)	OHF steel (%)
China	422.7	33.8	33.8	89.7	10.3	0.0
Japan	116.2	9.3	43.1	74.0	26.0	0.0
United States	98.6	7.9	51.0	43.1	56.9	0.0
Russia	70.8	5.7	56.7	61.6	18.4	20.0
India	49.5	4.0	60.6	42.1	55.9	2.0
Republic of Korea	48.5	3.9	64.5	54.3	45.7	0.0
Germany	47.2	3.8	68.3	68.9	31.1	0.0
Ukraine	40.9	3.3	71.5	56.4	9.8	33.8
Italy	31.6	2.5	74.1	37.4	62.6	0.0
Brazil	30.9	2.5	76.5	73.9	24.4	0.0
Other	293.2	23.5	100.0	–	–	–
Total	1 250.0	100.0	–	–	–	–

* Includes both the scrap/EAF and DRI/EAF routes.

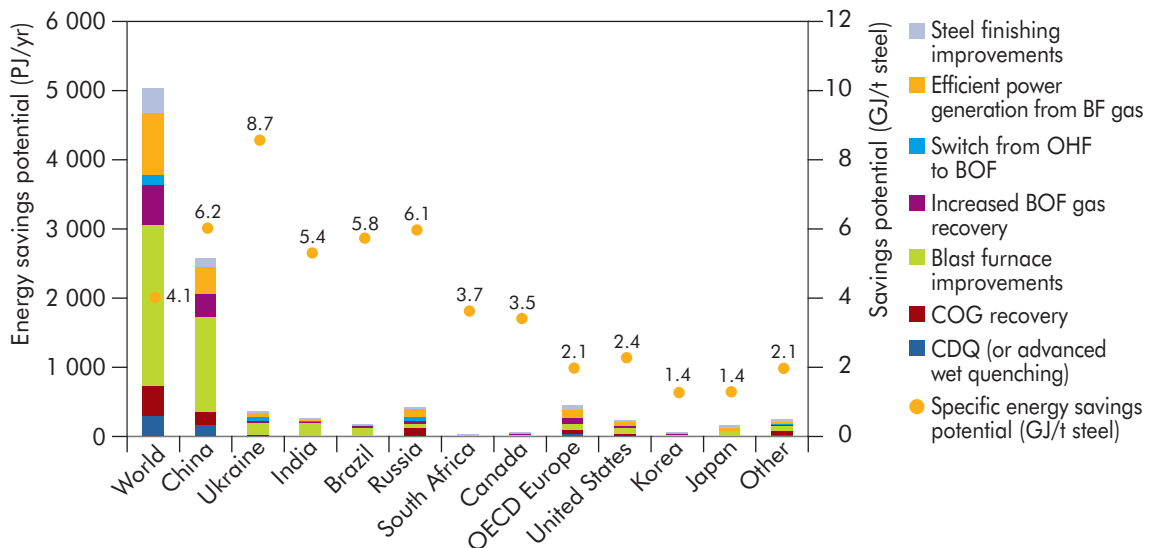
Source: IISI (2007).

A broad-based comparison of total sub-sector energy consumption per tonne of crude steel is of limited use because the production processes are very different. At the very least, the BF/BOF, scrap/EAF and DRI processes need to be treated separately. Even then, there are considerable differences in the energy efficiency of primary steel production between countries and even between individual plants. These differences can be explained by factors such as economies of scale, the level

of waste-energy recovery, the quality of iron ore, operations know-how and quality control. The necessary disaggregated energy data are not currently available to construct these detailed indicators. Neither are there comparable data to develop indicators for steel rolling and finishing on an aggregate level. More work is needed to collect the necessary data.

However, bottom-up estimates can be made of the energy and CO₂ reductions that could be achieved if best available technology were applied worldwide. Figure 2.1 provides a breakdown of the estimated technological efficiency potentials for individual countries based on current production volumes and current technologies.² This suggests that the total potential energy saving is around 5.0 EJ. If achieved, this would save around 390 Mt CO₂, about 20% of total direct CO₂ emissions in the iron and steel industry. China accounts for 51% of the potential energy saving, because of its high share of total world production. However, in terms of energy reductions per unit of steel produced, a number of other countries have higher potential. The average global potential is 4.1 GJ/t crude steel, equivalent to 0.3 t CO₂/t steel produced.

Figure 2.1 ► Energy savings potential in 2006, based on best available technology



Note: BF: blast furnace; OHF: open heart furnace; BOF: blast oxygen furnace; COG: coke oven gas; CDQ: coke dry quenching.

Source: IEA analysis.

Key point

The potential exists to save more than 5.0 EJ of energy, with country-specific savings potentials of 1.4 GJ/t to 8.7 GJ/t of crude steel.

The production of electricity from residual gases offers another opportunity for steel plants to maximise the use of input fuels. Net conversion efficiency ranges from 25% in India, Russia and Ukraine to 35% in Japan and Korea. The net efficiency of

2. Work at the IEA is ongoing to improve the quality of the underpinning data and to refine the methodologies used in calculating the savings potential in the industrial sector.

advanced conversion technologies is 42%. The total global primary energy savings potential is about 800 PJ (Siemens VAI, 2008). This excludes any additional savings that might arise from gas flow optimisation, *i.e.* from matching gas quality more closely to needs.

Efficiency improvements enable cost and resource reductions, which have benefits for developed and developing countries alike. The application of best available technologies more widely would also enable significant CO₂ emissions reductions.

Much of this potential could be realised with policies that are already in place today, as illustrated for example by the plans for the BRIC countries discussed in Box 2.1. As efficiencies are gained, further potential will become harder to achieve unless the introduction of new technologies enables additional savings.

Although the use of best available technologies could result in significant energy and CO₂ reductions, their potential is limited to around 20% of the world total. This is considerably less than the expected growth in energy demand that will result from production doubling between 2006 and 2050. A net reduction in energy demand and emissions will therefore be dependent on significant innovation strategies bringing new technological solutions on stream well before 2050.

Box 2.2 ▶ **Severstal energy efficiency loan by the European Bank for Reconstruction and Development**

Severstal is one of Russia's largest vertically integrated steel producers. Its main steel production facility in Russia in Cherepovets has an annual capacity of more than 11 Mt. Like many Russian plants, the specific energy consumption per tonne of steel at Cherepovets is more than 35% higher than the average of similar plants in Europe.

In 2007, the European Bank for Reconstruction and Development provided loans amounting to EUR 600 million to support Severstal's implementation of 11 high-priority energy efficiency investment projects. These have an estimated total cost of more than EUR 700 million from 2008 to 2015. They include the construction of new power generation facilities that will use a mixture of steel waste gases and natural gas; the installation of top-gas recovery turbines in blast furnaces; the modernisation of the compressed air system; the installation of a new air separation unit for oxygen production; and the modernisation of high-pressure steam boilers and electricity substations. A high-efficiency 155 MW combined cycle gas turbine unit is one of the options for power generation. In parallel, the company will implement an energy efficiency management system such as that applied in similar steel plants in Europe. Even at current low energy prices, all the projects are profitable, with payback periods between one and five years. The cumulative effect of these projects will be a 10% reduction in the amount of electricity used in Cherepovets and a 5% cut in the amount of natural gas consumed. At the same time, the plant will generate more than 2 500 additional GWh on site, providing 75% of the site's electricity needs, compared to the current level of 25%. Overall CO₂ emissions are expected to fall by around 1.25 Mt per year.

R&D programmes

Ultra-Low CO₂ Steelmaking (ULCOS) is a co-operative research and development (R&D) programme run by a consortium of 48 European companies and organisations from 15 European countries. The consortium consists of all the major European Union steel companies, energy and engineering partners, research institutes and universities. It is supported by the European Commission. The aim of the programme is to reduce the CO₂ emissions of today's best technologies by at least 50%. Technologies under evaluation include the new carbon-based smelting reduction process, new types of reactors, new blast-furnace processes, the use of biomass and CO₂ capture.

The first four-year stage of this programme had a budget of EUR 59 million (USD 90 million). It has resulted in the selection of four routes for further development: top-gas recycling blast furnace (TGR-BF), Isarna (a new smelting reduction process, the successor of the cyclone converter furnace that has been under development by Hoogovens and Corus since the early 1990s), new direct reduction processes and electrolysis.

These technologies will be demonstrated in the second phase. Following successful pilot plant testing of the oxygen blast furnace, a demonstration project for a full-size blast furnace is planned. This research will require considerable further investment. The implementation of the TGR-BF approach will, for example, cost about EUR 500 million (USD 750 million) (ESTEP, 2008).

In Japan, a JPY 25 billion (USD 250 million) R&D programme, COURSE50, to investigate the use of CCS and the use of hydrogen (H₂) instead of coking coal for iron-making has been announced (*Japan Times*, 2008). Basic research is being carried out on H₂ reduction. Japan has developed a new technology that uses the residual heat from coke ovens for reforming coke-oven gas to achieve higher H₂ yields. CCS for blast furnaces using chemical absorption is also being investigated. The goal is to reduce average CO₂ emissions in steel-making from 1.64 t CO₂/t crude steel today to 1.15 t CO₂/t crude steel in 2050.

In the United States, the Department of Energy's (US-DOE) USD 26.6 million Energy Intensive Processes initiative aims to leverage an additional USD 15.6 million in cost-share funds from the award recipients. Eight awards have been defined, including thermochemical recuperators for high-temperature furnaces to use waste heat for partial oxidation, the paired straight-hearth furnace, which, when combined with a smelter, provides a potential blast furnace alternative, and energy-efficient thermo-magnetic and induction hardening for heat-treating and net-shape forming applications (DOE, 2008). So far, there are no plans to research CCS in the iron and steel industry in North America. Basic research is focusing on breakthrough processes such as electrochemical steel-making.

In Australia, work is under way to recover heat from molten slag using a dry granulation and heat recovery process (Xie *et al.*, 2008). The process uses air

instead of water to cool the slag, and the heat from the air (at 600°Celsius) can be used for heating purposes. Plant trials are planned for 2009 to 2010, and commercialisation from 2010 onward.

Scenario analysis

Improvements in materials flow management focus on the increased recovery of steel scrap, the development of new steel types and the design of new steel products. For example, more steel can be recovered from municipal solid waste through mechanical waste separation. For new steel types, significant developments will be needed in the design of alloys and testing procedures.

Table 2.2 provides an overview of the levels of demand projected in different scenarios. The BLUE scenarios examine the implications of a policy objective to halve global energy-related CO₂ emissions in 2050 compared to today's level, while the Baseline scenarios assume business as usual.

Individual countries' and regions' production levels may differ from these demand levels depending on their levels of import and export. Two demand cases have been elaborated. They reflect different levels of decoupling between economic growth and steel demand. In both cases, global GDP quadruples. Global steel demand grows by 85% in the low-demand case and 122% in the high-demand case from 2006 to 2050.

Overall, demands for steel in the BLUE scenarios are very similar to those in the Baseline scenarios as they are affected by counter-balancing factors:

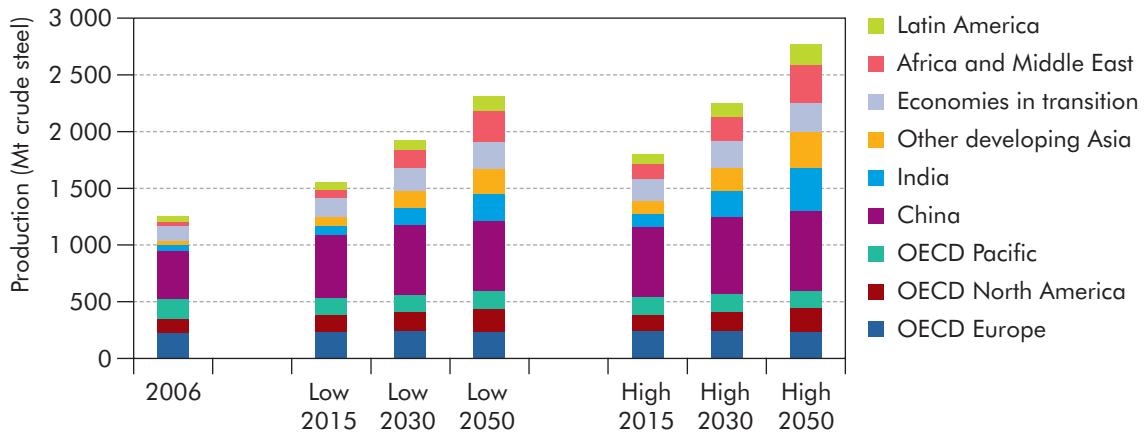
- Higher prices reduce demand, driving changes in materials efficiency, materials substitution, and reduced demand for materials services.
- Consumption patterns change. For example, electricity generation developments require additional steel for equipment and for buildings and infrastructure. But this is largely offset by iron and steel savings as lighter-weight materials are introduced, for example in the transport sector as car engine blocks are replaced by batteries or fuel cells. The net effect is either constant demand or an increase of a few per cent.
- The conversion of a tonne of steel from ore into finished products emits approximately two tonnes of CO₂. With CO₂ prices at USD 100/t CO₂, this translates into an additional cost of USD 200/t steel. The historical average price of finished steel products is around USD 600/t. The price increase is in the order of 30%. Although there are few historical data relating to the long-term elasticity of demand, typically a value of -0.2 is used, which means that demand declines by 0.2% for each percentage point price increase. So a price increase of 30% might result in a demand reduction of 6%.

Table 2.2 ► **Crude steel demand projections for the low- and high-demand cases, 2006 to 2050**

	Crude steel demand per capita (kg/cap)						
	2006	Low-demand case			High-demand case		
		2015	2030	2050	2015	2030	2050
Canada	590	550	525	500	550	525	500
France	286	280	275	270	286	286	286
Germany	512	476	476	476	500	500	500
Italy	658	500	500	500	550	500	500
Japan	652	625	600	550	625	600	550
Russia	300	400	440	500	400	475	525
United Kingdom	243	251	251	251	251	255	260
United States	429	429	429	429	430	430	430
Brazil	109	140	178	250	200	250	350
China	293	375	400	425	425	450	480
India	44	65	125	185	85	175	278
Mexico	243	262	322	424	275	340	500
South Africa	141	232	362	500	290	452	500
Other economies in transition	167	267	375	450	429	500	500
Other developing Asia	72	100	137	175	135	185	236
Other Latin America	76	99	121	170	133	164	230
Other Africa	25	35	42	60	47	56	81
Middle East	208	267	361	425	417	467	500
Other OECD Europe	426	500	500	500	500	500	500
Other OECD Pacific	823	500	500	500	500	500	500
World	190	214	234	254	249	275	305

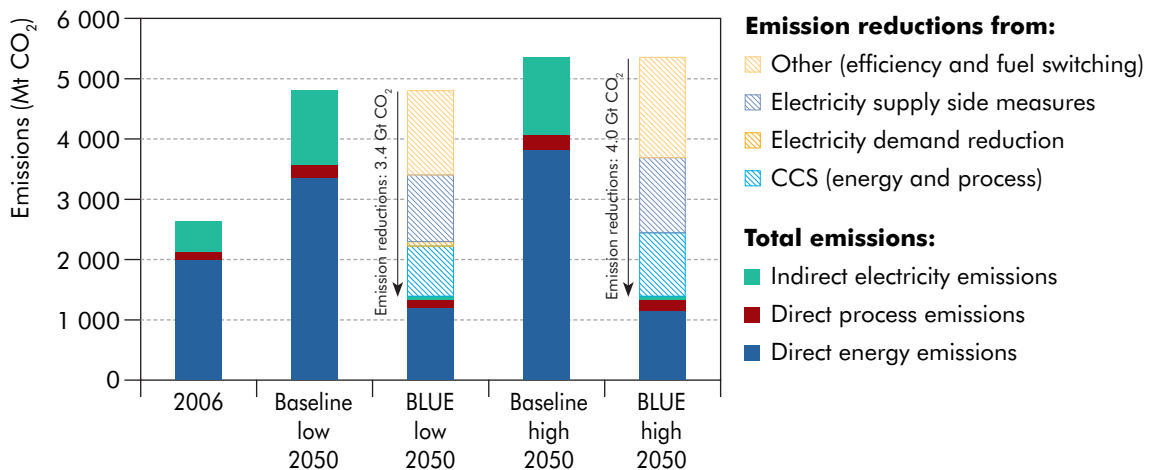
Note: Production levels differ from consumption levels because of international trade and inventories.

Crude steel production is estimated to increase from 1 250 Mt in 2006 to 2 311 Mt and 2 771 Mt in the low- and high-demand cases respectively. In both cases, China will remain the main crude steel producer, accounting for about 25% of the world production (Figure 2.2). India, other developing Asian countries (ODA), Africa and Middle East will, for their part, have the strongest growth rate. Between 32% and 38% of the production in 2050 will be from those regions.

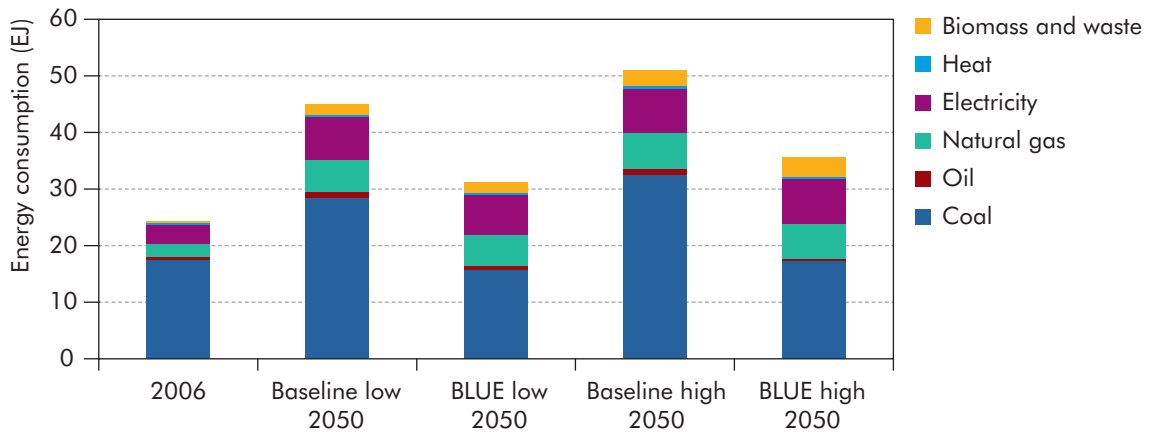
Figure 2.2 ▶ Regional crude steel production, 2006 to 2050**Key point**

India, Africa and Middle East and other developing Asia will account for 32% to 38% of the crude steel total production in 2050.

Figure 2.3 shows the iron and steel direct and indirect CO₂ emissions in the Baseline and BLUE scenarios. Total direct and indirect emissions in the BLUE scenarios will fall by 47% from 2.6 Gt CO₂ in 2006 to 1.4 Gt CO₂ in 2050. The near-decarbonisation of the electricity sector will play a major role in achieving these emissions reductions. Over 30% of the direct and indirect emissions reductions in the BLUE scenarios will come from the decarbonisation of the power generation sector. By 2050, about one-quarter of the reductions will be attributable to CCS. Additional reductions will come from improvements in energy efficiency, partly attributable to the replacement of old and inefficient technologies and the implementation of best practices, and from fuel switching to less carbon-intensive fuels such as natural gas and biomass and waste.

Figure 2.3 ▶ CO₂ emissions by scenario, 2006 and 2050**Key point**

About 25% of the emission reductions come from CCS.

Figure 2.4 ► Final energy consumption by scenario, 2006 and 2050

Note: Includes blast furnaces and coke ovens.

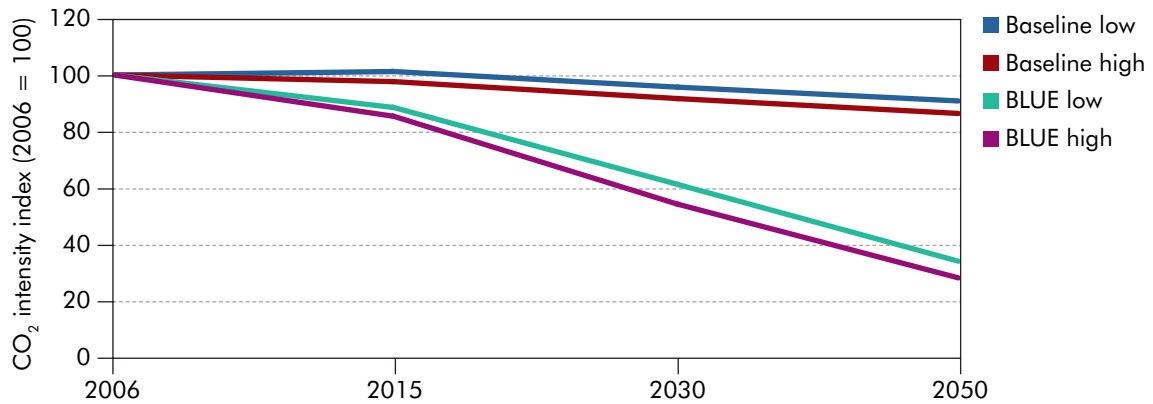
Key point

Efficiency gains and fuel switching limit the growth in coal demand in the BLUE scenarios.

Figure 2.4 shows the energy used by commodity in the Baseline and BLUE scenarios. In the Baseline scenarios, energy use doubles to 45 EJ in the low-demand case and 51 EJ in the high-demand case. In the BLUE scenarios, energy use rises only to 31 EJ and 35 EJ, thanks to the uptake of energy efficiency measures and efficient technologies, a growth of 28% to 46% compared to today's level. Coal use in the BLUE scenarios in 2050 is lower than the level in 2006. All the growth in energy demand is met by other energy forms such as natural gas, electricity, biomass and waste. Compared to the Baseline scenarios, only biomass and waste use increase significantly in relative terms in the BLUE scenarios in 2050. However this aggregate result hides important structural changes, such as the increased use of natural gas for DRI production offset by significant gas savings attributable to efficiency gains in steel finishing.

Figure 2.5 shows direct CO₂ emission intensity in the Baseline and BLUE scenarios. In the Baseline scenarios, emissions rise quickly between 2006 and 2015 and, thanks to the stronger decrease in CO₂ intensity, at a slower rate between 2015 and 2050. Total direct CO₂ emissions in the Baseline scenarios reach 3.6 Gt CO₂ and 4.1 Gt CO₂ in 2050. The CO₂ intensity of steel-making decreases by about 10% between 2006 and 2050 in the Baseline scenarios. In the BLUE scenarios, emissions continue to rise between 2006 and 2015, improvements in intensity are offset by increased production, but they decline in later years to reach less than 1.4 Gt CO₂ in 2050. This represents a decrease of about 38% in direct emissions compared to 2006. The CO₂ intensity decreases by about 70% between 2006 and 2050 in the BLUE scenarios largely as a result of technological innovation, the introduction of CCS and efficiency gains.

Figure 2.5 ▶ Iron and steel direct CO₂ intensity index in the Baseline and BLUE scenarios, 2006 to 2050



Note: Includes blast furnaces and coke ovens. Excludes indirect emissions in electricity production and process emissions.

Key point

In the BLUE scenarios direct CO₂ emissions are about two-thirds of the level of 2006.

Blast furnace steel production stays in the BLUE scenarios roughly at today's level. Smelting reduction grows 30- to 50-fold by 2050, but total metal production by smelting reduction is still only 15% to 22% of blast furnace hot metal production. Gas-DRI production grows six to eight times. Recycling increases to about 54% of total steel production, up from 33% in 2006.

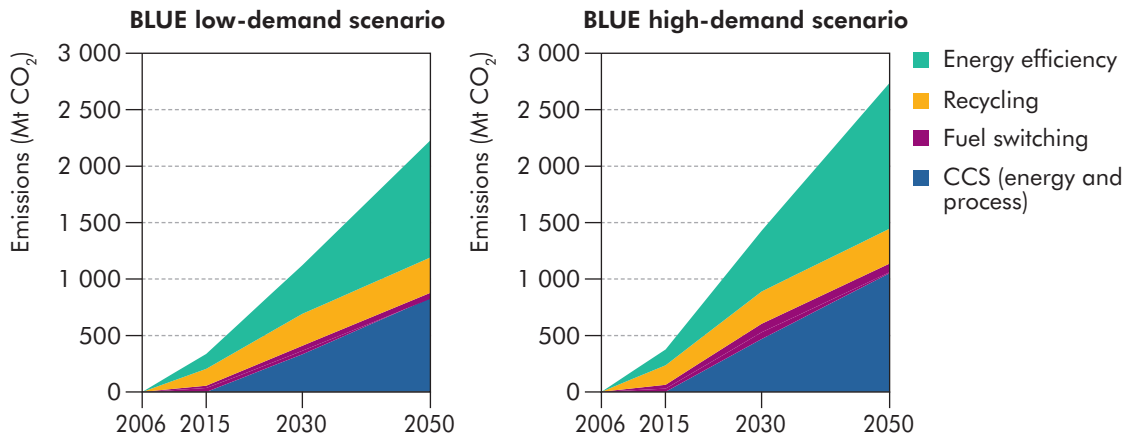
The overall energy intensity of crude steel production, including energy used as feedstock, drops by 31% and 34% from today's level in the BLUE low- and high-demand scenario respectively, representing an annual average improvement of 0.8% and 0.9% per year. Part of this decline can be attributed to structural effects such as increased production from scrap. The intensity improvements are partially offset by significant additional energy being used for CCS. CCS mitigates 0.8 Gt CO₂ in the low-demand case and 1.1 Gt CO₂ in the high-demand case. CCS in the iron and steel sector represents about 50% to 43% of total industrial CCS in the BLUE low- and high-demand scenario respectively.

Figure 2.6 provides a breakdown of the emissions reductions in the BLUE scenarios. Initially, energy efficiency and recycling dominates. From 2015 onwards, fuel switching and CCS start to play a more important role. Total direct emissions abated grow to 2.2 Gt CO₂ to 2.7 Gt CO₂ in 2050. About 37% to 38% of this total abatement can be attributed to CCS and about 11% to 14% to increased recycling. Energy efficiency and recycling are on top of the effort in the Baseline scenario, where both options already play a prominent role.

Figure 2.7 provides a breakdown of direct CO₂ emissions by region for 2006, the Baseline and the BLUE scenarios. In absolute terms, emission levels vary widely by region, with significant increases in regions where production grows fastest such as India, ODA, Middle East and Africa. For those three regions, the impact of the production growth on energy in the high-demand cases compared to the low-demand cases is not fully offset by higher reductions from energy efficiency, new technologies and CCS, so that emissions are higher in the BLUE high-demand

scenario than in the low-demand one. China accounted for 34% of total iron and steel production in 2006, but its emissions represented 47% of the total. China is, with India, the most CO₂-intensive country in 2006, but it is also the largest contributor to reductions in direct emissions in the BLUE scenarios, accounting for 46% to 55% of the CO₂ reductions from the 2006 base year. In the BLUE scenarios, all regions achieved at least a 55% improvement in their CO₂ intensity. In OECD Europe, emissions intensity decreases by 85% over the 2006 to 2050 period.

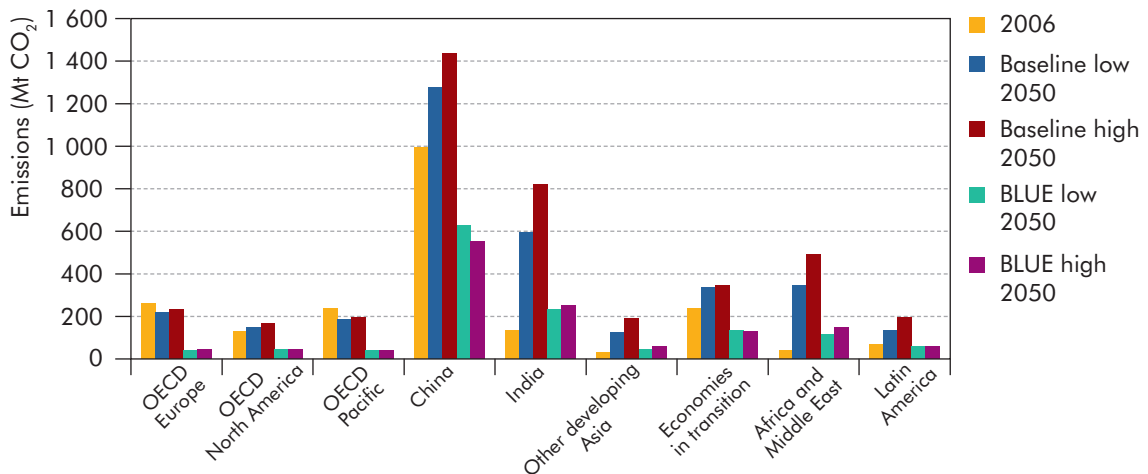
Figure 2.6 ► Direct CO₂ emissions reductions below the Baseline scenario, 2006 to 2050



Key point

Energy efficiency and CCS are the main options for emissions reductions.

Figure 2.7 ► Direct CO₂ emissions by region and by scenario, 2006 and 2050



Key point

China is the largest contributor to reductions in direct emissions in the BLUE scenarios.

Cost of CO₂ reductions in the iron and steel sector

The economics of various technology options depend on fossil fuel and electricity price assumptions, specific regional investment and operating costs, and capital costs. As a result, CO₂ reduction costs can vary widely. In Japan, for example, discount rates are low and fuel prices high: there is a strong incentive to switch to lower-CO₂ technologies. In Russia and South Africa, however, energy prices are low and capital costs high as investors demand a risk premium to compensate for the lack of long-term stability and fluctuating economic conditions. These factors may raise the cost of switching to lower-CO₂ technologies.

Costs are also affected by the nature of the investment. Retrofitting is more expensive and often less efficient than undertaking a new build when a plant is approaching the end of its technical life. Scrapping and replacing a plant before it has reached the end of its technical life span is generally the most expensive option.

The economics of different reduction options are compared in Table 2.3. In locations with readily available resources, these technologies are marginally cost-effective today. With more expensive resources or in regions with less favourable conditions, costs increase significantly. The cost estimates in the table do not account for competition for resources (e.g. biomass for biofuels instead of charcoal) that may result in a higher margin for fuel suppliers, higher fuel costs and therefore higher CO₂-reduction costs.

Table 2.3 ► Economics of fuel switching and reduction options

Category	Option	Reference price	Annualised cost (USD/t CO ₂)	Notes
Energy efficiency (BAT)			-50 to 50	
Fuel switching	Use of DRI (gas-based)	Gas price USD 1 to USD 15 per GJ	0 to 150	Attractive in locations with cheap stranded gas
	Use of charcoal	Charcoal price USD 5 to USD 15 per GJ	25 to 150	Charcoal transport up to 200 km
	Use of waste plastic in coke ovens	Mixed waste plastic	0 to 50	
	Use of CO ₂ -free electricity	Electricity price USD 10 to USD 20 per GJ	75 to 200	Plasma injection; includes electricity transmission cost
CCS	CCS (DRI)		25 to 50	Capture, transportation and storage
	CCS (smelting reduction)		25 to 50	Capture, transportation and storage
	CCS (oxygen blown blast furnace)		40 to 60	Capture, transportation and storage; includes productivity effects
Materials efficiency			-250 to 250	Product- and application-specific

Note: Engineering cost analysis.

Source: IEA analysis.

Table 2.4 ► Investment needs for iron- and steel-making, 2010 to 2050

	Capacity 2050		Investment (USD/t)	Multiplier (–)	Investment	
	Baseline (Mt)	Blue (Mt)			Baseline (trillion USD)	Blue Low (trillion USD)
New blast furnaces	1 296 to 1 569	806 to 920	200	1.75 to 2.25	0.45 to 0.55	0.36 to 0.41
CCS (excl. pipelines)	0	833 to 1 052	150	1 to 1.25	0	0.16 to 0.20
DRI coal	121 to 145	0	200	1	0.02 to 0.03	0
DRI gas	194 to 233	337 to 417	150	1.5 to 1.75	0.04 to 0.05	0.09 to 0.11
Smelting reduction	20	125 to 199	250	1.5 to 1.75	0.01	0.05 to 0.09
Scrap collection	868 to 1 027	1 249 to 1 484	150	2	0.26 to 0.31	0.37 to 0.45
EAF	1 005 to 1 193	1 391 to 1 662	150	2	0.30 to 0.36	0.42 to 0.50
BOF	1 305 to 1 578	920 to 1 109	100	1.75 to 2	0.23 to 0.28	0.18 to 0.22
Sintering	1 944 to 2 353	1 208 to 1 380	75	1.75 to 2.25	0.26 to 0.31	0.20 to 0.23
Coke-making (t/year)	361 to 427	200 to 204	300	1 to 1.25	0.11 to 0.13	0.07 to 0.08
Charcoal-making (t/year)	65 to 78	81 to 92	450	1 to 1.25	0.03 to 0.04	0.05
CDQ (t coke/year)	150	180	300	1.5	0.07	0.08
Advanced gas systems (t/year)	750	850 to 900	200	1.5	0.23	0.26 to 0.27
Total (trillion USD)					2.0 to 2.3	2.3 to 2.7

Note: Includes all investments required both within and outside the iron and steel sector. The numbers listed do not account for early retirement or retrofit, which would raise the cost.

Source: IEA analysis.

In recent years, global steel production has been growing faster than ever, driven by development in China. As a consequence, one-third of the steel-making capacity and half of the iron-making capacity are currently less than 10 years old. This new capital stock will be operating for 20 to 30 years unless it is replaced before the end of its technical life span.

Table 2.4 provides a breakdown of the investment needs implicit in the Baseline and BLUE scenarios. Total investments in the Baseline scenarios amount to between USD 2.0 trillion and USD 2.3 trillion between now and 2050. In the BLUE scenarios, these rise to between USD 2.3 trillion and USD 2.7 trillion. But parts of these additional investments are offset by significant fossil fuel savings. Annual fuel cost savings amount to USD 6 billion per year in 2050 in the BLUE low-demand scenario, and USD 3 billion per year in the BLUE high-demand scenario. Total undiscounted fuel savings for the period 2010 to 2050 amount to between USD 83 billion and USD 131 billion.

New technology options

New coal-based processes

Smelting reduction processes

Smelting reduction is a process where a significant part of the iron ore reduction takes place in a liquid iron bath. The reactor is similar to the lower part of a blast furnace. In smelting reduction, low-quality coal can be used instead of coke as mechanical stability is not an issue. The process generates a large amount of residual gas which, in the most effective designs, is used for pre-reduction of the solid ore. The latest smelting reduction-process designs use ore fines directly. The process has been demonstrated at a scale about half that of a typical blast furnace, but upscaling is planned. Issues relating to process control and reliability and to product quality control seem largely to be solved. Depending on the coke-oven efficiency, smelting reduction costs can be less than for blast-furnace processes. Smelting reduction also facilitates CCS.

The FINEX smelting reduction process, developed by POSCO, consists of a melting furnace with a liquid iron bath where coal is injected and a cascade of fluidised bed reactors for the pre-reduction of iron fines. The process uses ore fines and non-coking coal briquettes. This reduces feedstock costs and feedstock preparation needs. A 1.5 Mt per year demonstration plant has been operational since April 2007. The coal rate of this plant has dropped from 850 kg/t of product at start-up to 700 kg/t of product by April 2008, around the same rate as the best blast furnaces. Plant availability is on par with blast furnaces. Current developments are aimed at increasing the volume of powder coal to 35% of the coal input in order to improve heat exchange, which will further reduce the rate of coal use. FINEX investment costs are 80% of those of a blast furnace and operating costs are 85% of those for blast furnaces (POSCO, 2008).

The first demonstration of the HIs melt³ smelting reduction process is located in Kwinana, Western Australia. It consists of a Circoheat ore pre-heating unit and a HIs melt smelting reduction unit. This plant has been in operation since 2005 and has a capacity of 0.8 Mt per year. More than USD 750 million has been invested in the plant by Rio Tinto and its three partners, US steelmaker Nucor, Japanese trading house Mitsubishi and China's Shougang Steel. The Australian government has also contributed USD 93 million in grants (*Forbes*, 2006).

The plant has achieved a maximum production rate of over 80 tonnes of hot metal (thm) per hour and a sustainable production rate of 75 thm per hour. In the most recent operating period (spring 2008) a new record for daily production was set at 1 712 thm. The lowest coal consumption achieved so far is 810 kg/thm (HIs melt, 2008). HIs melt is currently modifying the configuration and is confident that specific coal consumption could be lowered significantly to a rate of 710 kg/thm. If HIs melt were combined with the Circofer pre-reduction process, a further reduction to 555 kg/thm would be possible. Depending on the efficiency of the coke oven, this could represent a saving of 20% of the coal demand of the coking, sintering and furnace stages of the blast furnace process.

Smelting reduction lowers the cost of iron-making by eliminating front-end processes such as coke ovens and sinter plants and by using cheaper iron ore fines, non-coking coals and steel plant wastes. Plant construction and operation are relatively simple because the HIs melt technology uses many traditional iron-making core-plant facilities, such as hot blast stoves, injection systems and power plants.

The HIs melt process will also be integrated with the Isarna process, which is an enhanced version of the cyclone converter furnace developed by European producers. The combination is named Hisarna. A pilot plant rated at 65 000 tonnes per year is to be built at Saarstahl (an ULCOS participant) in Völklingen, Germany. This unit is due to start operations in early 2010, and a three-year pilot testing phase is anticipated. It is planned to operate the system with 100% oxygen instead of the oxygen-enriched hot blast used at HIs melt.

Coal-based direct reduced iron (DRI)

The so-called Stelco-Lurgi/Republic Steel-National Lead (SL/RN) process is a widely used coal-based DRI-making process. Outotec has built 32 of these kilns, mainly in South Africa and India. This process generates significant amounts of residual gas, which is used for power generation. The advantage of this technology is its robustness and the potential to use low-quality coal, which makes it well suited for developing countries such as India and South Africa. However, coal consumption is

3. HIs melt (high-intensity smelting) is an iron bath reactor process. Fine ores, coal and fluxes are injected at high velocities via eight lances (Kwinana plant) over the bath level into the furnace. The iron oxides are rapidly reduced by the hot metal bath in which carbon from the coal is also dissolved. Carbon monoxide (CO) post-combustion (60%) is obtained by blowing oxygen-enriched hot air into the furnace. The transfer of post-combustion energy back to the iron bath is achieved via a turbulent liquid zone above the bath. Hot metal is continuously tapped slag-free through an open forehearth. The slag is removed from the furnace by batch tapping. To start up the plant, a molten hot metal heel is necessary.

considerably higher than for a blast furnace and the energy efficiency of individual plants depends on the efficient use of the large amounts of residual gas. Highly efficient DRI-making processes, FASTMELT and ITmk3®, effectively reuse exhaust gases in the iron-making processes.

FASTMELT is a new coal-based process that consists of a DRI production unit (FASTMET) and a melter (EIF). The product is hot metal (McClland, 2002). The process can use ore fines. Coke-making is eliminated. Fuel usage can be reduced and, since secondary combustion of close to 100% is achieved in the rotary hearth furnace (RHF), it is not necessary to recover and reuse exhaust gases. Heat losses are low as reduced iron is fed to the melting furnace for hot metal production. Energy consumption is 18 GJ/thm, which is less than for a mini blast furnace (APP, 2007).

ITmk3® uses the same type of RHF as the FASTMET process. The process can use low-grade iron ore and coal to produce iron nuggets with 97% iron content. The mixing, agglomeration, and feeding steps are the same as for FASTMET, but the RHF is operated differently. In the last zone of the RHF, the temperature is raised, melting the iron ore and enabling it easily to separate from the gangue. The result is an iron nugget containing iron and carbon with almost no oxygen or slag which can be processed in an EAF or a BOF.

Fuel switching

Gas-based DRI

Gas-based DRI-making is an established technology. As gas emits less CO₂ per unit of energy than coal, gas-based DRI produces less CO₂ than coal-based technologies. DRI technology is also well suited for CCS.

The MIDREX process represents 70% of the installed DRI capacity worldwide. Other processes such as HyL III are similar in design and performance. The largest plant in operation has a capacity of 1.76 Mt per year, about half the capacity of a standard-size blast furnace.

Gas-based DRI processes are particularly suited to areas where natural gas is readily available and relatively cheap. The MIDREX process is a shaft-type direct-reduction process where iron ore pellets, lump iron ore or a combination of pellets and ore are reduced in a vertical shaft or reduction furnace to metallic iron by means of a reduction gas. The reducing gas is produced from a mixture of natural gas and recycled gas from the reduction furnace. The mixture flows through catalyst tubes where it is chemically converted into a gas containing H₂ and carbon monoxide. The desired reducing gas temperature is typically in the range of 900°C. The gas ascends through the material column and removes oxygen from the iron carriers.

The product, DRI, is typically 90% to 94% iron. After the DRI exits from the bottom of the shaft, it can be compressed to hot briquetted iron (HBI) for safe storage and

transportation. DRI or HBI are virgin iron sources free from tramp elements and are increasingly being used in EAFs to dilute the contaminants present in the scrap. As there is no melting and no slag phase in DRI production, all gangue elements of the iron ores remain in the DRI and need to be separated via a slag in the EAF. This increases the electrical energy consumption of the EAF compared to steel scrap melting. If hot DRI is immediately transferred to the EAF melt shop, the heat from the direct reduction process lowers the cost of melting the DRI in the EAF, significantly cutting these energy costs and electrode consumption (Siemens, 2008). DRI plants are extremely energy-efficient, with natural gas consumption as low as 9.6 GJ/t DRI. Some MIDREX plant/EAF facilities emit only one-third of the CO₂ per tonne of steel of a BF/BOF complex (Midrex, 2008).

Table 2.5 compares the energy use of different DRI production technologies in use since the 1970s. The potential energy saving from injecting hot DRI into an EAF is not captured by the energy data in the table.

Table 2.5 ► Energy use for gas-based DRI production

	DRI production (t/h)	Natural gas (Nm ₃ /t)	Electricity (kWh/t)	O ₂ addition (Nm ₃ /t)	Total final (GJ/t)	Total primary (GJ/t)
Original practice: 1970s	88.8	268.6	135	0	10.2	10.9
Practice using lump ore: 1980s	100.3	262.3	120	0	9.9	10.5
Practice using coating of oxide feed materials: 1990s	110.2	257.9	109	0	9.7	10.3
Oxygen injection practice: late 1990s	121.5	260.3	99	17.5	9.7	10.3
Oxy + practice: 2000	129.2	265.8	93	30.2	9.9	10.4
Combined practice with oxygen injection & Oxy+: future	133.6	264.6	90	41.2	9.9	10.4

Note: Total final and primary energy intensity calculated using the energy-specific conversion factors.

Source: Kawamura *et al.* (2006).

Use of charcoal

World average charcoal production in 2001 to 2005 was around 43 Mt per year (approximately 1.3 EJ per year), and has been expanding by around 2% per year in recent years. Most of this charcoal is used for cooking in developing countries. Charcoal is still used for iron-making, notably in small scale blast furnaces in Brazil (37 million m³ per year in 2004, about 0.6 EJ per year). Charcoal does not have the mechanical stability of coke, but it has similar chemical properties. A

processed type of charcoal with better mechanical stability is under development. This “biocoal” could substitute for coke. Assuming complete replacement of fossil fuels, one t of charcoal requires 0.725 t of charcoal produced from 3.6 t of (wet) wood (Ferreira, 2000). Charcoal produced in Minas Gerais in Brazil costs about USD 200/t (Santos Sampaio, 2005). Given the recent rapid rise in the cost of coking coal to nearly USD 300/t, charcoal compares very favourably under current conditions. However, this situation may switch again rapidly as biomass feedstock costs become increasingly linked to fossil energy prices and if coking coal prices come down again. Feedstocks represent 50% to 70% of total charcoal production costs, and labour another 20% to 40% (Girard, 2007). The potential to reduce charcoal costs is therefore limited.

In the BLUE scenarios, the use of primary biomass and plastic waste in iron and steel-making rises to 1.8 EJ to 3.4 EJ in 2050, of which biomass for charcoal represents about two-thirds to three-quarters (1.2 EJ to 2.5 EJ of biomass). Modern efficient charcoal making can reach 70% energy efficiency, which implies 0.8 EJ to 1.8 EJ of charcoal. To achieve this level of growth sustainably will require integrated agriculture/food/environment/water management policies.

Use of waste plastic

Waste plastic can be injected into blast furnaces and/or coke ovens to help reduce CO₂ emissions. Japan used 0.46 Mt of waste in this way in 2005 and has set a target of one million tonne for 2010 (JISF, 2008a). In Europe, plastic waste is used only in Germany and Austria. In 2008, waste from automotive shredder residues began to be injected at blast furnace C of Salzgitter Flachstahl GmbH.

In the BLUE scenarios, the use of plastic waste increases from less than 0.1 EJ today to between 0.6 EJ and 2.0 EJ in 2050. The demand for plastics is set to triple between now and 2050, resulting in 250 Mt to 300 Mt of plastic waste. But there will be competition for this resource.

Electricity-based steel-making

As part of the joint American Iron and Steel Institute (AISI) and the US-DOE technology roadmap programme, research is currently under way at the Massachusetts Institute of Technology to produce iron by molten oxide electrolysis (MOE). This technique would generate no CO₂.

But substantial basic engineering problems stand in the way of MOE. No suitable anode material exists. The process is also expected to use 2 000 kWh/t iron, equivalent to 7.2 GJ/t steel (*New Scientist*, 2006). With losses in electricity generation, typically around 50%, the primary energy used in MOE is unlikely to be materially better than that for conventional steel-making technologies. It seems unlikely that an all-electric technology will gain a significant market share in the next 20 to 40 years.

The outlook may be better for plasma injection into existing processes. This is a proven technology that has yet to be applied for blast furnaces. Plasma injection would enable direct CO₂ emissions to be reduced by more than 50% (Schmöle and Längen, 2004).

Use of hydrogen

Molecular hydrogen cannot reduce liquid iron oxide: atomic or ionised hydrogen is needed to do so. But these states can only be achieved at very high temperatures, such as in the vicinity of an electric or plasma arc. H₂ plasma smelting reduction would require 14.3 GJ H₂/t of iron and 2.2 GJ electricity/t of iron (Hiebler and Plaul, 2004). If low-cost CO₂-free H₂ and electricity were available, this could be an alternative for smelting reduction processes with CCS. This option is being investigated in the United States by AISI, US-DOE and various steel companies sponsoring a project in the framework of the ULCOS programme at the University of Utah to examine the reduction of fine iron ore concentrate using H₂.

In Japan, the use of waste heat from coke ovens for gas reforming for H₂ production and iron-making is being researched. As the amount of waste heat from coke ovens is limited, this is a niche option that will generate less than 0.5 GJ additional H₂ per tonne of steel. Coke oven gas is rich in H₂ and can be used for iron-making, but the quantities are limited, typically 2 GJ/t iron produced in a conventional blast furnace.

CO₂ capture and storage

There are three approaches to CO₂ capture from blast furnaces:

- oxyfuelling to generate a pure CO₂ off-gas;
- using waste heat for chemical absorption;
- substituting coke and coal with H₂ or electricity.

None of these approaches captures all of the CO₂ from integrated iron and steel plants since substantial amounts are emitted from non-core processes, e.g. coke ovens, sinter plants, basic oxygen furnaces and rolling mills. But CO₂ reductions in the core process could amount to 75% of total process emissions. Capturing the remaining non-core CO₂ could only be achieved at a prohibitively higher cost.

Blast furnaces emit 1.5 t CO₂ to 2.0 t CO₂/t of iron produced. By redesigning the blast furnace to use oxygen, CO₂ can be removed from the flue gas. The potential for reducing CO₂ emissions in iron and steel production is large, up to 1.5 Gt per year. A number of initiatives have been taken to reduce emissions. Within Worldsteel, the CO₂ Breakthrough Programme is a platform to exchange information with the overall goal to radically reduce, eliminate or capture emissions. Similar programmes have been launched in Europe, North America, Japan, Korea, Australia and Brazil.

With oxygen injection into blast furnaces, CCS could result in a reduction of 85% to 95% of the CO₂ emissions attributable to the core processes. As part of the ULCOS-I project, the LKAB experimental blast furnace in Sweden started testing various configurations for a small-scale blast furnace with a capacity of one to two tonnes of iron per hour in 2007. Gas flows through the reactor remain to be optimised and issues regarding gas cleaning still need to be solved. The aim is to demonstrate an industrial scale TGR-BF and CCS in the period 2015 to 2020.

Post-combustion capture using chemical absorbents is not suitable for CO₂ capture in the iron and steel industry as insufficient waste heat is available. Separate combined heat and power (CHP) units would be needed to provide additional heat. Integrated oxyfuelling is therefore more appropriate.

Waste gases from existing blast furnaces are rich in carbon monoxide and CO₂. If this gas is reformed, the CO₂ concentration rises to between 50% and 60%. This could be achieved without major changes in the process configuration. Blast-furnace gas reforming and chemical absorption using waste heat are being investigated in Japan, Korea and China.

New smelting reduction technologies, which use oxygen, are well suited to CCS. In the FINEX process, for example, part of the CO₂ is removed from the recirculation gas. This is currently vented because of the lack of suitable storage sites. With some process redesign, all the CO₂ could be captured, with no efficiency penalty. Other similar processes such as HIs melt and Hisarna are under development as described earlier. Part of the ULCOS-II project is a large-scale pilot demonstration unit with a new CO₂ reduced iron-making process.

FINEX and HIs melt demonstration plants are ready for the application of CCS with 56% to 70% capture. The oxygen blast furnace would require major further development. In these smelting reduction processes, CO₂ separation is already part of the demonstration plants as it has to be removed in order to be able to recycle the off-gas. Once captured, transportation and storage would result in only relatively limited additional cost and energy use (Orth *et al.*, 2007). Both FINEX and HIs melt use chemical absorption processes. In the case of HIs melt, a CO₂ stream ready for sequestration with 99% CO₂ is currently available only from the Circofer plant. This is estimated to be about 70% of the CO₂ released in the complete process. Half of the steam for chemical absorption can be covered with waste heat from the process. The other half would need to be produced separately, probably in CHP units.

In the FINEX process, about half of the gas is recycled. CO₂ emissions after capture and sequestration would be 56% of that of a typical blast furnace. Complete CO₂ removal would be possible if the gas for power generation were also cleaned. Alternatively, the off-gas could be completely used for pre-reduction. CO₂ removal and recycling of the off-gas would increase energy efficiency by 2 GJ/t of iron produced. The process proposes to use pressure swing absorption (PSA) for CO₂ capture. The electrical energy needs for the PSA unit are 0.71 GJ/thm, excluding the electricity needed to pressurise the CO₂ to 100 bar.

Current estimates suggest that CCS for blast furnaces would cost around USD 40/t CO₂ to USD 60/t CO₂ in capture, transportation and storage costs, excluding any furnace productivity changes that could have a significant positive or

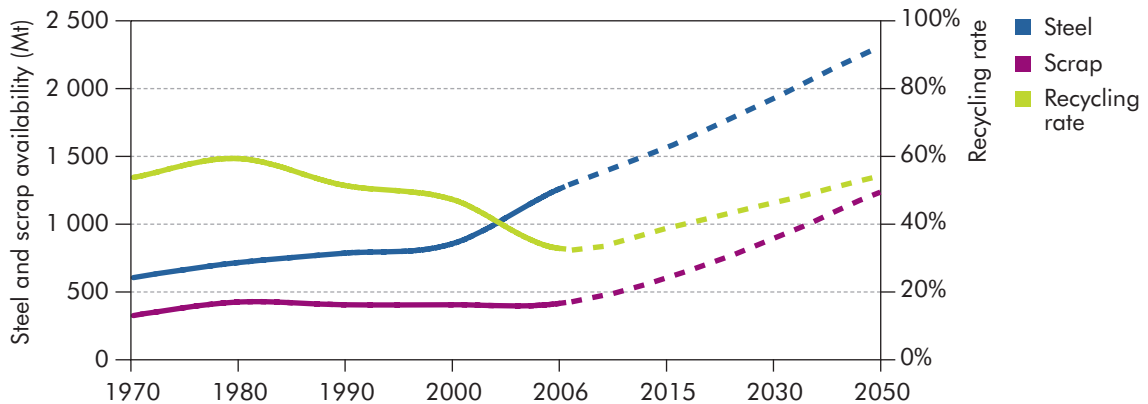
negative impact on the process economics. The marginal investment costs would be higher for retrofits than for new builds.

Gas-based DRI production would allow CCS at a relatively low cost, potentially as low as USD 25/t CO₂. But DRI facilities are concentrated in relatively few countries and are comparatively small-scale. As a result, this approach has so far received only limited attention.

Material flows and material flow optimisation

The IEA has built a capital stock turnover model of the world steel supply to identify scrap recovery levels and to estimate them for the future. Historical and future estimates of scrap availability are shown in Figure 2.8. This shows both steel scrap and total steel production, recognising that the volume of scrap is a function of past steel production subject to a one- to 100-year time lag, depending on the product category, for the scrap to become available for recycling. As steel scrap recovery levels are limited, the recent acceleration of world steel production has resulted in a declining share of recycling in production. Primary metal fills the gap between scrap availability and steel production. This gap is projected to rise from around 900 Mt in 2007 to between 1 000 Mt and 1 300 in 2050 in the BLUE Scenarios.

Figure 2.8 ▶ Steel scrap availability and recycling rate, BLUE low scenario, 1970 to 2050



Note: Solid lines represent historical values.

Sources: Neelis *et al.* (2006) for historical data; IEA analysis.

Key point

Recycling accounts for about half of total steel-making in 2050.

Steel scrap comes in three forms. Circulating scrap is that which is recycled within iron and steel plants. Prompt scrap is that which comes from iron and steel processing before reforming into consumer products. Obsolete scrap is that which

comes from post-consumer recycling. As steel plants have improved their materials efficiency and product quality control, the share of circulating scrap has declined significantly. The share of obsolete scrap has increased because of the stagnation of world steel production between 1970 and 2000. About 80% of the metal that becomes available is currently recycled for use in the iron and steel sector. The share of obsolete scrap will increase further.

Materials use and efficiency

2

Global consumption of finished steel products was estimated to increase from 1 198 Mt in 2007 to 1 279 Mt in 2008 (6.8%) (USGS, 2009). There are currently about 3 500 grades of steel with different physical, chemical and environmental properties. Steel is used in a wide range of applications from small home appliances to car bodies and oil and gas platforms.

Improving steel quality can have two effects. First, it can enable the design of the same products using less steel. Secondly, it can in certain cases reduce energy use and CO₂ emissions at the product use stage. Typical examples are boiler materials or materials that reduce the weight of cars.

Steel products are constantly evolving, driven in part by R&D conducted in collaboration with steel-using industries. Most of the steel products used today did not exist 20 years ago. Some examples of product innovations include (OECD, 2007):

- Corrosion-resistant steels: steel products have become increasingly resistant to corrosion and wear, have longer-lasting stability, and surface hardness can increasingly be tailored.
- High-strength low-alloy steels: these steels are stronger than ordinary carbon steels. They can be used, for example, to increase the fuel efficiency of cars by reducing the weight of their parts. These steels are also used in trucks, cranes and bridges.
- Improved heat resistance: steel products that are more heat-resistant enable the manufacture of machines that can operate at high temperatures. Since a given amount of steel used in these applications yields higher performance, the resource-savings are beneficial to the environment (Matsumiya, 2005).
- Efficient electrical steels: these can reduce the losses in electric motors and converters, and thus contribute towards energy savings.

Few quantitative studies have examined the potential for savings from improved materials. A Japanese study showed that the stock of new high-performance steels reduced Japan's CO₂ emissions by 9.64 Mt in 2000, compared to the steel quality of 1990. Of this, 3.14 Mt came from reduced crude steel production, 6.5 Mt from savings in applications, and 5.1 Mt from higher-strength automotive sheet. This represents a reduction of around 5%, compared to the total emissions from the Japanese iron and steel industry (JISF, 2008b).

Conclusion: transition pathway for the iron and steel sector

Maximising energy savings and CO₂ emissions reductions will depend on the pursuit of four main technology options:

- energy efficiency: through the deployment of existing best available technologies and the development of new technologies;
- fuel switching: through gas-based DRI, charcoal, plastic waste, CO₂-free electricity and H₂;
- CO₂ capture and storage;
- better materials flow management.

There is particularly significant potential for energy efficiency to contribute to fuel and emission savings through replacing small-scale facilities (e.g. beehive coke ovens and small-scale blast furnaces) in China and India, and outdated open-hearth furnaces and ingot casting practices in Ukraine and Russia. There is also significant scope more widely to increase waste heat recovery. In many cases, such equipment can be retrofitted to existing plants. Waste heat recovery should be mandatory for new plants.

Energy efficiency research would most promisingly focus on new technologies that allow the use of low-quality coal and low-quality ore. Smelting reduction technologies in combination with pre-reduction facilities seem to offer the best prospects. Although such technologies are being introduced, the rate of change is slow and insufficient to produce a material energy transition. These technologies can play an important role in their own right and also as enablers for CCS.

Although natural gas can be used in blast furnaces, it is particularly appropriate for the production of DRI, which accounts for nearly 10% of all primary metal production. Biomass, plastic waste, CO₂-free electricity and H₂ are other future options. Gas can be injected into blast furnaces, but volumes are limited by process conditions. Gas-based DRI production enables the complete replacement of coal and is a well-established technology. Such plants can use relatively small gas reserves, which may not be large enough to justify the development of liquefied natural gas (LNG) projects. New direct reduction projects should be equipped with CCS the cost of which is highly sensitive to the price of natural gas.

Charcoal for iron-making, primarily in small-scale blast furnaces, has been phased out in most parts of the world except South America. Brazil is emerging as an iron exporter and charcoal plays an important role in the country's iron-making. Although its production and export volumes are small compared to total global iron production, a significant share of Brazilian charcoal used is from natural tropical forests and deforestation for charcoal production is an important source of CO₂. Expansion of production could increase this pressure. An integrated agriculture/food/environment/water management policy will be needed to enable a large-scale transition to charcoal from sustainable plantations.

Waste plastic has been injected in blast furnaces in Europe and Japan, although varying feedstock quality poses operating challenges. In Japan, plastics are used both in coke ovens and in blast furnaces. Of these two approaches, the former seems to be the most solid one. Feedstock availability and competing uses, e.g. for plastic waste recycling or in cement kilns, will limit this option to less than 10% of total energy use in the iron and steel sector.

Hydrogen can be substituted for coal and coke in ore reduction. Although some H₂ can be recovered from coke-oven gas, quantities are limited. This option for iron-making is being investigated in Japan. But it is unlikely that there will be any significant amounts of CO₂-free H₂ for several years except for production from fossil fuels with CCS.

CCS can play an important role in reducing CO₂ emissions in the iron and steel industry. If up to 1.1 Gt CCS is to be achieved in the iron and steel sector by 2050, about 0.3 to 0.5 Gt CCS would be needed by 2030. This requires that the technology has been demonstrated at plant level by 2020 and leaves about ten years to demonstrate CCS for blast furnaces, smelting reduction plants and DRI.

To involve a range of equipment suppliers, five to ten demonstration projects will be needed. The cost of demonstrating a single blast furnace with CCS in Europe is estimated to amount to USD 450 million, so the cost of the full demonstration programme would be in the order of USD 2.3 billion to USD 4.5 billion. Current plans for CCS demonstration projects in the iron and steel industry amount to approximately USD 0.7 billion. For a robust demonstration programme, two to four times as much investment will be needed.

Chapter 3 CEMENT

Key Findings

- ▶ Cement production accounts for about 9.6 EJ of energy use, 85% of all energy used in non-metallic minerals production. It is an important source of CO₂ emissions. Total direct CO₂ emissions from cement production amounted to 1.9 Gt CO₂ in 2006, with around 0.8 Gt CO₂ emitted from fuel combustion and 1.1 Gt CO₂ from process emissions.
- ▶ China is by far the largest cement producer with 47% of world production in 2006. India, the second-largest producer, accounts for only 6% of global cement production.
- ▶ Cement production is energy intensive. The average final energy intensity for cement production for those countries with available data ranges from 2.9 GJ/t to 4.7 GJ/t cement, including electricity. The thermal energy needed per tonne of clinker produced ranges from around 3.2 GJ/t to 4.5 GJ/t clinker. The cement industry has made significant strides in reducing energy consumption, with China reducing its thermal energy intensity per tonne of clinker by a quarter since 1990. Coal accounts for around 60% of the fuel burned in cement kilns. The cement industry also uses significant amounts of electricity, around 1 EJ in 2006.
- ▶ The potential contribution of shifting today's existing cement kilns to BAT, as well as increasing the use of clinker substitutes could reduce thermal fuel consumption by around 27% (2.3 EJ). The CO₂ savings potential, including the use of alternative fuels in addition to BAT and clinker substitutes, is equal to 510 Mt CO₂.
- ▶ Reducing CO₂ emissions from the cement industry in 2050 to below today's level, given projected growth in demand, is very challenging. New technologies will need to be developed and implemented. In the BLUE scenarios, the cement industry's CO₂ emissions are reduced by 18% below 2006 levels through a combination of improved energy efficiency, the increased use of alternative fuels and clinker substitutes, and the application of CO₂ capture and storage. CCS is an essential component in achieving the BLUE scenario outcomes which require the storage of 0.5 Gt CO₂ a year in the BLUE low-demand scenario and 1.0 Gt CO₂ a year in the BLUE high-demand scenario in 2050.
- ▶ Applying CCS in the cement industry is likely to have a marginal abatement cost of between USD 40/t CO₂ and 170/t CO₂ abated. A longer-term possibility is that new low-carbon cements currently being developed might become available, although much remains to be done to prove and deploy these technologies.
- ▶ The availability of good-quality data is a prerequisite for high-quality analysis. The Cement Sustainability Initiative (CSI) project "Getting the Numbers Right", launched by the World Business Council for Sustainable Development (WBCSD), has collected energy and CO₂ data on a common, verified basis for over 70% of the cement production of Annex 1 countries and 20% of non-Annex 1 countries. Continuing to expand the coverage of the data collected by this project is important and should be encouraged.

Introduction

The cement industry is by far the largest energy consumer and CO₂ emitter in the non-metallic minerals sector. Although energy intensity per tonne of product is less than that of other energy-intensive materials such as aluminium and steel, the volume of production is much higher, with an estimated 2 600 Mt produced in 2007. As a result, the cement industry accounts for 85% of all energy use in the non-metallic minerals sector. The CO₂ emissions from thermal energy consumption and production processes were estimated to be 1.9 Gt CO₂ in 2006. The energy, CO₂ intensity and volume of cement produced makes the non-metallic minerals sector account for more than a quarter of the direct emissions from the manufacturing industry.

Cement is the “glue” that holds a concrete mixture together. Concrete’s ability to be poured into different forms and its stone-like qualities when set make it an excellent construction material. It is used extensively in buildings, bridges, walls and a multitude of other uses. Typically, concrete contains around 11% Portland cement, with the balance being made up of gravel (41%), sand (26%), water (16%) and air (6%).

Global cement production grew from 594 Mt in 1970 to 2 350 Mt in 2005 and to an estimated 2 600 Mt in 2007, an increase of 4.4 times between 1970 and 2007 and 2.24 times between 1990 and 2007. The vast majority of the growth since 1970 has occurred in developing countries. Since 1990, China accounted for around three-quarters of the 1 440 Mt increase in global production.

Cement production process and technologies

Cement is generally produced from a feedstock of limestone, clay and sand, which provides the four key ingredients required: lime, silica, alumina and iron. Mixing these ingredients and exposing them to intense heat causes chemical reactions that convert the partially molten raw materials into pellets called clinker. After adding gypsum, and possibly other minerals, the mixture is ground to form cement, a fine grey powder.

After the quarrying of raw materials and their delivery to the plant, materials are mixed in different proportions to create cements with specific chemical compositions. The raw materials are analysed at the plant to ensure their chemical composition is correct. They are then blended in the appropriate proportions and ground even finer. After grinding, the material is fed into a rotating kiln, in many cases passing first through a pre-heater and pre-calciner, before being heated in the kiln to around 1 500°C. The kiln is a horizontally sloped steel cylinder, lined with firebrick, turning from about one to three revolutions per minute.¹ Fuels such as pulverised coal, natural gas, fuel oils and petroleum are burned to feed a flame at the lower end of the kiln that reaches about 2 000°C, allowing the materials to be heated to around 1 500°C where they become partially molten.

1. Vertical shaft kilns also exist, notably in China, but consume significantly more energy.

The intense heat triggers the chemical and physical changes that transform the raw feedstock into clinker. A series of chemical reactions converts the calcium and silicon oxides into calcium silicates, cement's main constituent. When the limestone (CaCO_3) reaches about 900°C , it undergoes a chemical reaction called "calcination" in which CO_2 is released and calcium oxide is formed. The main chemical reaction is:



There are two basic types of cement production process and a number of different kiln types. These are referred to as either "wet" or "dry", depending on the water content of the raw material feedstock, although some types of cement fall somewhere in between. The wet process allows for easier control of the chemistry and is better when moist raw feedstocks are available, but it consumes more energy to evaporate the 30% plus slurry water before heating the raw materials to the necessary temperature for calcination. The dry process is more efficient, as it avoids the need for water evaporation (Table 3.1). The other major technology difference is between vertical shaft kilns and their more efficient counterparts, rotary kilns.

Today's state-of-the-art dry rotary kilns are more fuel-efficient than older kilns. The thermodynamic minimum energy required to drive the endothermic reactions is approximately 1.8 GJ/t clinker for dry limestone feedstock. In practice, it is much higher, as feedstocks contain significant moisture. The superior performance of dry-process rotary kilns with pre-calciners and pre-heaters makes them the technology of choice.

Table 3.1 shows the energy intensity of different kiln types. It is unlikely that the fuel efficiency of today's dry-process rotary kilns can be reduced much below their current optimum operating level of 2.9 GJ/t to 3.0 GJ/t clinker. In practice, average fuel consumption will be around 5% to 10% higher than this because of variations in feedstock moisture content and fuel characteristics, as well as operational and maintenance constraints that result in suboptimal plant operation. The practical BAT level of thermal energy consumption of a six-stage pre-heater and pre-calciner kiln is estimated to be in the range of 2.9 GJ/t to 3.3 GJ/t clinker (EIPPCB, 2007).

In the production of cement, it is the production of clinker from limestone and chalk that consumes most energy. Cement production is energy-intensive. Energy typically represents 20% to 40% of total production costs.

The most widely used cement type is Portland cement, which contains 95% cement clinker. Other types of cement use a variety of clinker substitutes, including granulated blast-furnace slag, fly ash and natural pozzolana, in blends with Portland cement to reduce specific CO_2 emissions and often cement costs. These clinker substitutes have properties similar to cement and can therefore be added to the feedstock for a kiln, or substituted for clinker in either the cement or concrete mix.

The typical composition of various cement types is shown in Table 3.2. Generally, cement types are defined by the quantity of clinker substitutes used by weight. Within each blended cement type, different grades are identified according to the percentage of clinker substitutes used.² A cement type is normally described as a

2. See CEN (2000) for a comprehensive listing of the 27 products in the family of common cements and the ranges of clinker substitutes that characterise each cement type.

CEMI cement if clinker substitutes are 40% or less by weight, or identified by the main clinker substitute used if it exceeds that level, e.g. Portland fly-ash cement or blast-furnace slag cement (Table 3.2).

Table 3.1 ► Heat consumption of different cement kiln technologies

Process	Fuel consumption (GJ/t clinker)
Vertical shaft kilns	~5.0
Wet process	5.9 – 6.7
Long dry process	4.6
One stage cyclone pre-heater	4.2
Two stage cyclone pre-heater	3.8
Four stage cyclone pre-heater	3.3
Four stage pre-heater + pre-calciner	3.1
Five stage pre-heater + pre-calciner	3.0 – 3.1
Six stage pre-heater + pre-calciner	2.9

Source: FLSmidth (2006).

Table 3.2 ► Typical composition of different cement types

Cement type	Portland cement (%)	Portland fly-ash cement (%)	Blast-furnace cement (%)	Pozzolanic cement mixes (%)
Clinker	95 – 100	65 – 94	5 – 64	45 – 89
Fly-ash	–	6 – 35	–	–
Blast-furnace slag	–	–	36 – 95	–
Pozzolana	–	–	–	11 – 55
Additional constituents (e.g. clinker dust, other mineral additives, etc.)	0 – 5	0 – 5	0 – 5	0 – 5

Note: percentages exclude gypsum, typically 5%.

Source: Based on CEN 197-1, 2000.

The availability of waste slag is limited and not all fly-ash is suitable for blending. Pozzolana³ can be obtained only in certain locations. This tends to limit their use, as the long-distance transportation of cement or cement feedstocks is rarely economic given the low value of the product. In addition, local standards, building codes and market structures often limit the addition of blends to levels significantly lower than the technically feasible level.

3. Pozzolana are nature volcanic materials with properties similar to cement.

Trends in efficiency, energy and CO₂ emissions

Although cement production has grown rapidly over the last 20 years, growth slowed between 1997 and 2000 as a result of the Asian financial crisis. It is expected to slow again in coming years on account of the recession in OECD countries and slower growth in developing countries. However, the longer-term prospects for cement production remain positive, given the rapid growth of developing countries and their need to develop essential infrastructure.

In 2006, China accounted for 47% of global cement production (Table 3.3). The next 19 largest producers accounted for around 37% of global production. OECD countries in the top 20 producers accounted for 19% of global production.

3

Table 3.3 ▶ Global cement production, 2006

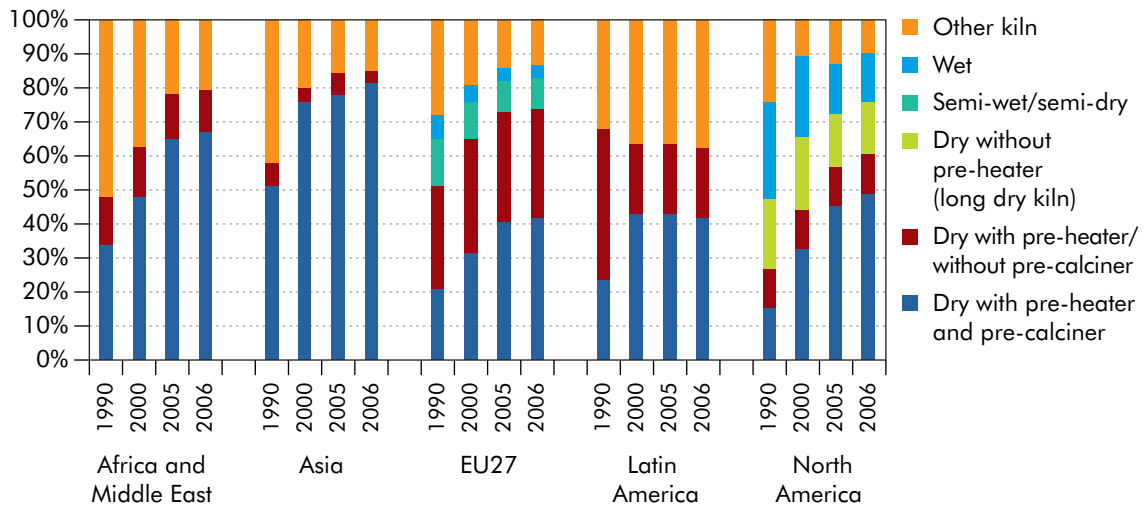
	Production (Mt/yr)	Share (%)	Cumulative Production share (%)
China	1 204	47.2	47.2
India	160	6.3	53.5
United States	100	3.9	57.4
Japan	73	2.9	60.3
Korea	55	2.2	62.4
Russia	55	2.1	64.6
Spain	54	2.1	66.7
Italy	48	1.9	68.6
Turkey	47	1.9	70.4
Mexico	41	1.6	72.0
Brazil	40	1.6	73.6
Thailand	39	1.5	75.1
Indonesia	35	1.4	76.5
Germany	34	1.3	77.8
Iran	33	1.3	79.1
Vietnam	33	1.3	80.4
Egypt	29	1.1	81.5
Saudi Arabia	27	1.1	82.6
France	22	0.9	83.4
Pakistan	20	0.8	84.2
Other	405	15.8	100.0
World	2 553	100.0	

Source: US Geological Survey (USGS), 2008 and JCA.

Technology and fuel consumption in cement production

The thermal energy consumption of the cement industry is strongly linked to the type of kiln used. The more efficient dry process with pre-heaters and pre-calciners is the technology of choice for new plants as shown by trends in the stock of plants in operation (Figure 3.1). Since 1990, dry technologies have exhibited a marked increase in all the regions for which data are available. However, at a country level, the share of the more energy-efficient dry process varies significantly, by between 12% and 100% (IEA, 2007).

Figure 3.1 ▶ Share of cement kiln technology by region 1990 to 2006



Source: CSI (2008).

Key point

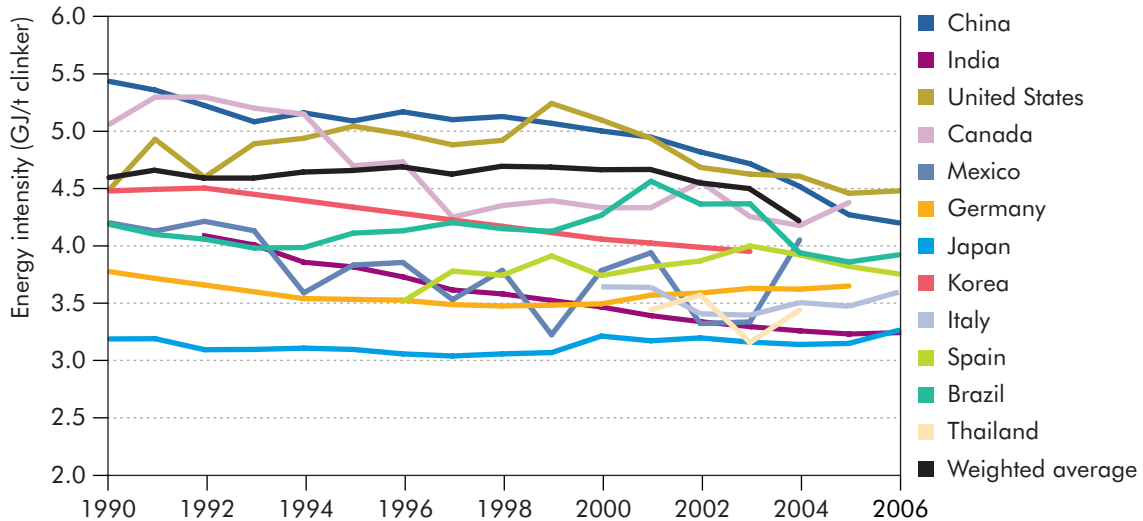
The share of the more efficient dry kilns with pre-heaters and pre-calciners has risen in all regions since 1990.

The increasing share of dry-process kilns with pre-heaters and pre-calciners has had a clear impact on energy consumption in clinker production. Figure 3.2 presents the data for the average thermal energy consumption per tonne of clinker in some of the largest cement-producing countries. Efficient dry kilns using pre-heaters use approximately 3.3 GJ/t clinker; a wet kiln can use between 5.9 GJ/t and 6.7 GJ/t clinker. In the European Union, the average energy consumption per tonne of Portland cement is currently about 3.7 GJ/t clinker (CEMBUREAU). China continues to invest in dry kilns and currently consumes around 4.1 GJ/t clinker, while Canada and the United States both require around 4.5 GJ/t clinker. Together, these three countries account for just over half of total cement production. For most of the other countries presented, the range is between 3.2 GJ/t and 4 GJ/t clinker.

Higher energy prices in recent years, coupled with buoyant global economic growth and growth in the demand for cement, has resulted in lower energy intensities.

Developing countries have added new large-scale dry capacity to meet demand, thereby reducing the share of smaller less efficient kilns. Higher energy prices have also encouraged cement producers in developed countries to invest in new more efficient plants or energy efficiency retrofits. China, for example, has increased the share of dry kilns from 6% in 1995 (Cui, 2006) to around 56% in 2007 (Lei and Hongzhou, 2008) and 61% in 2008 (Cui, 2009). In the United States, energy intensity has fallen from a high of 5.2 GJ/t clinker in 1999 to 4.5 GJ/t clinker in 2006, in part as a result of higher energy prices.

Figure 3.2 ▶ Thermal energy consumption per tonne of clinker by country, including alternative fuels, 1990 to 2006



Note: Care must be taken in interpreting the absolute values of data in this figure, given the possibility that different system boundaries and measurement methods (low or high heating values) may have been used. The Japanese method of calculating net energy consumption per tonne of clinker yields a value of 2.94 GJ/t clinker for 2006. The data for Japan has a break in the time series for clinker production in 2000 when a different definition of clinker was adopted.

Sources: CSI (2008); Soares and Tolmasquim (2000); Worrell et al. (2001); IBGE (2008); EEA (2006); AITEC (2008); USGS (2008); PCA (2008); NRCAN (2008); Japan Cement Association (2006) and METI (2008); OFICEMEN (2008); Siam Cement Company Ltd. (2005); INEGI (2008); VDZ (2008); LBNL, IEA and Tshinghua University estimates.

Key point

Japan and India are the most efficient clinker producers, while many countries have achieved reductions in the energy required to produce clinker since 1990.

Alternative fuel use in cement production

The use of alternative fuels in the cement industry is a long-established practice in many countries. It offers the opportunity to reduce production costs and fossil fuel use, and to dispose of waste. Where fossil fuels are replaced with alternative fuels such as waste products that would otherwise have been incinerated or land filled, CO₂ emissions can be reduced. Cement kilns are well suited for waste combustion because of their high process temperature and because the clinker product and limestone feedstock act as gas cleaning agents. Used tyres, wood,

plastics, chemicals, treated municipal solid waste and other types of waste are co-combusted in cement kilns in large quantities.

European cement manufacturers derived 3% of their energy needs from waste fuels in 1990 and 15% in 2005. Cement producers in Austria, the Czech Republic, France, Germany, Belgium and the Netherlands have reached substitution rates of between, 7% and more than 43% of the total energy used (Figure 3.3). Some individual plants have achieved nearly 100% substitution using alternative fuels. Where alternative fuels are used at high substitution rates, tailored pre-treatment and surveillance systems are needed. Municipal solid waste, for example, needs to be screened and processed to homogenise calorific values and feed characteristics. A well-designed regulatory framework for waste management is an important factor in facilitating the use of waste.

Box 3.1 ► Cement sector data

The IEAs work on energy indicators is an ongoing effort to improve end-use energy statistics across all sectors. These indicators can be used for the analysis of trends in energy efficiency and CO₂ emissions, while decomposing out impacts such as changes in industrial structure and activity to calculate a more representative measure of energy efficiency than is possible with simple indicators such as energy consumption per unit of value added in industry (see for example IEA [2004] and IEA [2007]).

The data availability for the cement sector is mixed, ranging from excellent data collected by national statistics offices or industry associations, to estimated energy consumption based on assumed energy intensity values for the sector.

The WBCSD CSI project “Getting the Numbers Right” is an example of an industry-led project to improve the accuracy and transparency of the energy and CO₂ emissions data for a specific sector. The data are collected according to an agreed protocol, with data subject to independent validation in many cases. The raw data are retained by an independent third party to avoid the release of any commercially confidential data.

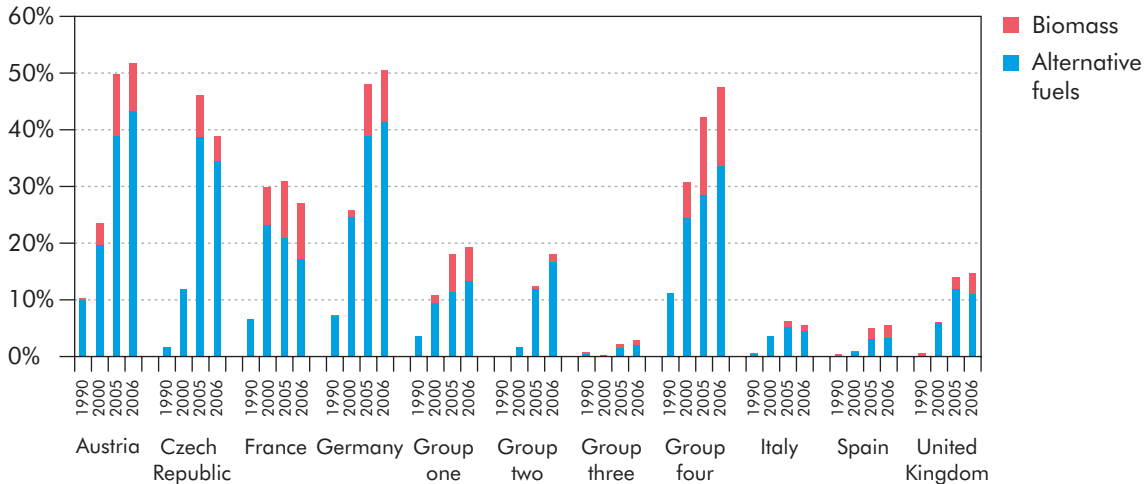
The availability of data of this quality makes robust analysis of the cement sector possible. The continued collection of these data to allow analysis of trends over time, as well as the continued extension of the number of participating companies should be encouraged. The collection of these data will allow policy makers and decision makers to take decisions on the basis of accurate and transparent data, avoiding potentially costly errors that could be made with a less complete data source.

Outside the OECD, the use of alternative fuels is not widespread. In developing countries, although interest is growing, substitution rarely exceeds 1% of the cement industry’s fuel needs. There is significant scope to increase waste substitution globally with benefits for profits and the environment.

In Europe, the burning of alternative fuels in cement kilns is covered by Directive 2000/76/EC of the European Parliament and Council. However, in some countries waste combustion is controversial, because cement kilns may not be subject to

stringent emission controls. Clear guidelines and public information campaigns could help reduce misconceptions and facilitate the increased use of waste in cement kilns.

Figure 3.3 ▶ **Alternative fuel use in clinker production in Europe, 1990 to 2006**
(percentage of total thermal fuel use)



Notes: Because of confidentiality issues, some countries have been grouped together. Group One: Denmark, Finland, Sweden, Norway, Ireland. Group Two: Estonia, Latvia, Poland, Hungary. Group Three: Portugal, Greece, Romania, Slovakia, Bulgaria. Group Four: Belgium, Luxembourg, the Netherlands.

Sources: CSI (2009).

Key point

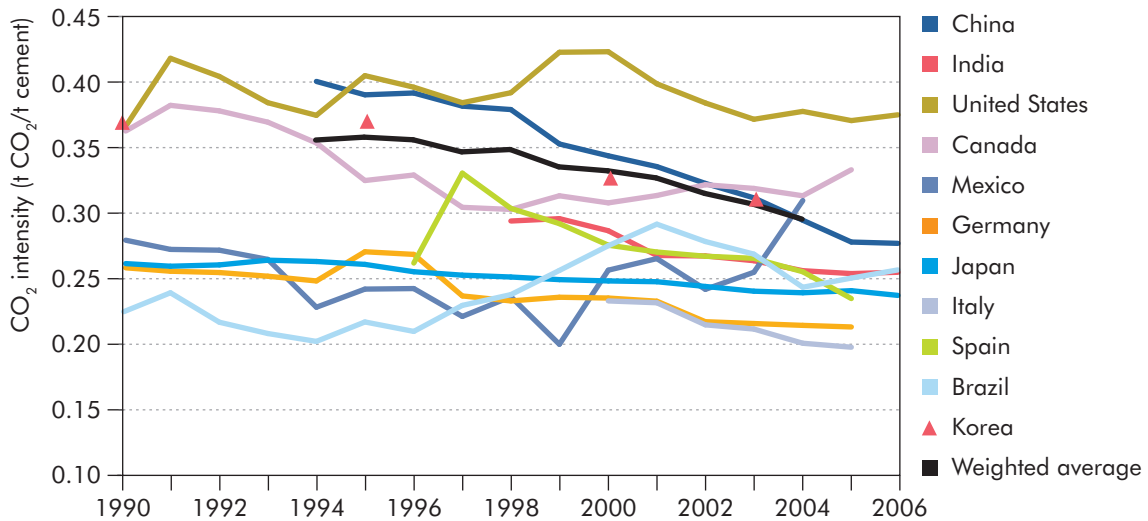
The use of alternative fuels in the cement industry has reached high levels in some European countries.

CO₂ emissions from cement production

The production of clinker involves two main sources of direct CO₂ emissions: process emissions from the chemical decomposition of limestone and combustion emissions from the burning of fossil fuels. The process emissions normally show only small variations over time and between plants and regions; they typically make up more than half of total direct emissions. The energy combustion emissions are highly dependent on the energy efficiency of the kiln system and the fuel mix used.

Figure 3.4 shows total emissions from thermal energy consumption in t CO₂/t of cement. It therefore excludes upstream electricity generation emissions and process emissions. Many of the countries for which data are available have achieved significant reductions in CO₂ emissions from thermal fuel consumption since 1990, with the global average, dominated by the decline in China, falling by 17% between 1994 and 2004.

Figure 3.4 ▶ Thermal fuel CO₂ emissions per tonne of cement by country, 1990 to 2006



Note: Includes impact of electricity generation from waste heat in Japan. Boundary definitions may differ by country.

Sources: IEA statistics and as for Figure 3.2.

Key point

Canada, China, Germany, India, Italy, Japan, Korea and Spain have achieved significant reductions in the CO₂ intensity of cement production.

Best available technology and technical savings potential

Current BAT for the cement industry is a dry-process kiln with pre-heater and pre-calciner. Up to six stages of pre-heating can be used if the raw material feed has a low moisture content (<6%; VDZ, 2008), although a five-stage pre-heater is the norm in Europe for new plants.

Pre-calcination has been available to the cement industry since the 1970s. In these kilns, the heat input is divided between two points. Primary fuel combustion occurs in the kiln burning zone, and secondary burning takes place in a special combustion chamber located between the rotary kiln and the pre-heater. Although it is a secondary combustion chamber, up to 60% of total fuel use can occur in this chamber depending on how the kiln is designed and operated. The energy used in the secondary combustion chamber starts the calcination process of the raw feedstock, which, with five- and six-stage pre-heaters, is almost completely calcined when it enters the kiln. Although the mix enters the kiln 75% to 95% calcined, most pre-calciner kilns are still equipped with a rotary kiln with a calcining zone. The material feedstock leaves the calciner at about 870°C, before being cooled.

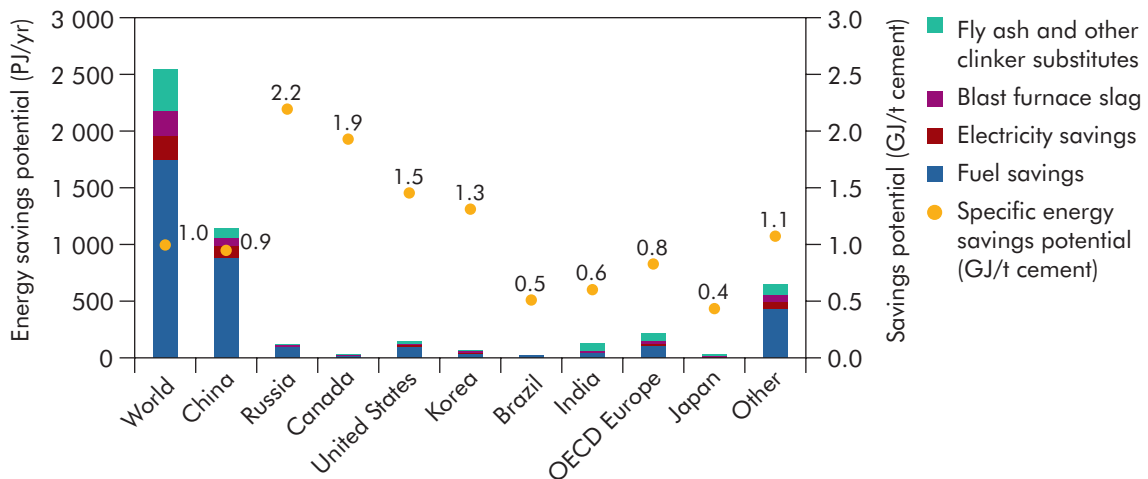
The size of a new plant is determined by feedstock availability, market opportunities and by considerations of economies of scale. Plants with a capacity of up to 15 000 t/day

are technically possible, although new plants in Europe typically have a capacity of 3 000 to 5 000 t/day. Inland plants tend to be more modest in size, as transport costs mean that they can only economically serve a 200 km to 300 km radius.

Current BAT for six-stage pre-heater and pre-calciner kilns is in the range of 2.9 GJ/t and 3.3 GJ/t clinker. For five-stage pre-heater and pre-calciner kilns, this range is between 3.1 GJ/t and 3.5 GJ/t clinker. BAT for electricity consumption in the cement industry depends on the type of plant, but is in the range of 95 kWh/t to 100 kWh/t cement. The increased use of alternative fuels, however, tends to increase electricity consumption for pre-treatment and handling.

If all plants were BAT, assuming an average fuel need of 3.2 GJ/t clinker, 1.7 EJ of energy (42 Mtoe) of thermal fuel use could be saved, or around 21% of current consumption. Shifting to BAT for electricity consumption would achieve savings of around 0.2 EJ (56 TWh). The availability of clinker substitutes is sufficient to allow the clinker ratio to be reduced to 0.7 globally, theoretically enabling a saving of a further 0.6 EJ (14.2 Mtoe) of thermal energy.⁴ Taking into account all of these potentials, the global intensity of cement production could be reduced by 1 GJ/t of cement produced, with significantly higher savings possible in many countries and regions (Figure 3.5).⁵

Figure 3.5 ▶ Energy savings potential based on best available technology in 2006



Source: IEA analysis.

Key point

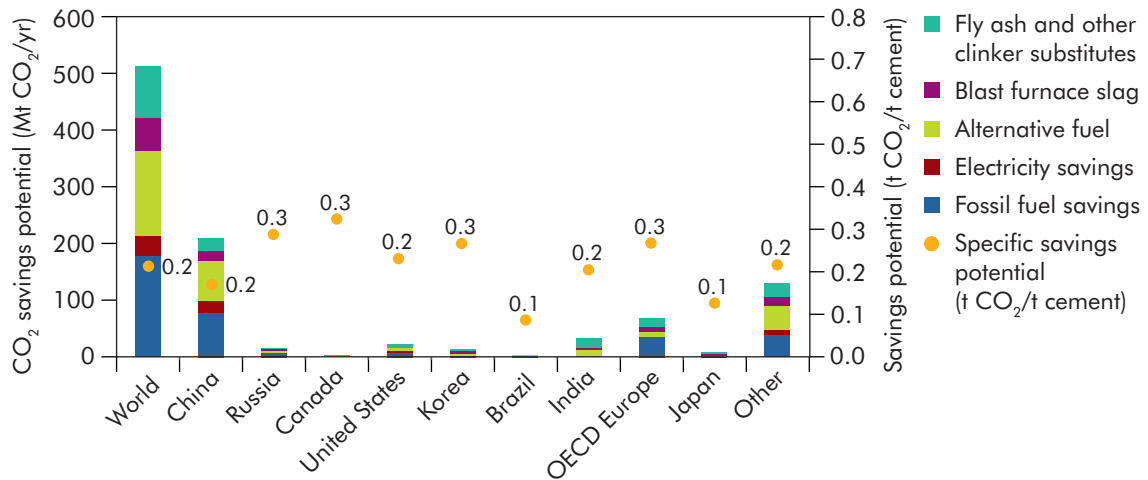
China has the largest absolute potential for energy savings, but other countries have larger energy savings potential per unit of output.

4. The use of clinker substitutes is not based on a BAT definition, but on the availability of clinker substitutes and current use, where this information is available. For instance, the potential of clinker substitute availability for the United States takes into account the fact that most of the blending is done in concrete, not cement.

5. The savings potential calculation is based on the assumption that the energy efficiency of cement kilns is improved first, so that subsequent savings are evaluated relative to the BAT. So energy savings from clinker substitutes are based on the BAT level of energy consumption. An alternative approach would have been to assess the savings from clinker substitutes at current energy efficiencies and then assess the BAT savings from the lower level of clinker demand. This approach would have yielded a slightly lower share of savings from energy efficiency and slightly more from clinker substitutes.

CO₂ savings tend to parallel energy savings. In Russia, a higher-than-average share of gas means that the CO₂ savings from reductions in consumption are relatively less than implied by the fuel savings. The calculations also take into account the impact of raising alternative fuel use, assuming that 35% of fuel comes from alternative sources, of which 40% are CO₂-neutral such as waste biomass.⁶ Shifting to BAT, maximising the use of clinker substitutes and increasing the proportion of alternative fuels could result in CO₂ savings of around 510 Mt CO₂ per year at a global level, including savings in process emissions. China would account for 41% of those savings, and India 6%.

Figure 3.6 ▶ CO₂ savings potential based on best available technology in 2006



Source: IEA analysis.

Key point

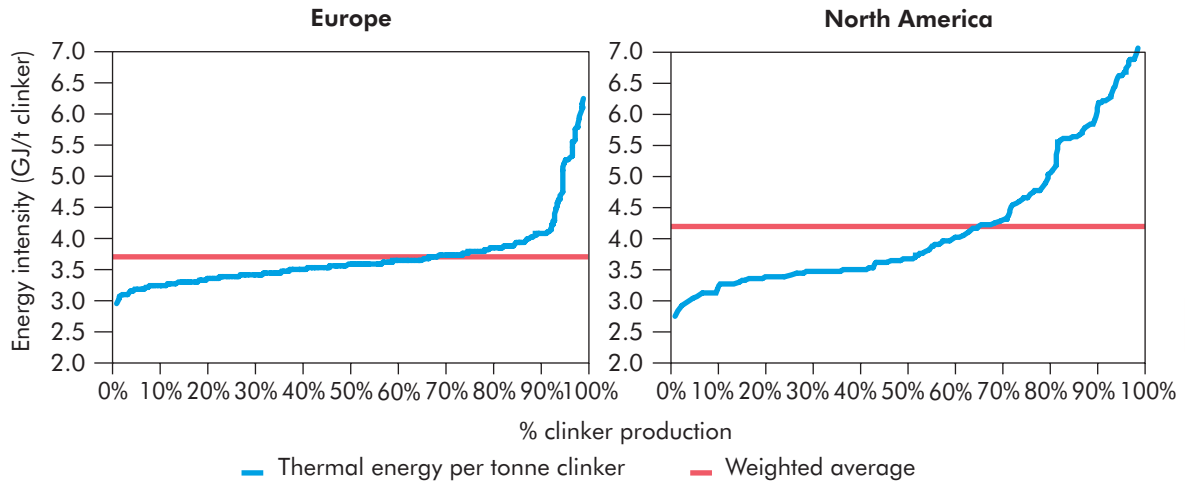
The application of BAT could reduce CO₂ emissions by over 500 Mt globally.

Although there are a number of energy efficiency retrofit options available to the industry, shifting to BAT is only possible when a new cement plant is constructed, or at the end of a plant's life. Cement plants can last 50 years, meaning that there is a low rate of capital stock turnover in the cement industry. This rate of turnover sets the speed at which energy efficiency improvements can be achieved. To understand the potential rate of improvement in energy efficiency in the industry, it is necessary to know the age profile of cement plants. Unfortunately, at a global level, data availability is poor. In the United States, data from the Portland Cement Association (PCA) indicate that approximately half of the cement plants in operation were built since 1980, while 22% were built in the 1970s, 16% in the 1960s and 10% before.

An alternative way of looking at the issue of capital stock is to look at the distribution of energy consumption for clinker production. Although this is not the same as the age profile, it gives a good view of the share of production which is particularly energy-intensive, *i.e.* those plants that could be most suitable for replacement or retrofit. Figure 3.7 presents the data for North America and Europe.

6. Including packing crates, municipal solid wastes, building wastes, agricultural residues, etc.

Figure 3.7 ▶ Distribution of thermal fuel consumption for clinker production in Europe and North America, 2006



Source: CSI (2008).

Key point

Europe has a flatter distribution of thermal energy consumption per tonne of clinker than North America.

The data reflect the age distribution of the capital stock. Plants producing at around 3.5 GJ/t clinker or less are new, built since the 1980s. In North America, they represent about half of the stock. In Europe, a much flatter distribution, with a relatively small tail, implies that the capital stock is generally newer than that in North America, and that there are therefore fewer opportunities for energy efficiency improvement.

In addition to shifting to BAT for all new plants or major refurbishments, a range of energy efficiency options can be retrofitted, either at the end of the economic life of a component of the cement plant or when major refurbishment is required. A sample of retrofit options is listed below:

- using grate coolers instead of planetary or rotary coolers;
- adding pre-heater stages if process design allows and/or a pre-calciner if one is not already installed;
- installing waste-heat recovery for electrical power generation (although this is less viable the more efficient the plant is);
- upgrading the automation/control systems of older plants;
- using improved refractories for the kiln lining; and
- using variable speed motors in all practical applications.

This list is not exhaustive and there are a number of other technology options that can result in useful energy savings.

Retrofits generally offer relatively modest energy savings, unless the plant is particularly old. In these cases, it is often more economical and attractive from an

operational perspective to replace the kiln with a modern pre-calciner and pre-heater dry kiln.

R&D programmes

The cement industry is a mature industry with well-defined technologies that are approaching the limit of practical efficiency. Research efforts in the cement sector are attempting to improve processes and efficiencies. One area with the potential for R&D is in the use of steel slag as a substitute for clinker. This is currently not viable for a number of technical and economic reasons.

In the United States, the Portland Cement Association currently has more than 70 research projects in its core programme. These projects span cement and concrete, including product standards and technology, sustainability and environmental technologies.

In Europe, the European Cement Research Academy was founded in 2004 as a platform to support the cement industry in research activities in the production of cement and its application in concrete.

Venture capitalists from outside the cement industry are also financing new start-ups that are investigating new and novel cement types with lower CO₂ emissions. Examples of new firms with serious financial or industrial backing include Novacem (United Kingdom), Calera (United States), and Calix and Zeobond (Australia). All four firms are planning initial pilot plants in 2009/10, although the impact of the economic crisis may delay these plans, while much will then remain to be done to prove and deploy these technologies on a global scale.

Scenario analysis

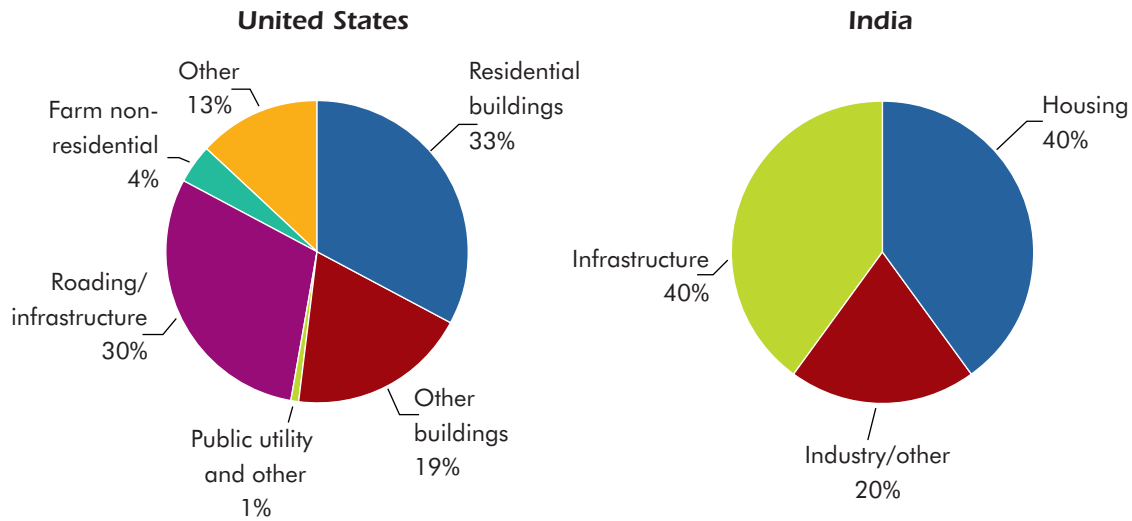
Cement production has experienced significant growth in recent years on the back of rapid growth in consumption in developing countries, particularly China. Projections of cement demand need to take account of different structural, economic, demographic and regulatory environments in different countries and regions, and are accordingly uncertain. Scenario analyses have thus been based on separate high- and low-demand assumptions. The scenario analysis compares expected outcomes on energy use and CO₂ emissions for the sector in the Baseline scenarios with those in the BLUE scenarios where global energy sector emissions will fall to half of those of 2006 by 2050.

Demand for cement is dominated by the construction of buildings and the development of infrastructure (Figure 3.8). Current global economic difficulties are likely to have a significant impact on the amount of cement used in construction in the next few years as new building starts to decline.

Cement consumption per capita varies significantly between countries, depending on a wide range of factors, including income, population density, and the extent of infrastructure development. Korea and Spain currently show some of the highest

levels of per capita cement consumption, although slowing building construction in Spain will see this reduce in coming years. More mature economies generally consume less cement per capita, as the residential and commercial building stock is relatively large and mature, and essential infrastructure has usually been built. Cement consumption per capita tends to be higher in developing countries which are investing in rapid growth in the building stock and in essential infrastructure. As these economies mature, it can be expected that there might be a decline in per capita cement consumption to lower and more stable levels.

Figure 3.8 ▶ Cement consumption by sector in the United States and India



Source: PCA (2008); BEE (2008).

Key point

Demand for cement in India and the United States is dominated by the buildings and infrastructure sectors.

Cement demand can be assessed in several ways, including by comparing per capita cement demand to per capita income, by examining cumulative cement demand per capita, and by comparing cement demand to GDP. However, none of these single indicators can adequately capture the range of different factors affecting cement demand.⁷ Given these considerations and the data available, high and low cement demand projection scenarios have been based on per capita demand assumptions in different regions of the world. The different assumptions for annual per capita cement consumption are shown in Table 3.4.

7. Given the complexity and the variety of drivers affecting the level and rate of growth in cement demand, an econometric analysis of the different demand drivers would be necessary to decompose the factors affecting the level of demand and rate of growth across countries. This analysis is beyond the scope of this chapter.

Table 3.4 ► Cement demand scenario projections (kg per capita)

	Low demand-case				High demand-case			
	2005	2015	2030	2050	2005	2015	2030	2050
Canada	440	440	440	440	440	443	448	453
France	352	352	352	352	352	352	356	356
Germany	407	407	410	450	407	407	433	460
Italy	812	800	700	700	812	812	824	833
Japan	547	500	500	500	547	554	578	665
Russia	384	450	450	500	384	478	480	586
United Kingdom	200	200	200	225	200	200	208	230
United States	333	333	333	333	333	333	333	336
Brazil	209	267	342	450	209	269	341	532
China	918	1 150	750	550	918	1 200	923	652
India	144	225	300	400	144	230	346	461
Mexico	388	418	450	450	388	418	464	490
South Africa	274	400	447	450	274	409	565	596
Other economies in transition	520	450	450	450	520	572	598	625
Other developing Asia	188	260	356	450	188	281	416	523
Other Latin America	231	299	368	450	231	299	368	529
Other Africa	100	138	164	200	100	149	186	287
Middle East	529	550	500	500	529	571	625	636
Other OECD Europe	506	450	450	450	506	515	540	556
Other OECD Pacific	889	800	700	600	889	839	808	741
World	392	460	404	403	392	458	468	543

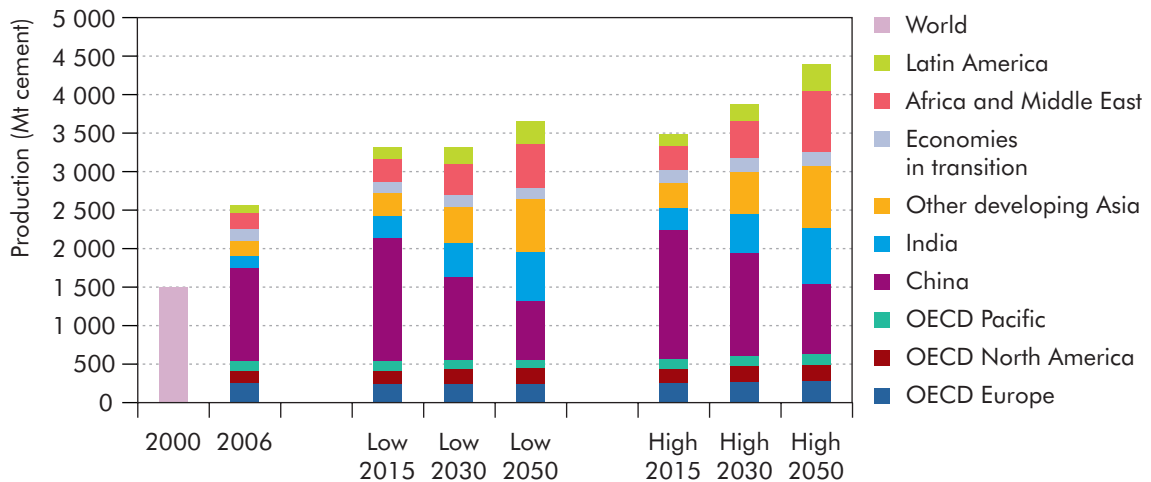
Source: USGS and IEA.

In the low-demand scenario, per capita demand in China rises more slowly in the short-term, and declines more rapidly between 2015 and 2050, than in the high-demand scenario (Figure 3.9). The other major driver in the differences between the two demand scenarios is the rate at which developing regions other than China approach per capita cement consumption levels of industrialised countries. Given the current correlation between economic activity, income levels and cement consumption per capita, the rate of growth in per capita consumption is linked to growth in per capita GDP. The current poor economic situation is not expected to have a long-term impact on economic growth, although recent weakness in cement

demand is assumed to affect cement consumption in 2015. Some OECD countries are expected to experience only modest increases in per capita consumption between 2030 and 2050.

Between 2006 and 2050, cement demand is projected to grow by 0.8% in the low-demand case and 1.2% in the high-demand case, from around 2 550 Mt in 2006 to 3 660 Mt or 4 400 Mt in 2050. Demand in China peaks between 2015 and 2030 in both scenarios, with per capita cement consumption levels then declining to around more developed country levels. China's consumption is lower in both scenarios in 2050 than the 1 204 Mt it consumed in 2006, at 766 Mt (low demand) or 908 Mt (high demand). Between 2006 and 2050, more than 95% of the growth in cement demand will come from non-OECD countries, reflecting the fact that many OECD countries are projected to experience declining populations between 2030 and 2050. Although some of the demand in the high-demand case may be related to measures to address climate change, e.g. in building wind farms, cement will be competing with other potentially less energy-intensive options. The net impact on demand is difficult to predict.

Figure 3.9 ▶ Regional cement production, 2006 to 2050

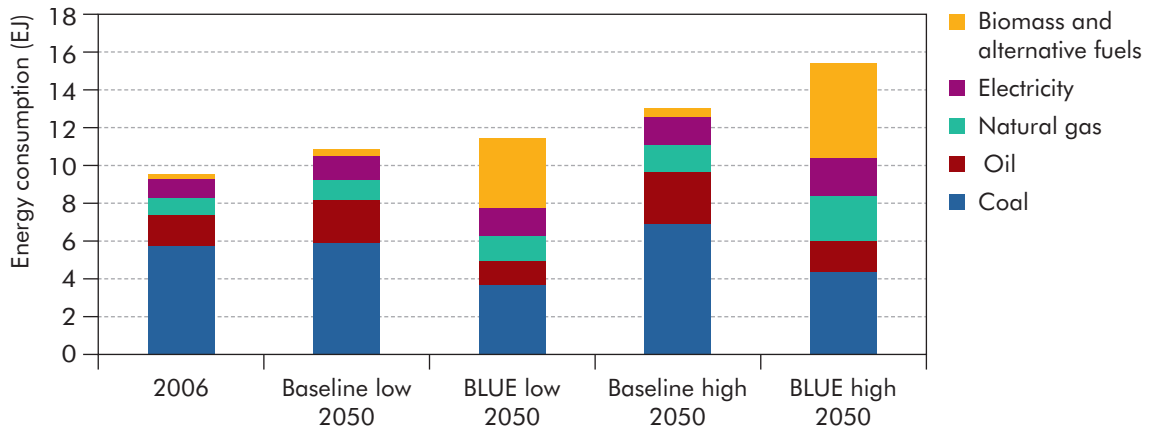


Sources: USGS and IEA.

Key point

China will continue to dominate cement production until 2030. In 2050, global cement demand will be more evenly distributed between non-OECD regions.

Total final energy consumption in the cement sector is projected to grow from 9.6 EJ in 2006 to 10.9 EJ in 2050 in the Baseline low-demand scenario and to 13 EJ in the Baseline high-demand scenario (Figure 3.10). In the BLUE low-demand scenario, energy use will be higher than 2006 levels at around 11.5 EJ. Around 1.9 EJ of this consumption is due to the installation of CCS at around a quarter of cement plants globally. In the BLUE high-demand scenario, energy consumption in 2050 is 15.4 EJ. The additional fuel consumption compared to the Baseline scenario is due to the installation of CCS at around 40% of all cement plants, requiring an additional 3.7 EJ.

Figure 3.10 ► Final energy consumption by scenario, 2006 and 2050**Key point**

Greater shares of biomass and alternative fuels will replace coal and, to a lesser extent, oil use in the BLUE scenarios.

The clinker-to-cement ratio declines from an estimated 80% globally to around 71% in 2050 in the BLUE low-demand scenario and 73% in the BLUE high-demand scenario, as the use of clinker substitutes continues to grow. The availability of clinker substitutes would technically allow greater levels of substitution than this (Table 3.5), but the suitability of much fly ash, increasing costs and some limits in the applications of blended cements mean that a clinker ratio lower than 0.7 is unlikely.

Table 3.5 ► Availability of clinker substitutes in the BLUE scenario, 2005 and 2050

	2005 (Mt)	2050 (Mt)
Fly ash	590	368
Blast-furnace slag	308	364
Other clinker substitutes	50	100
Other additions, e.g. ground limestone	267	500
Total	1 215	1 332

High-carbon content fly ash cannot easily be used in cement. However, a number of technologies have been developed that can reduce the carbon content from 18% to 2.5% and allow it to be used as a clinker substitute, although at additional cost. This technology is currently applied in the United Kingdom and Israel.

The use of biomass and other alternative fuels is expected to grow rapidly in order to reduce costs and avoid CO₂ emissions, with consumption reaching between 3.7 EJ and 5 EJ in 2050 in the BLUE low- and high-demand scenarios respectively. Potential alternative fuel sources are varied and significant quantities are likely to

be readily available (Table 3.6). Economics will determine the extent to which the estimated potential alternatives will be utilised, but with high long-term energy prices and an increasing focus on recycling or reusing waste materials, the potential for a significant proportion of these fuels to be used in cement kilns is real.

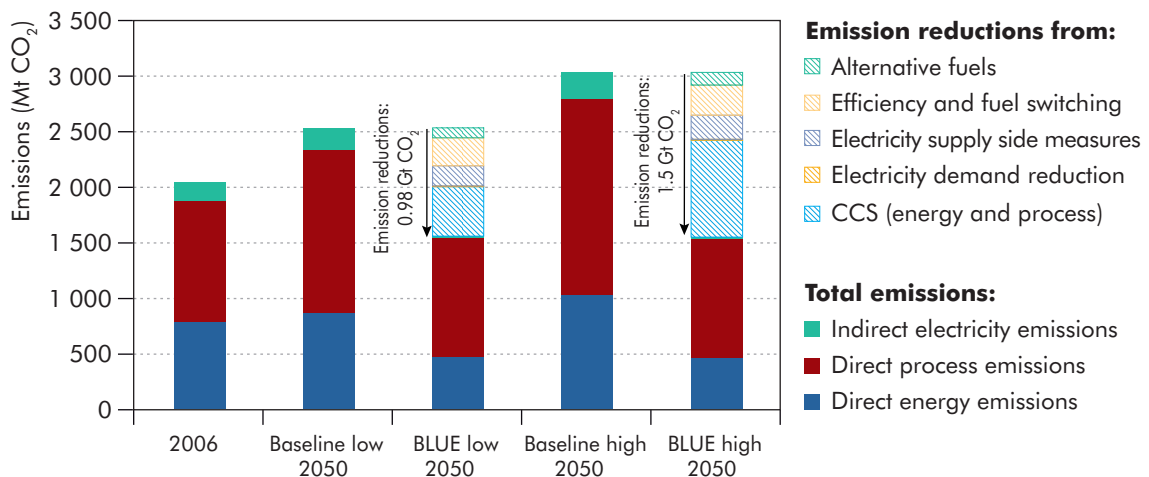
Table 3.6 ▶ **Estimated availability of selected alternative fuels, 2005 and 2050**

	2005 (Mt)	2050 (Mt)	2050 (EJ)
Waste tyres	6	20	0.70
Plastic/fibres in MSW	100	200	7.0
Chemical waste			0.54
Waste pallets	2	3	0.05
Demolition wood and other wood waste	225	300	4.5
Sewage sludge	30	50	0.25
Total			13

3

The shift to BAT, the increased use of clinker substitutes and alternative fuels, and the application of CCS reduces direct CO₂ emissions from the cement industry by around 18% below 2006 levels in the BLUE high- and low-demand scenarios (Figure 3.11). This represents a reduction from the Baseline level in 2050 of between 0.98 Gt CO₂ in the BLUE low-demand scenario and 1.5 Gt CO₂ in the BLUE high-demand scenario. CCS is expected to contribute most of the savings, with a net contribution of 0.45 Gt CO₂ in the BLUE low-demand scenario and 0.88 Gt CO₂ in the BLUE high-demand scenario. In both scenarios, CCS is essential to reduce emissions below today's levels.

Figure 3.11 ▶ **CO₂ emissions by scenario, 2006 and 2050**



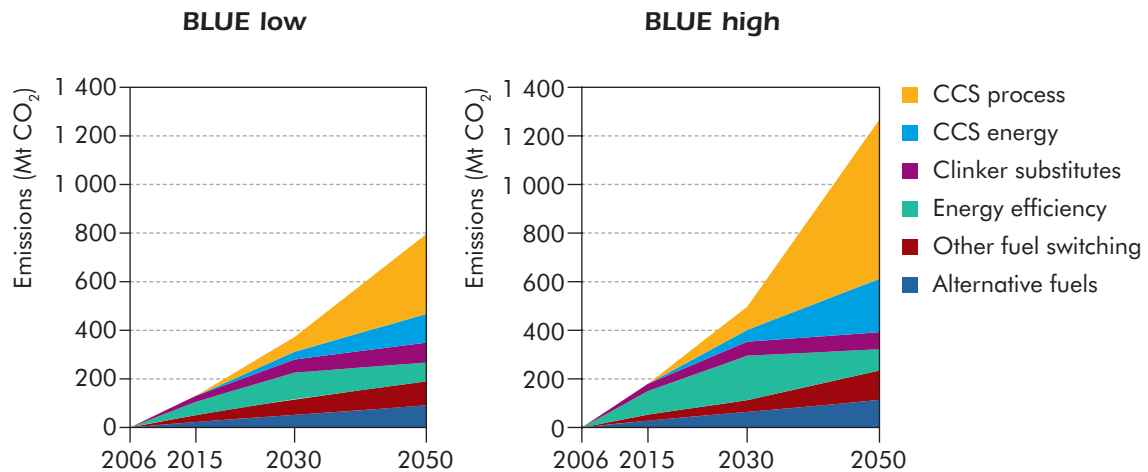
Key point

CO₂ emissions are 24% below 2006 levels in the BLUE scenarios in 2050.

The breakdown of savings by source is shown in Figure 3.12. The net reduction below the Baseline scenario levels, after allowing for the additional thermal energy consumption required for CCS plants, is dominated by CCS. Almost all the savings in the BLUE high-demand scenario over those in the BLUE low-demand scenario derive from additional CCS installation, as energy efficiency options are already more or less completely deployed in the BLUE low-demand scenario.

Figure 3.12 also highlights the relatively modest savings that can be achieved in the short-term, given low capital stock turnover and the modest gains that can be achieved by energy efficiency retrofits. But after 2015, savings start to accelerate as CCS is deployed on a modest scale initially, ramping up rapidly after 2030. Efficiency improvements in the BLUE scenarios over and above the Baseline scenarios achieve their maximum effect in 2030. Thereafter, their contribution to savings declines, as the Baseline scenarios already assume that most of the available energy efficiency options are implemented by 2050. CCS dominates total savings by 2050, accounting for more than half the reduction below the Baseline scenarios by that time.

Figure 3.12 ► CO₂ emissions reductions below the Baseline, 2006 to 2050

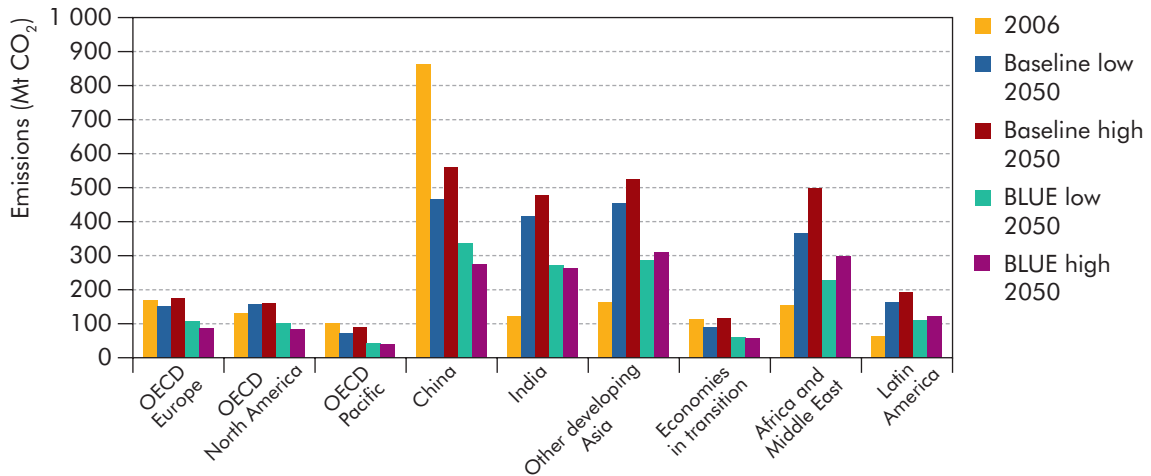


Note: Excludes impact of electricity supply-side measures.

Key point

CCS represents the largest share of CO₂ savings in the cement sector.

Figure 3.13 shows the CO₂ emissions from the cement sector by region and scenario. China uniquely has lower CO₂ emissions in 2050 than in 2006 in the Baseline scenario, as a result of slowing cement demand. China and India have the largest CO₂ reductions in absolute terms in the BLUE low- and high-demand scenarios below the Baseline in 2050, with a reduction of between 131 Mt CO₂ and 287 Mt CO₂ and between 144 Mt CO₂ and 244 Mt CO₂ respectively for these two countries. The percentage reductions below the Baseline scenario are largest in the OECD regions, reflecting in part the earlier deployment of CCS.

Figure 3.13 ▶ Direct CO₂ emissions by region and by scenario, 2006 and 2050**Key point**

All regions will need to significantly reduce emissions in the BLUE scenarios.

Costs of CO₂ reduction in the cement sector

The cost and economics of the available technology options define the marginal cost and investment needed in the BLUE scenarios. The estimated cost of these options depends on the projections of fossil fuel and electricity prices and on the specific capital and operating costs associated with each option.

Although a wide range of CO₂ reduction costs exist for each technology option, depending on the individual country and plant, the analysis here concentrates on the global level, taking into account a range of uncertainties around the estimated investment costs. As a result, the analysis does not attempt to take account of regional variations in perceived risk which would lead to different discount rates over time, or of the maturity of financial markets in different emerging economies, or of such factors as credit constraints.

The analysis of investment costs also needs to distinguish between the differing costs of retrofits and new build. New build generally offers greater opportunities for low-cost energy efficiency and clean technology options, often at the same time as other economic or qualitative benefits such as expanded plant size, improved product quality, reduced noise, and better pollution control. The rapid forecast growth in global cement production is expected to create significant demand for new cement plant, which will enable low-cost opportunities for energy efficiency and clean energy investments to be taken, except in OECD countries where existing capital stock and modest demand growth will limit the scope for such investments.

Table 3.7 shows the incremental investment needs in the BLUE scenarios over and above the Baseline. Total investment needs increase by between USD 354 and USD 572 billion in the BLUE low-demand scenario and by between

USD 520 and USD 843 billion in the BLUE high-demand scenario. This compares to total investment of USD 760 billion in the Baseline low and USD 970 billion in the Baseline high-demand scenario. The potential increase in investment needs is therefore between 47% and 75% in the BLUE low and between 54% and 87% in the BLUE high-demand scenario.

Table 3.7 ▶ **Estimated cumulative additional investment needs in the BLUE scenarios, 2005 to 2050**

	BLUE Low	BLUE Low	BLUE High	BLUE High
	Incremental cost (billion USD above baseline)			
	Low end	High end	Low end	High end
Increased use of clinker substitutes	0.4	2.2	0.2	1.2
Increased use of alternative fuels	2.9	8.7	4.1	12.3
Energy efficiency retrofits and shift to BAT	29.0	159.3	41.9	236.4
CCS	321.8	402.2	474.3	592.9
Total	354	572	520	843

Additional investment needs for the cement sector are dominated by the additional up-front costs of installing CCS at cement plants in the BLUE scenarios. Post-combustion CCS could double the investment needs of a cement plant in Europe, although this is reduced if oxyfuelled CCS options were to be adopted. CCS accounts for between 70% and 91% of the total additional investment needs between the Baseline and BLUE scenarios. Total investment needs and the marginal cost of abatement in the cement sector are critically sensitive to the future costs of CCS.

New technology options

Shifting to BAT in the cement industry, the increased use of clinker substitutes and alternative fuels will not on its own be enough to meet aggressive CO₂ reduction goals such as the 50% global reduction in energy-related CO₂ emissions in 2050 envisaged in the BLUE scenarios. New technologies will need to be brought on stream if the cement sector is to reduce emissions below today's level to any significant extent.

Several technologies offer significant potential to reduce the CO₂ emissions associated with the cement industry. CCS has been identified as a critical technology for ambitious emissions reduction strategies (IEA, 2008) in industry, electricity generation and the fuel transformation sector. Important R&D is being undertaken and commitments have been made to demonstrate a range of CCS technologies. Geopolymer and other new cement types are emerging from R&D and start-up companies. Geopolymer cements do not need to be burnt like standard clinker. Instead, the reaction in alkaline media produces a three-dimensional inorganic aluminosilicate polymer network which results in a relatively high-strength

hardened product. Much work needs to be done to prove and commercialise these new cements, but they are potential breakthrough technologies.

CO₂ capture and storage

There are three main approaches to the capture of CO₂ in cement production:

- post-combustion capture, where CO₂ is separated from the flue gas;
- pre-combustion capture, where the fuel is reacted with oxygen and steam to produce a mix of CO₂ and H₂; and
- oxy-combustion where the fuel is burnt in oxygen, yielding a CO₂-rich exhaust stream.

Pre-combustion capture would not capture the CO₂ emissions from calcination and is therefore of less interest to the cement industry, and will not be discussed in this analysis

Oxyfuel technology as part of CO₂ capture and storage

Oxy-combustion is likely to be the subject of a number of demonstration plants in the power sector in coming years. It is also a promising potential technology to support CO₂ capture from cement kilns. Oxygen enrichment has already been tested in the United States to increase production capacity. However, oxy-combustion is only likely to be relevant for new kilns, since retrofitting existing kilns would be technically challenging and very costly.

The technology relies on using oxygen for combustion instead of ambient air. The result is a very high concentration of CO₂ in the exhaust gas, at or above 80%, the balance being made up of water, nitrogen and sulphur oxides. This compares to the 14% to 33% concentration of CO₂ in exhaust gases when a kiln is fired with ambient air. Maintaining kiln burner temperatures will require that some of the flue gas is recycled back into the kiln. The rate at which flue gas is recirculated can be used to control the temperature.

The oxygen required for oxyfuelling can be produced in several ways. For large-scale plants, cryogenic air separation, an established and well-developed technology, is likely to be the preferred method of production. Other options include pressure swing adsorption or membrane systems. Membrane technology is developing rapidly and air separation by membranes is likely to provide the cheapest solution for low-volume oxygen demand, although this will be of limited applicability to cement kilns.

The high concentration of CO₂ in the flue gas allows for a relatively simple CO₂ separation and purification facility. After purification, the gas is compressed and ready to be delivered to the transportation network for storage. The level of CO₂ purification required for CCS is part of an ongoing debate about the future regulatory framework for CCS, and much depends on whether CO₂ is treated as "waste" or not. In addition to the storage of CO₂, CCS with oxyfuelling also has the advantage of virtually eliminating emissions of other noxious substances.

Oxyfuelling is currently a novel technology and many barriers remain. Experience of oxyfuelling in power generation will not necessarily readily transfer to cement kilns, given the different nature of the processes involved. Oxyfuelling with flue gas recirculation could have an important impact on plant operation and potentially cement quality. The high pressure of CO₂ in the kiln is likely to have an impact on calcination. These aspects need to be explored and better understood. Burner technologies are also different in electricity plant steam boilers and in rotary cement kilns. Notwithstanding these challenges, oxyfuel technology with flue gas recirculation is likely to be a promising route for the application of CCS in new cement kilns and warrants further exploration in more detail at a demonstration level.

Post-combustion technologies: absorption

Post-combustion capture has the advantage of not requiring any fundamental changes in the clinker production process, allowing retrofit at existing cement kilns as well as being used for new kilns. The most promising post-combustion technology, given the operational experience already gained in a number of industrial applications and the fact that high abatement efficiencies could be achieved, is chemical absorption. Another potential pathway is the use of membrane technology. Other post-combustion techniques, such as physical absorption or mineral adsorption are at an earlier stage of development and appear at this stage to be less promising.

Post-combustion technologies capture CO₂ from the exhaust gas at low pressure and at low concentrations. The efficiency of post combustion capture is positively correlated with the CO₂ concentration of the exhaust gas. Cement kilns are therefore likely to present lower-cost CCS abatement options than power generation, as the clinker burning process produces exhaust gases with CO₂ concentrations of around 30%, compared to between 10% and 15% in coal-fired power plants. But this advantage is offset to some extent by the need to clean the exhaust gas from cement kilns of impurities, such as dust. The removal of CO₂ from the exhaust gas requires the removal of nitrogen and oxygen, as well as flue gas impurities such as sulphur oxides (SO_x), nitrogen oxides (NO_x) and particulates.

Carbon dioxide separation by absorption can be achieved by physical, chemical or hybrid processes. In the physical absorption process, CO₂ is absorbed in a solvent. In chemical absorption, the CO₂ reacts with the absorbent, creating weakly bonded compounds. As the name implies, hybrid systems combine the attributes of physical and chemical absorption. Absorption technologies offer the potential to capture up to 90% of the CO₂ in the exhaust gas.

Chemical absorption is likely to be the preferred route for post-combustion capture, as chemical solvents have a high absorption capacity at the low partial pressures that are typically found in flue gas. Chemical absorption with alkaloamines is a proven technology. It has an extensive history in the chemical and gas industries, although usually at a much smaller scale than would be necessary in the cement industry. One advantage over power generation is that the higher CO₂ concentration in kilns would allow smaller absorber structures. But significant modification and research will still need to be completed before this technology could be used in cement kilns.

Solvents are generally expensive, and are usually regenerated and reused to minimise costs. The most common solvent in the chemical industry is monoethanolamine (MEA). More advanced amines are commercially available and even more efficient solvents, based on ammonia or activated potassium carbonate, are at the development stage.

However, the regeneration of solvents is very energy-intensive. The solvents also degrade more rapidly in the presence of SO_2 and oxygen. Cleaning up the flue gas through the use of a wet scrubber and a high-efficiency filter helps slow the solvents being degraded by SO_2 and oxygen impurities, but adds to the cost. NO_x concentrations may also pose problems.

CCS abatement costs in cement kilns

The abatement cost of CCS in cement kilns remains uncertain given the lack of experience in operating large-scale CCS plant either in power generation or industry. Cost estimates range between USD 38 to USD 115/t CO_2 avoided (ECRA, 2008) and USD 63 to USD 170/t CO_2 avoided, taking into account upstream emissions from electricity generation (IEA GHG, 2008). Post-combustion capture in cement production seems likely to be more expensive than in power generation, principally because of the smaller scale of cement kilns. OxyfueLLing seems likely to be the most economic form of CCS for the cement industry, but is as yet undeveloped as a technology in this context. All this implies that achieving rapid reductions in CO_2 emissions from the cement industry through CCS is likely to be a very expensive abatement option.

New low-carbon cements

A number of new low-carbon or carbon-negative cements are currently being developed by start-up companies that expect to build pilot plants in 2009/10.

- **Novacem** cement is based on magnesium oxide (MgO) and special mineral additives. It offers the prospect of lower-carbon cement through the use of an innovative production process which can use a variety of non-carbonate-based feedstocks and a novel cement composition that accelerates the absorption of CO_2 from the environment by the manufactured construction products. Novacem's MgO production method is based on the chemical transformation of magnesium containing minerals, such as magnesium silicates, to MgO using low-temperature processes. Magnesium silicates ($x\text{MgO} \cdot \text{SiO}_2 \cdot z\text{H}_2\text{O}$) are available worldwide in large quantities, estimated to exceed 10 000 billion tonnes.
- **Calera** cement is a mixture of calcium and magnesium carbonates and calcium and magnesium hydroxides. Its production process involves bringing sea-water, brackish water or brine into contact with the waste heat in the flue gas of power stations. The contact between the liquid and the gaseous phase can be accomplished through the use of infusers, bubblers, fluidic Venturi reactors, spargers, gas filters, sprays or packed column reactors.

- **Calix's** cement is produced by the rapid calcination of dolomite in superheated steam at about 420 °C in a reactor, with a residence time of seconds to inhibit sintering and phase separation, followed by rapid quenching. The CO₂ emissions from the flash calciner can be captured using a separate CO₂ scrubbing system in which waste heat is utilised to decompose mineral sorbents, the decomposed sorbents are then brought into contact with cold flue gases where the sorbents re-carbonate, capturing the CO₂ (and SO_x) from the flue gas. The carbonated sorbents are then recycled back to the first step where they are decomposed again and the CO₂ released is captured and potentially sequestered.
- **Zeobond's geopolymers** cement utilises waste materials of fly ash and bottom ash from power stations, blast-furnace slag from iron-making plants and concrete waste to make alkali-activated cements. The performance of such a system is dependent on the chemical composition of the source materials (including the Si/Al ratio), the concentration of sodium hydroxide (NaOH) and potassium hydroxide (KOH) chemical activators and the concentration of soluble silicates in the activating solution. The geopolymerisation reactions are more complex when the feedstock is made up of a number of different minerals. High curing temperatures are usually required for good strength development, especially with glassy aluminosilicates such as fly ashes and many natural pozzolana, and this limits the range of applications in which the product can be used. If very reactive man-made pozzolana such as metakaolin are used, it is also difficult to obtain long working times.

Geopolymer cements have only recently been commercialised in limited facilities for demonstration purposes. They have not yet been used in applications where strength is critical. The potential for the large-scale development of geopolymer cements is likely in practice to be limited, given that the availability of reactive components, such as fly ash and slag, is limited or expensive as in the case of metakaolin.

The mechanical properties of these novel cements are similar to those of regular Portland cement. The necessary geological resources for the raw material feedstock are available on all continents.

Geopolymer cements have the potential to reduce CO₂ emissions because they do not rely on the calcination of calcium carbonate and because their production does not require high-temperature kilns. Another potential advantage is that geopolymer production facilities would require less capital investment than a conventional plant.

The first industrial geopolymer cement plant is currently being built in Australia. The anticipated CO₂ emissions are estimated to be around 300 kg CO₂/t product, around half that for the production of a CEM II cement. It is estimated that geopolymer cement will initially cost around 20% more than normal cement, but that this margin could be reduced to zero in the future.

Conclusion: transition pathway for the cement sector

Achieving the outcomes envisaged in the BLUE scenarios will require the cement sector to deliver CO₂ emissions reductions through:

- improvements in energy efficiency by deploying existing BAT for new plant and for the retrofit of more energy-efficient technologies where it is economic to do so;
- switching to less carbon-intensive fossil fuels and expanding the use of biomass and alternative fuels;
- implementing CCS, which will be essential to achieve significant reductions in CO₂ emissions; and
- expanding the use of clinker substitutes.

The results of the BLUE scenarios cannot be achieved unless all of these technologies and opportunities are exploited. No single option can yield the necessary emissions reductions.

The implementation of BAT in the cement industry will have an important contribution to make. In particular, it will be important that most small-scale and vertical shaft kilns, especially in China, are replaced with larger more efficient ones (subject to raw material availability and transport infrastructure). This will also facilitate the least-cost application of CCS. Energy efficiency improvements will be particularly important in reducing the emissions in Africa, Canada, China, Other developing Asia, the former Soviet Union, the Middle East and the United States.

CHP is an opportunity that can be pursued where the waste-heat temperature and electricity price make the option viable, although this will not be a priority in the BLUE scenarios. The retrofit of energy efficiency options for the kiln and for the grinding process should be pursued where sufficient plant life remains to make these options attractive from a CO₂ abatement and economic perspective.

Fuel switching and the use of alternative fuels can offer important CO₂ reductions and in some cases result in lower operating costs. There is likely to be relatively limited incentive for plants to shift from coal to gas given the projected relative prices of these fuels. However, the use of alternative fuels, particularly waste or biomass, offers much greater opportunities. Cement kilns require only modest additional investments to utilise alternative fuels, such as waste tyres, waste plastics and agricultural residues, and these can be attractive from an economic and CO₂ reduction perspective.

Regulatory or institutional barriers can inhibit the use of alternative fuels at cement kilns. Coherent policy frameworks on waste and the life-cycle of waste are needed at a national level to help ensure that increasing quantities of waste are available and that they are treated so as to be useable in cement kilns. Clear information about the benefits of such an approach will also be necessary in order to address any potential public resistance to the incineration of wastes.

Waste may become more expensive over time as higher energy prices increase the competition for waste as fuel, and as other energy-intensive sectors seek to reduce

their energy costs. Outside the OECD, cement manufacturers have little experience in the use of waste. The dissemination of the technical and operational knowledge that has been built up in OECD countries is particularly important.

The expanded use of clinker substitutes (granulated blast-furnace slag, fly ash, pozzolana) is hampered in some cases by regulatory or institutional barriers. Building regulations may specify the use of specific cements, even if blended cements could do the job adequately or require only slight modifications in the laying of the concrete or the design of the construction. Other problems include a lack of awareness of the opportunities to use blended cement in the construction industry. Addressing these barriers will be vital in ensuring that the use of clinker substitutes grows.

The widespread application of CCS is essential if the cement sector is to reduce CO₂ emissions below today's levels in the future. In the BLUE low- and high-demand scenarios, 505 Mt CO₂ and 987 Mt CO₂ respectively are sequestered annually in 2050. Reaching these levels implies that CCS needs to be demonstrated at cement plants from around 2015 in order to ensure that a number of technology platforms are tested as early as possible. This would be an essential precursor to the beginning of commercial deployment in 2020 to 2025. The scenarios imply that between 220 and 430 large (6 000 t/day) production facilities with CCS need to be operating in 2050, with around 50 to 70 plants commissioned by 2030.

Such a rapid expansion of CCS will require between 20% and 30% of new plants to be equipped with CCS by 2030 and that some retrofits of post-combustion technology occur. As with other sectors, this implies that there is a ten-year window in which CCS needs to be demonstrated if it is to be deployed at its lowest possible cost. If CCS were not commercially available until 2030, achieving the BLUE scenarios would require prematurely retrofitting CCS to large or medium-scale plants after 2030 in order to ensure that between 26% and 40% of the stock of cement kilns in 2050 are fitted with CCS. This would significantly increase the marginal cost in the BLUE scenarios. A key problem is the high investment and operating costs of CCS, as industry is unlikely to deploy CCS on any significant scale unless there is a clear long-term policy framework that stimulates the reduction of CO₂ emissions. It is critical that this covers non-OECD countries after 2020, not just to avoid carbon leakage, but also because it is not possible to achieve the results for the BLUE scenarios without global participation. In addition, the legal and regulatory framework for CCS must be decided upon and implemented in order to facilitate the development of the essential CO₂ pipelines and storage facilities.

Chapter 4 CHEMICALS AND PETROCHEMICALS

Key Findings

- ▶ *The chemical and petrochemical sector is by far the largest industrial energy user. It accounts for roughly 10% of total worldwide final energy demand and is responsible for 7% of global CO₂ emissions.*
- ▶ *For most chemicals, global production is expected to double or quadruple between 2006 and 2050. Growth of high-value chemicals (HVCs) will be highest in the Middle East and Africa, and in developing Asia.*
- ▶ *The application of best practice technologies (BPT) in chemical processes (including electricity) could save around 5.2 EJ/yr. The application of CHP, recycling, energy recovery, process intensification and process integration could save another 5.0 EJ/yr.*
- ▶ *In order to achieve more substantial savings, a range of new technologies must be developed and applied. These include novel olefin production processes (including the greater use of catalysis), membranes and other novel separation processes, process intensification, bio-based chemicals and plastics and CCS. The application of new technologies would enable reductions in energy use and CO₂ emissions from reducing direct fuel use, improving energy efficiency and fuel switching.*
- ▶ *CCS in ammonia, HVCs and large-scale CHP plants could save approximately 300 Mt of CO₂ per year. CCS is particularly attractive for ammonia plants because of the availability of pure CO₂ and lends itself particularly well to early demonstration and application.*
- ▶ *The scenario analysis shows that abatement measures which cost up to USD 200/t CO₂ could reduce direct emissions to the level of 2006 notwithstanding production growth.*
- ▶ *It is challenging for the chemical and petrochemical sector to reduce CO₂ emissions due to a high share of feedstock energy. As a result, the sector has the lowest emissions reduction potential (in percentage terms). The use of alternative feedstocks is the key to deeper reductions in emissions. Increased use of biomass feedstocks and recycling more plastic waste could reduce life-cycle CO₂ emissions substantially.*
- ▶ *There is a need for countries to develop much more consistent and reliable chemical and petrochemical data. Analytical models need to be developed, as they have been in other sectors such as iron and steel and cement, to support much more robust analysis of CO₂ abatement potentials.*

Introduction



The global turnover of the chemical and petrochemical sector amounted to approximately EUR 2 400 billion in 2007 (VCI, 2008). This amount doubled from 1995 to 2007, growing on average at 5.8% a year.

It is difficult to measure the physical production of the organic chemical industry given the large number of intermediate products that are traded at all levels of production. Polymer production represents both the largest and the fastest-growing segment of the chemical and petrochemical sector, representing approximately 75% of the total physical production, and growing at nearly 6% a year to approximately 300 million tonnes in 2006 (PlasticsEurope, 2007; SRI Consulting, 2008). While growth has levelled off in some industrialised countries, polymer production in China and some other emerging economies has continued to grow rapidly. Worldwide growth has been affected by the global economic turmoil.

Fossil fuels are used in the sector both for energy production and as feedstocks for the production of organic chemicals and a number of inorganic chemicals including ammonia. The non-energy use of fossil fuels in the sector has increased from 16.3 EJ in 2000 to 20.1 EJ in 2006 (3.6% per year). Most of the growth of organic chemicals has occurred in China and India (4.9% and 5.2% per year respectively) between 1990 and 2006. Most of the growth in inorganic chemical production, predominantly ammonia, from 2000 to 2005 has been in China (67% of worldwide growth), followed by Trinidad & Tobago and by Russia (13% and 12% respectively).

In 2006, the chemical and petrochemical sector's demand for energy and feedstocks accounted for approximately 10% of worldwide final energy demand, equivalent to 35 EJ/yr.¹ It is the largest energy-consuming sector in industry, accounting for approximately 30% of the total industrial final energy demand. The energy use attributable to this sector increased by 2.2% a year on average between 1970 and 2006 (IEA, 2008e). In 2006, the process energy requirements of the chemical and petrochemical sector generated approximately 1 240 Mt CO₂ (IEA estimate), excluding indirect emissions from power use and from the treatment of post-consumer waste, e.g. from the incineration of plastics.

The bulk of the sector's total feedstock and process energy requirements comes from oil and gas-derived products. The input costs of the chemical industry have as a result changed very significantly in recent years. Coal accounts for approximately 6.5% of the total final energy demand. Bio-based feedstocks account for around 5%.

Strategies for reducing energy use and CO₂ emissions in the chemical and petrochemical sector include measures to increase energy efficiency, CHP, CCS, the use of bio-based feedstocks and the recycling of polymers and other chemicals

1. Final process energy is the total of demand of fuel (excluding feedstock energy), steam use and electricity. Final energy is the sum of final process energy and feedstock energy. Primary energy use is the sum of final energy and the conversion losses for producing steam and electricity.

such as solvents and lubricants. The energy savings potential of these options in the sector is examined in more detail below.

Trends in energy efficiency and CO₂ emissions

The other chapters of this book establish the potential for energy savings and CO₂ emissions reductions by comparing the current performance of a sector to the performance it could achieve if all the industrial plants in that sector were to have adopted the BAT (best available technologies) for the sector. These are technologies that, although they are usually in operation in some modern plants, are often not yet widely proven at industrial scale either technologically or economically.

In the chemical and petrochemical sector, given the scale of most plants, it is more appropriate to analyse potentials by reference to the most advanced technologies that are currently in use at industrial scale, *i.e.* what is more appropriately referred to as best practice technology (BPT). BPT is generally, by definition, economically viable. The analysis in this chapter uses BPT.

Energy efficiency improvement potentials in the chemical and petrochemical sector are established by comparing fuel use (including steam) statistics for the sector from the IEA database with the BPT values for each of the 57 processes covered. Multiplying production volumes by BPT values gives the potential minimum energy use associated with each process at the country level. At a sector level, adding together the BPT energy use for all 57 processes, scaling this up by dividing by the average coverage value² and comparing this with the IEA energy statistical data gives an energy improvement potential, *i.e.* a measure of the extent to which current practice compares to potential best practice if BPT were to be used throughout the sector.³

An alternative approach would be to estimate the energy efficiency improvement potentials solely for process energy use. Such an approach would reflect more accurately the fact that no savings can be made in the heating value of organic chemicals. However, given the lack of statistical consistency between countries in the definition of energy and non-energy uses in energy statistics (Weiss *et al.*, 2008), process energy use and feedstock energy use cannot be reliably separated. The IEA plans in future to undertake separate analysis of process energy usage. But this will only be feasible if a major effort is made by all national statistics offices and industry associations to ensure consistent reporting of feedstock use.

BPT energy values for 57 processes (covering 66 products) are provided in Table 4.1.⁴ The values for the most important chemicals (olefins, aromatics,

2. An average coverage value of 95% is used.

3. The data refer to the best practice technology in new industrial plants. Savings by revamping existing plants can be smaller. Therefore, the analysis seeks the improvement potential when the whole industry switches to new plants according to best practice technology.

4. Steam cracking and aromatics extraction are counted as one process each. Methanol from natural gas and coal is counted as two processes. Ammonia production from natural gas, oil, and coal is counted as three processes. The production of resins, fibers and rubber products are counted as individual processes (see related footnotes in Table 4.1).

ammonia and several intermediates), taken from Schyns (2006), come from an analysis of the BPT in Europe, rather than worldwide.⁵

This table also reports electricity use, although energy efficiency potentials have been established only for fuels, including steam. Only one-third of the total electricity use of the chemical and petrochemical sector can be accounted for by bottom-up energy analysis using process energy data (IEA, 2009). The remainder is probably used to run pumping equipment for pipelines and tanks and auxiliary uses for which no detailed data are available. The overall short- to medium-term savings potential in electricity use in the sector has been estimated at 20% (IEA, 2009).

The BPT values in Table 4.1 are plant-specific net energy requirements expressed as lower heating values. They refer to the core of the process excluding options for heat cascading and the process integration of material flows across individual plants on a site, and for CHP systems. Steam exports from production processes with exothermic reactions, such as steam from steam cracking and from ammonia production, are accounted for as negative values. This approach assumes that all excess heat can be used on the site.

The system boundaries of the data used in this analysis can be described as “factory gate to factory gate”. For example, for steam cracking the data refer to the conversion of naphtha to olefins. For an intermediate chemical such as ethylene oxide, the data cover only the conversion of ethylene to ethylene oxide, excluding the raw materials and energy used in upstream processes.

Processes that result in several products are common in the chemical and petrochemical sector. They represent a particular challenge when modelling energy use and emissions. This is especially the case for steam cracking which is by far the largest multi-product process in this sector. In this chapter we use the definition of high value chemicals (HVCs) used by Solomon Associates (who are known for their benchmark studies on steam cracking). According to this definition, HVCs include ethylene, propylene from the pyrolysis gas of steam crackers, benzene (contained amounts, excluding extracted amounts), butadiene (also contained), acetylene and hydrogen (sold as fuel). Unlike the previous IEA publication (2008a), in the present analysis toluene and xylene are not included in the definition of HVCs.

The average fuel use of a BPT steam cracker is 13.1 GJ per tonne of HVCs. This value, shown in Table 4.1, covers all steam cracker HVCs. The product of this value and the production volumes of HVCs results in a figure for the total BPT fuel use (in PJ) of steam crackers. The same calculation is repeated for steam, electricity and feedstock in order to calculate the total energy use of steam crackers.

The chemical and petrochemical sector extracts aromatics from the pyrolysis gas of steam crackers and from refinery flows. These processes are assumed to use an average of 2 GJ final energy per tonne of extracted benzene, toluene and xylene,

5. Synthetic rubber is an exception: for confidentiality reasons the BPT data used refer to the global situation, but not to Europe.

as is the separation of butylene and propylene from fluid catalytic cracking units (FCC).⁶

Feedstock consumption is estimated by means of the calorific value of the chemicals resulting from the first conversion of fossil fuels to chemicals such as benzene, ethylene and propylene. These chemicals are raw materials for the production of intermediates and their derivatives. To avoid double-counting, the calorific values of intermediates and derivatives are excluded. As a result, it is not possible to attribute energy efficiency improvements to the feedstock used for the production of organic chemicals.

Table 4.2 shows the energy improvement potential for the global chemical and petrochemical sector. Process energy and feedstock uses are combined in this analysis to remove the uncertainties caused by different countries adopting different definitions for the individual components in their energy statistics.

Given the quality of the data, these figures are no more than an indication of actual energy saving potentials. They are not robust enough to provide a basis either for target setting or for country comparisons. They can, however, provide valuable information on trends in industry's efforts to improve energy efficiency. Using this approach would suggest that the minimum theoretical global energy use for the 57 processes, if all were to adopt BPT, is 27.0 EJ. Actual energy use in 2006 according to energy statistics was 31.5 EJ. This suggests an energy saving potential of around 4.5 EJ/yr.

In China, most ammonia is made from coal, and in India a mix of natural gas and oil is used. In China, methanol production is almost exclusively coal-based; large amounts of acetylene are also made from coal. In order to estimate the improvement potentials in currently applied ammonia and methanol production processes, given recent major investments in coal-based processes, BPT values for China have assumed the continued use of current feedstock mix for ammonia production and exclusively coal for methanol production. The same assumption has been made in respect of India. If natural gas-based BPT values were adopted, the production of ammonia and methanol also in China and India, the energy saving potential would increase by 0.4 EJ/yr.

In the chemical and petrochemical sector, the ten most energy-consuming processes account for more than 85% of the final BPT energy use (including feedstock). Steam cracking accounts for 35%, ammonia production from natural gas and coal for 17%, the extraction of aromatics for 15%, and methanol and butylene production for 4% each.

Energy efficiency improvement potential through the use of BPT are of the order of 5% to 15% in Brazil, Canada, Japan, France, Italy and Taiwan. In some other countries, such as Saudi Arabia and the United States, the potential is almost certainly significantly higher, of the order of 20% or more. Energy statistics need to be improved if they are to provide a basis for wider country comparisons.

6. Although FCC plants are part of refineries, propylene production via this route is accounted for under the production statistics and the energy statistics of the chemical and petrochemical sector.

Table 4.1 ► BPT values on the specific energy consumption for the production of key chemicals(left: in final energy terms, denoted with index "f"; right: in primary energy terms, denoted with index "p")¹

Process	In final energy terms (GJf/t)			In primary energy terms (GJp/t)			Source
	Electricity	Feedstock	Fuel	Electricity	Feedstock	Fuel	
Organic							
Acetic acid	0.5			4.1	1.2		4.6 Meyers, 2005
Acetone	0.2			9.8	0.5		10.9 Chauvel and Lefebvre, 1989
Acrylonitrile (ACN)	0.8		0.3	-6.4	2.1	0.3	-7.1 Schyns, 2006
Adipic acid ²	0.5		1.0	18.5	1.2	1.0	20.6 Chauvel and Lefebvre, 1989
Benzene (steam cracking)	0.3	0	13.1	-1.4	0.7	0	13.1 Schyns, 2006
Benzene (aromatics extraction)	0.1	45		2.0	0.1	45	2.2 Schyns, 2006
Butadiene (steam cracking)	0.3	0	13.1	-1.4	0.7	0	13.1 Schyns, 2006
Butadiene (C ₄ separation)	0.5	45		6.7	1.3	45	7.5 Schyns, 2006
Butylene	0.1	45		2.0	0.1	45	2.2 Schyns, 2006
Caprolactam	1.1		0.2	-3.2	2.6	0.2	-3.6 Schyns, 2006
Cumene			2.1	-2.8		2.1	-3.1 Meyers, 2005
Cyclohexane ²	0.1			-1.6	0.2		-1.8 Industrial sources
Dimethyl terephthalate (DMT) ²			4.7			4.7	Industrial sources
Diphenylmethane diisocyanate (MDI) ²	3.2			0.9	8		1 Industrial sources
Ethanol ^{1,2,3}	0.8			22.2	2		23.1 BREW Study, 2006
Ethylene ⁴	0.3	45	13.1	-1.4	0.7	45	13.1 Schyns, 2006
Ethylbenzene (EB)	0.1			3.3	0.2		3.6 Meyers, 2005
Ethylene dichloride (EDC)	0.2		4.4		0.6	4.4	4.4 IEA estimates
Ethylene glycol (EG) ²	0.2		0.8	3.5	0.5	0.8	3.9 Industrial sources

Table 4.1 ► BPT values on the specific energy consumption for the production of key chemicals

(left: in final energy terms, denoted with index "f"; right: in primary energy terms, denoted with index "p") (continued)

Process	In final energy terms (GJf/t)			In primary energy terms (GJp/t)			Source
	Electricity	Feedstock	Fuel	Electricity	Feedstock	Fuel	
Ethylene oxide (EO) ²	0.8		2.5	2		2.5	Industrial sources
Formaldehyde ⁵	0.8			1.9			IPTS/EC, 2003
Isopropyl alcohol (IPA)	0.1		5.2	0.2		5.2	Chauvel and Lefebvre, 1989
Maleic anhydride	0.1			0.3			IEA estimates
Melamine ⁵	1.9		7.9	4.7		7.9	Schyns, 2006
Methacrylate	0.1			0.3			IEA Estimates
Methanol from natural gas ⁶		20			20		IEA Estimates
Methanol from coal ⁶		20			20		IEA Estimates
Methyl tert butyl ether (MTBE)	0.1			0.1			Schyns, 2006
Oxo alcohols	2.5			1			Meyers, 2005
Phenol	0.6			1.5			Meyers, 2005
Phthalic anhydride	0.7		20.0	1.8		20	IEA Estimates
Propylene (steam cracking)	0.3	45	13.1	0.7	45	13.1	Schyns, 2006
Propylene (FCC) ⁷	0.1	45		0.1	45		Schyns, 2006
Propylene oxide ²	0.8			2.1			Industrial sources
Purified terephthalic acid (PTA)	0.3			0.8			Meyers, 2005
Styrene				7.7			JPCA, 2009
Toluene (aromatics extraction) ⁸	0.1	22.5		0.1	22.5		Schyns, 2006
Toluene diisocyanate (TDI) ⁵	2.8			7			IEA Estimates
Xylene (aromatics extraction)	0.1	45		0.1	45		Schyns, 2006

Table 4.1 ► BPT values on the specific energy consumption for the production of key chemicals(left: in final energy terms, denoted with index "f"; right: in primary energy terms, denoted with index "p")¹ (continued)

Process	In final energy terms (GJf/t)				In primary energy terms (GJp/t)				Source
	Electricity	Feedstock	Fuel	Steam	Electricity	Feedstock	Fuel	Steam	
p-Xylene	0.2		6.3	0.8	0.5		6.3	0.9	Meyers, 2005
Vinyl acetate monomer ²	3			2.8	7.5			3.1	Industrial sources
Vinyl chloride monomer	0.4		2.7		1		2.7		Meyers, 2005
Urea	0.3			2.2	0.6			2.5	Schyns, 2006
Plastics									
Phenolic resins ⁵				10				11.1	IEA Estimates
Polycarbonate	2.2			10.3				11.5	Schyns, 2006
Polyethylene, high density (HDPE)	0.9			1.0	2.2			1.1	Schyns, 2006
Polyethylene, low density (LDPE)	3.5			-2.1	8.8			-2.4	Schyns, 2006
Polyethylene, linear low density (LLDPE)	0.4			1.6	1.1			1.8	IPTS/EC, 2007a
Polyethylene terephthalate (PET)	0.7		4.1		1.8		4.1		Boustead, 2008
Polypropylene (PP)	0.9			0.1	2.2			0.1	Schyns, 2006
Polystyrene (PS)	0.4		0.5		1		0.5		Hydrocarbons processing, 2003
Polyvinyl chloride (PVC)	0.6		0.5	1.2	1.6		0.5	1.4	Schyns, 2006
Urea formaldehyde (UF) and other resins and fibres ^{2,9}	0.2			2	0.5			2.8	Industrial sources
Synthetic rubber and latex ⁹	2.5			19.9	6.2			22.1	Schyns, 2006
Inorganic									
Ammonia from natural gas ⁶	0.3	20.7	10.9	-3.9	0.7	20.7	10.9	-4.3	Schyns, 2006

Table 4.1 ► BPT values on the specific energy consumption for the production of key chemicals(left: in final energy terms, denoted with index "f"; right: in primary energy terms, denoted with index "p")¹ (continued)

Process	In final energy terms (GJf/t)			In primary energy terms (GJp/t)			Source	
	Electricity	Feedstock	Fuel	Electricity	Feedstock	Fuel		Steam
Ammonia from coal ⁶	3.7	20.7	17.3	-1.3	20.7	17.3	-1.4	AICHe, 2008; IFA, 2009b
Ammonia from oil ⁶	0.5	20.7	16.1	-1.5	20.7	16.1	-1.7	IFA, 2009b
Carbon black ¹⁰	1.8	32.8		4.5	32.8			Leenderste and van Veen, 2002
Chlorine ¹¹	10			1.9	25		2.1	IPTS/EC, 2001; Gielen, 1997
Oxygen	0.6				1.6			IEA Estimates
Soda ash ¹²					10		11.1	IPTS/EC, 2004
Titanium dioxide ¹³	2.8		4.1	8.4	7	4.1	9.3	IPTS, 2007b

1. Final energy has been converted to primary energy assuming a steam production efficiency of 90% and a power generation efficiency of 40%.

2. Where BPT values are not available, BPT are assumed to be capable of achieving a 20% saving on current specific energy use values.

3. The value for steam use (22.2 GJ/t) includes both the production of ethanol from fermentable sugar (13.9 GJ/t) and the production of fermentable sugar from agricultural crops (8.3 GJ/t).

4. This dataset has been used for all ethylene production except ethylene production by steam cracking of ethane, for which the fuel use is estimated to be 5 GJ/t higher.

5. No feedstock value is given for formaldehyde, melamine, TDI and phenolic resins because this has already been accounted for in the production of the relevant raw materials.

6. Natural gas feedstocks assumed for all countries except India and China where coal (final energy use assumed to be 50% higher than natural gas) and oil (final energy use assumed to be 30% higher than natural gas) are widely used as feedstock.

7. Approximated using the dataset for aromatics extraction.

8. The feedstock value of toluene is corrected by the share of its consumption (~50%) which is further processed to other aromatics.

9. The BPT for Urea Formaldehyde (UF) resin production only, but used for the entire product group.

10. Net energy requirements. This means that released energy in the form of steam or power is credited.

11. For one tonne of chlorine production, but cover the electrolysis of sodium chloride as a whole, i.e. including the concentration of sodium hydroxide to 50% concentration. Steam use for brine preparation and sodium hydroxide (NaOH) concentration is accounted for as well as power requirements for rectifiers. Power required for NaOH cooling, hydrogen cooling and drying, liquefaction/evaporation of chlorine and its gas compression are excluded from the system boundaries. For the by-product hydrogen, no credits are given (approximately 3.4 GJ/t-Cl₂ based on the LHV of hydrogen by-produced).

12. Synthetic production only, i.e. excluding any potential savings from soda ash production in the United States and Canada.

13. The lowest recorded energy use of the chloride process route.

Table 4.2 ► Energy improvement potential by BPT in the global chemical and petrochemical sector, 2006

	Final process energy and feedstock use (incl. electricity)				Final process energy and feedstock use (excl. electricity)			
	Reported energy use (PJ/yr)	BPT energy use (PJ/yr)	EEl	Improvement potentials	Reported energy use (PJ/yr)	BPT energy use (PJ/yr)	EEl	Improvement potentials
United States	7 321	5 655	0.77	22.7%	6 412	4 928	0.77	23.1%
China	5 323	5 332	1.00	(-0.2%)	4 301	4 514	1.05	(-5.0%)
Japan	2 252	1 959	0.87	13.0%	2 053	1 800	0.88	12.3%
Korea	1 562	1 594	1.02	(-2.1%)	1 416	1 477	1.04	(-4.3%)
Saudi Arabia	1 369	1 058	0.77	22.7%	1 369	1 058	0.77	22.7%
Germany	1 241	1 209	0.97	2.6%	1 064	1 068	1.00	(-0.3%)
India	1 096	1 133	1.03	(-3.3%)	1 096	1 133	1.03	(-3.3%)
Benelux	1 092	1 147	1.05	(-5.1%)	1 004	1 077	1.07	(-7.3%)
Taiwan	859	738	0.86	14.1%	736	640	0.87	13.1%
Canada	843	766	0.91	9.2%	776	712	0.92	8.2%
France	714	631	0.88	11.6%	627	561	0.90	10.5%
Brazil ²	651	576	0.88	11.5%	572	513	0.90	10.4%
Italy	457	408	0.89	10.7%	389	354	0.91	9.1%
World	35 217	29 940	0.85	15.0%	31 529	26 990	0.86	14.4%

1. Assuming an energy coverage of 95% (see footnote 2). This estimate needs further validation.

2. In the case of Brazil, the production of bioethanol is not accounted for because of data limitations.

Sources: Chemweek (2007a, b, c, d); IEA Energy Balances for OECD and non-OECD countries (2008c, d); IFA (2009a); RFA (2009); SRI Consulting (2008); USGS (2007a, b); IEA Estimates, Definitions of terms (compare also Table 4.1).

The values shown in Table 4.2 are subject to several uncertainties. For example, production statistics in Europe and the United States include the production of all pure chemicals, including those produced on refinery sites, ethanol used as biofuel and anti-knocking agents as products of the chemical and petrochemical sector. But it is unclear whether all national and international energy statistics strictly follow this definition. Additional uncertainty may derive from the production data used.⁷ It would be more reliable to use measured data for all major existing plants. But although such datasets have been collected in the context of the Emissions Trading

7. Production data for all organic chemicals and polymers (except for polycarbonate) are taken from SRI Consulting. For most of inorganics and polycarbonate production, volumes are taken from Chemweek (2007a,b,c,d). Production volumes of other inorganics are taken from *US Geological Survey Minerals Yearbook* (USGS, 2008a and b). Ethanol production data are taken from Renewable Fuels Association (RFA, 2009) and the production volumes for urea were provided by the International Fertilizers Association (IFA, 2009a).

Scheme (ETS) in the European Union and in the context of some benchmarking projects, these data are generally confidential. They are also unavailable for many major countries.

Germany, China, India, Benelux and Korea show negative improvement potential. This implies that, in these countries, the existing processes are all as efficient as BPT and partly even more efficient. The negative improvement potentials calculated for China and India derive from the decision to base BPT on coal and oil feedstocks for ammonia and methanol production in those countries. If BPT were based on the use of natural gas, as for other countries, China would show an improvement potential of 4.1%. Even on this basis, however, India would show a negative improvement potential of -0.4%. This suggests that the choice of feedstock is not the only problem with the data. The negative improvement potentials may partly be caused by erroneous production statistics and/or erroneous energy statistics also in other countries. On the other hand, the negative improvement potentials may be credible for the following reasons:

- the BPT values used represent the best practice in the *European* chemical and petrochemical sector (*worldwide* BPT data were not available but if they were, they would be lower than or equal to *European* BPT data);
- a particularly high level of energy integration on chemical sites, e.g. by heat cascading (this is not accounted for by the BPT values);
- the methodology does not consider efficiency improvements by CHP.

While negative improvement potentials were calculated for some countries, the calculated energy efficiency potential for Japan is larger than expected. The improvement potentials calculated for the United States and Saudi Arabia may also be overestimated.

The analysis presented provides potentially useful indications of the scope for energy efficiency improvement. But even more importantly, it also shows the need for countries to develop much more consistent and reliable chemical and petrochemical data, and for analytical models to be developed as they have been in other sectors such as iron and steel and cement, to support much more robust analyses of CO₂ emission and abatement potentials.

Best available technology and technical savings potential

Table 4.2 reports only the energy savings that would be achieved by implementing BPT in core chemical processes. There are further opportunities within the sector for achieving energy savings in the short-to-medium term. As discussed in more detail in an IEA Information Paper (2009), process intensification/integration, CHP, recycling and energy recovery all offer opportunities for reducing the industry's energy use and CO₂ emissions. The total worldwide potential saving from these measures and from applying BPT is approximately 10.2 EJ/yr in final energy and

approximately 12.1 EJ/yr in primary energy use (Table 4.3). Regional potentials based on this methodology are shown in Figure 4.1.

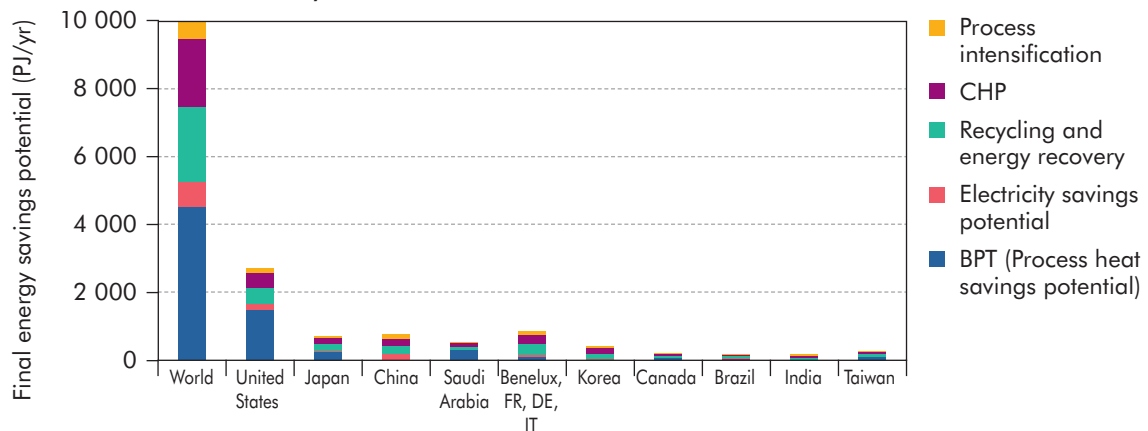
Table 4.3 ► **Worldwide energy saving potential by means of BPT and other measures related to the chemical and petrochemical sector, 2006**

	Estimated savings (EJ/yr)	
	Final energy	Primary energy
BPT – Process heat ¹	4.5	5.0
BPT – Electricity ^{1,2}	0.7	1.8
Process intensification and integration ¹	0.8	0.9
CHP ³	2.0	2.0
Recycling and energy recovery	2.2	2.4
Total	10.2	12.1

1. Primary energy savings have been estimated assuming 40% average power generation efficiency and 90% steam production efficiency.
2. It is likely that the total energy saving potential, which is based on the situation in OECD Europe, is under-estimated especially in developing countries and some newly industrialised countries.
3. Energy savings from increased use of CHP are assigned to fuel due to the negligible share of power which is used as input to generate electricity.

Source: IEA estimates.

Figure 4.1 ► **Regional breakdown of final energy savings potential by means of BPT and other measures related to the chemical and petrochemical sector, 2006**



Note: No BPT energy savings potential is shown for those countries with apparently negative improvement potential.

Source: IEA analysis.

Key point:

The current technical potential for global energy savings in the chemical and petrochemical sector is estimated at 10 EJ.

Process integration and process intensification at site level

Process integration offers energy saving opportunities both at the process level and at the site level. The use of waste heat is already an integral part of BPTs. But further energy savings can be achieved by heat cascading (including Pinch technology) and by process integration in material flows (e.g. by using by-products as raw materials). The total savings potential from improved process integration has been estimated at 5% to 10% (Martin *et al.*, 2000; IEA, 2007). The bulk of this potential is estimated to arise from improvements at the process level. Process intensification can also offer opportunities for energy efficiency improvements at the site level of the order of 3%.

Combined heat and power (CHP)

The chemical and petrochemical sector accounts for 20% to 40% of the entire CHP capacity in industry. CHP offers a range of benefits, including energy efficiency, emissions reductions, energy supply security and energy cost savings. The extent of any energy savings and CO₂ emissions reduction depends on local circumstances. In existing chemical plants, primary energy savings can be more than 20%, especially in countries using coal as the dominant fuel. In new chemical plants, energy savings can range from around 4.5% in developed economies with gas-based electricity systems, to more than 10% in emerging economies replacing coal-based systems.

CHP provides 10% to 25% of the chemical and petrochemical sector's total power demand in most countries (IEA, 2009). In countries with favourable policy regimes such as the Netherlands and Canada, the share is as much as 70% to 90%. There is a need for governments clearly to define CHP and then to align statistical data to ensure consistency.

Although CHP systems offer significant primary energy savings, market and policy barriers, such as emission limits as specified by the Clean Air Act (in the United States) and highly unfavourable tax rates and feed-in tariffs, often prevent the realisation of these benefits. The potentials identified here are accordingly, in the absence of political will and internationally applied statistical standards, theoretical.

Recycling and energy recovery

At the end of the useful life of plastics, energy savings can be made through mechanical recycling, feedstock recycling, and energy recovery. Mechanical recycling is worldwide by far the most widely used approach. The main alternatives to energy recovery are incineration and landfilling. Mechanical recycling to polymer substitutes can save as much as 50 GJ/t compared to landfilling. Japan and Europe recycle or incinerate with energy recovery significantly more of their post-consumer plastics than average.

Worldwide plastics consumption, excluding polymers used as coatings and adhesives, is 245 Mt/yr. This gives rise to 120 Mt of plastic waste of which around

10 Mt is recycled. If all this were recycled to produce polymer substitutes, this would represent a saving of approximately 500 PJ a year. In practice, recycling leads to polymer substitutes only in respect of one-third of the waste, with the other two-thirds being converted to non-polymer substitutes which give rise to negligible savings. About 30 Mt of plastic waste is incinerated. Energy recovery saves approximately 600 PJ in primary energy terms or 3% of the total process energy used in the chemical and petrochemical sector.

The primary energy savings potential from recycling is estimated at 2.4 EJ per year relative to landfilling. This savings potential is somewhat overestimated because it does not take account of energy savings already achieved in some countries by incineration with energy recovery.

Recycling and energy recovery cover the processing of post-consumer waste from products originating from the chemical and petrochemical sector. Realising the savings potential outlined from these two options will require actions taken outside the boundaries of the sector, and government support in the form of waste policies will be needed.

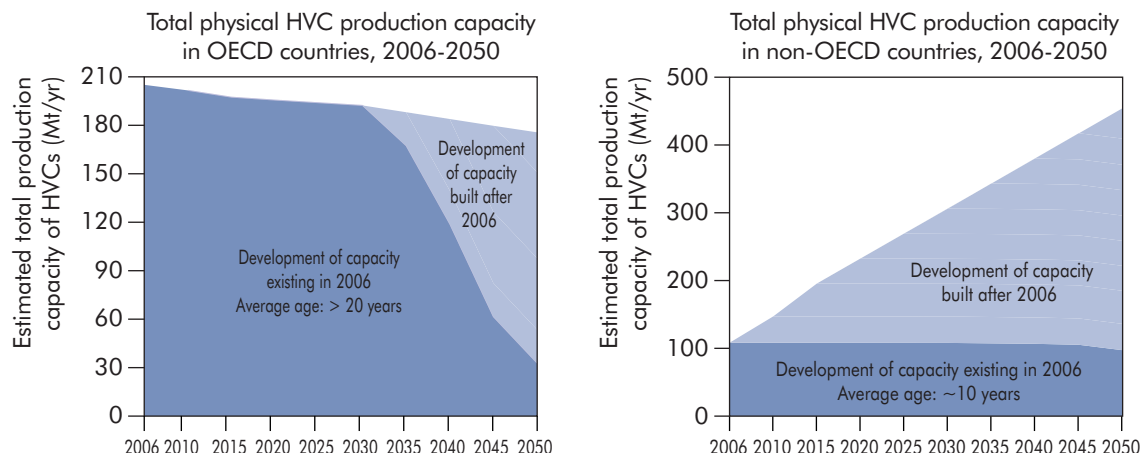
Age of capital stock and transition to BPT

Decisions on investment in BPT and new technologies are determined by various factors including current and expected future raw material and energy prices, capital costs, the age of the capital stock, environmental regulations and other aspects. In industrialised countries, technology optimisation is undermined by the existence of depreciated production facilities, lack of space, the disaggregation of large plants on integrated sites and business uncertainty. In many developing countries, unstable investment conditions, unreliable supplies of raw materials, infrastructure weaknesses and a lack of a trained workforce can all deter investment.

Worldwide production of HVCs, other intermediates and ammonia has been growing rapidly, especially in the Middle East and in China. The average age of the chemicals production capacity in China is the lowest worldwide at less than 10 years. The capital stock in Middle Eastern and African countries is on average only marginally older. The average age of the capital stock in Europe and North America is more than 20 years.

Figure 4.2 shows for OECD and non-OECD regions the estimated HVC capacity additions in the BLUE scenarios until 2050, assuming a plant lifetime of 60 years. Capacity additions projected for OECD countries in the next 30 to 40 years is very limited, *i.e.* most of the installed technology in 2006 will remain in operation. Only after 2050, all this capacity will be retired. As a result, there will be few opportunities to replace the existing stock in OECD countries with BPT until 2050. Since most current capacity in the non-OECD region is relatively modern, it is likely to stay in service for the next 50 years or more. But as the economies of the non-OECD regions continue to expand, there will be ample opportunity for implementing modern, energy-efficient technologies.

Figure 4.2 ▶ **Estimated development of HVC production capacity in OECD and non-OECD countries in the BLUE scenarios, 2006 to 2050**



Sources: SRI consulting (2008) and IEA analysis.

Key point

Almost all the existing capacity in OECD countries will still be operational in 2030, while in non-OECD countries rapid addition of new capacity will take place with new capacity expected to triple by 2030.

Scenario analysis

The Baseline scenarios reflect developments that are expected on the basis of currently implemented and planned energy and climate policies. The BLUE scenarios examine the implications of a policy objective to halve global energy-related CO₂ emissions in 2050 compared to today's level. Total direct and indirect emissions in the chemical and petrochemical sector in the BLUE scenario in 2050 are 30% lower than 2006 levels. Demand projections for HVCs (ethylene, propylene, benzene, toluene and xylene),⁸ ammonia and methanol are estimated on the basis of projected income per capita and historically derived relationships for the demand for chemicals.

In the G8 and the plus five countries, per capita HVC consumption increases between 2006 and 2050 by 5 to 85 kg/cap/yr in the low-demand case and by 40 to 145 kg/cap/yr in the high-demand case (see Table 4.4). In both scenarios, per-capita demand for HVCs in OECD Pacific countries other than Japan will decrease, by 72 kg/cap and 25 kg/cap in the low- and high-demand case respectively. The expected increase among the low-income countries is only 1 to 34 kg/cap/yr in the low-demand case and 4 to 50 kg/cap/yr in the high-demand case. The difference in chemicals and petrochemicals consumption between the richest and the poorest countries is, therefore, expected further to increase. In both scenarios the largest

8. The definition of HVCs used here differs somewhat from the definition of Solomon Associates (used in the indicators section). In addition to ethylene, the definition used here includes the production of all benzene, toluene, xylene and propylene regardless of which source they are manufactured from.

Table 4-4 ► Per capita low- and high-demand scenario consumption projections of HVC, ammonia and methanol for 2005, 2015, 2030 and 2050 (all values in kg/cap)

	HVC				Ammonia				Methanol			
	2006	2015	2030	2050	2006	2015	2030	2050	2006	2015	2030	2050
Canada	245	239-280	250-300	250-300	149	71	80	80	17	18-19	21-23	25-29
France	106	118-131	131-153	137-169	11	13-14	15-17	18-20	0	53	60	60
Germany	155	169	194	208-219	34	39-41	48-53	57-63	15	17-18	20-23	23-27
Italy	75	83-93	99-122	111-153	10	12-13	15-17	19-21	0	52	60	60
Japan	205	207-230	230-284	250-300	10	11-12	13-15	19-21	0	51	58	60
Russia	39	53-60	74-88	121-182	89	76-80	78-80	79-80	30	50-52	57-60	57-60
United Kingdom	109	118-131	127-157	127-174	17	19-20	23-24	25-27	0	55	60	60
United States	199	198-200	220-247	244-300	35	36-38	44-47	53-58	4	4	4-5	5-6
Brazil	35	46	52-58	68-94	6	7-8	9-10	15-16	2	2	2-3	3-4
China	22	32-39	47-71	82-156	36	38-42	40-48	41-55	7	13-14	22-25	46-54
India	9	11-14	17-27	28-50	12	14-15	17-19	21-23	0	0	0	1
Mexico	20	25-26	36-39	54-61	6	6	7	9-10	1	1	1	1
South Africa	19	25-31	35-58	56-116	12	19-20	29-32	58-64	0	28	47	60
Other economies in transition	11	14-17	19-27	31-45	54	76-80	78-80	79-80	0	6	24	54
Other developing Asia	25	35	43-47	59-73	11	15	19-21	29-32	1	2	2-3	4
Other Latin America	9	12	14-15	17-24	33	41-43	48-52	75-80	38	47-50	55-60	57-60
Other Africa	2	3	3-4	3-6	4	5	6	9-10	2	2-3	3	4-5
Middle East	89	136-159	184-247	240-300	46	56-59	74-80	79-80	41	50-52	57-60	57-60
Other OECD Europe	94	101-112	114-141	119-163	32	36-38	44-48	50-55	3	3	4	4-5
Other OECD Pacific	325	250-300	250-300	250-300	23	30-31	35-38	52-57	6	8	9-10	13-16
Total	42	47-52	55-70	69-98	23	25-27	28-31	32-37	6	11-12	14-15	18-20

Source: SRI Consulting (2008) and IEA estimates.

growth in HVC demand is expected to occur in China (60 to 135 kg/cap) and in the Middle East (150 to 210 kg/cap).

Worldwide HVC production is projected to grow by 7 to 11 Mt/yr from 2006 to 2050 (Figure 4.3). This is similar to the 10 Mt/yr growth from 1990 to 2006. The increase in production between 2006 and 2050 will amount to 350 to 600 Mt in the Baseline scenarios and 260 to 360 Mt in the BLUE scenarios. In the BLUE scenarios, most of the production growth is expected to occur in the Middle East (110 to 160 Mt), followed by China (70 to 110 Mt) and other developing Asia (ODA) (~55 Mt). Production in OECD Europe decreases by 0.4 Mt in both Baseline scenarios. In the BLUE scenarios, total production decreases in OECD Europe by 10 to 20 Mt, in OECD Pacific by 10 to 13 Mt and in North America by 6 to 20 Mt.

Ammonia production is projected to increase at a higher rate between 2006 and 2050 than in the last decade, increasing by 50% (140 Mt) in the low-demand scenario and doubling (increasing by 180 Mt) in the high-demand scenario. The largest production increase is expected to occur in the Middle East (40 to 50 Mt) followed by other developing Asia (~30 Mt), India (20 to 22 Mt), Russia and Latin America (15 to 20 Mt). Other regions in Africa will also increase capacity by 12 to 13 Mt. No increase in capacity is expected in OECD Europe and North America, except for minor additions in Mexico. China will remain the largest producer but, as higher growth is expected in many other regions, China's share of global production will decrease from 31% in 2006 to 18% in 2050.

Methanol production is also projected to increase at a higher rate between 2006 and 2050 than in the last decade, doubling both in the high- and low-demand scenario. Methanol production is projected to increase by 115 Mt from 2009 to 2050 in the high-demand scenario and by slightly less than 100 Mt in the low-demand scenario. China will contribute more than half of the production increase in both scenarios (56 Mt), followed by Latin America (12 Mt) and the Middle East (11 Mt). The increase in North America and OECD Pacific countries will be minor.

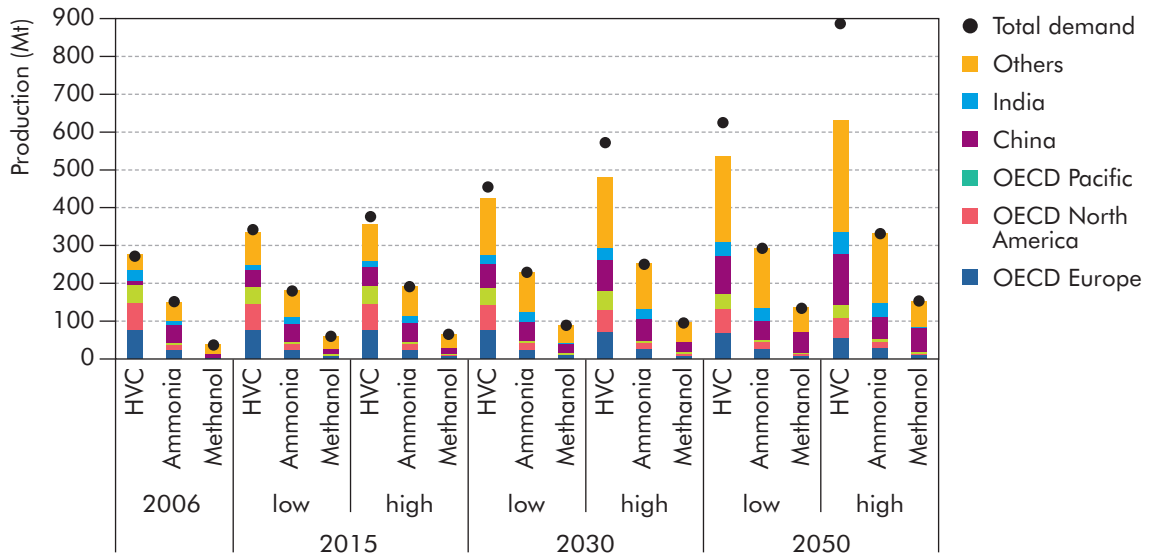
Box 4.1 ► Fertilizer demand for biofuels production in 2050

The total use of biodiesel and second-generation ethanol biofuels will increase from the current level of 0.5 EJ/yr to approximately 30 EJ/yr by 2050 in the BLUE scenario (IEA, 2008a). Biofuels would then make up more than a quarter of the fuel used in the transport sector, compared with 2% in the Baseline scenarios. The largest increases are projected to occur in biomass-to-liquids (BtL) diesel and lignocellulosic ethanol which will account for 85% of all biofuel production by 2050. Grain and sugar-cane ethanol and oil-seed biodiesel will provide the balance.

Meeting the demand for biofuel in the BLUE scenarios will require significantly more fertilizers use in agriculture compared to the Baseline scenarios. At the same time, the demand for ammonia fertilizers for the cultivation of food and feed is projected to decrease in the BLUE scenarios. The two developments balance each other out and, as a consequence, the total production volume of ammonia is projected to remain the same in both scenarios.

In the BLUE scenarios, the total fertilizer consumption for biofuels will be around 30 Mt ammonia/yr in 2050. This is approximately 10% of all ammonia production as compared to around 1% to 2% in the Baseline scenarios, an increase of more than 25 Mt/yr.

Figure 4.3 ► **Regional HVC, ammonia and methanol production and total consumption between 2006 and 2050 in the BLUE scenarios**



Note: The difference between the regional production of HVCs (bar sections) and total global production (bullets) is accounted for by the recycling of post-consumer plastic waste in the BLUE scenarios. In the Baseline scenarios the increase in total global demand will be fully met by the primary production of chemicals.

Sources: SRI Consulting (2008) and IEA analysis.

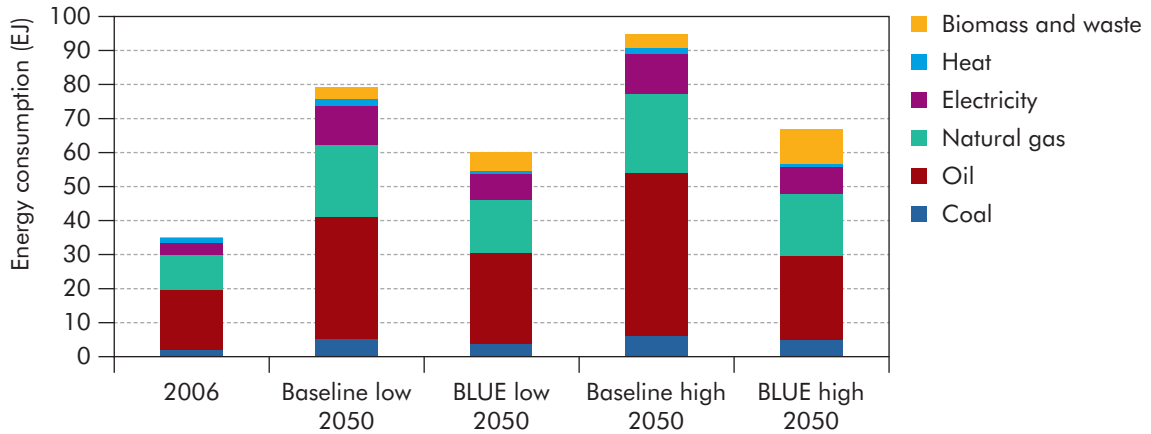
Key point

Future production growth will be dominated by China, India and other non-OECD countries.

In the Baseline scenarios, total final energy use increases by 125% to 170% by 2050 compared to 2006. In the same period, the BLUE scenarios project an increase of 70% to 90% (Figure 4.4). In the Baseline scenarios total energy use in 2050 reaches nearly 80 EJ and 95 EJ compared to just 35 EJ in 2006. Energy use in 2050 in the BLUE scenarios rises much less, reaching 60 EJ and 67 EJ as greater levels of energy efficiency will help to reduce energy intensity.

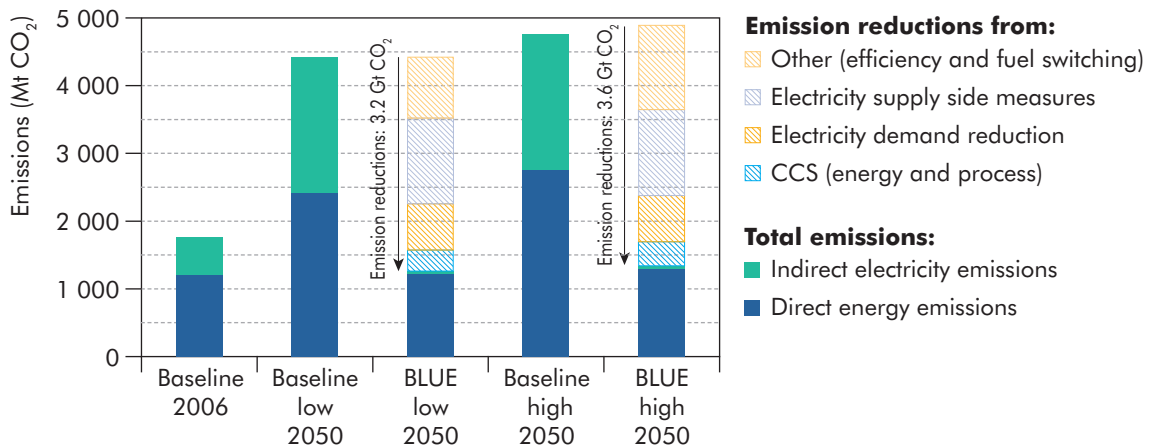
All sources of energy will show a significant increase in demand with oil showing the largest increases in both the Baseline and BLUE scenarios. Higher levels of coal use can be attributed to strong growth in China and India, and strong production growth in the Middle East will boost demand for natural gas. The main difference in the fuel mix between the two sets of scenarios is the share of biomass used. In the BLUE scenarios, biomass accounts for 9% (BLUE low-demand scenarios 2050) and 15% (BLUE high-demand scenarios 2050) of total energy use, compared to just 4% in the Baseline 2050 scenarios.

Worldwide direct CO₂ emissions in the Baseline low- and high-demand scenarios are projected to at least double by 2050, increasing from 1.2 Gt/yr in 2006 to 2.4 Gt/yr and 2.8 Gt/yr respectively in 2050. Worldwide direct CO₂ emissions by 2050 in the BLUE low- and high-demand scenario at around 1.2 Gt/yr are, by contrast, lower than 2006 emissions. In the BLUE scenarios, total (direct and indirect) worldwide CO₂ emissions in the chemical and petrochemical sector in 2050 are reduced by approximately 30% compared to 2006 levels, and by at least 70% compared to projected 2050 levels.

Figure 4.4 ► Final energy consumption by scenario, 2006 and 2050**Key point**

Energy consumption will rise sharply under the Baseline 2050 and BLUE 2050 scenarios compared to 2006 energy use.

Compared to the Baseline scenarios, approximately 40% of the projected direct and indirect CO₂ savings in the BLUE scenarios result from the use of CCS in power supply and from other electricity supply-side measures. Reductions in electricity demand and other measures (captured as “efficiency and fuel switching” in Figure 4.5) contribute 50% of the savings. The contribution of the application of CCS in the chemical and petrochemical sector accounts for no more than 10% of the total savings.

Figure 4.5 ► CO₂ emissions by scenario, 2006 and 2050

Note: Energy recovery from waste plastics reduces global emissions by displacing fossil-fuel use, therefore the total height of the stacked bar rises from the Baseline to BLUE scenarios.

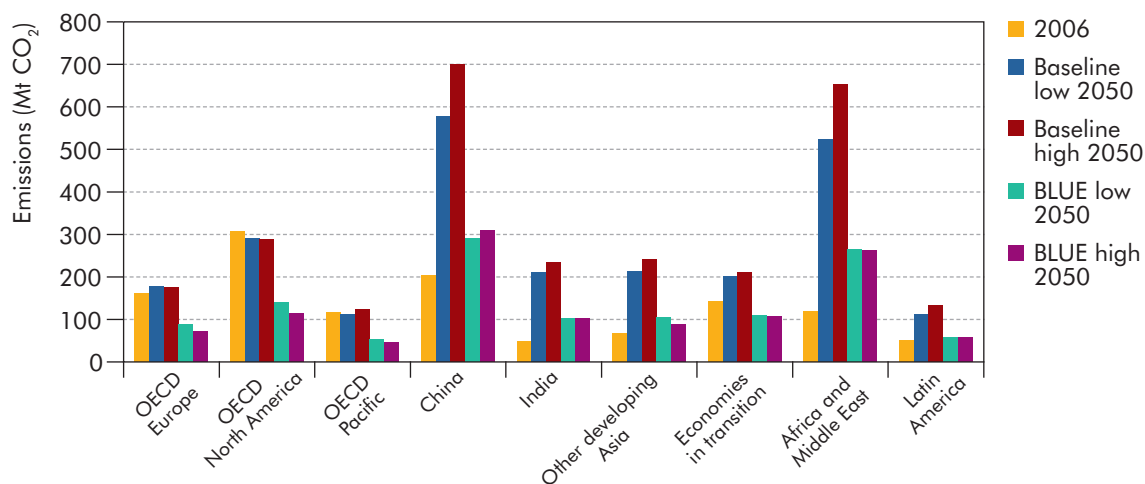
Key point

CO₂ emissions under the BLUE scenarios to 2050 can be reduced through a combination of energy efficiency measures, fuel switching, CCS and decarbonisation of the power sector.

The findings for regional direct emissions are shown in Figure 4.6. In the chemical and petrochemical sector, OECD North America is the largest CO₂ emitter in 2006, followed by China, OECD Europe, the Middle East and other developing regions. In all scenarios, China contributes most to the increase of CO₂ emissions in the sector until 2050.

In the BLUE scenarios, all OECD regions reduce their emissions in the period 2006 to 2050. In the BLUE low-demand scenario, emissions in North America show the largest savings falling by 40% compared to 2006. OECD Pacific and OECD Europe reduce their emissions by approximately 35% and 30% respectively in the BLUE low-demand scenario.

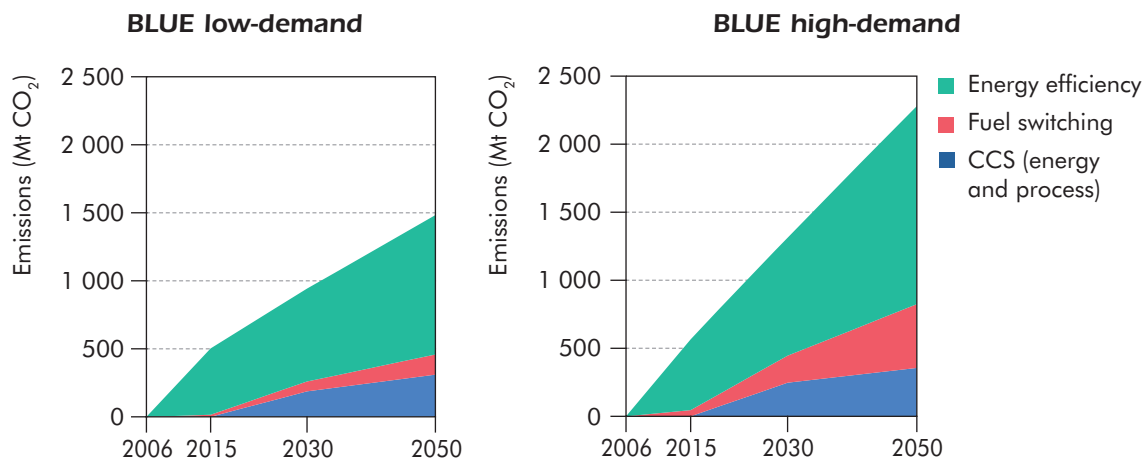
Figure 4.6 ► Direct CO₂ emissions by region and by scenario, 2006 and 2050



Key point

CO₂ emissions will grow strongest in China, Africa and the Middle East.

In the BLUE scenarios, as shown in Figure 4.7, the largest reductions in direct emissions in the global chemical and petrochemical sector compared to the Baseline, around 750 Mt and 775 Mt CO₂, is from thermal efficiency improvements. Around 680 Mt CO₂ of the emissions reduction potentials come from reducing electricity demand. While in the BLUE high-demand scenario fuel switching contributes to emissions reductions as much as 470 Mt CO₂, in BLUE low-demand scenario its potentials are less and amounts to only 150 Mt CO₂. CCS accounts for between 310 Mt and 350 Mt CO₂ for the BLUE low- and high-demand scenarios respectively. Emissions reduction from CCS will come from the application of the technology in ammonia plants, HVC production and large-scale CHP units.

Figure 4.7 ► CO₂ emission reductions below the Baseline scenario, 2006 to 2050**Key point**

Energy efficiency offers the largest opportunities for CO₂ savings in the chemical and petrochemical sector.

Costs of CO₂ reduction in the chemical and petrochemical sector

The BLUE scenarios bring into effect technologies that are cost-effective with a carbon price of up to USD 200/t CO₂. Cumulative investment needs until 2050 are estimated at USD 4.1 trillion in the Baseline low and USD 4.7 trillion in the Baseline high. In the same period, additional investment of USD 0.4 trillion is needed in the BLUE low-demand and 0.5 trillion in the BLUE high-demand, resulting in cumulative investments of USD 4.5 trillion for the BLUE low and USD 5.2 trillion for the BLUE high-demand.

If successfully developed, membrane technology and catalysts could be realised at very low or even negative additional investment costs. This may also be the case at least for some applications of process intensification. Additional investment costs could, however, be substantial for process integration and for CCS (lower for ammonia plants but much higher for other, especially smaller plants). Investments for new olefin technologies could be substantially larger than current technologies because of the increase in the process steps involved. Additional investments costs for bio-based plastics and chemicals could also be substantial but it is very likely that there will be a large variation across the products.

New technology options

New olefin production technologies

Olefins are primarily produced from the steam cracking of naphtha, ethane and gas oil, together with large amounts of aromatics which are formed as by-products. Worldwide, steam cracking accounts for approximately 3 EJ of final energy use and

approximately 200 Mt CO₂ emissions, about 20% of the total final energy use and about 17% of the total CO₂ emissions of the chemical and petrochemical sector. A number of new technologies are being developed to manufacture olefins from natural gas, coal and biomass (see Table 4.5).

Table 4.5 ► Comparison of conventional olefin production by steam cracking with new processes

	Cumulative fossil process energy use (GJ/t HVCs) ¹	Cumulative CO ₂ emissions (t CO ₂ /t-HVCs)
Conventional processes		
Naphtha steam cracking		
State-of-the-art	16	0.8
World average	24	1.0 -1.6
Ethane steam cracking		
State-of-the-art	17	0.9
World average	22.5	1.5
Natural gas to olefins		
Methane FT naphtha (commercialised by Shell and Sasol)	33	1.0
MTO	29	1.2
Lurgi MTP	30-33	1.5
Coal		
Coal FT naphtha + steam cracking	≥ 51	≥ 2.8
Biomass		
Ligno naphtha + steam cracking	-1	-0.1
Ligno naphtha + steam cracking with large power cogeneration	-67	-3.8
Maize starch ethanol to ethylene	39	2.1
Sugar cane ethanol to ethylene	-15	-0.9
Lignocellulosic ethanol to ethylene		
with moderate cogeneration of power	6	0.3
with low cogeneration of power	10	0.5
with high cogeneration of power	-25	-1.4

1. Cumulative: from raw material extraction to final product. The energy content of feedstocks and HVCs is excluded.

Source: Ren *et al.* (2008); Ren (2009).

Methanol-to-olefin processes (MTO) and the oxidative coupling of methane (OCM) offer new ways of producing olefins from natural gas. Both routes, unlike steam cracking, involve catalysis. The first industrial MTO plants will come on line in Nigeria

(by 2012), Egypt and China. Recently, Total Petrochemicals have commissioned the start-up of a pilot plant in Feluy, Belgium which will use MTO technology to produce lower and higher olefins. No large-scale plants using OCM are currently planned. MTO and OCM require more fossil fuels and cause more GHGs than the conventional production of olefins by steam cracking of naphtha. For MTO this is largely due to the energy requirements and associated CO₂ emissions of the methanol synthesis step, which calls for further technology development.

Oxidative dehydrogenation of ethane and propane to olefins offer potential savings of around 6 to 9 GJ/t of HVCs, as much as 45% compared to conventional ethane/propane steam crackers. But these technologies do not yield enough quality products at high rates to be viable. The catalytic cracking of naphtha for the production of olefins, aromatics and other high-value chemicals is also possible. Results achieved in a pilot plant located in Korea show that savings of approximately 8 GJ/t of HVCs can be achieved, although this process also suffers from technological and economic drawbacks.

Other catalytic processes can be used to produce olefins from coal and biomass. Coal-based routes require three times more process energy and produce more GHGs than the steam cracking of naphtha. Bio-based olefin production requires much less fossil energy than the conventional steam cracking of naphtha and can even, for example through producing power for feeding to the grid, make the process a net energy producer.

Other catalytic processes with improvement potential

Catalysis offers energy savings potentials for the production of a wide range of compounds other than olefins by increasing the energy efficiency of existing conversion steps and by enabling new, often simpler, process routes.

In the BLUE scenario, the gap to a thermodynamically optimal catalytic process is closed by some 65% to 80% through R&D work in the next four decades. Improved selectivity is assumed to increase yields, reducing feedstock requirements. At 2006 activity levels, approximately 1.2 EJ/yr to 1.6 EJ/yr, around 4% of the sector's final energy use, would be saved in the production of largest volume HVCs.

Catalysis could also contribute to energy savings and emissions reductions in several other processes, including the direct transformation of alkanes to intermediates. The manufacture of these chemicals nowadays involves at least two steps: from alkanes to olefins and from olefins to the desired products. Some processes involving the catalytic oxidation of hydrocarbons, such as the conversion of butane to acetic acid and to maleic anhydride, have been applied commercially. The first-in-kind plant for the conversion of propane feedstock to acrylonitrile is to be brought into operation by Asahi Kasei Chemical Corby in Thailand by late 2010. It is likely that many further opportunities will be identified and developed.

The total potential energy saving through catalytic olefin production processes (1 EJ/yr) and other catalytic processes (1.2 to 1.6 EJ/yr) constitute the 2.4 EJ/yr total savings from catalysis in the BLUE scenario. This is approximately 7% of the total

savings attributed to the final energy use of the chemical and petrochemical sector, including feedstocks.

Membranes and other separation technologies

Separation technologies account for 40% to 45% of total final energy consumption in the chemical and petrochemical sector. Around 90% of the energy used in separation is used for distillation. Separation can account for 50% of plant operating costs. Separation processes in olefins production account for 15% of all the separation energy required in the chemical industry. The separation of other hydrocarbons and aromatics accounts for more than one-third of the energy required for separation. Several research programmes continue to focus on novel separation technologies which can replace today's energy-intensive processes.

Currently, membranes do not play an important role in separation in the chemical and petrochemical sector although their use is expected to grow very substantially in the medium-to long-term. Fouling, the high cost of membrane materials (related to durability and resistance) and down times for maintenance all reduce the current economic viability of membranes even though they offer the prospect of improved product quality and large energy savings potentials.

Energy savings of the order of 30% to 40% have been estimated for oxygen production by ion-transport membrane (ITM) compared to cryogenic processes (Kauranen, 2008). Using palladium-based membranes for hydrogen separation can save 2 GJ per tonne of ammonia. Despite the long history of R&D on this type of membrane, high metal costs represent a major shortcoming. Future research aims to develop membranes with higher selectivity and lower production costs (by use of new materials and thin film technology).

Membranes are already used for the separation of vapour and gas mixtures, e.g. monomer recovery in polymer plants. Further scope exists for economic energy-saving measures in this area (Baker, 2006; Nunes and Peinemann, 2006). Energy can also be saved by separating hydrogen from light hydrocarbons in order to avoid its flaring. Vapour and hydrocarbon mixtures in steam crackers are separated through cryogenic distillation. The use of membrane separation technologies in more than the 250 steam crackers that are currently in operation worldwide would offer energy savings of more than 150 PJ/yr.

For the separation of organic mixtures, recent research shows that pervaporation hybrid systems have a large potential for replacing conventional technologies. Despite their potential, current use is limited essentially to the dehydration of ethanol and isopropanol. Future potential exists in the separation of organic azeotropes with close-boiling mixtures. Membranes can also be used to separate liquid mixtures from esterification processes. Such applications could save 130 PJ/yr globally.

Energy savings can also be achieved by other novel separation technologies. Taken together, these technologies, including membranes, offer the potential to save up to 30% of the final energy used for separation purposes, equivalent to 5% of the total final energy use of the chemical and petrochemical sector. This would save around 1.4 EJ/yr at 2006 production levels.

Future process intensification potentials

Process intensification is defined as improving the efficiency of a chemical plant by spatial (e.g. miniaturisation), thermodynamic (e.g. using high gravity), functional (e.g. synergy between reaction and separation) and/or temporal (e.g. reverse flow) optimisation (Van Gerven and Stankiewicz, 2009). It offers opportunities to achieve higher energy efficiency, increased product quality and lower production costs. Process intensification potentially offers 15% energy efficiency improvements in heat limited reactions, 20% in mass transfer limited fast reactions, 5% in ethylene cracking, up to 30% in process energy use of ammonia production and 20% in energy-efficient separations (Creative energy, 2008). More than 60 technologies have been identified which can contribute to such savings in the next 10 to 40 years, with the potential to achieve energy efficiency improvements of 5% in the next 10 to 20 years and 20% in the next 30 to 40 years (Creative energy, 2008). Excluding savings attributed above to other technologies, the long-term energy-saving potential of process intensification is estimated at 10% of the final energy use for fuel purposes. This would amount to some 1.1 EJ/yr globally at 2006 production levels.

Bio-based chemicals and plastics

The first man-made chemicals and plastics were made of bio-based polymers, most of which have been displaced by synthetic polymers since the 1930s. Synthetic polymers raise a number of issues, such as waste management and long-term impacts from littering or disposal, the high cost and security of supply of fossil fuel feedstocks, and incompatibility with wider policy goals (including climate policy). Bio-based chemicals and plastics offer the potential to mitigate a range of these issues.

There are three principal ways to produce bio-based polymers:

- to make use of natural polymers such as primarily starch polymers and cellulose. This is currently the most prevalent approach;
- to produce bio-based monomers by fermentation or conventional chemistry and to polymerise these monomers in a second step. The first large-scale plants are beginning operation on this basis; and
- to produce bio-based polymers directly in micro-organisms or in genetically modified crops. This approach is still at the laboratory stage, although the potential could be considerable in the longer term.

It has been estimated that bio-based plastics could, from a purely technical point of view, replace around 80% of petrochemical-based plastics (Shen *et al.*, 2009). The production of most bio-based chemicals and polymers requires much less fossil energy than the production of their petrochemical equivalents offering significant CO₂ savings.

While technology development risks are not negligible, the success or failure of the large-scale production of bio-based chemicals and plastics will depend on a number of factors, including production costs (with raw material costs being

key), product properties and the market price they can fetch, the availability of feedstocks, consumer perception, and policy.

CO₂ capture and storage in the chemical and petrochemical sector

Ammonia plants and large-scale CHP units produce large flows of CO₂-rich flue gases. This makes them potentially good candidates for CO₂ capture and storage. In principle, CCS could also play a role in other plants with high CO₂ concentrations such as the production of ethylene oxide and ethylene, and ethanol production by fermentation although, since the CO₂ volumes are generally much smaller, these options are relatively expensive. Petrochemical plants such as those producing ammonia, ethylene and ethylene oxide produce more than 3% of the total emissions of worldwide large stationary CO₂ sources (IPCC, 2005; Dooley, 2008).

A benchmarking survey by the International Fertilizers Association (IFA) concluded that 1.5 to 3.1 t CO₂ is emitted per tonne of ammonia produced in petrochemical plants. A major share of the process CO₂ is consumed for the production of urea and nitrophosphates, the remaining is emitted.

A summary of the wide range of costs given in the literature for CCS in the chemical and petrochemical sector is given in Table 4.7. These costs tend to be higher than for large-scale CCS plants such as those used in the power industry, apart from in large ammonia plants. CCS fitted to individual chemical plants will have higher unit costs. These can be reduced if chemical plants can feed into larger CCS systems.

Table 4.6 ► Overview of estimated CCS costs in the chemical and petrochemical sector

	CO ₂ concentration (%)	Estimated cost range (USD/t CO ₂)
Ammonia	98-99	< 50
Ethanol	95	< 50
Ethylene	12	> 50
Ethylene oxide	100	–

Source: Hendriks *et al.* (2004); IPCC, (2005); Shah *et al.* (2006); Bernstein *et al.* (2007); Wright, (2007).

The other main sources of CO₂ in the chemical and petrochemical sector are furnaces, steam boilers and an increasing number of CHP plants. Recovery technology in CHP plants is similar to that of power plants. The total potential mitigation that could be achieved by CCS in the sector is 310 Mt CO₂ /yr by 2050 (IEA estimates).

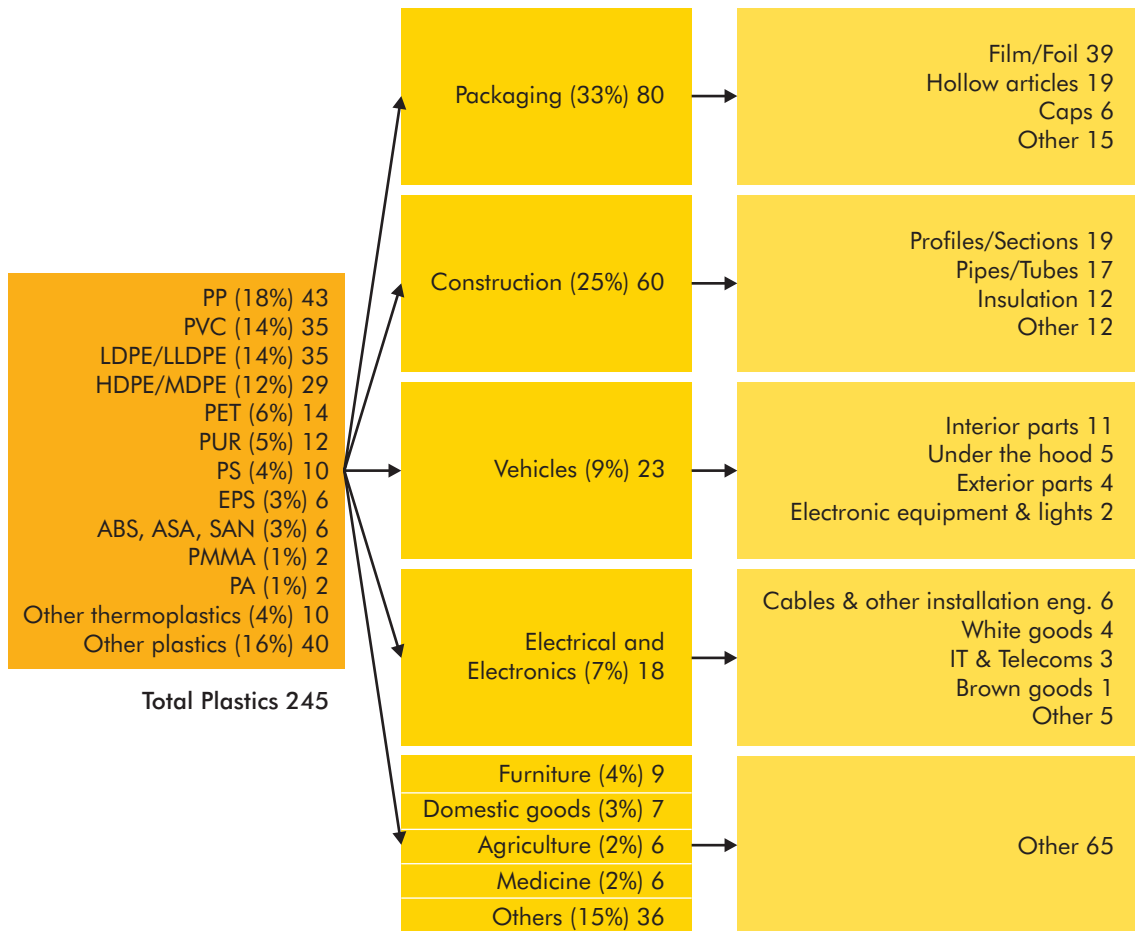
Material flows and material flow optimisation

Recycling is often costly, whereas disposal in landfills and by incineration is comparatively cheap. Some recycling processes are also energy-intensive, including

the energy used in waste collection. The most energy- and CO₂-efficient rates of recycling, for example of used plastics, will vary both regionally and according to the material and its waste flow.

Figure 4.8 shows the global petrochemical mass balance. In 2004, 345 Mt of hydrocarbons (equivalent to about 16 EJ in heating value) were converted into 310 Mt of petrochemical products, of which plastics represented 73%.

Figure 4.8 ▶ Estimated plastics flows to end-sectors and final products in the global economy, 2006 (all values in Mt/yr)



LDPE: low-density polyethylene (PE), LLDPE: linear low-density PE, HDPE: high-density PE, MDPE: medium-density PE, PP: polypropylene, PS: polystyrene, EPS: expanded polystyrene, PVC: polyvinylchloride, ABS: acrylonitrile-butadiene-styrene, ASA: acrylonitrile-styrene-acrylate, SAN: styrene acrylonitrile, PMMA: polymethylmethacrylate, PA: polyamide, PET: polyethyleneterephthalate, PUR: polyurethane.

Sources: Consultic, 2004; Consultic 2008; PEMRG (2007); Plastics Europe (2008). Figure has been scaled up to the world on the basis of data from Germany referring to years 2003 and 2007.

Key point

Packaging and construction account for over half of all plastics consumption.

Other significant products include synthetic fibres, solvents, detergents and synthetic rubber. About 120 Mt of the raw material (hydrocarbon feedstock) were stored in products. The remainder was released into the atmosphere as CO₂ or as solid and liquid waste. The majority of this waste was disposed of.

A considerable amount of energy and carbon is embodied as calorific value in organic chemicals and polymers. To minimise energy use and GHG emissions, these products need to be kept as long as possible in the economy in useful forms rather than wasted through disposal and replacement. Disposal by landfilling, except where biodegradable materials contribute to landfill gas recovery, represents a waste of energy. Although incineration with energy recovery is preferable to landfilling, it still results in higher GHG emissions than power production in a gas-fired steam plant.

The carbon impact of organic chemicals and polymers in the economy can be reduced by avoidance measures, such as fiscal tools to encourage packaging reductions, re-use such as in the conversion of bottles to fibres, and recycling. At the end of the life-cycle, as much as possible of the calorific value of the organic chemicals and polymers should be recovered. This can be realised by municipal solid waste incineration plants with highly effective energy recovery.

Conclusion: transition pathway for the chemical and petrochemical sector

In the last few decades, the sector has experienced very substantial growth. Even though the pace is expected to slow down to some extent, the sector is expected to grow significantly in the coming decades.

Developments in the last fifty years have seen the products of this sector such as plastics increasingly substitute for other engineering materials such as steel and glass. Major productivity increases and improvements in material and process performance in other sectors, for example yields in the agricultural sector, have been enabled to a substantial extent by chemical products. The chemical and petrochemical sector continues to be very innovative. But it is unclear how it will develop in future, for example if substantially higher oil and gas prices slow down demand. Even so, a growing world population is likely to require more fertilisers from the petrochemical industry for food and to meet increased demand for biomass as a fuel and a feedstock. The chemical and petrochemical sector is also likely to play an important role in developing and supplying the materials needed to support growth in renewable energy growth and to enhance energy efficiency, such as lightweight materials for vehicles and more powerful batteries, and more effective agents for the removal of CO₂ from flue gases.

If the expected substantial growth in the chemical and petrochemical sector in the coming decades is to be sustainable and to be consistent with achieving broader goals for CO₂ emissions reductions, steps will need to be taken to bring to fruition many of the technological developments described in this chapter.

The implementation of BPT in the short-term and of new technologies in the long-term would enable the sector to significantly reduce both its energy needs and its

CO₂ intensity. A wide range of technology options needs to be applied in order to reach the emission levels implicit in the BLUE scenarios. Ambitious R&D, spanning from basic to applied research followed by technology development, is required in order to reach these goals. New developments in catalysts, membranes and other separation processes, process intensification and bio-based chemicals could bring about very substantial energy savings. Globally, countries should strive to achieve BPT levels by 2025. New technologies will need to be brought on stream from 2020 onwards.

CCS offers an important contribution to reducing emissions in the sector and early deployment should focus on implementation in ammonia plants. CCS in combination with large-scale CHP and in HVC production will also need to be developed for the sector to realise the full potential of this option.

Bio-based plastics and chemicals offer the potential to reduce CO₂ emissions from the sector, for which oil and gas are currently the most important feedstocks. To some extent, the existing production facilities in the chemical and petrochemical sector can be extended by new conversion processes in order to use biomass feedstocks (e.g. for bio-based ethylene).

New investments are likely to remain in place in the long term. Companies will, therefore, have to make a fundamental choice regarding their feedstock. First-in-kind large-scale plants for the production of bio-based chemicals and plastics are currently being built. The experience made with these plants and with their products in the next 10 to 20 years will determine to a large extent the success or failure of these options. Policy support for bio-based chemicals and plastics needs to extend over relatively long periods in order to be successful, with supply security, local employment, innovation and other features to produce positive side effects. Designing suitable and affordable policies for bio-based chemicals and plastics is a challenge given the complexity of the sector and its products, international trade agreements and the need to avoid distortions in food production.

In order to fully exploit the potentials related to recycling, some R&D on materials development and adapted design is required (e.g. to maximise material efficiency and to facilitate disassembly and separation). Strong policy support is needed in order to implement collection schemes and subsequent valorisation systems. The latter should include an optimum portfolio of mechanical and chemical recycling (ideally set up as cascade), followed by highly efficient incineration with energy recovery.

Active government policies will be essential in order to enable and promote over decades the transition to more efficient and/or low-carbon technologies. Given the nature of the chemical industry, these policies need to extend from fundamental R&D schemes (in particular for continued research on catalysis, membrane technology, process intensification and the fundamentals of bio-based chemistry) to demonstration plants and support schemes for early implementation. In order to formulate suitable policies and continuously to evaluate their effectiveness, statistical data on energy use and production volumes will have to be improved and suitable analytical methods will have to be developed and continuously applied in close collaboration with the chemical and petrochemical sector.

Chapter 5 PULP AND PAPER

Key Findings

- ▶ *Future growth in demand for pulp, paper and paperboard products will remain strongest in Asia as the region's per-capita income rises. Europe and North America will see their share of global production decline as capacity expands in China, Russia and Brazil.*
- ▶ *Recovered paper utilisation rates in the pulp and paper sector have risen sharply in the last 20 years, reaching a global rate of 54% in 2006. Utilisation rates in many countries are already nearing their practical limits. Although there remains scope for some countries to increase their recycling rates, the overall potential for further energy savings from increased recycling is only moderate.*
- ▶ *A transition to best available technology (BAT) combined with higher CHP penetration and additional recycling would offer an energy savings potential of 1.4 EJ, equivalent to 20% of current energy use.*
- ▶ *Fuel switching, especially in the United States and China, offers significant potential for CO₂ reductions in the sector. This option represents half of all estimated CO₂ savings in the sector in the BLUE scenarios.*
- ▶ *The most promising new technologies which need to be developed for the pulp and paper sector include black liquor gasification, lignin removal from black liquor and biomass gasification. These technologies offer significant energy efficiency and the opportunity to produce additional energy on site.*
- ▶ *Carbon capture and storage has the potential to further reduce CO₂ emissions and, in some countries where biomass availability is high, could allow the sector to become a net CO₂ sink. As CCS moves from demonstration to commercialisation, government support will be needed to ensure the development of an adequate CO₂ transportation network and storage system near large industry sources of CO₂.*
- ▶ *The scenario analysis shows that a USD 200/t CO₂ incentive could reduce emissions in the pulp and paper sector by 46% by 2050 compared to today's levels.*
- ▶ *The additional investment needed to reach these levels of emissions reduction is estimated at between USD 120 billion and USD 140 billion, 10% above Baseline investments. Cheap capital needs to be available to the sector to stimulate investment in new technologies. Clear, stable, long-term policies will be crucial if the sector is to implement the technology transition needed to produce deep emissions reductions.*
- ▶ *There is a need to improve the consistency and quality of the energy data reported in the sector. Both the industry and national statistics offices need to improve the verification of reporting methodologies, especially for biomass and CHP use. Additional work is needed before the indicators can be used for target setting.*

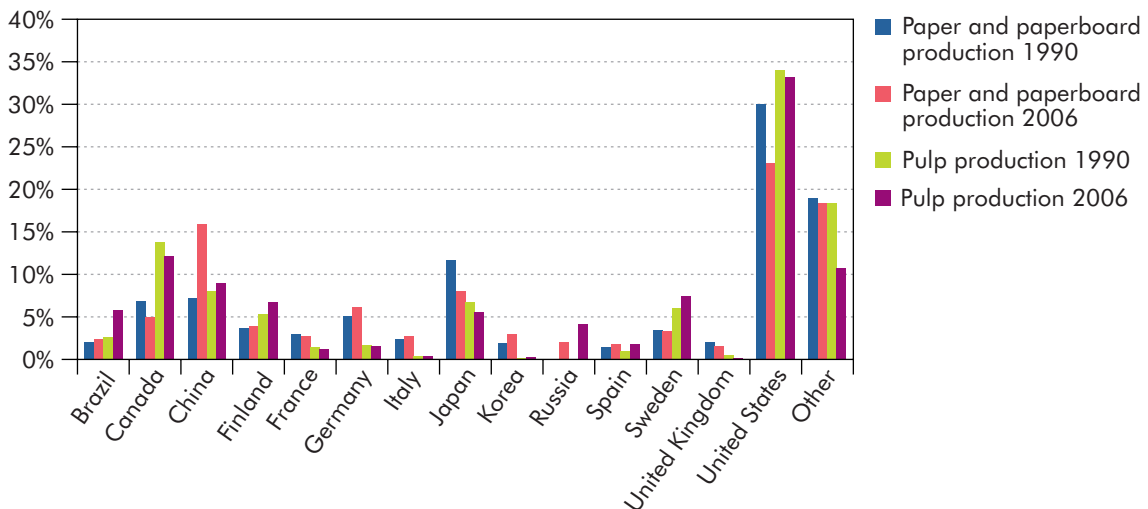
Introduction

The pulp and paper sector is the fourth-largest industrial sector in terms of energy use, consuming 6.7 EJ of energy in 2006, 6% of total global industrial energy consumption. The primary input for pulp and paper manufacture is wood. The industry, therefore, usually has ready access to biomass resources, and it generates from biomass approximately half of all its own energy needs. It also produces energy as a by-product. The majority of the fuel used in pulp and paper-making is used to produce heat and just over a quarter to generate electricity.

The large share of biomass use as fuel makes the sector one of the least CO₂-intensive, although large variations exist between different countries depending on biomass availability and industry structure.¹ The sector emitted 184 Mt of CO₂ in 2006, representing only 3% of direct emissions from industry.

Global paper and paperboard production has grown by more than 50% since 1990, totalling 365 Mt in 2006. The global paper industry is highly concentrated in the United States, China, Japan, Germany and Canada, which together accounted for 58% of total paper production in 2006. The strongest growth has occurred in China, which now produces 16% of all paper, as compared with 7% in 1990. Figure 5.1 shows the shifts in global paper and paperboard production with falling shares in the United States, Japan and Canada, being offset by rising production in China. The European paper industry seems to have fared better than its Japanese and North American counterparts with shares remaining relatively flat across most European countries.

Figure 5.1 ▶ Global paper and pulp production, 1990 and 2006



Source: FAO data.

Key point

China dominates growth in paper and paperboard production.

1. The combustion of biomass is considered carbon-neutral.

As recovered paper use has increased, pulp production since 1990 has grown less quickly than paper and paperboard production. Pulp production was 194 Mt in 2006, 17% higher than in 1990. In the same period, recovered paper collection more than doubled from 84 Mt in 1990 to 195 Mt in 2006. The six largest pulp-producing countries, the United States, Canada, China, Finland, Sweden and Brazil produced just under 70% of the world's pulp in 2006.

Brazil increased its pulp production share the most of all countries between 1990 and 2006, doubling from 3% to 6%. In the same period, Canada and the United States decreased the most. Although China's production of paper and paperboard tripled, its pulp production grew by only 30% because of limited wood resources. In Europe, investments in technology, new capacity and upgrades helped the European pulp sector increase its global market share from 19% to 22%.

Future growth is expected to follow a similar pattern with growth in paper and paperboard production continuing to be strongest in China as a result of continuing growth in consumption. Shares of pulp and paper and paperboard production are likely to continue to decline in Canada and the United States where relatively older capital stock has made the industry less competitive than in South America, Europe and Asia. In the United States, policies such as the renewable fuel mandate and the renewable electricity portfolio mandates will also increase demand for wood, which will lead to higher biomass prices. With significantly newer and more efficient mills, the European pulp and paper sector has been able to compete globally, but as uncertainties around the EU Emissions Trading Scheme and incentives for renewable energy push up the price of biomass, this may not be sustained.

Pulp and paper processes

Energy is used in the pulp and paper industry in a number of different production processes. The main processes are:

- chemical pulping;
- mechanical pulping;
- paper recycling; and
- paper production.

The main production facilities are either pulp mills or integrated paper and pulp mills, depending on proximity to markets and transportation facilities. An integrated mill is more energy-efficient than the combination of a stand-alone pulp mill and paper mill because pulp drying can be avoided. But integrated plants require grid electricity as well as additional fuel.

High-yield mechanical pulping processes are electricity-intensive, and there has been relatively little progress in reducing electricity demand in mechanical pulping so far. Most of the energy efficiency improvement that has been achieved has come from integrated mechanical, chemical, recycled pulp and paper mills where recovered heat can be used in chemical pulp and paper-making processes, for example to dry the paper. Investment in heat recovery systems in stand-alone mechanical pulp mills is not economically viable.

Chemical pulping yields black liquor as a by-product, which can then be processed in a recovery boiler to produce heat and electricity. Roughly 22 GJ of black liquor can be combusted per tonne of pulp. Large modern chemical pulp mills are more than self-sufficient in energy terms, delivering surplus electricity to the grid.

Recovered paper

The production of recovered paper pulp uses 10 GJ to 13 GJ less energy per tonne than the production of virgin pulp, depending on whether the recovered paper is de-inked and whether mechanical or chemical pulp is being replaced. Although less energy-intensive, the production of recovered paper pulp is generally more CO₂-intensive, as the production of chemical pulp, by using biomass for energy, is CO₂-neutral. In many cases, the energy used for the production of recovered paper pulp comes from fossil fuels. As a result, higher levels of recovered paper utilisation can significantly reduce energy intensity in the sector, but at the cost of higher CO₂ emissions.

Current levels of paper recycling are already high in many countries. They vary from 30% in the Russian Federation to 70% in Japan. Recycling rates can be increased in most regions, especially in many non-OECD countries where the recovery rate varies from 10% to 50%. Recovered paper usage in these countries is significantly higher than the recovery rate as a result of the import of large quantities of recovered paper from OECD countries. The upper technical limit to waste paper collection is 81% (CEPI, 2006), but practically the upper limit may be closer to 60%.

Trends in energy efficiency and CO₂ emissions

The IEA's indicators analysis for the pulp and paper sector aims to provide a comparison of trends in energy efficiency across the main pulp and paper-producing countries. Ideally these indicators would be developed at a product level, but this is not possible given the absence of data on energy use for specific products. So aggregate product indicators are used to assess heat consumption, electricity consumption and CO₂ emissions per tonne of pulp exported and paper produced. These energy efficiency indicators compare the actual fuel or electricity consumption for paper and pulp production in each country from IEA statistics with the fuel or electricity which would have been used with best available technology (BAT).

Energy efficiency index methodology

An energy efficiency improvement potential index which assesses current performance against BAT has been developed. Using IEA energy statistics for final energy use,² a BAT value is derived for each mechanical pulp, chemical pulp,³ recovered paper

2. As IEA statistics also include printing, an adjustment is made to remove energy use for printing on the basis of available energy data from national sources, or estimated by comparing countries with similar industry structure.

3. A reduction of 2.5 GJ is applied in integrated chemical pulp to reflect the reduced heat requirement for drying pulp.

pulp, de-inked recovered paper pulp and seven different paper grades. Multiplying production volumes by this BAT value gives a figure representing the practical minimum energy use. By dividing this figure by actual energy use (final energy), an energy efficiency index (EEI) is derived, from which the potential for improvement (the extent to which the index falls short of 100) can be calculated.

The European Commission (EC) BAT reference document was the main source for the BAT figures set out in Table 5.1.⁴ While specific countries may have their own national figures for BAT, the EC document is an internationally recognised and widely used BAT reference document. Heat and electricity are treated separately to allow for CHP analysis.

Table 5.1 ► Best available technology

	Heat (GJ/t)	Electricity (GJ electricity/t)
Mechanical pulping		7.5
Chemical pulping	12.25	2.08
Integrated chemical pulping	9.75	2.08
Dissolving wood pulp	17.00	2.10
Recovered paper pulp	0.20	0.50
De-inked recovered paper pulp	1.00	2.00
Coated papers	5.25	2.34
Folding boxboard	5.13	2.88
Household and sanitary paper	5.13	3.60
Newsprint	3.78	2.16
Printing and writing paper	5.25	1.80
Wrapping and packaging paper and board	4.32	1.80
Paper and paperboard not elsewhere specified	4.88	2.88

Sources: EC (2001); Finnish Forestry Industries Federation (2002); Jochem *et al.* (2004).

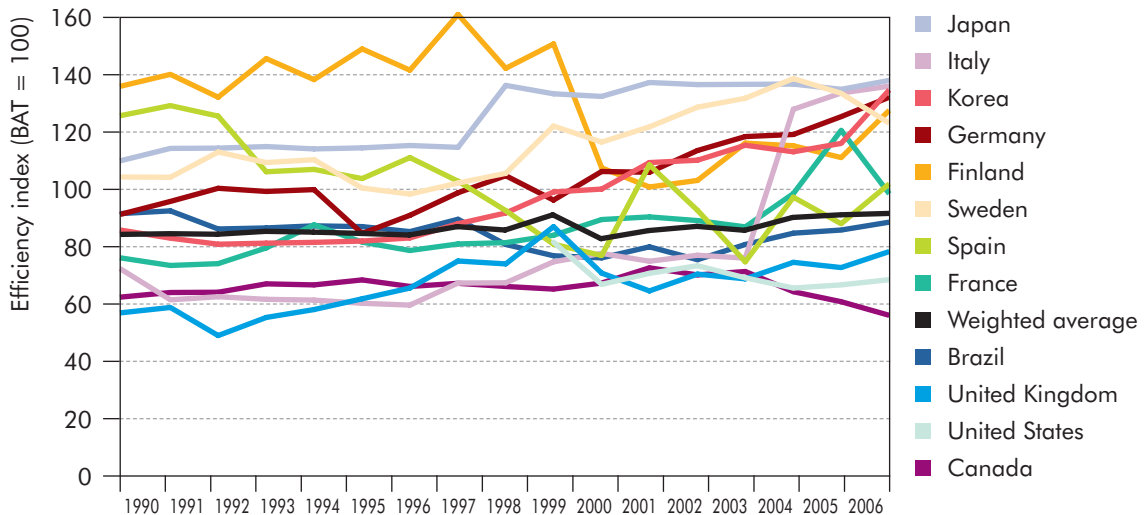
Multiplying the BAT figures with the quantities of mechanical pulp, chemical pulp, waste paper pulp and paper and paperboard produced by each country yields the total heat and electricity consumption that would be expected if all that country's production were based on BAT. This is then compared to the total energy used for these processes from IEA statistics. Figures for heat (steam) demand in each country are estimated on the basis of reported fuel consumption in the industry and assume 80% efficiency for all fuels except for biomass where 70% efficiency is applied.

4. In the EC BAT reference document, also known as IPPC BREF document, a range was often given to reflect an assessment of costs versus benefits and, thus, could also be considered as best practice. Where a range was given, a comparison was made with other papers to determine a suitable BAT value.

This updated analysis also seeks to factor in the different levels of integrated and non-integrated mills in each country. The energy efficiency of integrated pulp and paper mills is approximately 10% to 40% better, depending on the grade of paper produced, than that of stand-alone mills. In a stand-alone chemical pulp mill, a significant amount of heat (approximately 2.5 GJ) is required to dry the pulp before transport, and greater use of heat recovery systems can be exploited by integrated mills versus stand-alone ones.

A country's energy efficiency index (EEI) would be 100 if the energy used was the same as that which it would use if it adopted exclusively BAT. Values below 100 indicate that energy consumption is higher than BAT levels and signify an opportunity for greater energy efficiency. Figures above 100 could mean that the BAT figures are too conservative or that they give insufficient credit for the relatively high efficiency levels of integrated mills. They might also result from accounting inconsistencies between countries. Countries with more modern pulp and paper mills should normally have an EEI close to 100, while those with older facilities would be expected to have significantly lower EEI.

Figure 5.2 ► Heat efficiency potentials



Note: In 1998 METI (Japan) made significant changes in the way it accounted for energy use in the pulp and paper sector. As a result, Japanese data are no longer consistent with other countries. In Finland, changes of ownership of CHP units appear to have resulted in a change in reporting, which has reduced the allocation of fuel use to pulp and paper. In Canada all biomass used in industry is reported under the pulp, paper and print sector, leading to a significant over-reporting of energy use. This explains Canada's larger than average improvement potential in the figure above.

Source: IEA statistics and analysis.

Key point

The energy efficiency index for heat use shows the largest opportunities for savings in Canada and the United States.

The results of this analysis (Figure 5.2) show that the heat used in pulp and paper production varies widely between countries. Although data for Canada and the United States appear to show significant potential to improve energy efficiency through the application of BAT, the fact that Japan, Korea, Finland, Sweden,

Germany and Italy show performances above BAT levels suggests a need for improvement in the underlying energy data and/or a revision of the BAT values used in the analysis.

Data issues

The quality of the energy data has made it very difficult to develop reliable indicators for this sector. Although the potentials shown in Figure 5.2 offer an indicative view of trends of the efficiency improvement potentials in the sector in each country, the country-by-country comparison of the energy improvement potentials is only valid if the system boundaries of the data collected are identical for all countries. It is clear from the numerous breaks in data, and from further investigation of the energy data, that countries are not reporting under a consistent methodology. More needs to be done in terms of data collection by both industry and governments to develop a set of indicators, which can be used for effective policy making.

Box 5.1 ► Energy statistics in the pulp and paper sector

On 23 January 2009, the IEA Secretariat held a workshop with representatives from national and regional industry associations and national energy and statistics agencies to discuss ways of improving energy statistics in the pulp and paper sector. This meeting included representatives from Canada, Finland, Japan, Sweden and the United States. The IEA indicators analysis for the sector has raised a number of issues related to the consistency and comparability of energy statistics between countries. The workshop identified a number of significant differences in national reporting methodologies. It discussed possible approaches to improving the consistency of reporting for the sector which could also be applied to other countries.

International Council of the Forests and Paper Associations (ICFPA) members,⁵ have undertaken a self-assessment of the energy data collected by their industry associations and have found that surveys are comparable and similar. Differences, however, exist in terms of coverage, frequency, detail and units of measurement. More attention also needs to be given to the quality of the data provided by industry to statistical offices.

Important discrepancies exist between IEA statistics and industry data sources and definitions. The measurement of CHP, where energy statistics define and model electricity production on site in the electricity sector rather than in the pulp and paper sector, raises particular issues. Significant differences also exist in energy reporting at the national level, especially in the reporting of biomass use. Additional effort is needed by both industry and national statistics agencies to improve data consistency. The IEA will continue to refine its indicators methodology as additional data become available. Data availability and consistency need to be improved and the indicators need to be further developed before they can be used as the basis for establishing policies.

5. ICFPA members involved in the self assessment include the Confederation of European Paper Industries (CEPI), Forest Products Association of Canada (FPAC), Japan Paper Association (JPA) and American Forest and Paper Association (AF&PA).

As well over 50% of the energy used in the sector comes from biomass, it is particularly important to develop a consistent methodology for biomass reporting. Greater consistency in CHP accounting is also needed. In the latest statistics submitted to the IEA, a number of countries have revised their biomass use in the sector downwards compared to earlier submissions. Table 5.2 shows the reported use of biomass in the sector in aggregate and for chemical pulp production, alongside data for biomass used in other non-specified industries. Some countries, including Germany and China, report no biomass use despite the fact that they report producing chemical pulp. The data suggest that, as appears to be the case for Germany, the biomass used in pulp, paper and print production is often allocated to other non-specified industries. The wide range in the ratio of biomass use per tonne of chemical pulp produced suggests a need for additional analysis on biomass reporting across countries. The IEA is working closely with industry and national statistics offices to improve the consistency and comparability of the energy statistics in the pulp and paper sector.

Table 5.2 ► Analysis of reported biomass use in 2006

	Biomass/t chemical pulp ¹ (GJ)	Chemical pulp production (Mt)	Biomass pulp and paper (PJ)	Share of biomass in fuel use (%)	Biomass other non-specified industries (PJ)
Brazil	21.8	10.7	231.8	83%	17.24
Canada	30.2	11.6	350.5	73%	0.00
China	0.0	1.8	0.0	0%	0.00
Finland	16.4	7.9	130.0	74%	0.43
France	15.8	1.5	24.4	28%	0.00
Germany	0.0	1.5	0.0	0%	24.53
Japan	10.6	9.6	101.4	41%	0.00
Korea	11.2	0.4	4.8	9%	0.75
Russia	0.0	5.2	0.1	0%	0.11
Spain	10.1	1.9	19.3	27%	2.65
Sweden	17.3	8.3	143.8	86%	0.74
US	19.2	47.0	903.5	50%	48.42
World	16.1	129.8	2 094.2	46%	1 924.18

Source: IEA statistics and FAO.

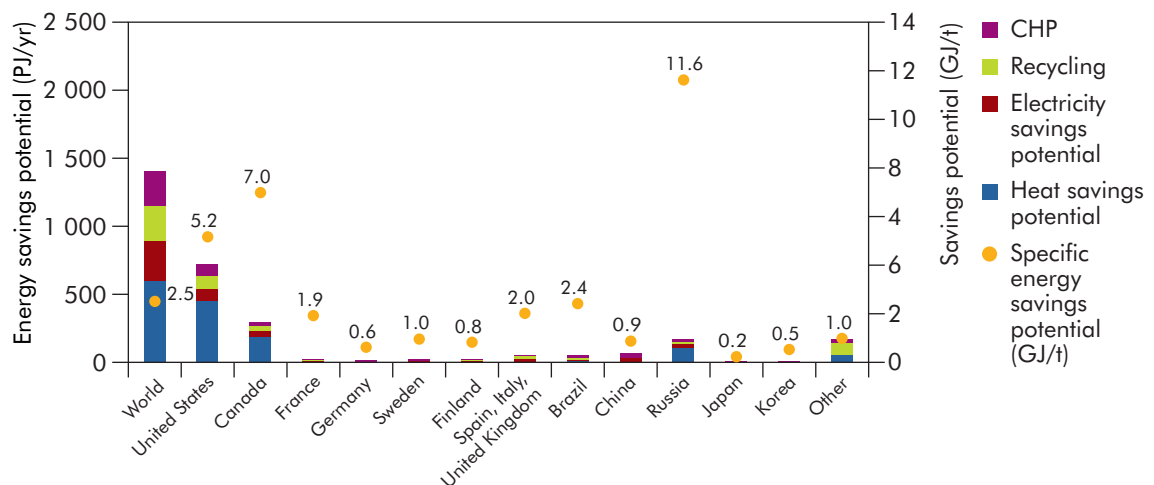
1. This ratio is calculated by dividing the chemical pulp production by the reported biomass use in the pulp, paper and print sector in IEA statistics.

Best available technology and technical savings potentials

The EEI can be used to assess the energy savings that could be achieved from the application of BAT, from increasing the use of CHP and from improving recycling rates. Although given the data quality issues described above the indicators need to be used cautiously, analysis suggests a global potential for 10% heat efficiencies and 11% electricity efficiencies, equivalent to 600 PJ of heat and 300 PJ of electricity. If global recycling was increased to 60% (the current EU level) another 250 PJ of energy could be saved. Higher CHP use could achieve an additional saving of approximately 250 PJ. Total savings for the sector are estimated at approximately 1 400 PJ or 20% of total current energy use.

The estimates are theoretical potentials. They do not take into consideration the age profile of the existing capital stock, or regional differences in energy prices and regulations, such as for CHP the existence of regulatory frameworks which facilitate the sale of surplus electricity to the grid. These local factors may limit the ability of countries to realise improvement options in the short- and medium-term. The analysis does not also consider process economics. So the economic potential will be substantially lower than the theoretical potential. But changing market conditions and values for CO₂ could affect the process economics significantly. The theoretical potential is, therefore, a useful indicator of what might be aimed for in individual countries and the scope for improvements in energy efficiency.

Figure 5.3 ► Energy savings potentials in 2006, based on best available technology



Note: The potential shown for China is significantly understated as a result of substantial underreporting in national energy statistics for the sector. Many small pulp and paper mills are not included in national accounts. The IEA assess that actual energy consumption could be 30% to 50% higher than is reported.

Source: IEA analysis.

Key point

The global technical potential for energy savings is estimated at 1.4 EJ with the largest savings potential seen in Canada and the United States.

Table 5.3 ► Energy efficiency technologies: energy savings, cost and CO₂ reductions

	Fuel savings (GJ/t)	Electricity savings (GJ/t)	Primary energy savings (GJ/t)	Carbon emissions reduced (kgC/t)	Cost of conserved energy (USD/GJ)	Cost of measure (USD/t)
Pulping: mechanical						
Refiner improvements	0	0.81	1.63	0.2	3.05	7.7
Biopulping	-0.5	2.04	3.41	0.78	5.16	27
Pulping: thermomechanical (TMP)						
Heat recovery in TMP	6.05	-0.54	7.52	0.27	3.27	21
Improvements in Chemi-TMP	0	1.1	2.23	0.25	na	300
Pulping: chemical						
Continuous digesters	6.3	-0.27	8.4	7.21	7.02	196
Continuous digester modifications	0.97	0	1.39	2.63	0.39	1.3
Batch digester modifications	3.2	0	4.55	2.59	0.55	6.6
Chemical recovery						
Falling film black liquor evaporation	0.8	0.001	1.14	1.95	23.81	90
Lime kiln modifications	0.46	0	0.46	1.01	1.63	2.5
Papermaking						
High consistency forming	1.5	0.15	2.43	3.11	8.97	70
Extended nip press (shoe press)	1.6	0	2.28	5.76	5.96	70
Reduced air requirements	0.76	0.02	1.12	3.01	2.61	9.5
Waste heat recovery	0.5	0	0.71	1.35	9.77	17.6
Condebelt drying	1.6	0.07	2.46	8.37	3.5	28.2
Dry sheet forming	5	-0.75	5.59	3.18	81.07	1504
General measures						
Efficiency motor systems	0	0.62	1.25	19.57	1.55	6
Pinch analysis	1.79	0	2.54	3.22	0.95	8
Efficient steam production and distribution						
Boiler maintenance	1.26	0	1.79	2.26	0.04	0
Improved process control	0.54	0	0.76	2.41	0.04	0.4
Flue gas heat recovery	0.25	0	0.36	1.13	0.29	0.7
Blowdown steam recovery	0.23	0	0.33	0.86	0.82	0.8
Steam trap maintenance	1.79	0	2.54	8.04	1.1	1.2
Automatic steam trap monitoring	0.89	0	1.27	4.02	0.19	1.2

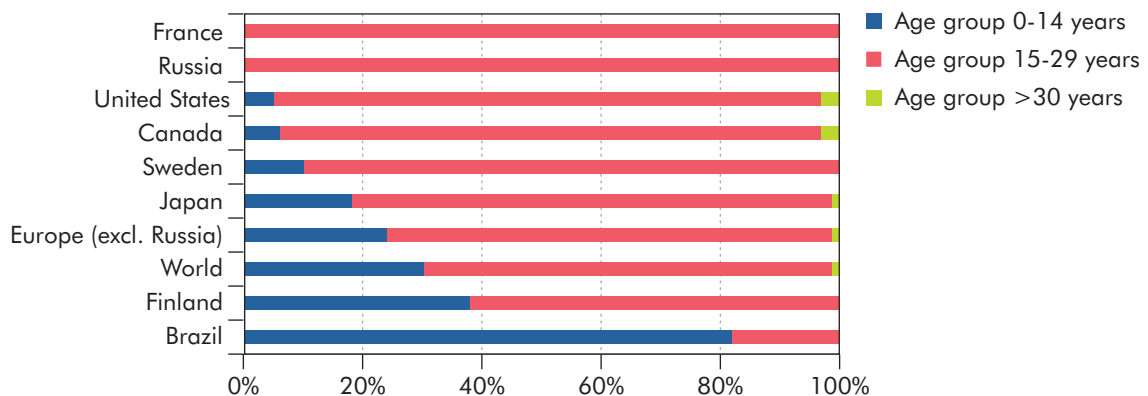
Source: Martin et al. (2001)

The rate at which a country can, in practice, move towards the theoretical BAT level will depend on its rate of investment in new technologies, *i.e.* the rate at which new or replacement BAT plants are brought on stream or at which a range of energy efficiency options are retrofitted, either at the end of the economic life of a component of the mill, or when major refurbishment is required. Table 5.3 outlines these options, their potential and costs. Figures were prepared for the United States market: different national circumstances could give rise to different figures.

Age of the capital stock and transition to BAT

To better understand the economic opportunity for upgrading or replacing older, less efficient technologies with BAT, additional data have been collected on the age of the capital stock in the sector in a number of countries. Figures 5.4 and 5.5 show the age distribution for pulp mills and paper mills respectively. Only five countries have pulp mills more than 30 years old and these older mills represent 3% or less of their capacity. All countries have some paper mills over 30 years old.

Figure 5.4 ► Age distribution of pulp mills



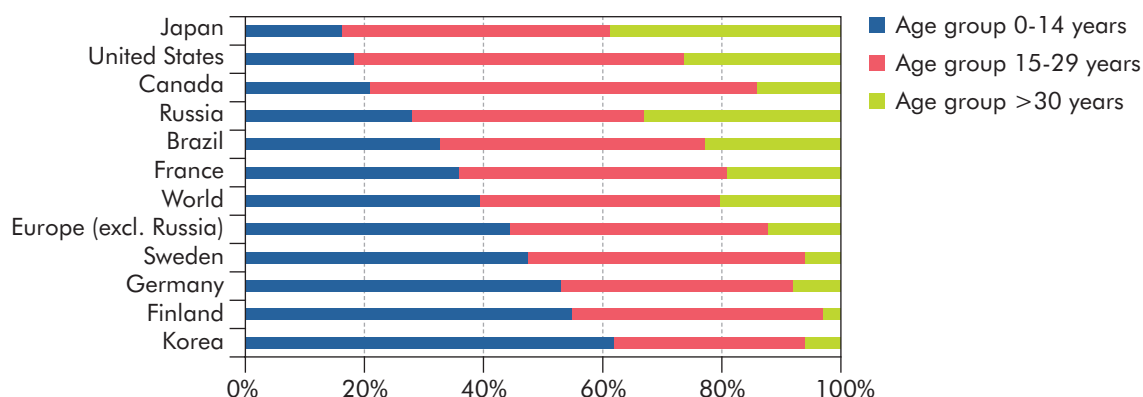
Source: Poyry data.

Key point

The age of pulp mills varies from country to country, with the newest mills located in Brazil and Finland.

Canada, the United States and Russia have the largest share of older pulp and paper mills. Brazil and Finland have the largest share of newer facilities. The EEI for heat use shown in Figure 5.2 are consistent with this indicator of capital stock age: countries with older facilities show greater efficiency improvement potentials than countries with newer capital stock whose improvement potential is limited.⁶ Additional analysis on the age of boilers is needed to better understand the potentials of emerging efficiency technologies which focus on boiler replacements.

6. New paper machines are not always more energy-efficient than older ones. New machines are often larger and heavier, which may result in higher energy intensity.

Figure 5.5 ▶ Age distribution of paper mills

Source: Poyry data.

Key point

The age of paper mills is relatively younger than pulp mills, with Korea and Finland having the largest share of new mills.

Scenario analysis

The IEA scenario analysis compares expected outcomes on energy use and CO₂ emissions for the sector in the Baseline scenarios with those in the BLUE scenarios where global emissions will fall to half of those of 2006 by 2050. The emissions reductions are based on the assumption that there will be an incentive to implement all technology options with a cost of up to USD 200/t CO₂ saved. In addition to the CO₂ incentive, significant policy changes will also be needed.

Table 5.4 ▶ Paper and paperboard demand projections for 2005, 2015, 2030 and 2050

	2006	2015	2030	2050	2015	2030	2050
	Low demand				High demand		
	(kg/cap)	(kg/cap)	(kg/cap)	(kg/cap)	(kg/cap)	(kg/cap)	(kg/cap)
Canada	218	215	215	215	220	225	230
United States	304	300	280	270	305	285	275
Europe	172	180	180	180	190	195	195
Russia	42	79	100	125	93	160	180
China	46	75	100	125	95	150	178
India	5	10	16	30	10	21	42
OECD Pacific	219	225	225	225	245	255	263
Latin America	43	53	66	85	60	80	115
Other developing Asia	16	23	30	40	24	38	55
Other	10	15	21	30	18	28	45
World	55	64	69	75	70	86	101

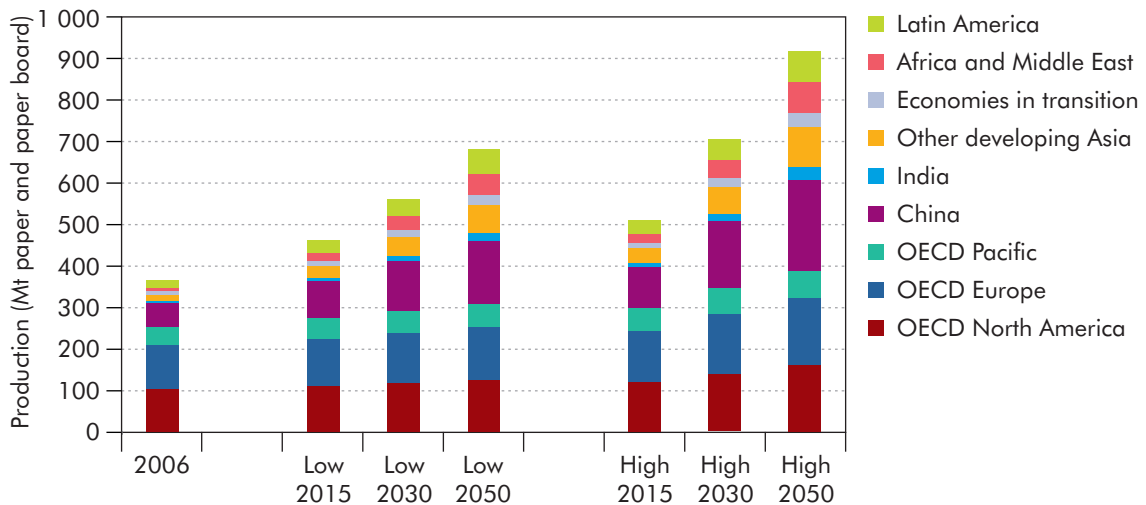
Sources: FAO statistics and IEA estimates.

Estimates of future demand for global paper and paperboard consumption are based on assumptions of per-capita demand in different regions of the world. Given high levels of uncertainty in future consumption patterns, the analysis is based on two separate cases, one representing low-demand assumptions, the other high-demand assumptions. Table 5.4 shows the estimated per-capita and total consumption figures for different countries and regions under both the low- and high-demand cases.

Under the high-demand case, paper and paperboard consumption patterns in developing countries move closer to those of OECD countries where a small increase in per-capita consumption is assumed, to reflect increases in per-capita GDP.

In the low-demand case, the global drive for sustainable development is assumed to have a greater impact on consumption patterns worldwide. Growth in paper and paperboard consumption in developing countries is assumed to rise at a slower rate than under the high-demand case. In OECD countries, growth is assumed to remain relatively flat. World paper production is estimated to reach almost 700 Mt by 2050 in the low-demand case and over 900 Mt in the high-demand case (see Figure 5.6).

Figure 5.6 ► Regional paper and paperboard production, 2006 to 2050



Sources: FAO statistics and IEA analysis.

Key point

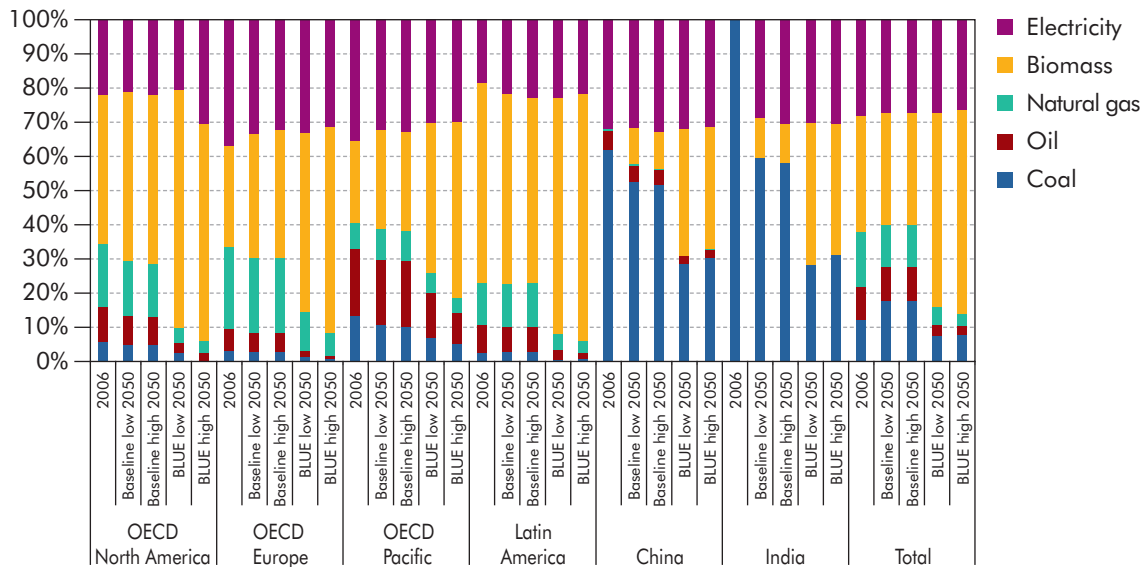
Future paper production will be dominated by China and other non-OECD regions.

Paper and paperboard consumption is assumed to continue to grow strongest in non-OECD countries, especially in Asia where demand from China is expected to quadruple under the high-demand case from current levels by 2050. As a consequence, the share of paper and paperboard consumption shifts significantly from OECD to non-OECD countries with the share from OECD countries falling from 65% today to between 35% and 40% by 2050. Consumption in China and India could match that of all OECD countries by 2050 in the high-demand case.

Demand growth is expected to be highest for packaging, printing and writing papers. The share of newsprint is expected to continue to decline as digital information continues to displace print media. Future pulp production will follow the trends in paper and paperboard production with strong growth expected in the demand for chemical pulp and lower growth for mechanical pulp as the share of newsprint declines. Recent and future forest plantations in China will help provide most of the needed pulpwood resources for strong chemical pulp demand, but a shortfall is still expected. This will be met by imports of market pulp from Brazil, Russia and Indonesia. China's policy to reduce the production of non-wood pulp, which is more energy- and CO₂-intensive, will limit the growth of non-wood pulp globally. The market share of non-wood pulp is expected to fall from 11% today to just 5% in 2050.

Recovered paper utilisation today is already relatively high with a global recycling rate of 54%. Many countries are already at or near their practical limits. But others, especially developing countries, have relatively low levels so that some growth can be expected in the future. In the Baseline scenarios, recovered paper utilisation is expected to reach 55% in 2050, while in the BLUE scenarios these levels are assumed to grow further, to 61%.

Figure 5.7 ► Energy use by fuel and region in 2006 and 2050 by scenario



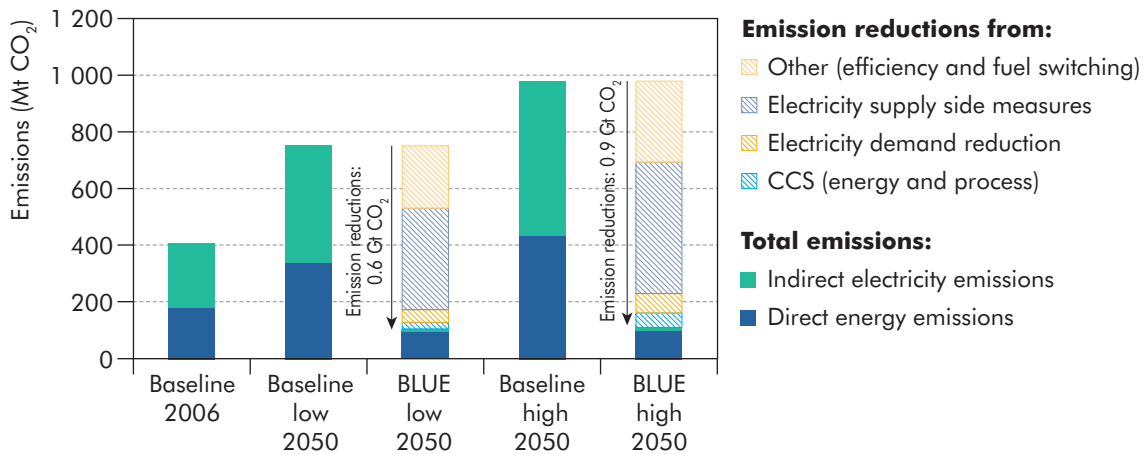
Key point

All regions will show a sharp increase in biomass use in the BLUE 2050 scenarios.

Energy use in the pulp and paper sector is expected to rise from 6.7 EJ in 2006 to 11.1 EJ in 2050 in the Baseline low-demand scenario. Under the BLUE low-demand scenario, energy use will reach 9.6 EJ in 2050, 14% less than in the Baseline scenario as higher energy efficiency reduces energy intensity.

Biomass today represents 32% of total energy use and this is expected to rise to approximately 60% in 2050 in both the BLUE low and high-demand scenarios as fuel switching takes place to reduce emissions. Electricity consumption in the sector in 2050 is expected to rise from 1.8 EJ in 2006 to 2.9 EJ to 3.8 EJ in the Baseline scenarios and to 2.6 EJ to 3.3 EJ in the BLUE scenarios. In all regions the share of fossil fuels will need to fall significantly to achieve the BLUE scenario outcomes, although fossil fuels will still represent a large share of total fuel use in China and India.

Figure 5.8 ► CO₂ emissions by scenario, 2006 and 2050



Key point

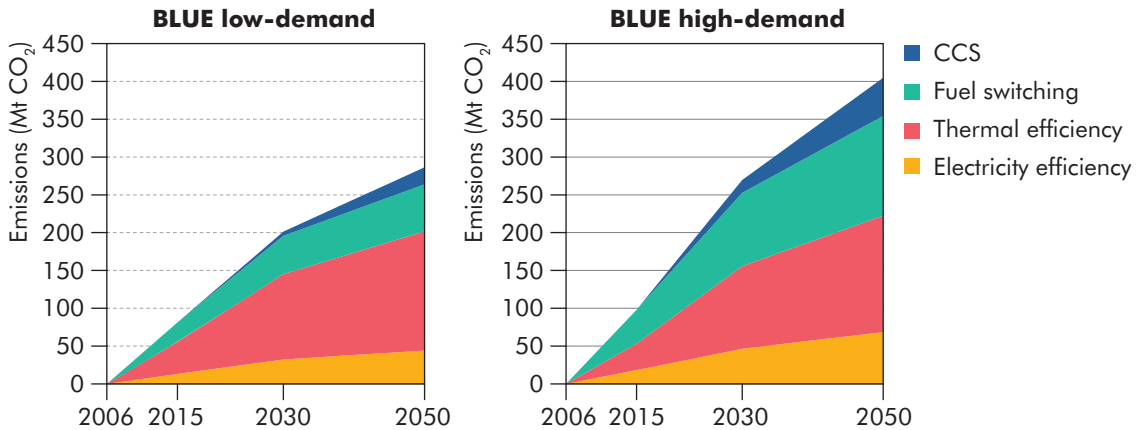
CO₂ emissions will fall sharply in the BLUE 2050 scenarios due to a combination of energy efficiency, fuel switching, the decarbonisation of the power sector and CCS.

In the BLUE scenarios, as CO₂ capture is added to black liquor gasifiers, in some regions the sector becomes a CO₂ sink, contributing a gross reduction in global emissions. Total direct and indirect emissions in the BLUE scenarios will fall by 74% from 410 Mt CO₂ in 2006 to about 110 Mt CO₂ in 2050. The decrease in direct energy emissions is somewhat less at 46%, reflecting the importance of a near-decarbonised power sector on emissions in this sector. More than half of all emissions reductions in the BLUE scenarios will come from improving the energy efficiency and an additional 22% to 33% will come from fuel switching. It is assumed that the majority of all old⁷ black liquor boilers are replaced with gasifiers by 2050 and that CCS is deployed in 2030. By 2050 it is assumed that one-third of all CO₂ emitted from black liquor gasification will be captured and stored. The use of CCS generates additional demand for electricity for CO₂ capture and pressurisation.

7. High temperature and pressure boilers, which are common in Japan, already have high energy efficiency and hence are excluded from the category of old boilers.

Figure 5.9 shows the source of emissions reductions in 2050 in the BLUE scenarios compared to the equivalent Baseline scenarios. Energy efficiency plays the most important role in reducing emissions and accounts for 70% and 55% of the emissions reduction in the BLUE scenarios. Fuel switching represents 22% of the savings in the low-demand scenario, and 33% in the high-demand scenario. By 2050, total emissions reductions in the sector reach close to 300 Mt CO₂ in the low-demand scenario and 400 Mt CO₂ in the high-demand scenario. CCS, which is a later option for the sector, will begin to have an impact by 2030 and will account for 8% of the reductions in the BLUE low and 13% in the BLUE high-demand scenario.

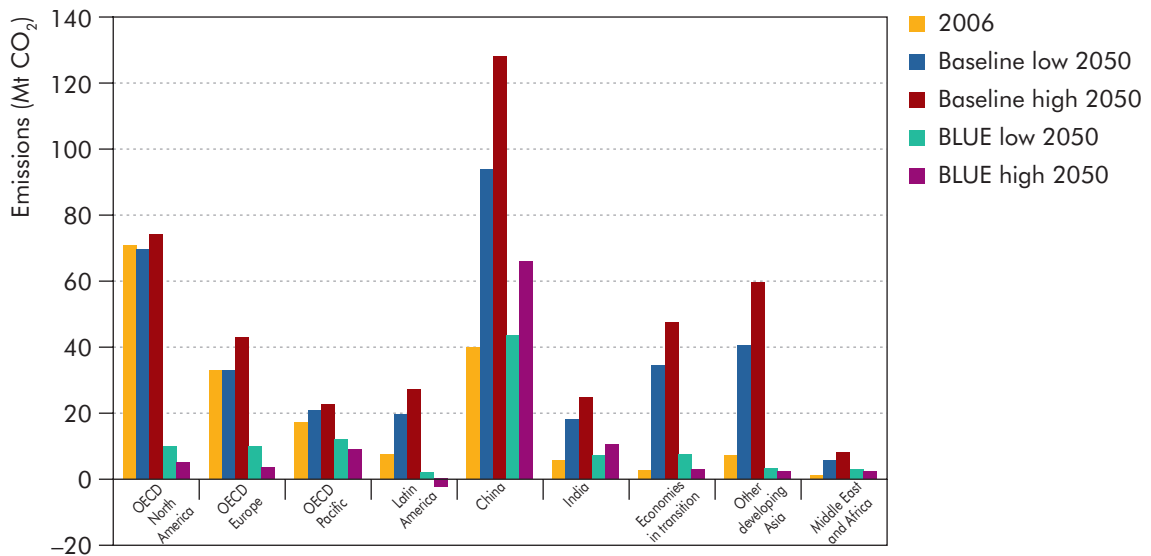
Figure 5.9 ► CO₂ emission reductions below Baseline scenario, 2006 to 2050



Key point

Energy efficiency will represent the largest contribution to CO₂ savings in the pulp and paper sector.

Figure 5.10 ► Direct CO₂ emissions by region and by scenario, 2006 and 2050



Key point

All regions will show significant emissions reduction in the BLUE 2050 scenarios compared to Baseline.

Achieving a global direct emissions reduction of 45% in the pulp and paper sector in the BLUE scenarios requires different levels of reduction in different regions. Canada and the United States, where there is scope for the greatest energy efficiency improvement, will need to make the largest contribution. In the United States, fuel switching will also be important. Europe also will need to make significant emissions reductions in the sector. This can be achieved through a combination of fuel switching and CCS. Emissions in China will see the largest increase as high growth in demand will lead emissions to rise, although the CO₂ intensity will fall as more wood-based biomass is used.

Costs of CO₂ reduction in the pulp and paper sector

The economics of individual technology options depend on fossil fuel and electricity prices, specific regional investment and operating costs, and capital costs. Japan, for example, has a low discount rate and high fuel prices. By contrast, countries such as Brazil and Russia have low energy prices and high capital costs as investors demand a risk premium to compensate for a perceived lack of long-term stability and fluctuating economic conditions. These different circumstances lead to individual technologies being brought forward at different rates in different countries.

A distinction also needs to be made between investments in new plants, either in the form of new capacity or of plants that need replacement because they have reached the end of their technical life, and investment in the retrofit of existing capacity. Retrofit is more expensive and often less efficient than new build. The costs of these options can vary significantly.

Table 5.5 provides a breakdown of the investment needs for the Baseline and BLUE scenarios. Total investments in the Baseline scenarios amount to between

Table 5.5 ► Investment needs for pulp and paper making, 2010 to 2050

	Capacity 2050		Investment		Total investment	
	Baseline (Mt)	Blue (Mt)	Cost (USD/t)	Multiplier	Baseline (USD bn)	Blue (USD bn)
Market kraft pulp mills	48 to 50	35 to 27	1495	1.5 to 2	108 to 112	106 to 111
TMP mill	28 to 30	27 to 35	300	1.5	13 to 14	12 to 16
Deinked recovered paper plants	128 to 155	154 to 183	730	1.5	140 to 169	169 to 200
Recovered paper plants	128 to 155	154 to 183	550	1.5	106 to 127	127 to 151
Stand alone paper mills	199 to 227	199 to 227	1 200	1.5 to 1.75	358 to 408	418 to 476
Integrated chemical pulp and paper mills	161 to 168	118 to 124	2 000	1.5 to 2	482 to 503	474 to 497
Additional cost for black liquor gasification	139 to 143	219 to 225	60	1.5 to 2	13 to 14	26 to 27
Additional cost for biomass gasification with syngas production	35 to 36	73 to 75	70	1.5 to 2	4	10 to 11
Total					1 223 to 1 350	1 343 to 1 487

Sources: IEA estimates.

USD 1.2 trillion and USD 1.35 trillion for the period between now and 2050. In the BLUE scenarios, the additional investment costs over Baseline investments are USD 120 billion in the low-demand scenario and nearly USD 140 billion in the high-demand scenario.

New technology options

Technology could play an important role in increasing energy efficiency and reducing CO₂ emissions in the pulp and paper industry. Current facilities in many OECD countries are nearing the end of their operating life and will need to be replaced over the next 10 to 15 years. This offers an excellent opportunity for new technology to have an impact on energy savings in the sector in the medium term. The most promising energy-saving technologies in the industry are black liquor gasification, advanced drying technologies and biorefineries.

Black liquor gasification

The pulp and paper sector produces large amounts of black liquor as a by-product of chemical pulp production. In 2006, the combustion of black liquor produced an estimated 2.6 EJ of energy and is expected to reach between 4.0 EJ and 6.0 EJ by 2050. The efficiency of current black liquor boilers is low and could be increased significantly through the use of gasification. In gasification, hydrocarbons react to syngas, a mixture mainly of carbon monoxide and hydrogen. The syngas can be used in gas-turbine power generation or as a chemical feedstock. This technology, called black liquor integrated gasification combined cycle (BLIGCC), allows the efficient use of black liquor, and also enables the co-combustion of other biomass fuels such as bark and wood chips. Or the syngas can be used as a feedstock to produce chemicals, in effect turning the paper mill into a “biorefinery”. In Europe, policies aimed at increasing the share of biofuels in transportation have sparked interest in using black liquor gasifiers to produce dimethyl ether (DME) as a replacement for diesel fuel.

The introduction of black liquor gasification would make a mill a net supplier of electricity to the grid, enabling the export of approximately 220 kWh to 335 kWh of electricity per tonne of chemical pulp produced. Assuming that a 10% electricity efficiency improvement could be achieved, 4.0 EJ of black liquor per year could yield an additional 300 PJ to 450 PJ of electricity annually. This represents a primary energy savings potential of 600 PJ to 900 PJ and a CO₂ reduction potential of 80 Mt to 120 Mt per year, depending on whether gas- or coal-fired electricity was displaced.

Further research is needed to increase the reliability of gasifiers. A gasifier with a gas turbine needs to be demonstrated within the next five years if gasification is to replace current standard boiler systems. The capital cost of a BLIGCC system is approximately 60% to 90% higher than that of a standard boiler.

Lignin production from black liquor

The Lignoboost process, which removes lignin from black liquor, allows kraft pulp mills that are currently limited by the size of their recovery boilers to increase production by up to 50%. An estimated 25% to 50% of the lignin can be removed from black liquor through this process. The average Lignoboost installation would produce 50 000 tonnes of lignin per year, equivalent to approximately 32 000 tonnes of fuel oil, *i.e.* three to five times the amount currently used in a typical pulp mill in the northern hemisphere. Lignoboost plants producing well over 100 000 tonnes of lignin per year are considered. (Axegard, 2009)

If the surplus lignin sells for USD 5.5/GJ, assuming costs of USD 3.9/GJ for the additional forest residues required, the sale of surplus lignin would offset all variable costs. If the sale price for the surplus lignin was greater than USD 5.5/GJ, this process would generate additional profits for the mill.

Biomass gasification with syngas production

The co-production of transport fuels through biomass gasification offers an opportunity for integrated pulp and paper mills to produce additional products on site and increase profitability. Both the gasification and synthesis processes produce large amounts of by-product steam or fuel gas, which can be integrated into the energy system of a pulp and paper mill.

The EU Biofuels Directive provides an incentive for producing transport fuels from biomass gasification. The commercialisation of this technology is expected in Finland within the next five years. Biomass gasification is more expensive than black liquor gasification, but as there is less interaction with the pulp mill chemical recovery cycle, there is also a smaller availability risk for the mill. For gasification, the biomass input to the mill would need at least to double, which might require additional investments in infrastructure. This technology option seems most suited for old recovery boilers and in new integrated mills in South America where there is significant potential to increase capacity.

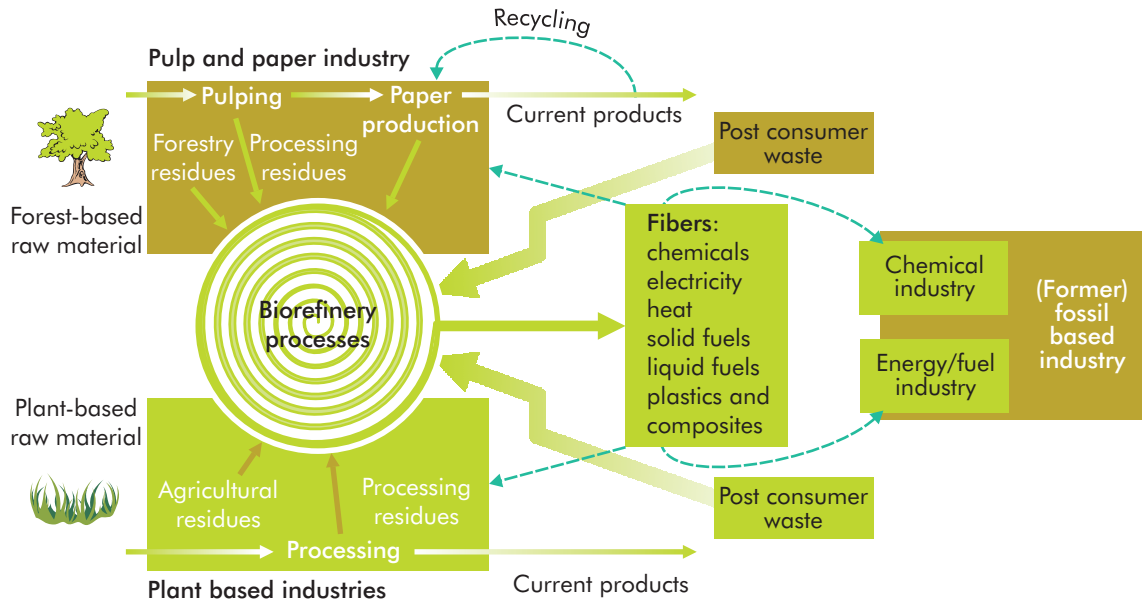
Biorefinery concepts

Competition from developing countries with lower raw material, energy and labour costs, combined with greater environmental constraints, has led the pulp and paper sector in Europe and North America to develop more innovative technologies. These would allow the sector to expand beyond its traditional business to develop existing and new product areas such as electricity, biofuels, chemicals, plastics and composites. Modern chemical pulp mills are already net suppliers of energy. New technologies such as black liquor gasification, biomass gasification and lignin production from black liquor have the potential to provide significant added value to the sector's traditional pulp and paper business.

In Europe, Canada and the United States, the pulp and paper sector is working together with the chemical and energy sectors to develop biorefineries, which aim to provide a wide range of pulp, paper, energy and chemical products from biomass

(see Figure 5.11). Wood, and forestry and agricultural residues will be the primary feedstock for these biorefineries. Biorefinery roadmaps have been developed in Canada, the European Union and the United States.

Figure 5.11 ► Material and product flows for a biorefinery



Source: Forest-Based Sector Technology Platform (2007).

Key point

The pulp and paper sector has the potential to diversify into a wide range of energy and chemical products.

CO₂ capture and storage (CCS)

Black liquor IGCC technology is similar to coal-fired IGCC technology, and similarly capable of being equipped with CO₂ capture. The electric efficiency of a BLIGCC is 28%, which would reduce to 25% with CO₂ capture. The steam efficiency would remain at 44% in both cases. Capital costs would increase by USD 320/kW of electricity if CO₂ capture was installed. Biomass combustion in combination with CCS results in an energy chain that removes CO₂ from the atmosphere, enabling the offsetting of emissions in other parts of the energy system. This may become especially important if ambitious low emission targets are set. Total black liquor production worldwide is around 72 Mtoe, which gives a CCS potential of around 300 Mt of CO₂ per year.

Hektor and Berntsson (2007a) have analysed the use of chemical absorption technology for black liquor boilers and conclude that, in modern pulp mills that generate sufficient surplus heat for the capture process, CCS would be economic at a price of USD 30 to USD 50/t CO₂. They also conclude that, for integrated pulp and paper mills, the most economic configuration would be to power the mill by CCS-fitted natural gas combined cycle (NGCC) plant, allowing the maximum use of by-product biofuels elsewhere (Hektor and Berntsson, 2007b).

Major financial, economic, legal and regulatory barriers will need to be overcome before CCS can be widely deployed. Governments will need to take a leading role in overcoming these barriers, particularly in respect of CO₂ transportation and storage. As CCS builds from demonstration to commercialisation, CO₂ transportation networks will need to be co-ordinated on a regional and national level to optimise infrastructure development and to lower costs.

Paper-drying technologies

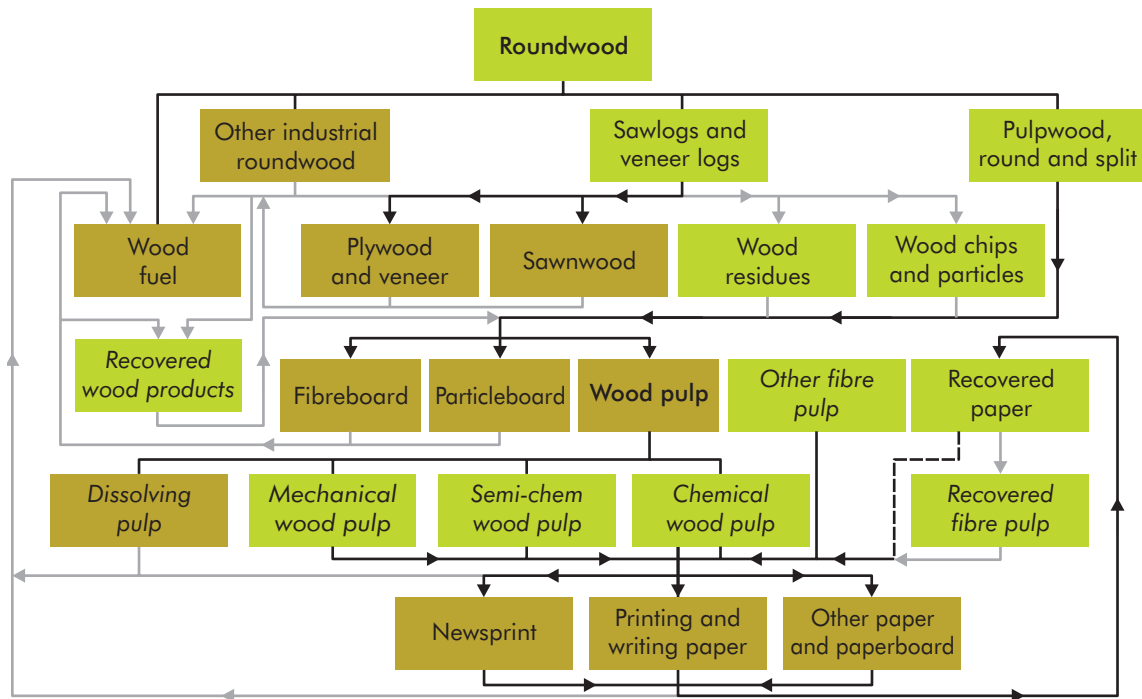
The energy used to dry paper currently accounts for approximately two-thirds of total energy use at a paper mill, equivalent to about 25% to 30% of the total energy used in the pulp and paper industry. New process designs focus on more efficient water-removal techniques, for example by combining new forming technologies with increased pressing and thermal drying. Assuming that a 20% to 30% efficiency improvement is possible at this production stage, overall energy savings are estimated at 400 PJ. The United States Agenda 2020 Technology Alliance's *Forest Products Industry Technology Roadmap* outlines a Breakthrough Manufacturing Technologies Platform, which aims to reduce energy consumed in paper dewatering, pressing, and drying by at least 50% (Agenda 2020 Technology Alliance, 2006).

Reducing water use in paper making would also have significant energy efficiency benefits. Research on technologies for paper making without water should be given higher priority. The use of ethanol or super-critical CO₂ has been suggested to replace water as the forming medium. Other ways of managing the fibre orientation process for optimal paper quality, such as the use of super-critical CO₂ or nanotechnology, may also be possible.

Material flows and demand analysis

Forest products consist of pulp and paper, wood products (logs, wood chips, sawn wood and wood panels) and secondary processed wood products (e.g. furniture). The pulp and paper sector accounted for the largest share of trade in the forest products sector at around 45% in 2006. Total annual wood consumption is estimated at around 3.5 billion m³ (FAO, 2005) growing on average over the last 20 years at 0.3% per year. The low rate of growth can be attributed to higher levels of recycling, improved recovery and the wider use of new composite products.

Just under half of today's wood is used in industry. Pulp and paper accounts for 16% of the total. The bulk of the remaining share of industrial wood use is accounted for by the buildings and construction sector. The largest share of wood consumption today is for energy in heating and cooking, for producing electricity and to a much smaller degree for liquid transport fuels.

Figure 5.12 ► Wood products flow

Source: FAO (2005b).

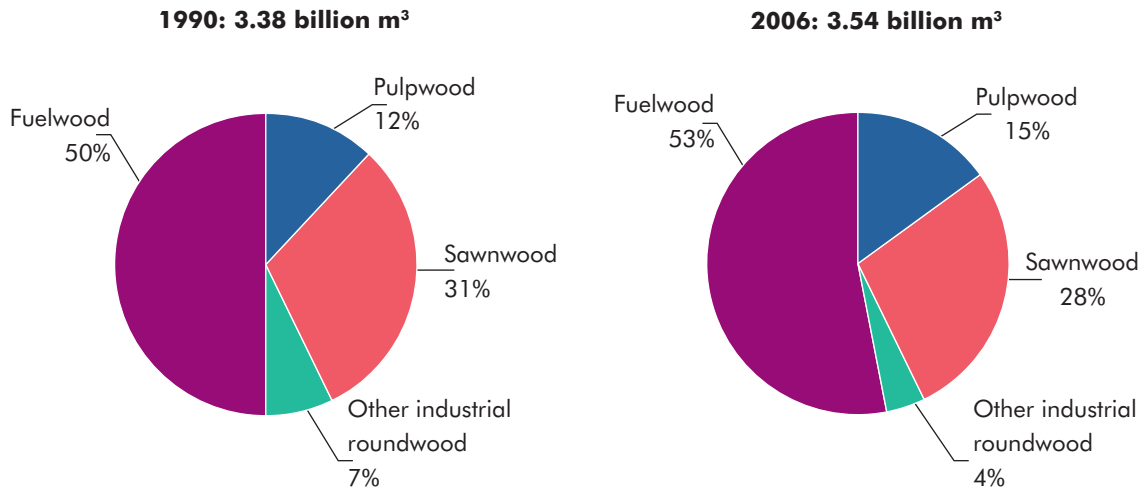
Key point

The wood products industry accounts for a large and diverse group of products.

Wood consumption is expected to rise significantly faster than in the past as stronger growth in demand comes from Asia, especially China and India, and as recent energy policies in Europe and North America stimulate additional biomass demand, especially for transport fuels. The UN FAO estimates that wood consumption could reach approximately 6.2 billion m³ by 2030 (FAOSTAT, 2008).

In 2006, 1.87 billion m³ of fuel wood, equivalent to 45 EJ of energy, was produced. This represents 53% of total wood production. Biomass accounts for the largest share, at 35 EJ, followed by commercial heat and power at 8 EJ, and liquid transport fuels at 2 EJ.

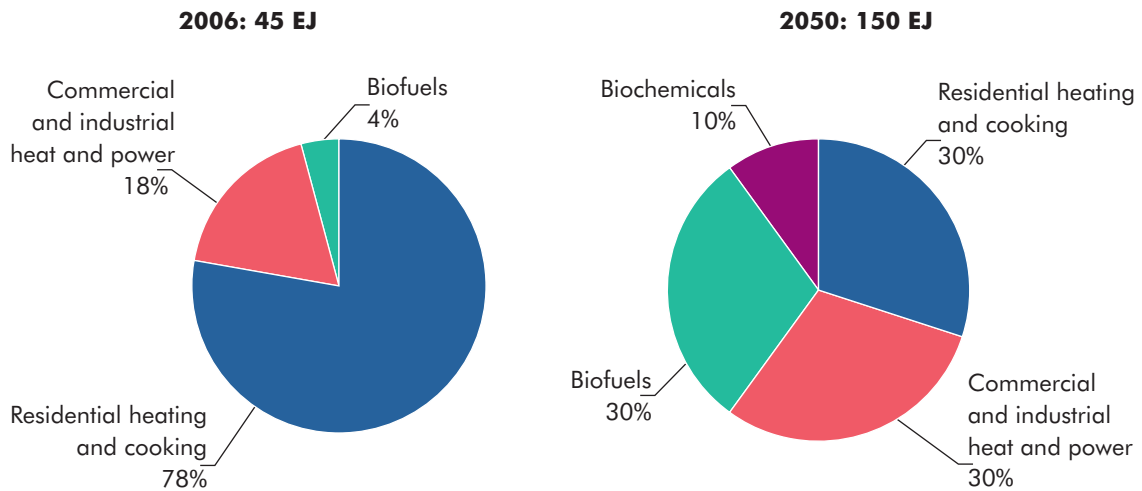
In the BLUE scenario, in which CO₂ emissions are to fall by 50% from current levels by 2050, strong growth in biofuels production combined with biomass use for electricity, biochemicals, heating and cooking will lead biomass consumption to rise to 150 EJ. Of this total, 80% will be from wood, equivalent to 5 billion m³ to 5.5 billion m³ of fuel wood. This implies that fuel wood consumption by 2050 would almost triple from current levels. Fuel-wood consumption would represent an estimated 65% to 75% of total wood consumption in 2050, compared to 53% in 2006. High growth in demand for fuel wood could have significant impacts on the economics of the pulp and paper sector.

Figure 5.13 ► Wood production by category, 1990 and 2006

Source: FAO (2005a).

Key point

Fuel wood accounts for more than half of all wood consumption.

Figure 5.14 ► Biomass use by application in 2006 and BLUE 2050

Source: IEA statistics and estimates.

Key point

The share of biomass consumption for heating and cooking will fall sharply in 2050 and will be offset by strong growth for biofuels, biochemicals and commercial heat and power.

Conclusion: transition pathway for the pulp and paper sector

The implementation of BAT and the future implementation of newly emerging technologies would enable the sector significantly to reduce both its energy needs and its CO₂ intensity. A wide range of technology options and opportunities need to be applied if the outcomes implicit in the BLUE scenario are to be achieved.

No single option can yield the necessary emissions reductions. Energy efficiency alone will not be sufficient to reduce emissions in the sector as demand is expected to continue growing rapidly. Government policies are needed to facilitate a transition to more efficient and/or lower-carbon technologies.

This transition needs to focus on deploying the most energy-efficient technologies available. All countries need to try to achieve BAT levels by 2025 and to improve BAT by 15% to 20% by 2035 through the wide deployment of black liquor and biomass gasification, increased waste heat recovery and new paper-drying technologies. Greater use of CHP would also provide a relatively low-cost opportunity for the sector to increase energy efficiency, although higher levels of CHP will only be possible if there is a suitable regulatory framework that facilitates the sale of surplus electricity to the grid. Gasification technology and wood-based biorefineries have the potential to turn the pulp and paper sector into a major energy supplier in the future.

In addition to improved energy efficiency, CO₂ emissions in the pulp and paper sector can be reduced through fuel switching from fossil fuels to biomass. Large forest plantations in China should increase the availability of biomass to the sector, which should help the industry to switch away from coal. In many OECD countries, CO₂ incentives will make fuel switching more attractive, but competition from other sectors will be an obstacle as demand for, and the price of, biomass rises. In the BLUE scenarios, an estimated 60% of all fuel will need to be biomass by 2050, compared with 34% today.

RD&D priorities should focus on improving gasification technology, more efficient water-extraction technologies and reducing the use of water in paper making. Improved reliability and gas clean-up for gasification is needed in the short term. Early commercial BLIGCC plants need to be deployed within the next five to ten years and wider deployment should occur from 2015 to 2025. In addition to black liquor gasification, lignin production from black liquor and biomass gasification with synfuel production also offer attractive opportunities to increase biomass use in the sector and to raise the profitability of pulp and paper mills.

These three technology options offer different benefits and are suitable for different types of mills. By 2030, 50% of all old boilers should be replaced with either black liquor gasification or biomass gasification, rising to 75% by 2050. In OECD countries, significant attention has been placed on developing biorefineries within the forest-based industries. The development of biorefineries within the pulp and paper industry could have positive impacts on the energy intensity, carbon intensity and profitability of the sector.

Additional CO₂ emissions reductions can be achieved if CCS is developed for BLIGCC technology. The scenario analysis shows that an additional 23 Mt to 51 Mt of CO₂ can be saved in the sector with CCS. To reach this level of CCS, at least two demonstration plants would need to be on stream by 2020 to 2025 with more extensive deployment beginning by 2030. To achieve the outcomes of the BLUE scenarios, by 2050 approximately one-third of all CO₂ emitted from black liquor gasification would need to be captured and stored.

Such a transition will only be possible when the policy framework supports the necessary technology development and its adoption. Cheap and available capital will be needed to stimulate investment in new technologies. Achieving the results outlined in the BLUE scenarios will be very challenging for the sector and will require significant co-ordination and collaboration between industry and government, as well as action from all major pulp and paper-producing countries.

Chapter 6 ALUMINIUM

Key Findings

- ▶ Global primary aluminium production has doubled over the last 20 years; 38 Mt of aluminium were produced in 2007. The main primary aluminium-producing regions are: China, Russia, North America, Australia and Latin America, with production growing rapidly in the Middle East. Recycled aluminium production has more than tripled since 1980 to almost 17 Mt in 2006.
- ▶ The production of primary aluminium is very electricity-intensive. Aluminium smelters used 2 EJ of electricity in 2007, about 3.5% of global electricity consumption. In total, the aluminium industry emits 0.4 Gt CO₂-equivalent of greenhouse gases, including process emissions and indirect emissions from electricity production, just under 1% of total global greenhouse gas (GHG) emissions.
- ▶ The industry has steadily improved its energy efficiency in recent years. Smelters used 15.5 MWh/t of aluminium in 2007. China and Africa have the newest and most efficient smelters. Average energy consumption in alumina refineries is now around 16 GJ/t of alumina. China has the most energy-intensive alumina refineries because of the characteristics of its bauxite deposits.
- ▶ There are still significant differences in performance among aluminium refineries and smelters. The widespread implementation of today's best available technologies could reduce energy consumption by up to 12% compared with current levels. This is equivalent to final energy savings of about 0.4 EJ per year and CO₂ savings of 44 Mt.
- ▶ In the longer term, further reductions in GHG emissions will be necessary. Increasing the use of electricity from zero-carbon sources is the single most important option for reducing emissions. Further savings can also be achieved through more recycling and from introducing new technologies such as drained cathodes and inert anodes and possibly carbothermic reduction and carbon capture and storage.
- ▶ In the Baseline scenarios, CO₂ emissions from the aluminium industry increase between 2.6 and 3.5 times to reach 1.0 Gt to 1.4 Gt by 2050, with most of the increase coming from Asia. In the BLUE scenarios, the use of decarbonised electricity, combined with more efficient new technologies and increased recycling, could reduce CO₂ emissions in 2050 by between 70% and 77% to a level slightly lower than today's. Total additional investment needs from 2006 to 2050 in the BLUE scenarios are between USD 60 billion and USD 90 billion more than in the Baseline scenarios.
- ▶ Further research, development, demonstration and deployment (RDD&D) of technologies are needed. In the short term, the focus should be on technologies to improve energy efficiency at all stages of production, including through the use of combined heat and power (CHP) systems. In the longer term, the focus should be on the development of new technologies that can further reduce CO₂ emissions, particularly in smelting. The potential role of CCS also needs to be investigated.

Introduction

Aluminium can be produced from bauxite (primary production) or from the recycling of scrap. Around 38 Mt of aluminium was produced from bauxite in 2007, more than twice the amount that was produced 20 years earlier. The main primary aluminium-producing regions are China, Russia, North America, Australia and Latin America (Table 6.1). Production in China, India and particularly in the Middle East is growing rapidly, while it has been declining in the United States and Europe in recent years.

Table 6.1 ► Global primary aluminium production, 2007

	Production (Mt/yr)	Production share (%)	Cumulative production share (%)
China	12.60	33.2%	33.2%
Russia	3.96	10.4%	43.6%
Canada	3.09	8.1%	51.7%
United States	2.55	6.7%	58.4%
Australia	1.96	5.2%	63.6%
Brazil	1.66	4.4%	68.0%
India	1.22	3.2%	71.2%
Norway	1.30	3.4%	74.6%
South Africa	0.90	2.4%	76.9%
Dubai	0.89	2.3%	79.3%
Bahrain	0.87	2.3%	81.6%
Venezuela	0.61	1.6%	83.2%
Mozambique	0.56	1.5%	84.7%
Germany	0.55	1.4%	86.1%
Tajikistan	0.42	1.1%	87.2%
Iceland	0.40	1.0%	88.3%
Other	4.46	11.7%	100.0%
Total	38.00	100%	

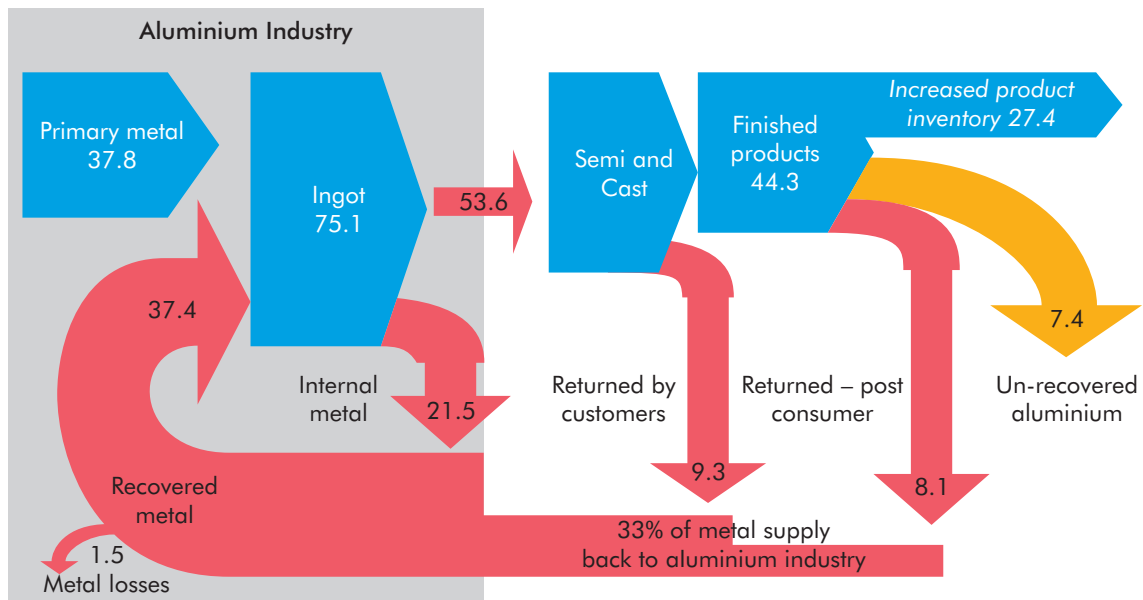
Source: USGS (2009).

The production of aluminium from scrap has increased even more rapidly than primary production, tripling since 1980 to almost 17 Mt in 2006 (IAI, 2008a). Recycled production has increased to around 30% of the total amount of aluminium produced each year, although the share has levelled out in recent years as total

demand has increased. Figure 6.1 shows the global flows of aluminium in 2007 from production to use, including recycling.

Final energy consumption in the global aluminium industry in 2007 was estimated to be 3.5 EJ. The industry is very electricity-intensive. Primary aluminium smelters used just over 2 EJ of electricity in 2007, equivalent to about 3.5% of global electricity consumption.¹ Total GHG emissions are estimated to be around 0.4 Gt CO₂-equivalent (including process emissions and indirect emissions from electricity production).² This is just under 1% of total global GHG emissions.

Figure 6.1 ► Global aluminium flows, 2007



Source: Martchek (2007) updated with information from IAI (2008b).

Key point

A substantial share of aluminium production comes from recycled metal.

Trends in energy efficiency and GHG emissions

The energy efficiency and GHG emissions of aluminium production can be analysed using a number of indicators (Table 6.2).

1. IEA estimate based on IAI data for 2007 on the global average specific power consumption of smelters and global production of primary aluminium.

2. Non-CO₂ GHGs, notably perfluorocarbons (PFCs), constitute a significant proportion of total GHG emissions from the aluminium industry. They are, therefore, included in the analysis of historical trends in this chapter.

Table 6.2 ▶ **Primary energy use in the aluminium industry by process step**

Process	Typical energy use (GJ/tonne)	Multiplier	Total energy use (GJ/tonne aluminium)	Key indicators
Primary aluminium production				
Mining	0.15	5	0.75	
Refining	16	1.9	30	• Specific energy consumption of metallurgical alumina production
Anode	9	0.44	4	• Energy use for anode production
Smelting	117	1.02	120	• Smelter technology mix • Specific power consumption for aluminium smelting • PFC emissions per tonne of aluminium • Sources of electricity production
Total			155	
Recycled aluminium production				
Remelting	10	1	10	• Share of recycled production

Source: Based on data from IAI (2007, 2008c and 2009b).

Primary aluminium is produced in three distinct steps: bauxite (ore) mining, a low energy intensity physical process; alumina refining, a medium energy intensity physico-chemical process; and aluminium smelting, a highly energy-intensive electrochemical process.

Mining

Bauxite is found in many parts of the world. More than 80% of global bauxite production is in Australia, Brazil, Guinea, Jamaica, China and India. The energy used in bauxite mining varies widely depending on the quality of the ore, with a range of 40 MJ/t to 470 MJ/t of ore (IAI, 2009b). To be commercially exploitable, ore generally needs to contain at least 40% alumina. Bauxite is processed to alumina near the bauxite mine, or shipped to alumina plants in other parts of the world.

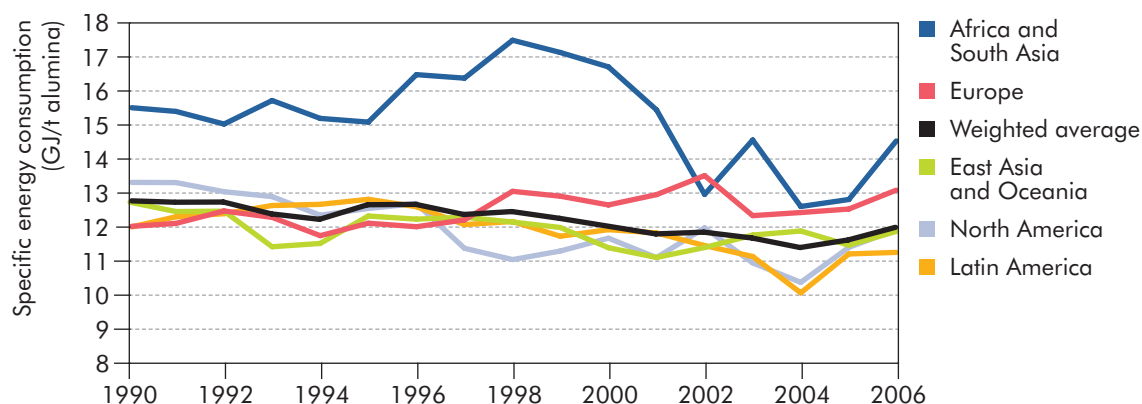
Alumina refining

The majority of alumina is produced using the Bayer process. This involves the digestion of bauxite, the clarification and precipitation of alumina, and calcination (drying). Most of the energy used in alumina refineries is in the form of steam used to heat caustic soda in the digestion process. The calcining of the alumina also requires large amounts of high-temperature heat. Around 90% of the total energy used in alumina production comes from fossil fuels, with most of the remainder being electricity. Given the high demand for steam, the opportunity exists for

many plants to introduce combined heat and power (CHP) systems and thereby significantly to increase overall energy efficiency.

The International Aluminium Institute (IAI) conducts an annual survey of facilities worldwide³ to collect information about energy use and production. The average energy intensity of alumina refineries reporting in the IAI statistical system was 12.0 GJ/t of alumina in 2006, with a range among different world regions between 11.2 GJ/t in Latin America and 14.5 GJ/t in Africa and South Asia (IAI, 2008c). The IAI statistics also show that the specific energy consumption of alumina refining has declined by 6% between 1990 and 2006, although it has increased in the later years of that period (Figure 6.2).

Figure 6.2 ► Regional average energy use of metallurgical alumina production



Note: Excludes data for China.

Source: IAI (2008c).

Key point

The efficiency of alumina refining has slowly improved in most regions.

These figures do not include full coverage of China. Many Chinese bauxite deposits have high silica content and so are of a low grade. These require a more complex refining process. As a result, China has a higher average energy intensity than other countries. Only 14% of China's output is produced by the standard Bayer process; the remainder uses a combination of sintering and part of the Bayer process (Li *et al.*, 2008). The energy intensity of such combination processes is from 24 GJ/tonne to 52 GJ/tonne of alumina (Liu *et al.*, 2006; Li *et al.*, 2008), making them between two and four times more energy-intensive than the ordinary Bayer process.

The world average 2006 energy intensity, including Chinese and other non-reporting facilities, is estimated to be 16.0 GJ/t of alumina produced. The members of the IAI have an objective to reduce global energy use per tonne of alumina produced by 10% by 2020 from this 2006 baseline.

3. The survey covers around 70% of global metallurgical alumina and primary aluminium production.

Anode production

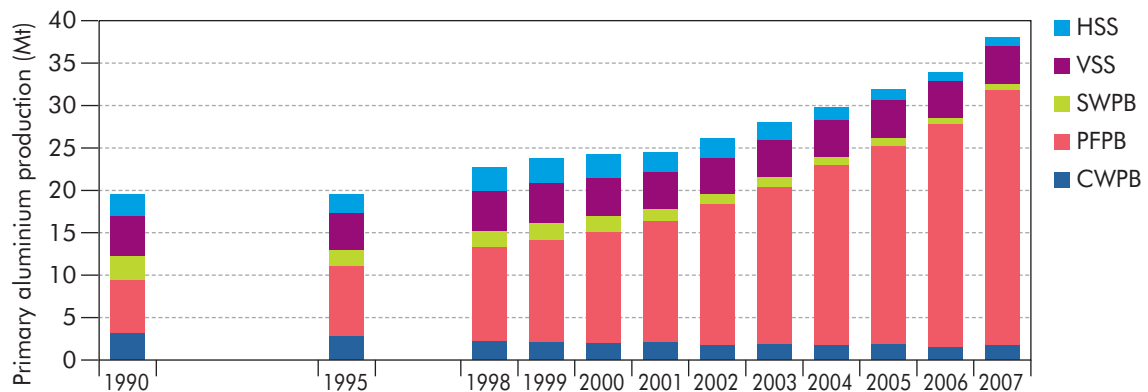
Anodes are produced by heating tar pitch or coke from refineries at high temperatures in gas-heated furnaces. Anodes can be produced on site at the smelter or in specialist manufacturing plants. The current average specific energy consumption for anode production is around 8 GJ/t anode (IAI, 2007). A typical modern smelter uses around 0.44 kg of anode per tonne of aluminium.

Smelting

Smelting is the most energy-intensive step in the production of aluminium and is based on the Hall-Héroult process. Alumina is dissolved in an electrolytic bath of molten cryolite within a large carbon- or graphite-lined steel container known as a “pot”. A low-voltage, very high-amperage electric current is passed through the electrolyte between a carbon anode, made of petroleum coke and pitch, and a cathode, formed by the lining of the pot. The strongly bonded aluminium and oxygen atoms in the alumina are split as the high current pulls oxygen ions towards the anode, where they react with the carbon, leaving molten aluminium that is deposited at the bottom of the pot and siphoned off from time to time.

More than 80% of primary aluminium production is now from smelters using modern pre-baked anodes although some facilities still use an older Søderberg technology with *in situ* baked anodes (Figure 6.3). Pre-bake smelters use 13.6 to 15.7 MWh/t of aluminium whereas Søderberg smelters use 15.1 to 17.5 MWh/t of aluminium (EC, 2008).

Figure 6.3 ▶ Smelter technology mix, 1990 to 2007



Notes: SWPB: side work pre-bake; PFPB: point fed pre-bake; CWPB: centre work pre-bake; HSS: horizontal stud Søderberg; VSS: vertical stud Søderberg.

Source: IAI (2009a).

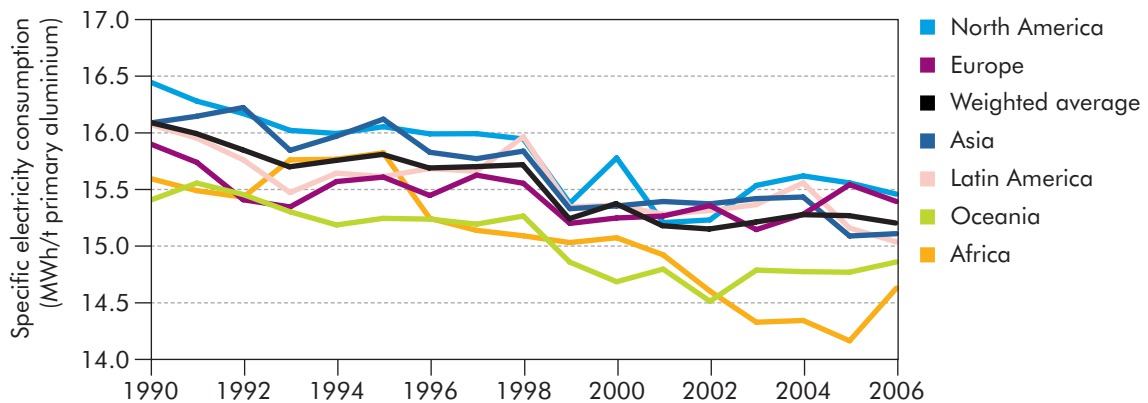
Key point

Most aluminium production is now from smelters using modern pre-baked anodes.

Specific power consumption for primary aluminium production has declined in most regions (Figure 6.4). This has been achieved by building new, more energy-

efficient capacity and by retrofitting old capacity with new cells. Global average electricity consumption in the industry has declined by about 0.4% per year over the last 25 years. It is now around 15.5 MWh/t of aluminium. The range across regions is relatively narrow compared to the differences in energy efficiency among regions that have been observed in other manufacturing industries. Africa has the most energy-efficient smelters in the IAI dataset, reflecting their relatively young age, although anecdotal evidence suggests that China (which is not included in the IAI energy statistics), has on average even more efficient production (Tao and Liang, 2008).

Figure 6.4 ► Regional specific power consumption in aluminium smelting



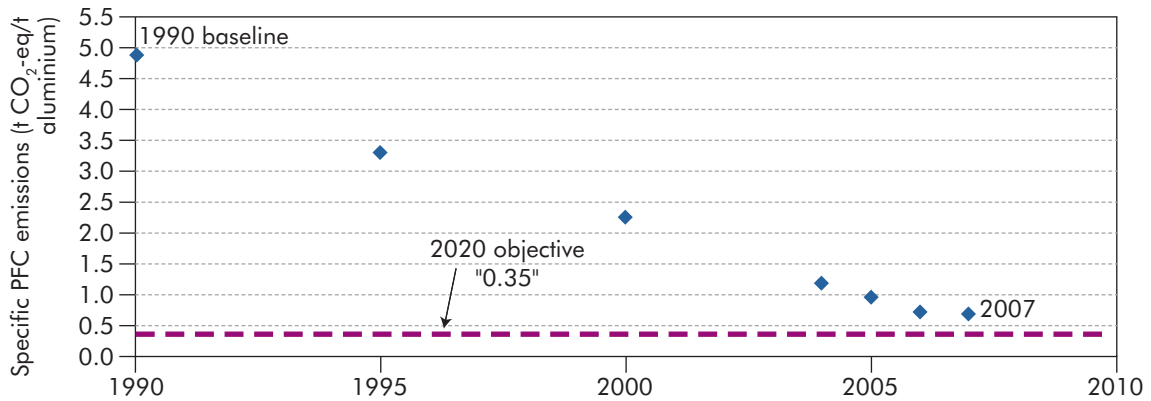
Note: Europe includes EU25 plus Iceland, Norway, Switzerland, Bosnia and Herzegovina, Croatia, Romania, Russia, Serbia and Montenegro, and Ukraine.

Source: IAI (2008c).

Key point

Africa has some of the most energy-efficient aluminium smelters worldwide.

In addition to being a major electricity user, the smelting process is also a significant source of process CO₂ emissions (from the consumption of carbon anodes) and of perfluorocarbons (PFCs). PFCs are formed when the level of dissolved aluminium oxide in the cell drops to a point where the electrolytic bath itself begins to undergo electrolysis. In recent years, the aluminium industry has put considerable efforts into reducing PFC emissions through the use of improved process controls and the phasing-out of older technologies (in particular SWPB, VSS and HSS cells). As a result, average PFC emissions per tonne of aluminium were reduced by 87% between 1990 and 2007 (Figure 6.5). This equates to a 74% reduction in global PFC emissions over the same period, despite a doubling in aluminium production. However, there is still a considerable range of performance between facilities using the same cell technology. This suggests that there is scope for further reducing PFC emissions in the future. The global aluminium industry has a voluntary objective to reduce its PFC emissions per tonne of aluminium produced by 50% between 2006 and 2020, equivalent to a 93% reduction from 1990.

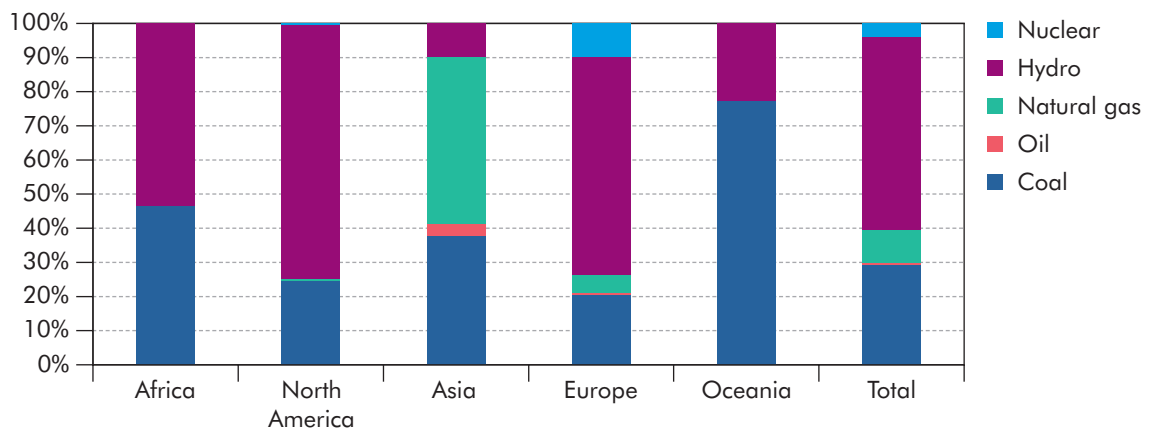
Figure 6.5 ▶ Average PFC emissions per tonne of aluminium

Source: IAI (2008b).

Key point

Specific PFC emissions have been reduced dramatically.

Even though around 55% of the electrical energy supplied to IAI survey respondents is based on hydropower (see Figure 6.6), which has very low emissions of GHGs, around 60% of the total GHG emissions attributable to the global aluminium industry comes from electricity use. The rest comes from direct emissions from the production process (Marks, 2007). The CO₂ emissions intensity of the industry is, therefore, strongly dependent on the carbon intensity of the electricity that it uses.

Figure 6.6 ▶ Sources of electricity production for aluminium smelting by region

Source: IAI (2008c).

Key point

Hydropower is a significant source of the electricity used for aluminium smelting.

There are significant differences in fuel shares between regions. In North America, hydropower provides 74% of total electricity requirements, compared to 10% in Asia. Coal, which has the highest CO₂ intensity, provides 20% of total needs in

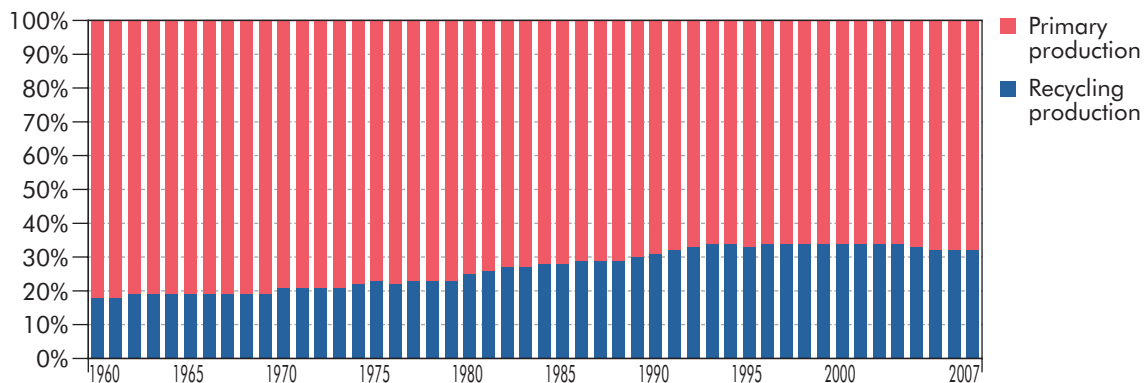
Europe, but 77% in Oceania. The inclusion of China in the data would reduce the global average contribution of hydropower from around 55% to between 40% and 50%, as China generates a majority of its electricity from fossil fuels.

Recycled production

Producing aluminium from scrap requires only about 6% to 7% of the energy required for primary production because of its relatively low melting temperature (700°C to 800°C) and the fact that it is not bonded to oxygen. A number of technologies are used to recycle aluminium scrap, including reverberatory and induction furnaces. Typical reverberatory furnaces in use today consume between 3 GJ and 9 GJ of fuel per tonne of aluminium.

Recycling rates are growing as a proportion of total production (Figure 6.7). Developed countries, such as in Europe and North America, which have high energy prices and plenty of scrap available owing to a long history of aluminium use, recycle more than other countries. Recycling is increasing in China, India and Russia and is expected to rise further in the future.

Figure 6.7 ▶ Share of scrap in aluminium production, 1960 to 2010



Source: GARC (2006).

Key point

The share of recycled production has grown steadily over many years.

Best available technology and technical savings potentials

There are a number of ways to improve the energy efficiency of alumina production from the Bayer process. Improved process controls and equipment modifications can increase yields. Heat losses can be reduced through greater use of CHP, better heat transfer efficiency, improvements in calciner technologies and operations, and more effective waste-heat recovery and use. Such measures could reduce total

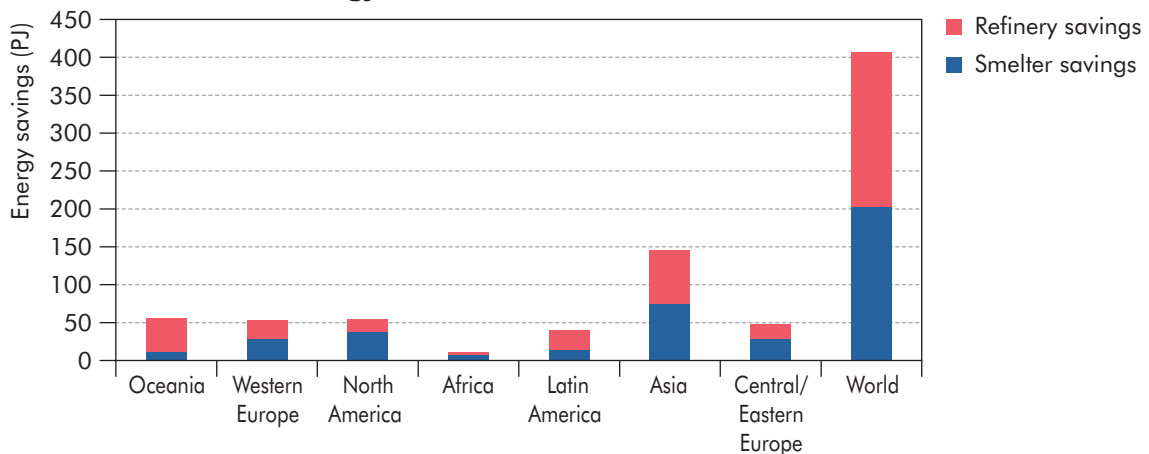
fuel and electricity use to between 9.5 GJ/t and 10 GJ/t of alumina, a 20% saving compared to the average consumption today (ISR, 2000; Worrell *et al.*, 2008). In China, best practice levels for the combination process are currently around 25 GJ/t (Li *et al.*, 2008). Although this is about a third less than the average for this process, it is still twice as high as the world average for the Bayer process. Further energy savings could be achieved in China by pre-processing the bauxite to remove mineral impurities, thereby allowing the Bayer process to be used (Gu, 2008).

The performance of smelters has improved significantly in recent years, but there remains considerable scope for further energy savings. The main opportunities involve the replacement of old smelter technologies with modern pre-bake cells, the development of process controls, which can optimise cell operating conditions, improving insulation to reduce heat losses, and electricity savings in auxiliary uses such as compressors and fans. The current aim of the International Aluminium Institute's members is to retrofit or replace existing smelters in order to reduce electricity consumption to 14.5 MWh/t of aluminium in the short term, with further reductions thereafter. New world-class plants can achieve around 13.5 MWh/t, a saving of 13% compared to the current world average (Keniry, 2008).

Smaller energy savings are also possible in other processes, such as in anode manufacture and in recycling. The BAT fuel consumption for anode production is 2.45 GJ/t anode (Worrell, 2008), around 70% less than the current average. The BAT for recycling using natural gas-fired regenerative furnaces consumes about 2 GJ/t to 2.5 GJ/t of aluminium (Worrell, 2008; Bayliss and Marks, 2008), around 50% less than conventional cold air technologies.

As shown in Figure 6.8, BAT offer the opportunity to reduce energy use in aluminium production by up to 12% compared with current levels. This is equivalent to final energy savings of about 0.4 EJ per year and CO₂ savings of 44 Mt.

Figure 6.8 ► Energy savings potentials in 2006, based on best available technology



Source: IEA analysis.

Key point

Implementation of best available technologies in both refineries and smelters offers opportunities for energy savings.

Scenario analysis

Future energy use and CO₂ emissions in aluminium production have been analysed through the use of two scenarios, Baseline and BLUE, each with high- and low-demand cases. The Baseline scenarios reflect developments that are expected on the basis of currently implemented and planned energy and climate policies. The BLUE scenarios examine the implications of a policy objective to halve global energy-related CO₂ emissions in 2050 compared to today's level. Modelling results indicate that this will require a CO₂ incentive of USD 200/t CO₂. Significant policy changes will also be needed.

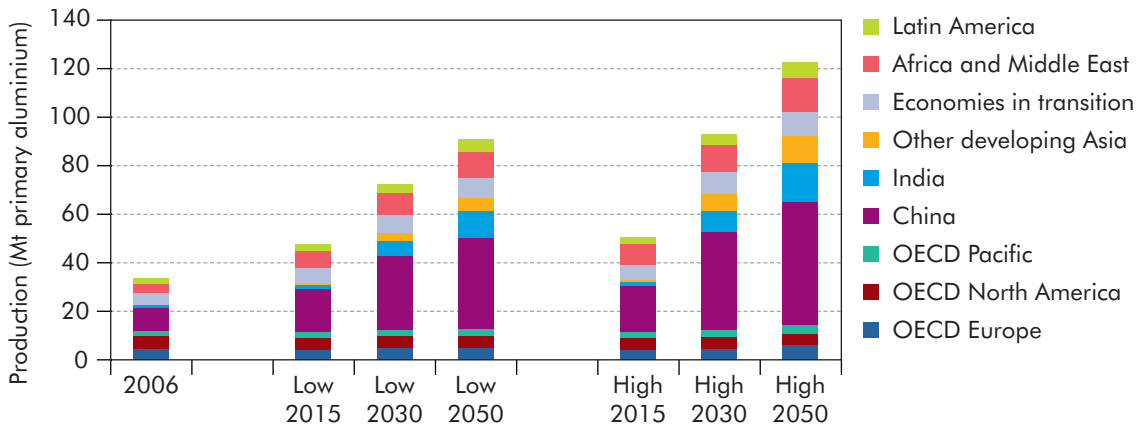
Demand for aluminium is projected to grow substantially to 2050 because of higher consumption across a wide range of sectors, especially transport, buildings and engineering. World average per-capita demand almost doubles in the Baseline low-demand scenario, and grows by more than 2.5 times in the Baseline high-demand scenario (Table 6.3). Given population growth, this means that total demand increases by 2.7 times in the low-demand case and by 3.7 times in the high-demand one. In absolute terms, demand in the rapidly growing economies of Asia increases most, but there are also substantial percentage increases in Africa and South America.

To meet this increased demand, primary aluminium production reaches 91 Mt by 2050 in the Baseline low-demand scenario, and increases to 123 Mt in the high-demand case (Figure 6.9). In both scenarios, most growth is outside the OECD, with strong increases in China, India, the economies in transition, and Africa and the Middle East.

Table 6.3 ► Per capita and total aluminium demand by region (Mt)

	Per capita consumption			Total consumption		
	2006	2050-low	2050-high	2006	2050-low	2050-high
OECD North America	28.5	32.1	38.1	12	18	22
OECD Europe	22.7	28.1	36.7	12	16	20
OECD Pacific	13.9	21.5	31.3	3	4	6
China	5.1	22.6	32.3	7	32	45
India	1.0	6.0	8.8	1	10	14
Economies in transition	3.8	11.8	26.5	1	3	3
Latin America	3.5	10.7	15.3	2	7	10
Middle East and Africa	0.7	2.0	3.0	1	5	7
Other developing Asia	2.0	10.6	15.0	2	16	26
Total	6.3	12.1	16.8	41	110	153

Figure 6.9 ▶ **Primary aluminium production in Baseline scenarios, 2006 to 2050**



Key point

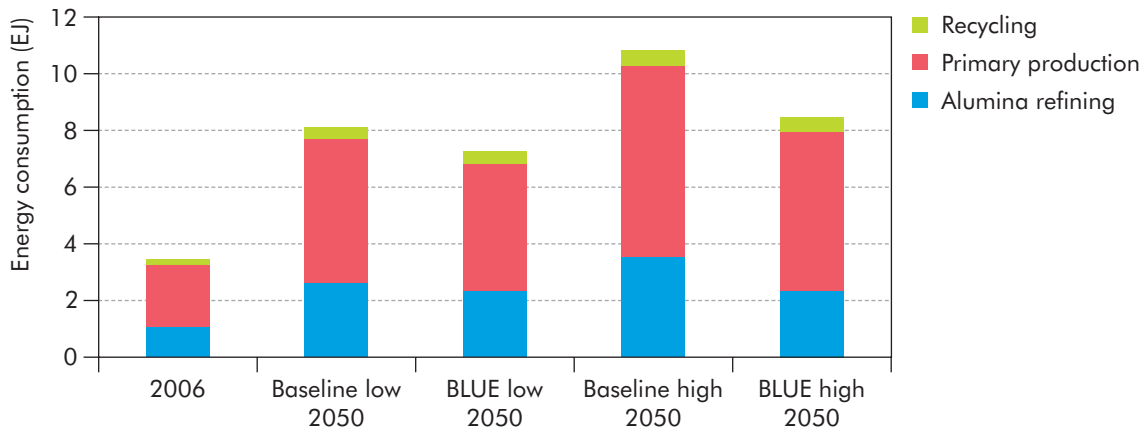
Aluminium production is forecast to increase substantially, with most of the growth in non-OECD countries.

Aluminium recycling is also expected to increase strongly. In the Baseline scenarios, recycled production rises to 47 Mt in 2050 in the low-demand case and 63 Mt in the high-demand case, continuing to represent around one-third of total aluminium production. In the two BLUE scenarios, total aluminium production is assumed to be the same as in the corresponding Baseline scenarios, but the share of recycling increases to 55 Mt and 76 Mt in 2050 under low- and high-demand BLUE scenarios respectively, representing almost 40% of total aluminium production.⁴

As a result of these production increases, final energy use grows strongly in the Baseline scenarios to reach 8.1 EJ in 2050 in the low-demand case and 10.8 EJ in the high-demand case (Figure 6.10). It grows more slowly than does aluminium production due to continued efficiency improvements in both smelting and refining, where past improvement rates are assumed to continue. This means that by 2050, global average electricity use in refining falls to an average of 14 GJ/t of alumina, and in smelting to around 13 MWh/t of aluminium. The global distribution of energy use reflects the shifting pattern of aluminium production.

In the BLUE scenarios, energy use in 2050 is 11% to 22% lower than in the Baselines. In the BLUE low-demand scenario, these energy efficiency gains are largely achieved through further developments of existing technology together with some deployment of more novel technologies. In the BLUE high-demand scenario, the widespread introduction of wetted drained cathodes and inert anodes from 2015 and of carbothermic reduction technologies from 2030 is assumed to reduce the global average electricity intensity of smelting in 2050 to 10.5 MWh/t of aluminium.

4. Production of aluminium is higher than demand as some of the aluminium is returned for recycling by customers before being made into finished products, and a small percentage is lost during the recycling process.

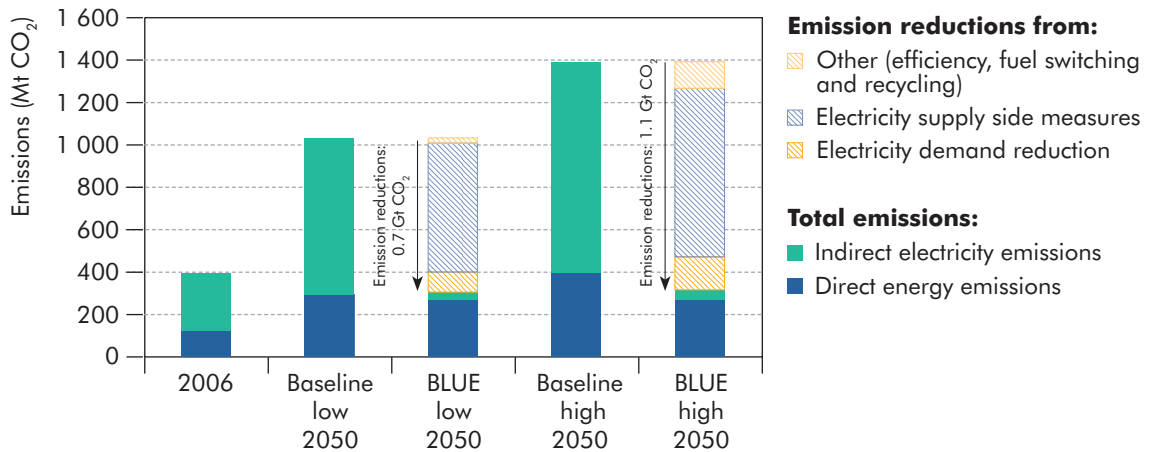
Figure 6.10 ► Final energy consumption by scenario, 2006 and 2050**Key point**

New technologies can improve energy efficiency, but energy use still grows substantially from current levels under all scenarios.

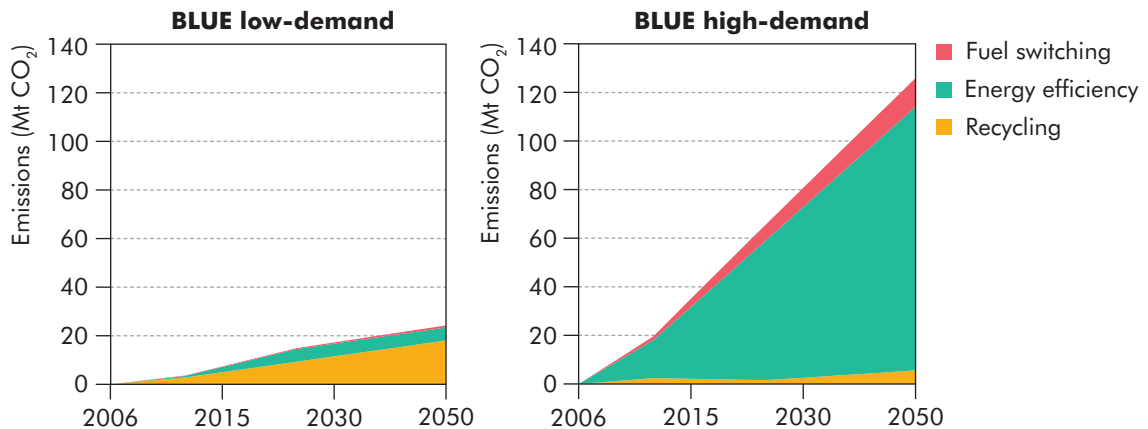
In the Baseline scenarios, total direct and indirect CO₂ emissions grow from around 0.4 Gt in 2006 to between 1.0 Gt and 1.4 Gt by 2050 (Figure 6.11). The increase in emissions is less than the increase in final energy use, reflecting lower CO₂ intensity of the fuel mix, due to fuel switching. In the BLUE scenarios, CO₂ emissions fall by 70% (low-demand) or 77% (high-demand) to 0.3 Gt in 2050, around 20% lower than current levels. Most of the CO₂ emissions reductions come from the use of low-carbon electricity rather than from measures to reduce direct emissions from the aluminium industry itself, which have higher CO₂ abatement costs. In the BLUE low-demand scenario, over 80% of the emissions reductions are from electricity use, while in the BLUE high-demand scenario the equivalent figure is over 70%. This suggests that an important part of the strategy for reducing emissions in this industry may lie in locating smelters close to sources of CO₂-free electricity such as hydro or nuclear power stations.

Once the electricity supply has been largely decarbonised, any additional CO₂ savings will need to come from direct emissions. Reductions in direct emissions are, therefore, significantly greater in the BLUE high-demand scenario than in the BLUE low-demand scenario (Figure 6.12). In the latter case, direct emissions savings are largely achieved through increasing recycling and through relatively small additional efficiency gains in both refining and smelting. In the BLUE high scenario, recycling makes a much smaller contribution, with the largest share of reduction coming from improved energy efficiency and reduced process emissions.⁵

5. While not explicitly examined in these scenarios, an alternative way of reducing direct CO₂ emissions would be to implement CCS on smelters rather than relying on reducing CO₂ emissions from the introduction of new smelter technology, such as inert anodes.

Figure 6.11 ► CO₂ emissions by scenario, 2006 and 2050**Key point**

Decarbonising electricity offers the biggest opportunity for future CO₂ savings in the aluminium industry.

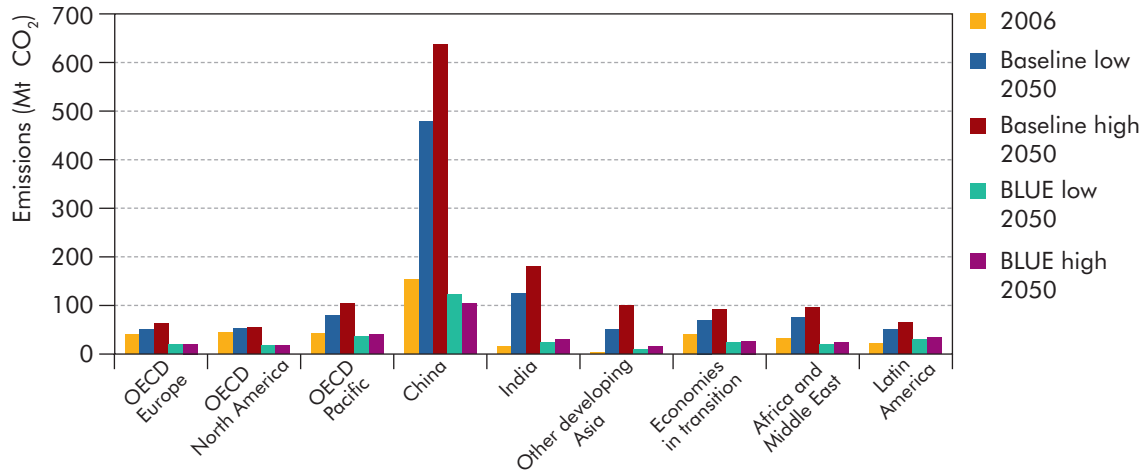
Figure 6.12 ► Direct CO₂ emission reductions below Baseline scenario, 2006 to 2050**Key point**

Achieving deep cuts in CO₂ emissions under the high growth scenario, requires significant reductions in direct emissions.

Figure 6.13 shows that in the Baseline scenarios, almost half of all CO₂ emissions come from China in 2050. This reflects high levels of production combined with less energy-efficient alumina production and a high share of coal use both directly in the aluminium industry and for electricity generation. Emissions in India also grow strongly, as they do in other parts of developing Asia. In the BLUE scenarios, all regions show very large reductions in emissions. China and India show the

biggest CO₂ savings in 2050 between the Baseline and BLUE scenarios. This reflects a switch away from coal in power generation, combined with higher average efficiencies in the aluminium industry itself as a higher share of new, more efficient capacity meets increased production. Emissions reductions in 2050 are lowest in Latin America as, even in the Baseline scenarios, the electricity sector has a high share of zero-carbon production and so there is less scope for reducing the emissions intensity of electricity use.

Figure 6.13 ► CO₂ emissions by region and by scenario, 2006 to 2050



Key point

The aluminium industry in all regions needs to make deep cuts in CO₂ emissions.

Costs of CO₂ reductions in the aluminium sector

Implementing today's best practice technologies is likely to be cost-effective in many circumstances if undertaken as part of the natural cycle of plant replacement. But, given the long life of refinery and smelter assets, this replacement cycle will not be sufficient in itself to achieve the CO₂ reductions that are needed in the BLUE scenarios. Table 6.4 shows the costs of some of the most important smelter upgrade options. For refineries, the use of CHP can offer some of the largest energy savings. However, CHP is a capital-intensive technology with costs for larger plants around USD 1 000 to USD 1 400 per kW.

Estimating the costs of the new technologies that will be needed to achieve the BLUE scenarios is necessarily uncertain, since by definition they have yet to be commercialised. An inert anode facility with a capacity of 2 200 t, estimated to cost between USD 10 million and 15 million, would be needed for a 250 000 t/yr smelter (Keniry, 2001). This compares with around USD 160 million for a conventional carbon-anode plant for the same smelter. Overall operating costs could be up to 15% lower with inert anodes (Morrey, 2004). For wetted drained cathodes, the main additional costs are the wettable material needed to line the cell, which is estimated to cost USD 80 000 more per cell than a conventional

lining (Keniry, 2001). The operating costs of a wetted drained cell would be around 2% lower than a conventional cell, mostly as a result of power savings offsetting increased maintenance costs. Greater cost savings may be achievable by using carbothermic reduction, with aluminium production costs estimated to be between 3% and 7% lower than for a world-class Hall-Héroult smelter (Choate and Green, 2006).

Table 6.4 ► **Cost of aluminium smelter upgrade options**

	Cost (USD per tonne of capacity*)	Typical energy savings (%)	Factors affecting cost
Pot control and point feeders	400 – 800	3	
New cathodes	500 – 1 500	3	Whether part of normal cell relining
Conversion of Søderberg to pre-bake	600 – 1 100	10	With or without anode plant

*Cost per tonne of additional metal (except conversion of Søderberg, where costs are per tonne of replacement capacity).
Source: Morrey (2004).

Combining these figures with the technology mix and production volumes in the scenarios indicates that total investment costs over the period 2006 to 2050 under the Baseline scenarios are USD 660 billion (low-demand) and USD 910 billion (high-demand). For the BLUE scenarios, the net additional investment costs are USD 60 billion (low-demand) and USD 90 billion (high-demand), around 10% more than in the equivalent Baseline scenarios.⁶ This takes account of the additional investment costs of more efficient refinery and smelter technologies, plus some investment savings in anode production as carbon anodes are replaced by inert anodes.

New technology options

Most RD&D has been focused on technologies that can reduce the energy consumption of smelting, since this is the most energy-intensive process step in aluminium production. Research has centred on two main areas: improvements in the current Hall-Héroult cell and alternative production processes, such as carbothermic and kaolinite reduction.

Improvements to the Hall-Héroult cell

Theoretically, it should be possible to produce a tonne of aluminium using just over 6 MWh of electricity. No current cell design comes close to this thermodynamic minimum (Choate and Green, 2003). The industry's long-term goal is to reduce energy consumption to 11 MWh/t, through the use of a combination of wetted

6. The investment calculation excludes the additional costs of low- or zero-carbon electricity generating capacity.

drained cathodes and inert anodes. Over time, electrolysis process designs using aluminium chloride or carbothermic processes could become the most energy-efficient way to produce primary aluminium.

Wetted drained cathodes

In existing Hall-Héroult cells, molten metal aluminium collects at the bottom of the cell on top of the carbon cathode lining before being periodically removed. The large electrical forces in the cell cause the aluminium to undulate, creating an uneven surface. So to avoid shorting, the anode has to be positioned some distance away from the surface. Wetted drained cathodes have the potential to reduce energy consumption significantly by allowing molten aluminium to be drained away continuously. A drained cathode presents a flat stable surface. This means that the anode-cathode distance can be decreased, so reducing the resistance and therefore the energy needed. A wetted drained cathode could offer energy savings of up to 20% compared to a modern Hall-Héroult cell, reducing energy use to around 11 MWh/t aluminium (Choate and Green, 2003).

Inert anodes

Carbon anodes are consumed in the current Hall-Héroult process, so they need to be replaced from time to time. Anode changing upsets the stability, production and energy efficiency of the cell. The use of inert anodes would avoid these problems and eliminate both process-related PFCs and CO₂ emissions from aluminium production.⁷ The inert anode reaction requires additional energy, but it enables more efficient alumina feeding and greater control of the anode-cathode distance.

Despite extensive testing at laboratory and batch scales, no recent information is available on industrial scale tests (Pawlek, 2008). The hope is that, when inert anodes are used in conjunction with a wetted drained cathode, they should match the energy performance of the best cells in operation today and reduce CO₂ emissions from smelting by up to 40% compared to today's levels. It may also be possible to retrofit inert anodes into existing pre-bake cells, but the energy impacts are more uncertain.

Alternative technologies

Carbothermic reduction

The carbothermic reduction of alumina is the only non-electrochemical process that has shown promise for primary aluminium production. The process involves reactions of carbon with alumina at temperatures around 2 000°C. The technology has been the subject of extensive research for 50 years, given its potential to achieve significant energy and cost reductions over the Hall-Héroult cell. But

7. An alternative to inert anodes might be to use carbon anodes made from biomass. In theory, these anodes would release no net CO₂ over their life cycle. However, research is at an early stage and more work is needed to quantify the overall environmental benefits of such an approach.

the process requires highly complex thermodynamic controls and sophisticated equipment and construction materials, which have not yet been demonstrated at commercial scale. The latest research involves the use of new high-intensity electric arc-furnace technology and indications are that this process is both technically and economically feasible. Using such a system could lower the energy requirements to as little as 8.5 MWh/tonne of aluminium, a saving of almost 40 % compared to the best new plants using Hall-Héroult cells (Choate and Green, 2006).

Kaolinite reduction

Kaolinite reduction is an alternative to the Bayer refining and Hall-Héroult electrolysis route for primary aluminium production. The process involves the chlorination of alumina-containing kaolin clays, in which the alumina containing portion of the clay is converted into aluminium chloride. The crude aluminium chloride is then purified before electrolysis takes place in an aluminium chloride smelting cell to produce high-grade aluminium and chlorine gas. The potential advantages of this process are that the raw materials are widely distributed and inexpensive. Overall energy use could be up to 35% lower than the current production route.

Carbon capture and storage

CCS offers the possibility of reducing CO₂ emissions both from alumina refining and from aluminium smelting. However, very little work has been published so far on the subject. Post-combustion capture could offer a significant opportunity for removing CO₂ emissions from refinery flue gases. At least one major aluminium producer is also researching the use of carbon capture as a way of reducing CO₂ emissions from smelting. One of the main challenges is how to capture and concentrate the CO₂ from the electrolysis cell in a way that makes separation economically viable. While some of the early results have been promising, a number of challenges remain and further research will be necessary before the technology can be demonstrated at scale (Nord, 2009).

Aluminium markets

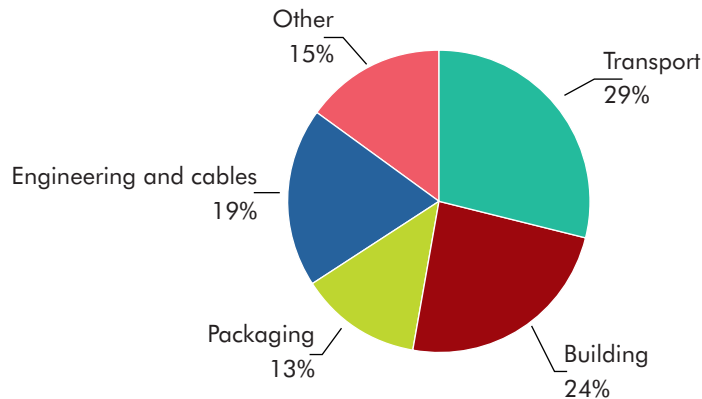


Demand for aluminium has been growing rapidly in recent years. Aluminium is used primarily in transport, buildings, engineering and cables, and packaging (Figure 6.14). Almost 30% of wrought and cast aluminium alloy is used in cars, commercial vehicles, aircraft, trains and ships (GARC, 2006).

Aluminium products are increasingly being used to reduce vehicle weight to help improve fuel efficiency. There has been a substantial increase in the use of aluminium in cars, mostly in the engine and gearbox. The use of sheet aluminium in car bodies is, however, still limited. Worldwide, the aluminium content of light-duty vehicles averages 113 kg per vehicle and is projected to reach around 135 kg by 2020 (Aluminum Association, 2009). Modern aircraft use aluminium as their main construction material, comprising about 80% of the unladen weight. A number of studies have looked at the energy benefits of reducing the weight of vehicles

through greater use of aluminium. These have concluded that the CO₂ emissions benefits over the vehicle life can outweigh the emissions from additional aluminium production.

Figure 6.14 ► **Global end-use markets for aluminium, 2006**



Source: IAI.

Key point

Transport and buildings account for more than half of all aluminium use today.

6

Aluminium is also widely used in buildings and for packaging. In buildings, the main demand comes from the construction of windows, doors and facades, roofs and walls. Aluminium packaging can be subdivided into two types: rigid and semi-rigid packaging such as food and beverage cans, aerosol cans, closures and menu trays; and flexible packaging where a thin aluminium foil is laminated as a barrier material to plastics or cardboard. Aluminium is impermeable and keeps out air, light, odour and bacteria. This also makes it useful for preserving cosmetics and pharmaceutical products.

Industry forecasts suggest that the main increases in aluminium demand in the next 10 to 15 years will come from buildings, road and other transport, and electrical cables.

Conclusion: transition pathway for the aluminium sector

Significant progress has been made by the aluminium sector in recent years in improving energy efficiency and reducing GHG emissions. But the performance of different plants and regions still varies widely. This shows that there remains substantial scope for additional energy and GHG savings through implementing BAT. Recognising the potential for further improvements, the members of the International Aluminium Institute have set out a number of short- to medium-term aims for improvements both in energy efficiency and in reducing PFCs.

The widespread deployment of current BAT could reduce energy use by 12% or 0.4 EJ compared to today's levels, with associated CO₂ reductions of 44 Mt.

Energy efficiency improvements in both refining and smelting have an important role to play. Realising these savings in refineries will require improved controls and processes to increase yields of alumina, combined with reduced heat loss, better heat transfer and improved waste-heat recovery, including the introduction of more CHP. In smelting, the main savings will come from improved process controls, reduced heat losses and electricity savings in auxiliary uses such as compressors and fans. Many of these savings are likely to be cost-effective if undertaken as part of the natural cycle of plant replacement. However, the long life of refinery and smelter assets constrains the early realisation of the full benefit from the introduction of new technology.

Implementing current BAT alone will not be sufficient in the longer term if the aluminium industry is to play its full part in global efforts to achieve the levels of CO₂ emissions reduction envisaged in the BLUE scenarios. Further changes will be needed, in particular to:

- increase the use of low-carbon electricity sources;
- increase recycling;
- introduce new smelting technologies and/or CCS; and
- increase the use of aluminium in products where this achieves net energy savings over the whole life cycle of the product.

Reducing CO₂ emissions from the electricity used in smelters is the single largest opportunity for long-term emissions reduction. Currently, around 40% to 50% of the total electricity used by the aluminium industry comes from zero-carbon hydroelectric sources, often in remote locations where there are few competing uses for the electricity. Measures to create a global carbon price would encourage new aluminium plants to be sited where they have access to cheap, low-carbon electricity. In the longer term, the average CO₂ intensity of grid electricity is likely to decrease substantially in many countries so that by 2050 low-carbon grid electricity may become the norm.

Increasing the share of recycling in total production can help reduce energy use and CO₂ emissions. But given the long lifetime of aluminium in some markets and products, over three-quarters of the aluminium ever produced is still in use. Globally, recycled production accounts for around one-third of total aluminium production. In the BLUE scenarios, it is assumed that by 2050 this can be increased to 40% of total production. Although this is a relatively small percentage increase, in absolute terms it is very significant.

Future technological developments could also offer opportunities to reduce the direct emissions of CO₂ from aluminium smelting. But although the two most promising technological developments, inert anodes and carbothermic reduction, have both been the subject of research for many years, neither has yet reached commercial scale. An alternative would be to combine conventional cell technologies with CCS, but again this option is still at the research stage.

Life-cycle analysis shows that increasing the aluminium content of some products can offer overall energy and CO₂ savings compared to the materials currently in use. For instance, a number of studies have concluded that using aluminium to reduce the weight of vehicles can result in reductions in CO₂ emissions over the life of the vehicle, which outweigh the emissions from additional aluminium production.

Chapter 7 CROSS-CUTTING OPTIONS

Key Findings

- ▶ There are a number of cross-cutting options that will be important if industry is to reduce carbon dioxide (CO₂) emissions significantly. Those identified by the scenario analysis include: greater biomass and waste use, fuel switching, carbon capture and storage (CCS), motor and steam systems, combined heat and power (CHP) systems and increased recycling.
- ▶ Fuel switching will be important in most sectors. The use of biomass and waste in the BLUE scenarios will be two to four times higher than current levels, saving between 0.7 Gt CO₂ and 1.3 Gt CO₂ in 2050. Achieving this level of reduction will require fundamental improvements in agriculture and forestry.
- ▶ CCS accounts for 30% to 34% of the direct industry CO₂ reductions in the BLUE scenarios and can play an important role in most carbon-intensive industrial sectors. However, major financial, economic, technical, legal and regulatory barriers still exist. Governments need to take a leading role in overcoming those barriers and in supporting the expansion of research and development (R&D) projects on sector-specific CO₂ capture.
- ▶ Industrial motor and steam systems could deliver efficiency improvements of the order of up to between 9 EJ and 12 EJ of primary energy savings compared to current energy use. This potential fails to be achieved largely because of a lack of awareness by industry, consultants and suppliers. This could be addressed through a combination of policy and educational initiatives.
- ▶ CHP is already making an important contribution to meeting industrial heat and electricity demand in many sectors. But barriers to CHP need to be addressed to allow wider use of the relevant technologies. An estimated 4.5 EJ per year of primary energy savings potential remains for CHP use in industry.
- ▶ The increased use of recycled materials offers an important opportunity to reduce energy demand and CO₂ emissions in the iron and steel, aluminium, paper and chemical industries. The recycling of materials also conserves landfill space and raw materials. The increased use of recycled materials in 2050 saves around 7 EJ to 9 EJ of energy in the BLUE scenarios.
- ▶ The use of waste can reduce global emissions by displacing fossil fuels at industrial facilities. It also results in CO₂ and methane (CH₄) emissions reductions in waste handling.
- ▶ Most of the cross-cutting options to reduce energy use and related direct CO₂ emissions will have an impact on, or be affected by, changes in other sectors. Full life-cycle analysis would be required to obtain a global impact assessment of the different options proposed. Such analysis is beyond the scope of this publication.

Introduction

The BLUE low- and high-demand scenarios analysed in this book are driven by the assumption that worldwide CO₂ emissions in 2050 will be half the level they were in 2006. To achieve this in the most cost-effective way, the industrial sector would have to reduce its direct energy and process emissions by approximately 21% between 2006 and 2050.

CO₂ emissions reductions on this scale cannot be made with the technologies available today (IEA, 2008a). Fuel switching, the widespread use of best available technologies, the development of more efficient technologies, efficiency measures and CCS, where appropriate, will be needed in combination with the development, deployment and use of technologies which are not yet available at a commercial scale.

CO₂ emissions in industry can be reduced in four main ways: through fuel and feedstock substitution, such as the greater use of biomass; through CCS; through the use of efficient technologies such as CHP; and through efficiency measures. The objective of this chapter is to provide an overview of those measures and technologies that have the potential to play a part in more than one industry sector, *i.e.* biomass, waste, alternative fuels, the use of recycled and recovered materials, the development and deployment of CCS, and system optimisation.

The chapter estimates the energy and CO₂ reduction potentials associated with each of these cross-cutting measures in industry and assesses their viability. It does not, however, seek to provide a full life-cycle analysis of material options (*e.g.* assessing the impact of the recycling of concrete in the cement sector). That is beyond the scope of this chapter.

Fuel switching, that is substituting fossil fuels with low-carbon energy sources, has an important part to play in reducing CO₂ emissions from industry. For example, biomass and waste will constitute between 16% and 20% of industry's (including electricity generation) fuel and process feedstocks in the BLUE low- and high-demand scenarios respectively in 2050, up from 7% in 2006. Between 0.7 Gt CO₂ and 1.3 Gt CO₂ of the reduction in direct CO₂ emissions in the BLUE scenarios is attributable to the increased use of biomass and waste. Achieving this would require fundamental improvements in agriculture and forestry. Paper, iron and steel, cement and chemicals will have to compete for biomass and waste feedstock with the energy transformation, residential, transport and commercial sectors. Growing competition may increase the price of this feedstock substantially. The development and use of high-yield crops, water management, soil management, land-use policies and ecological sustainability will all need to be taken into account in a closely co-ordinated and coherent manner in order to ensure that biomass is used in an environmentally and economically sustainable way.

A number of common systems, such as pumping, compressed air, and fan systems (referred to collectively as motor systems), steam systems, and process heating systems, are widely used in industrial applications. Substantial opportunities exist for improving the energy efficiency of these systems. Realising this potential is hindered by barriers that are primarily institutional and behavioural, rather than

technical. The fundamental problem is lack of awareness of the energy efficiency opportunities by industry, consultants and suppliers, and insufficient training on how to implement them. Even if energy-efficient components are applied, this is no assurance of an efficient operating system. A system-wide perspective is needed.

The proven, reliable and cost-effective technologies that enable CHP, or co-generation, are already making an important contribution to meeting industrial heat and electricity demand. But their development and adoption by industry is restrained by a range of barriers that need to be overcome if industry is to be able to take advantage of the reductions that they can achieve.

In the BLUE scenarios, CCS in the iron and steel, cement, chemicals and paper sectors would account for about 30% to 34% of the total direct emissions reductions in the industrial sector. Although CO₂ capture technology is already at the demonstration stage in many sectors, transportation and storage still pose important challenges. More research is required to identify appropriate storage sites in different regions of the world and to prove their suitability for long-term storage. Initial assessments suggest that storage capacity might be limited in some regions. Some of the sites currently identified are relatively far from the point sources at which CO₂ can be captured. The sustainable transportation and storage of CO₂ will depend on industry and other potential users of CCS working closely with governments at several levels in order to develop a system that will maximise economic benefit. Industries need rapidly to expand CO₂ capture technology research, development and deployment, so that these technologies are in a position to deliver when governments resolve the legal and financial problems associated with CO₂ transportation and storage.

The recycling of materials and the use of waste products as energy sources conserve energy, landfill space and, in the case of recycling, raw materials. Using recycled and waste materials enables industries to reduce their energy needs and associated CO₂ emissions. They are therefore attractive options for industry. The greater use of recovered paper and the recycling of scrap aluminium and iron and steel could save about 7 EJ to 9 EJ of energy a year.

The substitution of fossil fuels by alternative fuels and other materials such as municipal waste reduces global emissions and also results in CO₂ and CH₄ emissions reductions in waste handling. Municipal solid waste is currently responsible for 13% of total global CH₄ emissions (IEA, 2008a). Increasing competition for waste resources will increase prices. It is estimated that the price of waste may increase to between 25% and 35% of the coal price in 2030 and between 65% and 75% by 2050. Policies related to waste will have to be co-ordinated to ensure that its use in combustion does not result in a net increase in overall greenhouse gas (GHG) emissions, for example as a result of less stringent emission controls on industrial installations than on waste incineration installations.

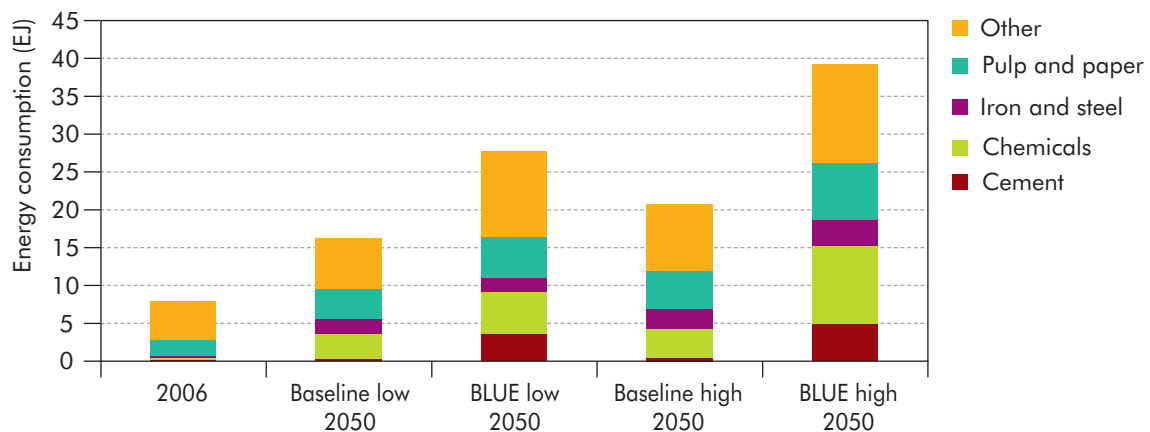
Biomass and biomass-waste use

Renewable biomass is considered as a CO₂-free energy carrier, as it absorbs in its growing phase the carbon it emits when it is combusted. The substitution of

biomass for fossil fuels is an attractive means of reducing CO₂ emissions in the iron and steel, cement, chemicals and petrochemicals, and pulp and paper sectors.

In the BLUE scenarios, industry's use of biomass and waste will be two to four times higher in 2050 than in 2006, increasing from 7 EJ to 28 EJ in the low-demand case or 39 EJ in the high-demand case. The largest increase will be in the chemical and petrochemical sector, followed by the cement and iron and steel sectors (Figure 7.1). In the pulp and paper sector, biomass already represents 36% of total energy use and this share is expected to rise to about 60% in the BLUE scenarios in 2050. In the iron and steel sector, the use of biomass and waste rises to 1.8 EJ and 3.4 EJ in 2050 in the BLUE low- and high-demand scenarios respectively. Bio-based feedstock and biomass used as energy in the chemical and petrochemical sector will represent between 9% and 15% of total energy used. In the cement sector, about 32% of alternative energy used in 2050 is assumed to come from combustible biomass, with the use of tyres, rugs and other waste accounting for the remainder.

Figure 7.1 ► Use of biomass and waste in the industrial sector



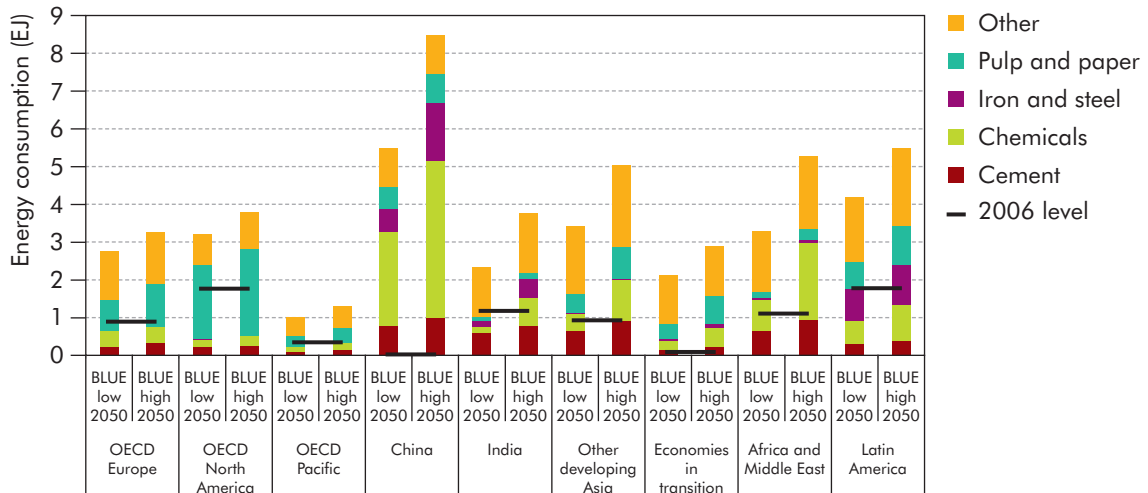
Sources: IEA analysis; IEA (2008b and 2008c).

Key point

Use of biomass and waste in industry will be three to five times higher in 2050 than in 2006.

The increased use of biomass in the industrial sector will be smaller in countries where it is already widely used than in countries where biomass is currently primarily used in other applications such as residential heating and cooking. So, for example, OECD North America will increase its use of biomass from 1.7 EJ in 2006 to between 3.2 EJ and 3.8 EJ in 2050 while in China the use of biomass in industry will increase from zero in 2006 to between 5.5 EJ and 8.5 EJ in 2050.

The industrial sector will have to compete with other sectors of the economy for biomass resources. To assess whether or not the increased use of biomass by industry is sustainable, it would be necessary to analyse at global, national and sub-national levels the use of biomass throughout the economy through a full life-cycle analysis. This chapter provides some insight into the estimated future potential of biomass, but a full life-cycle analysis is beyond the scope of this publication.

Figure 7.2 Use of biomass in the industrial sector by region

Sources: IEA analysis; IEA (2008b and 2008c).

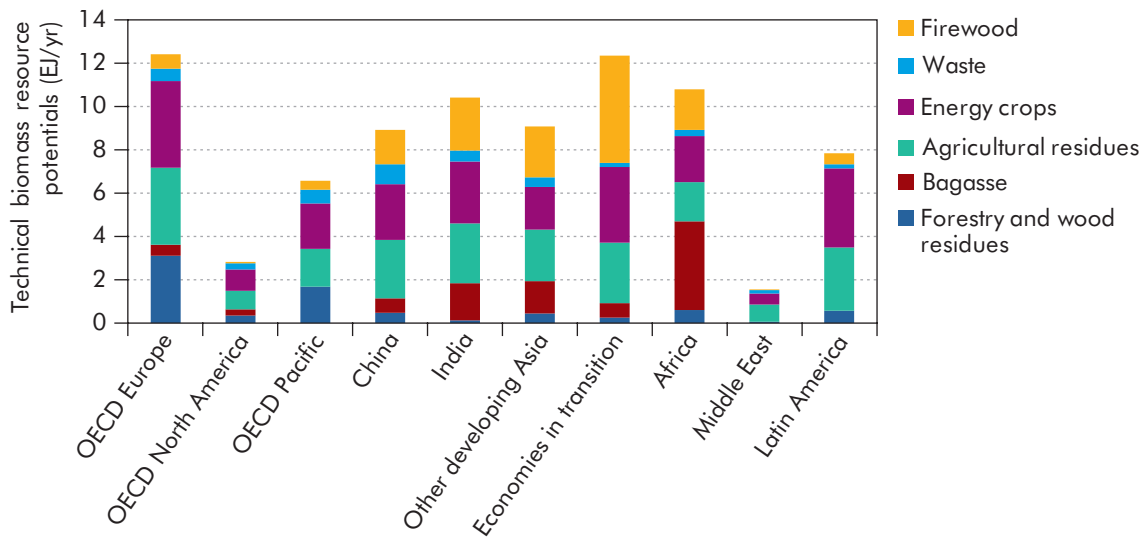
Key point

Biomass and waste will be used increasingly in all regions, but most notably where it is not currently widely used by industry.

Predictions of land availability and crop yields, environmental requirements, and the future availability of woody biomass and crop residues vary widely. As a result, estimates of the biomass energy resources that can be produced sustainably from waste, energy crop, agricultural, forest and industrial residues also vary significantly.¹

Competitive demand for the limited amounts of biomass available to meet the energy needs of the industry, power generation, transport, commercial and residential sectors will increase prices. If demand is concentrated in certain countries and regions, particularly in food-producing areas, it could have substantial impacts in terms of crop displacements and other land-use changes. Rapid increases in the production of biofuels in the United States and Europe in recent years, for example, appear to have contributed to rises in the price of certain agricultural commodities (such as corn in the United States and rapeseed oil in Europe) as competition for crops and land has increased (IEA, 2008a). Bio-based (including biodegradable) chemicals and plastics have also been receiving increased attention in the last decade in response to problems with waste management (limited capacities and littering), recent high prices for fossil fuels and feedstocks, unclear medium- to long-term supply security issues, technological progress and policy goals (including climate policy). Close monitoring and full life-cycle analysis would be necessary to develop measures to ensure that biomass is used in a sustainable manner and to mitigate potential negative environmental and economic impacts.

1. See for example IPCC (2007): 125 EJ to 760 EJ by 2050; Hoogwijk *et al.* (2003) and IEA Bioenergy (2007): 40 EJ to 1 100 EJ; Parikka (2004): 104 EJ; Haberl *et al.* (2007): 78 EJ to 450 EJ; and Fisher and Schratzenholzer (2001): 350 EJ to 450 EJ. Regional analysis by the VTT Technical Research Centre of Finland (VTT, 2007) projects a more moderate potential of 83 EJ by 2050.

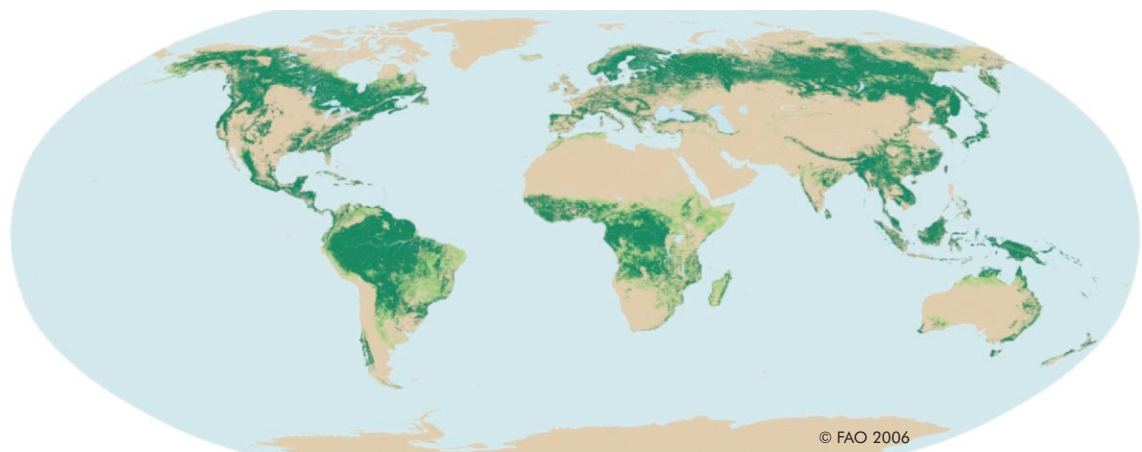
Figure 7.3 ▶ Technical biomass resource potentials by region in 2050

Source: VTT (2007).

Key point

The technical biomass potentials and their source vary greatly from region to region.

In 2006, 1.87 billion m³ of fuel wood was produced. This represents approximately 45 EJ of energy. In the *Energy Technology Perspective BLUE Map scenario* (IEA, 2008a), strong growth in biofuels production combined with biomass use for manufacturing industries, electricity generation, biochemicals, heating and cooking, leads to biomass consumption rising to 150 EJ in 2050. Of this, 80% will be from wood, equivalent to 5 billion m³ to 5.5 billion m³ of fuel wood. This implies that fuel wood consumption by 2050 would almost triple from current levels. Fuel wood consumption would constitute an estimated 65% to 75% of total wood consumption in 2050, compared to 53% in 2006.

Figure 7.4 ▶ The world's forests

Forest Other wooded land Other land Water

Source: Food and Agriculture Organisation of the United Nations (2006).

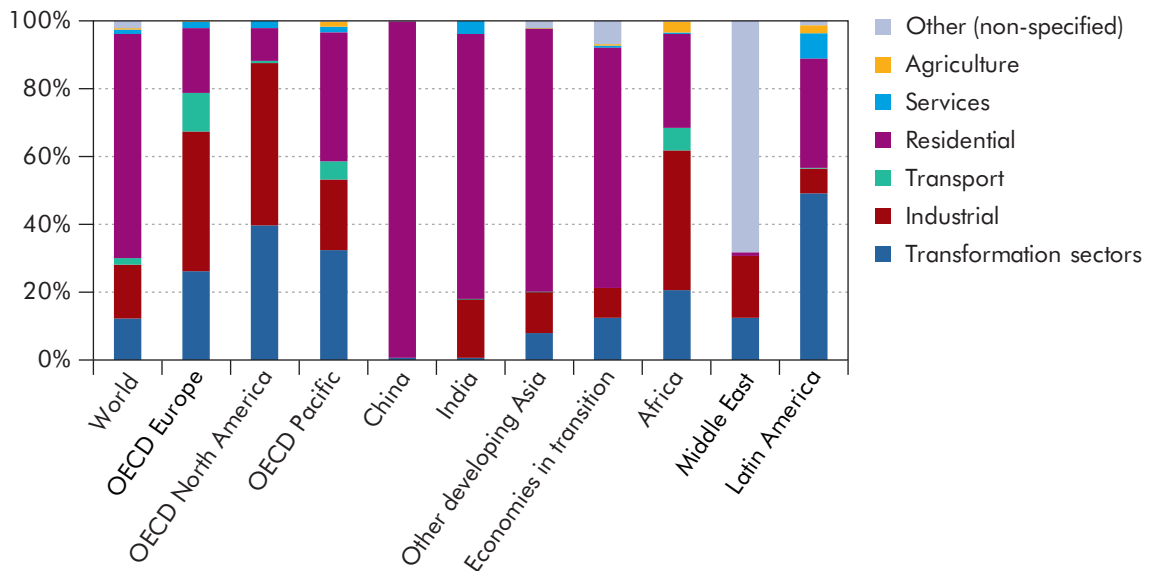
Key point

Biomass availability is limited in most countries.

Bioenergy is estimated technically and economically to be able to supply up to between 250 EJ and 450 EJ a year in 2050 (EUBIA, 2005). This suggests that there will be enough to meet the increased demand for bioenergy in the BLUE Map scenario, where about 150 EJ of biomass is required. In the industry BLUE scenarios, between 28 EJ and 39 EJ of biomass and waste will be used.

Biomass availability is limited in most countries. On a regional basis, the uses of biomass and waste vary widely. In non-OECD countries, 75% of the biomass used is used in the residential sector; the second-largest user is the industrial sector at 12%. For OECD countries, the largest user is the industry sector (33% of total biomass), followed by the transformation sector (31%) (Figure 7.5). Only 25% of the biomass used in OECD countries is used in the residential sector. Globally, 66% of biomass is used in the residential sector; the industry and transformation sectors use 16% and 12% respectively.

Figure 7.5 ► Final consumption of biomass and waste by region in 2006



Sources: IEA analysis; IEA (2008b and 2008c).

Key point

In non-OECD countries biomass and waste is mostly used in the residential sector.

In the BLUE high-demand scenario in 2050, the industrial sector would use between 4.5% in OECD Pacific and 20.5% in Europe of the total bioenergy potentially available (Table 7.1).

For some regions, the availability of biomass might become an issue. For example, the industrial sector in Asia is expected to utilise between 13% and 16% of the biomass potentially available in 2050; this percentage is much higher than the 9% used in 2006. This shows the importance of improving the efficiency of the use of biomass in all sectors and of defining other steps to increase the availability and sustainability of biomass. More detailed data on the expected use of biomass in sectors other than industry as well as more work on the bioenergy potential

of individual countries would be required to accurately assess the availability of biomass, its sustainable use as an alternative source of energy and its impact on food production and prices.

Table 7.1 ► **Biomass and waste usage in the industrial sector and potential**

	Biomass and waste use in industry 2006		Biomass and waste use in industry 2050		Total bioenergy potential 2050		Use/potential 2050	
	(EJ)	(% of total)	BLUE low (EJ)	BLUE high (EJ)	Low estimates (EJ)	High estimates (EJ)	Low	High
OECD North America	1.7	41.3%	3.2	3.8	40.5	51.5	7.9%	7.4%
Africa and Middle East	1.1	8.9%	4.2	7.3	80.7	103.0	5.3%	7.1%
Latin America	1.8	41.3%	4.2	5.5	40.4	50.5	10.4%	10.9%
OECD Pacific	0.3	48.0%	1.0	1.3	22.4	28.2	4.5%	4.6%
Asia	2.1	8.8%	11.2	17.3	98.5	125.1	11.4%	13.8%
Former Soviet Union	0.1	8.3%	3.0	4.1	35.0	43.8	8.6%	9.4%
Other Central and Western Europe	0.8	21.4%	2.7	3.3	13.4	17.0	20.5%	19.1%
TOTAL	7.9	15.9%	29.6	42.5	330.9	419.2	9.0%	10.1%

Sources: Fisher and Schratzenholzer (2001); IEA analysis.

Given the many uncertainties associated with the use of biomass and biofuels and their impact on the environment and agricultural systems, it is important to manage these changes carefully and to seek the most environment-friendly and least land-intensive approaches, using waste and/or land not otherwise best used for crops wherever possible. For example, to avoid displacing food production, ligno-cellulosic feedstock in the chemical sector can come from crop and forest residues, or be cultivated on marginal or degraded land. Policies related to the use of biomass and biofuels will need to be co-ordinated internationally if sustainability is to be maximised.

Developments in the use of biomass in the BLUE scenarios would require fundamental improvements in agriculture and forestry. The world population is expected to grow by 50% by 2050, with food intake rising correspondingly. The development and use of high-yield crops, water management, soil management, land-use policies and ecological sustainability all need to be closely co-ordinated.

Apart from biomass, there are several other forms of renewable energy which may contribute substantially to reduce fossil fuel energy demand in some sectors in suitable climate zones. For example, solar thermal energy can be used in the

chemical sector for drying and evaporation processes and power can be taken from renewable or nuclear sources. These opportunities need to be further explored.

Systems optimisation

Electric motor-driven systems

Motor-driven equipment such as compressors, pumps or fans account for 60% of the electricity consumed in the industrial sector and for more than 30% of all electricity use. Improved motors could save significant amounts of energy. Optimisation of motor systems can typically result in 20% to 25% efficiency gains.

It is estimated that up to 7% of global electricity demand could be saved if the energy efficiency of motors and their related drive systems were to be cost-optimised. In Europe alone, studies suggest that the implementation of energy efficiency options for motors could result in 29% savings. The total investment cost of such a programme would be USD 500 million, while the annual saving would amount to USD 10 billion (Keulenaer *et al.*, 2004).

The performance of motor systems can be improved by optimising them to meet end-use requirements. Since the power consumption of the drive varies with the cube of the motor rotation speed, small changes in motor speed can yield large energy savings. In the absence of electronic variable-speed controls, the bulk of the energy used on motors in many industries is simply converted into waste heat.

The electricity demand of industrial motor systems can be reduced by:

- Using high-efficiency motors.
- Proper sizing of the motor to the load requirements. Many motors are oversized and, therefore, run at sub-optimal load factors. This significantly reduces efficiency and power use.
- Using adjustable-speed drives (ASD) to match speed and torque with the load requirements. The savings potential here depends critically on the load. Systems operating at around full load would be less efficient by about 3% if they used ASD electronics. The savings potential, therefore, needs to be assessed for each individual motor system. In general, savings of 10% to 20% can be achieved, but savings of up to 60% are possible for specific systems if ASD is applied instead of throttling.
- Replacing inefficient throttling devices and/or simplifying or avoiding wasteful mechanical transmissions.
- Optimising systems, including the motor-driven equipment (fans, pumps, compressors, traction and conveyance systems), distribution (pipes, ducts, and flow control devices such as valves, regulators and dampers) and end-use equipment (including tools, presses, heat exchangers and mixers) used to deliver energy services.

- Proper maintenance and repair. For example, poor rewinding can damage motors and lower their efficiency significantly, and dirty heat-exchange surfaces or filters can reduce system efficiency.
- Maintaining acceptable levels of power quality.

Modern high-efficiency motors use better-quality materials, are made more precisely, and are about 85% to 95% more efficient than many motors in current use, depending on size. Although the cost of an efficient motor may be 20% more than standard motors, motor losses decrease by 20% to 30%. In most applications, the payback time is less than three years. Using new motors instead of rewinding used ones is another efficiency option, as rewinds cause an overall efficiency reduction of 1.5%.

The replacement of standard-efficiency motors with high-efficiency models is likely to capture only about 10% of the total energy saving potential available. The remainder will come from a combination of proper motor sizing, appropriate use of ASD, and other measures listed above. More than 90% of all industrial motors in the European Union operate at or below standard efficiency, while more than 70% of all motors in the United States and Canada are high- or premium-efficiency motors (Brunner and Niederberger, 2006). The potential of some of the more significant improvements in available motors and systems is set out in Table 7.2. Depending on the application, some measures can be applied as retrofits to existing motors and motor systems, while others can only be applied to new motors. Most systems can be adapted in some way to improve energy efficiency.

Compressors, pumps and fans consume more than half the energy used in industrial motor applications. Pumps are very important in the chemical industry, where they use 37% to 76% of motor power, but compressor consumption varies widely in the same industry, from 3% to 55%. Pump systems, compressor systems and fans are often coupled with over-powerful motors, especially for small- and medium-power uses. As a consequence, the systems operate most of the time at only a fraction of their optimal load. This results in significant efficiency losses. In industrial pumps, energy efficiency can vary between 40% and 90%, depending on the design and the application.

The prevalence of energy efficient motors has substantially increased, but the potential increase in motor system efficiency remains largely unrealised due to the lack of national standards and policies to encourage companies to integrate energy efficiency into their management practices. Given the savings potential in terms of total electricity use, a much more comprehensive approach is warranted and needed.

The total energy savings potential for upgrades in motors and motor systems has been estimated to be from 15% to 25%. It could be higher when emerging technologies are included. The total energy savings will depend on the market penetration of new motors, controls and system improvements. In turn, this rate will depend on the success of government programmes to support their adoption and of technology transfer programmes.

Table 7.2 ► Cost estimates for emerging motor technologies

Technology	Current capital costs	Capital costs by 2025	Operating and management costs	Payback by 2025	Notes
New motors					
Super-conductor	Higher than existing motors	Lower than existing motors	Lower than existing motors	Up to one year	If wire costs decrease, the payback period will be short to none. At present only for large motors.
Permanent magnet	Roughly equal	Roughly equal	Lower	One to three years	
Copper rotor	Higher	Potentially lower	Lower	Up to one year	If die casting costs decrease, payback periods will be short to none.
Written pole	60% higher	30% higher	Lower		
Switched reluctance	50% higher	25% higher	Unclear		Controls are more complex, but switched reluctances are more efficient. The choice will be driven by reliability.
System and end-use improvements					
Optimisation by experts	None	None	Higher initially, then lower	Up to one year	Cost of expertise outweighed by energy efficiency savings.
Optimisation tools	None	None	Higher initially, then lower	Up to one year	Cost of time spent on tools outweighed by energy efficiency savings.
Training programmes	None	None	Higher initially, then lower	About one year	Cost of employee time (in training) outweighed by energy efficiency savings.
Premium lubricants	50% to 150% higher	50% to 150% higher	Lower	About one year	Premium lubricants last three to four times as long.
Controls					
Advanced adjustable-speed drives	Higher	Higher	Significantly lower	One to four years	Initial capital costs are comparable to those for conventional ASDs. Advanced ASDs that provide sag control pay for themselves once they prevent a single shut-down.

Source: Worrell et al. (2004).

Steam systems

A large share of industrial energy use is in the form of low-temperature heat, for which steam is usually the preferred energy carrier. The efficiency of steam boilers can be as high as 85%, but average efficiency is lower, mainly because of low load factors and poor maintenance. Average boiler efficiency in China is about 65%. Boilers are usually only one part of a steam supply system. Steam and heat

losses from pipes and ducts are important as well. There are no detailed statistics regarding overall system efficiencies.

The main efficiency improvement options are to replace the steam boiler with a CHP system or with a heat pump. The resulting efficiency gains are very site-specific. Energy efficiency can be enhanced by improving steam supply systems, but even greater emissions savings may be achievable by reductions in steam demand. In the last few decades, for example, the chemical industry has successfully developed new catalysts and process routes that significantly reduce steam use.

The data in Table 7.3 indicate the savings potential for steam systems only and do not include any possible measures related to reducing steam demand.

Table 7.3 ► Steam system efficiency measures

	Typical savings (%)	Typical investment (USD/GJ steam)	Use in OECD countries (%)	Use in non-OECD countries (%)
Steam traps	5%	1	50%	25%
Insulation pipelines	5%	1	75%	25%
Feedwater economisers	5%	10	75%	50%
Reduced excess air	2%	5	100%	50%
Heat transfer	1% to 2%	-	75%	50%
Return condensate	10%	10	75%	50%
Improved blowdown	2% to 5%	20	25%	10%
Vapour recompression	0% to 20%	30	10%	0%
Flash condensate	0% to 10%	10	50%	25%
Vent condenser	1% to 5%	40	25%	10%
Minimise short cycling	0% to 5%	20	75%	50%
Insulate valves and fittings	1% to 3%	5	50%	25%

Sources: United States Department of Energy (2002); IEA estimates.

Much of this potential has already been achieved in OECD countries, but inadequate attention to the routine maintenance of some measures, such as steam traps, valves and heat-transfer surfaces significantly reduces the benefit derived from these measures. In many developing countries, the losses from steam supply systems remain substantial. Insulation is often non-existent in Russia, for example. In China, many small-scale boilers operate with considerable excess air and incomplete combustion of coal. Poor coal quality is the main cause for the low efficiency of Chinese boilers.

For more information on systems optimisation, readers are referred to the IEA publication *Tracking Industrial Energy Efficiency and CO₂ Emissions* (IEA, 2007).

Combined heat and power (CHP)

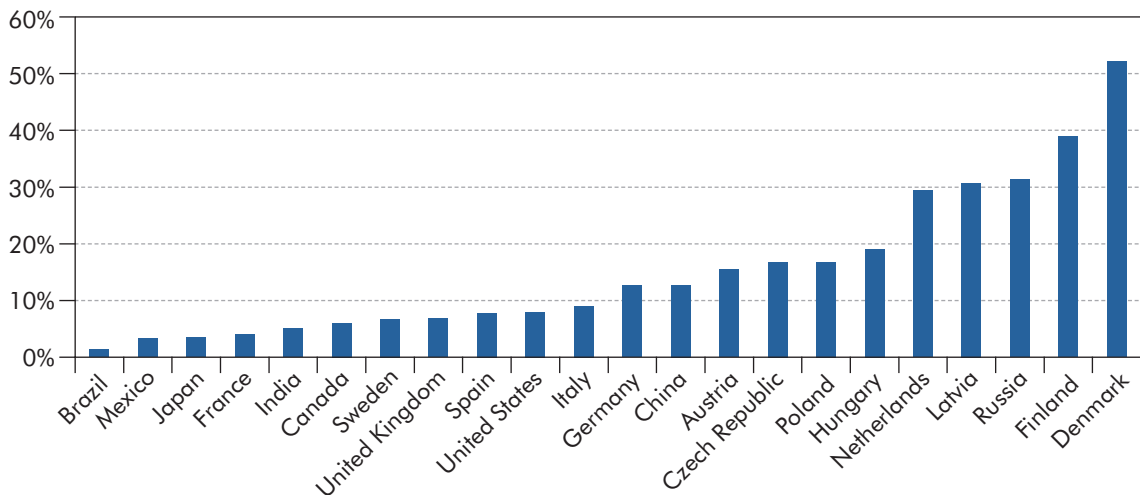
CHP, or co-generation, is already making an important contribution to meeting industrial heat and electricity demand. For example, over 50% of Denmark's electricity generation is from CHP. But although some regions have been able to achieve a high share of this technology, most countries have been much less successful. The estimated savings from the use of CHP are 4.5 EJ (IEA, 2007).

Policy makers and industry are supporting the wider use of CHP because it can deliver a variety of energy, environmental and economic benefits, including:

- cost savings for the energy consumer;
- lower CO₂ emissions;
- reduced reliance on imported fossil fuels;
- reduced investment in energy system infrastructure;
- enhanced electricity network stability through reduction in congestion and “peak-shaving”; and
- beneficial use of surplus local energy resources, particularly through the use of waste, biomass and geothermal resources in district heating/cooling systems (IEA, 2009).

As shown in Figure 7.6, although a few countries have successfully expanded the use of CHP to more than 20% of their total power generation, most have not achieved anything like that level.

Figure 7.6 ► CHP share of total national power production



Source: IEA (2009).

Key point

Only a few countries have successfully expanded the use of CHP to between 30% and 50% of total power generation.

CHP technologies

CHP involves the exploitation of surplus heat and power from industrial processes or from energy generation which would otherwise be wasted. To optimise the energy use, CHP systems need to be designed to meet the heat demand imposed on them since it costs less to transport surplus electricity than surplus heat. It makes sense therefore to regard CHP as a source of heat, with electricity as a by-product, rather than vice versa.

CHP can take many forms and encompasses a range of technologies. But it will always be based upon an efficient, integrated system that combines heat recovery and electricity production. By using the heat output from the electricity production for heating or industrial applications, CHP plants generally convert 75% to 80% of the fuel source into useful energy. Modern CHP plants can reach efficiencies of 90% or more (IPCC, 2007).

CHP plants consist of four basic elements: a prime mover (engine or drive system), an electricity generator, a heat recovery system, and a control system. In driving the electricity generator, the prime mover creates usable heat that can be recovered. CHP units are generally classified by the type of application, prime mover and fuel used. Almost any fuel is suitable for CHP, although natural gas currently predominates in new systems coming on stream. Other common fuel sources include fossil fuel-based commercial fuels, municipal solid waste and biomass. As biomass and industry-derived gases become more available and cheaper, they will be of increasing importance, given growing environmental and energy security concerns. Some CHP technologies can use multiple fuel types, providing valuable flexibility at a time of growing fuel insecurity and price volatility.

CHP applications

CHP systems can be utilised at most industrial sites that meet the following criteria:

- a ratio of electricity to fuel costs of at least 2.5:1;
- annual demand for heating and/or cooling for at least 5 000 hours a year;
- the ability to connect to the grid at a reasonable price, with the availability of backup and “top-up” power at reasonable and predictable prices; and
- availability of space for the equipment and short distances for heat transportation (IEA, 2009).

CHP is already widely used in those industrial applications which have large concurrent heat and power demands. Advances in technology development have led to the availability of smaller CHP systems, with reduced costs, reduced emissions and capacity for greater customisation. As a result, CHP systems are increasingly being used for smaller-scale industrial applications, including in food processing, ceramics, textiles and other industries. These applications are summarised in Table 7.4.

Energy-intensive industrial sites in the food-processing, pulp and paper, chemicals, metals and oil-refining sectors represent more than 80% of the

total global electric CHP capacity (IEA, 2007). These plants generally have predictably steady, high process-related thermal requirements not subject to daily and seasonal weather-related fluctuations. Energy is normally an important part of their business, so operational and maintenance staff is available and competent to manage CHP systems. In some industries, low-cost fuel sources (*i.e.* waste streams) are available for use in CHP systems. While industrial systems over one MW_e make up the bulk of global CHP capacity, many smaller-scale industrial sites have smaller systems, utilising technologies similar to those used in commercial buildings.

Table 7.4 ► **CHP applications**

Feature	CHP: industrial applications
Typical customers	Chemical, pulp and paper, metallurgy, heavy processing (food, textile, timber, minerals), brewing, coke ovens, glass furnaces, oil refining
Ease of integration with renewables and waste energy	Moderate to high (particularly industrial energy waste streams)
Temperature level	High
Typical system size	1 to 500 MW _e
Typical prime mover	Steam turbine, gas turbine, reciprocating engine (compression ignition), combined cycle (larger systems)
Energy/fuel source	Any liquid, gaseous or solid fuels; industrial process waste gases (<i>e.g.</i> blast furnace gases, coke-oven waste gases)
Main players	Industry (power utilities)
Ownership	Joint ventures/third party
Heat/electricity load patterns	User- and process-specific

Source: IEA (2009).

The introduction and sizing of CHP in the industrial sectors depends on the availability of fuel resources such as waste fuels in the pulp and paper sector or natural gas in other sectors. It also depends on heat and electricity demand and on arrangements with the electricity grid both for the sale of surplus power and for the purchase of backup power. The grid can provide backup power for many CHP plants during maintenance or down times, although different types of industrial facilities have different levels of tolerance for the loss of thermal load. The availability and price of natural gas, the fuel of choice for most new industrial CHP systems, will be an important factor in the growth of CHP in industrial applications.

CHP barriers and policy solutions

CHP faces a complex set of economic, regulatory and social/political barriers that restrain its wider use. These include:

- difficulty in securing a fair market value for any electricity that is exported to the grid;
- high upfront costs compared to large power plants;
- difficulty in concentrating suitable heat loads in favourable locations;
- timely and cost-effective grid access. Incumbent utilities are usually resistant to losing customers to CHP;
- non-transparent and technically demanding interconnection procedures;
- a lack of knowledge among consumers and policy makers about CHP energy/cost/emission savings;
- industry perceptions that CHP is an investment outside their core business; and
- a lack of integrated planning for heat supply that would make projects more cost-effective.

A few countries such as Denmark, Finland and the Netherlands have been successful in addressing these barriers by investing in policies that allow CHP to compete on equal terms in the marketplace. The evidence from these and other countries is that the success of industrial CHP depends less on substantial financial incentives than on targeted, effective government policies. For example, Finland does not provide financial or other fiscal incentives for CHP. Instead, it requires utilities to provide grid access for all CHP plants. This has resulted in one of the most vibrant markets for CHP in the world (IEA, 2008d).

There are a variety of policies that countries have used to address these barriers, including:

- utility supply or interconnection obligations;
- more effective local infrastructure and heat planning;
- supportive measures on climate change mitigation (e.g. double benchmarking in emissions trading schemes to recognise the heat and power outputs of CHP plants); and
- capacity building and outreach.

The IEA has fully analysed and assessed these policies in a recent report (IEA, 2009). The Agency continues to work on these issues through the International CHP/DHC Collaborative (see www.iea.org/G8/CHP/chp.asp).

Carbon capture and storage (CCS)

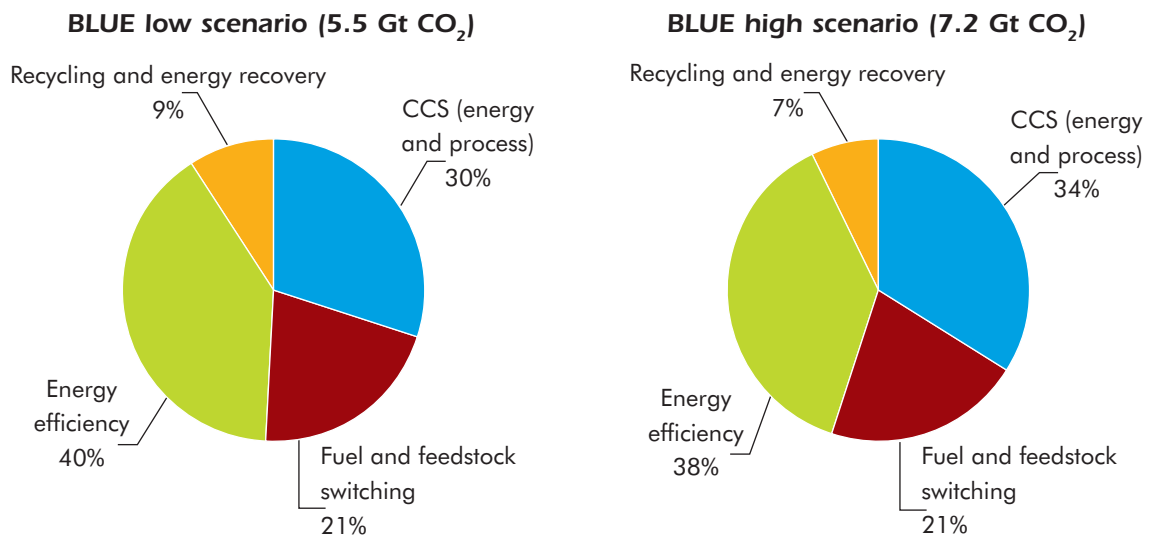
CCS is the only technology available to mitigate CO₂ emissions from large-scale fossil-fuel use in the power and industrial sectors. The *Energy Technology Perspectives* scenarios (IEA, 2008a) indicate that CCS will need to contribute nearly one-fifth of the emissions reductions required to achieve an overall 50% reduction

in CO₂ emissions by 2050 at a reasonable cost. Attempting to achieve this level of reduction without using CCS would increase the annual cost by 71%.

Directly or indirectly, manufacturing industries account for more than one-third of global energy use and CO₂ emissions. The iron and steel and cement sectors represent over half of industry's emissions; the chemical and petrochemical sector is the next largest source. Achieving the 21% reduction in direct energy and process CO₂ emissions that is needed from industry to support the delivery of the overall outcomes implicit in the BLUE scenarios will be difficult and will require the widespread application of CCS at large, energy-intensive plants.

Overall, between 1.7 Gt CO₂ and 2.4 Gt CO₂ emissions reductions need to be achieved through the application of CCS in industry in the BLUE low- and high-demand scenarios respectively, accounting for between 30% and 34% of the total direct emissions reductions against the Baseline scenarios in 2050 (Figure 7.7). Without CCS, direct CO₂ emissions in the industrial sector in 2050 would be 3% to 13% higher in 2050 than in 2006.

Figure 7.7 ► Reductions in industry direct CO₂ emissions in the BLUE scenarios against the Baseline scenarios, 2050

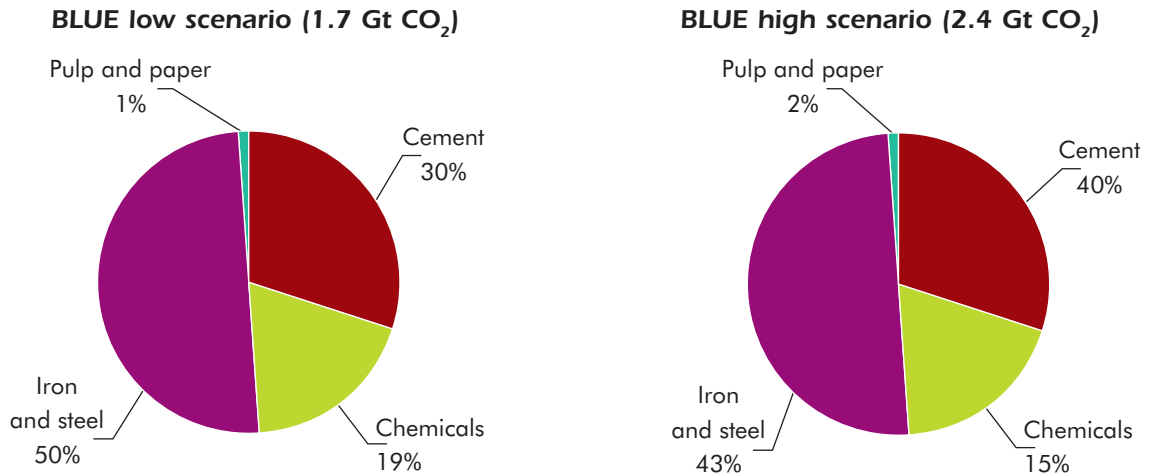


Key point

Over 70% of the CO₂ reductions in the BLUE scenarios will come from improved energy efficiency and CCS.

In the BLUE scenarios, CCS technology is applied in the iron and steel, pulp and paper, chemical and petrochemical and cement sectors. In the iron and steel sector, CO₂ is captured from blast furnaces, smelting reduction and direct reduced iron production plants. Capture in the cement sector is from rotary kilns for clinker production. In the chemical and petrochemical sector, capture is mainly in ammonia production and from CHP units. In the pulp and paper sector, capture is used with large CHP units and black liquor gasifiers in pulp production (Figure 7.8).

Figure 7.8 ► Breakdown of industrial CO₂ emissions reductions from CCS by sector, 2050

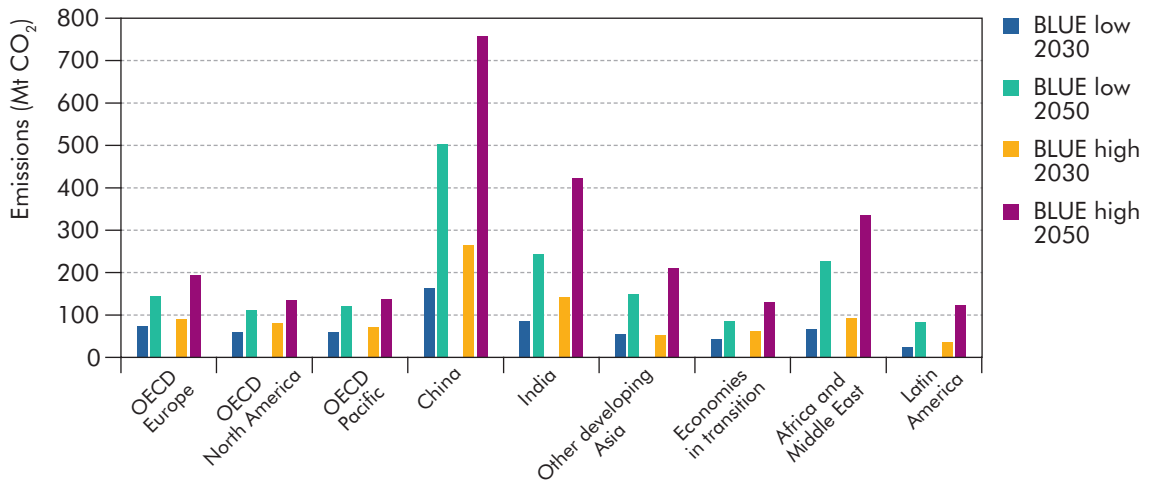


Key point

There are important opportunities for CCS in the iron and steel and cement sectors.

Figure 7.9 shows CCS in the industry sector by region in the BLUE scenarios. In 2030, about 30% of total capture takes place in OECD countries. This share is down to 23% and 19% in 2050 in the BLUE low- and high-demand scenarios respectively. China and India alone account for between 45% and 48% of the total capture in the industrial sector in the BLUE scenarios in 2050.

Figure 7.9 ► Regional breakdown of CCS in the industry sector in the BLUE scenarios



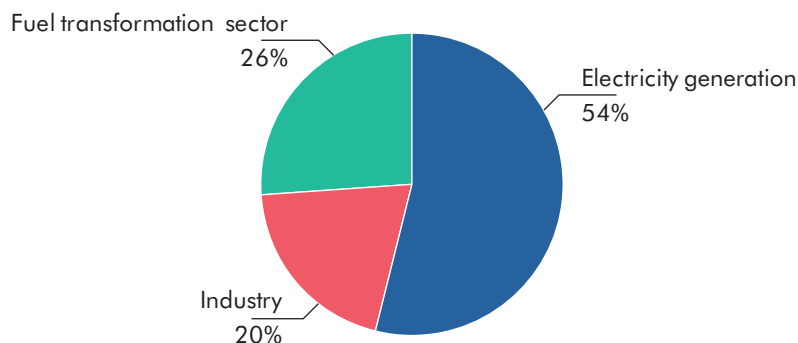
Key point

Non-OECD countries will account for an increasing share of the total CCS in industry.

Developing countries account for the bulk of the economic activity and for two-thirds of the CO₂ emissions in the Baseline scenarios. Spreading CCS technology to these countries will require international co-operation to maximise the impact of CCS as an abatement option.

The capture and storage of CO₂ emissions is an important contributor to the achievement of the BLUE Map outcomes not only for the industrial sector but also for the electricity generation and fuel transformation sectors (Figure 7.10). CCS in industry accounts for only 20% of the total reductions from CCS in the BLUE Map scenario (IEA, 2008a).

Figure 7.10 ▶ Share of CCS by sector in the BLUE Map scenario



Source: IEA (2008a).

Key point

Not only will CCS play an important role in the decarbonisation of the electricity generation sector, it will be key to the reductions in industry and fuel transformation.

Given the role that CCS needs to play in a number of sectors, the co-ordination for the development of CO₂ pipeline transportation infrastructure and storage sinks will be particularly important. As CCS builds from demonstration to commercialisation, CO₂ transportation networks will need to be co-ordinated on a regional, national and international level to optimise infrastructure development and to lower costs.

Table 7.5 provides a breakdown of regional CO₂ capture potentials in the industrial sector in the BLUE low- and high-demand scenarios alongside the storage potential of each region. The capture and storage potentials provide a snapshot of the current state of play in CCS development. Although CCS is an important option for limiting CO₂ emissions, some regions may at some point in time face storage limitations. For example, India has an expected capture potential of 900 Mt per year; capture from industry in the BLUE high scenario is expected to account for 51% of this, leaving only 49% of the potential for the fuel transformation and electricity generation sectors. Suitable CO₂ storage capacity may also be an issue in other regions such as Japan and Europe.

Figure 7.11 shows the location of the most promising sites for CO₂ storage. Storage in oil and gas wells, where enhanced oil and gas recovery can mitigate

costs, is expected to provide an early start for CO₂ storage. In the longer run, it is widely expected that saline formations will offer the most appropriate CO₂ storage options. As a result, governments are investing in capacity so as to be able to assess saline formations for their suitability for CO₂ storage. More needs to be done to develop CO₂ site selection methods and to build up capacity among national regulatory bodies.

Table 7.5 ► **Regional capture potential and industrial capture in the BLUE scenarios, 2050**

	Capture in BLUE low 2050 (Mt)	Capture in BLUE high 2050 (Mt)	Total capture potential 2050 (Mt/yr)	Industry CCS as a share of total potential for BLUE low 2050 (%)	Industry CCS as a share of total potential for BLUE high 2050 (%)
Europe	146	194	600	24.3%	32.3%
Russia and economies in transition	85	129	400	21.4%	32.4%
China	504	758	2 000	25.2%	37.9%
India	243	422	900	27.0%	46.9%
Japan	97	100	150-250	64.7% – 37.8%	66.8% – 40.1%
OECD Pacific	25	38	200-400	12.3% – 6.2%	18.8% – 9.4%
Other developing Asia	150	210	900	16.7%	23.3%
United States	62	80	1 700	3.7%	4.7%
Canada	12	15	850	1.4%	1.7%
Brazil	35	49	400	8.8%	12.3%
Other countries	312	451			

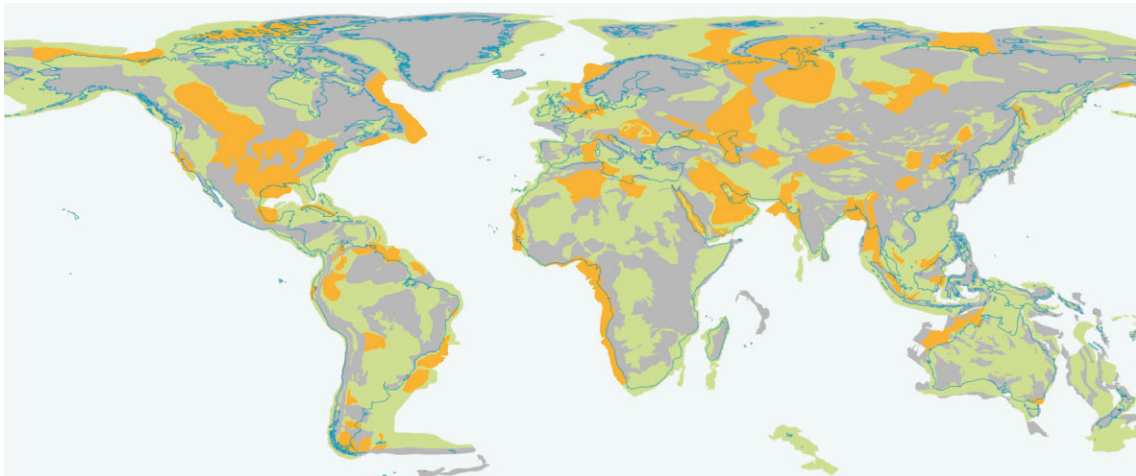
Sources: IEA analysis; IEA (2008e).

CO₂ needs to be transported from the point of capture to storage sites. Transportation costs depend on the volumes that need to be transported and the distances involved. Regional hub and spoke networks are likely to be the most efficient way of connecting many emitting nodes to storage sites. Transportation systems will need to be carefully planned to allow the development of common infrastructure at least cost.

Although most attention has so far been given to pipeline transportation, CO₂ might also be transported by ship. In some circumstances, ship transport could be less costly. It could also enable the use of CO₂ storage reservoirs that could not be

easily accessed by pipelines. The cost of transportation via ships would be about USD 20/t CO₂ to USD 30/t CO₂ (IEA-GHGRD, 2004). This option would allow countries with limited direct access to storage to use CCS.

Figure 7.11 ▶ Map of sedimentary basins and their storage potential



Storage prospectivity ■ Highly prospective ■ Prospective (low to high) ■ Non-prospective

Source: Bradshaw and Dance (2004).

Key point

Geological basins that are highly prospective for storage are mainly found in the United States, Siberia, Middle East and North Africa, as well as offshore.

With the recent development of a more robust methodology for storage capacity estimates, governments urgently need to conduct detailed evaluations of their national CO₂ storage capacities, working in partnership with bordering nations that share the same storage space. In the medium-term, depleted oil and gas reservoirs, unmineable coal seams and deep saline formations are the best options for CO₂ storage. Deep saline formations appear to offer the potential to store several hundreds of years' worth of CO₂ emissions. This must be validated, and site selection criteria must be developed and shared internationally to identify the most appropriate storage sites. International collaboration and consensus on the viability, availability and permanence of CO₂ storage will be essential if CCS is to realise its potential.

Major barriers need to be addressed in order for CCS to be deployed at large scale. Governments need to develop comprehensive and detailed legal and regulatory frameworks; suitable financial incentives and/or regulatory mandates are required for investments to occur; international co-operation is needed to accelerate CCS deployment; and capacity building is needed to assess CO₂ storage capacity options in many regions.

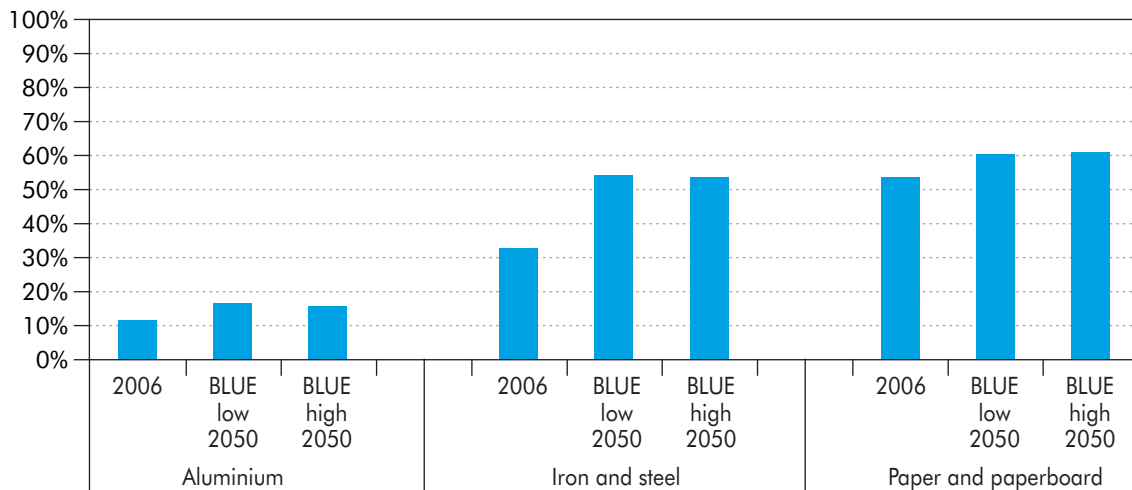
The IEA recently published a report on the role of CCS in climate change mitigation, including an analysis of the cost, performance and policy implications, which contains further detail on these issues (IEA, 2008e).

Recycling

The recycling of materials conserves energy, landfill space and raw materials. The use of recycled materials by industry, where appropriate, reduces energy needs and associated CO₂ emissions. Recycling is a particularly attractive option for the aluminium, iron and steel, paper, and chemical and petrochemical industries. While an increase in recycling can be achieved at low cost, achieving very high rates of recycling might not be a cost-effective option for industry.

The proportion of recycled material relative to overall production is expected to increase by 4 percentage points (p.p.) in the aluminium sector, 21 p.p. in the iron and steel sector and 8 p.p. in the paper sector between the Baseline and BLUE scenarios. For these sectors, between 7 EJ and 9 EJ of the energy reductions in the BLUE scenarios come from the increased use of recycled materials. Although the large number of variables involved make it difficult to estimate such savings with any degree of certainty, it is clear that the use of recycled materials will have an important contribution to make in achieving the necessary 21% reduction in the industrial direct energy and process CO₂ emissions implicit in the BLUE scenarios.

Figure 7.12 ▶ Share of recycled materials by industry



Source: IEA analysis.

Key point

The increased share of recycled materials in overall production will contribute to reduced energy use and CO₂ emissions.

Use of recycled aluminium

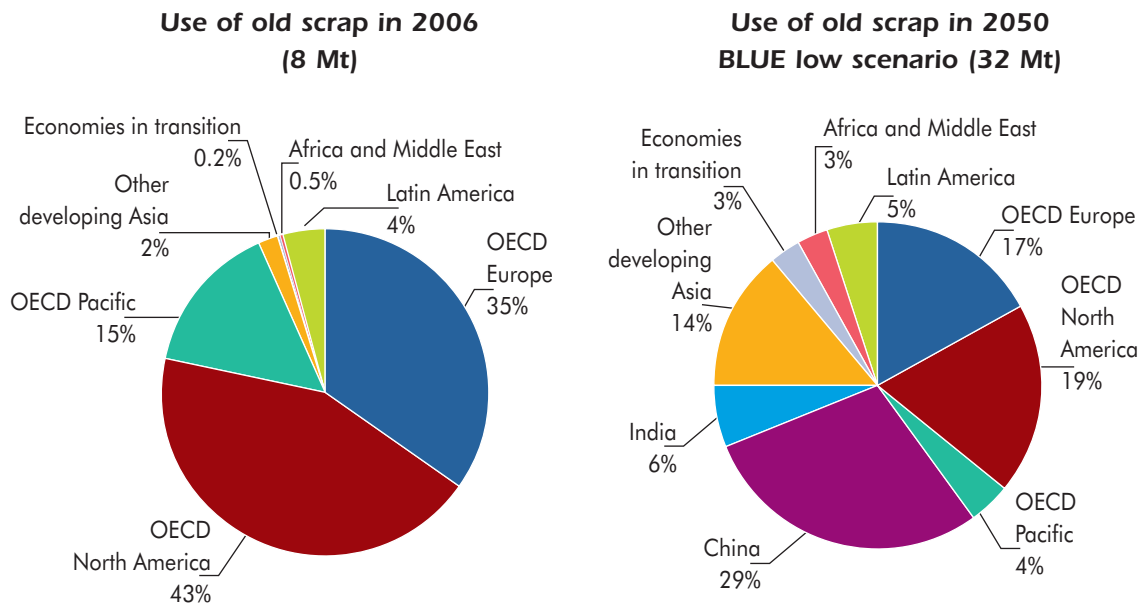
Out of an estimated total of over 700 Mt of aluminium produced in the world since commercial manufacture began in the 1880s, about three-quarters is still in productive use. About 31% is located in buildings, 29% as electrical cable and

machinery and 28% within moving objects such as cars, commercial vehicles, trains and ships. The metal currently stored in objects in use represents about 18 years of primary aluminium output (IAI, 2006). Today, 44% of the scrap used in recycled aluminium comes from transport, 28% from packaging and 10% from engineering and cables. Only 7% comes from building applications because of its long use (IAI, 2006).

Production from recycled aluminium uses only 5% to 8% of the energy needed to produce aluminium from primary materials. In 2006, about 11.5% of the primary aluminium produced was from recycled scrap aluminium. In 2050 in the BLUE scenarios, this share increases to 15.7%. The increased share of recycled materials in the BLUE scenarios accounts for about 0.5 EJ to 0.7 EJ of the expected energy reduction in 2050.

Aluminium recycling is of particular importance in developed countries, such as in Europe and North America. These countries, have plenty of scrap available owing to their long history of aluminium use. Recycling is also increasing in China, India and Russia and will increase further in the future. Figure 7.13 shows the use of aluminium scrap by region in 2006 and in 2050 for the BLUE low-demand scenario.

Figure 7.13 ▶ Use of aluminium scrap by region in the BLUE low scenario, 2050



Sources: IAI (2006); IEA analysis.

Key point

Non-OECD countries will dramatically increase their use of recycled aluminium in the production process.

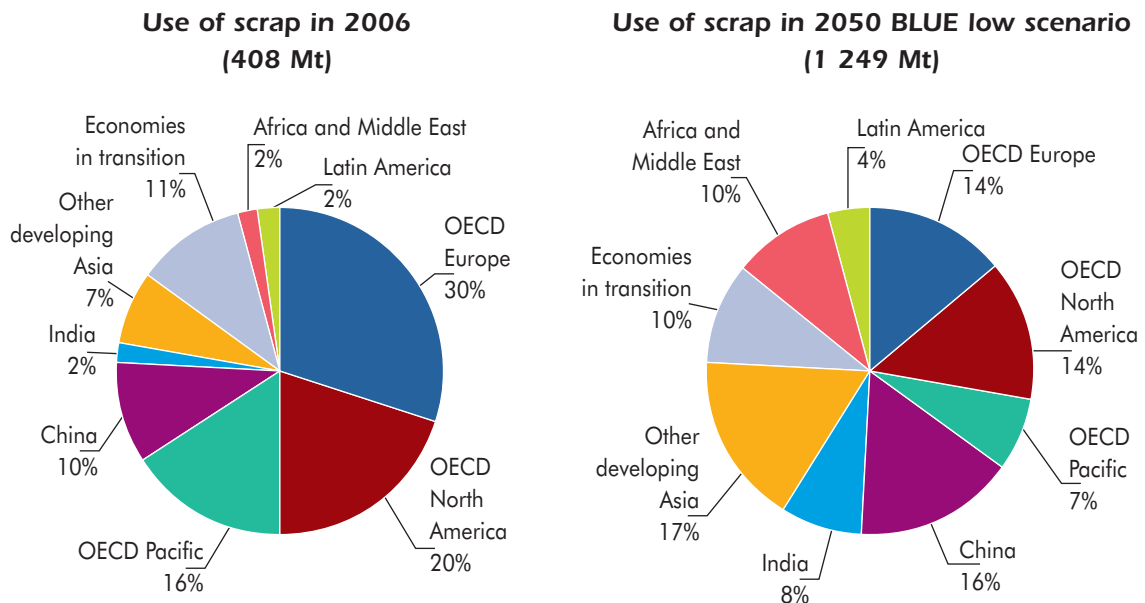
Use of scrap iron and steel

The iron and steel sector can also make use of recycled materials to reduce its energy consumption. The remelting of scrap requires less energy than the production of iron and steel from iron ore, typically requiring about 40% less electricity.

In 2006, about 33% of all steel was produced from scrap. In the BLUE scenarios, it is estimated that this share will increase to 54% in 2050. The increased share of scrap iron and steel accounts for about 6 EJ to 7 EJ of the energy reductions in the BLUE low-demand scenario, and direct CO₂ reductions of about 0.3 Gt CO₂.

Because scrap comes from such sources as discarded cars and consumer durables, industrial machinery, manufacturing operations and old buildings, the relatively mature industrialised economies are generally the main producers of scrap (USGS, 2006). Depending on the product category, it may take up to 100 years before the scrap becomes available for recycling. But as the primary source of obsolete steel is vehicles which have relatively short life spans, a growing world population and increased demand for vehicles in developing countries are expected to contribute to a dramatic rise in the amount of vehicle scrap in the next 25 years. Figure 7.14 shows the use of scrap by region in 2006 and in 2050 for the BLUE low-demand scenario.

Figure 7.14 ► Use of iron and steel scrap by region in the BLUE low scenario, 2050



Key point

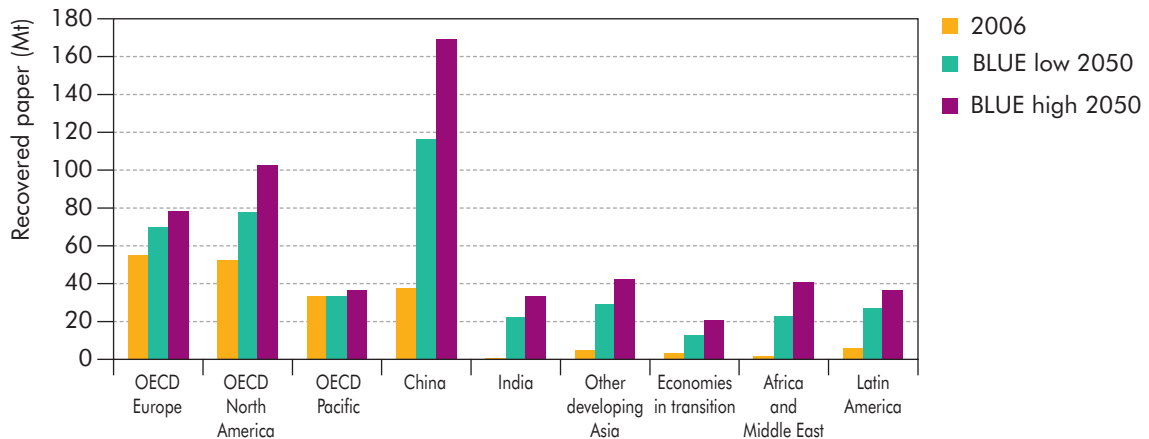
Use of steel scrap will become more important in countries where production increases the most.

Use of recovered paper

The pulp and paper industry can also reduce its energy use through recycling. The increased share of recovered paper in the BLUE low-demand scenario translates into energy savings of about 0.5 EJ to 0.7 EJ compared to the Baseline scenarios. The use of recovered paper also has the advantage that it displaces the use of biomass that can then be used by other sectors. However, it is important to note that the increase in the use of recovered paper in the BLUE scenarios is limited by the fact that the industry is already near its practical limit for the use of recovered paper.

Although less energy-intensive, the impact of the use of recovered paper on CO₂ emissions is less clear. The impact will depend on the technology and the energy sources used in producing the pulp. In general, the CO₂ intensity of recycling through chemical pulping is lower than that for the production of paper from new feedstocks, given the large amount of biomass used. Figure 7.15 shows the regional breakdown of recovered paper used in the 2006 Baseline and in the BLUE low- and high-demand scenarios in 2050.

Figure 7.15 ▶ Use of recovered paper by region



Sources: FAO (2006); IEA analysis.

Key point

While the use of recovered paper is close to its technical limit in OECD countries, there is still an important potential in non-OECD countries.

Use of recycled plastic

Plastics can be reused in the chemical and petrochemical sector. Worldwide, only 10 Mt of plastic waste is recycled today. This is less than 10% of the overall waste plastic generated, although Japan and Europe achieve significantly higher levels of recycling than the average. These figures may not, however, fully account for

recycling in developing countries such as India where nearly 50% of the plastic waste is recycled (Mutha *et al.*, 2006). In the BLUE scenarios, the demand for plastic is expected to triple between now and 2050. Plastic waste levels are expected in the same period to rise to between 250 Mt and 300 Mt, approximately half of which could be used for recycling and energy recovery.

Three main recovery options exist for plastics: mechanical recycling, feedstock recycling, and energy recovery. Only 20% to 30% of plastic waste can be mechanically recycled. In the BLUE high-demand scenario, this will constitute 50 Mt to 90 Mt of waste that will be available for mechanical recycling. The recycling of 10 Mt of waste plastic to polymer substitutes would represent 500 PJ of savings.

Of the 160 Mt to 250 Mt of waste that cannot be mechanically recycled, up to 30% can be used for energy recovery. The rest can be used as a feedstock by other sectors. In the iron and steel sector, technologies have been developed to inject plastic waste into blast furnaces as a substitute for coke and coal. Plastic waste can also be added to coking ovens. Experience shows that using plastic waste in the coke oven results in better process stability than using it as a coke or coal substitute. In the BLUE scenarios, the use of plastic waste increases from less than 0.01 EJ today to 0.6 EJ and 1.0 EJ in 2050.

Waste plastic can also be used by other sectors as an alternative energy source. Given the CO₂ reductions that will result from its use, competition for plastic waste may increase significantly in the future.

Worldwide, approximately 245 Mt/yr² of plastics are consumed each year, resulting in approximately 120 Mt of plastic waste. The primary energy savings potential if all of this was be recycled in the most appropriate way rather than sent to landfill is estimated to be 2.4 EJ a year.

Municipal solid waste and by-products

The recycling of waste biomass, paper and metals reduces the use of energy and CO₂ emissions in the industrial sector, and decreases the amount of municipal waste that has to be landfilled or incinerated.

Other municipal waste, such as construction waste, tyres and carpets, can also be used by industry to help in reducing their use of conventional energy and their CO₂ emissions. Municipal waste can be used as energy or as a feedstock in the chemical and petrochemical, iron and steel and cement sectors. The greater use of wastes as fuel reduces global emissions by displacing fossil fuel use. It also reduces CO₂ and CH₄ emissions in waste handling, although it only transfers those emissions from waste-handling facilities to industrial plants. In the analysis presented in this book, those reductions have not been credited to the different sectors. A full life-cycle analysis would be required to assess the impacts of the use of municipal solid waste and by-products by industry.

2. Total polymer production was reported to be 300 Mt in the chemicals and petrochemicals chapter. The difference (55 Mt) represents so-called non-plastics, *i.e.* polymers used as coatings, adhesives and other applications.

Cement kilns are well suited for waste combustion because of their high process temperature and because the clinker product and limestone feedstock act as gas-cleaning agents. Used tyres, wood, plastics, chemicals and other types of waste are already co-combusted in cement kilns in large quantities. However, very high substitution rates can only be accomplished if the waste is subjected to tailored pre-treatment and surveillance. Municipal solid waste, for example, needs to be pre-treated to obtain homogeneous calorific values and feed characteristics.

Iron and steel making generates slag. Blast-furnace slag can be used in cement making as a clinker substitute which reduces energy needs. About half of all blast-furnace slag worldwide is currently used for cement making. This leaves about 100 Mt of slag that could be recycled. If recycled, this would reduce global CO₂ emissions by 50 Mt CO₂. This emissions reduction would occur in cement making, rather than in the iron and steel sector.

The iron and steel, cement and chemical sectors will have to compete with others to have access to these alternative sources of energy. As a result, the price of waste may be as high as 25% to 35% of the coal price in 2030 and 65% to 75% in 2050.

Reducing other GHG emissions

The CO₂ concentration in the atmosphere is approximately 385 parts per million (ppm), and is rising by about 2 ppm per year. In 2004, 49 Gt CO₂-equivalent emissions were released, of which 77% was CO₂ (IPCC, 2007). CO₂ emissions from fossil fuel combustion accounted for only slightly over half of the total emissions of the six groups of GHGs covered by the Kyoto Protocol (CO₂, CH₄, N₂O, SF₆, PFCs, HFCs). The non-CO₂ GHGs have a greater global warming potential (GWP) than CO₂. As such, the stabilisation of climate at two to three degrees Celsius will also require substantial cuts in emissions of non-CO₂ GHGs and in non-energy-related CO₂ emissions.

Most of the energy reduction options discussed in this book will lead to reductions in more than one GHG. However, renewable biomass is the notable exception; while it is considered CO₂-free, the combustion of biomass releases CH₄ and N₂O. The efficiency of the technology used to combust biomass, the type and quality of biomass combusted and the fuel displaced all have to be taken into account to fully assess the overall GHG impact of an increased use of biomass.

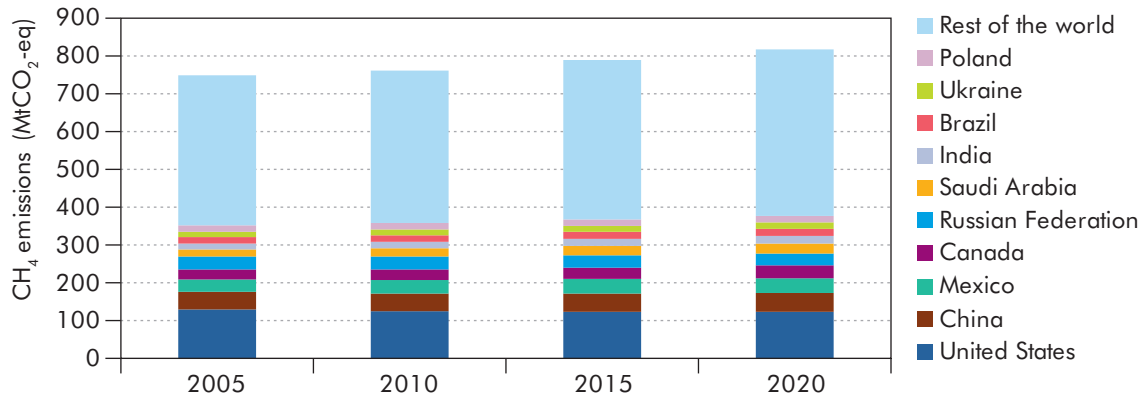
CH₄ is a potent GHG with a GWP of 21 (*i.e.* one tonne of CH₄ emitted is equivalent to 21 t CO₂ emitted). CH₄ is produced through the natural process of the bacterial decomposition of organic waste under anaerobic conditions in sanitary landfills and open dumps. The increased use of municipal waste by different sectors will reduce the increase in CH₄ that would otherwise be expected.

As shown in Figure 7.16, CH₄ emissions from landfills are expected to decrease in industrialised countries and increase in developing countries. Industrialised countries' baselines are expected to decline as the result of expanded recycling and composting programmes, increased regulatory requirements to capture and combust landfill gas (LFG), and improved LFG recovery technologies. Developing

countries' LFG emissions are expected to increase together with expanding populations. This, combined with a trend away from open dumps to sanitary landfills with increased anaerobic conditions, is conducive to CH₄ production.

The global analysis of the integrated impacts on GHG emissions for the overall economy is beyond the scope of this book. For more detail on non-CO₂ GHGs, readers are referred to the *IEA World Energy Outlook 2008*.

Figure 7.16 ▶ Methane emissions from solid waste management



Source: US EPA (2006).

Key point

While OECD countries have stabilised methane emissions from solid waste management, non-OECD countries are expected to see their emissions increase as they shift from open dumps to sanitary landfilling practices.

Chapter 8 IMPACTS ON MATERIALS DEMAND

Key Findings

- ▶ *Deep emissions reductions will have mixed impacts on the demand for materials. The overall demand for most major commodities will not be significantly affected, although constraints on the availability of certain specialty materials could reduce the penetration levels of some low-carbon technologies.*
- ▶ *The material intensity of most carbon-free power technologies is significantly higher than that of gas- and coal-fired technologies. But the transition to a carbon-free power sector will have a limited impact on overall materials demand as the sector represents only a relatively small share of total materials use.*
- ▶ *In the BLUE scenarios, the demand for specialty materials, such as fibreglass and rare commodities used in thin-film PV technologies, could have a significant impact on overall demand levels for these materials. Bottlenecks could develop if capacity additions do not keep up with demand. The move to thin-film photovoltaic technologies could be severely constrained as the demand for tellurium and indium for high levels of cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS) production outstrips supply.*
- ▶ *The growth of low-carbon transport technologies will have significant impacts on materials requirements. In the BLUE scenarios, electric vehicles would require nearly all the known reserves of lithium by 2050 to provide batteries, even with high recycling levels. Technological improvements, which result in lower lithium use per battery or alternative battery technologies, should be prioritised in order to reduce this risk.*
- ▶ *Increased demand for copper and platinum-group metals for hybrid and electric vehicles, catalysts and fuel-cell systems could also have significant implications for the respective resource bases.*
- ▶ *High levels of recycling will be necessary to keep up with material input requirements, particularly in the transport sector. During periods of rapid growth, recycling is unlikely to provide a substantial share of raw materials requirements.*
- ▶ *Achieving the BLUE scenarios outcomes in the building sector will require significant additional construction activity. New and refurbished buildings will have to meet tighter energy standards for the building envelope. This can be achieved with relatively modest increases in the most important materials, i.e. wood, bricks and tiles, cement and steel. However, it will require almost a doubling of insulation materials use and a 30% to 50% increase in the use of glass over and above what is forecast under the Baseline scenarios to 2050.*
- ▶ *Additional data collection and analysis is required to provide a more comprehensive assessment of the impact of a low-carbon economy on the demand for materials.*

Introduction



The transformation of global energy use that is implicit in the achievement of the outcome of the BLUE Map¹ scenario in *ETP 2008* will have significant impacts on the demand for materials. As demand for more capital-intensive energy technologies increases, demand for materials, and in particular for more advanced and more energy-intensive materials, will also increase.

This chapter provides an indicative first analysis of the impact of the energy technology changes outlined in *ETP 2008* on the materials sector. It covers the power sector and some parts of the transport and building sectors. In the power sector, the main focus is on generation. Some initial results are also shown for electricity transmission. In the transport sector, the analysis is limited to light-duty vehicles. In the building sector, it is limited to building envelopes.

Data availability has been a major challenge for this analysis. The results described here are, therefore, far from conclusive and additional effort will be needed to refine and expand this analysis. Since the analysis is partial, and the range of materials considered is so wide, no attempt is made to aggregate the demand for different materials into a single total requirement in the BLUE Map scenario. Given uncertainties about the requirements of emerging technologies for specialty materials, the analysis is largely qualitative. Material constraints could limit the implementation of a given technology or lead to alternative technologies. The development of such alternative technologies may help to address some of the material constraints outlined here.

The analysis focuses on materials that are energy- and CO₂-intensive to produce and on specialty materials or rare commodities where there may be resource constraints or where a rapid increase in capacity will be needed to meet the demand for new technologies. The materials covered in this analysis include steel, cement, aluminium, copper, plastics, fibreglass, uranium, silicon, indium, selenium, gallium, tellurium, cadmium, germanium, nickel, lead, magnesium, platinum-group metals, rubber, glass, bricks and tiles, wood and insulation material.

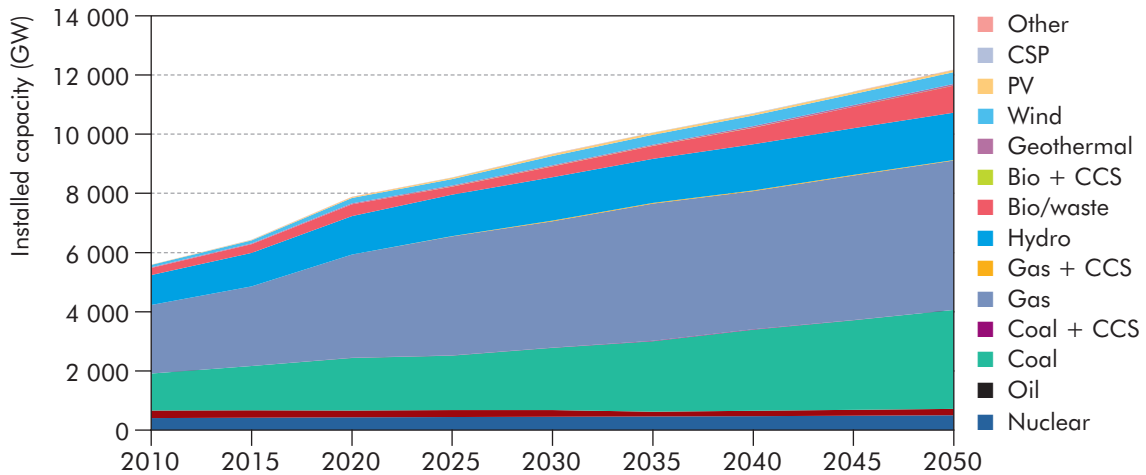
The IEA Baseline scenarios reflect developments that will occur with the energy and climate policies that have been implemented to date. The BLUE Map scenario analysis, which aims for a halving of global emissions by 2050, implies a very rapid change of direction. Costs are not only substantially higher, but also much more uncertain, because the BLUE Map scenario demands the deployment of technologies that are still under development, whose progress and ultimate success are difficult to predict. The BLUE Map scenario, based on optimistic assumptions about progress of key technologies, envisages the deployment of all technologies costing up to USD 200/t CO₂ saved.

1. In *Energy Technology Perspectives 2008* a number of BLUE scenarios were developed to look at the implications of a policy objective to halve current emissions by 2050. In the power sector, five variants have been analysed and four variants in the transport sector. The analysis in this chapter is based on the BLUE Map scenario which assumes relatively optimistic assumptions for all key technology areas.

Power sector

Achieving the outcomes in the BLUE Map scenario will require a global revolution in the way that energy is supplied. The power sector would need to become virtually CO₂-free, which would require unprecedented levels of growth in renewable and nuclear power generation and the widespread installation of CCS. Low-carbon generation technologies would need to displace very large capacities of coal- and gas-fired generation. The scale of the change needed in the technologies used to supply electricity is obvious from Figures 8.1 and 8.2 that show the evolution of installed power capacity in the Baseline and BLUE Map scenarios to 2050.

Figure 8.1 ▶ Installed power capacity by technology in the Baseline scenario, 2010 to 2050

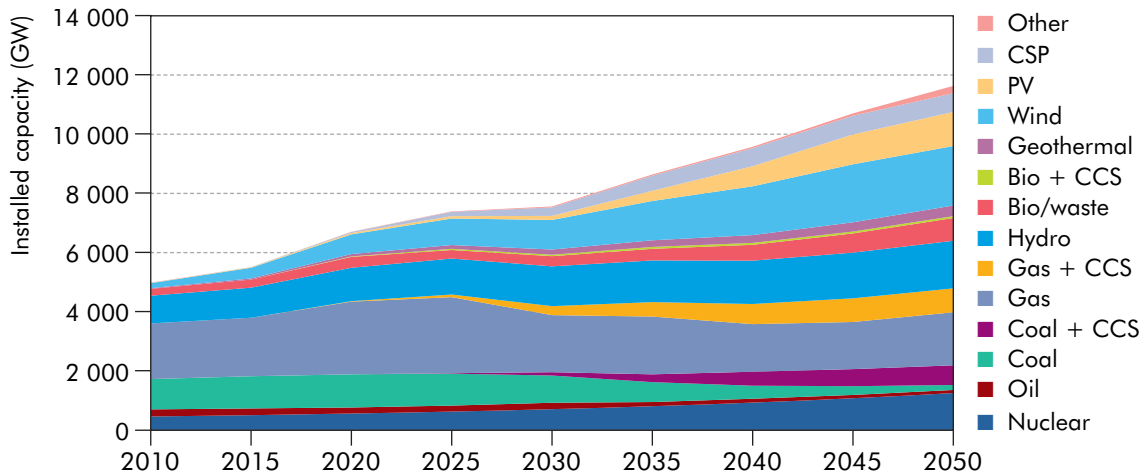


Key point

In the Baseline scenarios, installed capacity will remain predominantly based on fossil fuels.

In the Baseline scenarios, total installed capacity is expected to rise from 5 800 GW to over 12 000 GW by 2050. Coal- and gas-fired plants, which today represent approximately 60% of global capacity, will continue to dominate. In the BLUE Map scenario, the total installed capacity in 2050 is well below 12 000 GW as higher levels of efficiency reduce the demand for electricity. The full benefits of such efficiency shifts are partially offset, however, by the need for additional backup capacity for very high levels of renewable power. Coal-fired and some of the gas-fired capacity which is built in the Baseline scenarios will be replaced by a combination of wind, solar, biomass and nuclear and by coal and gas plants with carbon capture and storage (CCS). By 2050, the global power sector will be virtually CO₂-free in the BLUE Map scenario.

Figure 8.2 ▶ Installed power capacity by technology in the BLUE Map scenario, 2010 to 2050



Key point

In the BLUE Map scenario, power generation from renewables, nuclear and fossil fuels with CCS will grow significantly.

The decarbonisation of the power sector will have important implications for materials needs, particularly as many lower-carbon technologies will require more materials than the technologies they displace. In addition, given the lower efficiency of renewable sources of generation, more installed renewable capacity will be needed than the coal- or gas-fired capacity it replaces. Table 8.1 shows the average material use per MW of installed capacity for different technologies. Expected growth in demand for thin-film photovoltaic (PV) technology will also increase demand for a number of specialty materials such as indium, selenium, gallium, tellurium, cadmium and germanium.

The cumulative consumption of steel for the power sector in the BLUE Map scenario is estimated to reach over 600 million tonnes by 2050, 70% higher than in the Baseline scenarios. This represents an additional annual consumption of around 1.5% of current annual steel consumption. The transition to a carbon-free power sector is, therefore, not expected to have a significant impact on overall steel demand. However, additional analysis is needed to ensure that the demand for specialty steels, for example for seamless tubes needed to build the CO₂ transportation network to support CCS, would not create future demand bubbles in the BLUE Map scenario.

The power sector's demand for cement and aluminium grows more slowly than the demand for steel. Cumulative consumption is estimated at 400 million tonnes of cement and 35 million tonnes of aluminium in the BLUE Map scenario from 2010 to 2050, an increase of 43% (cement) and 12% (aluminium) above the Baseline scenarios. The additional consumption needed under the BLUE Map scenario is only a small fraction of the current annual consumption of these materials and no major

supply constraints are foreseen. In 2007, over 2 800 million tonnes of cement and 40 million tonnes of aluminium were consumed globally. Cumulative consumption of copper is expected to be around 10% less in the BLUE Map scenario than in the Baseline scenario as increased energy efficiency reduces the need to expand the transmission and distribution networks.

Table 8.1 ▶ Average material use by technology

	Steel (Mt/MW)	Cement (Mt/MW)	Plastics (Mt/MW)	Aluminium (Mt/MW)	Copper (Mt/MW)	Uranium (Mt/MW)	Fiberglass (Mt/MW)
Nuclear	50	43				0.18	
Coal	80	55					
NGCC	25	9					
Hydro		138					
Biomass	104	66					
Onshore wind	120	45	1.9	0.26	1.8		9
Offshore wind	150	150	2.1	0.42	2.8		9
PV	73	10	10	7	5		
Carbon capture Coal	18						
Carbon capture NGCC	12						
Carbon transportation/km	42						
Electricity transmission/km	40			15	50		

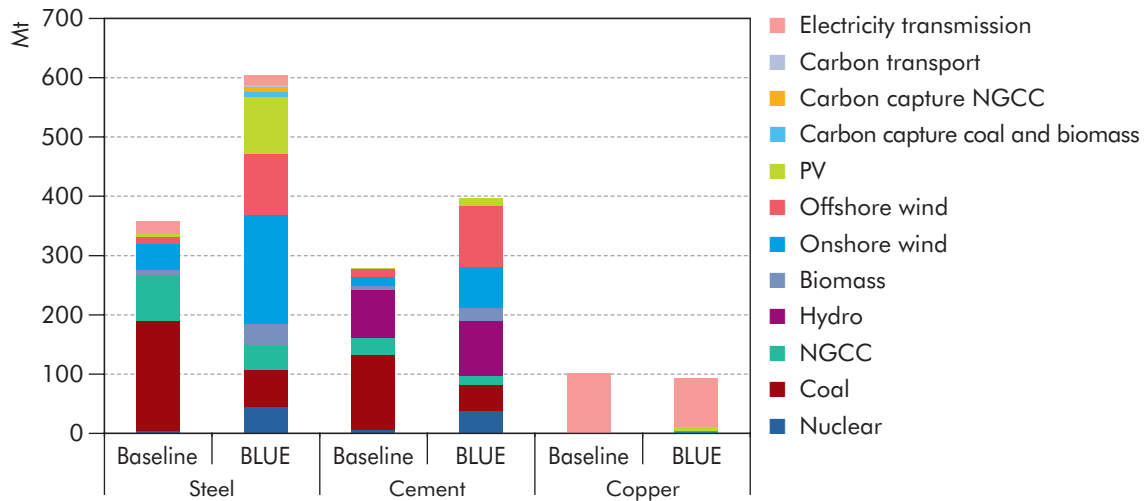
Note: The figure for steel use in carbon transportation will depend on the diameter of the pipeline which will be determined by the flow of CO₂. A pipeline for coal-fired plants will have a larger flow than gas-fired plants as more CO₂ is captured. Flows from industry CO₂ capture will be much smaller than for power plants. The figure applied here represents steel demand for pipelines based on gas-fired plants. Coal-fired plants would require an estimated 93 tonnes of steel per km. Further refinement is needed, which calculates demand based on requirements for different CO₂ pipeline networks.

Sources: NREL (2004), Kleijn (2008), Peterson *et al.* (2005), NEA (2008), and IEA estimates.

The demand for plastics and fibreglass in the power sector will grow significantly in the BLUE Map scenario as the growth in wind generation and PV stimulates demand. Cumulative consumption from 2010 to 2050 for plastics in the BLUE Map scenario is projected to reach 17 million tonnes, ten times the level in the Baseline scenarios. This represents only a small increase relative to the global annual plastics consumption of 225 million tonnes. Higher consumption of fibreglass may have a more significant impact on the market: estimated cumulative demand from 2010

to 2050 from the power sector in the BLUE Map scenario at 20 million tonnes is almost five times the 2007 global consumption of 4.2 million tonnes. The average annual growth from 2010 to 2050 in fibreglass demand for wind power in the BLUE Map scenario currently represents a 10% increase in annual fibreglass consumption, but future demand increases will not be linear and supply bottlenecks could arise in the future.

Figure 8.3 ▶ Cumulative steel, cement and copper consumption in the Baseline and BLUE Map scenarios, 2010 to 2050



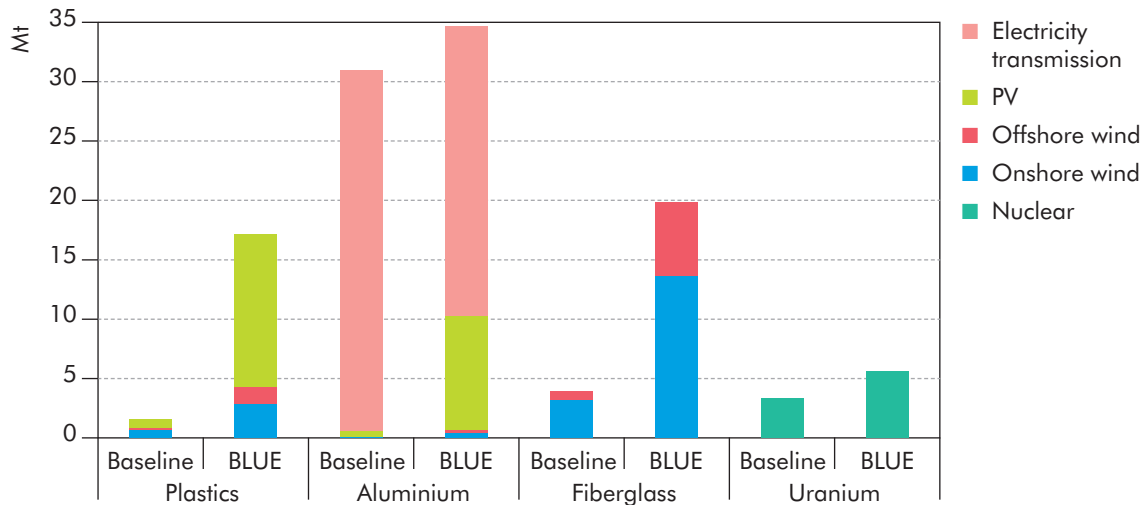
Key point

Cumulative demand for steel and cement from the power sector will be significantly higher in the BLUE Map scenario, while demand for copper will fall.

As a result of higher nuclear power production in the BLUE Map scenario, uranium consumption will amount to 5.6 million tonnes between 2010 and 2050, 70% higher than in the Baseline scenarios in which the growth of nuclear power will also be significant. This is larger than the current known conventional resources of 5.4 million tonnes² (NEA, 2008). Without the exploitation of unconventional resources, the growth in nuclear power production may require a shift to new technologies such as those being researched under the GEN IV programme which requires significantly less uranium than current reactors. Unconventional resources contained in phosphate rocks and in sea water are currently estimated at 22 million tonnes (NEA, 2008).

2. This figure is based on current known resources. Interesting new discoveries have been made in recent years and this figure could rise as exploration continues.

Figure 8.4 ▶ Cumulative plastics, aluminium, fibreglass and uranium consumption in Baseline and BLUE Map scenarios, 2010 to 2050



Key point

Demand for plastics, aluminium, fibreglass and uranium rise sharply in the BLUE Map scenario.

Materials needs for PV technologies

In addition to steel, cement, aluminium, copper and plastics, PV technologies also require specialty materials as shown in Table 8.2. The analysis here focuses only on first-generation (crystalline silicon) and second-generation (thin-film) PV technologies, as data on materials needs for third-generation or novel PV devices are not available. The move from first- to second-generation PV technologies will significantly reduce the quantity of the materials needed to reach the levels of PV capacity envisaged in the BLUE Map scenario. Crystalline silicon technologies use approximately 0.95 tonnes of materials per MW, as compared with 0.09 tonnes for thin-film cadmium telluride (CdTe), 0.064 tonnes for thin-film copper indium gallium diselenide (CIGS) and around 0.002 tonnes for thin-film amorphous silicon germanium (aSiGe) technologies.

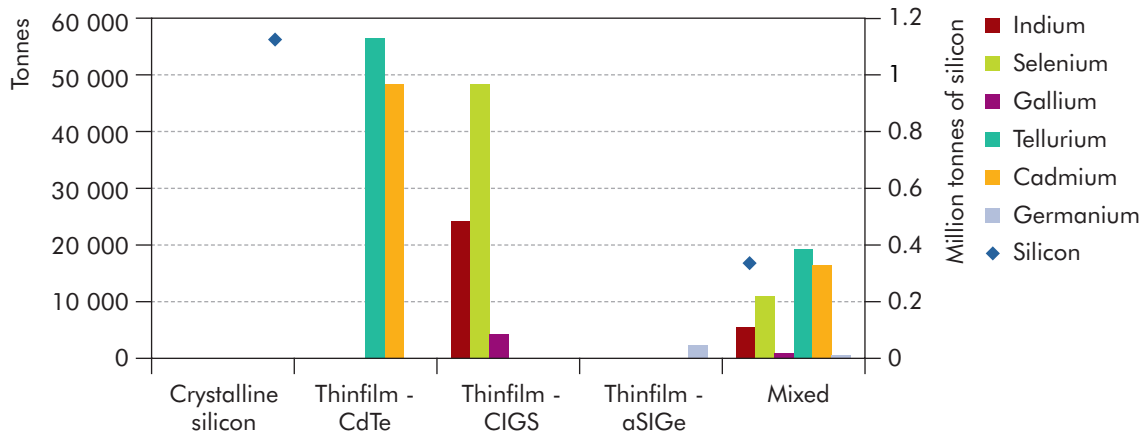
Table 8.2 ▶ Specialty material needs for various PV technologies

Mt / MW	Silicon	Indium	Selenium	Gallium	Tellurium	Cadmium	Germanium
Crystalline silicon	0.951						
Thin-film CdTe					0.047	0.040	
Thin-film CIGS		0.020	0.040	0.004			
Thin-film aSiGe							0.002

Source: NREL (2004).

Figure 8.5 shows the cumulative need for materials for each technology type, assuming in each case that all the additional capacity in the BLUE Map scenario is based on that technology. The materials requirement under the “mixed” case assumes that a mix of PV technologies is applied.³ The mixed case better reflects possible materials demands as different regions will choose different technologies depending on their resource availability and their technology development.

Figure 8.5 ▶ **Estimated cumulative materials needs (2010 to 2050) for PV technologies in the BLUE Map scenario assuming single technologies and a mix of technologies**



Key point

A move to thin-film PV technologies will have significant implications on materials demand for rare commodities.

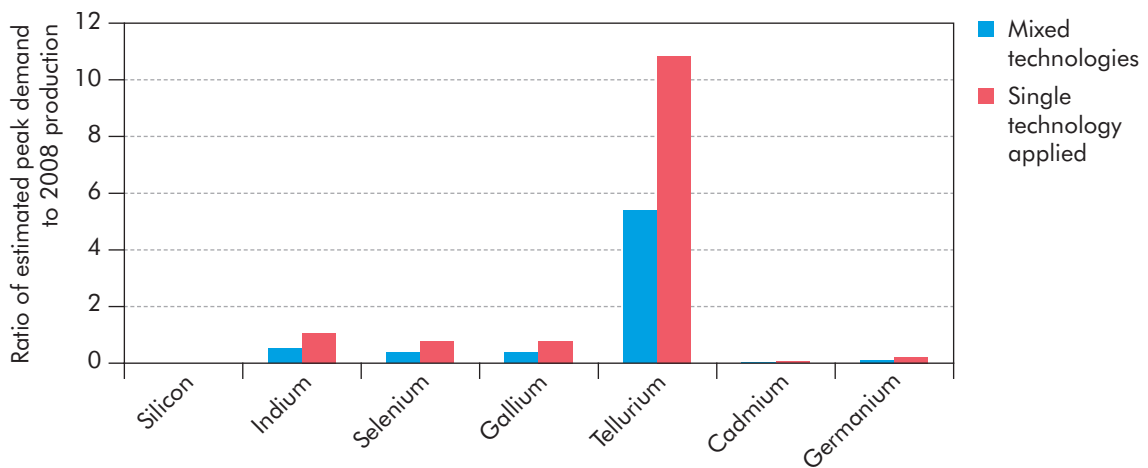
Many of the specialty materials needed for thin-film technologies are relatively rare. They are produced only in small quantities and only as by-products of other major commodities. Gallium, for example, is a trace constituent of bauxite and may or may not be recovered during aluminium processing. Tellurium is likewise a trace constituent of copper ores. This makes any rapid increase in production of these materials very difficult to achieve. It would require increased production of the parent metal and the installation of enhanced by-product capture and processing capacities. Figure 8.6 compares the estimated annual peak demand for the materials needed to reach the PV capacity levels implicit in the BLUE Map scenario with their 2008 production levels.

The demand for tellurium, which is needed for CdTe thin-film, is likely to be difficult to meet in both the mixed case and in the CdTe-only scenario. Future demand is estimated to be 5 to 11 times current production levels. Such an increase may not be practically feasible. CIGS thin-film may also be constrained by indium production levels. Demand for selenium and gallium will also be significantly

3. The technology mix assumed for this analysis is derived from the market shares shown in Figure 11.5 of *ETP 2008*. As no data are available for materials needs for novel devices, this analysis assumes that only first- and second-generation PV technologies are applied.

higher than current production levels. It is unclear whether the necessary increase in materials production will be possible. Meeting these levels of demand will require investment in new production capacity, which could influence the economics of moving to these options. Only SiGe thin-film appears to be unconstrained. Silicon is abundant and no material constraints exist for the production of crystalline silicon PV. And additional demand for germanium is relatively small compared to current production levels.

Figure 8.6 ▶ Estimated annual peak materials demand in 2010 to 2050 compared to 2008 production for a mix of technologies and for a single technology



Key point

The availability of rare commodities such as tellurium and indium could limit the development of CdTe and CIGS thin-film PV technologies.

Transport sector

In the ETP BLUE Map scenario, hybrid, plug-in hybrid, electric and fuel-cell vehicles are assumed to penetrate the market in significant volumes, especially after 2020. This may have a significant impact on the requirement for materials such as lithium for batteries and platinum-group metals (PGM) for catalysts and fuel-cell systems.

The IEA Mobility Model (MoMo) tracks the total demand for various materials through to 2050 as a function of the composition and number of passenger light-duty vehicles of different types sold around the world in different scenarios. The materials covered include ferrous metals, aluminium, copper, lead, nickel, lithium, magnesium, platinum-group metals (Pt and Pd), plastics, glass and rubber. Vehicle propulsion systems covered include gasoline and diesel internal combustion

engines (ICEs), hybrid and plug-in hybrid vehicles, and fuel-cell and full-battery electric vehicles.

MoMo builds on the evolution of global vehicle sales, on assumptions regarding the market shares of different types of vehicles and on the characteristics of these different vehicle types. This is done on a global basis, broken into 22 regions and countries. Vehicle attributes relevant to the materials analysis include power train types, energy storage technologies, and weight and efficiency. Assumptions regarding these vehicle attributes are endogenous in the model, *i.e.* they automatically change with the broader assumptions used in a scenario.

Vehicle sales shown here are based on MoMo projections from *ETP 2008*, as modified to be included in a forthcoming report. The characterisation of different vehicle types is derived primarily from two recent reports:⁴

- *Energy Requirements & Emissions for Vehicle Production*: report of the MIT/Camanoe Associates drafted in 2005 for the IEA Mobility Modelling project; and
- *Environmental Improvement of Passenger Cars (IMPRO-car)*: report published in 2008 by the Institute for Perspective Studies of the Joint Research Centre of the European Commission.

Base year (2005) estimates

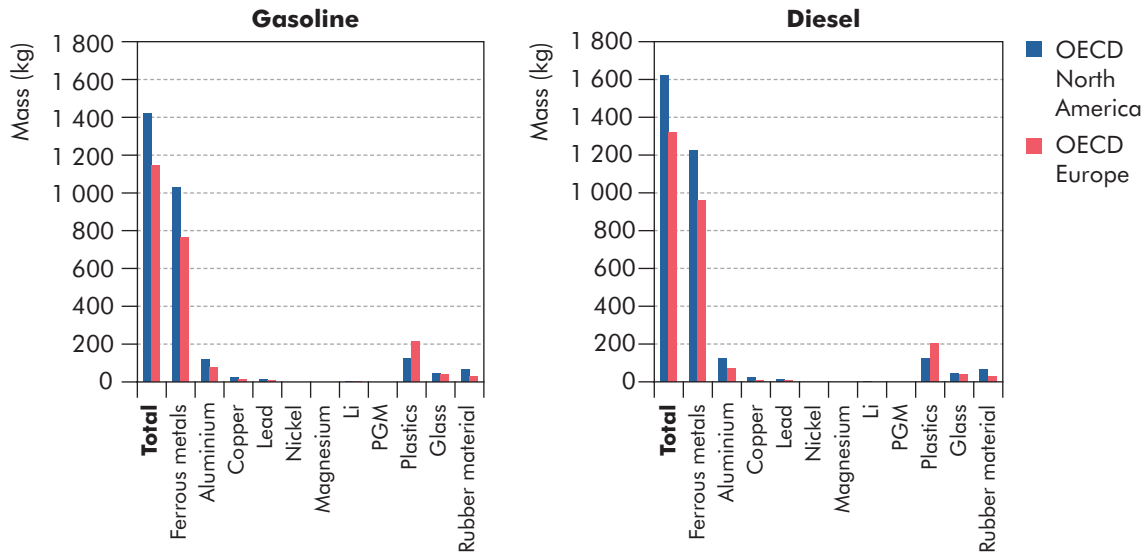
Figure 8.7 shows the average material composition of new gasoline- and diesel-powered light-duty vehicles in OECD North America and the European Union in 2005. The shares of individual materials are relatively similar. The figure also shows the greater average weight of vehicles in OECD North America. Similar estimates were generated for all countries and regions in the model.

In both gasoline and diesel vehicles, ferrous metals constitute most of the total weight, followed by plastics, aluminium and glass. Metals such as copper, lead, nickel and magnesium have only a marginal role on a weight basis. Nickel becomes more relevant for current gasoline and diesel hybrid vehicles, as shown in Table 8.3, because of its presence in nickel metal hybrid (NiMH) batteries. This is expected to change as lithium-ion batteries begin to replace NiMH batteries in all vehicle applications over the next few years, with a complete shift to lithium-ion for all car batteries assumed by 2015.

Similar assumptions have been used for other vehicle configurations such as hybrids, plug-in hybrid electric vehicles (PHEVs), electric vehicles (EVs), fuel-cell vehicles (FCVs). Table 8.3 summarises the shares of different materials in European vehicles in 2005 (although in many cases no production of vehicles of the relevant type were actually made in that year, so the numbers are theoretical). The compositions change in future years, as shown further below.

4. Additional information is drawn from the report *End-of-life vehicle regulation in Germany and Europe – problems and perspectives*, written by Railner Lucas at the Wuppertal Institut für Klima, Umwelt, Energie in 2001. The data for the characterisation of the composition of vehicles in regions other than OECD North America and the European Union are derived from the information published in the mentioned reports in combination with IEA assumptions built on previous work of MIT/Camanoe Associates (under contract to the IEA in 2004) intended to reflect size and weight differences across vehicles sold in different regions of the world.

Figure 8.7 ▶ Material composition and weight of North American and European gasoline and diesel LDVs, 2005



Key point

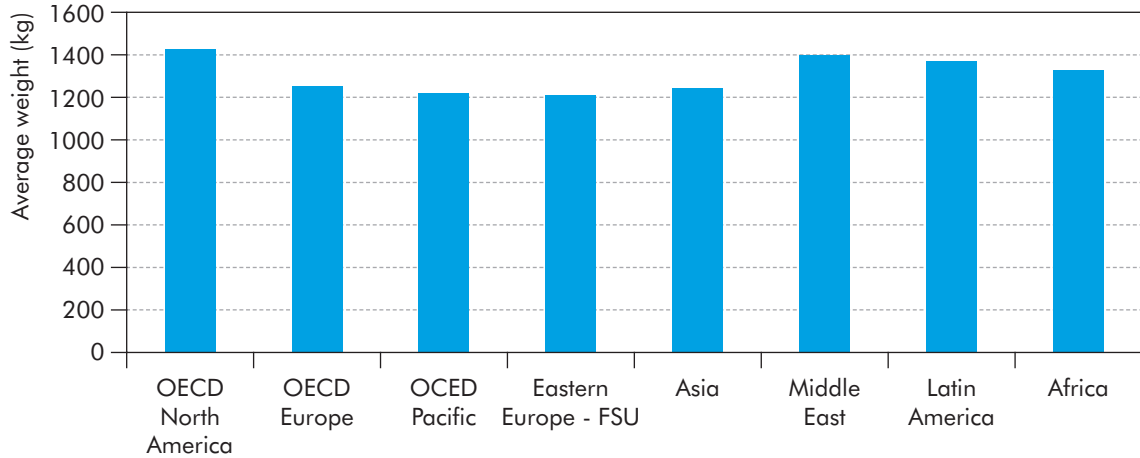
Diesel passenger light-duty vehicles are more material-intensive than gasoline vehicles.

Table 8.3 ▶ Material composition of European light-duty vehicles, 2005

	Gasoline	Gasoline hybrid	Gasoline plug-in	Diesel	Diesel hybrid	Diesel plug-in	Fuel cell	Electric
Total weight [kg]	1 141	1 245	1 317	1 370	1 474	1 546	1 218	1 338
Ferrous metals	66.8%	64.3%	60.8%	72.0%	69.5%	66.3%	54.1%	47.5%
Aluminum	6.5%	6.8%	6.4%	5.7%	6.0%	5.8%	7.0%	6.3%
Copper	0.9%	2.5%	2.4%	0.8%	2.2%	2.1%	6.5%	2.4%
Lead	0.8%	0.8%	0.7%	0.7%	0.6%	0.6%	1.6%	0.7%
Nickel	0%	1.7%	7.1%	0%	1.4%	6.0%	0%	20.8%
Magnesium	0.05%	0.05%	0.04%	0.04%	0.04%	0.04%	0.05%	0.04%
PGM	0.0002%	0.0001%	0.0001%	0.0002%	0.0001%	0.0001%	0.0068%	0%
Plastics	18.6%	18.1%	17.1%	15.5%	15.3%	14.6%	22.4%	16.8%
Glass	3.6%	3.3%	3.2%	3.0%	2.8%	2.7%	5.8%	3.1%
Rubber material	2.7%	2.5%	2.3%	2.2%	2.1%	2.0%	2.5%	2.3%

An estimate of the baseline value (year 2005) of the average vehicle weight in the main world regions, taking into account the weighted average of sales of gasoline and diesel vehicles, is shown in Figure 8.8.

Figure 8.8 ▶ Average vehicle weight by region, 2005



Key point

Vehicles are heaviest in OECD North America.

Future scenarios

The total materials demand associated with specific future scenarios has been estimated by combining assumptions related to the evolution of vehicle ownership, vehicle scrappage rates and materials recycling, and the evolution of materials used in vehicle manufacturing.

Three scenarios are considered here: a “Baseline” scenario, based on the IEA *WEO 2008* reference case projection to 2030, extended to 2050; a very low- CO_2 scenario, based on the *ETP 2008 BLUE Map* scenario, which includes very significant growth in the sale of plug-ins, EVs and FCVs; and a BLUE “EV Success” case with even more EVs but no FCVs.

In the Baseline scenario, vehicles are assumed to become lighter over time as high-strength steel and aluminium are increasingly used to replace conventional ferrous metals, together with a fairly limited take-up of larger vehicles outside the OECD. The Baseline scenario also reflects around a 25% improvement in fuel economy of conventional vehicles by 2030 as in the *WEO 2008*.

The expected materials evolution of eight vehicle technologies (gasoline internal combustion engines, gasoline hybrids, fuel cells and electric vehicles) is shown in

Figures 8.9(a) to (d), each with different scaling to better show the figures of lighter weight materials.

These data assume:

- Vehicles will become lighter in all regions over time, with the substitution of aluminium, plastics and high-strength steel for conventional steel.
- PHEVs need the same materials as hybrids, except for more nickel, copper, aluminium and lithium for the additional batteries. The driving range for PHEVs is assumed to be 40 km with 7.5 kWh of batteries required. This contrasts with about 1.5 kWh of batteries for non-plug-in hybrids.
- EVs have a 150 km range and are designed to be especially light and fuel-efficient. They are assumed to have 25 kWh of battery storage.
- FCVs use a decreasing amount of platinum and platinum-group metals (PGM) over time as fuel-cell stack systems are improved. They achieve a lower level of PGM requirement per vehicle than diesels after 2020. There may also be unpredictable shifts from platinum to palladium or to other metals.

Figure 8.9 ▶ Baseline materials projections by vehicle type

Figure 8.9 (a)

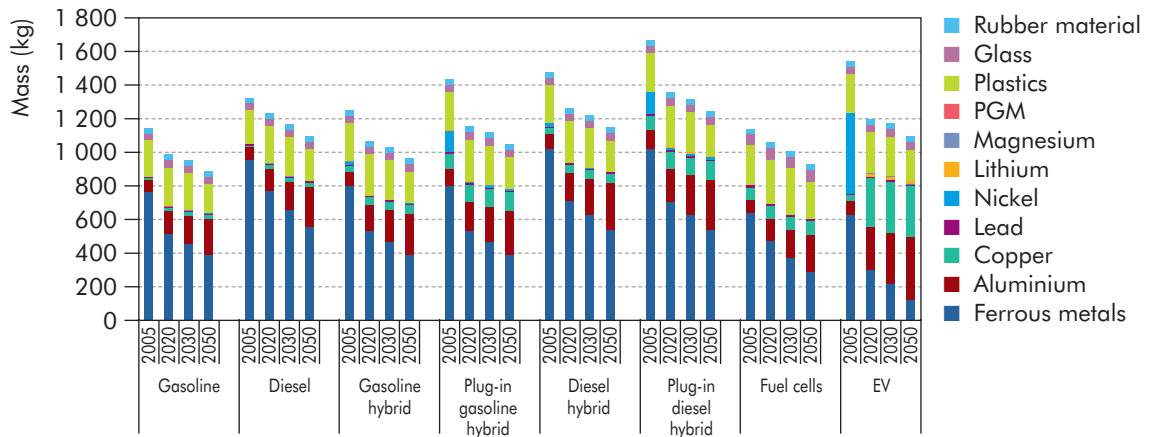


Figure 8.9 (b)

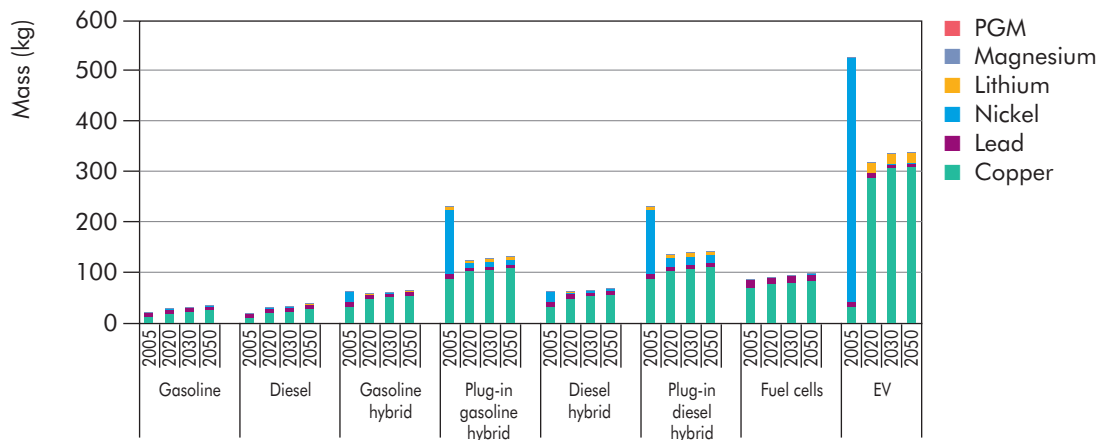


Figure 8.9 (c)

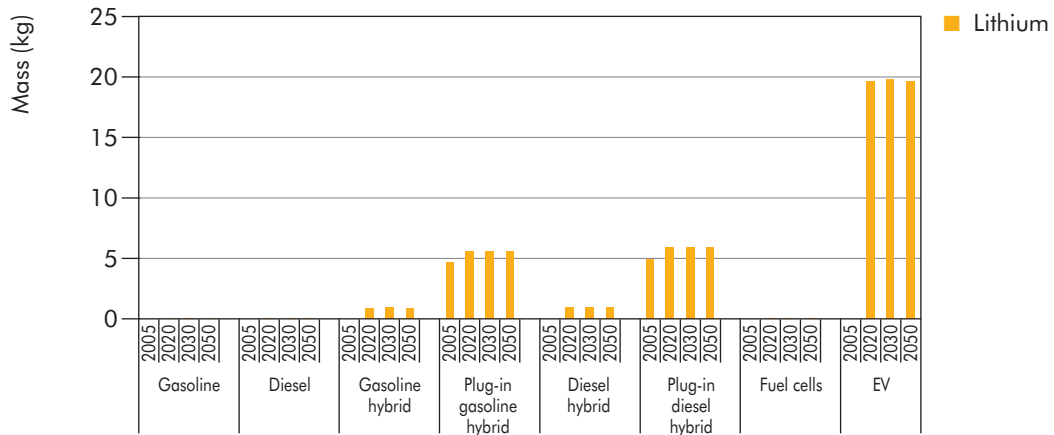
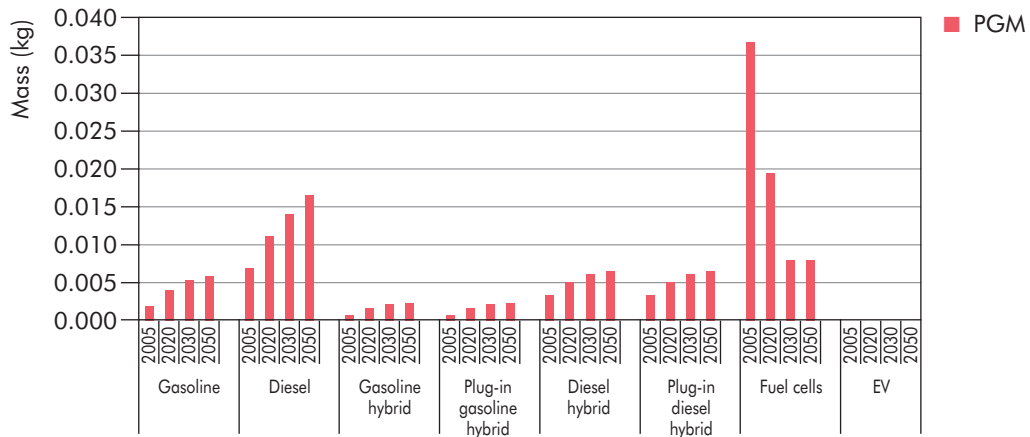


Figure 8.9 (d)



Source: IEA estimates.

Key point

Material use, especially for lithium and PGM, varies significantly by vehicle type and over time.

Vehicle sales and total materials use by scenario

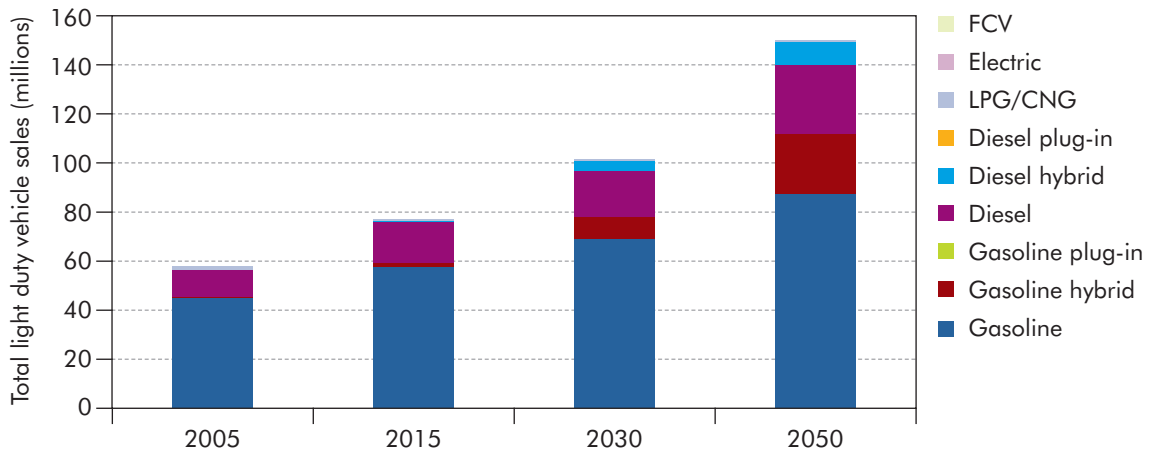
Four main factors affect the total demand for raw materials for the introduction of new passenger LDVs:

- The number of new vehicles being produced and sold each year.
- The type of vehicles produced (i.e. by propulsion technology and fuel type).
- The material characterisation of each vehicle type (based on the “average vehicle” for that type).
- The materials recycling rate.

The sales shares of different types of vehicle vary by region and by scenario. As shown in Figure 8.10, in the Baseline scenario vehicle sales more than double

between 2005 and 2050. Most growth will occur in the developing world, particularly in Asia. Conventional gasoline and diesel vehicles are expected to dominate throughout the Baseline scenario, with a limited increase in the penetration of hybrid vehicles and virtually no plug-ins, FCVs or EVs.

Figure 8.10 ▶ Light-duty vehicle sales by technology/fuel, Baseline to 2050

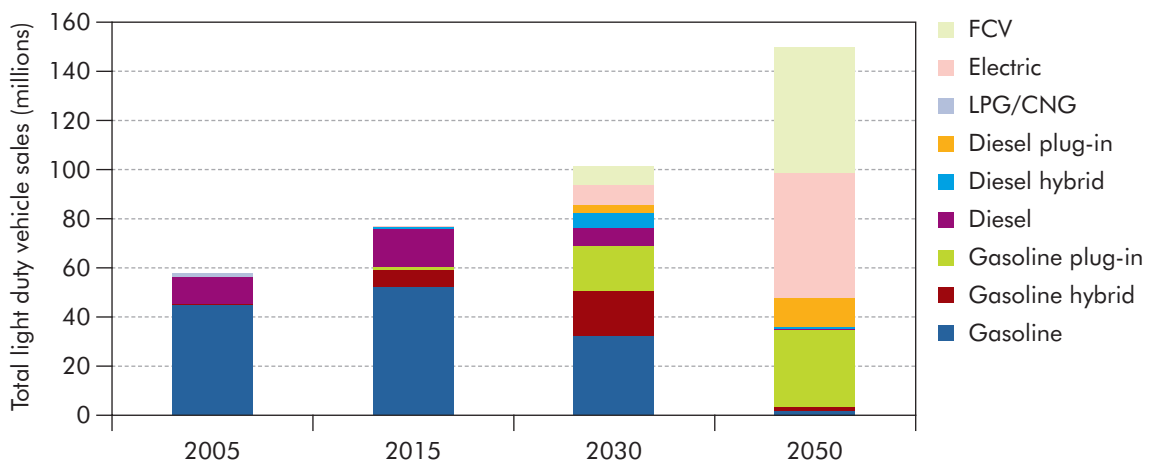


Key point

In the Baseline scenario, conventional gasoline and diesel vehicles are expected to dominate, with increasing hybridisation over time.

In the ETP BLUE Map scenario, the total number of vehicles sold remains similar to the baseline, but the share of different types of vehicles in terms of technologies and fuels changes significantly. The projection of vehicle sales by technology and fuel in the BLUE Map scenario is shown in Figure 8.11.

Figure 8.11 ▶ Light-duty vehicle sales by technology/fuel, ETP BLUE Map to 2050

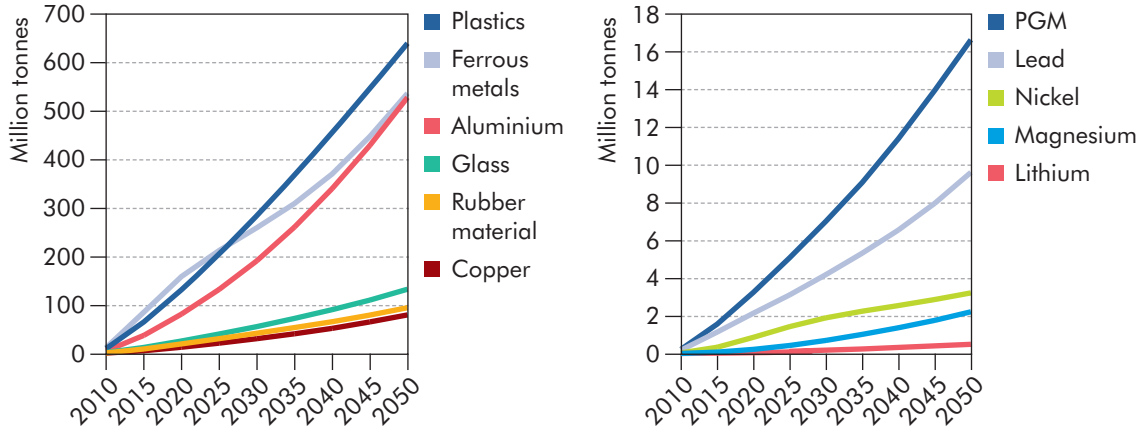


Key point

In the BLUE Map scenario, new-generation vehicles such as plug-in electric, electric and fuel-cell vehicles will replace conventional gasoline and diesel vehicles.

Figures 8.12 and 8.13 show the impacts of these vehicle sales scenarios on materials demand. The materials recycling rate is particularly important in analysing mature markets such as the OECD, since it can drive the total demand for newly extracted materials towards zero once the growth in the total number of vehicles in an economy starts to slow. However, in economies where the number of vehicles is growing rapidly, recycling does not provide a significant share of materials supply.

Figure 8.12 ▶ Cumulative demand over time, Baseline scenario

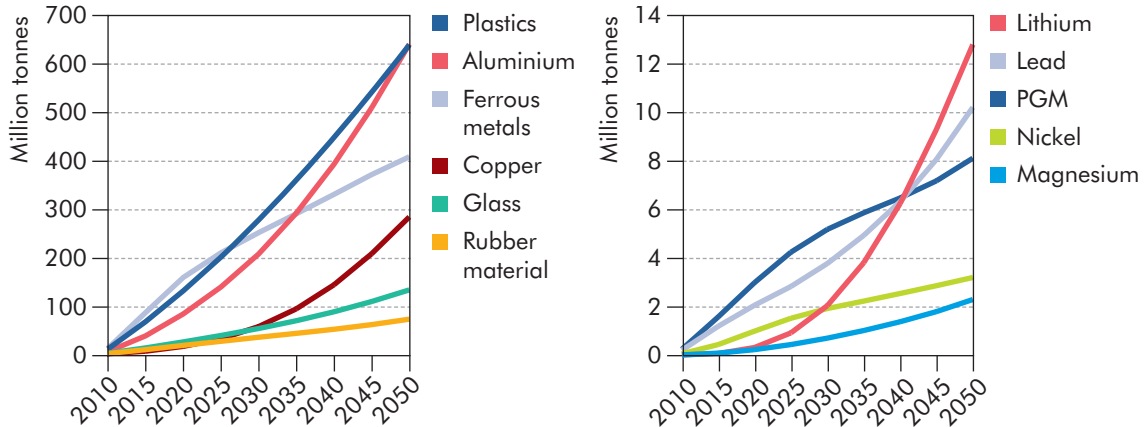


Source: IEA estimates.

Key point

Substantial long-term resource requirements for ferrous metals, aluminium and plastic materials will be needed to meet demand in the transport sector.

Figure 8.13 ▶ Cumulative demand over time, BLUE Map scenario



Source: IEA estimates.

Key point

In the BLUE Map scenario, demand for lithium will rise sharply as the share of electric vehicles rises.

Though scenarios were developed with and without recycling, only those assuming high degrees of recycling are shown here as they appear to be more likely to occur. Materials such as ferrous metals are already recycled in many countries to a large degree, and recycling requirements are likely to become more stringent in OECD and non-OECD countries over the coming decade.

Comparison of Figures 8.12 and 8.13 shows a strong increase in the demand for certain materials, including aluminium, magnesium and lithium in the BLUE Map scenario as compared with the Baseline scenario. Lithium shows by far the biggest increase. Demand for platinum-group metals decreases given the displacement of diesel vehicles in the Baseline scenario by FCVs in the BLUE Map scenario.

The Baseline scenario shows substantial long-term resource requirements for ferrous metals, aluminium and plastic materials, even assuming high recycling rates. Though when recycling is taken into account (as shown), net demand for raw resources of most materials is significantly lower than without recycling. The exception is plastics, since they have a relatively low recycling rate.

In the BLUE Map scenario, the cumulative demand for most materials is similar to or lower than the Baseline scenario, with the exception of lithium. By 2050, lithium requirements reach 15 million tonnes without recycling and about 12 million tonnes with recycling (as shown). In the BLUE EV Success scenario (not shown), where electric vehicle sales reach 80% of all light-duty vehicle sales around the world by 2050, lithium demand reaches 25 million tonnes, even with recycling.

The cumulative demand for PGMs is lower in the BLUE Map scenario than in the baseline, as the requirement per fuel-cell vehicle drops over time and becomes lower than that needed for catalysts in ICE exhaust systems, particularly for diesel vehicles. Thus, even though the number of FCVs sold after 2020 in the BLUE Map scenario is far higher than diesel vehicles in Baseline, total demand for PGMs in the BLUE Map is lower than in Baseline. This result could change either if FCVs require more PGMs per vehicle than anticipated, or if the requirements for catalysts in diesel vehicles drops more than expected.

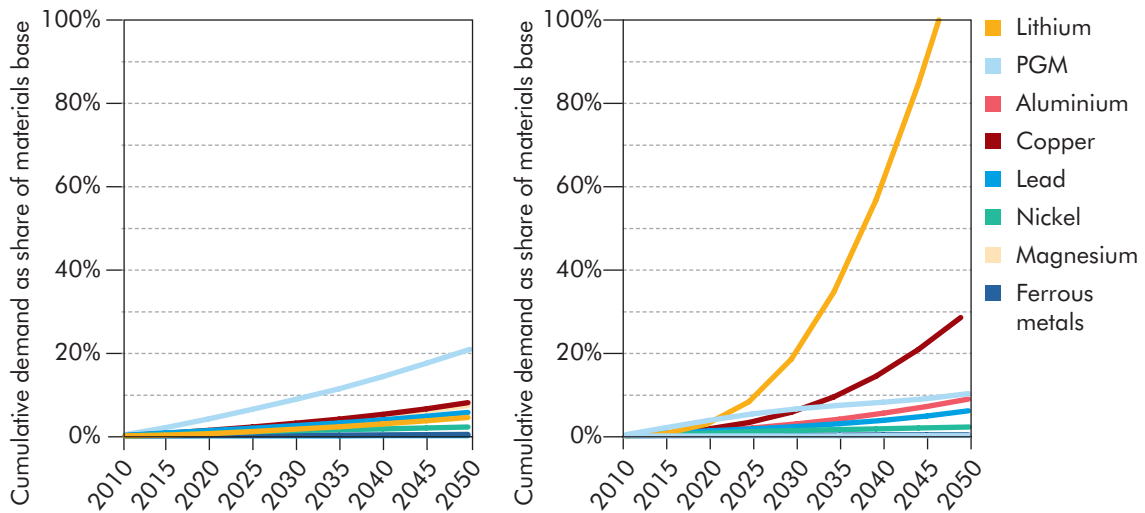
Table 8.4 shows a review of the most recent United States Geological Survey (USGS) estimates for the global reserve base for different materials.⁵ Figure 8.14 shows the total materials demand in the Baseline and BLUE Map scenarios, with recycling, for ferrous metals, aluminium, copper, lead, nickel, lithium, magnesium and PGMs as a percentage of the relevant reserve base using the USGS estimates.⁶

5. The USGS defines the reserve base as that part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth. It includes those resources that are currently economic, marginally economic, and some of those that are currently sub-economic.

6. Expressed as iron contained in iron ore; aluminium contained in bauxite; copper, lead, nickel, PGMs contained in the respective minerals from which they are extracted; and magnesium contained in magnesite.

Table 8.4 ▶ Production and reserves of various materials

Mt	Mine production		Reserves	Reserve base	Resources
	2007	2008			
Ferrous metals	940	1040	73 000	160 000	230 000
Aluminium	38	39.7	5 150	7 250	12 400
Copper	15.4	15.7	550	1 000	3 000
Lead	3.77	3.80	79	170	1 500
Nickel	1.66	1.61	70	150	130
Lithium	0.0258	0.0274	4.1	11	13
Magnesium	5.14	5.27	2 200	3 600	12 000
PGM	0.000422	0.000406	0.071	0.08	0.1
kt					
PGM	0.422	0.406	71	80	100

Figure 8.14 ▶ Baseline and BLUE Map use of materials base with recycling

Note: For ferrous metals and magnesium demand is less than 0.5% of the reserve base.

Source: IEA estimates.

Key point

Only demand for lithium exceeds the total reserve base by 2050.

In the Baseline scenario with recycling, no cumulative materials demand goes above 20% of the global reserve base by 2050. PGMs are the only material type to rise above 10%. In the BLUE Map scenario, with recycling, copper demand reaches

about 30% of the reserve base and lithium demand exceeds the reserve base. The benefits of recycling for lithium will be greatest once EV sales plateau, which does not occur in the BLUE Map scenario until after 2050.

In the BLUE Map scenario, EV sales reach about 33% of vehicle sales by 2050. Plug-in hybrids constitute 30% of sales. In the EV Success scenario, EVs reach 80% of vehicle sales, the required lithium doubles and is more than twice the estimated resource base. If EVs are eventually to dominate LDV markets around the world, additional cost-effective lithium resources must be found or less lithium must be used per unit of battery storage. Or a type of battery storage system which does not use lithium will eventually have to be found.

Building sector

The building sector is very material-intensive, using large quantities of cement, bricks, steel and mortar. Globally, buildings account for around 40% to 55% of cement use, equivalent to between 1 040 and 1 430 Mt in 2006.

The fragmented and often local nature of the building industry and the materials used make it difficult to establish meaningful global estimates for the materials used in buildings. The range is enormous, from traditional houses in Africa and Asia which use locally sourced natural products as building materials, through to the skyscrapers of Dubai and their construction based on cement, steel and other manufactured materials. Indicative ranges for the materials used in the average residential dwelling in OECD countries are set out in Table 8.5.

Table 8.5 ▶ Indicative range of materials used in residential dwellings, OECD

	Kg/m ₂ floor area habitable
Cement	20 to 80
Steel	10 to 70
Copper	0.01 to .2
Wood	2 to 25
Glass	0.5 to 3
Bricks/tiles	10 to 100
Insulation material	0 to 4
Plastic	1 to 4

Sources: Ortiz *et al.* (2009); Blengini (2009); Lopez *et al.* (2009); Alanne and Saari (2008); IEA estimates.

The main changes in the building sector between the Baseline scenario and the BLUE Map scenario are improvements in energy efficiency and a shift to clean energy technologies. More energy-efficient electrical devices and changes in energy

technologies have only a minor impact on future materials demand, in so far as basic appliances change very little. By far the largest impact on the materials use of the building sector will come from the need significantly to improve the energy performance of the building envelope in order to reduce space-heating and cooling demand.

The slow rate of building stock turnover is a significant constraint on the rate at which CO₂ emissions from space heating and cooling can be reduced in the building sector. Table 8.6 provides examples of the rate of retirement of the residential building stock in selected countries.

Table 8.6 ► Dwelling stock and retirement rates in selected EU countries, 1980 to 2002/03

	Total stock (000)					Retirements (000)					
	1980	1990	1995	2000	2002/03	1980	1990	1995	2000	2003	Average
Czech Republic	3 495	3 706	n.a.	3 828	n.a.	16	n.a.	n.a.	2	1.8	0.26%
Denmark	2 162	2 375	2 437	2 509	2 561	8	n.a.	n.a.	n.a.	n.a.	0.37%
France	24 717	26 976	28 221	n.a.	2 945	n.a.	22	22	18	21	0.29%
Germany	25 406	26 327	35 266	37 630	38 158	n.a.	n.a.	21.5	n.a.	n.a.	0.06%
Hungary	3 542	3 853	3 989	4 077	4 134	16.4	7.4	6.4	6.1	4.7	0.22%
Netherlands	4 849	5 892	6 283	6 651	6 764	14.9	11.6	13.7	13.5	17.8	0.24%
Poland	9 794	11 022	11 491	11 485	12 030	26.2	7.5	10	6.2	4.9	0.10%
Spain	14 580	17 220	n.a.	n.a.	14 184	116.6	10.1	8.9	15	15.5	0.32%
Sweden	3 680	4 045	4 234	4 294	4 351	2.1	1	2.5	4.6	1.5	0.06%
United Kingdom	21 517	23 383	24 341	25 283	25 617	45	15.1	n.a.	n.a.	n.a.	0.14%

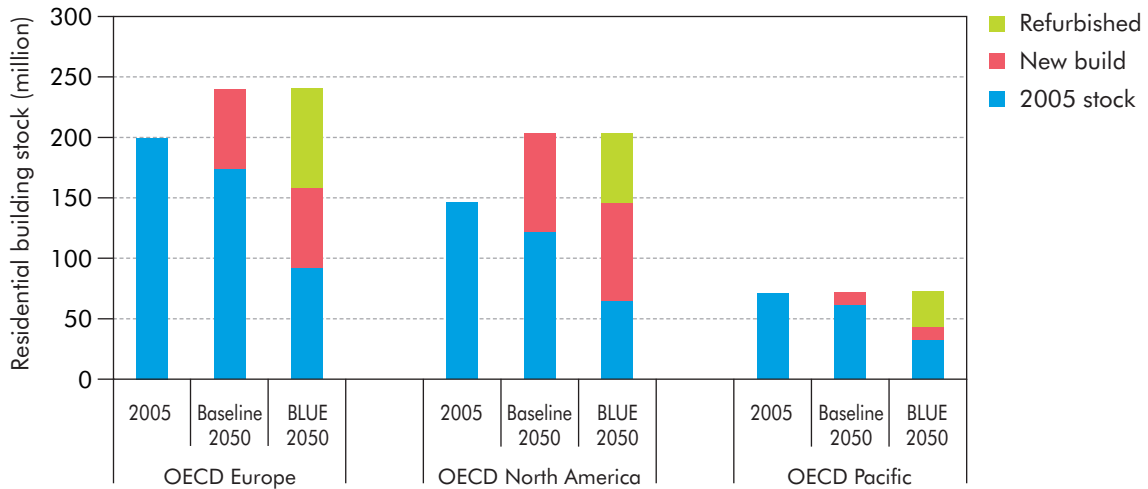
Source: Norris and Shiels (2004).

Achieving the outcomes in the BLUE Map scenario will require significant changes in standards for buildings constructed between now and 2050 and in the transformation of the existing building stock. This has important implications for the building materials required in new construction and in refurbishments.

In the BLUE Map scenario, all new residential buildings in cold-climate countries need to meet the equivalent of passive house energy requirements (*i.e.* 15 kWh/m²/year for heating, cooling and ventilation). In addition, as many as 200 million dwellings will need to be retrofitted to this level or to the “low energy”

building level (30 to 50 kWh/m²/year for heating, cooling and ventilation) in OECD countries. These retrofits can be achieved at least cost if they are incorporated into the renovations that most OECD buildings undergo every 20 to 25 years. However, this implies a significant departure from current typical renovation patterns where very little change in the thermal envelope of the building occurs, and will mean significant additional demand for some materials.

Figure 8.15 ► Existing, new build and refurbished residential building stock by scenario in the OECD (million households)



Source: IEA estimates.

Key point

In the BLUE Map scenario, a significant share of buildings will need to be refurbished in OECD regions.

Figure 8.15 shows the significant need for refurbishment in the BLUE Map scenario in the OECD. If CO₂ emissions reductions from the residential sector are to be achieved at minimum cost, at least 60% of the residential building stock will need to have undergone significant refurbishment to a more efficient energy consumption standard. Achieving this transformation of the OECD building stock will be an important policy challenge.

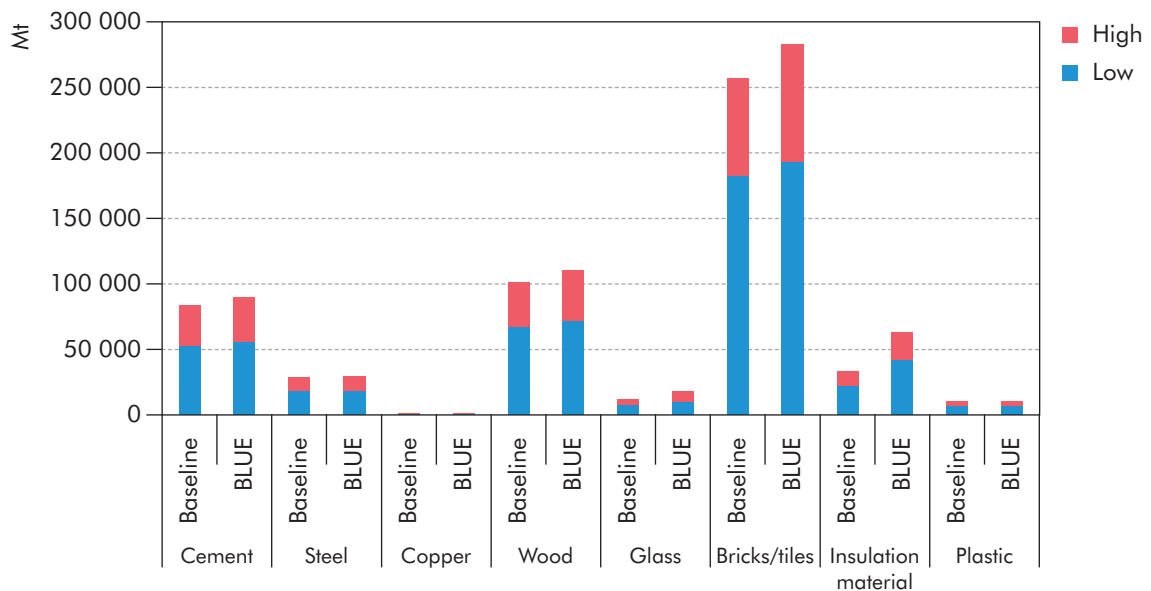
More demanding standards for the energy consumption of new residential and commercial buildings in the BLUE Map scenario, as well as the refurbishment of existing dwellings in OECD countries, imply additional materials demand. Overall, this is not significantly higher than in the Baseline scenario in most cases, although the additional demand is significant in absolute terms.

The exceptions, depending on the building solution chosen for the new standard, are for insulating materials and glass. In the Baseline scenario, only modest changes from an energy efficiency perspective are incorporated in most refurbishment plans in the OECD. Instead, owners prefer to focus on deferred maintenance and to enhance the aesthetic or amenity values of their homes, for example through the addition of floor area, façade renewal, and the modernisation of kitchens and bathrooms.

In the BLUE Map scenario, these refurbishments also include reducing the energy consumption associated with the building envelope by increasing insulation levels in walls, roofs and basements. In many cases it is not economic to replace existing double glazing, except where the windows need replacement. But all remaining single glazing will be replaced with new high-performance double glazing. And in some cases, given high enough carbon prices, it will also make economic sense to replace older double glazing. Moreover, significant insulation material will need to be added in these refurbishments. If façades are being renewed, the application of additional insulation will be economic in many cases, given the low incremental cost of adding insulation material relative to the overall cost. Where façade renewal is not already planned, carbon prices may need to be relatively high to justify the cost of additional insulation material.

Overall, 90% more insulation is required in the BLUE Map scenario than in the Baseline case. Demand for glass is between 29% and 52% higher than in the Baseline scenario.

Figure 8.16 ▶ Cumulative materials use in the OECD residential sector in the Baseline and BLUE Map scenarios, 2005 to 2050



Source: IEA estimates.

Key point

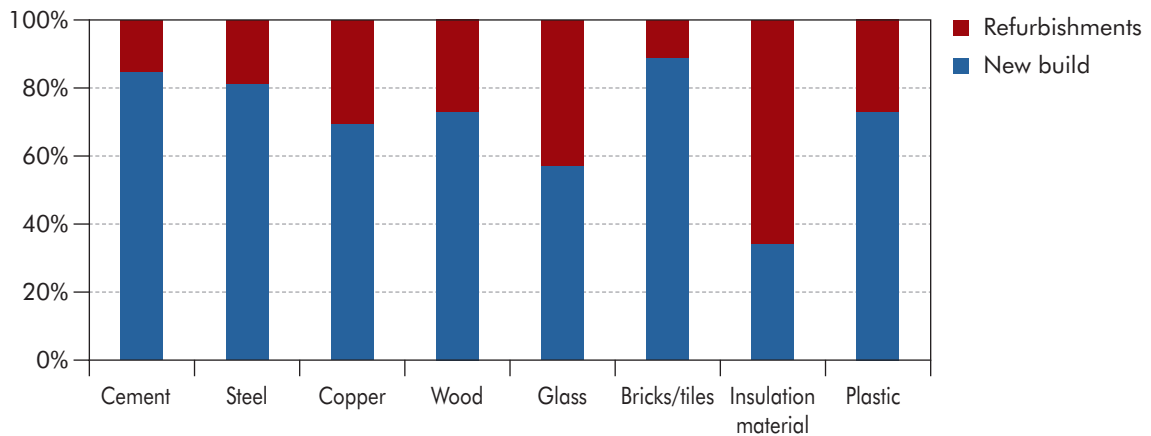
Demand for bricks and insulation materials will rise sharply in the BLUE Map scenario.

Cement demand is of the order of 6% to 7% higher in the BLUE Map scenario than in the Baseline scenario. This increase could triple if refurbishment proves unattractive compared to demolition. This may be the case where building regulations are flexible and the ability to develop a completely new building design could mean the creation of more value from the site, e.g. by replacing a three-floor building with four floors and underground parking, etc.

Steel demand is likely to be in the order of 2% to 4% higher, and wood demand about 7% to 10% higher. Additional brick and tile demand, by far the most important building materials by volume, could be between 5% and 9% higher than in the baseline scenario. The use of copper could increase by between 1% to 2% and that of plastics by 4% to 5%.

For insulation, around 65% of the cumulative additional demand is the result of the more energy-efficient building envelope that is needed in refurbishment (Figure 8.17). For glass, the share is somewhat lower, at 43% of the total.

Figure 8.17 ▶ Share of cumulative additional materials demand in the BLUE low-demand scenario by source, 2005 to 2050



Source: IEA estimates.

Key point

Refurbishments will lead to a high demand for glass and insulation materials.

Chapter 9 POLICY IMPLICATIONS

Key Findings

- ▶ Governments are using a wide range of policies to foster improved energy efficiency in industry. However, there remains considerable scope for further improvements in all sectors and the immediate focus should be on realising this potential through greater implementation of the many well-known, cost-effective policy instruments. The removal of energy price subsidies should be a priority in countries where they persist.
- ▶ Governments also need to adopt challenging but achievable long-term greenhouse gas (GHG) mitigation goals and allow flexibility to enable these goals to be met at least cost, thereby facilitating and encouraging innovation towards low-GHG solutions. Policy instruments can include market mechanisms, fiscal policies, regulatory measures and information schemes. Policies that foster increased recycling and/or changes in materials use can also play an important role.
- ▶ The current situation, in which developed countries are subject to GHG emission constraints while developing countries are not, gives rise to concerns about competitiveness and carbon leakage. These concerns risk hampering the delivery of ambitious GHG objectives in industry and need continued monitoring.
- ▶ A global system of emissions trading may eventually be a crucial policy instrument. In the short- to medium-term, sector-wide approaches covering some of the main energy intensive industries might be a practical first step in stimulating the deployment of new technologies, while addressing concerns about competitiveness and carbon leakage.
- ▶ Crediting mechanisms need to encourage investments in emissions reductions where they are least expensive, for example in developing countries. The design of such approaches should ensure that in the long-term they do not lead to the development of a subsidy to developing countries at the expense of countries with carbon constraints.
- ▶ Many new technologies need government support while in the RD&D phase, before they become commercially viable. There is an urgent need for both industry and governments to accelerate RD&D in breakthrough technologies which could significantly change energy use or GHG emission levels. This will require greater international collaboration, including through public-private partnerships, and will need to include mechanisms to facilitate the transfer and deployment of low-carbon technologies in developing countries.
- ▶ Strengthened international co-operative efforts to gather reliable industry-level energy and emissions data are also needed to ensure the development of sound and effective policies. Private sector-led initiatives have started paving the way towards consistent data gathering at international level through a common methodology. These initiatives could be best elaborated in the context of international standards.

Introduction

Earlier chapters have shown that making substantial reductions in CO₂ emissions from industry will require a transformation in the way energy is used and involve the widespread deployment of existing best available technologies (BAT) and new technologies. Realising this transformation will require significant policy intervention across all industry sectors.

In principle, the most effective way to influence the greenhouse gas (GHG) impact of future investment and technology choices is to impose an implicit or explicit cost on industry for the CO₂ and other GHG it emits. The BLUE scenarios indicate that, to achieve global CO₂ emissions in 2050 that are half the level they were in 2006, industry would need to reduce its emissions by 21%. Options costing up to USD 200/t CO₂ will be needed to reach this goal. This chapter examines how best that effect can be achieved globally, from a position where currently the emissions of emerging economies are unconstrained while some developed countries take the lead in creating systems to raise the cost of emissions.

Energy efficiency policies

Improving industrial energy efficiency often represents the cheapest and easiest way of reducing GHG emissions. Many options are available. These include maintaining and refurbishing equipment, retrofitting or replacing obsolete technologies, improving process controls, process re-engineering and streamlining, re-using and recycling products and materials, or increasing process productivity through decreasing product reject rates and/or increasing materials yields.

But even though energy costs often form a significant proportion of overall costs in industry, a number of issues limit the extent to which the industrial sector in practice takes steps to minimise its energy use (see, e.g. IEA, 2007; Krüger Enge *et al.*, 2007; Golove and Eto, 1996). These include the following:

- A failure to recognise the positive impact that attention to energy efficiency can have on profitability.
- Short investment payback thresholds and limited access to capital.
- A failure to consider the impact on energy efficiency of non-energy policies.
- Low public acceptance for unconventional manufacturing processes.
- A wide range of market failures, such as split incentives, limited access to information, distortionary fiscal and regulatory policies, the absence of full-cost pricing (including subsidies and/or a failure to account for externalities), lack of competition and undefined property rights.

Taken together, these issues mean that industry persistently under-reaches its energy efficiency potential, reducing economic performance and leading to unnecessary waste and unnecessarily high CO₂ emissions. As a result, governments have put in place a wide range of policy responses to attempt to address these issues (Figure 9.1). The main approaches include:

- Technology specifications and incentives in cases (e.g. motors and boilers) where equipment commonalities and pervasive barriers warrant direct government intervention.
- Introducing performance incentives, targets and agreements at the plant, firm or sector levels which, without specifying technologies and processes, encourage firms to identify and implement appropriate technical action.
- Laying down management specifications and incentives that stimulate firms to identify and carry out plant-specific technical actions.
- Putting in place supportive measures that provide industrial firms with information and improved tools for assessing their technical options.

Individual barriers are often best addressed in different ways in different situations. As a result, it is difficult to evaluate which policies are most effective. The way in which each individual policy or measure fits with its particular circumstances, and how well it fits with, or complements, other policies in the energy, environmental, sectoral or more general fields, needs to be considered case by case. Evaluation at this level requires a great deal of information and analysis, and is beyond the scope of this chapter.

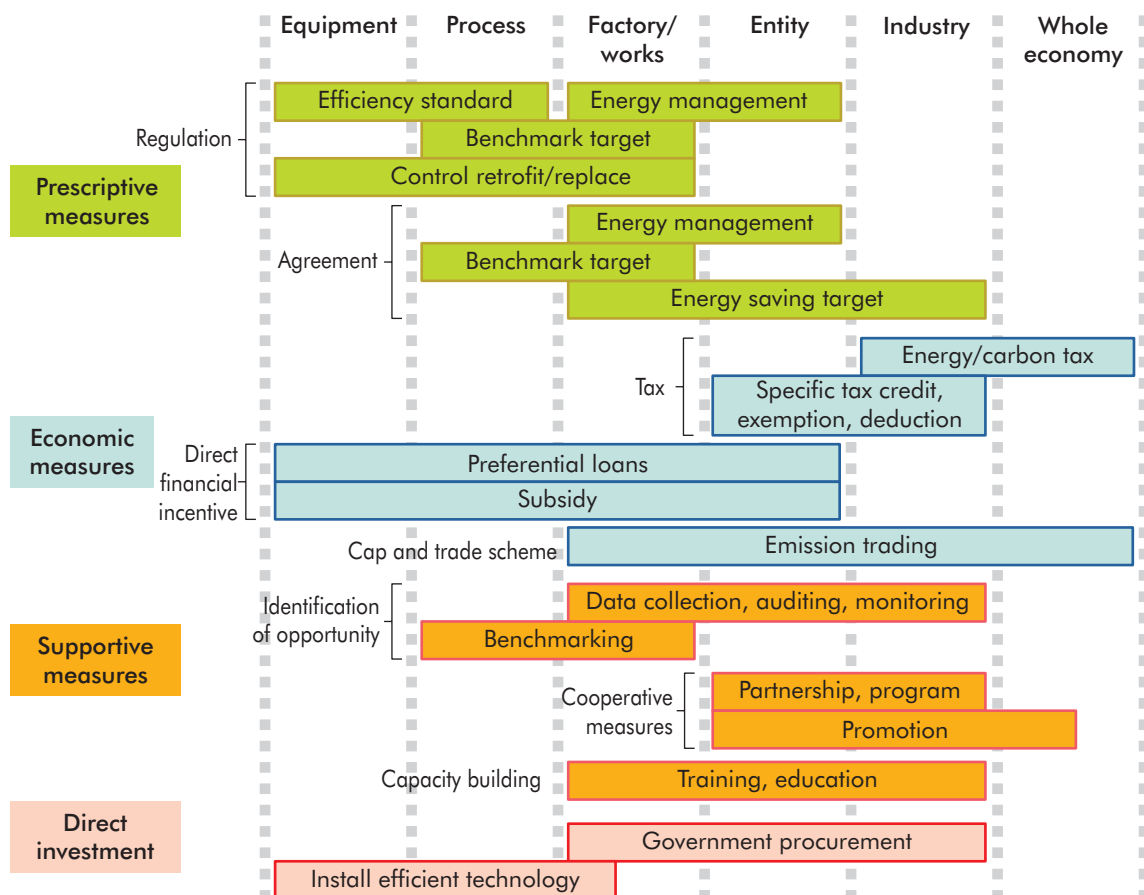
However, a forthcoming IEA Information Paper (Tanaka, 2009) has made a broad evaluation of some of the most common measures, analysing their potential to reduce energy use and CO₂ emissions, their implementation characteristics, and ancillary societal effects, such as their ability to stimulate additional long-term R&D. The results of this analysis are summarised in Table 9.1.

This analysis shows that regulating equipment performance standards has a high potential to reduce energy use and CO₂ emissions, but also requires a high level of technical support so that policies are designed in a way that leaves little flexibility for industry interpretation. Energy management policies are seen to be relatively effective under all criteria. The effectiveness of negotiated agreements and commitments in reducing energy use and CO₂ emissions depends on the targets agreed, but they have the advantage of allowing compliance flexibility. Taxes and cap and trade schemes certainly present strong potential. Financial incentives show medium results for reducing energy use and CO₂ emissions, although they may have positive longer-term impacts on accelerating R&D. Supportive policies are simple to design and implement, and can be effective at promoting R&D, but their effectiveness in improving energy efficiency in practice is difficult to quantify. On the basis on this analysis and others, the IEA has prepared a set of recommendations outlining policy priorities for countries in all sectors, including industry (IEA, 2008b).

As shown in the individual industry chapters, maximising overall levels of energy efficiency also depends on measures to change behaviours in the manufacture and use of products and in recycling. For example, there is considerable scope to use alternative materials, including municipal waste, to generate heat in cement kilns, a practice that is common in some countries.

The recycling of materials such as steel, aluminium and plastics can lead to very significant energy efficiencies. Recycling rates also vary widely between countries. Germany, for example, recycles around one-third of its plastic waste. The European Union average is only 20% and some countries recycle less than 10%. The effectiveness of national and regional recycling arrangements can have a material part to play. Governments should share best policy practice in recycling and materials use.

Figure 9.1 ▶ Energy efficiency policies and measures for industry



Source: Tanaka (2009).

Key point

A wide range of policy responses has been developed to promote industrial energy efficiency.

Table 9.1 Summary of reviewed policies

Criteria	Administrative policies				Economic policies			Supportive policies
	Regulations for equipment performance, process efficiency levels and process configuration	Regulations for energy management	Negotiated agreements / commitments	Taxes and cap and trade schemes	Directed tax reductions and financial incentives			
Potential to reduce energy use and CO₂ emissions								
Stringency and motivational power	High	Medium to high	Low to high	High	Medium			Low
Industry coverage	Low to medium	Low to medium	Medium to high	Medium to high	Low to medium			Medium to high
Policy design and implementation characteristics								
Technical design convenience	Low	High	Medium to high	Medium	Low to medium			High
- Ability to design policy without detailed technical understanding of energy efficiency opportunities								
Compliance flexibility	Low	High	High	High	Low to medium			High
- Degree of industry judgement in choice of energy efficiency measures								
Quantifiable results	Medium to high	Medium	Medium	Low	Medium to high			Low
- Ease of quantifying effects of energy efficiency improvement								
Ancillary societal effects								
Acceleration effects of long-term R&D	Medium	Medium	Medium	Low to medium	Medium to high			Medium to high

Source: Adapted from Tanaka (2009).

Research, development and demonstration

In addition to policies that stimulate market demand for more efficient and lower-carbon technologies, most new technologies will need support while in the research, development and demonstration (RD&D) phases, before they become commercially viable.

Government energy RD&D budgets in many member countries declined from the early 1980s through the 1990s. Since 1999, government expenditures on RD&D have slightly recovered and stabilised; they were estimated to be around USD 10 billion in 2006. Even so, energy RD&D as a share of total RD&D in OECD countries declined from 11% in 1985 to 3% in 2005. Trends in private-sector energy-related RD&D are more difficult to assess than those for government RD&D. There is a lack of comprehensive private-sector RD&D data, mainly owing to their proprietary nature. Data collected on RD&D spending in the largest companies have shown stable RD&D spending in chemicals and pulp and paper, and a gradual increase in industrial metals.

Given these trends, more investment in RD&D in promising new technologies will be needed if industry is to contribute to significant emissions reductions in the long-term. These new technologies include carbon capture and storage (CCS) for a wide range of industry applications, smelt reduction, separation membranes, biomass feedstocks, black liquor and biomass gasification, and inert anodes. While for some of these technologies, the necessary RD&D will be funded by industries themselves, others will require additional government support before they become commercially available.

Table 9.2 ► Key technology priorities for industry RD&D

Key RD&D technologies				
Iron and steel	Cement	Chemicals	Pulp and paper	Aluminium
Smelt reduction		Membranes	Lignin removal	Wetted drained cathodes
Electrification (MOE)		New olefin processes	Black liquor gasification	Inert anodes
Hydrogen		Process intensification	Biomass gasification	Carbothermic reduction
CCS for blast furnaces	CCS post-combustion	CCS for ammonia	CCS for black liquor gasification	
CCS for DRI	CCS oxyfuel	CCS for large-scale CHP		
CCS for smelt reduction	CCS pre-combustion	CCS for ethylene		

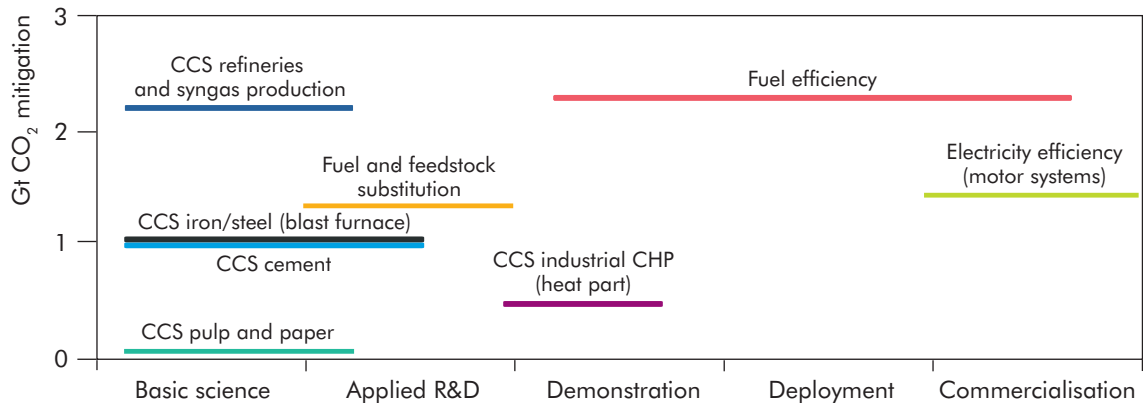
Table 9.2 identifies some of the key technology priorities that will be needed to deliver the outcomes in the BLUE scenarios. It is not intended to be exhaustive. The technologies listed are those that offer the greatest potential contribution to reducing CO₂ emissions, but that require strong technology breakthrough and

cost-reduction efforts. Investment is also needed in research to help identify new, potentially breakthrough technologies, which may have the capacity to overturn the limitations of current knowledge.

Priority near-term RD&D targets for the development of lower-carbon technologies

Achieving long-term and substantial reductions in CO₂ emissions from industry is dependent on a wide range of innovative industrial technology developments, including materials and product efficiency, process innovation, energy and feedstock substitution, and CCS. Figure 9.2 illustrates the stage of development in the next 10 to 15 years for each of the most important technologies and their relative contribution to CO₂ reductions in the BLUE scenarios. The positioning of the bars on the horizontal axis represents the near-term priority or priorities for each technology cluster. The longer the bar, the wider the need for effort at difference stages in the RD&D cycle. The position of the bar on the vertical axis shows the potential for CO₂ savings of each technology cluster in the BLUE scenarios compared to the Baseline scenario.

Figure 9.2 ▶ Near-term technology development priorities and CO₂ mitigation for industrial energy technologies



Note: Industrial CHP-related CCS includes only heat-related and not power-related CO₂.

Key point

CCS as well as fuel and feedstock substitution technologies need strong RD&D efforts in the near term.

Technology development will need to be driven by the following:

- *increased support for R&D* in energy technologies that face technical challenges and need to have their costs reduced before they can become commercially viable;
- *demonstration programmes* for energy technologies that need to prove they can work under relevant operating conditions on a commercial scale;

- *deployment programmes* for energy technologies that are not yet cost-competitive, but whose costs could be reduced through learning-by-doing; and
- *CO₂ reduction incentives* to encourage the adoption of low-carbon technologies.

Box 9.1 ► Technology transfer

Achieving improved energy efficiency and carbon reductions often implies technological change. This is a particular challenge in developing countries. In many cases, new technology is not available off the shelf. It may require imported equipment. In other cases, technology needs to be adjusted to local conditions, for example in terms of upscaling or downscaling, adjustment to different operating conditions, or taking account of the expertise of local service providers. This is especially an issue for small and medium-sized enterprises, generally less so for large energy-intensive industries. For these industries, access to new technology and intellectual property rights (IPR) pose an issue. Patents constitute one form of IPR; manuals, operating experience, knowledge about markets constitute other key elements that companies can use strategically to maintain a competitive edge in their technology area.

Within the international climate negotiations, the discussion around technology transfer is a key issue. However, it is typically discussed at a high aggregation level, often in terms of the development of technology transfer funds. Given the diversity of technology and the complexity of technology transfer, financing is only one aspect. For energy-intensive industries it may not be the most important barrier and, even if financing is in place, there is no guarantee that a successful transfer will take place. Achieving deep reductions in industrial CO₂ emissions will need to include mechanisms that can address all the relevant barriers and so facilitate the transfer and deployment of low-carbon technologies in developing countries.

Investing in the development of new technology is risky. It can fail. In many countries there is consensus that the government should invest in basic scientific and technological research to complement the nearer-to-market technology investments that the private sector will be prepared to make. Governments can also help industry mitigate its risk by creating a framework that will value the public benefits that are achieved or by directly supporting the RD&D investment and activities that will help move innovations to a point where they are commercial. These programmes should be phased out when the technology becomes cost-competitive.

Public-private partnerships

Public-private partnerships in applied RD&D can take the form of government direct and indirect funding of private-sector RD&D or collaborations between governments and industry researchers. Public-private partnerships in applied RD&D may, where effectively managed, be an efficient and targeted mechanism for stimulating priority private-sector energy RD&D by utilising limited resources more effectively. Indirect measures such as tax credits and inexpensive loans from governments can

also support private-sector RD&D. All such policies need to be evaluated regularly to ensure that they are achieving their aims in a cost-effective manner.

Governments can also help create demand for new technologies by putting in place regulatory requirements such as building standards that progressively challenge the supply side to improve performance. If governments adopt such an approach, they need to ensure that the regulatory objectives are likely to be attainable. Unplanned or unpredictable changes in requirements can significantly increase regulatory risk for the private sector and discourage investment.

Different industries have different motivations to reduce energy use. They have made differing degrees of progress in the past. And they have differing potentials for further savings in the future. For example, aluminium companies have long been competing to lower the electricity content of their product and to develop more efficient smelting cell technologies that they could then sell to their competitors.

In contrast, iron and steel and cement producers do not develop the technologies they use. Instead, they buy their process equipment from specialised suppliers. While the industry has come together to promote collaborative R&D in iron and steel, and more recently in cement, this is not the case in the aluminium industry.^{1,2}

As one example of such collaboration, 48 partners in the European steel industry have gathered together in an ultra-low CO₂ steel-making (ULCOS) programme (Birat, 2007). The programme has a total budget of EUR 59 million, 44% of which is funded by the European Commission. Its aim is to reduce the CO₂ emissions of today's best technologies by at least 50%. Technologies under evaluation include the new carbon-based smelting reduction process, new types of reactors, new blast-furnace processes, the use of biomass and CO₂ capture.

Other similar regional endeavours are under way in Japan, South Korea and the United States. Information on these is shared through the World Steel Association. The achievement of significant CO₂ emissions reductions in the iron and steel sector will be at least as much dependent on programmes such as those producing a breakthrough in technology, as on policies that factor in the cost of emissions, as currently envisaged CO₂ reduction technologies are unlikely to be economic even at relatively high carbon prices.

Chapter 3 on the cement sector describes some of the routes for substantially reducing CO₂ emissions per tonne of clinker, and the many uncertainties that have yet to be resolved. The Cement Sustainability Initiative, led and funded by the industry, is working together with the IEA on a technology roadmap for the cement sector.

International collaboration is essential to accelerate the development and global deployment of sustainable energy technologies in the most efficient way. The industry-led initiatives are good examples of how greater international collaboration is working to support R&D development in industry.

1. Alcan (2006) announced a major RD&D effort to deploy more energy-efficient smelting technologies across its activities in Europe and Canada. The commercial reward for Alcan is very clear in that its technology becomes the smelting technology-of-choice for newly installed capacity, outside China and Russia.

2. The aluminium industry has nonetheless acted co-operatively on other aspects of its GHG footprint as is shown later in this chapter.

Emissions trading

In 1992, the United Nations Framework Convention on Climate Change (UNFCCC) set an overall framework for intergovernmental efforts to mitigate climate change. Then, in 1997 countries ratified the Kyoto Protocol, which set targets on GHG emissions for developed (Annex I) countries and allowed them to be met in a number of ways; either directly, by trading emissions quotas among themselves, or by acquiring certified emissions reductions achieved by clean development mechanism (CDM) projects in developing countries.

This international architecture has paved the way for the introduction of domestic CO₂ emissions trading systems, such as the early national schemes introduced by the United Kingdom and Denmark, and for regional emissions trading systems such as the European Union Emissions Trading Scheme (EU-ETS). The economic motivation behind emissions trading is to ensure that the participants are encouraged to achieve the agreed emissions reduction at least overall cost (IEA, 2005 and others).

Table 9.3 provides an assessment of the state of play of existing ETS and of those currently under consideration. This shows that power generation and large energy-intensive industries have been the first targets of ETS, not surprisingly, given their potential to achieve significant reductions and the relatively small number of installations that need to be included within the schemes. Most schemes include a participation threshold, e.g. the minimum thermal capacity of installations.

These schemes are mostly in the early stages of implementation or have yet to start. It is, therefore, too early to draw broad conclusions about their effectiveness in stimulating CO₂ emissions reductions in industry or to identify best practice in terms of design. However, some analysis has been carried out on the first phase of the EU-ETS which operated from 2005 to 2007 (Ellerman and Buchner, 2008; Ellerman *et al.*, 2009). This concluded that despite the over-allocation of allowances, which existed in some member states and sectors, a significant price was paid for CO₂ emissions during 2005-2007 that induced emissions abatement estimated at between 120 and 300 Mt CO₂ over this period in the sectors covered by the scheme. The pilot phase also delivered some important lessons about the design and operation of an emissions trading market. The EU experience is now informing trading schemes that are being developed in other parts of the world.

Table 9.3 Overview of existing and considered emissions trading systems

Region	Participation	Timetable/ambition	Features
Australia (2011)	Carbon Pollution Reduction Scheme Facilities emitting over a defined threshold per year, plus upstream fuel. Discussion with agriculture about inclusion in 2015, and forestry sectors to be included on a voluntary basis from 2010	To start July 2011	Mandatory; all six Kyoto Protocol GHG
New South Wales (2003)	NSW Greenhouse Gas Reduction Scheme (GGAS) Power sector and (voluntarily) consumers > 100 GW	Set to 2012, will merge with national scheme	Mandatory; participants allocated annual benchmark, with fixed penalty/price cap
Canada (2010)	Power generation, iron and steel, cement, lime, chemicals	Domestic offset scheme starting 2010, with emissions trading in 2012	Mandatory (but with range of compliance mechanisms); all GHG
Alberta (2007)	Electricity, energy, chemicals (emitters > 100 t CO ₂ per year)	Annual targets	Mandatory (with buy-out options)
European Union (2005)	CO ₂ emissions from large combustion installations (>20 MWh rated input) from all sectors (including power generation), plus emissions from oil refineries, coke ovens, iron and steel, cement, lime, glass, ceramics, and pulp and paper (subject to certain size criteria).	Phase I: 2008-2012	Mandatory with cross-border trading; national caps set by member States and approved by the Commission; mostly free allocation.
	EU-ETS will be extended to include: <i>i</i>) aviation, chemicals, petrochemicals, primary and secondary aluminium; <i>ii</i>) the capture, transport and storage of all GHG emissions; and <i>iii</i>) new plants as a result of a harmonised definition of combustion installation.	Phase III: 2013-2020	Mandatory with cross-border trading; EU-wide cap with harmonised allocation rules; increased use of auctioning; exemptions from auctioning for trade-exposed activities
Japan (2005)	Industry (food, breweries, pulp, chemicals)	16-month trading periods	Voluntary; history-based allocation
New Zealand (2008)	Forestry (including deforestation), waste, liquid fossil fuels, stationary energy, industrial processes, agriculture	Forestry started in 2008, other sectors expected to join later	Mandatory; internationally tradable; range of penalties

Table 9.3 ▶ Overview of existing and considered emissions trading systems (continued)

Region	Participation	Timetable/ambition	Features
Norway (2005)	Energy production, refining, iron and steel, cement, lime, glass, ceramics	Phase II: 2008-2012 Phase III discussed with EU-ETS (2013-2020)	Mandatory; in 2008 it was merged with the EU-ETS
South Korea (2009)	Large emitting companies (including large buildings and public institutions)	Late 2009	Voluntary; discussion on a mandatory ETS
Switzerland 2008	Heating process fuels. Ceramics, glass, paper, chemicals, aluminium, lime, food, printing	2008-2012	Voluntary but legally-binding once committed; tax for non-compliance
United States (2009)	Waxman-Markey draft bill (American Clean Energy and Security Act of 2009) 85% of US GHG emissions, including power, industry, transport, commercial and residential sectors (sources >25 kt CO ₂ -eq per year).	Rolling 2 year compliance periods from 2012	Mandatory, US-economy wide
North East states (2009)	Regional Greenhouse Gas Initiative (RGGI) Power generation (coal, oil and gas-fired with capacity over 25MW)	3-year periods from 2009-2018	Mandatory; North East states participation
Selected US states and Canadian provinces (2012)	The Western Climate Initiative (WCI) GHG emissions from electricity and large industrial and commercial sources, expanding to cover emissions from transportation and residential, commercial and other industrial fuel	First phase proposed for 2012, with extension in 2015	Seven U.S. states and four Canadian provinces

Source: Updated from Reinaud and Philibert (2007).

The impacts of ETs on competitiveness and carbon leakage

One concern about the impact of the current piecemeal development of pricing carbon through regional and national emissions trading schemes is the possible impacts on competitiveness and carbon leakage. Firms within an ETS, where they compete with firms not subject to an ETS, are inevitably put at a commercial disadvantage equivalent to the cost of the CO₂ emissions within the scheme. This situation enhances the competitiveness (i.e. international market share and profit levels) of non-carbon constrained producers, and can lead to carbon leakage.³

Carbon leakage can take place in several ways (OECD, 2008).⁴ Differences in CO₂ cost levels, for example, can result in companies and consumers shifting the sourcing of emission-intensive products to facilities in lower carbon-constrained regions. In the long-term, differences in production costs could trigger changes in investment patterns. Energy-intensive industries will invest in new production capacities in countries where climate policy costs are low, leading in time to further changes in trade flow patterns (Reinaud, 2008a).

Among the sectors exposed to carbon leakage, the most vulnerable are those that produce a high level of CO₂ emissions per unit of output or that are particularly exposed to increases in their input costs, e.g. for electricity, where fossil-fuel power generation plants seek to pass their CO₂ costs on to wholesale markets, resulting in higher electricity prices.⁵ Emission-intensive industries are exposed to the cost of acquiring allowances to cover emissions, the cost of reducing their emissions, and the opportunity cost of holding allowances that have a market value. Their prices are likely to rise, or their margins to be squeezed.

Studies in the European Union, the United States and Australia⁶ have identified a range of sectors and sub-sectors that are vulnerable to carbon leakage, including cement and clinker kilns, lime, refineries, primary aluminium smelters, integrated steel mills, electric arc-furnace ovens, chemicals, pulp and paper, and ammonia. The extent to which ETS-driven cost increases results in a loss of competitiveness and carbon leakage depends very much on industry's ability to pass through additional costs into product prices without incurring a loss of market share. So the actual impact will depend on such considerations as demand elasticity, the sector's trade exposure (itself a factor of trade barriers, transport costs and product availability in non-carbon-constrained countries) and non-economic factors such as producer-client relationships, product quality and substitutability (see Reinaud, 2008a; Hourcade *et al.*, 2007).

Table 9.4 summarises various quantitative studies that have simulated potential leakage rates in specific industries. They make different assumptions on CO₂ prices

3. Carbon leakage is defined as the ratio of the increase in emissions outside the ETS region to the emissions reductions achieved within the ETS region.

4. Carbon leakage can also occur through emissions constraints raising the costs and suppressing the demand for fossil fuels in constrained regions, leading to a lowering of their price and triggering additional demand in unconstrained regions. OECD (2008) refers to the latter as the energy-intensity effect, but notes that the competitiveness-driven carbon leakage poses much more acute political problems.

5. See IEA (2003) for an early discussion of this issue and Sijm *et al.* (2008) for *ex post* evidence.

6. Reinaud (2008a and 2008b) Hourcade *et al.* (2007), Öko-Institut and Fraunhofer Institute (2008), Morgenstern *et al.* (2007) and Aldy and Pizer (2008).

and policy coverage, so comparisons between these studies are not generally valid. They find competitiveness-driven carbon leakage rates could range from the very low to significant, at 30% or more. None of the studies project emissions reductions in a region being completely offset by emission increases in other regions, *i.e.* a leakage rate of 100% or more. A recent study on the European cement sector issued by the Boston Consulting Group (BCG, 2008) stands out from others in predicting that more than 80% of EU cement production could move to countries on the southern shore of the Mediterranean and Turkey if all CO₂ allowances were auctioned in the EU.

Table 9.4 ▶ Carbon leakage estimates for different manufacturing sectors

Source	Sector	Region	CO ₂ price	Leakage rate ⁷
Aldy and Pizer (2008)	Chemicals, cement, paper, iron and steel, aluminium, bulk glass	US	USD 15/t CO ₂ on electricity	0.9% in the chemicals, 0.9% in the paper, 0.8% in iron and steel, 0.7% in aluminium, 0.7% in cement and 0.6% in bulk glass
Ponsard and Walker (2008)	Cement	EU-27	EUR 20/t CO ₂ EUR 50/t CO ₂	circa 70% 73% ⁸
Demailly and Quirion (2008)	Iron and steel	EU-27	EUR 20/t CO ₂	Varies from 0.5% to 25%, with a median value of 6% ⁹
Demailly and Quirion (2009)	Cement	Annex B countries except US, Australia and New Zealand	EUR 15/t CO ₂ tax	20%
Demailly and Quirion (2006)	Cement	EU-27	EUR 20/t CO ₂	40%
OECD (2003)	Iron and steel	OECD-wide carbon tax	USD 25/t CO ₂ steel and electricity used in steel	45%
			Unilateral policies with equal CO ₂ tax	60%
Gielen and Moriguchi (2002)	Iron and steel	Japan and EU-15	USD 11/t CO ₂ USD 21/t CO ₂ USD 42/t CO ₂	35% in 2020 55% by 2030 70% by 2030

Source: Reinaud (2008a).

7. Leakage rate is defined as the ratio of the increase in emissions outside the ETS region to the emission reductions achieved within the ETS region.

8. Part of the explanation for such a small difference in leakage rate (3%) for a large increase in CO₂ prices lies in the model. Above a certain CO₂ price (not revealed) non-EU firms start competing in the inland market, and inland firms cease competing in the coastal market.

9. This leakage rate takes into account indirect emissions due to the generation of electricity consumed by iron and steel production in the EU and abroad.

There are few operational ETS from which to draw lessons about the extent of carbon leakage in practice. One exception is the EU scheme, in place since 2005. In this case, statistical analysis of trade flows in vulnerable sectors in 2005 and 2006 showed no sign of changes in trade or production patterns in the case of cement, iron and steel, refined oil or aluminium¹⁰ (Reinaud, 2008a; Ellerman *et al.*, 2009, forthcoming).

However, several factors contributed to shield industry from possibly enhanced international competition. For example, the vast majority of allowances were allocated free to industry, and in some cases in quantities that were well above actual emissions in the period (Ellerman and Buchner, 2008; Trotignon and Delbosc, 2008). As a result, the only additional costs created by the ETS came from increased electricity prices as generators passed through the cost of their allowances into market prices (Sijm *et al.*, 2008). The boom in demand for industrial commodities during the period also mitigated the impact of the scheme. With limited excess capacity available and high growth in demand from emerging economies, prices rose rapidly, dwarfing any cost increases caused by the ETS.

Carbon leakage would in any case be expected to take some years to materialise. New investment and production decisions take time to come to fruition. The EU-ETS has not been in place long enough for such impacts to be felt. As climate policy develops, targets will become more binding, and most of the conditions that prevailed in the first phase of the ETS will disappear. Continued monitoring of carbon leakage will, therefore, be important.

Options to reducing carbon leakage

Allowances can be distributed to participants in an ETS in a number of ways, *i.e.* through auctions, by allocation on the basis of past emission levels or sector-wide benchmarks, or distributed on the basis of output volumes. The way in which they are distributed has a significant effect on the risk of adverse competitiveness and carbon leakage outcomes. Entities that must pay for all their emissions by acquiring allowances at auction will incur a cost that must be covered by tighter margins and lower profits, passed on to consumers, or avoided by investment in lower-emitting processes or reductions in production. Free allowances do not create such financial constraint. This distinction is reflected in the more lenient treatment that has been generally granted by governments to energy-intensive sectors that have been identified as being particularly exposed to international trade pressures.

Agreed revisions of the EU-ETS, the Australian ETS proposal and various bills that have been discussed in the United States Congress illustrate the political significance of competitiveness and carbon leakage issues.

Some countries focus on purely domestic solutions to address the risk of leakage (Table 9.5). These include free allowances or direct grants (e.g. state aid) to vulnerable manufacturing sectors to compensate for increased electricity prices. Such subsidies can be financed through the auction of allowances to sectors that

10. Although the latter was not covered by the ETS at the time, aluminium is highly electricity-intensive and as such would suffer from electricity price increases triggered by the cap on power generators.

are not susceptible to competitive risks. Other proposals include the development of co-operative measures that, by agreement between governments, seek equally to affect a range of competitor countries with a view to restoring a level playing field. Some such proposals seek to ensure that imports cannot benefit in domestic markets from a competitive advantage created by the ETS, for example by imposing border taxes or tariffs. To be fully effective against leakage, however, they would also need to rebate the carbon cost to exporters. It is unclear whether such border adjustment measures are compatible with countries' obligations as members of the World Trade Organization (Houser *et al.*, 2008). It has also been suggested (OECD, 2008) that border adjustments of this kind could have negative macro-economic effects on both the importing and exporting regions.

Table 9.5 ► **Measures to address carbon leakage**

Measures	Who proposed what?	
Domestic actions	<u>Under a fixed cap</u> Continued free allocation based on historical emissions or a benchmark: amount revised or declined after a specific period	European Commission (direct emissions) Australia (direct and indirect: Green paper 2008) New Zealand (direct and indirect emissions: remains to be passed by the Parliament) Switzerland (direct emissions) Lieberman-Warner amended bill (S.3036)
	<u>Under a relative cap</u> Free allocation based on output levels of the current trading period	Canada Discussions in some US bills (e.g. Bingaman-Specter S.1766 and Lieberman-Warner S. 2191) (direct and indirect emissions)
	<u>Revenue recycling</u>	Some EU member states (under discussion)
Measures with international implications	Carbon offsets for imports	European Commission France Lieberman-Warner bill (S. 2191) Bingaman-Specter bill (S. 1766)

Source: Updated from Reinaud (2008a).

Clearly, the best solution to carbon leakage would be a set of globally consistent measures which imposed a similar implicit or explicit marginal cost on GHG emissions on all players in a sector and in any sectors that compete with it. The absence of any carbon constraints on international, including maritime, freight is a further distortion in this respect.

Sectoral approaches

In the absence of any immediate prospect for an international agreement that would place binding caps on all countries, backed by a global system of emissions trading, or other mechanism for achieving a common carbon price, the possible role of sectoral approaches (SA) has been receiving considerable attention by policy makers in a number of countries. Rather than seeking country-wide commitments, SA are meant to start by addressing rapidly growing or particularly large CO₂ sources that share the same characteristics around the globe.

Many policy approaches to climate mitigation have been described as SA, including programmes of activities under the CDM, international technology co-operation mechanisms, and the analysis of mitigation potential sector by sector. In this chapter, a sectoral approach is taken to encompass only policy instruments that would deliver direct reductions in GHG emissions on a sector-wide basis in a country or group of countries. In theory, these options could take different forms:

- International support for the sharing of best technology and best policy practices in priority sectors. This could eventually lead to the promotion of technology transfer on a commercial basis.
- The establishment of a new GHG crediting mechanism covering a whole sector, not just projects.
- The introduction of sector-wide commitments by developing countries.
- The establishment of emission goals among a group of countries, also known as “transnational sectoral approaches”.

In the UNFCCC Conference of the Parties held in 2007 in Bali, participating countries opened the door for SA through a commitment to collaborate on technologies, practices and processes for GHG mitigation in all sectors. The Bali Action Plan gives the flexibility to Parties to adopt SA to enhance their mitigation action.¹¹

Beyond engaging developing countries more widely in GHG mitigation, some SAs have been prompted either by a desire to enhance the effectiveness of the CDM as a tool to foster GHG mitigation in developing countries or by existing industry initiatives that consider sectors on an international or transnational basis. International industry groups or federations have been at the forefront of this latter work.

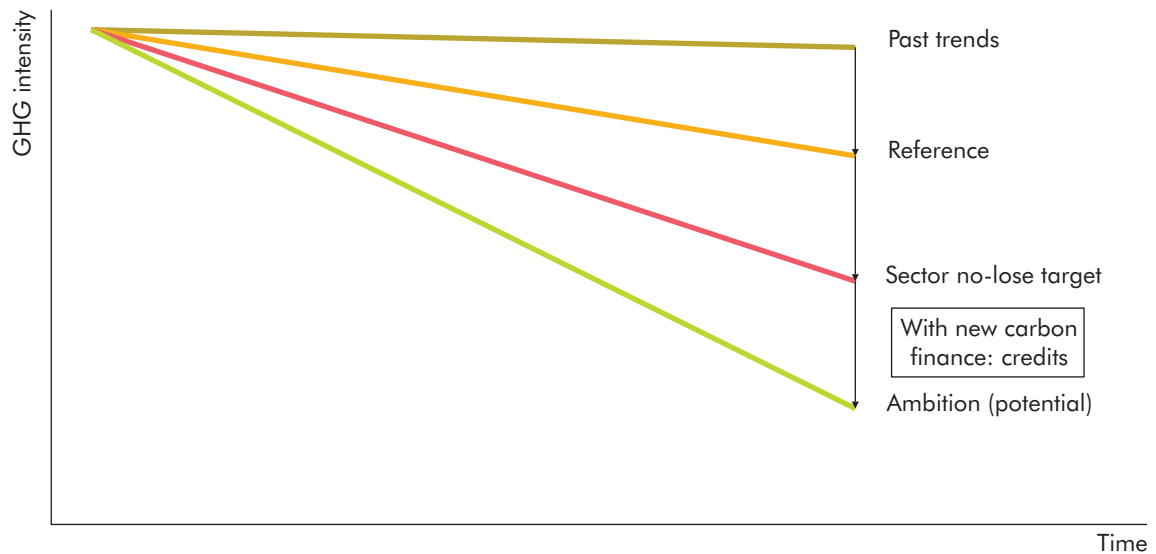
The crediting of emissions reductions raises a number of serious implementation and policy issues. Sectoral crediting offers the opportunity either to extend CDM directly to sectors, with sector-wide baselines being reviewed and approved by the CDM Executive Board, or for the creation of sectoral “no-lose” targets in which countries negotiate an ambitious baseline that goes beyond current trends and are credited if they outperform that baseline but are not penalised if they fall short of it (Helme, 2008).

It is generally envisioned in these schemes that baselines would be based on measures such as tonnes of CO₂ per MWh or per tonne of primary steel, clinker, cement, aluminium, etc. A sector in a country whose performance bettered the negotiated baseline would be rewarded with credits reflecting its performance multiplied by its output (Bosi and Ellis, 2005). Evidence suggests that stakeholders in China may prefer technology diffusion goals, which require, for example, that x% of production capacity in sector y is fitted with technology z by 2020 (CCAP *et al.*, 2008). The most radical innovation of these sectoral crediting mechanisms is that they target net savings in emissions.

11. For a full discussion on the mandates provided by Parties that could lead to progress on sectoral approaches, see Baron, Barnsley and Ellis (2008).

Baselines are negotiated to ensure that the sector achieves reductions from business as usual, only crediting further reductions below that level (Figure 9.3). Under the CDM, the first emissions reduction counts as a credit that offsets emissions in a Kyoto Party that will acquire the credit.¹²

Figure 9.3 ► Beyond offsets: an illustration of sectoral no-lose targets



Source: Based on Ward *et al.* (2008).

Key point

Sectoral crediting mechanisms could help achieve global targets.

Sectoral crediting mechanisms are particularly likely to be useful in respect of heavy industry, which is characterised by relatively small numbers of large point sources in generally cost-conscious sectors. These industries also manufacture end-products that are relatively homogeneous, so that the methodologies used to define the baseline of a sector in one country can relatively readily be applied to the same sector in another country. Heavy industry also offers the possibility of gathering together a relatively limited number of multinational companies to achieve sectoral change (Watson *et al.*, 2005).

In parallel to the UNFCCC policy discussions, a number of regional and international industry federations have been active in climate policy debates, either lobbying in domestic policy debates or providing international forums for their members on questions of climate change. The International Aluminium Institute (IAI), the Cement Sustainability Initiative (World Business Council on Sustainable Development) and the World Steel Association (WSA) have been particularly prominent in this respect (Baron *et al.*, 2007).

These groups have achieved some important outcomes. For example:

12. See Schneider (2008) for a discussion of how CDM could generate actual GHG benefits.

- The IAI has committed to achieve significant reductions in the emission of PFCs (perfluorocarbons, a class of potent GHG), and its members had already reduced PFCs emissions per tonne of product by 87% from 1990 levels by 2007. The IAI works with all its members to share best practice and train plant operators to reduce PFCs emissions.
- Members of the Cement Sustainability Initiative have all committed to set GHG emission goals. They are actively researching sectoral approaches for the cement sector, and developing a low-CO₂ technology road-map in collaboration with the IEA.
- WSA has for several years operated a CO₂ breakthrough programme, with a number of regional groups aiming to develop pilot plants for low-CO₂ steel production, sometimes supported by public funds, such as the ULCOS programme which is partly funded by the European Commission.

In addition, these groups serve a very useful purpose in collecting and comparing GHG emissions data across their sectors, as described in the individual sector chapters. The measurement protocols developed by these industries are a useful starting point for countries seeking to evaluate the performance of these sectors internationally. They could also help in the collection of appropriate data, especially for countries where limited industry-level energy information is available.

Another interesting development has been the formation of the Asia Pacific Partnership on Clean Development and Climate (APP). Since 2007, the APP has provided a forum for international public-private exchanges on technologies to improve energy efficiency and lower GHG emissions over the whole production and consumption chain in aluminium, cement, and iron and steel production.¹³ The APP brings together industry and governments from Australia, Canada, China, India, Japan, Korea and the United States. The iron and steel task force within the APP has started negotiating sectoral energy intensity reduction targets. The extension of the role of the Partnership beyond the sharing of best practice into the co-ordination of action to foster radical changes in these industries would be a significant development.

Implementing sectoral approaches

The challenge for policy makers is to turn current concepts for SA into effective international policy instruments which will foster the rapid, cost-effective deployment of BAT and provide a strong signal to these sectors to make GHG mitigation a priority for innovation.

Recent work undertaken for the European Commission illustrates the political acceptability of various options, as well as the conditions that need to be met if a sectoral crediting mechanism is to be effective (CCAP *et al.*, 2008). Other work has explored questions related to the process of arriving at feasible sectoral approaches under the UNFCCC regime (Baron *et al.*, 2008; Ward *et al.*, 2008). Separately,

13. Other task forces deal with the power sector including renewables and transmission, end-use efficiency (appliances and buildings), clean use of fossil fuels and coal mining.

Japan's submission to the UNFCCC Poznan meeting on SA has identified a number of steps that are needed for their successful implementation.¹⁴

Coverage and data availability

The establishment of sector-wide baselines at country level requires statistical data that may not exist or be readily available in most developing countries. Even in the areas where international industry federations have been active, coverage is often limited to member countries and/or companies. In other cases, sectoral statistics may exist but they may need to be evaluated to establish confidence that they could form the basis of emission baselines and of measures of performance that could be used to determine emission credits on the international market. The collection of such data also raises issues of data confidentiality at the plant level.

Industry initiatives have also shown the importance of establishing clear sectoral boundaries. Major progress has been achieved, including through the APP, to strengthen existing performance measurement practices (CCAP *et al.*, 2008). But there is also a need to allow for some flexibility in terms of the application of sectoral boundaries. For example, the Mexican cement sector is interested in building wind turbines for its electricity supply which would enable it to reduce its indirect CO₂ emissions. In most methodologies, electricity-related emissions are not accounted for at the end-use level, but in the power generation sector, thereby potentially limiting the value to the industry of direct measures to reduce emissions. One forum in which such methodological issues could be discussed with a view to developing standardised approaches is the International Organization for Standardization (ISO). The World Steel Association, for example, has already launched such an effort in co-operation with the ISO.

More work is also needed to establish the data that should underpin sectoral baselines. Countries may not be prepared to negotiate baselines without some knowledge of their own potential to reduce emissions, and of the cost of achieving such reductions. Much is already known about mitigation technologies and best practices. But the cost of avoiding CO₂ emissions depends very heavily on national circumstances. Japan's submission to the UNFCCC illustrates how an inventory of existing practice and technologies, in addition to robust performance measurements, needs to be established if governments and/or sectors are to set ambitious but achievable targets.

The speed of implementation of SA on a broad international scale will depend on efforts to gather such sector-level data. The EU-ETS experience shows that such schemes can be effective even if sectoral coverage is not entirely comprehensive. Cost-benefit analyses can help establish what share of total output would need to be covered to capture a sufficiently large share of emissions. The EU-ETS excludes installations which use less than a threshold amount of energy. Similar thresholds would be needed in SA to establish a manageable boundary to any scheme, although such thresholds could change over time to enhance coverage as schemes mature.

14. Japan's Submission on Application of Sectoral Approaches – memorandum, November 2008.

Domestic implementation issues

SA present particular implementation challenges within countries. In SA, the GHG performance of each installation contributes to the country-level performance against which emission credits are allocated. If half the installations in a sector better the target while the other half fails to meet it, there may be no credits to be shared among the better performers. Given such uncertainty, installations will have less incentive to invest in mitigation measures than they would if the targets had been set at installation level.

One response would be for governments to commit to reward installations that bettered the target, irrespective of the performance of those that failed to do so. To achieve this, governments would need to be prepared to underwrite the overall performance of the sector by acquiring credits from the carbon market to pass to the better national performers. This issue requires further research.

Carbon leakage

The discussion of SA in the UNFCCC has so far avoided focusing on climate-related competitive distortions between developed and developing countries. Until the Parties agree on what sort of SA they will accept, and decide on precise modalities, this issue will remain unaddressed.

There is a risk that sectoral crediting mechanisms could exacerbate carbon leakage (Ellis and Baron, 2005). In particular, a crediting mechanism is a subsidy to decarbonise, financed by the carbon market. The philosophy of no-lose targets is to encourage developing countries to take action through which they can achieve carbon credits, without the penalty of having to buy credits if the targets are not met. Similar industries in countries with ETS-driven constraints on emissions would face a carbon cost, and would have to compete against entities that obtained a benefit from adopting no-lose targets. Given the choice, new installations would be even more encouraged to locate in emerging economies than they would be in the absence of such a scheme.

If crediting is to be applied to sectors with globally traded GHG-intensive products, it will need, therefore, to be based on ambitious performance improvements, revised frequently, so as to avoid ever-growing subsidies to developing countries. The aim should be to use SA to pave the way for an effective carbon price signal, leading to a transition to much lower GHG emissions in these sectors globally.

To be acceptable, sectoral crediting in these activities should be accompanied by a clear collective view on how the system would evolve over time to limit the economic benefit to emerging economies against countries with actual caps. There are several proposals to limit the scale of crediting, via the discounting of credits or the negotiation of ambitious and dynamic emission baselines (see Chung, 2007; Schneider, 2008).

Challenges on the demand side

It is only recently that the scale of the credits that could be generated by a sectoral approach has started to be evaluated. Such evaluations depend on a wide range of assumptions and variables including:

- estimates of the rates of growth in the relevant sectors in developing countries;
- assumptions about the levels of ambition of reductions targets;
- assumptions about the countries and sectors which would be covered;
- projections of fossil fuel prices; and
- assumptions about the effect of mitigation policies on the demand for industrial materials (EPE-IDDRI, 2008).

The GHG mitigation potential of the cement sector for the main emerging economies has been evaluated on the basis of domestic analyses and technology information (CCAP *et al.*, 2008; IEA, 2008a). This evaluation suggests that China, Mexico and Brazil could deliver savings of around 460 Mt CO₂ in the year 2020. Under a no-lose target, these countries would benefit from only part of these reductions, and the remainder being their contribution to global mitigation.

Even if these countries obtain credit for only part of the saving, the impact on the carbon market is likely to be very significant. For example, the EU agreement on the climate-energy package reached in December 2008 establishes a ceiling on the advantage that can be taken of overseas credits. This is estimated at less than 3 Gt CO₂ for the period 2013 to 2020, or less than 375 Mt CO₂ on average each year. This may be increased if the EU agrees to a 30% reduction target for 2020. Other regions may also be in the market for credits, although there is no indication that they intend to rely massively on credits for compliance with their possible commitments after 2012.¹⁵

This suggests that, if all the 460 Mt CO₂ avoided in the cement industry of China, Mexico and Brazil were traded in 2020, it would offset all of the EU's potential demand. Although it is unlikely that all these reductions would be credited, there would also be other substantial credit demands on the market. For example, it has been estimated that between 70 Mt CO₂ and 560 Mt CO₂ could be credited annually for avoided emissions in the power sector in a set of developing countries that includes China and India (Amatayakul *et al.*, 2008).¹⁶

More work is needed to estimate the price at which overall supply and demand would balance. But the size of the mitigation challenge in developing countries and the commitments envisioned in developed countries make it unlikely that industrial sectors in developing countries could be credited for all of their avoided emissions through SA. Developing countries will have to make an important contribution to global mitigation, but with only a share of their reductions being credited against emissions in developed countries. This implies that other forms of support will need to be provided to developing countries to encourage them to maximise their potential for GHG emissions reductions.

15. Recent submissions by Japan include clauses not unlike the supplementarity clause of the Kyoto Protocol that seeks to minimise the reliance on credits for compliance with domestic goals. Legislative proposals in the United States Congress are also fairly restrictive on this score.

16. For reference, these two countries emitted 3 355 Mt CO₂ in power generation in 2006, according to IEA statistics.

Sectoral approaches: the logical next step for international action?

Achieving significant reductions in GHG emissions from industry will require costs to be attached to those emissions through policy measures. Existing schemes suggest that the system of caps and flexibility mechanisms embedded in the Kyoto Protocol architecture is not sufficient to trigger effective mitigation action. SA, which provide a means to engage effort in developing countries more effectively, could offer the promise of a “new deal” that would result in a more effective regime to reduce global GHG emissions.

At present, the main obstacles to SA are the following:

- Common measurement methodologies are needed for energy efficiency and CO₂ emissions in industry. ISO could be a useful forum for the development of these.
- They must provide incentives to industry in developing countries without skewing competition. The role of crediting should be carefully considered in this respect.
- They must support, rather than undermine, the carbon market. Their design, therefore, needs to take account of the supply-demand balance. Support measures other than crediting may be necessary for developing countries, starting with the sharing of today’s best practice among private-sector actors and governments.
- They should avoid creating sectoral niches or exemptions. Policy makers need to aim for a regime that delivers a similar cost of carbon on emissions of all activities. Above all, priority should be given to approaches that encourage sectors to compete to innovate and to deliver a least-cost solution to GHG mitigation.

Steps to achieve such outcomes will raise some contentious issues. Developing countries like China, India or Brazil have yet to engage in this discussion at the UNFCCC.

Conclusions

Like other GHG emitters, heavy industry must take steps to reduce its emissions. Energy efficiency and the implementation of BAT need to be given priority in the short-term. Government intervention will be needed in the form of standards, incentives and regulatory reforms, including removal of price subsidies, if the potential offered by current technologies are to be realised. The development and deployment of promising new technologies will also be needed; this will require substantial investment. Industry will continue to take the leading role but governments will need to go far beyond what they have done in the past to create economic and financial incentives to stimulate change. There is an urgent need for major acceleration in RD&D, with government support for demonstration projects being particularly important. This will require greater international collaboration and will need to include mechanisms to facilitate the transfer and deployment of low-carbon technologies in developing countries.

Achieving the CO₂ reductions necessary to stabilise the global climate will depend on CO₂ emissions creating costs for emitters. Not all regions are moving at the same pace, and trade frictions will start to arise with the threat of carbon leakage. As more countries embark on CO₂ pricing through ETS and consider linking them together, a more level playing field may arise. But emerging economies are still lagging behind. SA have been proposed to engage all countries in GHG reductions in large emitting sectors, including industry. Crediting mechanisms need to be developed to encourage investments in emissions reduction where they are least expensive, for example in developing countries. Such an approach will only be acceptable politically as long as it does not lead to the subsidy of developing countries' industries at the same time as developed countries apply cost increases on their companies.

Industry-led initiatives and public-private partnerships are making important contributions to this debate, starting with data-gathering protocols to allow for objective comparisons of energy and GHG performance. The iron and steel and, more recently, cement sectors have embarked on co-operative sectoral R&D programmes into low-CO₂ technologies, sometimes with public support. Governments should explore the possibility of public funding in this area. In the end, however, the climate policy framework should allow industry – and other sectors – to cut emissions at least cost. Some flexibility is essential in the face of major uncertainty about the long-term contribution of all emitting sectors to global mitigation.

Annex **A** REGIONAL DETAIL OF INDUSTRY ANALYSIS

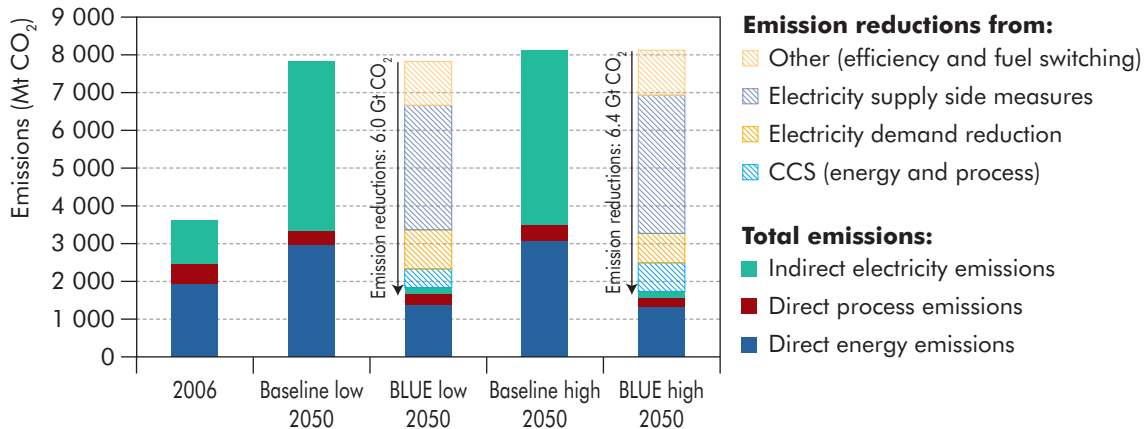
China

Under the Baseline low- and high-demand scenarios, industrial CO₂ emissions (direct and indirect) in China are expected to more than double from 3.6 Gt in 2006 to 7.8 Gt to 8.1 Gt in 2050. The largest increase in Baseline emissions will come from indirect electricity. Total industrial electricity consumption will increase from 6 EJ in 2006 to 22 EJ and 23 EJ in Baseline low- and high-demand scenarios.

In the BLUE low and high scenarios, indirect electricity emissions will fall sharply to less than 0.16 Gt and 0.18 Gt respectively in 2050 as the Chinese power sector becomes nearly decarbonised. The share of electricity use is expected to rise from 21% in 2006 to 37% in the BLUE low-demand scenario.

The largest contribution to emissions savings will come from measures taken in the power sector, which account for 57% of total emissions reductions under the BLUE scenarios. The CO₂ intensity of power is expected to fall from 720 kg CO₂/kWh in 2006 to just 33 kg CO₂/kWh in 2050 under the BLUE scenario. In contrast, the CO₂ intensity under the Baseline scenarios is expected to rise slightly to 727 kg CO₂/kWh.

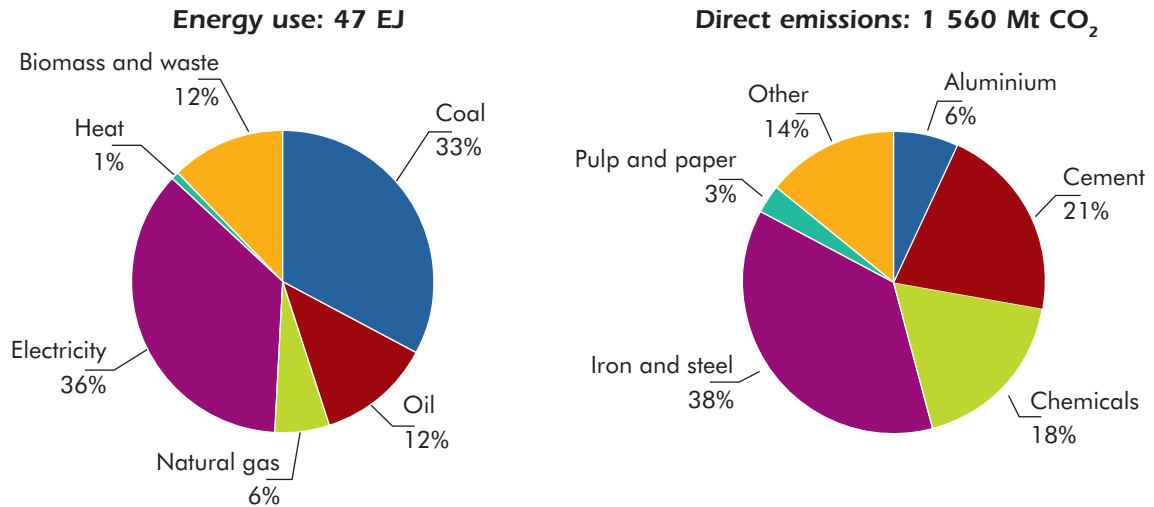
Figure A.1 ► Total industrial CO₂ emissions in China in Baseline and BLUE scenarios, 2006 and 2050



Direct process emissions are expected to fall from 0.53 Gt in 2006 to 0.36 Gt and 0.42 Gt in 2050 as cement production declines from 1.2 Gt in 2006 to 0.8 Gt and 0.9 Gt in 2050 under the Baseline low- and high-demand scenarios. Process emissions will fall still further under the BLUE low- and high-demand scenarios with the application of CCS, reaching just 0.28 Gt and 0.24 Gt in 2050. The share of emissions from the cement sector, which currently account for 35%, will decline to 21% and 19% under the BLUE low- and high-demand scenarios. This decline will be offset by a rising share of emissions from the chemical and aluminium sectors

as rapid growth in production will lead emissions to rise significantly in these two sectors.

Figure A.2 ▶ **Industrial energy use and CO₂ emissions in China in the BLUE low scenario, 2050**



Energy efficiency measures under the BLUE low- and high-demand scenarios will allow total energy use in 2050 to fall by 24% and 21% compared to the Baseline scenarios. Greater levels of CCS will be required in the BLUE high-demand scenario to offset higher growth in emissions from higher production levels and will result in additional energy use and hence in a lower reduction than in the BLUE low scenario. The reduction in energy intensity in industry will not be enough to offset high production growth, and total energy use will double from 28 EJ in 2006 to 47 EJ and 53 EJ in 2050 under the BLUE low- and high-demand scenarios respectively.

India

Rapid production growth in India will lead total industrial CO₂ emissions in 2050 to rise by over 400% from 0.57 Gt in 2006 to 2.8 Gt in Baseline low-demand and 3.3 Gt in Baseline high-demand scenarios. Despite measures taken to improve energy efficiency and the uptake of low-carbon technologies under the BLUE scenarios, total industrial emissions will still rise by 52% and 60% in 2050 compared to 2006 levels because of strong production growth. In particular, high growth in cement consumption means that 37% of total industrial emissions will come from the cement sector, where deep emissions reductions are particularly difficult and costly.

In contrast to China, where we expect a reduction in direct process emissions as cement demand declines, process emissions will rise sharply in India from 0.08 Gt in 2006 to between 0.28 Gt and 0.33 Gt in 2050 under Baseline low- and high-demand scenarios. The implementation of CCS in industry will allow significant reductions in process emissions under the BLUE scenarios, but these will still be more

than two-and-a-half times greater than current levels. Cement consumption in India is expected to rise from 160 Mt in 2006 to between 635 Mt and 735 Mt in 2050.

Figure A.3 ► Total industrial CO₂ emissions in India in Baseline and BLUE scenarios, 2006 and 2050

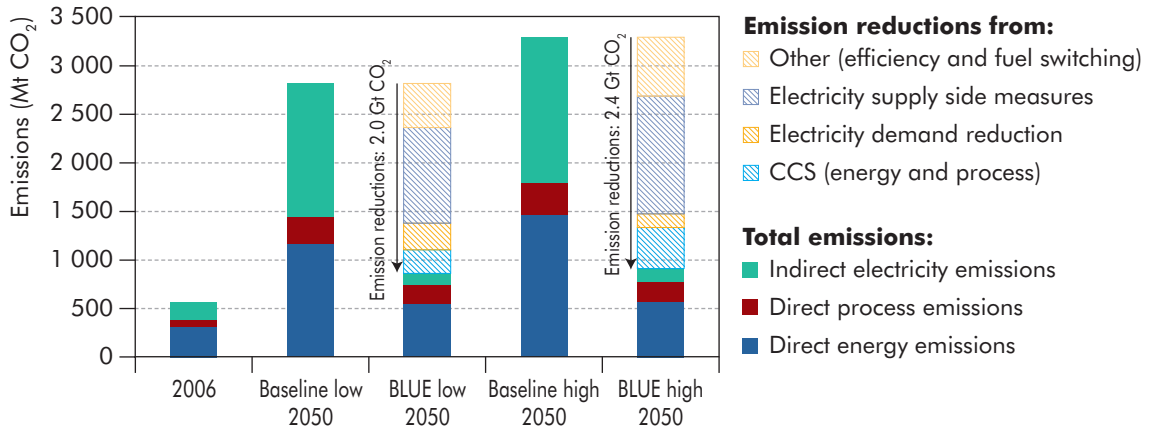
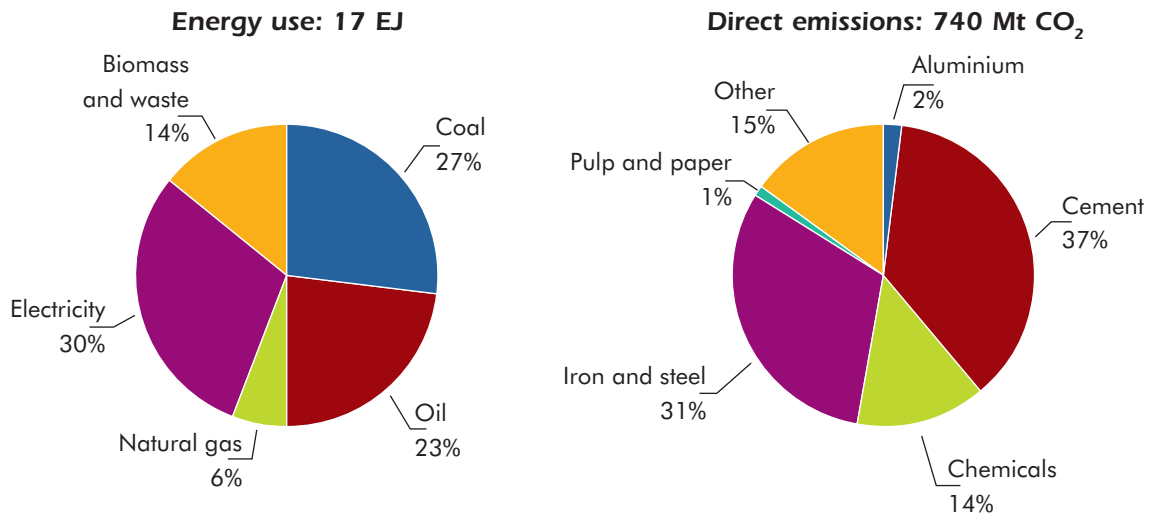


Figure A.4 ► Industrial energy use and CO₂ emissions in India in the BLUE low scenario, 2050



The largest contributor to total emissions reductions in industry will be measures taken in the power sector to decarbonise; they account for 50% of total CO₂ savings in the BLUE low- and high-demand scenarios. Indirect emissions, which rise from 0.18 Gt in 2006 to 1.4 Gt and 1.5 Gt in 2050 in the Baseline low- and high-demand scenario will decline by 36% below today's level in the BLUE scenarios. Reducing direct energy and process emissions in India will require a combination of improved energy efficiency, fuel switching and CCS. Under the BLUE high-demand scenario, the contribution of CCS to emissions savings will almost double to 0.42 Gt compared to 0.24 Gt under the BLUE low case.

OECD Europe

Total industrial CO₂ emissions in OECD Europe are expected to rise by between 15% and 16% in the Baseline low- and high-demand scenarios in 2050 compared to current levels. Almost all of this growth will come from indirect electricity emissions. Direct energy and process emissions will remain flat under the Baseline scenarios.

Figure A.5 ► Total industrial CO₂ emissions in OECD Europe in the Baseline and BLUE scenarios, 2006 and 2050

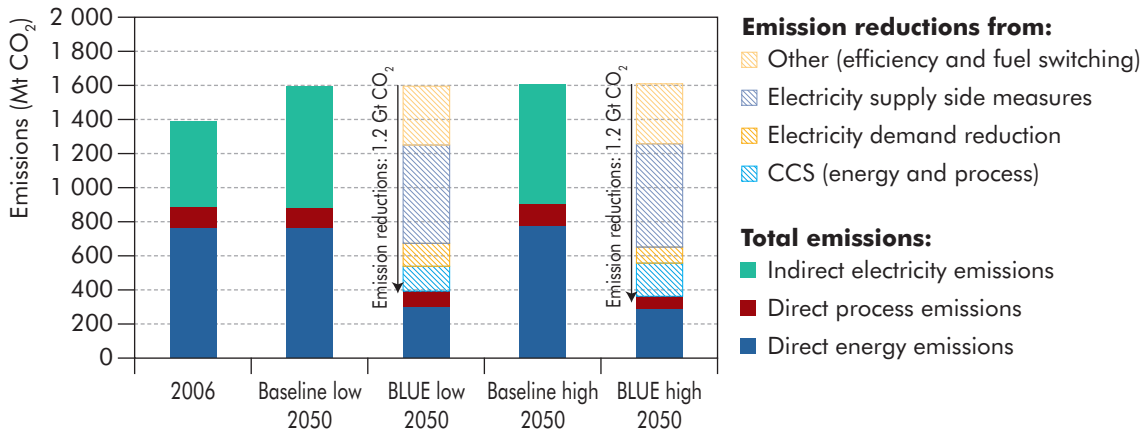
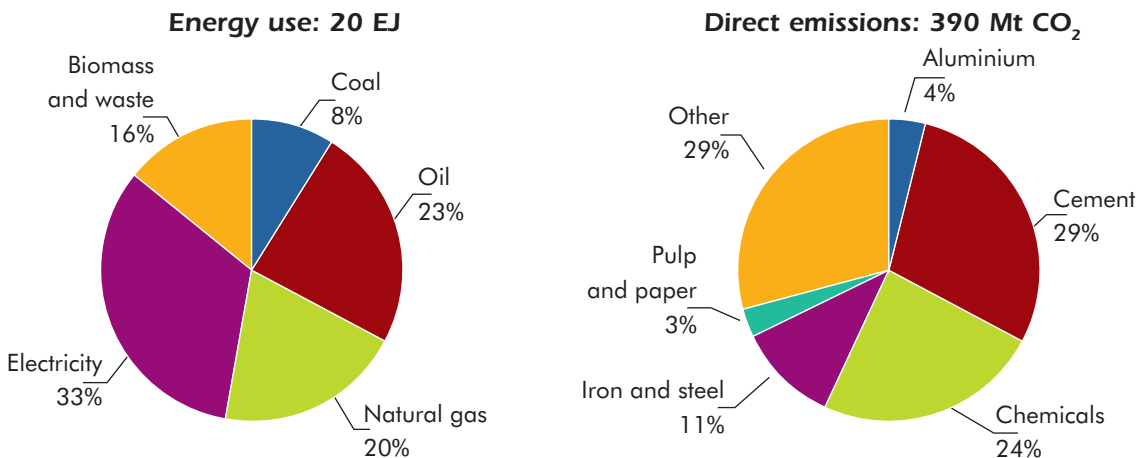


Figure A.6 ► Industrial energy use and CO₂ emissions in OECD Europe in the BLUE low scenario, 2050



Total direct and indirect emissions in 2050 fall by more than 70% to 0.39 Gt in the BLUE low-demand and to 0.36 Gt in the BLUE high-demand scenario. Indirect electricity emissions will disappear as the European power sector becomes decarbonised. Energy efficiency and fuel switching will contribute the largest reductions to direct emissions, saving 0.45 Gt in the BLUE low-demand and 0.44 Gt in the BLUE high-demand scenario. Industrial energy intensity will fall significantly under the BLUE scenarios, as total energy use declines by 23% from

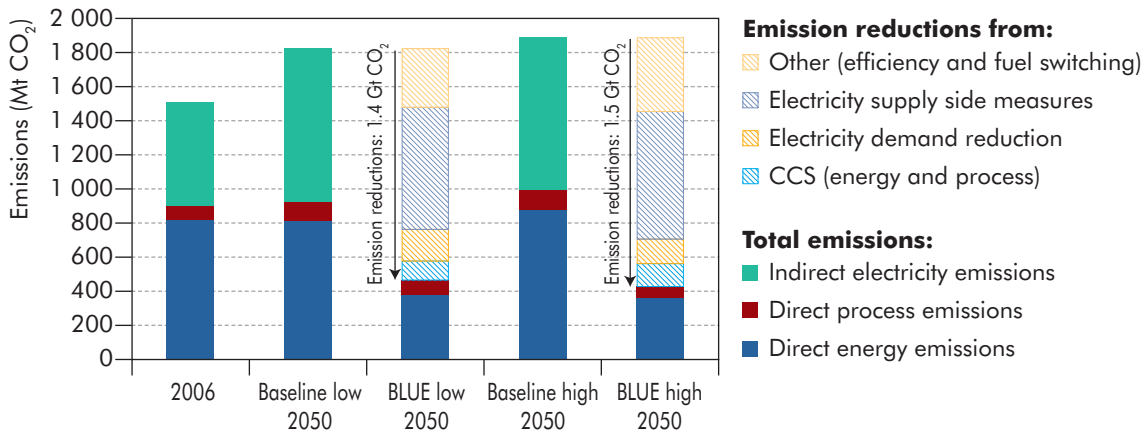
20 EJ in 2006 to 16 EJ in the BLUE low-demand scenario in 2050. The widespread application of CCS will allow for an additional reduction of 0.14 Gt in the BLUE low-demand and 0.19 Gt in the BLUE high-demand scenario.

In the BLUE low-demand scenario to 2050, the cement sector will account for the largest share of direct emissions, at 28%, followed by chemicals at 23%. Emissions from iron and steel, which currently represent 29% of industrial emissions decline to just 11%. CO₂-free fuel sources, including carbon-free electricity, biomass and waste and other renewables, represent half of all fuel use in the BLUE scenario.

OECD North America

Trends in emissions in OECD North America are very similar to those in Europe, with Baseline emissions rising by 21% in the Baseline low scenario compared to 2006. Emissions under the Baseline high-demand scenario are just marginally higher than in the low demand case as production volumes are only slightly different. Almost all of the growth in total emissions is attributable to higher indirect emissions from electricity, which rise from 0.61 Gt in 2006 to 0.90 Gt in the Baseline low and high scenarios in 2050. As the North American power sector is decarbonised by 2050 under the BLUE scenarios, indirect electricity emissions fall to zero.

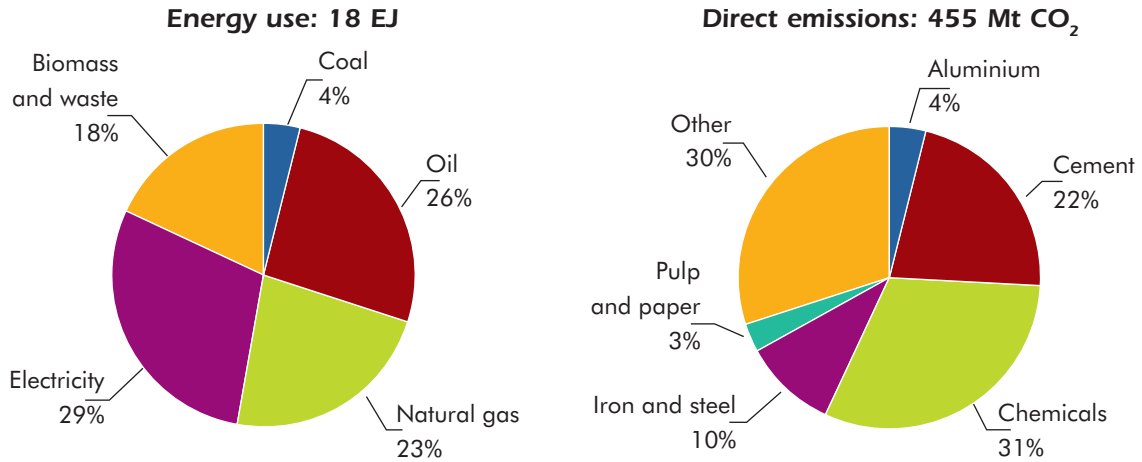
Figure A.7 ▶ Total industrial CO₂ emissions in OECD North America in the Baseline and BLUE scenarios, 2006 and 2050



Direct emissions in the Baseline demand scenario remain relatively flat, but fall by 47% and 53% in the BLUE low and high scenarios in 2050. They decline from 0.90 Gt in 2006 to 0.46 Gt and 0.42 Gt, respectively. Energy efficiency and fuel switching account for 80% of this decrease, with savings from CCS accounting for the remainder.

The chemical sector accounts for 31% of total direct emissions in the BLUE low scenario, cement for 22% and iron and steel for 10%. Total energy use falls to 18 EJ, 12% below the 2006 level of 21 EJ, and 24% below the Baseline low of 24 EJ. Fossil fuels will represent 53% of total energy use in the BLUE low in 2050. The share of coal will decline from 9% today to just 4% in the BLUE low demand scenario.

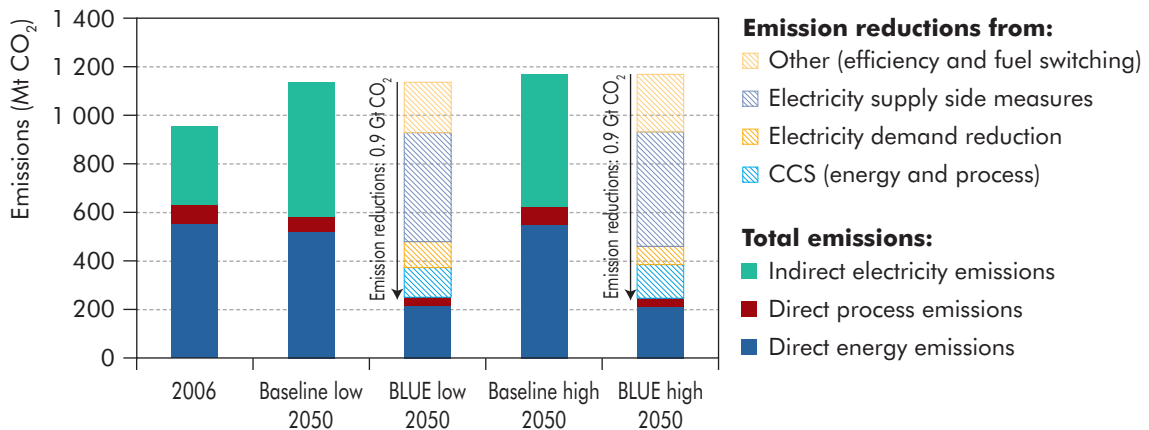
Figure A.8 ▶ Industrial energy use and CO₂ emissions in OECD North America in the BLUE low scenario, 2050



OECD Pacific

Total emissions in the OECD Pacific region are expected to rise by 18% in the Baseline low-demand scenario compared to 2006 levels with indirect electricity emissions accounting for this increase. Direct energy and process emissions show a decline as the production of cement and iron and steel falls in 2050. In the BLUE scenarios, total emissions fall by 72% from 1.0 Gt in 2006 to just 0.25 Gt in the Baseline low. As in the other OECD regions, electricity production will be carbon-free and hence no indirect electricity emissions are expected in the BLUE scenarios.

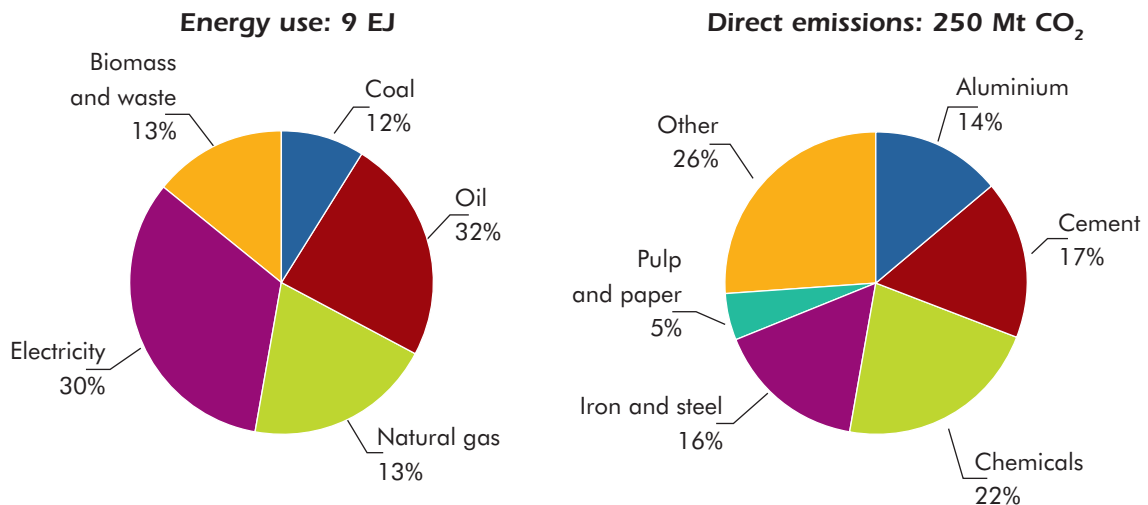
Figure A.9 ▶ Total industrial CO₂ emissions in OECD Pacific in Baseline and BLUE scenarios, 2006 and 2050



Accounting for 57%, the share of fossil fuel use in the BLUE low scenario is higher than in other OECD regions. The share of biomass and other renewables is also

significantly lower. The high share of fossil fuel use will mean that CCS will need to play a significant role in reducing emissions in this region. Given that the region has already some of the highest levels of energy efficiency today, the contribution from that area is lower than in other regions.

Figure A.10 ► Industrial energy use and CO₂ emissions in OECD Pacific in the BLUE low scenario, 2050



The share of direct emissions from the iron and steel sector will show the largest decline from 37% in 2006 to just 16% in the BLUE low scenario in 2050. Direct emissions in the iron and steel sector fall from 236 Mt to just 36 Mt. This decline will be offset by higher direct emissions from aluminium, which would double from 18 Mt to 36 Mt in the BLUE low scenario.

Other developing Asia

Total direct and indirect emissions in other developing Asian countries are expected to triple from 0.69 Gt in 2006 to 1.8 Gt and 2.2 Gt in the Baseline low and high scenarios to 2050. High materials demand, particularly in the cement sector, will lead energy use and emissions to rise. Direct process emissions are expected to more than triple in the Baseline scenarios and increase by between 26% and 31% in the BLUE scenarios from current levels of 0.09 Gt. The application of CCS in the BLUE scenarios will allow for significant reductions in direct process emissions compared to the Baseline cases. The share of direct emissions from the cement sector will rise from 32% in 2006 to 44% in the BLUE low-demand scenario in 2050. Like all regions, indirect electricity emissions will show the largest decline as the power sector reaches near-decarbonisation levels.

The chemical sector also shows a rising share of emissions reaching 16% of direct emissions in the BLUE low, up from 13% in 2006. The share of emissions from the iron and steel sector remains unchanged at 6%. In contrast to some of the other regions, the use of electricity in the BLUE low scenario is one of the lowest, at just 21%.

Figure A.11 ▶ Total industrial CO₂ emissions in other developing Asia in the Baseline and BLUE scenarios, 2006 and 2050

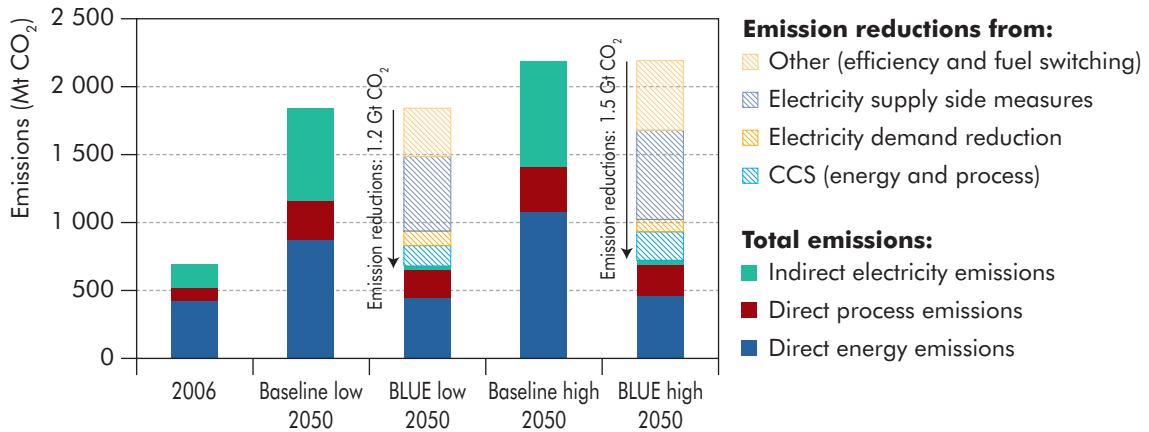
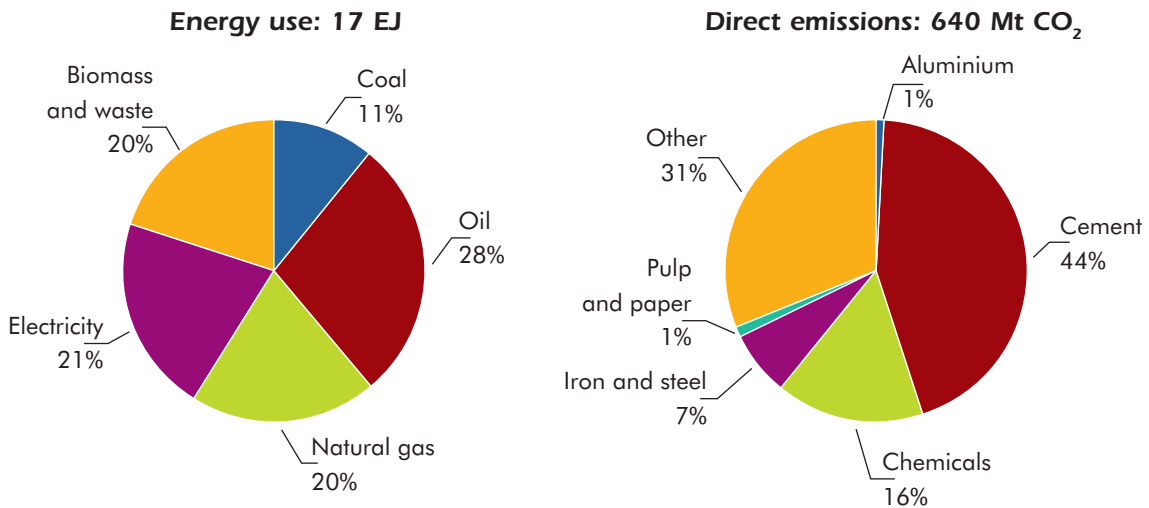


Figure A.12 ▶ Industrial energy use and CO₂ emissions in other developing Asia in the BLUE low scenario, 2050



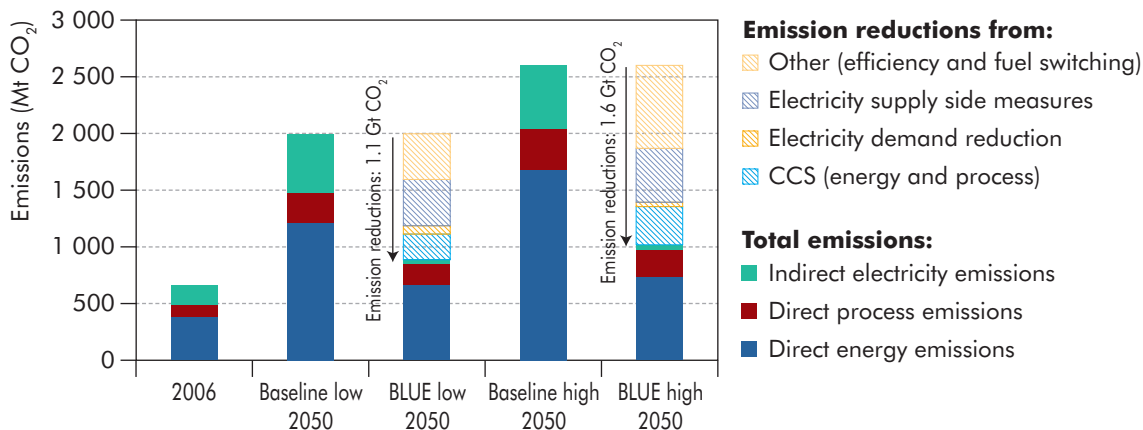
Energy efficiency measures under the BLUE scenarios will allow total energy use in 2050 to fall by 16% and 22% compared to Baseline low- and high-demand scenarios. The reduction in energy intensity in industry will not be enough to offset high production growth, and total energy use will almost double from 8 EJ in 2006 to 17 EJ and 20 EJ respectively in the BLUE low and high scenarios to 2050.

Africa and the Middle East

It is expected that Africa and the Middle East as a region will experience one of the most rapid growths in industrial production thanks to the abundance of low-cost natural gas and strong demand for materials. This region accounts for a significant growth in cement, chemicals, and iron and steel production. Total direct and indirect emissions are expected to triple from 0.66 Gt in 2006 to 2.0 Gt and 2.6 Gt under the Baseline low- and high-demand scenario to 2050. Unlike many

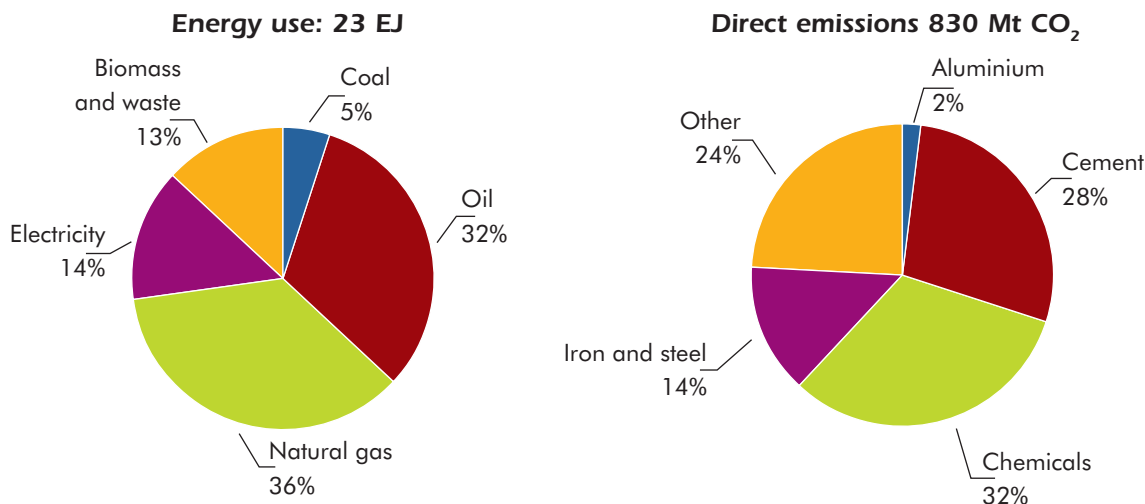
of the other regions, indirect electricity emissions represent a smaller share of total emissions as the share of electricity use is one of the lowest.

Figure A.13 ► Total industrial CO₂ emissions in Africa and the Middle East in Baseline and BLUE scenarios, 2006 and 2050



Total emissions are expected to show an increase of 35% and 53% compared to 2006 levels, reaching 0.89 Gt CO₂ and 1.0 Gt CO₂ in the BLUE low- and high-demand scenarios respectively in 2050. Compared to the Baseline scenarios, emissions will decline by 56% and 61% in the BLUE low and high scenarios. Increased energy efficiency and fuel switching, especially in the BLUE high scenario, contribute the largest share of emissions reduction, followed by measures in the electricity sector for near-decarbonisation of the power sector. CCS also represents an important share of emissions reduction, cutting direct emissions by 0.22 Gt and 0.32 Gt in the BLUE low- and high-demand scenarios respectively.

Figure A.14 ► Industrial energy use and CO₂ emissions in Africa and the Middle East in the BLUE low scenario, 2050



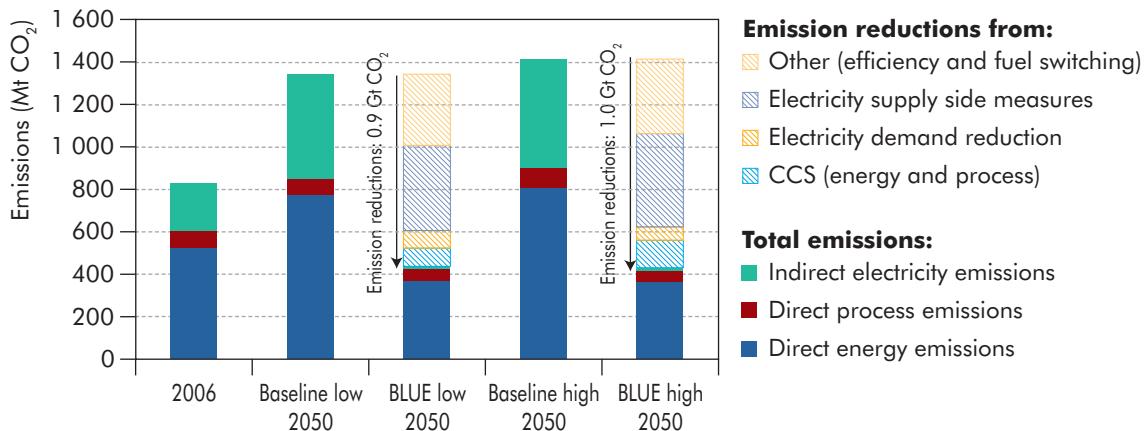
In the BLUE low scenario, the chemical sector is expected to represent the largest share of emissions, at 32%, while cement accounts for 28% and iron and steel for

14%. Total energy use in the BLUE low-demand scenario rises to 23 EJ, a 187% increase compared to 2006 levels of 8 EJ, but 18% lower than under the Baseline low-demand scenario of 30 EJ. Natural gas and oil represent almost 70% of total fuel use in the BLUE low-demand scenario in 2050. In contrast to most of the other regions, the share of coal and electricity in the BLUE low scenario is one of the lowest at just 4% and 14% respectively.

Economies in transition

Total industrial CO₂ emissions in economies in transition are expected to rise between 62% and 70% in the Baseline low- and high-demand scenarios in 2050 compared to current levels. The largest share of this increase will come from indirect electricity emissions. Direct process emissions in the Baseline low-demand scenario will show a small 4% decline as cement consumption falls. Under the high-demand scenario where cement consumption remains flat compared to 2006 levels, direct process emissions remain flat. Direct energy emissions show a 48% and 55% increase in the Baseline low and high compared to 2006 levels.

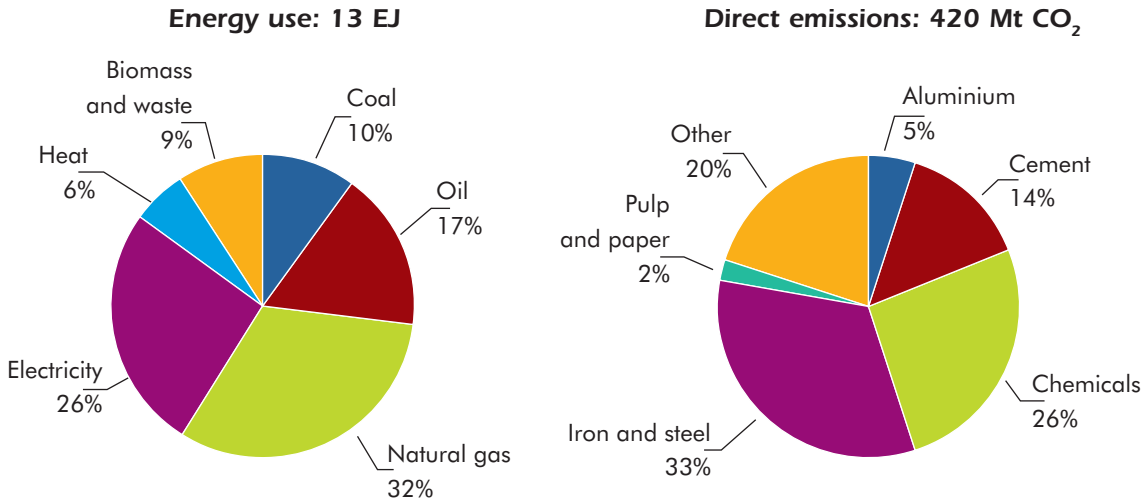
Figure A.15 ► Total industrial CO₂ emissions in economies in transition in the Baseline and BLUE scenarios, 2006 and 2050



In the BLUE scenarios, total direct and indirect emissions in 2050 fall by more than 48% to just 0.42 Gt under low and high demand compared to 2006 levels of 0.83 Gt. Indirect electricity emissions will almost disappear as the power sector reaches levels of near-decarbonisation. Energy efficiency and fuel switching will contribute the largest reductions to direct emissions, saving 0.42 Gt in both BLUE scenarios. Industrial energy intensity will fall significantly under the BLUE scenarios, as total energy use declines by 29% from 18 EJ in the Baseline low-demand scenario to 13 EJ in the BLUE low-demand scenario. The application of CCS will allow for an additional reduction of 0.89 Gt and 1.4 Gt in the BLUE low-and high-demand scenario.

In the BLUE low-demand scenario, the iron and steel sector will account for the largest share of direct emissions, at 30%, followed by chemicals at 27% and cement at 15%. Natural gas will represent the largest share of fuel use, at 31%, followed by electricity and oil at 26% and 16% respectively.

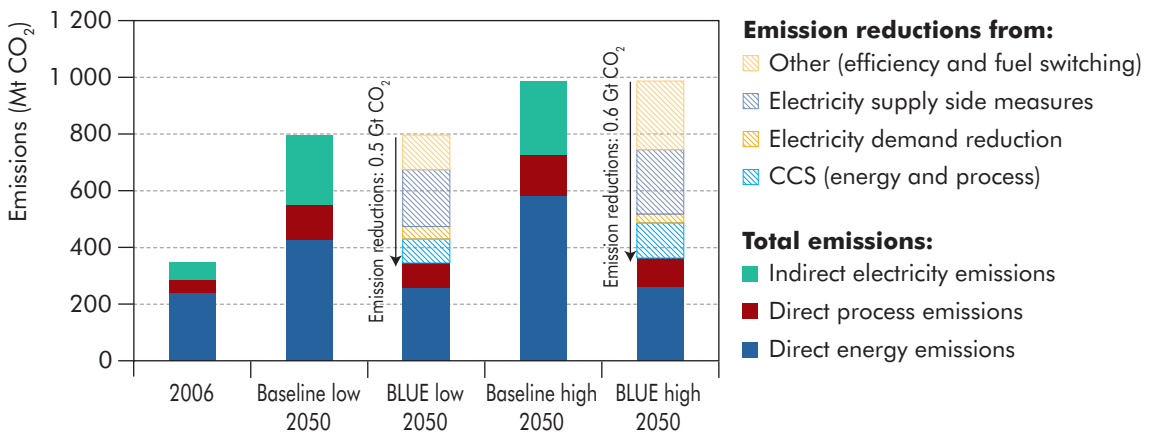
Figure A.16 ► Industrial energy use and CO₂ emissions in economies in transition in the BLUE low scenario, 2050



Latin America

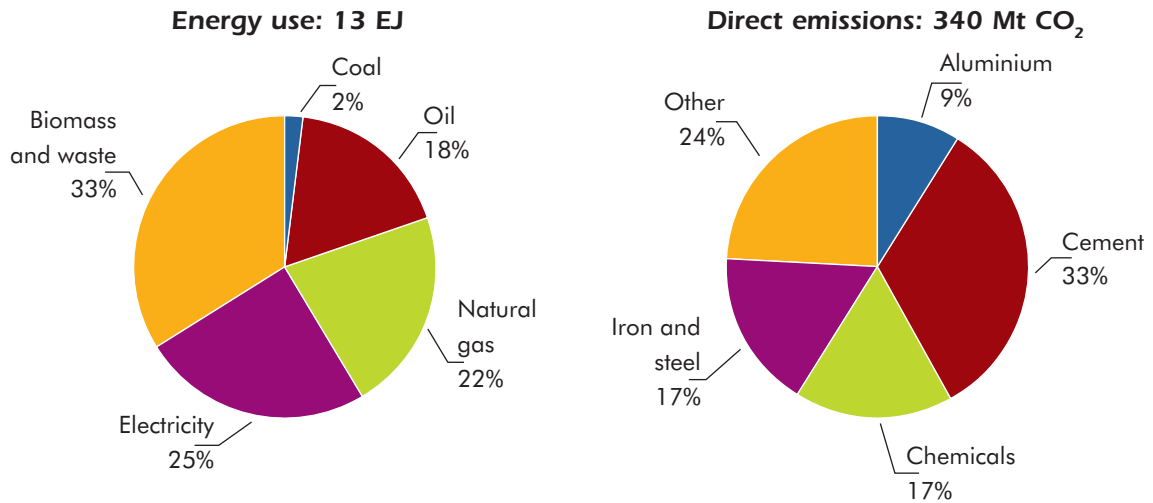
Total direct and indirect emissions are expected to rise by 131% in the Baseline low-demand scenario compared to 2006 levels with large increases expected in direct and indirect emissions. Today, indirect electricity emissions represent a relatively small share of total emissions as the CO₂ intensity of electricity in Latin America is the lowest in the world, thanks to an abundance of hydroelectricity. High production growth, especially in cement and iron and steel, will lead direct energy and process emissions to increase by 95% and 158% compared to 2006 levels, reaching 0.55 Gt and 0.73 Gt in the Baseline low and high scenarios in 2050.

Figure A.17 ► Total industrial CO₂ emissions in Latin America in the Baseline and BLUE scenarios, 2006 and 2050



In the BLUE scenarios, total emissions are flat compared to 2006 levels of 0.35 Gt and fall by 57% compared to Baseline low emissions of 0.80 Gt. Indirect electricity emissions will disappear as the power sector is decarbonised. Direct energy emissions will remain flat compared to 2006 levels and decline by 40% and 55% compared to the Baseline low- and high-demand scenarios. Direct process emissions will reach 0.08 Gt and 0.10 Gt, a 97% and 125% rise compared to 2006 levels, but 29% and 33% below Baseline low and high levels as the adoption of CCS, especially in the cement sector, significantly reduces both process and direct energy emissions.

Figure A.18 ► Industrial energy use and CO₂ emissions in Latin America in the BLUE low scenario, 2050



Note: Although pulp and paper is an important sector for this region, emissions in the BLUE scenarios for the sector are negative, as CCS with biomass removes CO₂ from the atmosphere.

Accounting for 33% in the BLUE low-demand scenario, biomass and waste represents the largest share of fuel consumption, followed by electricity and gas at 25% and 22%. The cement sector will account for the largest share of emissions, at 33%, followed by chemicals and iron and steel at 17% each. The share of emissions from cement will rise significantly compared to 2006 levels (22%), while the share of emissions from iron and steel will decline from 24% in 2006.

Annex **B** ENERGY AND CO₂ INDICATORS

Energy indicators based on economic and physical ratios

The IEA has analysed and reported indicators for industrial energy use and CO₂ emissions for some time (IEA, 1997; IEA, 2004). These indicators are based on economic ratios as they analyse energy use or CO₂ emissions per unit of value-added output. In addition, trends in energy use and emissions are decomposed into those changes that are due to structural effects and those related to energy efficiency effects, on the basis of an analysis of developments in the industrial sub-sectors. While such indicators may be adequate to capture aggregate energy and CO₂ trends, they are less suited to a detailed analysis of industrial energy efficiency developments over time or across countries, or for an examination of improvement potentials. This is because they do not take full account of product quality and composition, or the processing and feedstock mix, which can vary widely within a sub-sector. Furthermore, indicators based on economic ratios cannot be validated by technological data.

This study builds on the work contained in *Tracking Industrial Energy Efficiency and CO₂ emissions* (IEA, 2007) and presents indicators for industrial energy use and CO₂ emissions that are based on physical ratios, e.g. energy use per tonne of product. These indicators are often called the specific or unit energy consumption. They can account for structural differences in industries between countries and so enable a fair and consistent comparison of energy efficiency and CO₂ emissions performance. The analysis also uses explanatory indicators to examine some of the driving factors behind the patterns of energy use and emissions, such as technology differences and resource qualities. This again allows for a more robust comparison across countries. Other advantages of the approach are:

- Indicators based on physical ratios are closer to a measure of the “technical efficiency” of an industry and hence can be linked more directly to technology performance. They can therefore be used to identify the potential for efficiency improvements through new technologies.
- The indicators are not affected by cyclical variations in the price of industrial commodities, as is the case with indicators that use value added and so tend to be subject to less “noise” from economic fluctuations.
- The energy and emissions performance of specific process steps in an industry can be separately analysed and differences in product mix between countries and over time are more easily taken into account. The impacts of changing product mix need to be considered separately from technical efficiency gains, because the driving factors may change over time.

The following sections discuss the issues that need to be considered when developing physical indicators of industrial energy use and CO₂ emissions: the

availability and quality of energy and activity data; and the approach followed in this study. It also briefly describes other international activities that are developing indicator-based approaches.

Methodological issues

Energy use in many industrial sub-sectors is complex. Even when the necessary data are available, it is often not straightforward to calculate consistent and comparable indicators that are useful for policy analysis. Three areas, in particular, require careful consideration: aggregation levels, boundaries and allocation.

Aggregation levels

Energy use and CO₂ indicators can be developed at different levels of aggregation depending on the purpose for which they are to be used and the level of information available. The aggregation level is very important as it determines the extent to which structural differences affect the results observed. Structural differences can include:

- *Availability and quality of input resources.* The energy needs for some industrial processes will depend on the quality of the natural or other resources available, e.g. ore quality. The indicators need to account for the resource quality variations in cross-country comparisons. For example, countries with a more mature economy may have ample scrap resources available, while emerging economies may not. Scrap availability can have an important impact on the apparent energy performance of an industry. The energy and feedstock mix also matters. Coal-fired energy conversion processes are often inherently less efficient than processes that use natural gas or electricity. However, in certain cases, coal is the preferred fuel for chemical conversion, for example in iron production.
- *Definition of products.* Definitions require care. For example, in the case of the iron and steel industry, the choice for tonnes of iron, tonnes of crude steel, or tonnes of finished steel can make a big difference. The production ratio of these three categories is not the same for all countries.
- *Diversity of products.* Industrial products are not uniform. Indicators must be designed in a way that the product categorisation makes sense.

To address these issues, the sector chapters present a range of indicators at different levels of aggregation. In cement, for example, an indicator of thermal energy consumption per tonne of clinker is shown, as well as more detailed indicators such as alternative fuel use in clinker production.

Boundary issues

For a consistent analysis across countries, it is necessary to use common boundary definitions for each sub-sector. Such boundary limits relate to:

- *Production steps.* Industrial production processes often consist of several steps. The processes/production steps that are included or excluded from an indicator can make a difference in cross-country comparisons and need to be fully described. The treatment of combined heat and power (CHP) is particularly important for some sub-sectors (discussed below under Allocation issues). Indicators need to take into account the differences in the comprehensiveness of the process chain.
- *Embodied energy and carbon.* Both energy and carbon can be stored in materials. While energy can be recovered when materials are recycled or incinerated, any carbon stored in the products is released when they are incinerated. These factors and potentials should be assessed on a materials/product life-cycle basis, as they are not apparent from an industry sub-sector analysis. Furthermore, a large amount of fossil carbon is locked into synthetic organic products and therefore energy relevance is not equivalent to CO₂ emissions relevance.
- *Process emissions.* A significant share of industrial CO₂ emissions are process emissions, not related to the use of fossil fuels. Where important, these process emissions should be included along with those from fuel combustion.

In this analysis, the following general principles have been used in setting the boundaries:

- Included in the indicators:
 - Energy use and CO₂ emissions directly associated with the sub-sector.
 - Upstream (primary) energy use and CO₂ emissions associated with electricity production, but excluding mining and transportation of fuels to the electricity industry.
- Excluded from the indicators:
 - Electricity, heat and other fuels, blast furnace gas, sold to a third party.

Additional information can be found in *Tracking Industrial Energy Efficiency and CO₂ Emissions* (IEA, 2007).

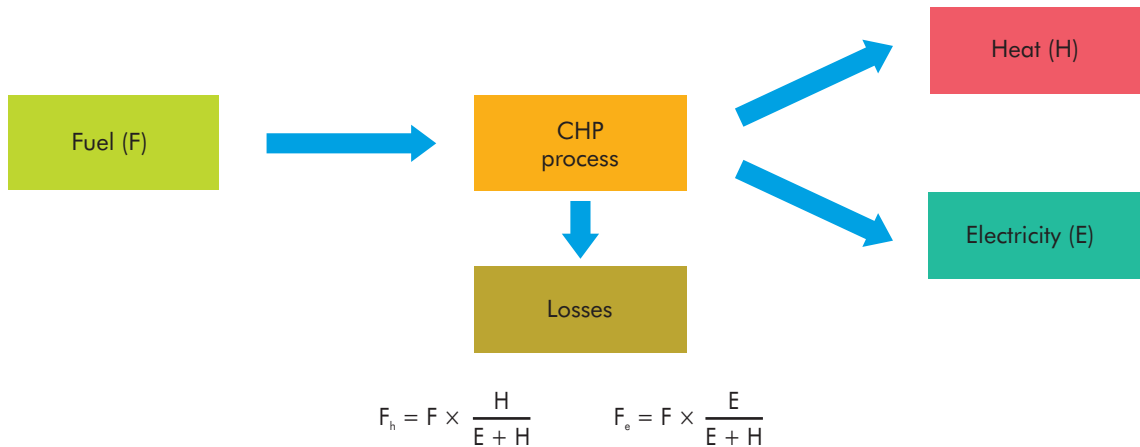
Allocation issues

In addition to setting consistent boundaries, a number of important allocation issues arise in constructing energy use and in CO₂ emissions indicators analysis.

- *Combined heat and power.* The treatment of CHP needs special consideration in those sub-sectors where it plays an important role to ensure that CO₂ emissions and efficiency gains from CHP are correctly reflected. There are a number of elements. First is the allocation of input fuels between those used for electricity production and those used for heat production. Secondly, fuel use and electricity and heat production by CHP plants may be recorded in statistical balances as part of final consumption in the industry sector or as part of the transformation sector, or a mixture of the two. In addition, electricity and/or heat may be sold to a third party and so not actually be used in the industry where the plant is located.

Figure B.1 illustrates the approach taken in IEA energy statistics. Fuel input to CHP is allocated between heat (F_h) and electricity (F_e) according to their shares of heat and electricity in total output. The fuel used for heat generation is then allocated to the industrial sub-sector where the CHP plant is located (net of any fuel used to generate heat that is sold, which is accounted for in the transformation sector), while the fuel used for electricity production is assigned to the transformation sector. This approach could lead to the potentially misleading result that most of the efficiency gains for increased CHP use are credited to the transformation sector, rather than to the industry sector.

Figure B.1 ► Allocation issues for CHP



Source: IEA (2005).

- *Treatment of waste fuels.* Industry uses large amounts of waste fuels. The CO₂ emissions from waste fuel use are not always significantly below those for fossil fuel use, but on an energy system basis the redirection of waste flows from incinerators to industrial kilns makes sense. Indicators should use an allocation system for waste emissions that is appropriate at a system level.
- *Autoproduction of electricity.* Some industries produce their own electricity. In terms of primary energy and CO₂ emissions allocation, it can make a big difference if the indicator uses country average efficiencies and emissions factors for electricity production, or industry-specific ones.

Definition of best available technology and best practice technology

One approach to compare energy use and CO₂ performance of an industry across countries and to estimate improvement potential is to make a comparison between the current level of energy use and what could be achieved through the

use of the *best available technology* (BAT).¹ Defining what BAT represents is not straightforward. It requires consideration of both technical and economic factors. In this study, BAT designation in relation to energy efficiency in a particular industry has been drawn from a range of sources, including technical documentation produced for the European Union Directive 96/61/EC concerning integrated pollution prevention and control (IPPC) and other technical and peer-reviewed literature.

The European Union IPPC Directive defines BAT as “the most effective and advanced stage in the development of activities and their methods of operation which indicate the practical suitability of particular techniques...”. This is further elaborated as:

- “Techniques” shall include both the technology used and the way in which the installation is designed, built, maintained, operated and decommissioned.
- “Available techniques” shall mean those developed on a scale which allows implementation in the relevant industrial sector, under economically and technically viable conditions, taking into consideration the costs and advantages...as long as they are reasonably accessible to the operator.
- “Best” shall mean most effective in achieving a high general level of protection of the environment as a whole.

In the language of the IPPC directive, BAT-associated environmental performance is usually represented with a range, instead of a single value. In general, the best achievable performance is not included in the range, because the BAT range also involves an assessment of costs versus benefits, sustainability, etc. So the term BAT needs to be interpreted within a given context and is not as rigid as, say, a theoretical thermodynamic minimum. Moreover, BAT will change over time as technology improves.

In contrast to BAT, *best practice* is a term that applies to technologies and processes that are currently deployed. BAT could, in many cases, be identical with best practice. In other cases, a new technology may have just emerged, but is not yet deployed. If this is the case, the BAT energy efficiency may be better than best practice. However, as best practice often refers to a more “proven” technology than the BAT, it may be more policy-relevant. The terms best practice and BAT are often mixed.

Data issues

An accurate analysis of energy efficiencies and CO₂ emissions using physical indicators requires good-quality disaggregated data on energy and physical production. For energy, the data available from IEA energy statistics and national energy balances are at a relatively high level of aggregation. Furthermore, the data that are submitted by countries to the IEA are the responsibility of the countries. The IEA cannot guarantee the quality of the data and performs limited checking, such as looking at the overall balance of supply and demand for individual energy carriers at a country level.

1. Industry analysis in this study also uses the term best available technology to examine the concept as it relates to technological performance, rather than the wide interpretation implied by technique.

Ideally, analyses of industrial energy efficiencies require more detailed data than are available through such statistical balances. A significant effort was undertaken as part of this study to identify and obtain better sources of data on energy use. These sources include information from national energy statistics and industry associations, such as Stahlzentrum in Germany and the Japanese Iron and Steel Federation. Many industries also have detailed data on energy use but cannot share these because of antitrust regulations. Antitrust laws prohibit anti-competitive behaviour and unfair business practices, which can include sharing information that could be used for price fixing.

As publicly available energy data are often scarce for a particular industry sub-sector, data availability itself creates a potential bias in the analysis. The most comprehensive data are often available for those companies that are well managed. These are usually the companies with relatively high energy efficiency. These data overestimate the energy efficiency of the industry on a global scale. This is evident when the data situation at a country level is assessed. There are better data available for OECD countries than for non-OECD countries, while the energy efficiency potential is higher in the latter category.

There is a clear need for the data situation to be improved if detailed industry indicators are to be reported on an annual basis, assuming adequate resources. For example, this could involve a permanent working group of the IEA Secretariat with certain key industry federations. Also the antitrust issue needs to be resolved.

Production data used in this study were taken from various sources, including the UN commodity statistics, the US Geological Survey, the UN Food and Agriculture Organization, industry federations such as the International Iron and Steel Institute, Cembureau and consultants.

There are also issues related to the coverage and quality of these data. Physical production data are confidential for particular products because of antitrust regulations. Also data on sales and production are sometimes not clear. For example, in the petrochemical industry, significant amounts of intermediate products are processed on-site, so the quantities of products traded are often much lower than the quantities produced. For some products, their definition is not clear. In the case of cement, data for clinker production are sometimes mixed with data for finished cement product. The cement production of stand-alone slag-grinding stations may or may not be included. Additions of cement clinker substitutes to concrete or the use of blast-furnace slag as replacement of cement binder in road foundations is not reported as cement production. Such accounting problems can have a significant impact on production data.

Care also has to be taken when combining energy and production data from different sources to ensure that they have a consistent coverage of an industry or process. In this analysis, industrial sub-sectors have been identified on the basis of their economic activities as defined by the International Standard Industrial Classification (Rev. 3). This classification system is commonly used for both energy

statistics and production data, e.g. for IEA energy statistics and UN commodity statistics.

A number of additional checks also have been carried out to try and eliminate major inconsistencies in the data. First, the energy data for a given sub-sector have been cross-checked using a bottom-up calculation of the expected energy use given the technology mix, typical energy consumption per unit of output by technology and physical production figures. Secondly, the energy indicators themselves can help identify potential issues. For example, if the energy use per tonne of production is lower than the thermodynamic minimum, it is evident that there is a data problem. But this does not mean that values well above the thermodynamic minimum are correct. As a rule of thumb, any country's energy intensity value that is more than two to three times above the world average has been treated as suspect. Both energy and production data were peer-reviewed by experts.

During this analysis it was found that the quality of information and the level of co-operation vary by sub-sector. The fertiliser and aluminium industries have data on international benchmarking efforts and regional average efficiency that are publicly available. Adequate information was found for the cement industry. For sub-sectors such as the pulp and paper and petrochemical industries, benchmarking is also an accepted form of energy management effort that compares similar plants across countries. However, these data are confidential. The quality of the energy data is an issue, especially for the pulp and paper industry because of the complexities around accounting for CHP and biomass use. Data availability and consistent reporting methodologies across countries also need significant improvement in the chemical sector. The iron and steel industry is the only sector for which there is no international benchmarking effort and the quality of the available data from energy statistics poses a challenge.

Practical application of energy and CO₂ emissions indicators

This section explains which indicators have been developed for each industry and how these should be interpreted. It is rarely possible to define a single "true" indicator that satisfactorily captures all the information that needs to be conveyed about energy use and CO₂ emissions in a sub-sector or a process. Selecting only one indicator for cross-country comparisons can produce a misleading picture. The key is to aim for transparency on how the indicator is constructed, e.g. in relation to boundaries and allocation rules so that differences in methodology are clearly understood and their impact on the results can be assessed.

Table B.1 ► Summary of indicators available for each sector

Sector	Energy use indicators	GHG emissions indicators	Explanatory indicators
Pulp and paper	<ul style="list-style-type: none"> Heat consumption in pulp and paper production vs. best available technology Electricity consumption in pulp and paper production vs. best available technology 	<ul style="list-style-type: none"> CO₂ emissions/tonne of pulp and paper produced 	<ul style="list-style-type: none"> Recovered paper use vs. recovered paper ratio Age of paper mills Age of pulp mills
Iron and steel	<ul style="list-style-type: none"> Total primary and final energy use per tonne of crude steel (including finishing) Total primary and final energy use per tonne of blast furnace-BOF steel production Total final energy use per tonne of DRI (split gas and coal-based processes) Total primary and final EAF steel (excluding finishing) 	<ul style="list-style-type: none"> Total direct CO₂ per tonne of crude steel 	
Aluminium	<ul style="list-style-type: none"> Specific power consumption in aluminium smelting Specific energy consumption of metallurgical alumina production Energy use for anode production 	<ul style="list-style-type: none"> PFCS emissions per tonne of aluminium 	<ul style="list-style-type: none"> Smelter technology mix Sources of electricity production Share of recycled production
Cement	<ul style="list-style-type: none"> Energy requirement per tonne of clinker, including alternative fuels Electricity consumption per tonne of cement Total primary energy equivalent per tonne of cement Process and energy (including electricity) CO₂ emissions per tonne of cement 	<ul style="list-style-type: none"> CO₂ emissions from energy consumption (including electricity) per tonne of cement 	<ul style="list-style-type: none"> Clinker-to-cement ratio Alternative fuel use in clinker production
Chemicals and petrochemicals	<ul style="list-style-type: none"> Total energy consumption vs. best available technology 	<ul style="list-style-type: none"> Total CO₂ emissions vs. best available technology 	

International initiatives: sectoral approaches to developing indicators

A number of other international initiatives are developing indicator-based approaches to analyse the energy and CO₂ emissions performance of key industries. In some cases, these initiatives have specific goals, which shape the

approach that is used. This section briefly reviews selective initiatives and notes how they relate to the analysis presented in this report.

Intergovernmental Panel on Climate Change (IPCC) reference approach

While not an indicator approach, the IPCC produces guidance on the calculation of CO₂ emissions from fuel combustion and industrial processes. Of relevance to a discussion on indicators is the IPCC treatment of three key areas: CHP, waste used as a fuel, and the treatment of emissions from chemical reactions in manufacturing processes.

- Emissions from CHP are attributed to the industrial branch in which the generation activity occurs, regardless of whether the electricity or heat is actually used in that branch.
- In cases where the combustion heat from waste incineration is used as energy, then this waste is treated as a fuel and the emissions are attributed to the industrial branch where the waste incineration occurs. However, only the fossil fuel-derived fraction of CO₂ from waste is included in the calculation. Emissions from the biomass fraction of waste are excluded.
- For emissions from gases obtained from processing feedstock and process fuels, if the emissions occur in the industrial sector which produced the gases emitted, they remain as industrial process emissions in that sector. If the gases are exported to another sector, then the fugitive, combustion or other emissions associated with them are reported in that other sector.

Pulp and paper initiatives

The International Council of Forest and Paper Associations (ICFPA), the global forum for the pulp and paper industry, has developed a CO₂ calculation tool to facilitate uniform CO₂ emissions reporting. The requirements in the EU Emissions Trading Scheme have now replaced this for the European mills. Under the IEA Implementing Agreement on Industrial Energy Related Technologies and Systems, a project to harmonise global definitions for energy use, energy efficiency and the different pulp and paper production processes has been completed, but has not yet been implemented by the sector.

Cement Sustainability Initiative

Under the umbrella of the Cement Sustainability Initiative (CSI) of the World Business Council for Sustainable Development (WBCSD), a number of major cement companies have agreed on a methodology for calculating and reporting CO₂ emissions. The latest edition of the Cement CO₂ Protocol was published in June 2005 and is aligned with the Greenhouse Gas (GHG) Corporate Protocol

(revised edition) <http://www.ghgprotocol.org> developed through a joint initiative of the WBCSD and the World Resources Institute (WRI).

The CSI protocol provides a harmonised methodology for calculating CO₂ emissions, with a view to reporting these emissions for various purposes. It addresses all direct and the main indirect sources of CO₂ emissions related to the cement manufacturing process in absolute as well as specific or unit-based terms. The basic calculation methods used in this protocol are compatible with the latest guidelines for national GHG inventories issued by the Intergovernmental Panel on Climate Change (IPCC), and with the GHG Corporate Protocol (revised edition). Default emission factors suggested in these documents are used, except where more recent, industry-specific data have become available. However, one area where the recommendations of the Cement CO₂ Protocol differ from the IPCC guidelines is in allowing credits for indirect emissions reductions related to the use of wastes as alternative fuels and for waste-heat exports. The premise for this crediting is that the combination of direct emissions impacts, indirect emissions reductions, and resource efficiency makes the substitution of alternative fuels for conventional fossil fuels an effective way to reduce global GHG emissions. The cement industry should be able to account for these wider benefits.

Asia Pacific Partnership on Clean Development and Climate (APP)

The APP is developing energy efficiency and CO₂ emissions indicators for the cement, iron and steel industries. In the case of cement, these indicators are aligned with the CSI Protocol and will be used to help set benchmarks and estimate the potential for CO₂ emissions reductions. Possible energy and CO₂ emissions indicators being considered include:

- heat intensity of clinker;
- power intensity of clinker;
- total energy intensity of clinker;
- power intensity of cement; and
- CO₂ intensity of cement.

For iron and steel, the APP proposes to develop separate indicators for steel production from both main types of furnaces. There is no further breakdown of energy use by individual processes. The approach includes energy consumption and CO₂ emissions from energy conversion and material preparation in upstream processes off-site from the steel plant, but does not count mining and transportation. Credits for energy sold to third parties are included in the calculation.

Benchmarking in the petrochemical industry

Benchmarking is an approach used by a number of industries to evaluate the energy performance of their processes in relation to best practice, usually within their own

industry. One process in the petrochemical industry for which benchmarking is widespread is steam crackers.

Steam cracking of hydrocarbon feedstocks, e.g. ethane, naphtha, is the most important source of olefins and aromatics, and as such the basis for the petrochemical industry. The key driver for benchmarking steam crackers is that energy accounts for up to 60% of olefin plant operational expenses. Feedstocks and operating conditions (pressure, temperature and residence time) can significantly affect the specific energy consumption of steam crackers; a performance comparison requires accounting for processing conditions. Solomon Associates Inc. (SAI) set up the first widely used international benchmarking system for crackers in the 1990s. Companies that participate in the benchmark are requested to fill in a detailed survey on the performance of their units, including energy consumption on a semi-annual basis. More than half of all steam crackers in the world participate in the survey, representing more than two-thirds of the total production capacity. SAI acts as a clearing house and provides to individual participants a comparison between their units and a distribution of the other plants participating in the survey, accounting for feedstock use and operating conditions.

Benchmarking provides to the participating companies valuable indicators on their energy efficiencies, operating expenses, manufacturing costs, and ultimately return on investment versus the top performing plants worldwide. However, because of participation clauses to the benchmarking surveys, detailed results are confidential and country-level averages are not made public. This limits its applicability for cross-country comparisons.

Annex **C** FRAMEWORK ASSUMPTIONS

This annex provides the framework assumptions used throughout this publication.

Demographic assumptions

The world's population was 6.5 billion in 2006 (OECD, 2008). Between now and 2050 world population will surge by more than 40% to 9.1 billion (UN, 2009), with Asia and Africa leading the way. The G8+5 population will drop from 56% of the world's population today to 48% in 2050 (Table C.1).

Table C.1 ► Population projections, 2006 to 2050

	2006 (million)	2015 (million)	2030 (million)	2050 (million)
G8 countries				
Canada	33	35	40	44
France	63	64	66	68
Germany	82	81	78	71
Italy	59	61	60	57
Japan	128	126	117	102
Russia	143	138	129	116
United Kingdom	61	64	68	72
United States	300	332	370	404
Plus five countries				
Brazil	189	203	217	219
China	1 312	1 396	1 462	1 417
India	1 110	1 294	1 485	1 614
Mexico	105	116	126	129
South Africa	47	52	55	57
Total (G8 +5)	3 631	3 961	4 274	4 369
World	6 536	7 302	8 309	9 150
Share (G8 +5)	56%	54%	51%	48%

Sources: OECD (2008); UN (2009).

Today, slightly more than half of the world's population lives in urban areas (UN, 2008), the majority in developing countries. The percentage of urban dwellers has increased by 10% in the last 25 years and is projected to increase to 70% by 2050 (UN, 2008). Between 2005 and 2050, Asia's urban population will increase

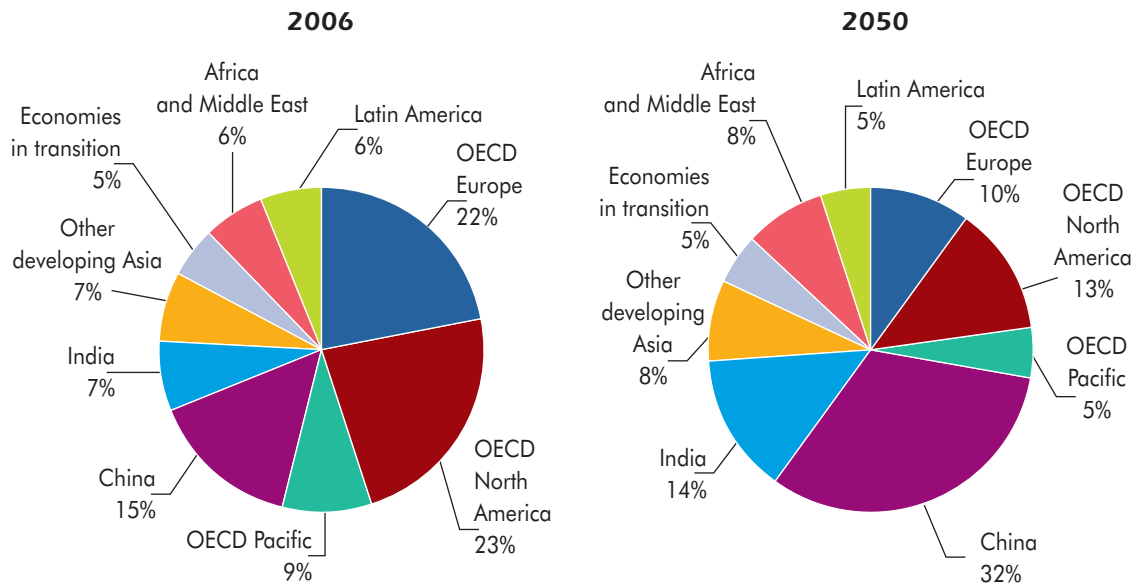
from 1.6 billion to 3.5 billion, Africa's from 373 million to 1 234 million, and Latin America and the Caribbean from 448 million to 683 million. As a result of these shifts, developing countries will have almost 85% of the world's urban population in 2050. By then, Africa and Asia will include almost seven out of every ten urban inhabitants in the world.

Today, the global median age is 28 years. Over the next four decades the world's median age will likely increase by ten years, to 38 years. The proportion of population 60 years and over is projected to rise from 11% today to 22% in 2050 (UN, 2009). This ageing will have important consequences for energy consumption as the life style and needs of older people differ from those of young people.

Macroeconomic assumptions

Global GDP is projected to grow more than fourfold between 2006 and 2050 to a level of USD 234 trillion. In European countries and in Japan, it nearly doubles (Table C.2). In North America it grows to almost two-and-a-half times its current level. The main growth will be in economies in transition and in developing countries (Figure C.1). GDP in China and India will grow nearly ninefold. Chinese GDP will be three times higher than that of the United States. India will be close to OECD North America in GDP terms. The global share of OECD countries is projected to decrease from 54% today to 28% in 2050.

Figure C.1 ► **World GDP by region in 2006 and 2050** (based on purchasing power parities)



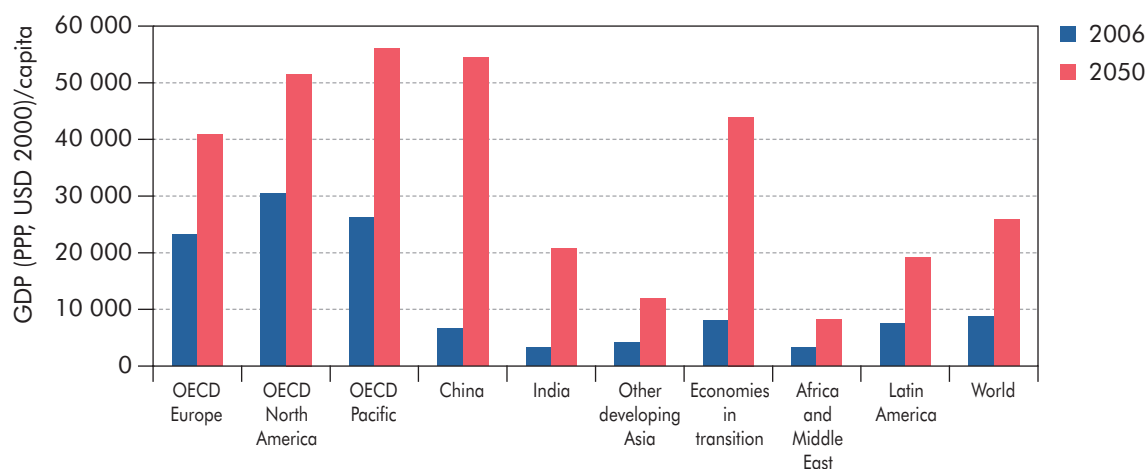
Sources: IEA (2008a and 2008b).

Table C.2 ► **GDP projections, 2006 to 2050** (based on purchasing power parities)

	1980-1990 (% / year)	1990-2006 (% / year)	2006-2015 (% / year)	2006-2030 (% / year)	2030-2050 (% / year)
OECD					
North America	3.1	2.9	2.3	2.2	1.6
United States	3.3	2.9	2.1	2.1	1.5
Europe	2.4	2.3	2.3	1.9	0.7
Pacific	4.2	2.2	2.1	1.6	1.6
Japan	3.9	1.3	1.3	1.2	1.3
Non-OECD					
E. Europe/Eurasia	0	0	5.6	3.7	3.4
Russia	n.a.	-0.2	5.7	3.6	3.4
Asia	6.7	7.2	7.9	5.7	3.6
China	8.8	9.8	9.2	6.1	3.8
India	5.8	6.1	7.8	6.4	3.6
Middle East	1.3	4.3	5.4	4.3	2.9
Africa	2.4	3.6	5.8	4.1	3.6
Latin America	1.2	3.2	4.3	3.1	2.8
Brazil	1.5	2.7	4	3	2.8
World	2.8	3.2	4.2	3.3	2.6

Sources: IEA (2008a and 2008b).

Figure C.2 shows per capita GDP in 2006 and 2050. While some convergence takes place, GDP in most developing countries remains significantly below the level of OECD countries. Global average per capita GDP grows by 193% to USD 25 810.

Figure C.2 ► **Per capita GDP in 2006 and 2050** (based on purchasing power parities)

Sources: IEA (2008a and 2008b).

International energy prices

Energy price projections are calibrated to the *World Energy Outlook 2008* (IEA, 2008b).

Table C.3 ▶ **Oil, gas and coal price projections for the Baseline scenarios**
(in USD 2007 price per unit)

Real terms (2007 prices)	Unit	2007	2030	2050
IEA crude oil imports	Barrel	69	122	130
Natural gas				
United States imports	MBtu	6.75	16.13	16.38
European imports	MBtu	7.03	14.19	14.52
Japanese imports	MBtu	7.80	16.05	16.38
OECD steam coal imports	tonne	73	110	115

Sources: IEA (2008a and 2008b).

Methodology

This analysis is based on a combination of approaches:

- **Global industrial perspective:** the Baseline demand scenarios for 2006 to 2030 are based on the World Energy Model as used for the IEA's *World Energy Outlook 2008*. This scenario has been further elaborated to include the period 2030 to 2050.
- **Sector perspective:** the IEA Secretariat has developed sub-sectoral models with country- and region-level detail for the industry sector. These spreadsheet models are detailed simulation tools that serve as repositories for information from experts and different models.
- **Technology perspective:** the assessment of the present and future characteristics of technology options and their potentials is based on expert information from the IEA Implementing Agreements and other sources. A global marginal abatement cost curve for 2050 has been developed.

Detailed demand-side models for all major end-uses in the industry were used. These models were developed to assess the effects of policies that do not primarily act on price. These demand-side models explicitly take capital stock turnover into account, and have been used to model the impact of new technologies as they penetrate the market over time.

Investment modelling limitations

The investment analysis presented is inevitably a partial assessment of the investment needs for energy-consuming equipment and, to a lesser extent, of the needs in the upstream energy sector. In the industrial sector, only major energy-consuming equipment and devices have been covered, as sufficient data do not exist to accurately project the quantity and price of a wide range of small energy-consuming devices. There is also a question of what boundary to place on investment costs.

As a result of these issues, and the generally more widely available information on the marginal cost of energy efficiency options, the relative increase or decrease in investment needs in the BLUE scenario compared to the Baseline scenario should be treated with greater confidence than the absolute level of investment in the Baseline.

The investment needs for the decarbonisation of the power sector have not been calculated in this study. However, *Energy Technology Perspectives 2008* estimated the additional investments required in the power sector to reach the BLUE scenario results to be USD 2.9 trillion by 2050.

Marginal abatement curve limitations

Marginal abatement cost curves are powerful tools for analysis and presentation purposes. However, a number of methodological problems may affect the use of marginal abatement curves for decision making for long-term energy policy making:

- There is no unique baseline reference technology, but the choice of the reference affects the emissions reduction potential and the cost.
- Options interact. For example, with regard to the allocation of scarce resources such as biomass, or the CO₂ impacts of electrification (which depends on the carbon intensity of electricity).
- The abatement curve does not really represent marginal cost/marginal CO₂ effects, because oil and gas prices are static.
- There is no single “true” cost figure for options that affect long-life capital stock, there is only a cost range.
- The more refined the analysis is in terms of regional detail, technology and demand characterisation, the wider the cost range will be and the more nuanced the estimate of emissions reduction potentials will be. This is especially important for renewables and the viability of CO₂ storage.
- Costs are not always clear. For example, with regard to energy efficiency, some economists argue that options with negative costs do not exist, while engineering analysis suggests otherwise.

- In certain cases, important fringe benefits may affect cost estimates significantly.
- 2050 technology projections are very uncertain, therefore only wide cost ranges can be given for certain options.

Annex

**D DEFINITIONS,
ABBREVIATIONS,
ACRONYMS AND
UNITS**

This annex provides information on definitions, abbreviations, acronyms and units used throughout this publication.

Fuel and process definitions¹**Adsorption**

Adsorption occurs in coal seams when methane accumulates on the surface of a solid or a liquid adsorbent, forming a molecular or atomic film (the adsorbate). The process is different from absorption, in which a substance diffuses into a liquid or solid to form a solution.

Aquifer

An underground water reservoir. If the water contains large quantities of minerals, it is a saline aquifer.

Aromatics

Type of petrochemicals characterised by a ring structure, that are produced in refinery reformers and petrochemical plants. The most common are benzene, toluene and xylenes.

Associated gas

Natural gas found in an oil reservoir, either separate from or in solution with the oil.

Back-to-feedstock recycling

Process where waste plastics are used for the production of oil-type products.

Back-to-monomer recycling

Process where used plastics are used for the production of olefins and other monomers.

Back-to-polymer recycling

Process where used plastics are used for the production of plastics.

Basic oxygen furnace

Process where liquid hot iron metal is converted into steel, using oxygen injection.

1. More detailed information can be obtained by consulting the annual IEA publications *Energy Balances of OECD countries*, *Energy Balances of Non-OECD Countries*, *Coal Information*, *Oil Information*, *Gas Information* and *Electricity Information*.

Bayer process

Process for production of alumina from bauxite ore.

Beehive coke oven

Coke oven built in a beehive-like hemispherical shape.

Best available technology (BAT)

Best available technology is taken to mean the latest stage of development (state-of-the-art) of processes, facilities or of methods of operation which include considerations regarding the practical suitability of a particular measure for enhancing energy efficiency.

Best practice technology (BPT)

In contrast to BAT, best practice is a term that applies to technologies and processes that are currently deployed.

Biomass

Biological material that can be used as fuel or for industrial production. Includes solid biomass such as wood and plant and animal products, gases and liquids derived from biomass, industrial waste and municipal waste.

Black liquor

A by-product from chemical pulping processes which consists of lignin residue combined with water and the chemicals used for the extraction of the lignin.

Blast furnace

A blast furnace is a type of metallurgical furnace used for smelting. Fuel and ore are continuously supplied through the top of the furnace, while air (oxygen) is blown into the bottom of the chamber, so that the chemical reactions take place throughout the furnace as the material moves downward. The end products are usually molten metal and slag phases tapped from the bottom, and flue gases exiting from the top of the furnace. This type of furnace is typically used for smelting iron ore to produce hot metal (pig iron), an intermediate material used in the production of commercial iron and steel.

Blast furnace gas

Blast furnace gas is produced in blast furnaces in the iron and steel industry. It is recovered and used as a fuel partly within the plant and partly in other steel industry processes or in power stations equipped to burn it.

Blast furnace slag

A by-product from the blast furnace iron production process.

Chemical pulp

This is a thermo-chemical process in which chips are combined with strong solvents and heated under pressure to separate fibres from lignin. Spent liquor (black liquor) can be concentrated and burned for process heat.

Coal

Unless stated otherwise, coal includes all coal: both coal primary products (including hard coal and lignite, or as it is sometimes called "brown coal") and derived fuels (including patent fuel, coke-oven coke, gas coke, coke-oven gas and blast-furnace gas). Peat is also included in this category.

Coke-oven coke

The solid product obtained from the carbonisation of coal, principally coking coal, at high temperature. Semi-coke, the solid product obtained from the carbonisation of coal at low temperatures, is also included, along with coke and semi-coke.

Coke oven gas

Gaseous by-product of coke making.

Coke oven

Pyrolysis process for conversion of coal into coke.

Coking coal

Hard coal of a quality that allows the production of coke suitable to support a blast furnace charge.

Combined heat and power (CHP)

Combined heat and power, also called cogeneration, is a technology where electricity and steam or electricity and hot water are produced jointly. This increases the efficiency compared to separate electricity and heat generation.

Diaphragm process

Process for chlorine and sodium hydroxide production where two compartments of the electrolysis cell are separated by a permeable diaphragm.

Direct reduced iron

Product made through chemical reduction of iron ore pellets in their solid state.

Dry kiln

A kiln that produces cement clinker without using a water/limestone slurry mix as the feedstock.

Electric arc furnace (EAF)

Furnace for smelting of iron scrap and other metals using electricity.

Electricity production

The total amount of electricity generated by a power plant. It includes own-use electricity and transmission and distribution losses.

Electrolysis

Process for chemical conversion that uses electricity for a chemical reaction.

Energy intensity

A measure where energy is divided by a physical or economic denominator, e.g. energy use per unit value added or energy use per tonne of cement.

Fly-ash

A residue from coal fired power plants that can be mixed with cement.

Fuel cell

A device that converts hydrogen or other fuels into electricity, it is also possible to convert electricity into hydrogen. Various types exist that can be operated at temperatures ranging from 80°C to 1 000°C. Their efficiency ranges from 40% to 60%. For the time being, their application is limited to niche markets and

demonstration projects due to their high cost and the immature status of the technology.

Gas

Includes natural gas (both associated and non-associated, but excludes natural gas liquids) and gas-works gas.

Gas to liquids (GTL)

The production of synthetic fuels from natural gas using the Fischer-Tropsch process.

Hard coal

Coal of gross calorific value greater than 5 700 kcal/kg on an ash-free but moist basis and with a mean random reflectance of vitrinite of at least 0.6. Hard coal is further disaggregated into coking coal and steam coal.

Heat

In IEA energy statistics, heat refers to heat produced for sale only. Most heat included in this category comes from the combustion of fuels, although some small amounts are produced from geothermal sources, electrically-powered heat pumps and boilers.

Hydro

The energy content of the electricity produced in hydropower plants assuming 100% efficiency.

Intermediates

Chemical components that are converted into other chemical components.

Intermittent kilns

Kilns that operate in batch mode.

Iron, pig iron and hot metal

Iron, pig iron and hot metal refers to various mineral aggregates from which the steel metal is obtained by the conversion of various iron ores by reduction either into pig iron (hot metal) or into a solid spongy form (sponge iron or direct reduced iron) or into lumps by various direct reduction processes.

Lime kilns

Kilns that convert limestone and dolomite into burned lime.

Li-ion batteries

Lithium-ion batteries are a type of rechargeable battery in which a lithium ion moves between the anode and cathode.

Liquefied natural gas (LNG)

Natural gas that has been liquefied by reducing its temperature to minus 162 °C at atmospheric pressure. In this way, the space requirements for storage and transport are reduced by a factor of over 600.

Mechanical pulp

Grinding and sharing of wood chips. Primarily used for low-grade papers. Mechanical pulping has a high yield but results in a pulp that contains substantial impurities that limit its use.

Membrane process

Process for chlorine and sodium hydroxide production where two compartments of the electrolysis cell are separated by an ion-exchange membrane, allowing only sodium ions and small water quantities to pass through it.

Molten oxide electrolysis (MOE)

Process where an electric current is passed through a liquid solution of iron oxide. The iron oxide then breaks down into liquid iron and oxygen gas, allowing oxygen to be the main byproduct of the process.

Monomers

A monomer is a small hydrocarbon molecule with a double bond between carbon atoms that may become chemically bonded to other monomers to form a polymer.

Motor systems

A motor system is a machine (e.g. pump, fan, or compressor), that is driven by a rotating electrical machine (motor).

Naphtha

Naphtha is a feedstock destined either for the petrochemical industry (e.g. ethylene manufacture or aromatics production) or for gasoline production by reforming or isomerisation within the refinery.

Natural gas

Comprises gases occurring in underground deposits whether liquefied or gaseous, consisting mainly of methane. In IEA statistics, it includes natural gas, both associated and non-associated as well as methane recovered from coal mines.

NiMH batteries

Nickel-metal hydride batteries - are a type of rechargeable battery in which a hydrogen-absorbing alloy is used for the negative electrode; the positive electrode is nickel oxyhydroxide (NiOOH).

Nuclear

Nuclear refers to the primary heat equivalent of the electricity produced by a nuclear plant with an assumed average thermal efficiency of 33%.

Oil

Oil includes crude oil, natural gas liquids, refinery feedstocks and additives, other hydrocarbons, and other petroleum products (such as refinery gas, ethane, liquefied petroleum gas, aviation gasoline, motor gasoline, jet fuel, kerosene, gas/diesel oil, heavy fuel oil, naphtha, white spirit, lubricants, paraffin waxes and petroleum coke).

Olefin

Class of unsaturated open-chain hydrocarbons that have the general chemical formula C_nH_{2n} . The simplest olefins, ethylene, propylene and butylene are gases.

Other petroleum products

Other petroleum products include refinery gas, ethane, liquefied petroleum gas, aviation gasoline, motor gasoline, jet fuel, kerosene, gas/diesel oil, heavy fuel oil, naphtha, white spirit, lubricants, paraffin waxes and petroleum coke.

Other renewables

Includes geothermal, solar, wind, tide, and wave energy for electricity generation. The direct use of geothermal and solar heat is also included in this category.

Perfluorocarbons (PFC)

A group of potent greenhouse gases. PFCs are made up of carbon and fluorine atoms only, such as octafluoropropane, perfluorohexane and perfluorodecalin. A perfluorocarbon can be arranged in a linear, cyclic, or polycyclic shape.

Pinch analysis

A methodology for minimising energy consumption of chemical processes by optimising heat exchange between various flows that need heating and cooling.

Polymerisation

Process of transforming a combination of monomers into a polymer using a chemical reaction.

Portland cement

The most common cement type.

Portland fly-ash cement

A cement type that contains fly-ash and cement clinker.

Pozzolana

Volcanic ash with properties similar to cement.

Power generation

Fuel use in electricity plants, heat plants and CHP plants. Both public plants and small plants that produce fuel for their own use (autoproducers) are included.

Pyrolysis furnace section

The high-temperature section of a steam cracker for ethylene production where the main chemical reaction takes place.

Pyrolysis gasoline

A naphtha-range product with a high aromatic content, used either for gasoline blending or as a feedstock for a BTX extraction unit. Pyrolysis gasoline is produced in an ethylene plant that processes butane, naphtha or gasoil.

Quenching

Quenching is the rapid cooling of a solid to lock it into a metastable crystal structure rather than allow it to cool slowly and revert to a softer structure. It is most commonly used to harden steel.

Reformate

Product from a petroleum-refinery reforming process (thermal or catalytic reforming).

Renewables

Energy resources, where energy is derived from natural processes that are replenished constantly. They include geothermal, solar, wind, tide, wave, hydropower, biomass and biofuels.

Purchasing power parity (PPP)

The rate of currency conversion that equalises the purchasing power of different currencies. It makes allowance for the differences in price levels and spending patterns between different countries.

Shaft kilns

Vertical kilns for cement making, significantly more energy intensive than horizontal dry kilns.

Sintering

Sintering involves the heating of fine ore, causing it to agglomerate into larger granules.

Steam coal

All other hard coal that is not classified as coking coal. Also included are recovered slurries, middlings and other low-grade coal products not further classified by type. Coal of this quality is also commonly known as thermal coal.

Steam cracking

A petrochemical process in which saturated hydrocarbons are broken down into smaller hydrocarbons. It is the principal industrial method for producing the olefins (ethylene, propylene, butadiene).

Steam systems

A combination of equipment that provides heat using steam.

Synthetic fuels

Synthetic fuel or synfuel is any liquid fuel obtained from coal or from natural gas. The best-known process is the Fischer-Tropsch synthesis. An intermediate step in the production of synthetic fuel is often syngas, a mixture of carbon monoxide and hydrogen produced from coal which is sometimes directly used as an industrial fuel.

Technology transfer

The term "technology transfer" has two definitions. The first definition is the process of converting scientific findings from research laboratories into useful products by the private sector. The second definition is used more in economic development literature and involves cross-border transmission of technology from one country to another.

Total final consumption (TFC)

The sum of consumption by the different end-use sectors. TFC is broken down into energy demand in the following sectors: industry, transport, other (includes agriculture, residential, commercial and public services) and non-energy uses. Industry includes manufacturing, construction and mining industries. In final consumption, petrochemical feedstocks appear under industry use. Other non-energy uses are shown under non-energy use.

Total primary energy supply

Total primary energy supply is equivalent to total primary energy demand. This represents inland demand only and, except for world energy demand, excludes international marine bunkers.

Wet kiln

A kiln that produces cement clinker using water/limestone slurry as the feedstock.

Regional definitions

Africa

Comprises: Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, the Central African Republic, Chad, Congo, the Democratic Republic of Congo, Cote d'Ivoire, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Rwanda, São Tomé and Príncipe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, the United Republic of Tanzania, Togo, Tunisia, Uganda, Zambia, and Zimbabwe.

Annex I parties to the Kyoto protocol

Australia, Austria, Belarus, Belgium, Bulgaria, Canada, Croatia, the Czech Republic, Denmark, Estonia, the European Community, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Liechtenstein, Lithuania, Luxembourg, Monaco, the Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Russia, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, Ukraine, United Kingdom and the United States.

Asia Pacific Partnership

Comprises: Australia, Canada, China, India, Japan, Korea, and the United States.

China

The People's Republic of China.

Commonwealth of Independent States (CIS)

which includes: Armenia, Azerbaijan, Belarus, Kazakhstan, Kyrgyzstan, Moldova, Russia, Ukraine, Uzbekistan and Tajikistan.

Developing countries

Comprises: China, India and other developing Asia, Central and South America, Africa and the Middle East.

EU15

Refers to the 15 member countries of the European Union prior to the accession of ten candidate countries on 1 May 2004. The EU15 includes: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Portugal, Spain, Sweden and the United Kingdom.

EU25

Comprises: Austria, Belgium, Cyprus, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Portugal, Spain, Slovakia, Slovenia, Sweden and the United Kingdom.

Europe-33

Comprises: Albania, Austria, Belgium, Bosnia, Croatia, Cyprus, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, Macedonia, Malta, the Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovak Republic, Spain, Sweden, Switzerland, Turkey and United Kingdom.

Group of Eight (G8)

Comprises: Canada, France, Germany, Italy, Japan, Russia, the United Kingdom and the United States.

G8+5 countries

The G8 nations (Canada, France, Germany, Italy, Japan, Russia, the United Kingdom and the United States), plus the five leading emerging economies – Brazil, China, India, Mexico and South Africa.

IEA member countries

Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, South Korea, Luxembourg, the Netherlands, New Zealand, Norway, Portugal, Slovakia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States.

Latin America

Comprises: Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, the Dominican Republic, Ecuador, El Salvador, French Guiana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, St. Kitts-Nevis-Anguilla, Saint Lucia, St. Vincent-Grenadines and Suriname, Trinidad and Tobago, Uruguay, and Venezuela.

Middle East

Comprises: Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, the United Arab Emirates and Yemen. For oil and gas production it includes the neutral zone between Saudi Arabia and Iraq.

OECD member countries

Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States.

OECD Europe

Comprises: Austria, Belgium, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, and United Kingdom.

OECD North America

Comprises: Canada, Mexico, the United States.

OECD Pacific

Comprises: Australia, Japan, Republic of Korea, New Zealand.

Other developing Asia

Comprises: Afghanistan, Bangladesh, Bhutan, Brunei, Chinese Taipei, Fiji, French Polynesia, Indonesia, Kiribati, Democratic People's Republic of Korea, Malaysia, Maldives, Mongolia, Myanmar, Nepal, New Caledonia, Pakistan, Papua New Guinea, the Philippines, Samoa, Singapore, Solomon Islands, Sri Lanka, Thailand, Vietnam and Vanuatu.

Economies in transition

Comprises: Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine and Uzbekistan

Western Europe

Comprises: Austria, Belgium, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey and the United Kingdom.

Abbreviations and acronyms

A SiGe	Amorphous silicon germanium
Al	Aluminium
Al ₂ O ₃	Alumina
ABS	Acrylonitrile-butadiene-styrene
ACN	Acrylonitrile
AF&PA	American Forest and Paper Association
AISI	American Iron and Steel Institute
APP	Asia-Pacific Partnership on Clean Development and Climate
ASA	Acrylonitrile-styrene-acrylate
ASD	Adjustable speed drives
BAT	Best Available Technology
BF	Blast furnace
BF/BOF	Blast furnace/Basic oxygen furnace
BLIGCC	Black liquor integrated gasification-combined cycle
BOF	Basic oxygen furnace
BPT	Best practice technology
BREF	Best Available Techniques reference document
BTL	Biomass to liquids

BTM	Back-to-monomer
BTX	Benzene, toluene, xylene
CaCO ₃	Calcium carbonate
CaO	Calcium oxide
CCS	CO ₂ capture and storage
CDM	Clean development mechanism
CdTe	Cadmium telluride
CDQ	Coke dry quenching
CEPI	Confederation of European Paper Industries
CH ₄	Methane
CH ₄ N ₂ O	Urea
CHP	Combined heat and power
CI	Compression ignition
CIGS	Copper indium gallium diselenide
CIEEDAC	Canadian Industrial Energy End-Use Data and Analysis Centre
CIS	Copper-Indium-Diselenide
CO	Carbon monoxide
CO ₂	Carbon dioxide
CO ₂ eq	Carbon dioxide equivalent
COG	Coke oven gas
CSI	Cement Sustainability Initiative
CWPB	Centre Work Pre-bake
DME	Dimethyl ether
DMFC	Direct methanol fuel cell
DMT	Dimethyl terephthalate
DRI	Direct reduced iron
EAF	Electric arc furnace
EB	Ethylbenzene
EC	European Commission
EDC	Ethylene dichloride
EDI	Energy development index
EEA	Environment and Energy Agency
EEl	Energy efficiency index
EEU	Eastern Europe
EG	Ethylene glycol
EO	Ethylene oxide
EOH	Ethanol

EOR	Enhanced oil recovery
EPRO	European Association of Plastics Recycling and Recovery Organisations
ERPC	European Recovered Paper Council
ESCO	Energy service companies
ETP	<i>Energy Technology Perspectives</i>
ETS	Emission Trading Scheme
EU	European Union
EUR	Euro
EV	Electric vehicle
FAO	Food and Agriculture Organization
FC	Fuel cell
FCC	Fluidized catalytic crackers
FCV	Fuel-cell vehicle
FPAC	Forest Products Association of Canada
G8	Group of eight
GDP	Gross domestic product
GGBFS	Ground granulated blast furnace slag
GHG	Greenhouse gas
GHR	Gas heated reformers
GWP	Global warming potential
H ₂	Hydrogen
HBI	Hot briquetted iron
HDA	Hydrodealkylation
HDPE	High density polyethylene
HFC	Hydrogen fuel cell
HFCs	Hydrofluorocarbons
HHV	Higher heating value
HSS	Horizontal Stud Søderberg
HVC	High value chemicals
IAI	International Aluminium Institute
ICE	Internal combustion engine
ICFPA	International Council of the Forests and Paper Associations
IEA	International Energy Agency
IETS	Industrial Energy-related Technologies and Systems (IEA Implementing Agreement)
IFA	International Fertilizer Industry Association
IGCC	Integrated gasification combined cycle

IPA	Isopropyl alcohol
IPCC	Intergovernmental Panel on Climate Change
IPPC	Integrated pollution prevention and control
ISO	International Organization for Standardization
ITM	Ion-transport membrane
JCA	Japanese Cement Association
JISF	Japan Iron and Steel Federation
JPA	Japan Paper Association
KOH	Potassium hydroxide
LC	Ligno cellulose
LCA	Life cycle analysis
LDPE	Low density polyethylene
LDV	Light-duty vehicle
LFG	Landfill gas
LHV	Lower heating value
LLDPE	Linear low density polyethylene
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
LULUCF	Land-use, land-use change and forestry
MDI	Diphenylmethane diisocyanate
MDPE	Medium density polyethylene
MEA	Monoethanol amine
MECS	Manufacturing Energy Consumption Survey
MEPS	Minimum efficiency performance standards
METI	Ministry of Economy, Trade and Industry (Japan)
MgCl ₂	Magnesium chloride
MgO	Magnesium oxide
Mm ³	Million of cubic meters
MOE	Molten oxide electrolysis
MoMo	IEA Mobility Model
MSW	Municipal solid waste
MTBE	Methyl tertiary butyl ether
MTO	Methanol-to-olefins
N ₂ O	Nitrous Oxide
NAFTA	North America Free Trade Agreement
NaOH	Sodium hydroxide
NGCC	Natural-gas combined-cycle

NH ₃	Ammonia
Nm ³	Normal cubic meters
NO _x	Nitrogen oxides
NRCAN	Natural Resources Canada
OCM	Oxidative coupling of methane
ODA	Other developing Asia
OECD	Organisation for Economic Co-operation and Development
OHF	Open heart furnace
PA	Polyamide
PCA	Portland Cement Association
Pd	Palladium
PE	Polyethylene
PET	Polyethylene terephthalate
PFC	Perfluorocarbons
PFPB	Point Fed Pre-bake
PGM	Platinum group metals
PHEV	Plug in hybrid electric vehicles
PMMA	Polymethylmethacrylate
PP	Polypropylene
PPP	Purchasing power parity
PS	Polystyrene
PSA	Pressure swing absorption
Pt	Platinum
PUR	Polyurethane
PV	Photovoltaics
PVC	Polyvinylchloride
R&D	Research and development
RD&D	Research, development and demonstration
RDD&D	Research, development, demonstration and deployment
RHF	Rotary heart furnace
SA	Sectoral agreements
SAI	Solomon Associates Inc
SAN	Styrene acrylonitrile
SF ₆	Sulfur hexafluoride
SL/RN	Stelco-Lurgi/Republic Steel-National Lead
SO ₂	Sulphur dioxide
SO _x	Sulphur oxide

SWPB	Side Work Pre-bake
TFC	Total final consumption
TGR-BF	Top-gas recycling blast furnace
thm	tonne of hot metal
TMP	Thermomechanical
UF	Urea formaldehyde
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States dollars
USDoE	United States Department of Energy
USGS	United States Geological Survey
VCM	VinylChlorideMonomer
VSS	Vertical Stud Söderberg
WAMS	Wide-area monitoring systems
WBCSD	World Business Council for Sustainable Development
WEO	<i>World Energy Outlook</i>
WRI	World Resources Institute

Units

bbbl	barrel
bcm	billion cubic metres
Bn	billion
°C	degrees Celsius
EJ	exajoule = 10^{18} joules
F_e	Fuel electricity
F_h	Fuel heat
GJ	gigajoule = 10^9 joules
Gt	gigatonne = 10^9 tonnes (1 tonne $\times 10^9$)
GW	gigawatt = 10^9 watts
GWh	Gigawatt-hour
ha	hectare
kg	kilogram
Kg/cap/a	Kilogram per capita per annum
km	kilometre
kt	Kilotonnes
kW	kilowatt = 10^3 watts
kWh	kilowatt-hour

l	litre
lge	litre gasoline equivalent
m ²	square metre
m ³	cubic metre
mb	million barrels
MJ	megajoule = 10 ⁶ joules
mm	millimetre
mpg	miles per gallon
Mt	megatonne = 10 ⁶ tonnes
Mtce	million tonnes of coal equivalent
Mtoe	million tonnes of oil Equivalent
Mtpa	million tonnes per annum
MW	megawatt = 10 ⁶ watts
MWe	megawatt electrical
MWh	megawatt-hour
Nm ³	normal cubic metre (at 0 degrees Celsius and at a pressure of 1.013 bar)
Pa	pascal
PJ	petajoule = 10 ¹⁵ joules
Ppbv	parts per billion by volume
ppm	parts per million
t	tonne = metric ton = 1 000 kilogrammes
t/h	tonnes per hour
toe	tonne of oil equivalent
TW	terawatt = 10 ¹² watts
TWh	terawatt-hour

Annex **E** REFERENCES

CHAPTER 1

IEA (2008a), *Energy Technology Perspectives*, OECD/International Energy Agency, Paris.

IEA (2008b), *World Energy Outlook*, OECD/IEA, Paris.

CHAPTER 2

APP (2007), "The State-of-the-Art Clean Technologies" (SOACT) for Steelmaking Handbook, Asia Pacific Partnership on Clean Development and Climate, December, <http://www.asiapacificpartnership.org/Steel%20TF/SOACT+1-7-08.pdf>.

APP (2008), "Status Review of Industry Indicators for Energy Saving", presentation at the Fifth Task Force Meeting, Busan, Korea.

DOE (2008), "DOE announces USD 26 million to develop energy efficient processes for US industry", US Department of Energy, Press Release 22 August.

ESTEP (2008), European Steel Technology Platform, http://cordis.europa.eu/estep/agenda_en.html.

Ferreira, O.C. (2000), <http://ecen.com/eee20/omar20be.htm>.

Forbes (2006), <http://www.forbes.com/forbes/2006/0918/122.html>.

Girard, P. (2007), "Advanced Technical Issues in Charcoal Production", Sustainable Charcoal Production, Trade and Use in Europe, Zagreb, Croatia, 5-6 June.

Hiebler, H. and J. F. Plaul (2004), "Hydrogen Plasma Smelting Reduction – An Option for Steelmaking in the Future", *Metalurgija* No. 43 (3) 155-162.

Hismelt (2008), http://www.Hismelt.com.au/EN/HO_PageView.aspx?pageID=39.

Kawamura A., G. E. Hoffmann, R. M. Klawonn and H. Uemura (2006), "Development of Energy Consumption and Productivity of a Gas-Based Direct Reduction Iron-Making Process", *R&D Kobe Steel Engineering Reports*, Vol. 56, No. 2, pp. 32-36.

IEA (2007), *Tracking Industrial Energy Efficiency and CO₂ Emissions*, OECD/International Energy Agency, Paris.

IISI (2007), *Steel Statistical Yearbook 2007*, IISI Committee on Economic Studies, International Iron and Steel Institute, Brussels. <http://www.worldsteel.org/pictures/publicationfiles/SSY2007.pdf>.

ISSF (2008), International Stainless Steel Forum, <http://www.worldstainless.org/Statistics/>.

Japan Times (2008), <http://search.japantimes.co.jp/cgi-bin/nb20080731n4.html>.

JISF (2008a), "Current State of Plastic Waste Recycling and Future Tasks", Japan Iron and Steel Federation, www.jisf.or.jp.

JISF (2008b), "Contribution of Steel Products to Energy Savings in Society", www.jisf.or.jp.

Lüngen, H.B. and P. Schmöle (2004), "Hot Metal Production in the Blast Furnace from an Ecological Point of View", paper presented at the Second International Meeting on Ironmaking and First International Symposium on Iron Ore, Vitoria, Brazil, 12-15 September.

Matsumiya, T. (2005), "Steel Research and Development in the Aspect for a Sustainable Society", *Scandinavian Journal of Metallurgy*, Volume 34, Blackwell Publishing.

McCelland, J. (2002), "Not all RHF's are created equal. A Rotary Harth Furnace Primer", direct from MIDREX, second quarter.

Midrex (2008), http://www.midrex.com/handler.cfm?cat_id=105.

Neelis, M. L. et al. (2006), *Long-Term Production, Energy Consumption and CO₂ Emission Scenarios for the Worldwide Iron and Steel Industry* Utrecht.

New Scientist (2006),
<http://technology.newscientist.com/article/dn9878-electrolysis-may-one-day-provide-green-iron.html>.

OECD (2007), "Research and Development in the World Steel Industry", DSTI/SU/SC(2007)41, Organisation for Economic Co-operation and Development, Paris.

OECD (2008), "The Financial Crisis and Outlook for Steel", DSTI/SU/SC (2008)37, OECD. Paris.

Orth A., N. Anastasijevica and H. Eichberger (2007), "Low CO₂ Emission Technologies for Iron and Steelmaking as well as Titania Slag Production", *Minerals Engineering*, Vol. 20, Issue 9, August, pp. 854-861.

POSCO (2008), "The FINEX Innovative Ironmaking Process", presentation at APP Fourth Steel Task Force Workshop, Busan, Korea, 16 April.

Santos Sampaio, R. (2005),
<http://www.bioenergytrade.org/downloads/sampaionovdec05.pdf>.

Siemens (2008),
http://www.industry.siemens.com/metals/en/processes/mp_proc_02_08.htm.

Siemens VAI (2008), "Siemens I&S MT, Deep Dive in Industrial Energy Efficiency Management, Project Plan for Cross Process Levers EMS & Power Plants", Tackenberg, 2 March.

USGS (2009), "Mineral Commodity Summaries", *Iron and Steel*, United States Geological Survey,
http://minerals.usgs.gov/minerals/pubs/commodity/iron_&_steel/.

Xie, D., J. Donnelley, R. Flann, Y. Pan, S. Sanetsis and B. Washington (2008), "Piloting the Integrated Dry Granulation and Heat Recovery Process at CSIRO", presented at CSRP'08 Conference, Brisbane.
http://www.csrp.com.au/_media/events/csrp08/Xie_CSRP08_DryGranulationHeatRecovery.pdf.

CHAPTER 3

Associazione Italiana Tecnico Economica Cemento (AITEC) (2000 to 2008), *Annual Report*, AITEC, Rome.

Battelle (2002), *Toward a Sustainable Cement Industry. Climate Change*, WBCSD, Geneva, <http://www.wbcSD.org>.

Comité Européen de Normalisation (CEN) (2000), "Cement – Part 1: Compositions, Specifications and Conformity Criteria for Common Cements", EN 197-1:2000, Brussels.

Cement Sustainability Initiative (CSI) (2008), "Getting the Numbers Right database", WBCSD, Geneva.

Cui, Y.-S. and X. Wang (2006), "The State of the Chinese Cement Industry in 2005 and Its Future Prospects", *Cement International*, No. 4/2006, pp. 36-43.

Cui, Y.-S. (2009), Personal communication.

European Cement Research Academy (ECRA) (2007), *Carbon Capture Technology – Options and Potentials for the Cement Industry*, ECRA, Dusseldorf.

European Environment Agency (2006), *Annual European Community Greenhouse Gas Inventory 1990–2004 and Inventory Report 2006*, EC, Brussels.

European IPPC Bureau (EIPPCB) (2007), *Reference Document on Best Available Techniques in the Cement and Lime Manufacturing Industries*, EC, Brussels.

F.L. Smidth (2006), "Cement Plant Pyro-technology", presentation to the IEA-WBCSD Workshop on Energy Efficiency and CO₂ Emission Reduction Potentials and Policies in the Cement Industry, IEA, Paris, September.

Instituto Brasileiro de Geografia e Estatística (IBGE) (2008), *Cement Sector Energy Consumption Statistics*, IBGE, Brasilia.

International Energy Agency (IEA) (2007), *Tracking Industrial Energy Efficiency and CO₂ Emissions*, IEA/OECD, Paris.

IEA (2008), *Worldwide Trends in Energy Use and Efficiency*, IEA/OECD, Paris.

International Energy Agency Greenhouse Gas R&D Programme (IEA GHG) (2008), *CO₂ Capture in the Cement Industry*, IEA/OECD, Paris.

Instituto Nacional de Estadística Geografía e Informática (INEGI), Balance Nacional de Energía, INEGI, Mexico City.

Japan Cement Association (JCA) (2006), "Cement Industry's Status and Activities for GHG Emissions Reduction in Japan" presentation to the IEA-WBCSD Workshop on Energy Efficiency and CO₂ Emission Reduction Potentials and Policies in the Cement Industry, IEA, Paris, September.

Yamashita, F. (2009), Personal Communication, Ministry of Economy, Trade and Industry (METI), 16 April.

Natural Resources Canada (NRCAN) (2008), "Comprehensive Energy Use Database", NRCAN, Ottawa.

OFICEMEN (2007), *Statistics of the Spanish Cement Industry*, www.oficemen.com.

Pahuja, A. (2008), "Established Technologies and Energy Management: The Path Towards GHG Mitigation in India, National Council for Cement and Buildings Materials", presentation to Stakeholder Discussion Forum: Building a Sustainable Cement Sector in India, New Dehli, 19-20 September.

Portland Cement Association (PCA) (2008), *North American Cement Industry Annual Yearbook 2007*. Skokie, Illinois.

Siam Cement Company Ltd. (2005), *Sustainable Development Report 2005*, Siam Cement Company Ltd, Bangkok.

Soares, J.B. and M.T. Tolmasquim (2000), "Energy Efficiency and Reduction of CO₂ Emissions Through 2015: The Brazilian Cement Industry", *Mitigation and Adaptation Strategies for Global Change* No. 5, pp. 297–318, Netherlands.

United States Geological Survey (USGS) (2008), *Minerals Yearbook*, USGS, Reston, Virginia.

USGS (various years), *Minerals Yearbook*, USGS, Reston, Virginia.

Verein Deutscher Zementwerke e.V. (VDZ) (2008), "Activity Report 2005-2007", VDZ, Dusseldorf.

Worrell, E., et al. (2001), "Carbon Dioxide Emissions from the Global Cement Industry", *Annual Review of Energy and Environment*, Vol 26, 2001.

Zhu L. and H. Xu (2008), "Cement Sector: Gaining strength through adjustment", *China Economic Net*,
www.en.ce.cn/Insight/200803/10/t20080310_14776607.shtml.

CHAPTER 4

AIChE (2008), "Safety in Ammonia Plants & Related Facilities Symposium", *AIChE Technical Manual 2008*, Volume 49, pp 341-352.

Baker, R.W. (2008), "Vapor and Gas separation by Membranes", In N.N. Li, A.G. Fane, W.S., Winston Ho, T. Matsuura (Eds.), *Advanced Membrane Technology and Applications* (pp.559-578), Wiley Interscience.

Bernstein, L., J. Roy, K. C. Delhotal, J. Harnisch, R. Matsuhashi, L. Price, K. Tanaka, E. Worrell, F. Yamba, Z. Fengqi (2007), *Industry in Climate Change 2007:*

Mitigation., Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY.

Boustead, I. (2008), "Eco-Profiles of the European Plastics Industry", Reports by I. Boustead for PlasticsEurope, <http://lca.plasticseurope.org/main2.htm> (continuously updated).

Bouwman, A.F., A. H. W. Beusen, K. W. van der Hoek and G. van Drecht (2006), "Modelling the fate: BREW Study", downloadable from <http://www.chem.uu.nl/brew/>

Chauvel, A. and G. Lefebvre (1989), "Petrochemical Processes- Technical and Economic Characteristics", Two Volumes, Editions Technip, Paris.

Chemweek (2007a), "Product Focus: Carbon Black", 31 January.

Chemweek (2007b), "Product Focus: Chlor-Alkali", 25 April.

Chemweek (2007c), "Product Focus: Polycarbonate", 28 November-5 December.

Chemweek (2007d), "Product Focus: Titanium Dioxide", 14-21 February.

Consultic (2004), "Plastics Production, Consumption and Recycling Data for Germany 2003", Consultic Marketing & Industrieberatungs GmbH. Produced for: PlasticsEurope Deutschland – Verband der Kunststoffherzeuger. Frankfurt/Main. 27 August.

Consultic (2008), "Produktion, Verarbeitung und Verwertung von Kunststoffen in Deutschland 2007", – Kurzfassung. Consultic Marketing & Industrieberatungs GmbH. Im auftrag von: BKV Beteiligungs- und Kunststoffverwertungsgesellschaft mbH & PlasticsEurope Deutschland – Verband der Kunststoffherzeuger. Frankfurt/Main.

Creative Energy (2008), "European Roadmap for Process Intensification", *Creative Energy – Energy Transition*, <http://www.senternovem.nl/energytransition/downloads/index.asp>.

Dooley, J. J. (2008), "Overview of Selected Issues Associated with the Potential for Large-Scale Commercial Deployment of Carbon Dioxide Capture and Storage Technologies", presentation from seminar organised by Center for Strategic & International Studies, 31 March 2008, Washington, DC.

Gielen, D. (1997), "Technology Characterization for Ceramic and Inorganic Materials", Netherlands Energy Research Foundation, Report No. ECN-C-97-064, Petten.

Hendriks, C., W. Graus and F. van Bergen (2004), *Global Carbon Dioxide Storage Potential and Costs*, Ecofys, Utrecht, the Netherlands.

Hydrocarbon Processing (2003), *Petrochemical Processes 2003*, Vol. 82, No. 3, pp. 72-124.

IEA (2007), *Tracking Industrial Energy Efficiency and CO₂ Emissions*, OECD/International Energy Agency, Paris.

- IEA (2008a), *Worldwide Trends in Energy Use and Efficiency*, OECD/IEA, Paris.
- IEA (2008c), *Energy Balances of non-OECD countries, 2008 Edition*, OECD/IEA, Paris.
- IEA (2008d), *Energy Balances of OECD countries, 2008 Edition*. OECD/IEA, Paris.
- IEA (2008e), *Energy Statistics of OECD countries*, OECD/IEA Paris.
- IEA (2009), "Chemical and Petrochemical Sector – Potential of Best Practice Technology for Improving Energy Efficiency", Information Paper on energy efficiency indicators, OECD/IEA, Paris.
- IFA (2009a), "Urea production for year 2006", personal communication with Mr. Michel Prud'Homme, International Fertilizers Association.
- IFA (2009b), "Best practice technology for ammonia production from coal", personal communication with Mr. Keith Wilson, International Fertilizers Association.
- IPTS/EC (2001), IPPC Reference Document on BAT in the Chlor-Alkali Manufacturing Industry, Institute for Prospective Technological Studies/European Commission, Brussels, December.
- IPTS/EC (2003), *IPPC Reference Document on BAT for Large Volume Organic Chemical Industry*, Brussels.
- IPTS/EC (2004), "Process BREF for Soda Ash", *IPPC Reference Document on BAT for Large Volume Solid Inorganic Chemicals Family*, Brussels, March.
- IPTS/EC (2007a), "Solids and Others Industry", *IPPC Reference Document on Best Available Techniques for the Manufacture of Large Volume Inorganic Chemicals*, Brussels, August.
- IPTS/EC (2007b), *IPPC Reference Document on Best Available Techniques in the Production of Polymers*, Brussels, August.
- JPCA (2009), Personal communication with Mr. Nobuaki Mita, Japan Petrochemical Industry Association.
- Kauranen, P. (2008), *Oxygen Carriers for Power Efficiency*, Tekes, Functional Materials Scientific Day, Helsinki, 10 September.
- Leendertse, A. and J. van Veen (2002), Dutch Notes on BAT for the Carbon Black Industry, <http://www.infomil.nl/legsys/bref/nl-carbon.pdf>.
- Martin, N., E. Worrell, M. Ruth, L. Price, R. N. Elliott, A. Shipley and S. J. Thorpe (2000), *Emerging Energy-Efficient Industrial Technologies*, Lawrence Berkeley National Laboratory, Ref. LBNL-46990. Berkeley, CA, October.
- Meyers, R.H. (ed.) (2005), *Handbook of Petrochemicals Production Processes*, McGraw-Hill, New York.
- Nunes, S. P. and K.V. Peinemann (eds) (2006), *Membrane Technology in the Chemical Industry*, 2nd ed. WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.
- Oil and Gas Journal* (2007), "Industry Survey of Ethylene from Steam Crackers", 16 July.

Patel, M. K., M. Crank, V. Dornburg, B. Hermann, L. Roes, B. Hüsing, L. van Overbeek, F. Terragni and E. Recchia. (2006), "Medium and Long-Term Opportunities and Risks of the Biotechnological Production of Bulk Chemicals from Renewable Resources - The BREW Project", prepared under the European Commission's GROWTH Programme. Final report, 420 pages, September. Downloadable from <http://www.chem.uu.nl/brew/>

PEMRG (2007), "Business Data and Charts, 2006", Status November 2007, Plastics Europe, Brussels.

Plastics Europe (2008), "The Compelling Facts About Plastics 2007", an analysis of plastics production, demand and recovery for 2007 in Europe, Brussels, October.

Ren, T. (2009), "Petrochemicals from Oil, Natural Gas, Coal and Biomass: Energy Use, Economics and Innovation", Ph.d. thesis, Utrecht University, the Netherlands.

Ren, T., M. Patel and K. Blok (2008), "Steam Cracking and Methane to Olefins: Energy Use, CO₂ Emissions and Production Costs", *Energy*, Vol. 33 (5), pp. 817-833.

RFA (2009), "Statistics", Renewable Fuels Association, <http://www.ethanolrfa.org/industry/statistics/>.

Schyns, V. (2006), "Towards a Simple, Robust and Predictable EU Emissions Trading Scheme, Benchmarks from Concrete to Practice", Utility Support Group, Geleen, the Netherlands.

<http://www.usgbv.nl/uploads/files/level0/Benchmarks%20to%20practice%20EU%20ETS%20Schyns%2021march06.pdf>.

Shah, M., D. Bonaquist and J. Shine (2006), "Overview of Industrial CO₂ Sources", presented at Fourth Annual Geologic Sequestration-EOR and CO₂-Carbon Management Workshop, 4-5 December, Houston, TX.

SRI Consulting (2008), *Production, Capacity and Capacity Average Age Data for selected chemicals and for selected countries and for OECD regions*, Menlo Park, CA.

USGS (2008a.), "Nitrogen" (Advance Release), *Minerals Yearbook*, United States Geological Survey, October.

USGS (2008b), "Soda ash" (Advance Release), *Minerals Yearbook*, United States Geological Survey, September.

van Gerven, T., A. Stankiewicz, "Structure, energy, synergy, time-the fundamentals of process intensification", *Industrial & Engineering Chemistry Research*, Vol. 48 (5) pp. 2465-2474.

Weiss, M., M. L. Neelis, M. C. Zuidberg and M. K. Patel (2008), "Applying bottom-up analysis to identify the system boundaries of non-energy use data in international energy statistics", *Energy*, Vol.. 33, pp. 1609-1622.

Wright, I, (2007), "The CCS Commercial Challenge", presented at Conference on Regulating and Financing Carbon Capture and Storage (CCS), IRGC, Swiss Re Centre for Global Dialogue, Rüşchlikon, Switzerland, 7 November.

X. X. Shen L., J. Haufe, M. K. Patel, "Product overview and market projection of emerging bio-based plastics", *PRO-BIP 2009, Final report*. Report commissioned by European Polysaccharide Network of Excellence (EPNOE) and European Bioplastics, Group Science, Technology and Society, Utrecht, 2009, pp. 243.

CHAPTER 5

Agenda 2020 Technology Alliance (2006), *Forest Products Industry Technology Roadmap*, American Forest and Paper Association, USA.

Axegard, P. (2009), Personal communication, STFI-Packforsk AB, 2 April 2009.

CEPI (2001), *Special Recycling Statistics*, Confederation of European Paper Industries Brussels.

CEPI (2006), "Europe Global Champion in Paper Recycling: Paper Industries Meet Ambitious Target", Press Release, July. Brussels.

China State Statistical Bureau (various years), *China Energy Statistical Yearbook*, China Statistical Publishing House, Beijing.

EC (2001), *Integrated Pollution Prevention and Control (IPPC)*, European Commission, Brussels.

FAO (2005a), "Trends in wood products 1961-2003", United Nations Food and Agriculture Organization, Rome.

FAO (2005b), "European Forest Sector Outlook Study", Rome.

FAO (2007), "Demand and Supply of Wood Products in China", Rome.

FAOSTAT (2008), United Nations Food and Agriculture Organization, Statistic Statistics Division, Rome.

<http://faostat.fao.org/site/381/DesktopDefault.aspx?PageID=381>.

Finnish Forest Industries Federation (2002), *Possibilities of Reducing CO₂ Emissions in the Finnish Forest Industry*, Helsinki.

Forest-Based Sector Technology Platform (2007), *A Bio-solution to Climate Change*, Brussels.

Francis, D.W. et al. (2002), *Energy Cost Reduction in the Pulp and Paper Industry – An Energy Benchmarking Perspective*, Natural Resources Canada, Ottawa.

Hektor, E. and T. Berntsson (2007a), "Reduction of Greenhouse Gases in Integrated Pulp and Paper Mills - Possibilities for CO₂ Capture and Storage", in *Chemical Engineering Transactions*, 12(1) pp. 145-150.

Hektor, E. and T. Berntsson (2007b), "Future CO₂ Removal from Pulp Mills - Process Integration Consequences", *Energy Conversion and Management*, Volume 48, Issue 11.

IEA (2008), *Energy Technology Perspectives: Scenarios & Strategies to 2050*, OECD/International Energy Agency, Paris.

Jochem, E. et al. (2004), *Werkstoffeffizienz. Einsparpotentiale bei Herstellung und Verwendung Energieintensiver Grundstoffe*, Fraunhofer Informationszentrum Raum und Bau, Stuttgart.

Martin, N. et al. (2001), *Opportunities to Improve Energy Efficiency in the US Pulp and Paper Industry*, Lawrence Berkeley National Laboratory, Berkeley, California.

Paprican (2002), *Energy Cost Reductions in the Pulp and Paper Industry, An Energy Benchmarking Perspective*, Natural Resources Canada, Ottawa.

Poyry (2009), Poyry database, Finland.

Reference Document on Best Available Techniques in the Pulp and Paper Industry, <http://www.infomil.nl/legsys/bref/papier.pdf>.

STFI-Packforsk (2005), "The Future Resource Adapted Pulp Mill", FRAM Final Report Model Mills, Report No 70, STFI-Packforsk, Stockholm.

Whiteman, A. (2005), *Recent Trends and Developments in Global Markets for Pulp and Paper*, United Nations Food and Agriculture Organization, Rome.

CHAPTER 6

Aluminum Association (2009), "Automotive Aluminum Use Reaches All-Time High in 2009", <http://www.aluminum.org/AM/Template.cfm?Section=Home&TEMPLATE=/CM/ContentDisplay.cfm&CONTENTID=28116>.

Bayliss, C. and J. Marks (2008), "The Aluminium Industry", presentation to the IEA/ERI Workshop on International Comparison of Industrial Energy Efficiency, Beijing. http://www.iea.org/Textbase/work/2008/comparison/Bayliss_Aluminium_EN.pdf.

Choate, W. and J. Green (2003), "US Energy Requirements for Aluminium Production: Historical Perspective, Theoretical Limits and New Opportunities", report prepared for the United States Department of Energy, Office of Energy Efficiency and Renewable Energy, Washington, DC., http://www.secat.net/docs/resources/US_Energy_Requirements_for_Aluminum_Production.pdf.

Choate, W. and J. Green (2006), "Technoeconomic Assessment of the Carbothermic Reduction Process for Aluminium Production", *Light Metals 2006*, pp. 445-450.

EC (2008), IPPC Draft Reference Document on Best Available Techniques in the Non-Ferrous Metals Industry, European Commission, Brussels/Seville, <http://eippcb.jrc.ec.europa.eu/pages/FActivities.htm>.

GARC (2006), "Global Aluminium recycling: A Cornerstone of Sustainable Development", <http://www.world-aluminium.org/cache/fi0000181.pdf>.

Gu, S. (2008), "Chinese Bauxite and its Influences on Alumina Production in China", *Light Metals*, pp. 79-83.

- IAI (2007), "Life Cycle Assessment of Aluminium: Inventory Data for the Primary Aluminium Industry, year 2005 update", International Aluminium Institute. <http://www.world-aluminium.org/cache/fl0000166.pdf>.
- IAI (2008a), <http://www.world-aluminium.org/Sustainability/Recycling>.
- IAI (2008b), "Aluminium for Future Generations year 2007 update", <http://www.world-aluminium.org/cache/fl0000189.pdf>.
- IAI (2008c), IAI Statistics, <http://www.world-aluminium.org/Statistics>.
- IAI (2008d), "International Aluminium Industry's Perfluorocarbon Gas Emissions Reduction Programme - Update 2006", Results of the 2006 Anode Effect Survey, <http://www.world-aluminium.org/cache/fl0000205.pdf>.
- IAI (2009a), "International Aluminium Industry's Perfluorocarbon Gas Emissions Reduction Programme - Update 2007", Results of the 2007 Anode Effect Survey, <http://www.world-aluminium.org/cache/fl0000274.pdf>.
- IAI (2009b), "Fourth Sustainable Bauxite Mining Report", *in press*.
- ISR (2000), "Energy Efficiency Best Practices in the Australian Aluminium Industry", Department of Industry, Science and Resources, Canberra.
- Keniry, J. (2001), "The Economics of Inert Anodes and Wettable Cathodes for Aluminium Reduction Cells", *JOM Journal of the Minerals, Metals and Materials Society*, Volume 53, Number 5, pp. 43-47.
- Keniry, J. (2008), "Aluminium Smelting Greenhouse Gas Footprint and Sustainability", *Light Metals 2008*, pp. 369-373.
- Li, W. *et al.* (2008), "The Most Important Sustainable Development Issues of Chinese Alumina Industry", *Light Metals 2008*, pp.191-195.
- Liu, L. *et al.* (2006), "Analysis of the Overall Energy Intensity of Alumina Refinery Process using Unit Process Energy Intensity and Product Ratio Method", *Energy*; Vol. 31, Issues 8-9, July, pp. 1167-1176.
- Marks, J. (2007), "Present Progress and Scope for Further GHG Emissions Reduction during Production", presentation to an IEA and IAI Workshop on Energy Efficiency and GHG Emission Reduction in the Aluminium Industry, Paris, May, <http://www.iea.org/Textbase/work/2007/aluminium/marks.pdf>.
- Martchek, K. (2007), "2006 Global Aluminium Mass Flow", presentation to an IEA and IAI Workshop on Energy Efficiency and GHG Emission Reduction in the Aluminium Industry, Paris, May, http://www.iea.org/Textbase/work/2007/aluminium/martchek_mass.pdf.
- Morrey, G. W. (2004), *New smelter capacity required! Examining the options and costs from debottlenecking to greenfield investment*, Hatch Associates, http://www.hatch.ca/light_metals/Articles/new_smelter_capacity_required.pdf.
- Nord, L. (2009), Personal communication, Norsk Hydro ASA, 4 May 2009.
- Pawlek, R. P. (2008), "Inert Anodes: An Update", *Light Metals 2008*, pp.1039-1045.

Tao Z. and X. Liang (2008), "Energy Conservation and the Development of China's Electrolysis Aluminum Industry", presentation to the IEA/ERI Workshop on International Comparison of Industrial Energy Efficiency, Beijing, http://www.iea.org/Textbase/work/2008/comparison/KANG_Aluminum_EN.pdf.

USGS (2009), "Mineral Commodity Summaries", *Aluminium*, January 2008, United States Geological Survey, Reston, Virginia, <http://minerals.usgs.gov/minerals/pubs/commodity/aluminum/mcs-2009-alumi.pdf>.

Worrell, E. et al. (2008), *World Best Practice Energy Intensity Values for Selected Industrial Sectors*, Ernest Orlando Lawrence Berkeley National Laboratory, LBNL-62806 Rev 2, <http://ies.lbl.gov/iespubs/LBNL-62806.Rev.2.pdf>.

CHAPTER 7

Bradshaw, J. and T. Dance (2004), "Mapping Geological Storage Prospectivity of CO₂ for the World's Sedimentary Basins and Regional Source to Sink Matching", proceedings of the 7th International Conference on Greenhouse Gas Technologies, Vancouver, (5-9 September).

Brunner, C. and A. Niederberger (2006), *Motor System Model: A Tool to Support Efficient Industrial Motor System Policies and Programs*, A+B International, Zürich.

DOE (2002), *Steam System Opportunity Assessment for the Pulp and Paper, Chemical Manufacturing, and Petroleum Refining Industries*, prepared by Resource Dynamics Corporation for, the United States Department of Energy, Washington, D.C., DOE/GO 102002-1639.

EUBIA (2005), *Biomass Resources and Production Potential*, European Biomass Industry Association, <http://www.eubia.org/215.98.html>

FAO (2006), *Global Forest Resource Assessment 2005, Progress towards sustainable Forest Management*, on-line maps and figures, United Nations Food and Agriculture Organization, <http://www.fao.org/forestry/41256/en/>.

Fischer, G. and L. Schratzenholzer (2001), "Global bioenergy potentials through 2050", *Biomass and Bioenergy*, Vol 20, pp. 151-159.

Haberl, H., K.H. Erb and F. Krausmann (2007), *Human Appropriation of Net Primary Production*, Internet Encyclopaedia of Ecological Economics, The International Society for Ecological Economics, www.ecoeco.org/pdf/2007_march_hanpp.pdf, accessed 19 March, 2008.

Hoogwijk, M.A. et al. (2003), "Exploration of the Ranges of the Global Potential of Biomass for Energy", *Biomass and Bioenergy*, Vol. 25, pp. 119-133.

IAI (2006), *Global Aluminium Recycling: A Cornerstone of Sustainable Development*, International Aluminium Institute, London.

IEA (2007), *Tracking Industrial Energy Efficiency and CO₂ Emissions*, OECD/International Energy Agency, Paris, <http://www.iea.org/w/bookshop/add.aspx?id=298>.

IEA (2008a), *Energy Technology Perspectives: Scenarios and Strategies to 2050*, OECD/IEA, Paris, <http://www.iea.org/w/bookshop/add.aspx?id=330>.

IEA (2008b), *Energy Balances of OECD Countries, 2008 Edition*, OECD/IEA, Paris, <http://www.iea.org/w/bookshop/add.aspx?id=29>.

IEA (2008c), *Energy Balances of OECD Countries, 2008 Edition*, OECD/IEA, Paris, <http://www.iea.org/w/bookshop/add.aspx?id=31>.

IEA (2008d), *CHP/DHC Country Scorecard: Finland*, OECD/IEA, Paris, <http://www.iea.org/G8/CHP/profiles/Finland.pdf>.

IEA (2008e), *CO₂ Capture and Storage: a key Carbon Abatement Option*, OECD/IEA, Paris, <http://www.iea.org/w/bookshop/add.aspx?id=335>.

IEA (2009), *Cogeneration and District Energy*, OECD/IEA, Paris, <http://www.iea.org/files/CHPbrochure09.pdf>.

IEA Bioenergy (2007), *Potential Contribution of Bioenergy to the World's Future Energy Demand*, OECD/IEA Bioenergy, Paris, www.ieabioenergy.com.

IEA-GHGRD (2004), *Ship Transport of CO₂*, Prepared for the Executive Committee of the IEA Greenhouse Gas R&D Programme, Report number PH4/30, July.

IPCC (2007), *Mitigation of Climate Change*, Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK.

Keulenaer H. de, R. Belmans, E. Blaustein, D. Chapman, A. De Almeida, B. Wachter and P. Radgen (2004), *Energy Efficient Motor Driven Systems*, European Copper Institute, Brussels.

Mutha, N.H., M. Patel and V. Premnath (2006), *Plastics Materials Flow Analysis for India*, Resources Conservation and Recycling, pp. 224-244.

Parikka, M. (2004), "Global Biomass Fuel Resources," *Biomass and Bioenergy*, Vol. 27, pp. 613-620.

USGS (2006): *2006 Minerals Year Book: Iron and Steel Scrap*, United States Geological Survey, United States, http://minerals.usgs.gov/minerals/pubs/commodity/iron_&_steel_scrap/myb1-2006-fescr.pdf.

US EPA (2006), *Global Mitigation of Non-CO₂ Greenhouse Gases 1990-2020* (EPA Report 430-R-06-003), United States Environmental Protection Agency, Washington, DC, <http://www.epa.gov/nonco2/econ-inv/downloads/GlobalAnthroEmissionsReport.pdf>.

VTT (2007), *Bioenergy Technology Review, Internal Report for IEA*, VTT Technical Research Institute of Finland, Edita Prima, Helsinki, September.

Worrell, E., L. Price and C. Galitsky (2004), *Emerging Energy-Efficient Technologies in Industry: Case Studies of Selected Technologies* (LBNL-54828), Lawrence Berkeley National Laboratory, Berkeley, California.

CHAPTER 8

Alaane, K. and A. Saari (2008), "Estimating the environmental burdens of residential energy supply systems through material input and emission factors", *Building and Environment*, Vol. 43, pp 319-330.

Blengini, G. A. (2009), "Life cycle of buildings, demolition and recycling potential: a case study in Turin, Italy", *Building and Environment*, Vol. 44, pp 319-330.

Brinkler, Kelly (2004), *CARE Report on automotive glass recycling, 2004 Update*, Consortium for Automotive Recycling, http://www.caregroup.org.uk/Glass_Report_2004.doc.

EC (2000), "Directive 2000/53/EC of the European Parliament and of the Council on End-of Life Vehicles and Following Amendments/Revisions".

Institute for Perspective Studies of the Joint Research Centre of the European Commission (2008), *Environmental Improvement of Passenger Cars (IMPRO-car)* report, http://ec.europa.eu/environment/ipp/pdf/jrc_report.pdf.

Johnson Matthey (2002), *Platinum 2002. Diesel Cars & Platinum Demand*, http://www.platinum.matthey.com/uploaded_files/publications/diesel.pdf.

Kleijn, R., L. van Oers, G. Jan Kramer and E. van der Voet (2008), "Material constraints of selected energy pathways", in preparation Leiden University Netherlands.

Kuhndt, M. and B. Bilitewski (2000), *Towards Reduced Environmental Burden of Mobility: Improving the Automobile Life Cycle, a CHAINET case study report*, Wuppertal Institute for climate, Environment and Energy, Berlin.

Lopez-Mesa, B., et al. (2009), "Comparison of Environmental Impacts of Building Structures with In Situ CST Floors and with Precast Concrete Floors", *Building and Environment*, Vol. 44, pp 699-712.

MIT/Camano Associates for the IEA Mobility Modelling project (2005), *Energy Requirements & Emissions for Vehicle Production*.

National Renewable Energy Laboratory (2004), *PV FAQs*, prepared for US Department of Energy Office of Energy Efficiency and Renewable Energy, Washington, DC.

Norris, M. and P. Shiels (2004), *Regular National Report on Housing Developments in European Countries*, Department of the Environment, Heritage and Local Government, Dublin.

Nuclear Energy Agency (2008), *Nuclear Energy Outlook*, OECD/NEA, Paris.

Ortiz, O. et al. (2009), "Sustainability based on LCM of residential dwellings: a case study in Catalonia, Spain", *Building and Environment*, Vol. 44, pp 584-594.

Peterson, P.F. et al. (2005), *Metal and concrete inputs for several nuclear power plants*, University of California, Berkeley.

Plastics Europe, EuPC, epro, EuPR (2008), *The Compelling Facts About Plastics 2007. An analysis of plastics production, demand and recovery for 2007 in Europe*
<http://www.plasticseurope.org/Content/Default.asp?PageName=openfile&DocRef=20081020-002>.

U.S. Geological Survey (2009), *Mineral commodity summaries*,
<http://minerals.usgs.gov/minerals/pubs/mcs/2009/mcs2009.pdf>.

Wilburn David R. and Donald I. Bleiwas (2004), "Platinum-Group Metals—World Supply and Demand", *U.S. Geological Survey Open-File Report 2004*,
<http://pubs.usgs.gov/of/2004/1224/2004-1224.pdf>.

CHAPTER 9

Aldy, J. E. and W. A. Pizer (2008), "Issues in Designing U.S. Climate Change Policy", Resources for the Future discussion paper 08-20, June, www.rff.org

Aluminium Canada (Alcan) (2006) "Alcan Launches Breakthrough Aluminum Technology Initiative in France", Press Release, December 14.

Amatayakul W., G. Berndes and J. Fenhann (2008), "Electricity Sector No-Lose Targets in Developing Countries for Post-2012: Assessment of Emissions Reduction and Reduction Credits", CD4CDM Working Paper No.6, UNEP Risoe Centre, December.

Baron R., I. Barnsley and J. Ellis (2008), "Options for Integrating Sectoral Approaches into the UNFCCC", OECD/IEA information paper. COM/ENV/EPOC/IEA/SLT(2008)3, www.oecd.org/env/cc.

Baron, R., J. Reinaud, C. Philibert and M. Genasci (2007), "Sectoral Approaches to Greenhouse Gas Mitigation – Exploring Issues for Heavy Industry", IEA Information Paper, www.iea.org.

BCG (2008), "Assessment of the Impact of the 2013-2020 ETS Proposal on the European Cement Industry", final project report. The Boston Consulting Group.

Birat, J.P. (2007), "Ultra-Low CO₂ Steelmaking", presentation at the IISI Annual Meeting, Berlin, 9 October.

Bosi, M. and J. Ellis (2005), "Exploring Options for 'Sectoral Crediting Mechanisms'", OECD/IEA, Paris, www.oecd.org/dataoecd/55/61/34902644.pdf.

CCAP, CEPS, CCC, ZEW, IDDRI (2008), "Sectoral Approaches: A Pathway to Nationally Appropriate Mitigation Actions", Center for Clean Air Policy Interim Report, Washington, D.C., Executive Overview, December.

Chung, R. (2007), "A CER Discounting Scheme Could Save Climate Change Regime after 2012", *Climate Policy* Vol No. 7, pp. 171-176.

Demailly, D. and P. Quirion (2006), "CO₂ Abatement, Competitiveness and Leakage in the European Cement Industry under the EU-ETS: Grandfathering vs. Output-based Allocation", *Climate Policy*, 6(1), August, pp. 93-113.

Demailly D. and P. Quirion (2008a), "European Emission Trading Scheme and Competitiveness: A Case Study on the Iron and Steel Industry", *Energy Economics*, Vol. 30, pp. 2009-2027.

Demailly, D. and P. Quirion (2009), "Leakage from Climate Policies and Border Tax Adjustment: Lessons from a Geographic Model of the Cement Industry", in Roger Guesnerie and Henry Tulkens, editors (2009), *The Design of Climate Policy*, CESifo Seminar Series, The MIT Press, Boston, pp 333-358.

Ellerman, A.D. and B.K. Buchner (2008), "Over-Allocation or Abatement? A Preliminary Analysis of the EU ETS Based on the 2005-06 Emissions Data", *Environmental and Resource Economics*, Vol. 41, N° 2, pp. 267-287.

Ellerman, A.D. et al. (2009), *Pricing Carbon: The European Union Emissions Trading Scheme*, Cambridge University Press.

Ellis J. and R. Baron (2005), "Sectoral Crediting Mechanisms: An Initial Assessment of Electricity and Aluminium", OECD/IEA Information Paper, COM/ENV/EPOC/IEA/SLT(2005)8, www.oecd.org/env/cc.

EpE-IDDRI (2008), "Scenarios for Transition Towards a Low-Carbon World in 2050 : What's at Stake for Heavy Industries?", *Entreprises pour l'Environnement*, Institut du Développement Durable et des Relations Internationales, www.epe-asso.org; www.iddri.org.

European Commission (2009) "Directive of the European Parliament and of the Council", amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community, PE-CONS 3737/08.

Gielen, D., and Y. Moriguchi (2002), "CO₂ in the Iron and Steel Industry: an Analysis of Japanese Emission Reduction Potentials", *Energy Policy*, No. 30, pp 849-863.

Golove, W. H. and J. H. Eto (1996), "Market Barriers to Energy Efficiency: A Critical Reappraisal of the Rationale for Public Policies to Promote Energy Efficiency", Lawrence Berkeley National Laboratory, LBNL-38059, Berkeley, California.

Helme, E. (2008), "Sectoral Approaches to Post-2012 Climate Change Policy Architecture", presentation to the pre-MEM workshop on sectoral approaches, 16 April, www.iddri.org/Activites/Ateliers/Atelier-sur-les-approches-sectorielles/.

Hourcade, J.-C., D. Demailly, K. Neuhoff, M. Sato, M. Grubb, F. Matthes and V. Graichen (2008), "Differentiation and Dynamics of EU-ETS Industrial Competitiveness Impacts", final report, *Climate Strategies, Multinationality*.

Houser T., R. Bradley, B. Childs, J. Werksman and R. Heilmayr (2008), "Leveling the Carbon Playing Field – International Competition and US Climate Policy Design", Peterson Institute for International Economics, World Resources Institute. Washington, DC.

IEA (2003), "Emissions Trading and its Possible Impacts on Investment Decisions in the Power Sector", IEA Information Paper, OECD/International Energy Agency, Paris.

IEA (2005), *Act Locally, Trade Globally – Emissions Trading for Climate Policy*. OECD/IEA, Paris.

IEA (2007), *Mind the Gap – Quantifying Principal-Agent Problems in Energy Efficiency*. OECD/IEA, Paris.

IEA (2008a), *Energy Technology Perspectives 2008*, OECD/IEA, Paris.

IEA (2008b), "Energy Efficiency Policy Recommendations", prepared by the IEA for the G8 under the Gleneagles Plan of Action. OECD/IEA, Paris.

Krüger Enge, A., R. Holmen and M. Sandbakk (2007), "Investment Aid and Contract Bound Energy Savings: Experiences from Norway", Summer Study on Energy Efficiency in Industry – Improving Industrial Competitiveness: Adapting to Volatile Energy Markets, Globalization, and Environmental Constraints, American Council for an Energy-Efficient Economy, www.aceee.org.

Morgenstern Richard D. and William A. Pizer eds. (2007), "Reality Check – The Nature and Performance of Voluntary Environmental Programs in the United States, Europe and Japan", *Resources for the Future*, RFF Press, Washington, DC.

OECD (2003), "Environmental Policy in the Steel Industry: Using Economic Instruments", non-classified COM/ENV/EPOC/DAFFE/FCA(2002)68/FINAL, OECD, Paris, www.oecd.org.

OECD (2008), *Climate Change Mitigation: What Do We Do?*, OECD, Paris, www.oecd.org.

Öko-Institut, Fraunhofer Institute for Systems and Innovation Research, and German Institute for Economic Research (2008), "Impacts of the EU Emissions Trading Scheme on the Industrial Competitiveness in Germany", report on behalf of the Federal Environment Agency, UBA Climate Change 10/08. Dessau-Roßlau, September.

Ponsard, J.-P. and N. Walker (2008), "EU Emission Trading and the Cement Sector: A Spatial Competition Analysis", University College Dublin and Ecole Polytechnique, Paris, March.

Reinaud, J. (2008a), "Climate Policy and Carbon Leakage. Impacts of the European Emissions Trading Scheme on Aluminium", IEA Information Paper. OECD/IEA, Paris, www.iea.org.

Reinaud, J. (2008b) "Issues Behind Competitiveness and Carbon Leakage – Focus on Heavy Industry", IEA Information Paper. OECD/IEA, Paris.

Reinaud J. and C. Philibert (2007), *Emissions Trading: trends and prospects*, OECD/IEA Information paper, COM/ENV/EPOC/IEA/SLT(2007)9.

Schneider, L. (2008), "A Clean Development Mechanism (CDM) with Atmospheric Benefits for a Post-2012 Climate Regime", Discussion Paper, Öko-Institut e.V., Berlin, 25 September.

Sijm, J.P.M., S. J. Hers, W. Lise and B.J.H.W. Wetzelaer (2008), "The Impact of the EU ETS on Electricity Prices", Final report to DG Environment of the European Commission, ECN-E--08-007, Brussels, December.

Tanaka, K. (2009 forthcoming), "A Review of Energy Efficiency Policy in Industry", IEA Information Paper, OECD/IEA, Paris.

Trotignon R. A. Delbosc (2008), *Allowance Trading Patterns during the EU ETS Trial Period: What does the CITL Reveal? - Climate Report*, Issue No.13, Mission Climat, Caisse des Dépôts, Paris, www.caissedesdepots.fr/missionclimat/.

Ward M., C. Streck, H. Winkler, M. Jung, M. Hagemann, N. Höhne and R. O Sullivan (2008), "The Role of Sector No-Lose Targets in Scaling Up Finance for Climate Change Mitigation Activities in Developing Countries", *Climate Focus*, Ecofys, GTripleC report to DEFRA, United Kingdom, May.

Watson C., J. Newman, S. Upton and P. Hackmann (2005), "Can Transnational Sectoral Agreements Help Reduce GHG Emissions?" Round Table on Sustainable Development, OECD, Paris.

ANNEXES

International Energy Agency (IEA) (1997), *Indicators of Energy Use and Efficiency, Understanding the Link between Energy and Human Activity*, OECD/IEA, Paris.

IEA (2004), *Oil Crises and Climate Challenges. 30 Years of Energy Use on IEA Countries*, OECD/IEA, Paris, <http://www.iea.org/textbase/nppdf/free/2004/30years.pdf>.

IEA (2005), *Energy Statistics Manual*, OECD/IEA, Paris, http://www.iea.org/textbase/nppdf/free/2005/statistics_manual.pdf.

IEA (2007), *Tracking Industrial Energy Efficiency and CO₂ Emissions*, OECD/IEA, Paris, <http://www.iea.org/w/bookshop/add.aspx?id=298>.

IEA (2008a), *Energy Technology Perspectives 2008*, OECD/IEA, Paris.

IEA (2008b), *World Energy Outlook 2008*, OECD/IEA, Paris.

OECD (2008), *National Accounts of OECD Countries, Volume 1*, OECD, Paris.

UN (2008), *World Urbanization Prospects: The 2007 Revision*, United Nations Secretariat, Population Division of the Department of Economic and Social Affairs, New York.

UN (2009), *World Population Prospects: The 2008 Revision*, United Nations Secretariat, Population Division of the Department of Economic and Social Affairs, New York, <http://esa.un.org/unpp/>

The Online Bookshop



International Energy Agency

All IEA publications may be bought
online on the IEA website:

www.iea.org/books

You may also obtain PDFs of
all IEA books at 20% discount.

Books published before January 2008
- with the exception of the statistics publications -
can be downloaded in PDF, free of charge
from the IEA website.

IEA BOOKS

Tel: +33 (0)1 40 57 66 90
Fax: +33 (0)1 40 57 67 75
E-mail: books@iea.org

International Energy Agency
9, rue de la Fédération
75739 Paris Cedex 15, France

Special offer!

**Buy 3 IEA books and
get a FREE electronic version
of our forthcoming
IEA Scoreboard 2009!***

*offer expires October 15th 2009

IEA PUBLICATIONS, 9, rue de la Fédération, 75739 PARIS CEDEX 15
PRINTED IN FRANCE BY STEDI MEDIA, September 2009
(61 2009 22 1P1) ISBN : 978-92-64-06858-2
Cover design: IEA. Photo Credit: @ BASF