INTERNATIONAL ENERGY AGENCY

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RENEWABLE ENERGY: RD&D Priorities

Insights from IEA Technology Programmes

OECD

INTERNATIONAL ENERGY AGENCY

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Foreword

The key element towards the enhanced realisation of renewable energy technologies in the energy portfolio is accelerated technological advancement and subsequent cost reduction, combined with novel applications and deployment. This outcome can be significantly supported by a range of RD&D initiatives, if properly designed and implemented.

Renewable energies have great potential to contribute to improved energy security and reduced greenhouse gas emissions. But whilst hydropower and bio-resources have played an important role in the energy mix ever since the industrialisation of energy supply, some other renewable technologies have found it difficult to compete. However, recently selected applications of "new" renewable energies in favourable resource areas have become cost-competitive. Such market niches should be encouraged with deployment support. But costs must still come down substantially if more renewables are to be introduced into the mainstream.

At the International Conference for Renewable Energies in Bonn in June 2004, the IEA emphasised that the world needs a new generation of renewable technologies to reach the mainstream market for heat, fuels and electricity and that we need to use public funds as effectively as possible in achieving this. It called on IEA member countries to improve their strategy for market deployment of renewable energy technologies, to include externalities in policy considerations and – above all – to increase targeted renewables RD&D funding.

This publication, "Renewable Energy: RD&D Priorities, Insights from the IEA Technology Programmes", is intended to build on that call. It reviews the current status of the portfolio of renewable energy technologies and provides guidance on their mid- and long-term development. The study explores the options for the RD&D to achieve breakthroughs that will lead to large-scale markets and identifies what activities should take priority. It also looks at the benefits of increased RD&D funding in terms of technological advancement and cost improvement. It covers renewable energy technologies in the early research stage through to those that have reached a level of maturity.

The report is based on a substantial input from the IEA Implementing Agreements on renewable energy technologies and has received input from the members of the Renewable Energy Working Party and the IEA Secretariat. I hope it contributes to expanding the role of mature renewables and to moving second- and third-generation renewable energies a further step closer to the mainstream.

Claude Mandil
Executive Director

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Introduction

The development and deployment of renewable energy technologies are important components for the future of a balanced global energy economy. Renewables can make major contributions to the diversity and security of energy supply, to economic development, and to addressing local environmental pollution. In addition, considerable attention has been attracted to their potential to address global warming through zero or near zero net greenhouse gas emissions.

Climate change was recognised by the G8 at their Gleneagles Summit as a serious and long-term challenge that has the potential to affect every part of the globe. According to the IEA's World Energy Outlook (WEO) 2005, if we continue on present policies, global energy-related CO_2 emissions are set to grow by 52% between 2003-30, an increase of almost 13 billion tonnes over the 2003 level and a growth rate of 1.6% p.a. The Alternative Policy Scenario of the WEO shows how CO_2 emissions could be reduced by 16% in 2030 – if governments gave effect, through new policy measures, to their stated intention to do more. The share of renewables in the primary energy mix would then rise to 16%, compared with 14% in the Reference Scenario.

There is growing interest in distributed energy systems as an adjunct or partial replacement of traditional electricity and heating grids. Distributed energy systems directly address the growing need for energy security, economic prosperity and environmental protection.

The research, development and demonstration (RD&D) programmes of governments will play a vital role in enabling renewable technologies to deliver their potential. This publication recommends priorities for this vitally important effort, drawing extensively on studies and analysis carried out by the IEA's Working Party on Renewable Energy Technologies and the associated international technology programmes (Implementing Agreements). It also reviews the trends in government RD&D spending.

Current status of renewables

Renewable energy technologies currently supply 13.3% of the world's primary energy supply. Most of this is accounted for by well-established technologies such as hydropower, biomass, and geothermal. The contribution of these renewables is stable or, indeed, in the case of biomass in the developing world, declining. Second-generation renewable energy technologies – including wind, solar hot water, solar photovoltaics, and advanced bioenergy – are starting from a much lower base but are now growing rapidly. This is the result of RD&D investments, mainly by IEA member countries, that began in the 1970s and were originally stimulated by the oil supply crisis. A third generation – comprising concentrated solar power, ocean energy, advanced geothermal, advanced biomass and biorefinery technologies – is still under development but has great promise for the future.

The IEA's World Energy Outlook 2004 forecasts that the global share of renewables in electricity generation will increase from 18% today to 19% by 2030. The development of renewable-based power is expected to cost about USD 1.6 trillion, nearly 40% of power generation investment over the period.

First-generation renewable technologies are mostly confined to locations where a particular resource is available. Their future potential depends on exploiting the remaining resource (particularly in developing countries), on overcoming environmental challenges and winning public acceptance.

The second generation of renewables have been commercially deployed, usually with incentives in place intended to ensure further cost reductions through increased scale and market learning. Markets for these technologies are strong and growing, but only in a few countries. Some of the technologies are already fully competitive in favourable circumstances but for others, and for more general deployment, further cost reductions are needed. The challenge is to continue to reduce costs and broaden the market base to ensure continued rapid market growth worldwide. These technologies have very broadly followed the rule that each doubling of deployed capacity leads to a 20% reduction in investment cost. On this basis the potential for further cost reductions is considerable.

Third-generation renewables are not yet widely demonstrated or commercialised. They are on the horizon and may have estimated high potential comparable to other renewable energy technologies. However, they still depend on attracting sufficient attention and RD&D funding.

Government RD&D budgets

Historically, government energy RD&D budgets in IEA member countries increased sharply after the oil price shocks of the 1970s. By 1987, they had declined to about two-thirds of their peak level and thereafter they remained relatively stable at this lower level through to 2003. The share of renewable energy technologies in total energy RD&D spending remained relatively stable, averaging 7.6% for the whole period.

Within this total the shares of biomass, solar photovoltaic, and wind have increased while those of ocean, geothermal and concentrating solar power have declined – broadly reflecting the evolving consensus as to where the greatest potential lay. Of course, there are great variations in the balance of spending of individual countries, reflecting resource potential and national energy policies. The United States, Japan and Germany are the biggest total spenders on energy technology RD&D although, on spending per capita, Switzerland, Denmark and the Netherlands are the leaders.

Priorities for key technologies

Experience over the last 30 years shows that the move towards sustainable renewable energy options depends on resource availability, technical maturity and a policy environment that is conducive to both technology improvements and commercialisation. Because of the diverse nature of renewables, each country or region must promote technologies and options best suited to its own resources and needs.

Bioenergy in all its forms represents the largest current source of renewable energy and could play a major role in a low carbon energy economy of the future. It includes traditional low technology practices in rural economies, some of which will run down as modern energy becomes available, as well as advanced technologies, such as ethanol vehicle fuels, which already play a major role. In the short term, the key challenge is to make available relatively cheap feedstocks and to develop standards and norms for trading. In the medium term, there is a range of advanced conversion technologies with great potential, including bio-refineries capable of simultaneously producing a range of products, including energy, as well as further development of facilities producing ethanol from lignocellulosics. Key technologies for the longer term include those for the production of hydrogen from biomass and the development of sustainable ways to produce large amounts of feedstock worldwide. More effort is needed on the social and environmental acceptability of large-scale bioenergy across the complete chain, *i.e.*, from biofuel production to the delivery of services to the consumer.

Achieving greater energy supply from **hydropower** does not require technological breakthroughs, huge RD&D expenditures, or radical changes to the development of hydropower resources. Current requirements include continuous improvements in technology, increased public acceptance, and more efficient hydropower project approval processes supported by government policy. The technology is at a stage where implementation and development should be financed and supported jointly by the public and private sectors.

Geothermal power is, in some respects, a mature technology with a long history in many countries. However, there are several priority RD&D areas that offer the potential to accelerate its advancement worldwide. These would provide cost reduction, sustainable use, and the expansion of the technology for new applications. The benefits would include an extension of the use of geothermal, both for power generation and direct heat use, to cover much larger regions that are farther away from tectonic plate boundaries. More funding and manpower is needed for more rapid achievement of these priorities.

During the last five years, industry RD&D placed emphasis on developing larger and more effective **wind** energy systems, using knowledge developed from national and international generic RD&D programmes. Between 1981-98, production costs of wind turbines have been reduced by a factor of four, making wind energy cost competitive with other forms of electricity generation in favourable locations. Continued RD&D is essential to explore revolutionary new designs as well as for incremental improvements to provide the reductions in cost and uncertainty needed for widespread deployment. Research is needed to improve our understanding of aerodynamics and extreme wind situations, on aspects of grid integration, forecasting techniques, minimising environmental impacts, and on public attitudes to deployment.

In addition to space exploration and consumer products, **photovoltaics (PV)** are now in fully commercial use for illuminating signs, for water pumping, for lighting at remote locations, and for many other purposes. For mainstream power use, however, PV costs must come down substantially. While costs of PV are currently very high compared to other forms of generation, PV has great potential for future cost reductions. It is estimated that about half of the future cost reductions for PV will be the result of RD&D to improve materials, processes, conversion efficiency and design. Substantial cost reductions can also be gained through increasing manufacturing volume and streamlining installation procedures.

A comprehensive and ambitious applied RD&D programme is needed to develop competitive, advanced **solar heating and cooling (SHC)** systems. These systems would eventually be able to provide, cost effectively, 5% to 10% of the overall low-temperature heat demand of the IEA member countries. RD&D efforts need to focus on technical advances in material and components, storage, scaling up and increasing efficiency. They also need to include architecture, so that solar thermal collectors can gain the status of standard building components.

Solar radiation is the largest renewable source on Earth and **concentrating solar power (CSP)** is a serious candidate to provide a major share of the clean renewable energy that will be needed in the future. It can be sized for remote village applications as well as for grid-connected applications. However substantial cost reductions are needed before it can compete directly with conventional grid sources. There is considerable potential for cost reductions through increased scale; for this reason, incentive schemes should avoid restrictions on size. Better technology, including improvements in concentrator performance and cost, could also bring down the cost of CSP electricity dramatically. Improved storage systems could also contribute to cost reductions. New deployment efforts are also needed for CSP, which is not well served by many existing national renewable electricity incentive schemes. There may be potential for exporting CSP, for instance from well-endowed regions such as North Africa into Europe.

The oceans contain a huge amount of power capable of being exploited to generate useful energy. However, technologies to extract **ocean energy** are at an early stage compared to other sources of renewable energy, with a wide range of prototypes under consideration. Ocean energy technologies must solve two major problems concurrently: proving the energy conversion potential and overcoming a very high technical risk from the harsh environment of strong waves or currents. They also need to fulfil basic economic and environmental requirements including low cost, safety, reliability, simplicity, and low environmental impact. Every ocean energy concept has its own technical challenges that require RD&D work. However R&D on resource potential, energy production forecasting, simulation tools, test and measurement standards, and environmental impact, can address common barriers. Additional RD&D funding is needed to mitigate the substantial technical risk faced by device developers daring to harness the vast energies of the marine environment.

Conclusion

The purpose of this book is to assist governments in prioritising their RD&D efforts for renewable energy.

These RD&D activities have played a major role in the successful development and commercialisation of a range of new renewable energy technologies in recent years.

The Governing Board of the IEA, and the G8 leaders at their Gleneagles Summit, responded to the environmental, security, and economic challenges in the energy sector by calling for a "clean, clever, and competitive" energy future. Renewable energy technologies will need to play a major role in this future. This calls, amongst other things, for a redoubling of government RD&D efforts.

Successful RD&D programmes need to be well focused and of high quality. They need to be integrated with the efforts of industry towards commercialisation in the market, and they need to be co-ordinated with international programmes. In addition, they must reflect national energy resources, needs, and policies, and they form a coherent part of wider government strategies for the incentivisation and deployment of new energy technologies. They also need to have roots in basic science research.

These factors may be of greater importance, for achieving results, than the absolute level of spending. Nevertheless, the transformation that governments are now seeking in their energy economies will not be achieved without cost. The ability of energy markets to respond to the new challenges at prices that are acceptable to consumers will depend on the available technologies. We strongly recommend that governments consider restoring their energy RD&D budgets at least to the levels seen, following the first oil crisis, in the early 1980s.

This publication is largely the product of the IEA's network for international co-operation on renewable energy technologies (Implementing Agreements) under the leadership of the Working Party on Renewable Energy Technologies (REWP). Governments wishing to ensure that their energy RD&D efforts are well integrated into international programmes (whether they are members of the IEA or not) are strongly encouraged to consider participation in this network[1].

The book outlines the current status of each renewable energy source and the key technical challenges that each faces. Detailed RD&D priorities for each major technology are set out in Tables 1 to 8 at the end of the book. The publication also includes some analysis of RD&D budgets of IEA member countries and lists RD&D policies in those countries.

The challenge of global warming is so huge that many technologies will be needed, each applied in the geographical or other conditions to which it is best suited. It is appropriate, therefore, to continue RD&D efforts on a wide range of renewables on a global basis, although individual nations will wish to focus on those that are most relevant to them.

Industry can be expected to play a major role in the development of all technologies, whether or not yet commercially available. But it is important to recognise that previously mentioned second- and third-generation renewable technologies are still bound to depend – to a considerable extent – on government RD&D. In addition, even some first-generation technologies, such as biomass, may benefit from "next generation" developments based on advanced technologies that are not yet commercial.

There are some areas in which the current level of activity appears modest in relation to renewable energy potential. These include new geothermal technologies, solar heating and cooling, concentrating solar, and ocean energy. Perhaps they are less fashionable than some other areas, but there is no overwhelming reason why this should be so. We do not advocate "equal shares" for all technologies, however governments are encouraged to look carefully at whether greater effort in any of these areas is justified by national circumstances.

Issues of public acceptability, of grid connection and adaptation, and of managing intermittency, are common to a range of renewable energy technologies. They all need to be addressed in government RD&D programmes.

Finally, if renewable energy is seen as contributing to the solution to global warming, this can only be achieved if new renewable technologies are adopted by both developing and developed countries. Appropriate renewables can also contribute to economic and health development objectives. For these reasons, governments must consider including, in their renewable technology RD&D programmes, an element that specifically concerns the adaptation of renewable technologies to meet the needs of developing countries.

1. International Energy Agency Implementing Agreement (IMPAG) Web site (www.iea.org/ia/list.aspx).

Chapter 2
Introduction

Context

Energy security, climate and environmental concerns are strong drivers of national energy policies. This was underlined by the May 2005 IEA Ministerial meeting and the G8 Summit in Gleneagles in July 2005. The IEA projects an increase of almost 60% in world energy demand by 2030. Because coal will play an even more important role in meeting this demand than in the past, CO_2 emissions will increase slightly faster than energy consumption.

But this is not cast in stone. If IEA member countries were to adopt tougher environmental policies already under discussion, and accelerate technological progress in non-member countries, CO_2 emissions could be reduced by some 16% by 2030. Energy efficiency gains would be the largest contributors (58%) to this CO_2 emission mitigation. Renewable energy could contribute some 20% (IEA, 2005b). Reaching this goal would imply increased support for renewables to achieve a substantially higher level of investment, particularly in the power sector.

Global developments in 2004/05 indicate that the latter may become the more likely scenario, largely due to contributing factors such as uncertainties about sustainable oil supply, environmental concerns and – last but not least – the rapid technical and economic evolution of many renewable technologies. In fact, renewables are beginning to tip the confidence scales; many energy executives are boosting expectations of increased use of renewables and market shares are predicted to increase steadily over the next few decades. This growth – and the implied substitution of existing and new energy supplies by sustainable renewable options – will have positive impacts on local and regional economies and on the environment.

The IEA estimates a need for investment of USD 16 trillion for global energy supply infrastructures over the next three decades (IEA, 2003). The key to capturing increasingly significant market shares for renewable energy technologies is a multi-faceted strategy to concurrently achieve several goals. Accelerated technological advances and cost reduction among almost all renewable technologies are of primary importance, but these must be combined with novel applications and deployment in the context of distributed power generation, global production and trading of fuels (including hydrogen), and bulk transmission of renewables-generated electricity. The latter implies a need for new or improved approaches to integrate various emerging, intermittent renewable technologies (e.g., wind and PV) into electric grids.

The IEA Renewable Energy Working Party (REWP) and its related collaborative programmes, called Implementing Agreements (IA)[2], are committed to working together to define mid- to long-term RD&D priorities for renewable energy technologies, based on a targeted approach to achieve technological advancement and realise the subsequent cost reductions and increased market share[3].

2. *The renewable energy technology programmes considered here include: Bioenergy, Geothermal, Hydropower, Ocean Energy Systems, Photovoltaic Power Systems, Solar Heating and Cooling, Concentrating Solar Power and Chemical Energy Systems, and Wind Energy Systems.*
3. *The findings on RD&D necessities are mainly based on a questionnaire prepared for this book, which was circulated to the Renewable Energy Implementing Agreements.*

Status of renewable energy

The amount of renewable energy used in IEA member countries in the period 1970-2003 doubled in absolute terms from 141.5 Mtoe to 281.3 Mtoe. However, the share of renewable energy in total primary energy supply increased minimally – from 4.6% in 1970 to 5.5% in 2003. Most of this increase occurred between 1970-90, when renewables supply grew by 2.8% per year (from 1990-2003, some renewables, including hydropower and traditional bioenergy, grew more slowly). As a result, the share of electricity generated by renewable energy in IEA member countries actually declined from 24% in 1970 to 15% in 2003. The contribution of mature technologies (*e.g.*, hydro and geothermal) either remained constant or decreased over the period from 1990-2003. Nevertheless, hydropower remains the major source of renewable energy for electricity generation, accounting for almost 84% of the total contribution of renewables. Five IEA member countries derive more than 50% of their electricity production from renewables, primarily hydro: Austria (63%), Canada (59%), New Zealand (66%), Norway (99%) and Switzerland (55%).

The strong growth of emerging renewables over the last few years, particularly wind, solar electricity generation and modern bioenergy plants, is becoming statistically important. In 2003, renewables accounted for 2.3% of total IEA electricity generation. The contribution of these emerging options is becoming significant in some IEA member countries. In Denmark, for example, the contribution of wind grew from about 0.1% in 1970 to 18.1% in 2003. Biomass contributions also increased, but to a lesser degree. Countries that show significantly increased commercialisation of solar and wind energy include Denmark, Germany, Spain, the United States and Japan.

However, it remains true that use of these new renewables is concentrated in just a few IEA member countries. In 2003, 86% of IEA total installed wind power capacity was in four countries (Denmark, Germany, Spain and the United States) and about 84% of the installed solar photovoltaic capacity was in three countries (Germany, Japan and the United States). On the other hand, the European Union set an ambitious target to increase electricity generation from renewable energy sources to 21% by 2010 (EC, 2001), which would demand broader implementation of renewable energy support schemes.

Globally, renewable energy sources accounted for 13.3% of the world's total primary energy supply (IEA, 2005a) in 2003, mainly in three forms: traditional biomass for heating and cooking in rural areas, modern biomass combustion and hydropower. In an energy future based to a large extent on renewable energy, a wide range of new renewable technologies would need to contribute a major and continuously growing share to the world's energy portfolio. According to past work by the IEA, without major technology and policy intervention, renewables would increase by only 1.3% per year over the next 30 years – while global energy demand grew at a projected rate of 1.7% per year. It is therefore necessary to accelerate the rate of technology development in order to advance cost-effectiveness and market penetration of these sustainable energy options.

Lessons learned

The principle, broad lesson learned over the last 30 years is that the move towards sustainable renewable energy options depends on three inter-related elements: resource availability, technical maturity and a policy environment conducive to both technology improvements and commercialisation. Because of the diverse nature of renewable energy sources, it is important that each country or region promotes technologies and options that are well suited to its specific resource availability. Unlike the current energy system based on fossil fuels, the transition to renewable sources will need to be based on heterogeneity of technologies and applications.

Without question, technology improvements have been impressive over the last three decades and have resulted in significantly lower costs for delivered energy. In addition, there is clear understanding that environmental credits will play a role in deciding on new energy projects (for example, a market for greenhouse gas credits already exists). With the ratification of the Kyoto Protocol, there is a parallel effort to establish public policies that will help societies achieve the shift to sustainability.

Another very important lesson learned regarding RD&D in infant industries relates to the – often limited – involvement of the private sector. This also, particularly, holds for a number of renewable energies, since their deployment depends significantly on political framework conditions. As wind energy and PV mature, more and more RD&D activity can be seen. However, it is well understood that private sector companies are better suited to conducting applied research with internal resources because they then have a free hand in proceeding to commercialisation without encountering intellectual property right issues. Technology development and market experience are strongly linked and can function as a "virtuous cycle". The virtuous cycle takes into account the relationship between technology RD&D, improvements in manufacturing and learning from market experience – all of which can be enhanced by a supportive policy framework. A public policy environment that encourages more private sector involvement and, in particular, more stable market framework conditions, could enhance and accelerate renewable energy technology development and commercialisation.

Support for RD&D

Support for technology development by IEA member countries has been significant over the last few decades, but not always consistent. The recent IEA publication Renewable Energy Market and Policy Trends in IEA member countries highlights a number of conclusions related to renewables RD&D. The findings of the study can be summarised as follows (Figures 1 to 4):

- Total government energy RD&D budgets in IEA member countries increased sharply after the oil price shocks in the 1970s. Budgets declined to about two-thirds of their 1980 peak level by 1987 and remained relatively stable to 2003. However, as a percentage of total energy RD&D funding, funding for renewables has been fairly stable.
- Renewable energy technologies accounted for just 7.63% of total government energy RD&D funding from 1974-2003. Table 1 presents shares of different renewable technologies in energy RD&D in all IEA member countries.
- The United States, Japan and Germany accounted for 67.8% of IEA member country renewable energy RD&D funding from 1974-2003.
- RD&D spending on renewable energy by the private sector has grown gradually and selectively over the past 30 years.
- Renewable technologies, including solar photovoltaic, solar heating and cooling, and ocean energy, remain heavily dependent on public RD&D budgets.

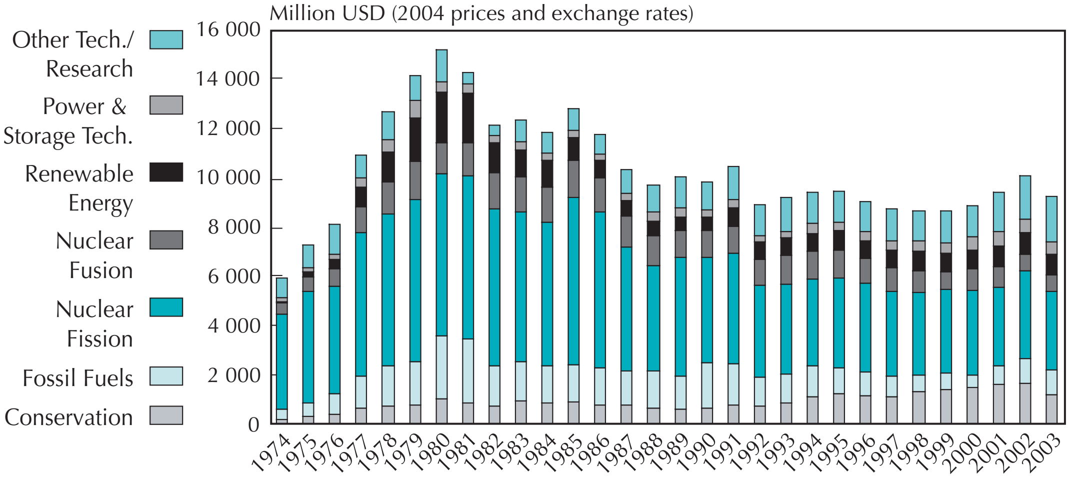
Table 1. **Shares of renewables in all energy RD&D spending by IEA member countries based on reported data**

	1974-2003	1974-1986	1987-2003
Renewables	7.63%	7.56%	7.72%
Solar Heating & Cooling	*0.92%*	*1.24%*	*0.55%*
Solar Photovoltaic	*2.08%*	*1.57%*	*2.68%*
Solar Thermal-electric	*0.02%*	*0.00%*	*0.05%*
Wind	*0.03%*	*0.00%*	*0.07%*
Ocean	*1.26%*	*1.60%*	*0.87%*
Biomass	*1.22%*	*0.86%*	*1.63%*
Geothermal	*0.24%*	*0.36%*	*0.09%*
Large Hydro (>10 MW)	*1.00%*	*0.87%*	*1.15%*
Small Hydro (<10 MW)	*0.83%*	*1.06%*	*0.56%*

Government RD&D expenditures towards energy technologies in IEA member countries were about USD 308 billion from 1974-2003 (2004 prices and exchange rates) (Figure 1). In 1974, total IEA government investment for energy RD&D was about USD 5.9 billion, of which only USD 69 million was for renewable energy. Budget outlays peaked in 1980 at USD 15 billion, but then declined to USD 10 billion in 1987. From 1987-2003, funding was relatively stable, averaging about USD 10 billion from 1987-1991 and USD 8.6 billion to USD 10.4 billion in the 1990s. Total energy RD&D expenditures in 2003 were USD 9.2 billion (61% of the 1980 value). Renewable energy RD&D expenditures in 2003, at USD 841 million, were about 41% of the 1980 value.

Even if renewable energy could keep pace with the overall increase in total primary energy consumption, current trends demonstrate that these stagnating RD&D efforts would not suffice to increase its market share in the fuel mix.

Figure 1. **Reported government energy RD&D budgets in IEA member countries, 1974-2003**

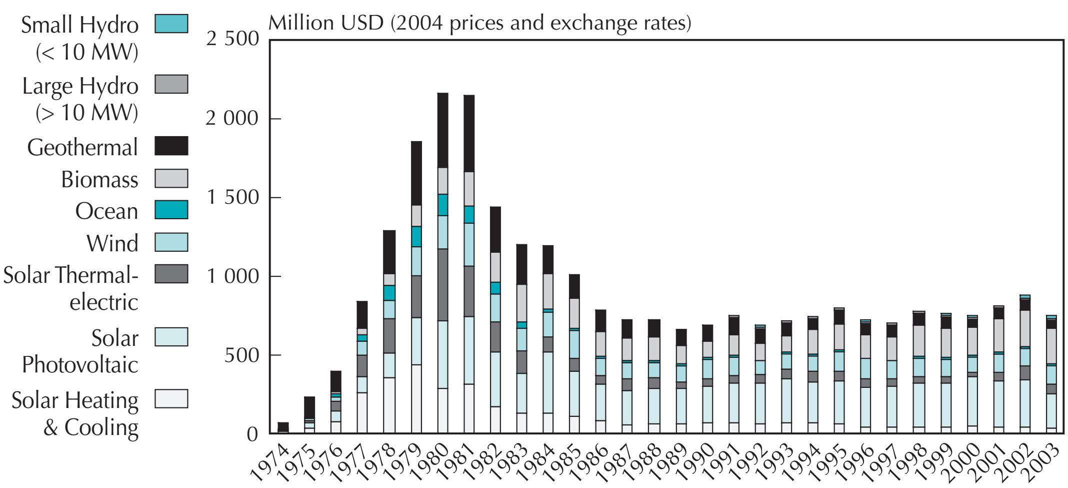


Aggregate IEA energy RD&D budget outlays for nuclear fission, fossil fuels and renewables decreased in the late 1980s and 1990s, while funding for nuclear fusion, conservation and power and storage technologies increased. RD&D investments in hydrogen and fuel cells (included in the "other technology" category) rose considerably in the 1990s and early 2000.

From 1974-2003, reported renewable energy RD&D budgets of IEA member countries totalled about USD 27.4 billion, some 7.6% of total energy RD&D funding. Expenditures for renewables RD&D grew rapidly in the late 1970s and peaked in 1980 at more than USD 2.1 billion. Expenditures halved in the early 1980s, but have been relatively stable since in the range of USD 666 million to USD 1.09 billion. Annual expenditures on renewables RD&D for all IEA member countries averaged about USD 752 million from 1990-2003 (Figure 2), or 8.2% of total government energy RD&D budgets (Figure 1).

Germany, Japan and the United States accounted for about 62% of total renewables RD&D funding in the period 1990-2003. It is in these countries that wind and PV developed most quickly. Wind energy technology in Denmark benefited from earlier efforts and therefore reached a rather mature stage in advance of the others. Italy, the Netherlands and Switzerland accounted for an additional 17% of total renewables RD&D funding for the same period. These six countries combined invested, on average, USD 609.3 million per year for renewable energy RD&D. Between 1990-2003, the United States had the highest average renewables RD&D budget of USD 231.9 million per year; Japan's average annual budget was USD 129.6 million and Germany's was USD 110.8 million.

Figure 2. **Reported government renewable energy RD&D budgets for IEA member countries, 1974-2003**

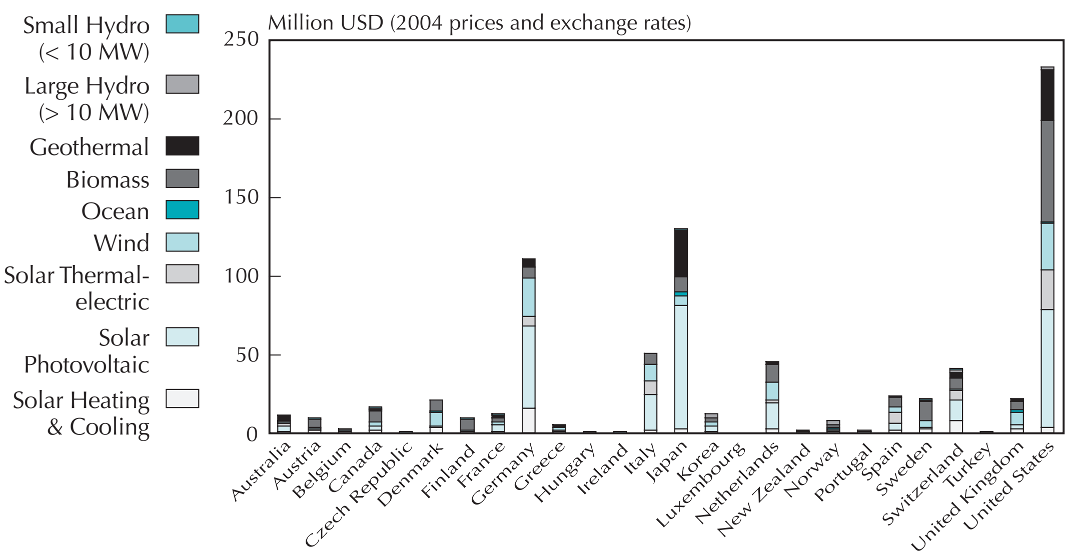


Renewable energy RD&D funding priorities typically reflect resource endowments. For example, New Zealand and Turkey have major geothermal resources; not surprisingly, 64% of RD&D funding in New Zealand and 44% in Turkey was for geothermal in 1990-2003. Norway allocated 37% of its renewables RD&D to large hydropower. On average, biomass accounts for 45% to 72% of the renewables RD&D budgets in Austria, Canada, Finland, Hungary and Sweden. About 44% of renewables RD&D in Denmark and 36% in the United Kingdom went to wind energy; both countries have significant wind energy potential. Natural resource endowments do not, however, always dictate renewable energy RD&D priorities.

Potential industrial opportunities often play a role in resource allocation. Germany has limited solar resources, but its budget for solar PV represented more than 47% of its renewable energy RD&D budget from 1990-2003.

RD&D budget priorities in the six IEA member countries with the largest public sector outlays for renewable energy from 1990-2003 reveal interesting trends (Figure 3). Germany spent 47.2% of its renewables RD&D budget on PV and 22% on wind technologies. Italy spent 43.1% on PV and 20% on wind. Japan dedicated 60.5% to PV and 23% to geothermal. In the Netherlands, the budget was divided so that 36.8% went to PV, 25.4% to biomass and 25% to wind. Switzerland spent 32.1% on PV and 19.5% on solar heating and cooling. The United States spent 29.9% on PV, 27.9% on biomass and 13.7% on geothermal. Such differentiation amongst technologies is evident in other countries as well.

Figure 3. **Average reported annual renewable RD&D budgets in IEA member countries, 1990-2003**



Examining average RD&D budgets on renewables of IEA member countries on a per capita basis for the years 1990-2003 offers another perspective (Figure 4). Switzerland spent more than USD 5.7 per capita per year in this period; Denmark spent more than USD 3.9 per capita. The Netherlands, Sweden, Norway, Belgium, Finland, Germany, Austria and Japan each contributed more than USD 1 per capita on RD&D.

Charting the shares of renewable energy technology RD&D funded through public resources shows distinct changes in technology priorities over time. In 1974, geothermal, solar heating and cooling, and solar thermal electric accounted for 84% of renewable energy RD&D (Figure 5). However, the trend has since reversed. In 2003, the predominant technologies were photovoltaics, biomass and wind, accounting for 76.3% of renewable energy RD&D; only 19.3% went into the former lead technologies.

Despite the drop of total RD&D expenditures on solar PV, from some USD 431 million in 1980 to USD 215 million in 1987, the relative importance of solar PV in the renewable

Figure 4. **Average reported annual renewable RD&D budgets in IEA member countries, 1990-2003 on a per capita basis**

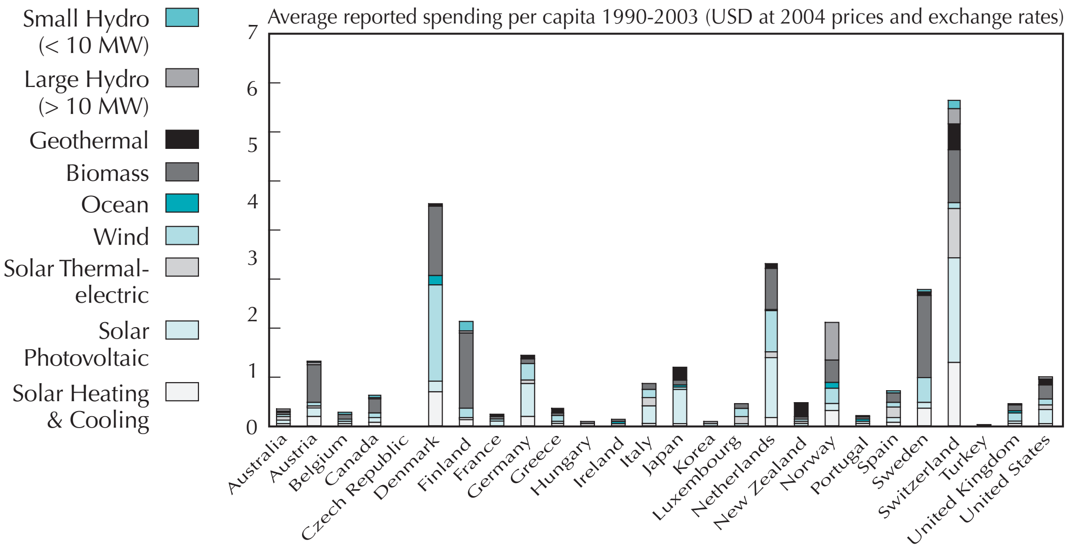
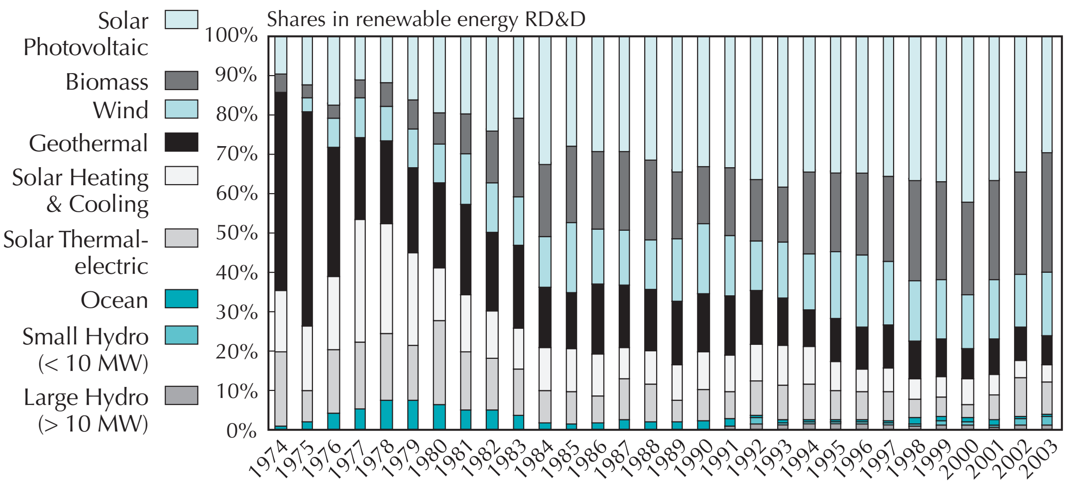


Figure 5. **Shares of renewable energy technologies in public renewable energy RD&D spending in IEA member countries, 1974-2003**



energy RD&D portfolio increased steadily. While the share of solar PV was 9.6% in 1974, it rose to 29.4% of the total reported renewable energy RD&D funding for 2003, with a funding peak of 42.6% of the budget, or some USD 316 million, in 2000.

Similar trends are visible in RD&D expenditures for biomass and wind technologies. The actual budget for biomass RD&D shrank from some USD 239 million in 1983 to only about USD 100.6 million in 1993; however, the relative importance increased steadily from 5% to 30.1% in the period from 1974-2003. Wind power received only 0.4% of the total budget in 1974, but 16.1% in 2003. The relative attention paid to wind stabilised in the 1980s and 1990s, with shares varying between 12.9% (1981 value, when the total budget spent on wind power peaked with some USD 277.9 million) and 18.1% (1996 value).

Geothermal experienced a very significant drop in RD&D attention: its share in the total renewable RD&D budget decreased sharply from 49.7% in 1974 to only 7.2% in 2003. Almost the entire budget came from the United States and Japan, which together made up for 78%, on average, of the geothermal RD&D budget throughout the period.

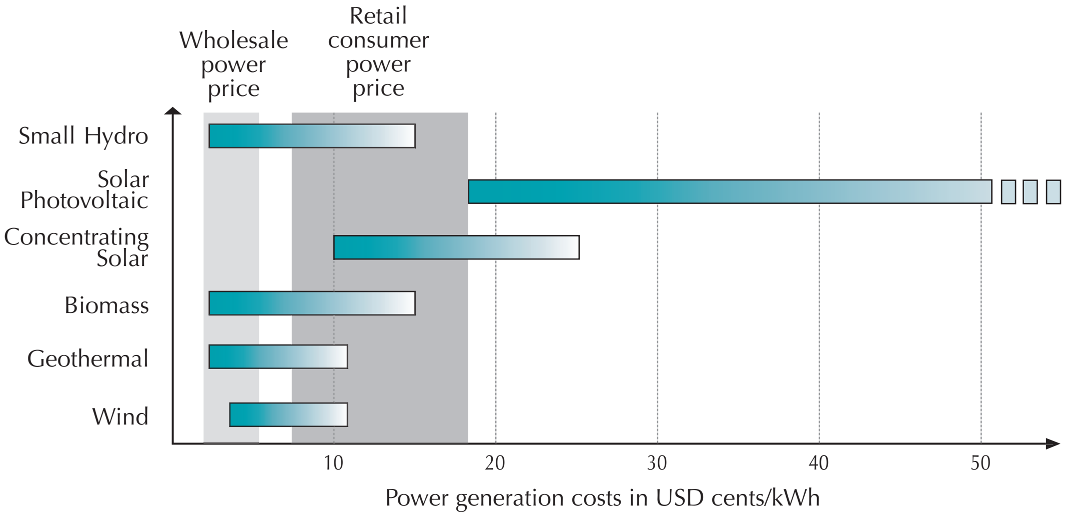
Solar thermal electric technologies faced similar trends. While up to 21.2% (1980 value) of the renewable budget was attributed to solar thermal in the late 1970s and early 1980s, the trend changed because of lessons learned on the potential RD&D payoff in this area. Resource allocations amongst technologies subsequently changed, with the result that only about 3.3% of the total funding went to this technology in 2000. It then increased again to 8.2% in 2003.

Impact of past market and policy trends on renewable energy

The principle constraint in advancing renewable energy over the last few decades has been cost-effectiveness. With the exception of large hydropower, combustible biomass (for heat) and larger geothermal projects (>30 MWe), the average costs of renewable energy are generally not competitive with wholesale electricity and fossil fuel prices (Figure 6). On the other hand, several renewable energy options for specific, small-scale applications can compete in the marketplace, including hot water from solar collectors and electricity from small hydro and other technologies.

The biggest challenge facing renewable energy technologies is to advance the state of the art to the point where more renewable options can generate energy at costs that are competitive with conventional sources. With worldwide adoption of stricter environmental standards and guidelines for greenhouse gas emissions, it is becoming clear that renewable energy systems will be credited for their inherent advantage in lowering emissions. These environmental credits will contribute towards making the delivered costs more attractive. In fact, they are already the driving force in policy initiatives in many IEA member countries. Nevertheless, achieving substantial technology breakthroughs to improve cost-competitiveness remains a priority.

Figure 6. **Cost-competitiveness of selected renewable power technologies**



Source: Renewables for Power Generation, Status and Prospects, OECD/IEA 2003.

In many IEA member countries, past policy initiatives to support renewable energy concentrated on research and innovation, market deployment and market-based energy. Although the purpose of the current initiative is to re-focus the RD&D component of the above, it is imperative to ensure that market-oriented policies complement technology initiatives. Based on experience to date, the following observations can be made regarding deployment:

- Significant market growth in renewable technologies results from a combination of policies that address specific barriers and/or complement existing policies. For example, in Japan, PV technology was supported by extensive RD&D investments to increase the competitiveness of the technology, through demonstration projects (to increase public awareness and acceptance), through financial incentives (to reduce the purchase price of PV systems) and by requiring utilities to accept, through net metering, excess power generated by PV systems at the retail price of electricity. In Spain, wind technology is supported by feed-in tariffs, low-interest loans, capital grants, and local support for manufacturing of turbines.
- Longevity and predictability of policy support are important to overall market success. In most cases, feed-in tariffs for renewable energy sources have an eight- to twenty-year time frame. The long-term support offered to biomass district heating plants in Austria provides an example. Conversely a 'stop–and-go' policy environment does not provide a sound basis to encourage the much-needed private sector involvement.
- With the trend towards market liberalisation, early support policies for emerging renewable energy technologies must be tailored carefully to insure against the impact of a significant drop in overall energy prices.

Maturity of renewable energy technologies

Conceptually, one can define three generations of renewables technologies, reaching back more than 100 years.

- First-generation technologies emerged from the industrial revolution at the end of the 19th century and include hydropower, biomass combustion, and geothermal power and heat – some of which are still in widespread use.
- Second-generation technologies include solar heating and cooling, wind power, modern forms of bioenergy, and solar photovoltaics. These are now entering markets as a result of RD&D investments by IEA member countries since the 1980s. The initial investment was prompted by the oil price crises of that period but the enduring appeal of renewables is due, at least in part, to environmental benefits. Many of the technologies reflect revolutionary advancements in materials.
- Third-generation technologies are still under development and include concentrating solar power, ocean energy, enhanced geothermal systems, and integrated bioenergy systems.

First-generation technologies

Hydropower

Hydropower is an extremely flexible technology from the perspective of power grid operation. The technology's fast response time enables hydropower to meet sudden fluctuations in demand or to help compensate for the loss of other power supply options. Hydro reservoirs also provide built-in energy storage, which assists in the optimisation of electricity production across the entire power grid. Large hydropower provides one of the lowest cost options in today's energy market, primarily because most plants were built many years ago and their facility costs have been fully amortised.

Capital costs for new large plants in IEA member countries are about USD 2 400/MW, with generating costs in the range of USD 0.03/kWh to USD 0.04/kWh. The technical potential of small hydropower capacity worldwide is estimated at 150 GW to 200 GW. Small hydropower costs are in the range of USD 0.02/kWh to USD 0.06/kWh; the lowest costs occur in good resource areas. Once the high up-front capital costs are written off, plants can provide power at even lower cost levels, as such systems commonly operate without major replacement costs for 50 years or more. At present, only 5% of the global hydropower potential has been exploited through small-scale sites. The principal barriers to exploiting more fully small hydro capacity worldwide, are access to transmission systems and environmental and social concerns.

Biomass combustion

Biomass combustion for heat and power is a fully mature technology. It offers both an economic fuel option and a ready disposal mechanism of municipal, agricultural and industrial organic wastes. However, the industry has remained relatively stagnant over the last decade, even though demand for biomass (mostly wood) continues to grow in many developing countries. One of the problems of biomass is that material directly combusted in cook stoves produces pollutants, leading to severe health and environmental consequences; although improved cook stove programmes are alleviating some of these effects. A second issue is that burning biomass emits CO_2, even though biomass combustion is generally considered to be "carbon-neutral" because carbon is absorbed by plant material during its growth, thus creating a carbon cycle. First-generation biomass technologies can be economically competitive, but may still require deployment supports to overcome public acceptance and small-scale issues.

Geothermal power and heat

Geothermal power plants can operate 24 hours per day, providing base-load capacity. In fact, world potential capacity for geothermal power generation is estimated at 85 GW over the next 30 years. The costs of geothermal energy have dropped substantially from the systems built in the 1970s. Generation costs at current plants in the United States are as low as USD 0.015/kWh to USD 0.025/kWh. New construction can deliver power at USD 0.05/kWh to USD 0.08/kWh, depending on the quality of the resource.

However, geothermal power is accessible only in limited areas of the world, the largest being the United States, Central America, Indonesia, East Africa and the Philippines. Challenges to expanding geothermal energy include very long project development times, and the risk and cost of exploratory drilling. Geothermal heat generation can be competitive in many countries producing geothermal electricity, or in other regions where the resource is of lower temperature.

Second-generation technologies

Solar heating and cooling

Solar thermal collectors are already widely used in certain countries, primarily for hot water production. Almost 70 GW of thermal capacity was installed in 2001. Various technologies are becoming more widely used, such as unglazed, glazed and evacuated tube water collectors, which have market shares of 30%, 50% and 20%, respectively. In principle, larger systems can be used for residential space heating and – in combination with absorption heat pumps – for cooling. However significant cost reductions are needed before the latter application will become cost-effective.

Wind energy

In 1990, wind power capacity in IEA member countries was 2 395 MW; by 2002 it had expanded to 28 054 MW, a 22.8% annual average growth rate. While a number of IEA member countries have significant potential based on wind resource assessments, in 2001 about 86% of the installed capacity was in only four countries: Germany, the United States, Spain and Denmark.

Wind technology has become very reliable, operating with availabilities of more than 98% and having a design life of 20 years or more. Moreover, as the costs of wind turbines have steadily declined, technical reliability has increased. The factors that currently limit wind energy's market penetration include intermittency, public acceptance and grid reliability. However, recent developments in electricity market reform, which promote better grid integration and improved management of natural cycles of renewables, diminish the technological barriers that have constrained market penetration.

In the area of wind energy, continued RD&D is essential to provide the necessary reductions in cost and uncertainty to realise the anticipated level of deployment. Other RD&D priorities include increasing the value of forecasting power performance, reducing uncertainties related to engineering integrity, improvement and validation of standards, reducing the cost of storage techniques, enabling large-scale use and minimising environmental impacts. Further expansion of wind power will promote significant reductions of greenhouse gases. With further deployment support, wind power may become generally competitive with conventional technologies by 2015-20; off-shore wind will likely become competitive to a degree after that.

Solar photovoltaics

The photovoltaic (PV) market has grown extensively since 1992. RD&D efforts, together with market deployment policies, have effectively produced impressive cost reductions: every doubling of the volume produced prompted a cost decrease of about 20%. But market deployment is concentrated: Japan, Germany and the United States accounted for 86% of total installed capacity of about 1 143 MW in 2002. PV still requires substantial RD&D investments, as well as deployment supports, to gain market learning. In the near term, RD&D efforts will focus on improving the balance-of-system components for both grid-connected and stand-alone applications. Even with these supports, PV is not expected to be generally competitive until after 2020 – although it will continue to compete well in a growing range of market niches in which the cost of deployment supports is moderate.

Modern forms of bioenergy

More modern forms of bioenergy include biomass-based power and heat generation, co-firing, biofuels for transport and short rotation crops for energy feedstocks. These are more advanced and each has its own unique benefits. Biomass is attractive for use either as a stand-alone fuel or in fuel blends, such as co-firing wood with coal, or mixing ethanol or biodiesel with conventional petroleum-based fuels. Anaerobic digestion has strong potential in countries with ample resources. Electricity generated from biomass is based on steam turbine technology. Many regions of the world still have large untapped supplies of biomass residues, which could be converted into competitively priced electricity using steam turbine power plants.

Co-firing is a low-cost and low-risk way of adding biomass capacity. Co-firing systems that use low-cost biomass supply can have payback periods as short as two years. In addition, biomass can substitute for up to 15% of the total energy input in a power plant, often with few modifications other than the burner and feed intake systems. Co-firing is of particular interest in developing countries, because it improves the economic and ecological quality of many older, coal-fired power plants.

Biofuels from agricultural biomass production is another well-developed conversion technology. Biomass grown as dedicated energy crops can provide new economic opportunities for farmers and forest owners. The primary barriers to increased use of biomass on a larger scale are the cost of systems required for dedicated feedstock production, harvesting, and transportation, as well as the fuel conversion technologies. With further RD&D and deployment support in 2020-30, these technologies could achieve commercialisation.

Third-generation technologies

Concentrating solar power

Three types of concentrating solar power (CSP) technologies support electricity production based on thermodynamic processes: parabolic troughs, parabolic dishes and solar central receivers. The cost of power generated with these up-to-date technologies is between USD 0.10/kWh and USD 0.15/kWh. Current RD&D efforts concentrate on parabolic trough technology. To achieve progress, much larger resources are needed than what is currently offered in public programmes. Optimal conditions for CSP are an arid or semi-arid climate, limiting its usefulness to southern Europe, north and southern Africa, the Middle East, western India, Western Australia, the Andean Plateau, north-eastern Brazil, northern Mexico and the US Southwest.

Ocean energy

Over the last 20 years, ocean energy technology received relatively little RD&D funding. However, there is renewed interest in the technology and several concepts now envisage full-scale demonstration prototypes around the British coast. But ocean energy technologies must still solve two major problems concurrently: proving the energy conversion potential and overcoming a very high technical risk from a harsh environment. Other non-technical barriers include resource assessment, energy production forecasting and design tools, test and measurement standards, environmental impacts, arrays of farms of ocean energy systems and dual-purpose plants that combine energy and other structures.

Enhanced geothermal systems

Enhanced geothermal systems, known as hot dry rock, utilise new techniques to exploit resources that would have been uneconomical in the past. These systems are still in the research phase, and require additional RD&D for new approaches and to improve conventional approaches, as well as to develop smaller modular units that will allow economies of scale on the manufacturing level. Several technical issues need further government-funded research and close collaboration with industry in order to make exploitation of geothermal resources more economically attractive for investors. These are mainly related to exploration of reservoirs, drilling and power generation technology, particularly for the exploitation of low-temperature cycles.

Integrated bioenergy systems

The biomass integrated gasifier/gas turbine (BIG/GT) is not yet commercially employed, but substantial demonstration and commercialisation efforts are ongoing worldwide, and global interest is likely to lead to market deployment within a few years. Overall economics of biomass-based power generation should improve considerably with BIG/GT systems as opposed to steam turbine systems.

The biorefinery concept for biomass feedstocks also has potential to meet a large proportion of future energy demand, particularly once dedicated crops tailored to biorefinery requirements are developed. Current RD&D efforts focus on reducing the costs of dedicated plantations, mitigating potential environmental impacts of bio-refineries and creating an integrated bioenergy industry that links bioenergy resources with the production of a variety of other energy and material products.

Conclusions

First-generation technologies are most competitive in locations where the resource endowment is strong. Their future use depends on exploiting the remaining resource potential, particularly in developing countries, and on overcoming challenges related to the environment and social acceptance.

Support for both RD&D and market deployment underpins the ongoing development of a second generation of renewable energy technologies. Some of these technologies are commercially available, albeit often with incentives to ensure cost reductions as a result of "market learning." In principal, market learning provides complementary improvements, as manufacturers refine products and manufacturing processes. Renewable energy technologies exhibit similarities in learning effects or learning ratio (*i.e.*, the per cent decrease in cost for each doubling of installed capacity) with other technologies. Markets for these technologies are strong and growing, but only in a few countries. The challenge is to broaden the market base to ensure continued rapid growth worldwide. Strategic deployment in one country not only reduces technology costs for users there, but also for those in other countries, contributing to overall costs reductions and performance improvement.

Third-generation technologies are not yet widely demonstrated or commercialised. They are on the horizon and may have potential comparable to other renewable energy technologies, but still depend on attracting sufficient attention and RD&D funding. These newest technologies include advanced biomass gasification, bio-refinery technologies, concentrating solar power, hot dry rock geothermal power, and ocean energy. Advances in nanotechnology also play a major role.

As first- and second-generation technologies have entered the markets, third-generation technologies, such as solar concentrating power generation, advanced geothermal, ocean energy and advanced biomass heavily depend on long term RD&D commitments, where the public sector has a role to play.

Some of the second-generation renewables, such as wind, have high potential and have already realised relatively low production costs. However, issues of intermittency present a challenge to their grid integration. In such cases, first-generation technologies, such as hydropower, can serve to level out intermittent sources. Together with grid improvements and more advanced load and generation management, it is reasonable to assume that renewables will form part of a much more advanced electricity supply structure in the future.

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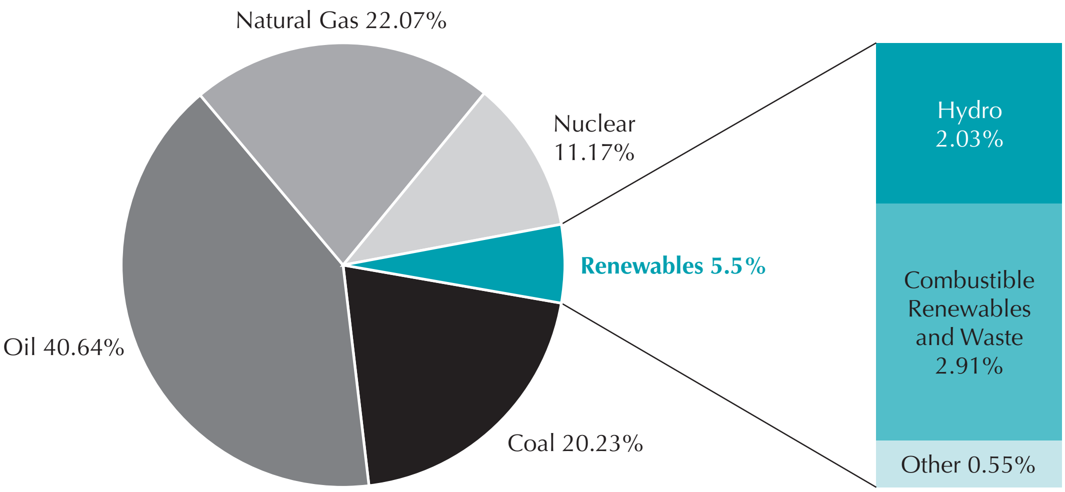
Chapter 3
Technologies

Across IEA member countries, the range of energy sources used for total primary energy supply is becoming more diverse and renewable sources play an increasingly important role. In 2003, biomass and waste contributed 53% of all renewable energy supply (including large-scale hydro) and 3% of the total primary energy supply, making them the most important renewable energy sources (Figure 1).

Figure 1. **Fuel shares of IEA total primary energy supply, 2003**



Source: IEA, 2005.

In 2003, renewable energy sources supplied 281.3 Mtoe, a figure corresponding to 5.5% of the 5,119.21 Mtoe of IEA total primary energy supply. The renewable energy sources portion included mainly: biomass and waste (2.91%) and hydropower (2.03%). "Other" renewable energy sources referenced in Figure 1 and their contributions to total primary energy supply in 2003 include: geothermal power (0.392%), solar (0.06%), wind power (0.098%), and tide (0.001%).

Despite recent impressive growth for some renewable energy sources (mainly wind power), biomass and waste remain the most important contributors. In fact, their relative contributions to total primary energy supply are not expected to change significantly in the foreseeable future.

The following sections highlight the main issues related to RD&D of eight renewable energy technologies: bioenergy, geothermal power, hydropower, ocean power, solar photovoltaic power, solar power for heating and cooling, concentrating solar power, and wind power. They also provide an in-depth review of the state-of-the-art, current trends and recommendations for future development in each area.

Chapter 3 • Technologies

Bioenergy

Highlights

- The term 'biomass' covers a wide range of products, by-products and waste streams derived from forestry and agriculture, as well as from municipal and industrial waste streams. Biofuels (solid, liquid or gaseous) are the only renewable energy sources that have the potential to directly replace fossil fuels.
- Bioenergy is the largest contributor to renewable energy supply. In 2003, total bioenergy supply was 149 Mtoe, accounting for 2.9% of total primary energy supply in IEA member countries and a full 53% of the IEA renewable energy supply.
- Over the past decade, bioenergy technologies achieved significant cost reductions in several important areas including: dedicated large- and small-scale combustion; co-firing with coal; combustion of municipal solid waste; biogas generation via anaerobic digestion; and in district and individual household heating. In certain geographical areas, cost reductions were also realised in liquid biofuels such as bioethanol and biodiesel.
- Biomass fuels and residues can be converted to energy via thermal, biological, mechanical or physical processes. Thermal processing currently attracts the most interest, while gasification receives the most RD&D support. Pyrolysis is still at a relatively early stage of development; combustion, biological conversion processes and mechanical processing are well established.
- One of the most significant barriers to accelerated penetration of all biomass conversion technologies is that of adequate resource supply. Feedstock costs vary widely depending on the type of biomass and the transport distance. The most economical approach is to use bioenergy on-site, *i.e.*, where biomass residue is generated.
- RD&D priorities for bioenergy include: making available relatively cheap feedstocks and further increasing conversion (short-term); capitalising on opportunities offered by bio-refineries (medium-term); and producing hydrogen from biomass and cultivating, in sustainable ways, large amounts of biomass worldwide (long-term).
- Efforts must also be undertaken to strengthen social and environmental integration of bioenergy along the complete chain, *i.e.*, from biomass production to provision of energy services to the consumer.
- Three factors underpin further growth: improved performance, reduced costs, and growing recognition of their environmental, economic and societal values.

Introduction

Bioenergy has several unique characteristics that distinguish it from the other renewable energy sources (RES) that, individually, can be considered as either advantages or disadvantages. But on the whole, biomass offers good potential as an important RES of the future.

Biomass is defined as any plant matter used directly as fuel or converted into other forms before combustion. Included are wood, vegetal waste (including wood waste and crops used for energy production), animal materials/wastes, sulphite lyes, also known as "black liquor" (an alkaline-spent liquor from the digesters in sulphate production or soda pulp during the manufacture of paper where the energy content derives from the lignin removed from the wood pulp) and other solid biomass.

Biomass in the form of biofuels (solid, liquid or gaseous) is the only RES that can directly replace fossil fuels (solid, liquid and gaseous), either fully or in blends of various percentages. In the latter case, the replacement can often be implemented without requiring any equipment modifications.

In the case of co-utilisation with fossil fuels and subsequent carbon sequestration, bioenergy offers the only option to actually withdraw carbon from the environment.

Biomass also has the advantage, in comparison to other RES, that it can be stored over long periods of time. On the other hand, in comparison to fossil fuels, it has the disadvantage of a relatively low energy density (energy content per unit volume or unit mass), leading to high transport cost.

Biomass is the only renewable energy source that is not freely available; producing it requires a long chain of activities such as planting, growing, harvesting, pre-treatment (storage and drying), upgrading to a fuel, and finally mechanical, thermochemical or biological conversion to an energy carrier (power, heat or biofuels for transport). Thus, biofuels (with the exception of untreated municipal waste) always have associated costs that must be carried by the end-user.

In contrast to the local nature of all other renewable energy sources, biomass and biofuels are traded on local, national and international markets. Although international trade in biomass fuels (solid or liquid) is still in its infancy, it is expected to play a major role in the development of a limited bio-economy.

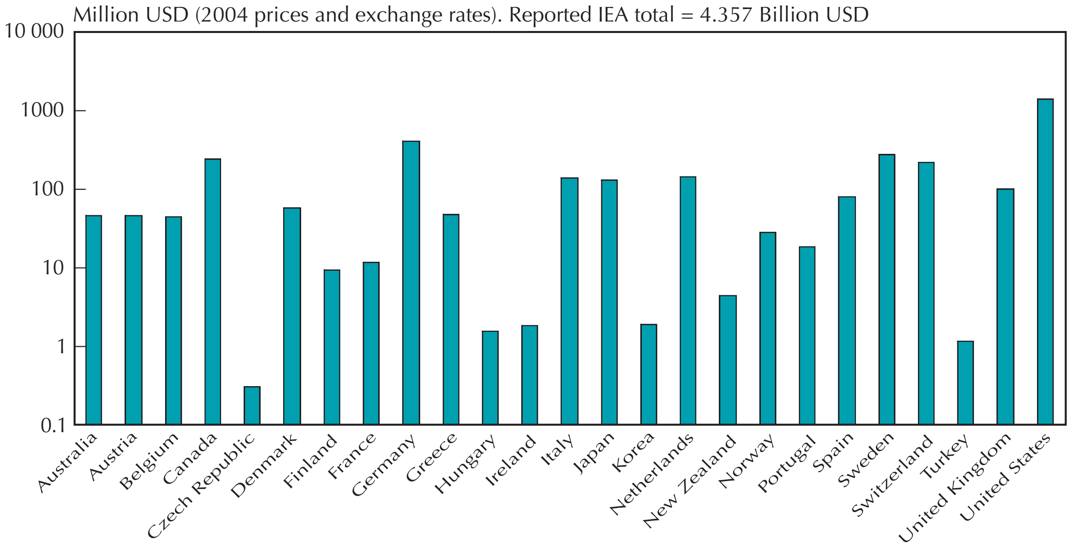
By its very nature, bioenergy cuts across several policy areas in addition to energy policy including: agricultural and forestry, environment, employment, trade and market, tax policies, regional development, et al.

Due to the limited availability of land, one can foresee a future in which biomass for energy must be balanced against the need for food, materials, biochemicals and carbon sinks. However, this point in time is beyond 2020 and, if international trade in biomass fuels becomes effective, this date could well be postponed beyond 2050.

Environmental concerns associated with biomass production (for food, products or fuels) still need to be addressed. This must be done with an overall systems approach—rather than in an isolationist manner—allowing for comparisons to other alternatives.

From 1974-2003, IEA member countries reported approximately USD 4.4 billion (2004 prices and exchange rates) of RD&D spending on bioenergy (Figure 1). The United States accounted for about 37% of governmental RD&D funding; other member countries—including Sweden, Canada, Japan, the Netherlands, Italy, Spain, Switzerland, Austria, United Kingdom, Denmark and Germany—also reported three-digit figures of USD million, amounting to approximately 44% of the total IEA member countries' RD&D budgets for bioenergy.

Figure 1. **Reported government bioenergy RD&D budgets in IEA member countries, 1974-2003**



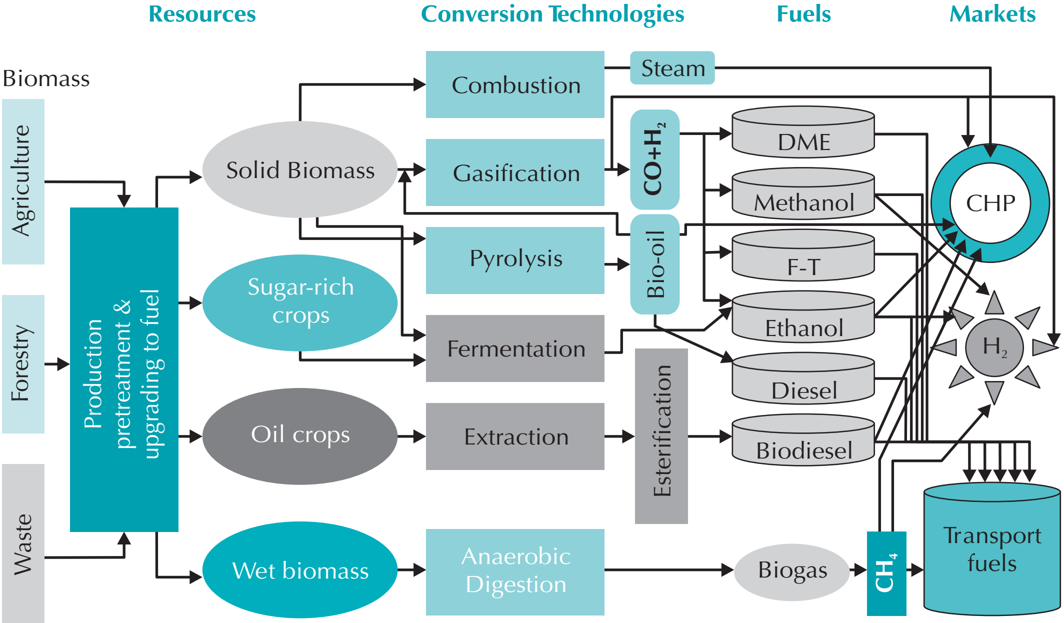
Current technology status

Generating bioenergy involves complex conversion processes that can follow many possible pathways from raw material to finished product, as well as a range of competing applications for various biofuels (Figure 2). A matrix of competing pathways further demonstrates the complexity of the sector (Figure 3). However, these diagrams also demonstrate the innovation capacity of the bioenergy research community and related industry: they have made it possible to use almost any type of biomass for multiple conversion technologies (after pre-treatment and upgrading to a fuel quality).

Over the past decade, bioenergy technologies achieved significant cost reductions in several important areas including: dedicated large- and small-scale combustion; co-firing with coal, combustion of municipal solid waste; biogas generation via anaerobic digestion; and in district and individual household heating. In certain geographical areas, cost reductions were also realised in liquid biofuels such as bioethanol and biodiesel.

However, operating costs still differ significantly from country to country due to wide variations in the cost of the biomass fuel delivered to the gate of the conversion plant. Such variations are due to two factors: a) the actual cost of the raw biomass; and b) local policies related to agriculture and forestry including: taxes; labour costs for the cultivation, production and harvesting of the resource; and labour costs for the operation of the conversion facilities. This variability makes it

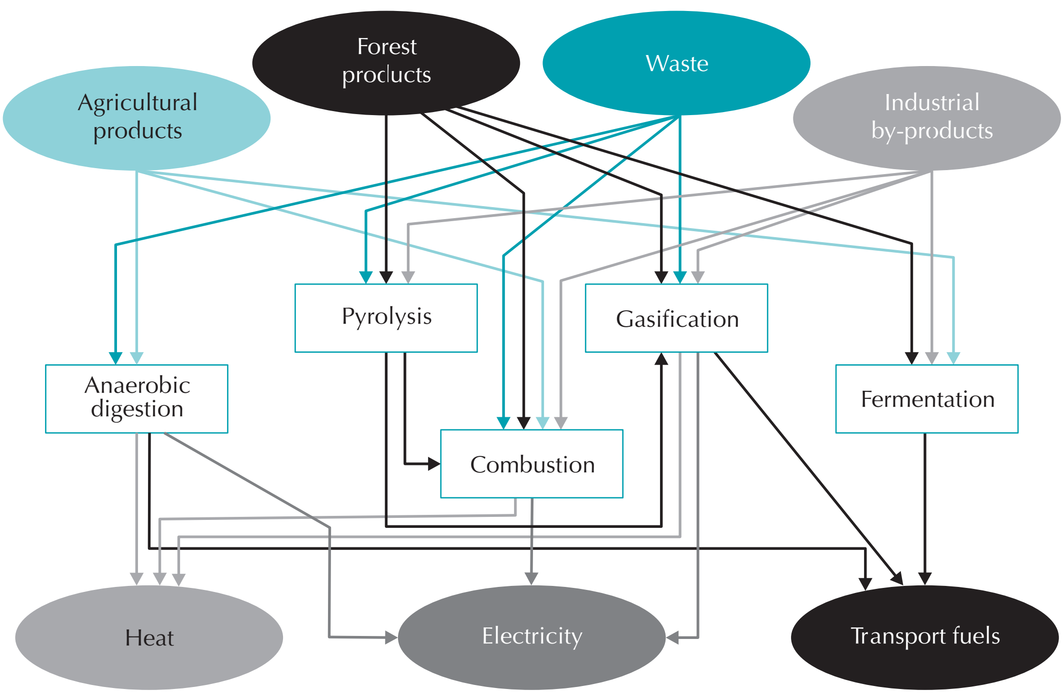
Figure 2. **Biomass conversion pathways to energy and fuels**



Note: Combustion not shown; Synthesis gas requires catalysts for upgrading

Indicates requirement of reformer

Figure 3. **Simplified bioenergy matrix**



impossible to generalise the production costs of biomass or biomass fuels delivered to the conversion plant or, indeed, the production cost of energy generated from biomass sources.

Some of the pathways shown in Figure 2, such as pyrolysis and the synthesis gas route for liquid biofuels, are still in the development phase and may require five to ten years further work before they can be considered as commercial technologies.

In an ideal scenario, all bioenergy applications should aim for polygeneration, i.e., the simultaneous production of heat, cooling, power and fuels, and – whenever possible – chemicals and materials. Such conditions are a prerequisite for maximising overall conversion efficiency and generating the greatest possible benefit per unit mass or unit volume of biomass. In practice, it is difficult to identify precise circumstances in which polygeneration can be applied under existing economic conditions. However, industry shows a clear tendency to advance beyond simple power generation to achieve polygeneration.

Reporting costs for bioenergy is equally complex, both for liquid biofuels (IEA, 2005a) and for gasification technologies (in pilot and demonstration plants) (IEA, 2005b). Costs for bioethanol (Table 1) can vary from USD 0.20 to USD 0.81 (a four-fold difference) subject to the location and the crop/resource used to produce the biofuel. Similarly, the cost for producing biodiesel can vary from USD 0.40 to USD 0.80 (a two-fold difference). There is good potential to further decrease production costs of both biofuels, especially in Europe and the United States, through innovative combinations of technologies and improved utilisation of process residues. It may also be possible to use municipal wastes as a feedstock.

Gasification technologies are still in the development stage and very few reference operating plants exist, thus making it difficult to generalise about production costs (Table 2). However, due to its flexibility in terms of final use of the fuel gas produced, gasification may offer significant opportunities once the sector is able to overcome remaining technical barriers, demonstrate reliability and further reduce costs.

Table 1. **Costs for liquid biofuels**

Biofuel	Country	Resource/Crop	Reference Year	Production Cost/litre (USD)
Bioethanol	USA	Corn	2004	0.32-0.55
	France	Sugar beet	2001	0.63
	Brazil	Sugarcane	2003	0.20
	UK	Sugarcane	2003	0.81
	USA	Wood	2004	0.40-0.50*
	Sweden	Wood	2002	0.61
	Sweden	Straw	2003	0.76
Biodiesel	USA	Oilseed	2003	0.62
	USA	Oilseed	2004	0.63-0.80
	EU	Oilseed	2003	0.77
	Germany	Oilseed	2004	0.66-0.77
	N.America	Used oils/fat	2004	0.42-0.60

* *Estimate.*

Table 2. **Costs for gasification applications**

Application	Country	Gasifier Type	Capacity MW	Installation Cost (USD/kW)	Operation Cost (USD/kWh)
Power	Switzerland	Moving Bed	0.055	5450	0.06-0.075
Power	Switzerland	Moving Bed	0.280	2860	0.06-0.075
Heat	USA	Moving Bed	--	1000	0.04
CHP	--	Atm. Fluid Bed	100	2151	0.072°
IGCC	USA	Pres. Fluid Bed	75	1626	0.068*
IGCC	USA	Pres. Fluid Bed	150	1312	0.06*

° estimate;
** estimate at USD 35/dry short ton of biomass.*

Current RD&D

Technology development and reliability

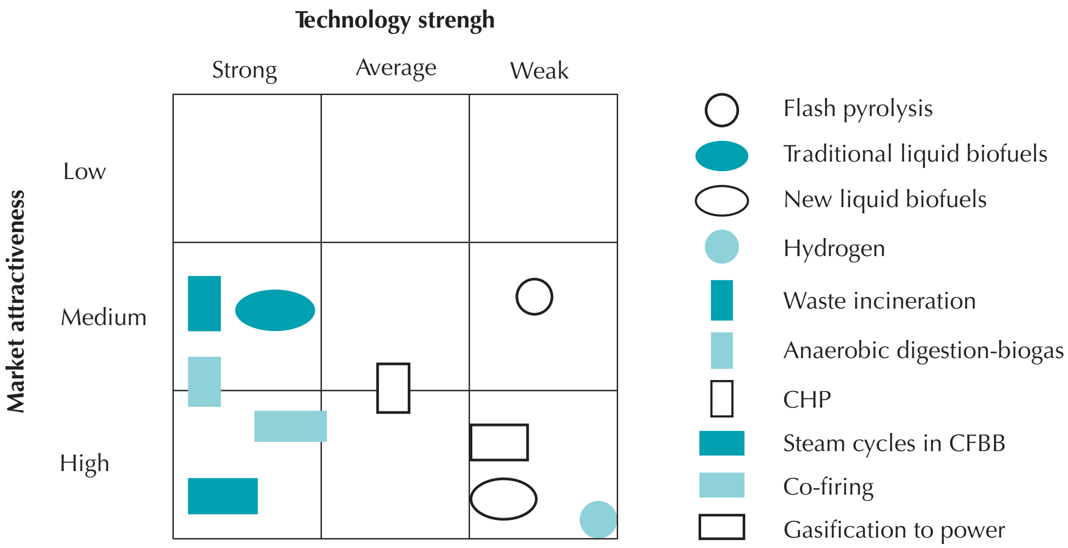
Biomass fuels and residues can be converted to energy via thermal, biological and mechanical or physical processes (Figures 2 and 3). Thermal processing currently attracts the most interest; gasification receives the most RD&D support largely because it offers higher efficiencies compared to combustion. Pyrolysis is still at a relatively early stage of development, but offers the benefits of a liquid fuel with concomitant advantages of easy storage and transport.

While gasification of fossil fuels is a relatively well-established process, similar technologies for biofuels are still at the development stage. However, gasification is attracting renewed interest thanks to the technical possibility to produce biofuels for transport (such as dimethyl ether, or DME), Fischer-Tropsh and methanol via the synthesis gas route and subsequent catalytic conversion. Such conversion pathways appeal in that they offer relatively high efficiencies and carbon dioxide balances, although they require at least five to eight years further development before they can be considered 'proven'. In the meantime, combustion, biological conversion processes (fermentation and anaerobic digestion) and mechanical processing (*e.g.*, pellets) are already well established and offered commercially.

In general, at a small scale, gasification promises higher efficiencies. However, at a larger scale, improvements in combustion are now also achieving higher efficiencies. The advantages of gasification systems arise from high efficiency in converting biomass to a gas and in utilising heat from combustion of the gas produced. This includes larger scale power generation of up to 100 MWe with integrated gasification combined cycle (IGCC) processes, which demonstrate predicted electricity production efficiencies of 40% to 50% compared with only 25% to 35% via traditional combustion. Small-scale power generation systems (up to 5 MWe) use engines that offer up to 35% efficiency. So far, neither of these thermochemical conversion processes has been able to penetrate markets to any significant extent. This is primarily due to high costs and a perception that the technologies must still be proven at large scales.

The key differences between thermal and biological conversion lie in the time involved, the end products and the resulting residues. Biological conversion is a slow process - typically taking hours, days, weeks (anaerobic fermentation) or years (landfill gas by digestion) to complete reactions - and delivers single or specific products such as ethanol or biogas (which contains up to 60% methane). Thermal conversion is characterised by very short reaction times (typically seconds or minutes) and its ability to deliver multiple and complex products. Often, thermal conversion uses catalysts to improve the product quality or spectrum. Biological conversion effectively converts only a fraction (about 50% to 60%) of the total feedstock (e.g., sugars or cellulose), resulting in large residual streams that can be used for other commercial purposes (e.g., compost or animal fodder). In contrast, thermal treatment converts the entire feedstock, leaving only ashes (about 2% to 4% weight). To date, few studies exist concerning the status of various biomass conversion technologies (Bridgewater and Maniatis, 2004). However, it is interesting to compare a tentative status for biomass conversion technologies in view of their market attractiveness for generating power, heat or liquid biofuels and in relation to the current strength of various conversion technologies (Maniatis, 2001) (Figure 4).

Figure 4. **Bioconversion technology status and strategic planning for development**



Anaerobic digestion is a successful technology for the production of biogas and is now used commercially all over the world - especially for waste effluents such as waste water, sewage sludge, and abattoir waste streams, as well as for the biological portion of municipal solid waste. While liquid state technologies are currently the most common, recently developed solid state fermentation technologies are also widely used, especially for substrates with moisture content in the range of 30% to 40% wt. Technically, anaerobic digestion technologies are very reliable. However, they are site specific and their scaling up capacity is limited; thus their market attractiveness is somewhat restricted. That said, it should be noted that the increasing costs of waste disposal are improving the economic attractiveness of anaerobic digestion processes.

Municipal solid waste incineration is a mature and reliable technology for a complex and heterogeneous feedstock. For example, in the Netherlands most of the waste generated per annum (50 Mton) is recycled, leaving only a relatively small portion (5.5 Mton) for final treatment in 11 waste incinerators (grate fired), which have average electric efficiency rates of 22%, or as high as 30% in the newly built lines. Associated pollutant emissions can be effectively controlled with state-of-the-art techniques. However, in order for solid waste incineration to claim its appropriate place in overall waste management strategies, efforts must be made to improve market attractiveness and generate more positive public acceptance.

Co-firing applications are perhaps the most interesting in terms of their potential for accelerated market penetration: thanks to the existence of the power cycle in coal-fired power plants, overall costs are relatively low (van Loo and Koppejan, 2002). In addition, co-firing has the advantage over co-combustion (in which biomass fuels are mixed with coal before or during the combustion process) in that the biomass residual ash is not mixed with the coal ash, which has an existing market as a construction material. Moreover, the technical risks of co-firing are low: because hot gas is used, there is no tar problem. Reburning applications (in which the fuel gas is introduced near the top of the coal boiler) show significant improvements in the environmental performance of the power station and in the replacement of fossil fuels by renewable biomass fuels.

Combined heat and power (CHP) applications are attractive for several reasons: overall efficiency is increased substantially, the technology is reliable and the need to identify a heat client is manageable. However, the combination of both the heat and power energy vectors makes CHP applications more site specific than when using each energy vector separately. In order to reduce operational costs, it is often necessary to implement multi-fuel operation, which increases the complexity of the feeding system and the flue gas cleaning. This results in some degree of increased maintenance. Recently, more attention is directed towards polygeneration systems that can produce power, heat and cooling, thereby maximising overall efficiency.

While downdraft gasifiers and fluidised bed systems are beginning to show a degree of success, gasification technologies to power still need to demonstrate reliable commercial operation (Bridgewater and Knoef, 2003). The main barriers are efficient tar removal (technical) and economics (non-technical). The success of the Värnamo plant in Sweden (Ståhl et al., 2001) - the first and only plant to demonstrate an integrated gasification combined cycle (IGCC) based on biomass - and recent advances on tar elimination indicate that these problems could be overcome in the short to medium future.

Flash pyrolysis for the production of bio-oil is another attractive process in that the bio-oil can be stored and transported, thereby separating the conversion and energy production processes. At present, no large-scale demonstration plants are able to provide reliability for commercial energy applications (Bridgewater, 2002), although Dynamotive recently established a production facility in West Lorne, Canada.

Production of bioethanol and biodiesel, from sugar and oil-based crops respectively, are well-established industrial processes. Their overall energy and carbon dioxide balance - although positive - could be improved significantly through on-site utilisation of the plant residues for CHP applications, as practised in Brazil with sugarcane and bagasse. The technical reliability of these traditional technologies is very high but their market attractiveness is limited in view of carbon emissions trading. New applications, such as biodiesel from used cooking oils and animal tallow, are coming on stream together with pilot facilities to produce ethanol from lignocellulosics. Again, it is necessary to prove the technical reliability of these applications but if these technologies can be commercialised, their market attractiveness will increase significantly. Production of biofuels for transport applications must also carefully consider fuel quality specifications to ensure operation ability of car fleets already on the market, which requires cooperation of the oil and automotive industries.

Biohydrogen is another potential alternative that can be produced from biomass in a variety of ways, the most straightforward being the reforming of biomethane produced from biogas and the reforming of bioethanol (it can also be created from synthesis gas via gasification). However, these technical approaches are at the very early research stage and relatively far from market applications.

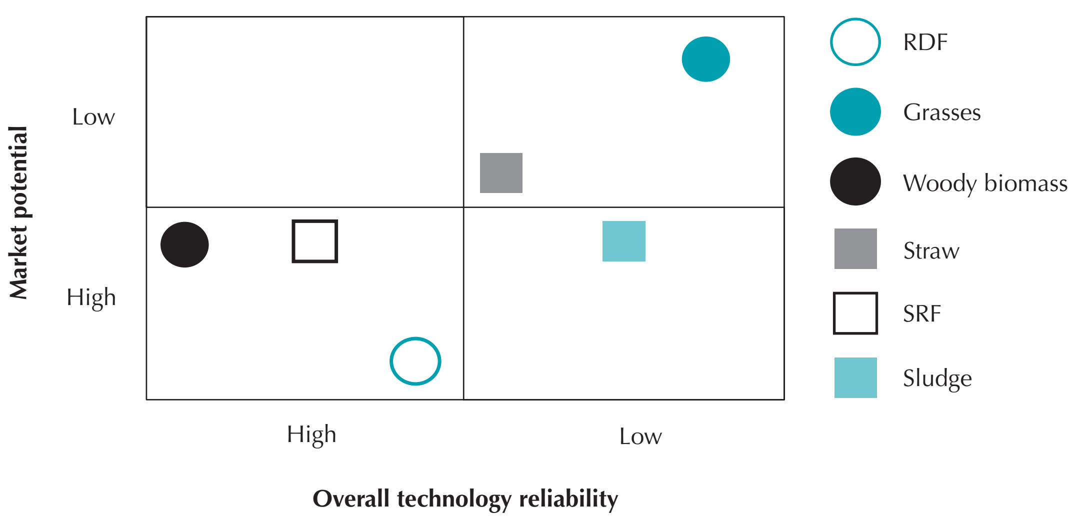
The complexity of bioconversion pathways (Figure 2) increases even further when one considers the full range of options based on the variety of available feedstocks. For example, although a steam cycle in a circulating fluidised bed boiler is considered a mature and reliable technology with solid biomass feedstocks, the technology is still at the development stage with grasses (e.g., miscanthus) because of handling and feeding complications. The problem of difficult-to-handle feedstocks (e.g., grasses and straw) can be reduced with multi-fuel operation, in which they are mixed with wood or 'pelletised' to improve handling characteristics. However, both approaches – especially the latter – significantly increase operating costs.

Feedstock technology reliability

One of the most significant barriers to accelerated penetration of all biomass conversion technologies is that of adequate resource supply. Figure 5 (Maniatis, 2001) depicts the technology reliability of using the most important feedstocks in thermochemical applications.

Clean biomass feedstocks are becoming expensive; with rare exceptions, there is very little reliable, long-term supply. In some countries, all industrial wood waste and other wood residues are consumed completely and there is no other clean biomass available to increase

Figure 5. **Status of feedstock technology reliability and market potential**



the contribution of bioenergy. In order to create new market opportunities for cheaper feedstocks, industry must explore relatively difficult fuels and fuels with little practical industrial experience. Waste-recovered fuels present the advantage that they often have a negative cost associated with their disposal, which can significantly decrease the operating costs of a plant. In addition, during the past decade there has been a significant interest in energy crops - especially short rotation forestry (SRF) - as a means of increasing production of biomass fuels while simultaneously creating new jobs for the farming community. SRF operations can also contribute significantly towards sustainability and to meeting Kyoto Protocol obligations. However, given that agricultural and forest lands are fixed, there will always be some competition between land for food and land for energy or carbon sinks.

Woody biomass has the highest reliability in feeding into a conversion reactor. Most problems related to bed sintering in fluidised bed reactors or slag formation on heat exchange surfaces are relatively well understood. Overall, industry has sufficient confidence to effectively use most types of woody biomass and has attained a high degree of reliability for pre-treatment operations such as drying, size reduction and storage. However, the market potential of woody biomass may be limited by the fact that most of the locally available feedstocks are already consumed in various industrial (*e.g.*, pulp and paper) or district heat applications. In some parts of the world, particularly in Europe, there is a net growth of forests, demonstrating that state-of-the-art forest management techniques can considerably increase the amount of fuel wood recoverable from existing forests.

Short rotation forestry (SRF) shows relatively good potential for use in non-arable land and provides a sustainable approach to energy. However, because the practice could block land for approximately 15 to 20 years, EU farmers, for instance, are reluctant to implement SRF schemes. The only exceptions are Sweden, where there is a long tradition of SRF, and the United Kingdom, where successful schemes were recently introduced to the farming community. The United States has an ambitious SRF-development programme; Canada has carried out significant work and is examining various SRF implementation schemes. Brazil successfully established eucalyptus plantations. To date, very few tests have been carried out with SRF feedstocks (although the United Kingdom has conducted combustion trials on most forms of biomass in dedicated and coal power stations). Thus, industry remains somewhat uncertain about the properties of SRF fuels. In addition, heavy metals are a sensitive area because some (e.g., cadmium) are easily taken up by plants.

Grasses are attracting more interest as a feedstock source, particularly because they can be cultivated in various places, even on the sides of highways, etc. However, their market potential remains uncertain: as yet, there are no dedicated plantations and experience with such feedstocks is relatively limited. Grasses present technical problems in all pre-treatment operations (e.g., size reduction, storage, drying); if not dried and stored properly, their relatively quick rates of biodegradability can result in significant weight loss. In addition, their low bulk density results in solids flow problems and can create local hot spots in conversion reactors. During combustion, grasses can cause corrosion (high chlorine content), fouling and slagging (high alkaline content). In Northern Europe, significant progress has been realised in implementing reed canary grass (now up to 15 000 ha) as a 'non-food' farming product for industrial CHP applications.

Because of its seasonable availability, straw has relatively low market potential. However, combustion technologies are improving and showing positive experiences in both fluidised bed and grate boilers, which is boosting the market of such technologies. Experience with straw gasification remains limited and fluidised bed gasifiers still struggle with severe problems of ash sintering and bed agglomeration. The fundamental problem is straw's low bulk density. In some applications, the straw has been pelletised with a degree of success, but this is an expensive operation. However, the IGCC Värnamo plant (Sweden) recently achieved a successful operation with 100% straw feeding (Ståhl, 2001).

Refuse-derived fuel (RDF) shows significant potential, partly because it can be used in operations that do not have a negative public image (e.g., incineration). In addition, industry already has sufficient experience: the cement industry uses significant quantities of RDF to replace coal. However, feeding systems for fluff RDF must be further developed to ensure reliable operation and more experimental results at large-scale applications are needed to prove efficient operation.

Finally, sewage and other industrial sludges can also be utilised in thermochemical energy applications. Although experience remains limited, it is expected that sludge applications will increase in the future. Technical reliability is at acceptable levels and the cement industry reports positive experience with handling and feeding large quantities of this waste stream. Sludges are also showing success when used commercially in anaerobic fermentation systems for the production of biogas.

Feedstock costs vary widely depending on the type of biomass and the transport distance from source to conversion plant. The most economical approach is to use the energy on site, i.e., at the location where the biomass residue is generated (e.g., at a paper mill, sawmill or sugar mill). Efforts to increase the energy density per unit volume of biomass fuels focus primarily on pelletising.

Bioenergy plants are now available for power, heat and CHP applications from a few kW upwards. The typical commercial range for biomass plants is between 20 MW and 100 MW, depending on geographical context and feedstock sources. However with dedicated supply systems, commercial CHP plants up to 500 MWth are now operating, including the world's largest biofuel CHP plant at Alholmens Kraft, Pietarsaari (Finland).

Two feedstock databases are now available, which provide a significant amount of information for a variety of biomass feedstocks (Hofbauer et al., 1997; NOVEM, 2000). Inclusion of the physico-chemical properties of biomass fuels gives gasifier developers and gasifier users easy access to basic information regarding the quality and suitability of various fuels for the gasification technologies.

Additional RD&D priorities

Short-term priorities

Short-term priorities for bioenergy focus on two primary areas: a) availability of large quantities of relatively cheap feedstocks to support a dedicated market of biomass fuels that can be traded locally, nationally and internationally; and b) further increasing conversion efficiency of basic processes while reducing their costs. To achieve the former, it is necessary to develop standards and norms on the fuel quality to be traded; the latter requires innovative approaches that may focus more on materials rather than conversion technology improvements. The situation is somewhat co-dependent: a functional international market for biofuels is a prerequisite for the global development of bioenergy; for such a market to develop, large quantities of biomass fuels must be available for international trade.

Medium-term priorities

Medium-term needs for bioenergy should address potential opportunities offered by biorefineries, which have the capacity to generate a variety of products (*e.g.*, biopolymers, food additives, etc.) – including energy – from process residues. Such applications would significantly increase overall efficiency of the processes, increase economic benefits and promote sustainability. It may be possible to develop dedicated crops, tailored to the needs of biorefineries (*e.g.*, by maximising the concentration of certain chemicals, such as sugars, in the crops). The most attractive options may be found in developing successful process and business integrations of residue utilisation in food, forest and waste management areas.

Long-term priorities

In order to propose long-term RD&D priorities, it is necessary to define a long-term vision of the energy supply. This vision currently focuses on a hydrogen economy, recognising that there are several pathways to hydrogen production (Figure 2). It is anticipated that gaseous (biogas or biomethane) and liquid biofuels (ethanol and eventually methanol) could be used as safe carriers for hydrogen. However, in addition to considering a hydrogen economy, it is necessary to continue focusing on sustainable ways to cultivate large amounts of biomass worldwide without hampering food supply, the local ecology and biodiversity. At the same time, efforts should continue on the biorefinery approach, through which biomass for products, food and energy would become an integral part of the economy.

Ongoing issues

One area of RD&D is particularly weak; continuous efforts must be undertaken to strengthen social and environmental integration along the entire chain from biomass production to provision of energy services to the consumer. This issue arises in part because the advantages of bioenergy must always be balanced with its disadvantages (eventual loss of biodiversity, claim on vast areas of land, environmental emissions, and hazards and health conditions of workers).

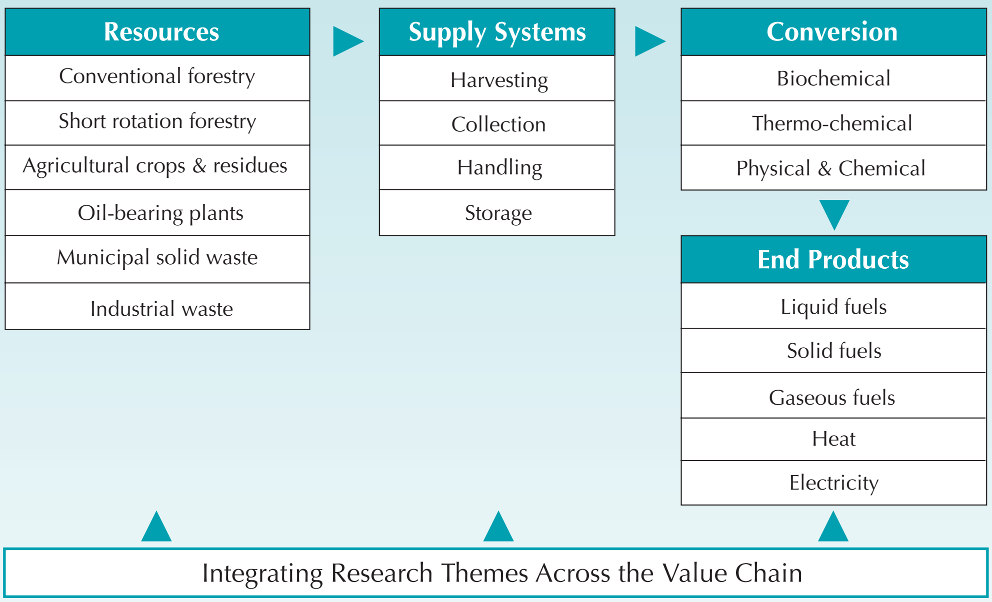
Conclusions

A further increase of renewables in market will be linked to improving performance and reducing costs, as well as to the growing recognition of their environmental, economic and societal values. Among all renewables, bioenergy is expected to provide the highest contribution for the short to medium term; it is the only renewable energy source that can directly replace fossil fuels (solid, liquid or gaseous). However, it is not yet possible to generalise bioenergy costs: due to its complex characteristics, bioenergy costs vary widely in relation to national policies, production costs, labour costs and conversion technologies. In spite of the significant cost reductions achieved during the last decade, bioenergy (like other renewables) is still more expensive than fossil fuels and nuclear energies. Thus, a need exists for continued legislative action to establish a level playing field. RD&D activities should assist this process and ensure that the role of bioenergy will remain pivotal in sustainable communities.

Current activities of IEA Bioenergy Implementing Agreement

The vision and mission statements for IEA Bioenergy Implementing Agreement focus on overcoming the environmental, institutional, technical and non-technical, and financial barriers to the near- and long-term deployment of bioenergy technologies. The scope of its work is shown in Figure 6 (Maniatis and Tustin, 2002). In 2003-05, the Implementing Agreement increased its focus on Tasks with "cross-cutting" themes (*e.g.*, Task 38: Greenhouse gas balances of biomass and bioenergy systems; Task 29: Socio-economic aspects of bioenergy systems) and those that seek to address strategic issues (*e.g.*, Task 41: Bioenergy system analysis).

Figure 6. **IEA Bioenergy: Scope of work**



Ongoing collaborations that previously focused on RD&D now increasingly emphasise deployment on a large scale. In 2005, IEA Bioenergy actively pursued 12 ongoing Tasks (IEA Bioenergy, 2005c) (Table 3). In addition, the programme recently published three position papers: The role of bioenergy in greenhouse gas mitigation; Sustainable production of woody biomass for energy; and municipal solid waste and its role in sustainability.

Table 3. **Current projects of IEA Bioenergy Implementing Agreement**

Project	Outline
Socio-economic Drivers in Implementing Bioenergy Projects	Achieve better understanding of social and economic impacts and opportunities of bioenergy systems to communities at the local, regional and international level; Synthesise and transfer important knowledge and new information in order to foster multi-disciplinary partnerships of key stakeholders in forest biomass production and utilisation research, planning and operations; improve impact assessment of biomass-production and utilisation to increase uptake of bioenergy; provide guidance to policy makers.
Short Rotation Crops for Bioenergy Systems	Acquire, synthesise and transfer theoretical and practical knowledge of sustainable short-rotation biomass production systems and thereby enhance market development and large-scale implementation in collaboration with the various sectors involved.
Biomass Production for Energy from Sustainable Forestry	Synthesize and transfer to stakeholders important knowledge and new technical information concerning conventional forestry systems for sustainable production of bioenergy.
Biomass Combustion & Co-firing	Expand use of biomass combustion for heat and power generation, with special emphasis on small and medium scale CHP plants and co-firing biomass with coal in traditional coal-fired boilers.
Thermal Gasification of Biomass	Review and exchange information on biomass gasification RD&D; seek continuing involvement with bioenergy industries and promote cooperation among the participating countries to eliminate technological impediments to the advancement of thermal gasification of biomass.
Pyrolysis of Biomass	Resolve technical issues and barriers which impede commercial implementation of fast pyrolysis.
Energy Recovery from Municipal Solid Waste	Maintain a network of participating countries as a forum for information exchange and dissemination.
Energy from Biogas & Landfill Gas	Review and exchange information on anaerobic digestion to produce, upgrade and utilise biogas as an energy source, to digestate it as an organic fertiliser and use the anaerobic degradation process as a link in the waste treatment chain.
Greenhouse Gas Balances of Biomass & Bioenergy Systems	Integrate and analyse information on greenhouse gases, bioenergy and land use, thereby covering all components that constitute a biomass or bioenergy system.
Liquid Biofuels from Biomass	Provide comprehensive information to assist with the development and deployment of biofuels for motor fuel use.
Sustainable International Bioenergy Trade: Securing Supply & Demand	Create insights in information, decision factors and preconditions for the medium-term results (four to ten years).
Bioenergy System Analysis	Supply decision makers with scientifically sound and politically unbiased analyses and conclusions needed for strategic decisions related to research or policy issues.

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Chapter 3 • Technologies

Hydropower

Highlights

- Hydropower is well established and considered a mature technology. Still, many opportunities remain for RD&D technologies and programmes to enhance its development globally.
- In 2003, total hydropower supply was 104 Mtoe, accounting for 2.0% of total primary energy supply in IEA member countries. The share of hydropower in renewable energy supply was 37%.
- The cornerstone of the energy policies of many governments is to reverse the declining trend of renewables as a proportion of national energy supply, and hence of the world's. Hydropower currently provides a significant portion of the world's renewable energy supply, in the form of electricity. Good potential exists to increase this proportion, particularly in the short term.
- Achieving greater energy supply from hydropower does not require technological breakthroughs, huge RD&D expenditures or radical changes to development of hydropower resources. Current requirements include continuous improvements in technology, increased public acceptance and hydropower project approvals supported by government policy. In addition, the technology is at a stage in which implementation and development should be financed and supported jointly by the public and private sectors.
- The hydropower equipment manufacturing and supply industry must embrace up-to-date technologies to meet the continuous improvement goals of power quality and dependability.
- The hydropower industry needs to maximise the use of its existing resources and adopt collaborative approaches to developing new projects that meet sustainability guidelines.
- Governments probably have the greatest role to play by supporting existing hydropower as and where it is sustainable, and by promoting and supporting development of new projects that meet sustainability guidelines.

Introduction

During the first half of the 20th century, hydropower became the world's principal source of electricity. Today it is considered a mature technology and still contributes a significant proportion of the world's renewable energy supply. Thanks to its inherent flexibility, it is now positioned as both a vital component of electrical systems and as the most significant short- to medium-term renewable resource. In 2003, total hydropower supply was 104 Mtoe, accounting for 2.0% of total primary energy supply in IEA member countries. It was also the main renewable energy source, with a share of 37% in total renewable energy supply.

From 1974-2003, IEA member countries reported approximately USD 113 million (2004 prices and exchange rates) of RD&D spending on large hydropower; they also dedicated significant amounts to small hydropower (Figures 1 and 2, respectively). Norway, the United States, Switzerland and Canada accounted for approximately 88% of governmental RD&D funding on large hydropower; other member countries accounted for low one-digit numbers. Canada, Switzerland, Finland, Japan and Spain accounted for two-digit numbers to small hydropower funding, together amounting to approximately 63% of IEA member countries' reported RD&D budgets in this area.

Hydropower continues to face challenges, both in terms of public acceptance and economics. In the latter case, the primary issues are related to the long approvals and construction cycle, high initial costs and, hence, long payback periods.

The maturity of hydropower as a technology, the longevity of existing hydropower plants and of the dams and waterways associated with them, and the high availability and reliability of the power output raises a legitimate question: What RD&D is there left to do or is even necessary? Because many organisations and governments have adopted this attitude, the hydropower improvement business has fallen behind in many areas. It now fails to attract RD&D funding and, in many regions, hiring well-qualified staff is difficult.

Figure 1. **Reported government large hydropower RD&D budgets in IEA member countries, 1974-2003**

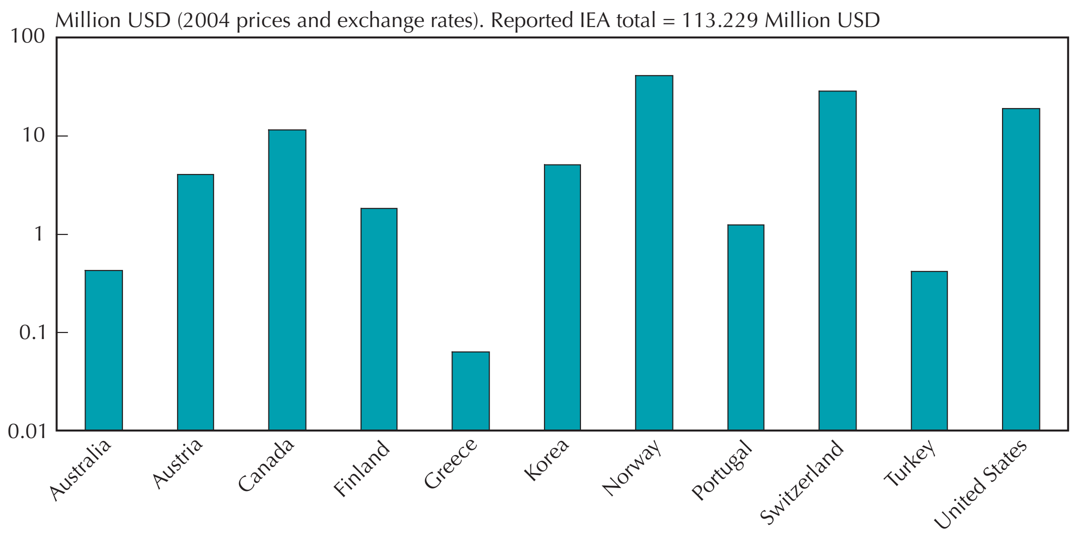
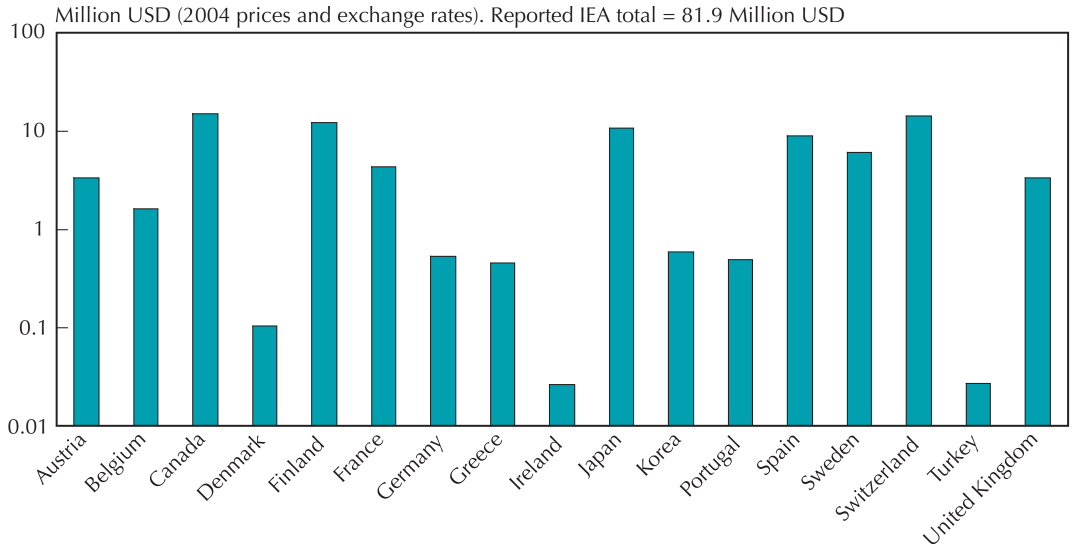


Figure 2. **Reported government small hydropower RD&D budgets in IEA member countries, 1974-2003**



Current technology status

Hydropower is considered a mature technology. Many projects built in the early decades of the 20th century are still operating today, though most have been rehabilitated, modernised or redeveloped.

The era of large hydropower projects began in the 1930s in North America and has since extended worldwide. Today, most large projects, either under construction or planned, are located in China, India, Turkey, Canada and South America. Potential remains, around the world, to expand both the large number of small hydropower projects and to upgrade existing power plants and dams to produce more energy. The status of current hydropower technology can be categorised into three areas:

- Large hydropower.
- Small hydropower.
- Additional energy at existing hydropower and dams.

Large hydropower

The technical challenges for large hydropower are mostly faced by the few manufacturers of large equipment and the numerous suppliers of auxiliary equipment and technology. To meet current technology needs and compete effectively, today's manufacturers and suppliers typically invest in RD&D for their own companies. Over recent years, no major breakthroughs have occurred in machinery; however, the advent of computers led to vast improvements in monitoring, diagnostics, and protection and control technologies, as well as in many other areas.

Building links between policy, industry and RD&D institutions and technology networks such as the IEA Technology Collaboration Programme, can guide the stakeholders to focus on areas identified as being significant for the future health and development of this energy sector. The resulting collaboration makes it possible to bring key issues to the attention of policy makers who, in turn, can provide guidance for appropriate policies.

Small hydropower

For small hydropower, the technical challenges are a by-product of the large hydropower industry and the application of appropriate technology by small manufacturers, organisations and agencies. Perhaps the greatest difference between the technology status of large and small hydropower is the huge variability of designs, layouts, equipment types and material types used in small hydropower. It can be said that there is no “state of the art” in small hydropower; rather there is a huge body of knowledge and experience in designing and building projects to fit the site and the resources of the developer.

Additional energy at existing power plants and dams

One of the greatest opportunities for quick gains to the renewable energy portfolio lies in maximising the energy produced from existing hydropower projects. Gains of 5% to 10% are not an excessive target for most hydropower owners; where there are significant numbers of non-generating dams, the numbers could be much higher. As with any modernisation project, the greatest challenge in this sector may be the risk that expected gains are never realised. This perceived risk, coupled with the challenges of re-licensing, results in an enormous potential being left untapped.

However, the technical challenges associated with understanding the issues and problems of an existing hydropower project can be significant – particularly if few drawings and limited records are available. Here again, the advent of computer technology, monitoring, diagnostics, assessment, modelling and design make it possible to better manage many of the uncertainties. Today’s advanced technologies build confidence that the majority of hydropower plants can be assessed correctly and that potential gains in energy – and hence value to the owner – identified accurately.

Current RD&D

Industry, utilities and governments are the primary initiators, sponsors and funders of RD&D in hydropower. Industry pursues its own objectives: by far the most significant funding comes from equipment manufacturers and suppliers, particularly in the design of more efficient and lower cost equipment and in system and computer technology applications. Hydropower utilities either operate their own RD&D divisions or undertake collaborative initiatives, nationally or internationally. Governments tend to either work internally and independently, or in collaboration with industry and utilities. They also provide, to a limited degree, funding for new technologies.

A recent review of key issues affecting the operation and management (O&M) of existing hydropower plants sought to better understand requirements for RD&D activities. The review included areas in which significant operating and capital expenditures currently occur and are likely to increase in the future. This review identified ten key issues (Table 1) and a number of broad concerns, for example:

- Ongoing operation and maintenance, particularly in relation to aging equipment.
- Managing forced outages and replacing failed equipment.
- Managing the consequences of risk and related issues such as non-compliance and collateral damages.
- Modernising plant equipment and prioritising investments.
- Preparing for operational changes in new markets.
- Integrating with new generation technology and new generation sources (*e.g.*, wind energy, hydrogen).

Table 1. **Key issues for hydropower plant owners**

1.	**Realise lowest operating costs possible through:**
	• Maintenance management system • Innovative staffing approaches • Training/competency management • O&M decision-making tools • New approaches to maintenance and repair
2.	**Increase plant output capacity and energy through modernisation of:**
	• Hydraulic and mechanical equipment and systems (generation and auxiliaries) • Electrical equipment and system (generation and auxiliaries) • Control, protection, annunciation and surveillance systems • Civil structures (concrete, earth/rock fill and structural steel)
3.	**Increase plant value/revenue through:**
	• Costing and selling ancillary services • On-line discharge measurement systems (hardware and software). • Asset management systems • Improved water management systems
4.	**Reduce losses through:**
	• Improvements in measurements and diagnostics • Hydraulic improvements
5.	**Extend asset life through:**
	• Identification of aging and improved maintenance practices for civil structures • Reliability and risk assessment/asset management • Improvements in surveillance systems and diagnostics
6.	**Implement materials/performance improvements in:**
	• Hydraulic, mechanical and electrical equipment and systems (e.g. transformers, generator stator windings, thrust bearings, turbine runners, gates and valves, etc.) • Civil structures
7.	**Increase public acceptance through:**
	• Positioning hydropower as sustainable • Making financing available for development

Table 1. **Key issues for hydropower plant owners** (continued)

8.	**Improve knowledge systems/decision support through development of:**
	• On-line databases (sharing) • Training/competency management • Guidelines on specific areas of interest • Asset management systems
9.	**Integrate non-firm renewables including:**
	• Wind-hydro system integration • Hybrid systems, including hydrogen
10.	**Become fully sustainable by applying:**
	• Assessment methods of sustainability • Environmental management/impact reduction/monitoring • Fish passage

A national industry group recently suggested four priority areas for additional research.

1. Promote hydropower development:

- Create methods to value the benefits of hydropower.
- Identify barriers to adding generation at existing non-power dams.
- Remove barriers to small hydropower development.

2. Enhance fish resources protection:

- Complete the ongoing Advance Hydropower Turbine Systems programme.
- Develop biological criteria.
- Identify protocols for measuring the effectiveness of mitigation activities.

3. Optimise water resources for multiple uses by improving:

- Methods for ensuring in-stream flow needs.
- Flow measurements.
- Sediment management.

4. Integrate hydropower with other renewable and distributed energy technologies.

One of the most recent comprehensive assessments of RD&D activities in the hydropower industry was the 2001 Hydro RD&D Forum (Hydro RD&D forum, 2001). Forty-eight organisations active in the RD&D field submitted project synopses; this collection did not reflect the totality of hydropower-related RD&D, but it did provide a representative sample of ongoing efforts. The forum resulted in a shortlist of projects deemed most worthy of pursuit and ranked them in order of priority (Table 2).

Table 2. **2001 Hydro RD&D Forum - most worthwhile RD&D projects**

Priority Ranking	RD&D Projects
1	Hydro's Value Compared to the Power Mix
2	Advanced Hydro Turbine System Programme Development and Deployment
3	Business Model for O&M Decision-support Based on Condition Monitoring
4	Methods to Quantify Costs and Benefits from Ancillary Services
5	Hydro Education and Outreach
6	"Green" Power's Acceptance for Hydro
7	Hydropower Competency Management Program
8	Hydro-Related RD&D Technology Transfer
9	Life Effects Due to More Severe Load Operations
10	Protocols for Measuring Mitigation Effectiveness
11	Advanced Decision-support at the Operational Level
12	Maximum Design Flood and Associated Hydrologic Components
13	Hydro Career Development Programme
14	Hydro and Renewable Energy Technology Integration
15	Decision-support Systems in a Deregulated Market
16	Biological Criteria Development
17	Removing Barriers to Small Hydro Development
18	Effectiveness of In-stream Flows
19	Hydro-meteorological Data Enhancement and Improvement
20	Procedures to Reduce Scale-up Errors from Hydraulic Model Tests
21	Turbine Efficiency Degradation Due to Cavitation Damage
22	High-voltage Generation
23	"HydroLink" Resource Base
24	Stator Core Material Improvement
25	Long-term Outlook for Hydro Competitiveness with Fuel Cells
26	Marketing Strategies for Small Renewables
27	Residual Strength of Soils Under Seismic Liquefaction
28	Hydro Stars Human Resource Awards Programme

Additional RD&D priorities

As indicated above, hydropower is considered, for the most part, a mature technology with few major advances expected. Thus, future RD&D will need to focus primarily on non-technical areas. These additional RD&D needs can be considered under the following categories:

- Technology.
- Public acceptance and project approvals.
- Implementation and development.

Technology

For each of the three areas of hydropower considered – large hydropower, small hydropower and additional energy from existing hydropower and dams – the technology challenges are similar, and include:

- Improve efficiency.
- Reduce equipment costs.
- Reduce operating and maintenance costs.
- Improve dependability (reliability and availability).
- Integrate with other renewables.
- Develop hybrid systems, including hydrogen.
- Develop innovative technologies.
- Develop environmental technologies.
- Facilitate education and training of hydropower professionals.

Public acceptance and project approvals

For each area of hydropower considered, challenges related to public acceptance and project approvals include:

- Identify and implement appropriate mitigation measures for environmental and social impacts.
- Increase acceptance of hydropower as renewable and sustainable.
- Establish renewable premiums and credits for all hydropower.
- Streamline legal and financial procedures for hydropower development and approval processes.
- Conduct impact assessments including both western and indigenous peoples' approaches.
- Seek certification as a sustainable energy source.
- Identify new hydropower sites that meet sustainability criteria.
- Improve public relations activity.

Implementation and development

For each area of hydropower considered, the implementation and development challenges include:

- Establish innovative financing, including cost sharing for multiple uses.
- Improve understanding of the true cost of hydropower compared with other energy sources.
- Create improved development mechanisms (such as clean development mechanism, or CDM, etc.).
- Address integration issues with wind and thermal.
- Resolve issues of integration into distribution systems.
- Improve understanding of risks for decision-making in plant modernisation.
- Develop suitable approaches to add hydropower plants to existing dams.
- Establish a systematic approach to development that fulfils sustainability requirements.

Drawing on information presented in Tables 3, 4 and 5, it is possible to generate a list of RD&D needs for advancing hydropower development. From the total of 25 initiatives, 16 are considered a 'High' priority; the remaining nine received a 'Medium' priority rating.

Table 3. **Technology needs for hydropower**

Large Hydro	Priority	**Small Hydro**	Priority	**Additional Energy at Existing Hydro Plants and Dams**	Priority
• **Equipment** - low head technologies, including in-stream flow - communicate advances in equipment, devices and materials	M	• **Equipment** - fish-friendly turbines - low head technologies - in-stream flow technologies	H	• **Equipment** - fish-friendly turbines	M
• **O&M Practices** - increased use of maintenance free and remote operation technologies	M	• **O&M Practices** - develop package plants requiring only limited O&M	M	• **Systems** - hydropower performance improvements	M
		• **Hybrid Systems** - wind-hydro systems - hydrogen-assisted hydro systems	H	• **Innovative Technologies** - *e.g.*, Hydromatrix and Powerformer	M

H - High
M - Medium

Table 4. **Public acceptance and project approval needs for hydropower**

Large Hydro	Priority	**Small Hydro**	Priority	**Additional Energy at Existing Hydro Plants and Dams**	Priority
• **Public Acceptance** - hydropower as renewable - renewable credits - multi-purpose uses - safety and security	H	• **Public Acceptance** - renewable credits	H	• **Public Acceptance** - additional energy as a premium product - safety and security	H
• **Project Approvals** - means to achieve shorter approval times - certification as "sustainable"	H	• **Project Approvals** - streamlined approval process	H	• **Project Approvals** - streamlined relicensing pro-cess	H
• **Environmental Impacts** - EIA process using a joint approach between western methods and indigenous peoples' approaches - establish impacts of development with consequences to natural and social environment	M	• **Environmental Impacts** - establish process to evaluate cumulative impacts of numerous small hydro compared with large hydro systems	M		

H - High
M - Medium

Table 5. **Implementation and development needs for hydropower**

Large Hydro	Priority	**Small Hydro**	Priority	**Additional Energy at Existing Hydro Plants and Dams**	Priority
• **Financing** - innovative financing for developing countries - sharing costs of multi-purpose uses - understanding the cost of hydropower compared with other energy sources	H	• **Financing** - private sector financing - cooperative systems	M	• **Risk Management** - understand risks of modernisation • **Financing** - private sector involvement	H
• **Development** - integration with wind energy - multi-purpose uses - CDM approaches - water resource management and optimisation - Institutional strengthening	H	• **Development** - Integration (DRD&DG) - firm energy (energy storage) - marketing of premium products - non-integrated areas	H	• **Energy from Dams** - innovative technologies	H
• **Training and Education**	H	• **Training and Education**	H	• **Training and Education**	H

H - High
M - Medium

Costs and benefits of additional RD&D

It is valuable to cross-reference these high and medium priority items with the hydropower areas they address, the entities best suited to initiate, sponsor or undertake the RD&D, and the benefits that could accrue to the industry (Table 6). Because hydropower is a relatively mature technology, highest priority was given to needs associated with public acceptance, project approval, and implementation and development. Technology RD&D received one high priority ranking – in the field of hybrid systems – and a number of medium priority rankings.

For many governments, the cornerstone of current energy policies is to reverse the declining trend of renewables as a proportion of national energy supplies – and, hence, of global supply. Hydropower already provides a significant portion of the world's renewable energy supply: almost half of the world electricity production from renewables comes from hydropower. Yet there is good potential to increase this proportion, especially in the short term.

Table 6. **Costs and benefits of additional RD&D for hydropower**

Priority	Hydropower RD&D Activity	Best Entity to Initiate or Sponsor	Programme Costs	Programme Benefits	Comments
H	Equipment development and improvements for small and existing hydro	Manufacturers	High	High	Economic justification
H	Hybrid systems for small hydro	Government	Moderate	Moderate	Important for remote areas and DG
H	Public acceptance of hydro as a premium product	Government	Low	High	Critical for increased development
H	Project approval process improvements	Government	Moderate	Moderate	Economic justification
H	Certification as sustainable	Government	Moderate	High	Critical for increased development
H	Financing methodology to increase development	Government and Utilities	High	High	Critical for increased development
H	Integrated development approaches	Utilities	Moderate	High	Critical for increased development
H	Risk management	Utilities	Low	Moderate	Important for plant modernisation
H	Energy from existing dams	Utilities	Moderate	High	Economic justification
H	Training and Education	Utilities	Moderate	Moderate	Continuous need for skilled professionals

H - High
M - Medium

Table 6. **Costs and benefits of additional RD&D for hydropower** (continued)

Priority	Hydropower RD&D Activity	Best Entity to Initiate or Sponsor	Programme Costs	Programme Benefits	Comments
M	Equipment development and improvements for large hydro and modernisation	Manufacturers	High	High	Economic justification
M	O & M practice improvements	Utilities	Moderate	Moderate	Economic justification
M	Environmental impact assessment in holistic ways	Utilities	Moderate	Moderate	Important for hydropower development

Realising greater benefit from hydropower does not require technological breakthroughs, huge RD&D expenditures, or radical changes to development of the hydropower resource. What is required, is continuous improvement in technology, public acceptance and approvals supported by government policy, and implementation and development financed and supported by the public and private sector. The technology sector that may require the most attention is the integration of hydropower and other "new" renewables.

There are specific ways in which each of the primary stakeholders in hydropower can contribute to achieving these objectives. The hydropower equipment manufacturing and supply industry needs to embrace up-to-date technologies, particularly to meet continuous improvement goals related to power quality and dependability. The hydropower industry needs to maximise use of existing resources and adopt collaborative approaches to developing new projects that meet sustainability guidelines. Governments probably have the greatest role to play, by supporting existing hydropower as and where it is sustainable and by promoting and supporting the development of new projects that also meet sustainability guidelines.

Current activities of IEA Hydropower Implementing Agreement

IEA Hydropower Implementing Agreement, a part of the IEA Technology Collaboration Programme, was put in place in 1995. The key objectives of the IEA Hydropower are to provide balanced and objective research and support for the increased development of hydropower as a significant renewable energy source. The year 2004 marked the end of Phase 2 of the Implementing Agreement, during which participants realised several important achievements:

- A highly successful web site that provides in-depth information on small hydropower (www.small-hydro.com).
- Hydropower Competency Network; this prepared web-based teaching materials for universities and technical institutes worldwide, and facilitated workshops for educators.
- Increased public awareness. IEA Hydropower continuously provided objective, balanced information on hydropower. Various international organisations collaborated to prepare a white paper on hydropower, as well as various articles and an extensive database of technical information available on the Internet (www.ieahydro.org).
- Hydropower good practice in which more than 70 studies that illustrate good practices in a number of key areas were collected.

The programme is currently entering its third phase. Table 3 presents current projects of the IEA Hydropower Implementing Agreement. Apart from these, it is planned that the programme will take on advanced research on integration of wind into hydropower systems, safety and security of hydropower facilities, best practice for hydropower performance, and development of hydropower in least developed countries. In 2005, the HIA comprised of five contracting parties.

Table 7. **Current projects of IEA Hydropower Implementing Agreement (2005)**

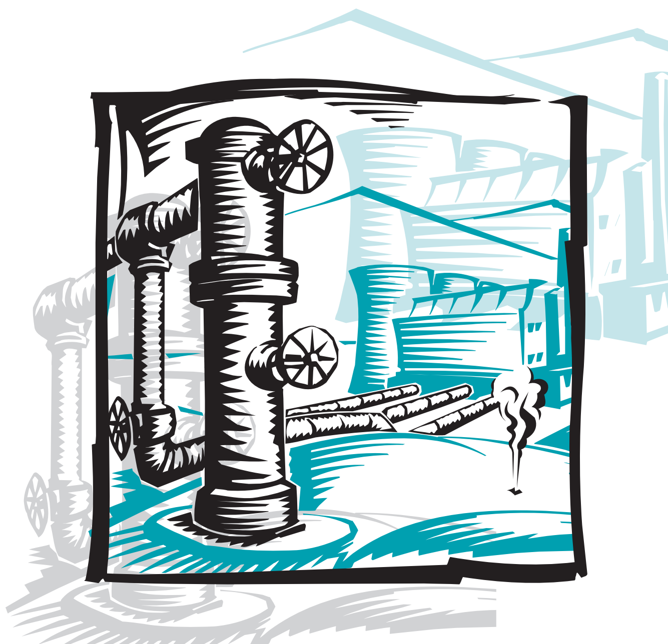
Project	Outline
Small scale hydropower	Address technological, organisational and regulatory issues related to small hydro projects (between 50kW and 10MW).
Public awareness of hydropower	Increase global understanding of the current and future roles and importance of hydropower in the global energy portfolio.
Hydropower competence network for educational training	Create a pilot version of an international network for personnel training in the hydropower industry.
Hydropower good practices	Develop training materials in the areas of planning, operations and maintenance of hydropower installations, making use of the latest information technologies to disseminate its results.

REFERENCES

Hydro RD&D Forum (2001), *2001 Hydro R&D Forum: Final Report*, HCI, Kansas City, USA.

Chapter 3 • Technologies

Geothermal



Highlights

- Geothermal is energy available as heat emitted from within the Earth, usually in the form of hot water or steam. Geothermal energy provides electricity and heat for a variety of direct uses in many areas of the world, and supplies domestic/district heating and cooling, through the use of ground-source heat pumps, virtually everywhere.

- To date, geothermal resources have been identified in more than 80 countries, with recorded geothermal utilisation in 71 countries. The number of countries utilising geothermal energy to generate electricity has more than doubled since 1975, increasing from 10 in 1975 to 24 in 2004.

- In 2003, total geothermal energy supply was 20 Mtoe, accounting for 0.4% of total primary energy supply in IEA member countries. The share of geothermal in total renewable energy supply was 7.1%.

- Over the last 20 years, capital costs for geothermal power systems decreased by a significant 50%. Such large cost reductions are often the result of solving the "easier" problems associated with science and technology improvement in the early years of development.

- Use of geothermal energy for electricity and direct heat applications is a mature technology with a long history in many countries. To achieve the desired and possible accelerated growth, the priority is to make it more competitive in the market place.

- Informing local, regional and national governments of the possibilities of utilising new technologies for power generation is another important element in helping geothermal gain market entry. Particularly as this technology encourages governments to make optimal use of local resources that diversify power production and create an environmentally sound energy sector.

- Although geothermal is among the lowest cost renewables, costs can and must be reduced further. At the same time, the geographical distribution of geothermal energy use must be increased. Significant progress in several priority RD&D areas will help geothermal accelerate its worldwide advancement. These are related to cost reduction, sustainable use, and the expansion of the technology for new applications and into new geographical regions.

- With greater funding and manpower, these priorities could be more rapidly achieved. The benefits include more extensive use of geothermal for power generation and direct heat use to much larger regions - even to areas far from tectonic plate boundaries.

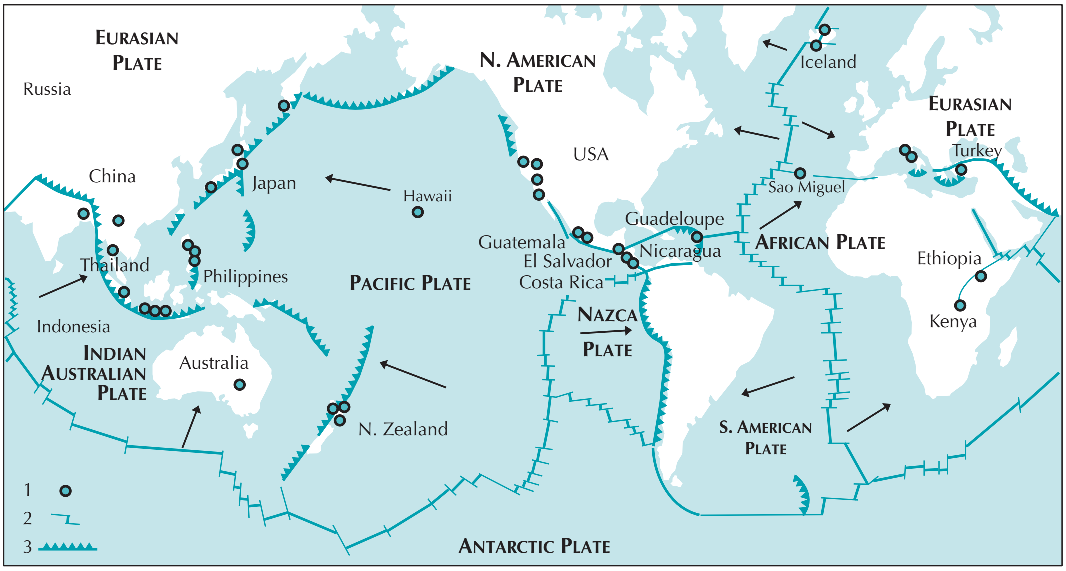
- Development and use of geothermal energy and other renewables in association with distributed generation is an important and necessary element of a global energy strategy.

Introduction

Heat energy continuously flows to the Earth's surface from its interior, where central temperatures of about 6 000°C exist. The predominant source of the Earth's heat is the gradual decay of long-lived radioactive isotopes (^{40}K, ^{232}Th, ^{235}U and ^{238}U). The outward transfer of heat occurs by means of conductive heat flow and convective flows of molten mantle beneath the Earth's crust. This results in a mean heat flux at the Earth's surface of approximately 80 kW/km^2. This heat flux, however, is not distributed uniformly over the Earth's surface; rather, it is concentrated along active tectonic plate boundaries where volcanic activity transports high temperature molten material to the near surface (Figure 1). Although volcanoes erupt small portions of this molten rock that feeds them, the vast majority of it remains at depths of 5 to 20 km, where it is in the form of liquid or solidifying magma bodies that release heat to surrounding rock. Under the right conditions, water can penetrate into these hot rock zones, resulting in the formation of high temperature geothermal systems containing hot water, water and steam, or steam, at depths of 500 m to >3 000 m (The World Bank, 2000).

Areas of higher than average heat flow also occur at locations far from plate boundaries (*e.g.*, in France and Eastern Europe). Groundwater circulating deeply along fracture zones in these regions can collect heat from large areas and concentrate it in shallow reservoirs, or discharge it as hot springs. The resulting fluids have lower temperatures than those produced in volcanic systems (The World Bank, 2000).

Figure 1. **World pattern of plates, oceanic ridges, oceanic trenches, subduction zones, and geothermal fields**



Source: Dickson and Fanelli, 2004.

Arrows show the direction of movement of the plates towards the subduction zones.
Legend at the lower left:
1. Geothermal fields producing electricity and country name.
2. Mid-oceanic ridges crossed by transform faults (long transversal fractures).
3. Subduction zones.

Even in the absence of water, vast amounts of heat are present in rock at accessible depths (< 5 km). This heat constitutes a potential significant worldwide resource. Investigation into its development and utilisation via enhanced geothermal system (EGS) projects is currently at the cutting edge of geothermal research.

The very shallowest depths of the Earth (~100 m) can also be used to provide a source for both heating and cooling through the application of geothermal heat pumps, which make direct use of the geothermal energy available virtually anywhere on Earth.

Geothermal resources can differ widely from place to place, depending on the temperature and depth of the resource, the abundance of groundwater and the chemical composition of the rock (The World Bank, 2000). Since the technology required to utilise geothermal energy is largely determined by these resource characteristics, technology types and capabilities must also span a wide range.

The general characteristics of geothermal energy that make it of significant importance for both electricity production and direct use include:

- Extensive global distribution; it is accessible to both developed and developing countries.
- Environmentally friendly nature; it has low emission of sulphur, CO_2 and other greenhouse gases.
- Indigenous nature; it is independent of external supply and demand effects and fluctuations in exchange rates.
- Independence of weather and season.
- Contribution to the development of diversified power sources.

Geothermal energy can be used very effectively in both on- and off-grid developments, and is especially useful in rural electrification schemes (*e.g.*, Indonesia and New Guinea). Its use spans a large range from power generation to direct heat uses, the latter possible using both low temperature resources and "cascade" methods. Cascade methods utilise the hot water remaining from higher temperature applications (*e.g.*, electricity generation) in successively lower temperature processes, which may include binary systems to generate further power and direct heat uses (bathing and swimming; space heating, including district heating; greenhouse and open ground heating; industrial process heat; aquaculture pond and raceway heating; agricultural drying; etc.)

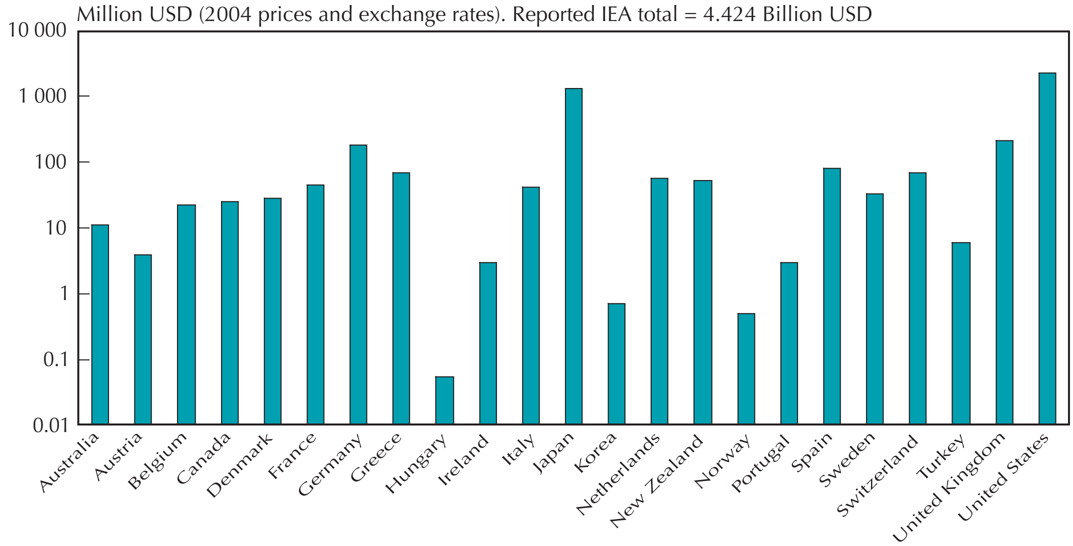
IEA member countries allocated approximately USD 4.1 billion (2004 prices and exchange rates) for RD&D on geothermal energy from 1974-2003 (Figure 2). Governmental RD&D funding is highly concentrated in the United States and Japan, which together account for almost 82% of spending; most other member countries contributed low, one-digit numbers.

Current technology status

Technology development

Geothermal energy, in the form of hot pools and springs, has been used for bathing, balneology, heating and washing purposes in many parts of the world for thousands of years. Electricity was first generated using geothermal energy in 1904, at Larderello (Italy), and it

Figure 2. **Reported government geothermal RD&D budgets in IEA member countries, 1974-2003**



was there that the first commercial generation began in 1913. Geothermal energy has been utilised on a large scale for both direct use and electricity generation for more than 45 years. At present, geothermal resources have been identified in more than 80 countries, with recorded geothermal utilisation in 71 countries. In 2003, total geothermal energy supply was 20 Mtoe, accounting for 0.4% of total primary energy supply in IEA member countries and 7.1% of total renewable energy supply.

In 2004, 24 countries used geothermal energy to generate electricity, with a total installed capacity of 8 902 MW_e, generating 56.8 TWh (Bertani, 2005) (Table 2). This is about 0.3% of the 2003 global electricity production (IEA, 2004a). For comparison purposes, Stefánsson (1998) estimated the worldwide geothermal potential for electricity generation at about 2 000 TWh/a for currently identified resources, and about 11 000 TWh/a for both identified and unidentified resources. This implies that there are sufficient geothermal resources available for electricity generation well into the future.

The history of worldwide installed geothermal capacities from 1975-2005 and electricity generation for 1995-2005 shows interesting trends (Table 2). After a rapid rise during 1975-80, average growth in installed capacity levelled off and has remained linear at about 200 MWe/year for the past 25 years (Figure 3). During the periods 1995-2000 and 2000-05, installed capacities increased by 17.3% and 11.6%, respectively, while corresponding increases in electricity generated were markedly higher at 30.5% and 15.4%, respectively.

The number of countries utilising geothermal energy to generate electricity has more than doubled in the past 30 years, increasing from 10 in 1975 to 24 in 2004. In several countries, installed geothermal capacity and energy generated make very significant national contributions (capacity, generation); in others, installed capacities have increased significantly in the past five years (Table 1). In addition, three new countries - Austria, Germany and Papua New Guinea - recently began generating geothermal power for the first time.

Many of the world's developing nations are located along active tectonic plate boundaries (Figure 1), and hence have good prospects for geothermal resources. Some have already

Table 1. **Countries with significant geothermal contributions**

Countries in which geothermal capacity and energy generated makes significant national contributions			Countries with significant increases in installed geothermal capacities	
	Capacity	**Generation**		**Increase**
Costa Rica	8.4%	15%	Iceland	19%
El Salvador	14%	24%	Indonesia	35%
Iceland	13.7%	16.6%	Kenya	182%
Kenya	11.2%	19.2%	Mexico	16%
Nicaragua	11.2%	9.8%	Nicaragua	10%
Philippines	12.7%	19.1%	Russia	244%

Source: IEA GIA

identified significant geothermal resources; others have begun installing or are already operating major geothermal developments. Consequently, geothermal is well placed to make important contributions to the development of these countries.

The capacity factors for geothermal electricity generation range from approximately 40% to 95%, with an average of about 70% for 21 countries in 1999. In many cases, when geothermal power stations operate as base load, their capacity factors exceed 95% (Hammons, 2004).

Cost of geothermal electricity

Geothermal power plants can range in size from very small (100 kW) to very large (100 MW), depending on the resource and the need. Geothermal technology is suitable for national grid, as well as rural electrification and mini-grid applications. As suggested above, geothermal energy can make significant contributions to the energy needs of developing countries.

The costs of geothermal power depend largely on the character of the geothermal resource and the size of the project, and range from USD 0.025/kWh to more than USD 0.10/kWh (Table 3). Major factors influencing costs are: the resource depth and temperature; well productivity; environmental compliance; economic factors (*e.g.,* scale of development and financing cost); and project infrastructure (The World Bank, 2000).

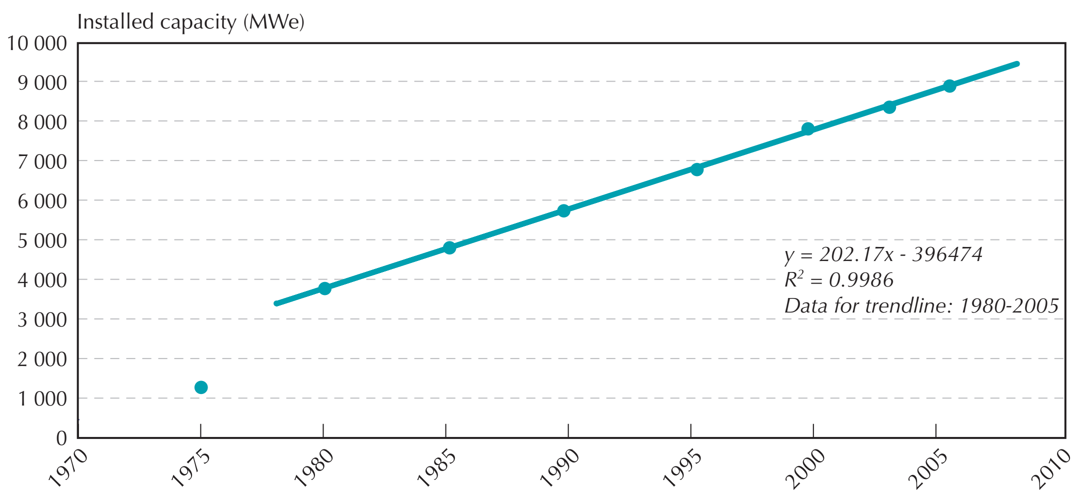
Direct capital costs for geothermal power developments also vary widely (Table 4), ranging from USD 1 150/kW installed capacity for a large plant utilising a high quality resource to USD 3 700/kW installed capacity for a small plant on a low quality resource. Indirect costs - which depend upon the site location and its accessibility, as well as the level of infrastructure and foreign expertise required - range from 5% to 10% of direct costs in a developed country to 10% to 30% in a remote area of a developed country. In a remote area of a developing country, they can rise as high as 30% to 60% of direct costs. Indicative operations and maintenance (O&M) costs for geothermal developments also vary according to the size of the project, ranging from USD 0.008/kWh to USD 0.014/kWh for small plants, from USD 0.006/kWh to USD 0.008/kWh for medium plants, and from USD 0.004/kWh to USD 0.007/kWh for large plants (The World Bank, 2000).

Table 2. **Installed geothermal capacity for 1975-2005 and electricity generation for 1995-2005**

Year	1975	1980	1985	1990	1995	2000	2003	2005
Geothermal Installed Generating Capacity (MW_e)	1 300	3 887	4 764	5 832	6 798	7 974	8 402	8 902
Increase Over Previous Five-year Period (MW_e) (Percent)	-	2 587 (199)	877 (22.6)	1 068 (22.42)	966 (16.6)	1 176 (17.3)	-	928 (11.6)
Electricity Generation (GWh/year)	-	-	-	-	37 744	49 261	-	56 831
Increase Over Previous Five-year Period (GWh/year) (Percent)	-	-	-	-	-	11 517 (30.5)	-	7 570 (15.4)

Source: All data from Bertani (2005), except for 2003, which is from Dickson and Fanelli (2004).

Figure 3. **Worldwide installed capacity for 1975-2005**



Source: Data from Table 2.

Table 3. **Cost of geothermal electricity as a function of resource quality and plant size**

Plant Size (MW)	Unit Cost (USD/kWh)*		
	High Quality Resource (T> 250 °C)	**Medium Quality Resource (T = 150-250 °C)**	**Low Quality Resource (T < 150 °C)**
Small (< 5)	0.05-0.07	0.055-0.085	0.06-0.105
Medium (5-30)	0.04-0.06	0.045-0.07	NNS
Large (> 30)	0.025-0.05	0.04-0.06	NNS

Source: The World Bank, 2000.
** These are costs for single flash separation developments in year 2000 USD assuming a capacity factor of 90% (pers. comm. Entingh, 2004).*
NNS = normally not suitable.

Table 4. **Direct capital costs for geothermal developments**

Plant Size (MW)	Direct Capital Costs (USD/kW Installed Capacity)*		
	High Quality Resource (T> 250 °C)	**Medium Quality Resource (T = 150-250 °C)**	**Low Quality Resource (T < 150 °C)**
Small (< 5)	1 600-2 300	1 800-3 000	2 000-3 700
Medium (5-30)	1 300-2 100	1 600-2 500	NNS
Large (> 30)	1 150-1 750	1 350-2 200	NNS

Source: The World Bank, 2000.
** These are costs for single flash separation developments in year 2000 USD (pers. comm. Entingh, 2004).*
NNS = normally not suitable.

Total costs for geothermal development for electricity production can be subdivided into several categories (Bloomquist and Knapp, 2003):

- Environmental impact assessments for proposed development
  USD 100 000 to USD 1.0 million.
- Reconnaissance
  Up to USD 100 000.
- Exploration programme
  Up to several million USD.
- Well drilling (exploration and production)
  Several million USD per well, with about 60% success rate for exploration wells. Thus, drilling costs are typically 30% to 50% of the total development costs.

The lowest power plant costs are for the rare steam fields (*e.g.*, Larderello and Geysers), where steam from the well is piped directly to the turbine. For the more common high temperature, liquid-dominated systems (*i.e.*, the reservoir fluid is hot water or steam/water mixture), either a single or double flash system is used to separate the steam, which is piped to the turbine. The remaining separated hot water is available for further electricity generation (via a binary plant) and direct use (heat) applications. Binary cycle systems, which use heat from the geothermal fluid to vaporise a secondary fluid that drives a turbine, can operate using lower temperature fluids and are more economic for the lower temperature systems (T <175 °C). Flash system power plant costs are generally higher than those for the steam fields. Although binary systems are generally the most expensive, recent analyses indicate that they are becoming competitive with flash systems, with capital costs of approximately USD 1 800/kW (Entingh, 2004).

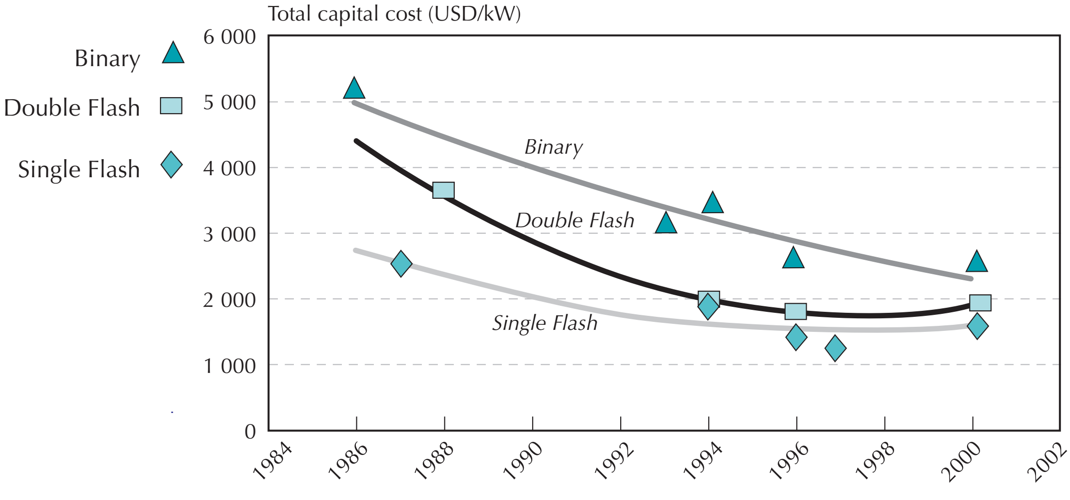
The unit cost of geothermal power decreases rapidly with increasing plant capacity factor, *i.e.*, maximum return is obtained from maximum operation. An increase in plant capacity factor from 50% to 90% would be expected to reduce the cost of producing electricity by almost 50% (Entingh, 2004).

Cascaded use of geothermal fluid at successively lower temperatures allows multiple applications of the original fluid, thereby increasing thermal utilisation efficiency and reducing overall production costs. For example, the separated hot water from a high temperature geothermal power development can be used in a binary cycle plant to produce more electricity at lower temperatures. The water from the binary cycle plant may be used at still lower temperatures in the production of silica and other marketable products (zinc, arsenic, manganese, lithium, etc.) or for direct heat uses (agriculture, aquaculture, district heating, bathing, etc.).

A recent review of the public sector information available on geothermal power development for the period 1986-2000 provides interesting insights (Entingh and McVeigh, 2003).

Figure 4 indicates that capital costs for double flash systems decreased from about USD 3 500/kW in 1988 to about USD 1 800/kW in 2000 (a drop of 49%). Costs for single flash declined from USD 2 500/kW in 1987 to USD 1 500/kW in 2000 (40%). Binary plant costs show the most significant decrease, declining from approximately USD 5 100/kW in 1986 to USD 2 400/kW in 2000 (55%). Consequently, overall costs in geothermal power

Figure 4. **Capital costs for single flash, double flash and binary cycle technologies – USD/kW**



Source: modified from Entingh and McVeigh, 2003.

production fell by almost 50% from the mid-1980s to 2000. As mentioned above, current binary costs can be as low as USD 1 800/kW (a 65% decrease since 1986), making this technology competitive with flash systems (Entingh, 2004).

Clearly, significant cost reductions – as high as 50% – have been realised for both flash and binary technologies over the past 20 years. Binary costs show a continuous decline; flash costs decreased until about 1996-97, then appear to level out - and even increase slightly - in the later 1990s.

Such large cost reductions often result from solving the “easier” problems associated with the early years of science and technology development. Future cost reductions may come in smaller steps and be more difficult to attain.

Current RD&D

Advancement of “mature” technologies

Geothermal energy for electricity and direct heat applications is a mature technology with a long history in many countries. Some estimates project the potential for a substantial growth rate in geothermal electricity production in the next couple of decades. Much of development could be from known suitable resources, particularly in the developing countries of Southeast Asia, Latin America and Africa, where many of the untapped resources are found and demand is growing rapidly. In addition, significant opportunities exist for continued rapid growth in direct heat use, which already experienced a doubling in utilisation between 1995 (112 441 TJ/year) and 2000 (190 699 TJ/year), and again between 2000-05 (261 418 TJ/year) (Table 5: Lund et al, 2005) Geothermal heat pumps contributed greatly to the latter increase (amounting to 33% of the 2005 total direct heat use) and demonstrated that geothermal energy can be utilised almost anywhere in the world, for both heating and cooling (Table 5: Lund et al, 2005).

For geothermal, as with other more technically mature technologies, to achieve the desired and possible accelerated growth, the priority is to become more cost-effective in the market place. In this case, the obstacles include cost and the market's perception of cost. These result partly from the failure of the market place to fully account for the external cost of competing conventional technologies. Another barrier lies in the difficulty of characterising the geothermal resource prior to making a major financial commitment. Other impediments to market penetration arise from a general lack of public awareness and experience with the technologies, and from social and environmental barriers linked to lack of experience with planning, regulation, and gaining public acceptance. As with other renewable energy sources, energy from geothermal resources has significant positive environmental benefits at the global level. However, deployment can have a local impact (mainly for limited-time operations such as drilling), so projects do not always enjoy universal local support.

In addition, the considerable decrease in RD&D public funding, discussed above, has added to the difficulties. Several conditions should be met before government RD&D funding for a “mature” renewable technology is reduced to a minimum level - indeed, it may never be appropriate to stop it entirely. The technology must be understood and fully accepted by financers, energy developers and users, and be relatively cost-competitive with the other energy technologies. It is also especially important that all environmental issues be resolved.

Table 5. **Summary of various worldwide direct-use categories, 1995-2005**

Direct use category	Capacity (MW_t)			Utilization (TW/y)			Capacity Factor		
	2005	**2000**	**1995**	**2005**	**2000**	**1995**	**2005**	**2000**	**1995**
Geothermal Heat Pumps	15 723	5 275	1 854	86 673	23 275	14 617	0.17	0.14	0.25
Space Heating	4 158	3 263	2 579	52 868	42 926	38 230	0.40	0.42	0.47
Greenhouse Heating	1 348	1 246	1 085	19 607	17 864	15 742	0.46	0.45	0.46
Aquaculture Pond Heating	616	605	1 097	10 969	11 733	13 493	0.56	0.61	0.39
Agricultural Drying	157	74	67	2 013	1 038	1 124	0.41	0.44	0.53
Industrial Uses	489	474	544	11 068	10 220	10 120	0.72	0.68	0.59
Bathing and Swimming	4 911	3 957	1 085	75 289	79 546	15 742	0.49	0.64	0.46
Cooling/Snow Melting	338	114	115	1 885	1 063	1 124	0.18	0.30	0.31
Others	86	137	238	1 045	3 034	2 249	0.39	0.70	0.30
Total	**27 825**	**15 145**	**8 664**	**261 418**	**190 699**	**112 441**	**0.30**	**0.40**	**0.41**

Source: Lund et al., 2005.

Market entry of "new" technologies

Several criteria are prerequisites for market entry of new technologies. First, it is necessary to have a technology that is cost-competitive in relation to other energy sources. It is also important to clearly explain the technology and its effects and benefits (social, economical, technical and environmental) to the communities involved. Partnerships between developers and local communities or landowners that own the resource are extremely valuable for gaining support and should be devised in ways that allow benefits to feed back to the community. Informing local, regional and national governments of the possibilities of utilising new technologies for power generation is another important element in helping geothermal gain market entry.

Deployment support is another important aspect of ensuring market entry of new technologies, especially in developing countries. Since local support of a project is very important to its success, it may be a good idea to re-structure some deployment supports such as RD&D.

Governments can also play an important role in market penetration. To encourage the development of "new" technologies, governments could consider positive environmental policies and the reduction of CO_2 emissions. Where feasible, use of new renewable technologies, could be encouraged – particularly in rural electrification and mini-grid power systems.

Additional RD&D priorities

In the case of geothermal energy, several topics are identified as being key to its advancement in the global market place. These are related to cost reduction, sustainable use, expansion of use into new geographical regions, and new applications (GIA, 2003). The priorities are categorised as "general" or specific to RD&D.

General priorities:

- Life-cycle analysis of geothermal power generation and direct use systems.
- Sustainable production from geothermal resources.
- Power generation through improved conversion efficiency cycles.
- Use of shallow geothermal resources for small-scale individual users.
- Studies of induced seismicity related to geothermal power generation (conventional systems and enhanced geothermal systems (EGS)[4]).

Specific RD&D priorities:

- Commercial development of EGS.
- Development of better exploration, resource confirmation and management tools.
- Development of deep (>3 000 m) geothermal resources.
- Geothermal co-generation (power and heat).

4. EGS have been conceived to extract the natural heat contained in high temperature, water-poor rocks in the earth's crust. Heat is extracted from rock formations that are either too dry or too impermeable to transmit available water at useful rates.

- Reduce costs of geothermal well drilling, logging and completion.
- Increase direct use of geothermal resources for space and district heating, and multipurpose "cascading".
- Understand and mitigate environmental effects.

Additional spending would provide significant, and possibly necessary, assistance to complete the current RD&D priorities within a time frame that enables geothermal to make significant contributions to meeting accelerating worldwide energy demands. It would also make it possible to investigate new topics that have become internationally important such as: a) optimising production rates to secure longevity of resources and support sustainability of geothermal utilisation; and b) investigating induced seismicity related to conventional and EGS geothermal power generation.

Costs and benefits of additional RD&D

More renewables RD&D funding is necessary if renewable energy sources, including geothermal, are to make the major contributions desired and expected. In several countries, recent funding cuts to geothermal have created a situation in which RD&D has been cut back to basic levels and expertise is being lost due to job cuts. More funding would help stem – and maybe reverse – both trends, while also facilitating acquisition of the manpower needed to realise more rapid achievement of the identified priorities.

The benefits would include extending the use of geothermal, for both power generation and direct heat use, to areas far from tectonic plate boundaries and covering much larger regions. Geothermal could provide dependable, affordable, environmentally friendly power to areas now without power or where power is currently provided by oil. Increased efficiencies in power production would be expected from development of deeper, hotter geothermal resources, as well as from more effective use of resources through co-generation and cascading systems. Mineral extraction from geothermal fluids could also reduce energy costs, generate revenue through mineral sales, and make the final fluid more environmentally acceptable.

Conclusions

Geothermal represents large global potential in renewable resources and has a proven ability to provide electricity and heat for a variety of direct uses in many regions of the world. In addition, it can supply domestic or district heating and cooling, through the use of ground-source heat pumps, virtually anywhere.

Several barriers to this technology must still be overcome to make significant advances in the global market place. A major one is cost and several priority RD&D areas have been identified where significant progress will help accelerate worldwide advancement. These areas include EGS, development of deep resources, further cost reduction of drilling and so on.

Another important and necessary element of the global energy strategy is the development and use of geothermal energy and other renewables in association with distributed generation.

Government support of renewables technology RD&D, education and skills transfer, and effective private-public co-operation are vital to advancing the use of renewables, especially in developing countries.

Since the large overall reduction in government renewables RD&D funding in the early 1980s, geothermal has felt the brunt of the decrease. This is compounded by the small contribution from industry; there is a need for government to stimulate their participation.

Thus it is also essential to inform governments, industry and the public about geothermal energy; its capabilities and benefits, and the RD&D required to extend its use.

Current activities of IEA Geothermal Energy Implementing Agreement

The IEA Geothermal Energy Implementing Agreement (GIA) officially went into effect on 7 March 1997, being designed to operate for an initial period of five years. In late 2001, the GIA's mandate was extended for another five-year term, to 31 March 2007.

The GIA provides an important framework for wide-ranging international cooperation on geothermal issues. It brings together important national programmes for exploration, development and utilisation of geothermal resources, emphasising the assemblage of specific expertise and increasing effectiveness by establishing direct cooperative links among the geothermal experts in the participating countries. The GIA's present activities are directed primarily towards the coordination of the ongoing national programmes of the participants.

As of October 2005, the European Commission (EC) and ten countries: Australia, Germany, Iceland, Italy, Japan, Korea, Mexico, New Zealand, Switzerland and the United States were members.

The GIA is currently pursuing five active RD&D programmes as part of its action plan to support and advance geothermal energy in the market place (Table 6). These programmes are all task-shared, with participants providing their own financial support, principally from public funds. In addition, the GIA added new sub-Tasks pertaining to induced seismicity in EGS and field studies of EGS reservoirs (to Annexes I and III, respectively). Two other new Annexes are currently in draft form.

Table 6. **Current projects of IEA Geothermal Implementing Agreement**	
Project	**Outline**
Environmental Impacts of Geothermal Energy Development	Encourage sustainable development of geothermal resources in an economic and environmentally responsible manner; quantify adverse or beneficial effects that geothermal development may have on the environment; devise and adopt methods to avoid, mitigate or minimise such impacts.
Enhanced Geothermal Systems (EGS)	Address new and improved technologies, which can artificially stimulate a geothermal resource to enable commercial heat extraction.
Deep Geothermal Resources	Address issues relevant to commercial development of geothermal resources at depths of >3,000 meters.
Advanced Geothermal Drilling Techniques	Pursue advanced geothermal drilling research and investigate all aspects of well construction with the aim of reducing costs associated with this essential and expensive part of exploration, development and utilisation. The consequences of reducing cost are often impressive; drilling and well completion can account for more than half of capital costs.
Direct Use of Geothermal Energy	Define and characterise direct use applications for geothermal energy, with emphasis on defining barriers to widespread application; identify and promote opportunities for new and innovative applications; define and initiate research to remove barriers, enhance economics and promote implementation; test and standardise equipment; develop engineering standards.
Sustainability of Geothermal Energy Utilisation	Estimate production of energy from geothermal resources under different scenarios, with a view to determining optimal production strategies to secure the longevity of resources.
Geothermal Power Generation Cycles	Investigate reference scenarios as a basis to compare cycles, plant performance and availability, economics, and environmental impact and mitigation.

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Chapter 3 • Technologies

Wind energy

Highlights

- Wind energy is a global market place; whilst some well-established markets such as Denmark, Germany, Greece, Sweden and the United States are slowing, others in Europe, Asia, Canada and Australia are stepping in to maintain a very positive picture.
- In 2003, total wind energy supply was 5.0 Mtoe, accounting for 0.1% of total primary energy supply in IEA countries. The share of wind energy in renewable energy supply was 1.8%.
- Global growth in 2004 matched that of 2003 at 21.1%, sustaining the very high level seen over the last decade. Global wind capacity reached 47.5 GW by the end of 2004. Off-shore wind accounted for 1.2% of the total global wind capacity.
- Average capital costs for complete wind farms vary according to country, but range generally from USD 1200/kW to USD 1550/kW of installed capacity.
- Between 1981-98, production costs of wind turbines decreased by a factor of four. Today, wind energy is cost competitive with other forms of electrical generation at locations with a good wind resource. Thanks in a large part to successful RD&D, the wind energy market is in a state of rapid development.
- The cost of wind-generated electricity has fallen steadily for the past two decades, driven largely by technological development, increased production levels, and the use of larger machines. In many areas of the United States, the projected cost of energy for utility-scale production can be as low as USD 0.04/kWh to USD 0.06/kWh. The costs of energy in Norway, New Zealand, Ireland, Greece and Finland were comparable to United States' values.
- During the last five years, industry RD&D placed emphasis on developing larger and more effective wind turbine systems, often utilising knowledge developed from national and international generic RD&D programmes.
- Continued RD&D is essential in order to provide the reductions in cost and uncertainty needed to realise the anticipated level of deployment; it will also support both incremental improvements and revolutionary new ideas. Further investigation will improve understanding of how extreme wind situations, aerodynamics, and electrical generation affect wind turbine operation – and may indeed influence future design.
- Priority research areas include increasing value and reducing uncertainties, continuing cost reduction efforts, enabling large-scale use, and minimising environmental impacts.

Introduction

Globally, in the short- to medium-term, wind energy will be exploited predominately in the generation of electricity through on-shore and, increasingly, off-shore installations. In the longer term, there is also high potential for integrating wind and other renewables within the complete energy supply system. Activities will, therefore, also examine the use of wind energy in non-electricity generating applications (*e.g.,* desalination) and within energy systems such as those exploiting hydrogen and other forms of energy storage.

For the mid-term time frame, RD&D areas of major importance for future deployment of wind energy are forecasting techniques, grid integration, public attitudes and visual impact. RD&D to develop forecasting techniques will increase the value of wind energy by allowing electricity production to be forecasted from six to 48 hours in advance. RD&D to facilitate integration of wind generation into the electrical grid – as well as on demand-side management – will be essential when it becomes necessary to transport large quantities of wind-generated electricity through grids. RD&D designed to provide information on public attitudes and the visual impact of wind developments will be necessary to adequately consider such concerns during the deployment process for new locations for wind energy (especially off-shore).

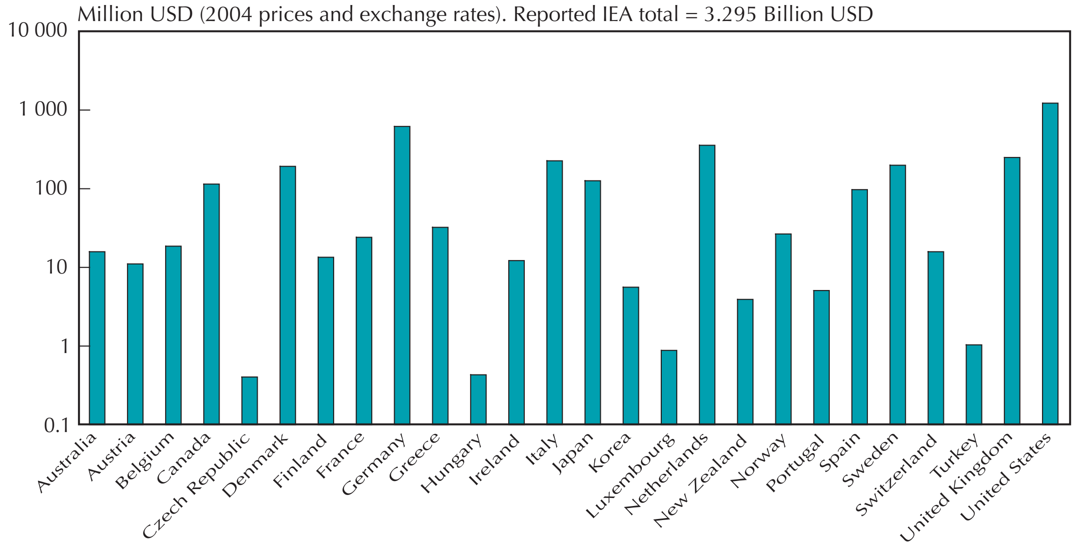
For the long-term time frame, it is vitally important to pursue the RD&D necessary to take large and unconventional steps to make wind turbine and its underlying infrastructure interact in close co-operation. Adding intelligence to the complete wind system, and allowing it to interact with other energy sources, will be essential in areas of large-scale deployment. RD&D to improve electrical storage techniques for different time scales (minutes to months) will increase value at penetration levels by more than 15% to 20%. There is a need to balance efforts for continued long-term research supported by the public sector and internal product development and research carried out within the industry.

IEA member countries reported approximately USD 3.3 billion (2004 prices and exchange rates) for RD&D on wind energy from 1974-2003 (Figure 1). The United States accounted for about 34% of governmental RD&D funding. Other member countries, including Germany, the Netherlands, Sweden, the United Kingdom, Italy, Denmark, Japan and Canada, also reported three-digit numbers of millions USD on wind energy, together amounting to about 57% of RD&D budgets for this technology.

Wind energy is expected to continue to show the very strong growth now experienced for many years. Wind energy is a global market place and whilst some well-established markets such as Denmark, Germany, Greece, Sweden and the United States are slowing, others in Europe, Asia, Canada and Australia are stepping in to maintain a very positive picture (Table 1).

Global growth in 2004 matched that of 2003 at 21.1% (Table 1), sustaining the very high level seen over the last decade. (Figure 2) Within the IEA countries reporting on wind RD&D, growth reflected the global picture at 19.5%, which would be expected because IEA member countries account for 90.7% of the world's installed capacity. This is a very strong performance and expectations for the coming years are of continued high growth, which has been sustained at approximately 30% per year since 1994. At the end of 2004, the global wind capacity reached 47.5 GW. Total installed capacity in the IEA RD&D wind countries reached 42.5 GW including 577.5 MW of off-shore capacity, a share of 1.4% (Table 1).

Figure 1. **Reported government wind energy RD&D budgets in IEA countries, 1974-2003**



In 2003, the combined output of all the turbines within the IEA member countries reporting on wind RD&D generated electricity equivalent to more than the entire needs of Switzerland or nearly twice that of Denmark. This was approximately 64 TWh, up 26% from the previous year. Globally, it is estimated that wind generated approximately 67 TWh of electricity in 2003. Expressed in Mtoe, wind energy supply amounted to 5 Mtoe, accounting for 0.1% of total primary energy supply in IEA countries. Thus wind energy's share in IEA renewable energy supply was 1.8%.

The value of new wind installations worldwide is estimated at USD 7 billion for 2003. This figure is based on an average total project cost of USD 1000/kW installed, excluding operation and maintenance costs.

Current technology status

A brief history

In the mid-1970s, the oil crisis prompted investigations into energy sources derived from material other than fossil fuels. Wind energy was considered one such energy source that could reduce dependency on fossil fuels. Various designs of wind energy systems were tested and at last, the propeller type, horizontal axis wind turbine was identified as the most promising system for converting the kinetic energy of wind into electricity.

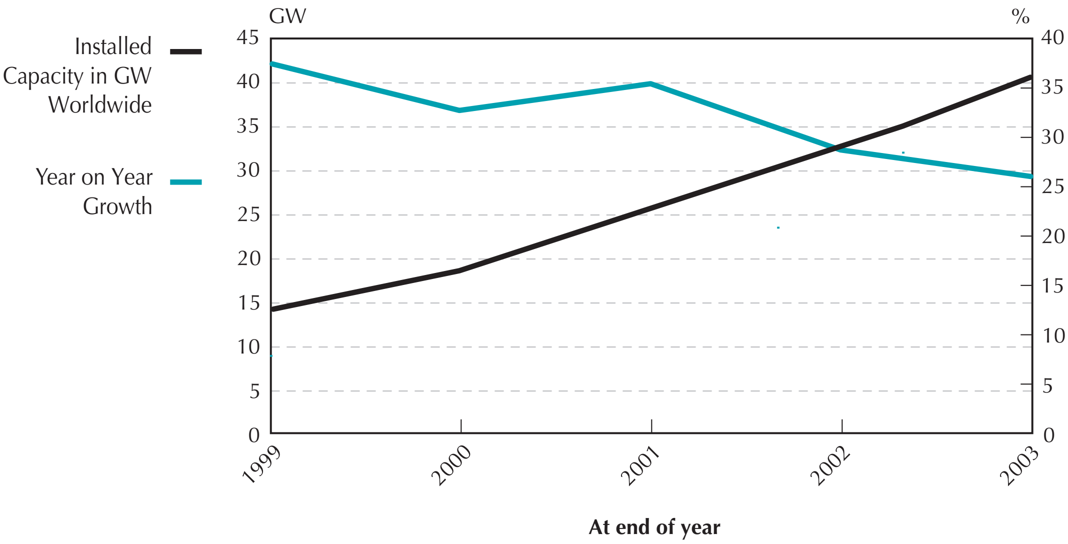
Two kinds of groups began to carry out efforts to develop effective wind turbines. The first one, working within governmental programmes, focused on big, multi-megawatt wind turbines that would be operated by utilities. The second group consisted of activists and entrepreneurs building small turbines, starting at 20 kW. Both groups discovered that designing wind turbines was far more complicated and costly than initially expected.

Table 1. **Global installed wind capacity**

Country/ Region	Capacity at Year end 2003 (MW)	New Capacity (MW)	Offshore Capacity at Year-end 2004 (MW)	Total Capacity at Year-end 2004 (MW)
Australia	198.0	182.0		380.0
Austria	414.0	193.0		607.0
Belgium	67.6	29.4		97.0
Canada	317.0	127.0		444.0
Denmark	3 115.0	3.0	406.0	3 118.0
Finland	47.0	35.0		82.0
France	198.0	192.0		390.0
Germany	14 609.0	2 020.0		16 629.0
Greece	424.0	43.6		467.6
Ireland	189.0	71.2	25.2	260.2
Italy	908.0	357.0		1 265.0
Japan	506.0	434.0		940.0
Mexico	2.2			2.2
Netherlands	905.0	167.0		1 072.0
New Zealand	35.9	132.1		168.0
Norway	100.0	60.0		160.0
Poland	58.0			58.0
Portugal	298.0	264.0		562.0
Spain	6 202.0	2 061.0		8 263.0
Sweden	404.0	38.0	22.5	442.0
Switzerland	5.4	3.5		8.9
United Kingdom	647.6	253.2	123.8	900.8
United States	6 381.0	359.0		6 740.0
China	566.0	198.0		764.0
Cost Rica	71.0			71.0
Egypt	69.0	76.0		145.0
India	2 120.0	863.0		2 983.0
Morocco	54.0			54.0
Ukraine	51.0	6.0		57.0
Rest of World	241.0	112.0		353.0
Grand Total	**39 203.7**	**8 461.7**	**577.5**	**47 483.7**

Source: IEA, 2005

Figure 2. **Installed cumulative capacity and growth rates per year**



Source: EWEA, 2004.

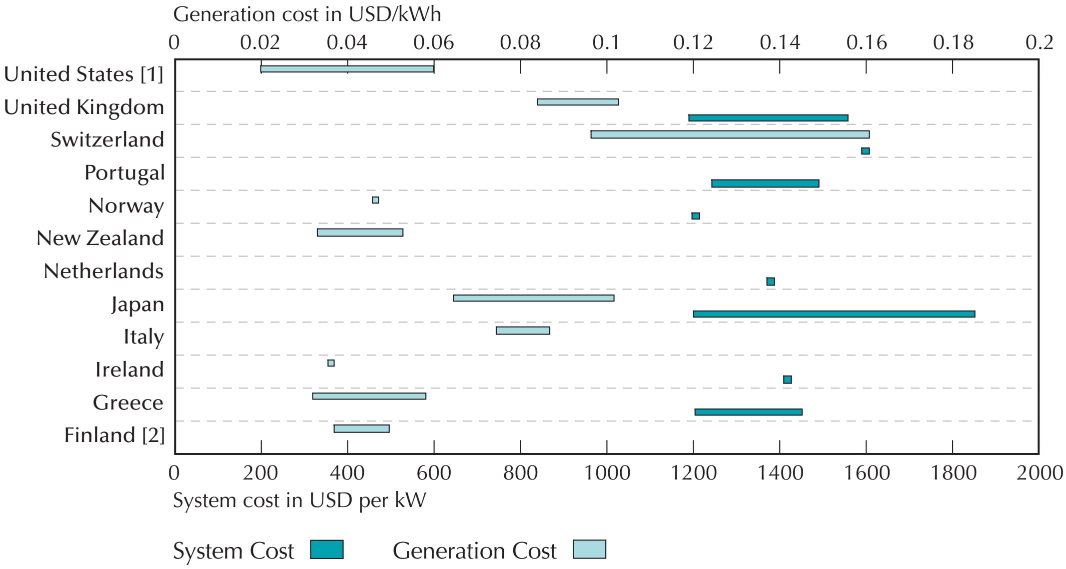
At the time, the design knowledge base was rudimentary or outdated. The need for RD&D was identified at an early stage and, as a result, many countries initiated national RD&D programmes. Early studies demonstrated that existing knowledge in meteorology, electrical machinery, and aeronautical fields could be applied in wind engineering. Accordingly, wind energy research organisations were, to a large extent, coupled to meteorological and aeronautical research institutes and universities. As time passed and knowledge increased, research topics were directed towards more specific questions relevant to wind technology (*e.g.,* wind modelling, resource assessment, aerodynamics, and structural dynamics). To illustrate the application of the technology, a number of MW-size demonstration programmes were established in the early 1980s. Their main objectives were to improve technology and system integration in order to demonstrate feasibility.

Commercial turbines appeared on the market around 1980, coinciding with the boom in market demand for small turbines (50 kW to 200 kW) in Denmark and California. In spite of the good market conditions, many companies went bankrupt due to technical problems and poor understanding of loads interacting with the wind turbine. The demonstration programmes of MW-class machines in the United States, Germany, Denmark, and Sweden also had problems, mainly related to fatigue. These prototype turbines provided useful information of system behaviour, which was applied in later years.

Later in the 1980s, wind turbines became larger (250 kW to 300 kW). Market demand increased mainly due to subsidies and tax credits. However, an expected lifetime of 20 years was difficult to achieve because of reliability and system integration problems. The technology could not compete economically without support.

In the beginning of the 1990s, wind turbines became larger again and were installed in small groups called wind farms. Increasing national RD&D programmes promoted the trend towards larger turbines with a standard size of around 500 kW. This period's engineering challenges related to the bigger turbine size and the conditions turbines experienced in wind

Figure 3. **Comparison of onshore wind system and generation costs**



Source: IEA, 2005.

1. Generation costs include an investment subsidy of 30%.
2. Value of USD 0.02 includes available tax credits and refers to lowest bids given in tender auctions.

farms. Problems related to fatigue were reduced through better understanding of the interaction between loads and structures. But the market was turbulent: new companies appeared, smaller companies were purchased, and new collaborations were formed.

Throughout the remainder of the 1990s, turbine sizes increased further. At good wind sites, wind turbines started to become competitive with traditional fossil fuel and nuclear energy generation. The number of turbines in each wind farm also grew. In some areas, resulting penetration of wind-produced electricity on the grid was high, from time to time reaching 100%, creating a need to develop knowledge of power quality and interaction with weak grids. Taylor made electric generators were developed, thereby substantially improving grid connection and at the same time reducing loads to the mechanical structures of wind turbines. In addition, there was the need to find new locations off-shore and in complex terrain where wind resources were strong. Around the world, new developments in standardisation and design codes supported market development and international trading.

Cost of energy

The cost of wind-generated electricity has fallen steadily over the past two decades, driven largely by technological development, increased production levels, and the use of larger machines. In many areas of the United States, the projected cost of energy for utility-scale production can be as low as USD 0.04/kWh to USD 0.06/kWh, given an excellent resource and MW-plus scale turbines (IEA, 2005). The cost of energy in Norway, New Zealand, Ireland, Greece and Finland were comparable to United States' values. Costs are somewhat higher in the UK, Japan and Italy. In Switzerland, the highest costs are reported as USD 0.1/kWh to USD 0.16/kWh (Figure 3). In Switzerland good wind power locations however are situated at altitudes starting at 800 m above sea level in hilly or mountainous country with difficult climatic conditions (ice, cold), turbulent wind, difficult access and landscape protection problems (IEA, 2004b).

Capital costs

For complete wind farms, the estimates of average cost vary according to country, between USD 1 200/kW to USD 1 550/kW of installed capacity. In Japan the highest costs – up to USD 1 850/kW for small installations – are reported (Figure 3), which reflect additional transport costs resulting from turbine imports from Europe and the United States. Average installation costs may also be higher because of mountainous terrain (IEA, 2004b). In reality, system costs have a range that depends on location, project size and other factors. The cost of the turbine and tower alone can vary between USD 800/kW and USD 1 150/kW, with USD 950/kW being typical. These costs show a split of roughly 75% for the turbine (including tower) and 25% for the balance of plant (foundations, electrical infrastructure, and roads) (IEA, 2005).

For the recent MW-plus machines, the installed costs per unit capacity might not be lower, but overall economics continue to improve. This is because the turbines are on taller towers, which places them in zones of higher wind speeds and, thus, improves energy yields.

Operating costs

Operating costs on turbines include servicing, repairs, site rental, insurance, and administration. A thorough study, conducted in Denmark, tracked operating costs for turbines in the size range of 150 kW to 600 kW. It shows near contemporary turbines (500 to 600 kW) having annual operating costs steadily increasing from 1% of the investment cost in the first year to 4.5% after 15 years. These figures are consistent with Portuguese estimates of 2% to 4% and Dutch estimates of 3.4% for smaller projects. Maintenance and repair costs account for roughly one-third of total operating costs (IEA, 2005).

Performance

Cost of energy is the correct economic performance measure for wind turbines. In general, installed turbines perform well with few operational difficulties. On average, commercial plants operate with availabilities of more than 98%. Finland reports lower availabilities, resulting from the turbines operating in extremely cold climates. Capacity factors are typically between 0.20 and 0.35, depending on the wind speed and the turbine used. Spain reported an average capacity factor of 0.21 for 2003, and the United States estimates an average capacity factor of 0.29. Capacity factors for wind turbines installed in Ireland to date generally exceed 0.35, and capacity factors exceeding 0.40 are not uncommon (IEA, 2005).

Turbine life

Wind turbines are designed with a lifespan of 20 years or more. Consumables, such as gearbox oil and brake pads, are often replaced at intervals of one to three years. Parts of the yaw system might be replaced every five years and vital components exposed to fatigue loading (*e.g.,* main bearings and gearbox bearings, etc.) might be replaced once in the design life. A cost model developed in Denmark (based on statistics from 1991, 1994 and 1997) includes a re-investment of 20% of the turbine cost in the 10th year, financed over the following ten years. The average age of machines on the German Scientific Measurement and Evaluation Programme is ten years; to date, no significant increase in failures with operational time has been found (IEA, 2005).

Reliability

Overall reliability can be considered high, as reflected in the availabilities achieved. Occasional component faults affect a large number of operating machines and, over the years, there have been several such cases involving gearboxes and blades. These require large retrofit programmes, typically conducted at the expense of the component or turbine manufacturer (IEA, 2005).

In 2003, two rare events caused turbine failures in Japan and Portugal. An exceptionally powerful typhoon struck Miyako Island (Japan), causing severe damage to a wind farm of seven turbines. Three had tower failures, three lost their blades, and one lost its nacelle cover. In Portugal, a succession of unlikely problems contrived to cause the over-speed and collapse of a single Mitsubishi 500 kW wind turbine. Problems arose with a grid loss, followed by the failure of two rotor over-speed protection systems. The failure was attributed primarily to a poorly installed blade, set to the wrong pitch angle during routine maintenance (IEA, 2005).

Clearly the level of maintenance affects turbine life. In Germany, it is estimated that one permanent service person is required for every 20 MW installed (IEA, 2004a).

Current RD&D

In 1995, the need for continuing RD&D was discussed at a Topical Expert Meeting sponsored by the IEA RD&D Wind Implementing Agreement. Participants concluded that:

"… we have now reached a stage where the industry should be able to foot a larger share of the RD&D bill. Also the fact that the industry has moved from the pre-competitive phase into the competitive stage indicates, that most of the product and component development should take place within the companies. However, there was consensus on the view, that there is still a need for basic, generic research to be carried out outside the companies and wholly or partly funded by public money, and that this need will continue as long as there is wind energy development" (IEA, 2001).[5]

These conclusions are still valid today. During the past five years, industry RD&D efforts emphasised developing larger and more effective wind turbine systems, utilising knowledge gained from national and international generic RD&D programmes.

Most grid-connected wind energy markets operate with a supporting policy framework. Consequently markets and the mechanisms used to establish them are of great interest and relevance to all member countries and further supports are considered valuable. Support

5. Ad Hoc Group Report to the Executive committee of the International Energy Agency Implementing Agreement for Co-operation in the Research and Development of Wind Turbine Systems.

mechanisms have evolved over the past two decades, creating a wealth of experience. However, the current scenario is complicated by liberalisation of electricity markets, wide variations in overall energy and environmental policies, and the historic investments and support for conventional generation industries. There is a drive to establish a level of harmonisation in Europe that enables international trading of energy and environmental credits. Such trading mechanisms aim to help meet overall pollution and emission reduction commitments.

While IEA member countries identify support mechanisms as relevant to their national situations, the Agreement itself is thought to be only partially appropriate as a means of addressing them. This may stem from the strong RD&D role of the Agreement and the bias of the group. In spite of this, a majority of participants remain in favour of some activity in the area of support mechanisms.

Up to the close of 2003, most grid-connected wind generation received government- or state-led incentives. The main market stimulation instruments used in IEA countries include a combination of capital subsidy and the payment of premium prices for energy produced. Increasingly, premium prices are preferred to capital investment subsidies. Premium prices come in several different forms, ranging from a pre-determined fixed pricing regime (*e.g.,* Germany, Spain and most recently by Korea) to a separate free market for green certificates to increase the value over the selling price of the electricity alone (*e.g.,* the United Kingdom, the Netherlands and Italy). The principal drivers of wind energy development in North America are tax incentives in the United States and generation subsidies in Canada.

RD&D has been an essential activity in achieving the cost and performance improvements in wind generation to date. Continued RD&D is essential in order to provide the reductions in cost and uncertainty needed to realise the anticipated level of deployment; it will also support both incremental improvements and revolutionary new ideas. Further investigation will improve understanding of how extreme wind situations, aerodynamics, and electrical generation affect wind turbine operation – and may indeed influence future design. The challenge is to try to find those evolutionary steps that can further improve wind turbine technology. Consider the example of attempts to achieve large-scale integration of wind turbines into the electric generation grid: incorporating wind-forecasting results and information on grid interaction with other energy sources may eliminate uncertainties that would otherwise inhibit development of the technology in deregulated electricity markets.

Additional RD&D priorities

There is strong support for continued activity in all the areas of wind energy RD&D, with no issues taking precedence over others. However, two topics are key: off-shore wind development and the role of wind energy within hydrogen-based energy supply systems. Off-shore wind energy, although in its infancy, is increasingly seen as a vital element of renewables development in several IEA member countries. Technology and environmental issues raised by off-shore wind energy development are the subject of much research and are likely to form an important part of future activities. In addition to using wind energy for electricity production, the technology could be applied to other energy applications in the longer term - particularly hydrogen generation.

Priority research areas identified include:

- Continue cost reduction.
- Increase value and reduce uncertainties.
- Enable large-scale use.
- Minimise environmental impacts.

Continue cost reduction

Improved site assessment and identifying new locations, especially off-shore – Sites with high winds are crucial for economic utilisation of wind energy. One key fact is not yet sufficiently recognised: energy production is related to mean wind speed to the power of three. In practical terms, this means that a 10% increase in wind speed will result in an energy gain of 33%. Improved site assessment and siting require better models and input from measurements. Another aspect of improving site assessment relates to finding better measures to predict extreme wind, wave and ice situations – at different types of locations and in wind farms. This may eventually make it possible to design site-specific systems that can utilise cheaper, lighter and more reliable turbines.

Better models for aerodynamics and aeroelasticity – Improved methods for predicting 3-D aerodynamic behaviour and aeroelastic stability are essential for calculation of loads on turbines. With the increasing size of turbines, new stability problems can occur. Solving the aeroelastic problems is a prerequisite for reliable up scaling. Incorporation of such methods in aeroelastic models of the whole wind turbine, including the electric system is essential for optimised turbines that eventually will lower the weight and thus price.

New intelligent structures/materials and recycling – Wind turbines operating in the wake of another turbine are exposed to excessive loads due to wind-speed deficits behind the upstream turbine. Reducing loads by improving design and adding intelligence to individual turbines in a wind farm will help optimise land use. Intelligent materials that utilise adaptive control and interact with the structure can also be used to reduce strains and/or to control aerodynamic forces. In addition, development of new materials that can participate in natural recycling processes would help decrease environmental impact – and increase the value – of wind turbines. For example, new ways to decommission glass fibre blades are essential.

More efficient generators, converters – Current generator technology results in large and very heavy machines. Finding viable concepts and improving the design of direct-driven generators are two areas that show great potential for manufacturing more efficient and lighter machines. It is also important to find combined solutions for electricity generation and transmission, from low voltage alternating current (AC) to high voltage direct current (DC). Ideally, this would be combined with achieving an adaptable power factor (cos phi) and high power quality (low harmonic content and flicker frequency). It may be possible to reduce the cost of transmission lines by adding power plant characteristics to individual wind turbines or by utilising spinning reserve.

New concepts and specific challenges – Specific challenges include fly-by-wire concepts, adding intelligence to the turbine, and incorporating aspects of reliability and maintainability. Condition monitoring of components, such as blade bearings and generators, could reduce O&M costs - an aspect that is especially interesting for remote locations both on land and off-shore. New concepts could include such things as highly flexible downwind machines and diffuser-augmented turbines.

Stand-alone and hybrid systems – Stand-alone turbines will be built in vast numbers, but the installed total capacity may not be large. Still, the value of electricity from these machines can be of great importance, particularly in the case of remote locations where grid connection is not feasible. Integrating wind generator systems with other power sources, such as photovoltaic solar cells (PV) or diesel generating systems, is essential in small grids that require high reliability.

Increase value and reduce uncertainties

Forecasting power performance – The value of wind energy will increase if reliable predictions of power output can be made on different time scales such as six to 48 hours in advance. This requires model development and strategies for online introduction of data from meteorological offices, as well as actual production figures from wind turbines in large areas. Current models have an uncertainty of 15% to 20%. Improvements are possible and could lead to a reduction in uncertainty, which can yield 5% to 10%.

Engineering integrity, improvement and validation of standards – RD&D activities in many fields of wind engineering will support background basics for standardisation work. The market-driven up-scaling and off-shore applications for wind energy require better understanding of extreme environmental conditions, safety, power performance and noise. Development of international standards is essential for the successful deployment of wind energy in different countries. This work will also help remove trade barriers and, indeed, facilitate free trade.

Storage techniques – Effective storage of electricity could enhance the value and reduce the uncertainty of wind generated electricity by making it possible to level out delivered power. This is especially important when penetration levels rise above 15% to 20%.

Enable large-scale use

Projections of installed capacity indicate that deployment figures will increase during the next 20 years. The contribution of wind generation will be substantial on a local and/or national level. This will put unique demands on the transmission grid and its interaction with the wind turbine generation units.

Electric load flow control and adaptive loads - Development of tools for modelling and controlling energy supply to the electric grid will be essential to large-scale deployment of wind energy, especially in areas where the share of wind energy is high. Combined technologies for generation and transport of large quantities of electricity will need to incorporate innovations in automatic load flow controls, adaptive loads and demand-side management. Extensive use of high capacity power electronic devices for high voltage DC (HVDC) links will also be required in national networks. In addition, there is a need to study concepts for storage and AC/DC concepts in co-operation with other energy sources.

Better power quality – Improvements to grid stability are a main concern, as is the ability to correct grid deficiencies (*e.g.,* voltage drops and flicker) especially in weak grids.

Minimise environmental impacts

Finding suitable locations in terms of wind potential - at which there is also general acceptance for implementing wind turbines – has become increasingly complicated. Conflicting land-use goals amongst different interest groups is becoming more pronounced. Thus, the following topics warrant serious investigation.

Compatible use of land and aesthetic integration – The environmental advantages of wind energy (*e.g.,* reduced emissions of CO_2 and other green house gases) must be conveyed to the public. Public attitudes toward wind energy must be incorporated into the deployment process to ensure that issues related to visual impact and interacting land-use concerns of different interest groups are adequately considered.

Noise studies – Understanding noise generation and transportation across large distances is essential; challenges off-shore relate to the acoustically hard water surface. Initial estimations that wind turbines may emit more noise off-shore without disturbing on-shore dwellings must be studied further. In addition, better methods for design and prediction of noise must be validated against actual experiences.

Flora and fauna – Careful consideration of interaction between wind turbines and wildlife must be incorporated in the deployment process. This requires better understanding of background data and the behaviour of various species in both on-shore and off-shore environments.

Table 2. **Research priorities in the mid- and long-term time frame**

Area	**Focus on**	**Time Frame/ Priority**	
		Mid-term	**Long-term**
Increase value and reduce uncertainties			
Forecasting power performance	Increase value of electricity	++	
Reduce uncertainties related to engineering integrity, improvement and validation of standards	Supply background material	++	
Storage techniques	Storage for different time scales		++

Table 2. **Research priorities in the mid- and long-term time frame (continued)**

Area	Focus on	Time Frame/ Priority Mid-term	Time Frame/ Priority Long-term
Continue cost reductions			
Improved site assessment and new locations, especially offshore	Extreme wind and wave situations, forecasting techniques	++	
Better models for aerodynamics/aeroelasticity	3-D effects, aeroelastic stability	++	++
New intelligent structures/materials and recycling	Extremes, adaptive intelligent structures, recycling		++
More efficient generators, converters	Combined solutions for generation and transmission	++	+
New concepts and specific challenges	Intelligent solutions for load reduction		+
Stand-alone and hybrid systems	Improved system performance	++	
Enable large scale use			
Electric load flow control and adaptive loads	Improve models, load flow control, power electronics		++
Better power quality	Power electronics	++	
Minimise environmental impacts			
Compatible use of land and aesthetic integration	Information and interaction	++	
Noise studies	Offshore issues	++	
Flora and fauna	Background data	++	

++ denotes high priority.
+ denotes priority.
Source: IEA, 2001.

Costs and benefits of additional RD&D

The benefits of past RD&D in the wind energy sector are clearly demonstrated by the increasing sizes of turbines and the lower prices per installed production capacity of electricity. Between 1981 and 1998, production costs of wind turbines decreased by a factor of four. The future looks even more promising as the cost of wind energy in 2020 is projected to be USD 0.025/kWh (projection based on installed capacity of 80 GW in 2010 and 1 200 GW by 2020) (BTM,1999,2000).

Thanks in large part to successful RD&D, the wind energy market is currently in a state of rapid development. The market for wind turbine generators is growing faster than the personal computer industry and almost as quickly as the cellular phone market. In the past three years, a number of growth studies regarding wind energy were undertaken. One study called Wind Force 10, presents a scenario for producing about 3 000 TWh of electricity from wind by 2020 (EWEA, 2004), corresponding to approximately 12% of the expected world electricity consumption in that year. Under this scenario, the annual investment needed to achieve this goal would be USD 7 billion in 2003 and USD 81.2 billion by 2020. This level of development would increase employment in the wind industry and supplying sector from about 237 000 people in 2004 to 2.4 million in 2020. The environmental benefit from this scenario would be an annual reduction of CO_2 emissions of 1 832 million tonnes by 2020.

Current activities of IEA Wind Energy Systems Implementing Agreement

The mission of the IEA Wind Energy Systems Implementing Agreement (Wind IA) is to stimulate co-operation on wind energy research and development and to provide high quality information and analysis to both member countries and commercial sector leaders. Thus, Wind IA initiatives should address technology development and deployment, while also providing objective information about the benefits of wind energy. They should also seek to develop markets and policy instruments that support the use of wind energy.

One of the most important ways in which the Wind IA can enable deployment is by finding ways to reduce costs and overcome barriers to encourage a diverse, secure and sustainable energy supply. Further, the Agreement has a mandate to produce objective information and analysis that will inform government policy rather than directly generating policy advice. The Wind IA is expanding both internal and external information exchange. It publishes newsletters presenting results from task work, joint actions, recommended practices, and analysis of implementation progress. In addition, policies are published and described in various public conferences and forums. The Wind IA enables highly informed exchanges on national government-supported programmes and findings, and is ideally placed to establish effective collaboration on basic research.

In addition to government-sponsored RD&D, considerable effort and resources are invested within the commercial sector by the manufacturing industry, developers, and consultancy services, and in providing the physical infrastructure. In 2005, the Wind IA comprised 23 contracting parties. Wind IA participants are currently pursuing six programmes (Table 3). In this way, Wind IA activities provide a vital forum for international co-operation that can accelerate cost reduction and enable more rapid deployment.

Table 3. **Current projects of IEA Wind Energy Systems Implementing Agreement**

Project	Outline
Base Technology Information Exchange	Further development of wind energy conversion systems through co-operative action and information exchange.
Wind Energy in Cold Climates	Gather and share information on wind turbines operating in cold climates.
HAWT Aerodynamics and Models from Wind Tunnels Tests and Measurements	Compare theoretical aerodynamics model predictions of wind turbine blade and structural performance and load with actual measurements.
Dynamic Models of Wind Farm Power System Studies	Address effects on power systems of interconnecting and operating large numbers of wind turbines.
Offshore Wind Energy Technology Deployment	Address relevant issues of offshore wind development, including deployment in deep water.
Integration of Wind and Hydropower Systems	Conduct cooperative research concerning the generation, transmission and economics of integrating wind and hydropower systems ; provide a forum for information exchange.

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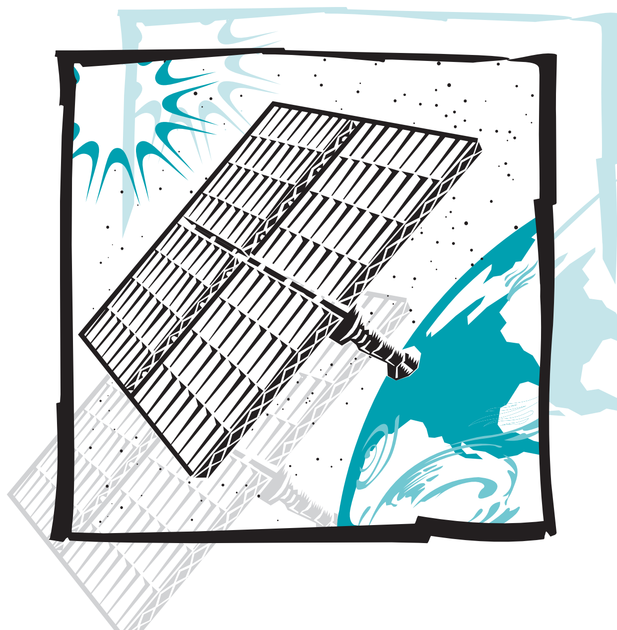
Chapter 3 • Technologies

Photovoltaics



Highlights

- Photovoltaic (PV) systems are flexible and modular. The technology can be implemented on virtually any scale and size, connected to the local electricity network or used as stand-alone or off-grid systems, easily complementing other energy sources. PV produces electricity with no greenhouse gas or other emissions and no noise.
- In recent years, the PV market has been very dynamic with growth rates exceeding 30% per year. Total installed capacity was 110 MW in 1992 and had risen to 1 809 MW in 2003, with three countries accounting for 85% of the output: Japan (860 MW), Germany (410 MW) and the United States (275 MW).
- In 2003, PV electricity production from grid connected PV systems is estimated to have been 1300 GWh, accounting for only 0.007% of total electricity production and for 0.05% of total renewable electricity production in the world. Total PV supply was estimated at 112 ktoe, accounting for 0.002% of total primary energy supply in IEA member countries.
- PV technology is currently dominated by two module technologies, crystalline silicon (c-Si) and thin-film modules. The first, which uses wafer-based crystalline silicon, currently controls 90% of market share. Thin film market share decreased over the past ten years, as crystalline silicon production increased.
- Average installation prices for building-integrated, grid-connected PV systems are around USD 5/W to USD 9/W. In the off-grid sector up to 1 kW, system prices vary considerably from USD 10/W to USD 18/W.
- Today's lowest generation costs range from USD 0.20/kWh to USD 0.30/kWh for installations with low investment costs (around USD 4 500/kW) and high energy output (more than 1 500 kWh per kW per year).
- Between 1998-2003, Japan consistently invested more public funds in support of PV development than any other IEA member country. In 2003 alone, Japan spent more than USD 200 million. During the same year, a full 38% of the European financial effort came from one country: Germany.
- Approximately half of future cost decreases for PV are expected to result from RD&D related to improving materials, processes, conversion efficiency and design. Substantial cost reductions can also be gained by increasing manufacturing volume and economies of scale, by increasing the size of components and plants, and by streamlining installation procedures.
- In order for PV to rapidly realise its potential as an energy option, RD&D efforts need to be further increased and need to be leveraged with those of the private sector. The most cost-effective way to advance the technology's learning rate is to align the vital market deployment efforts with three other activities: defining appropriate strategies for PV RD&D through system orientation; maximising synergies with other technology sectors; and allocating sufficient and continuous RD&D funds.

Introduction

Photovoltaic (PV) technology permits the transformation of solar light directly into electric current. PV systems can deliver electric energy to a specific appliance and/or to the electric grid. PV has the potential to play an important role in the transition towards a sustainable energy supply system of the 21st century and to cover a significant share of future electricity needs. In addition, the technology could improve security of future energy supply, provide environmentally benign energy services and enhance economic and social welfare. In combination with other renewable energy technologies and energy efficiency, PV technology is becoming a key technology for the future.

In 1992, installed capacity of photovoltaics amounted to 110 MW. By 2003, the figure had risen to 1809 MW, with three countries accounting for 85% of total installed capacity: Japan (860 MW), Germany (410 MW) and the United States (275 MW). Although PV capacity saw remarkable growth rates in 2003, PV electricity production from grid-connected systems remained relatively low at 1300 GWh, accounting for only 0.007% of total electricity production and 0.05% of total renewable electricity production in the world. Total PV supply for the same year is estimated at 112 ktoe, or 0.002% of total primary energy supply in IEA member countries.

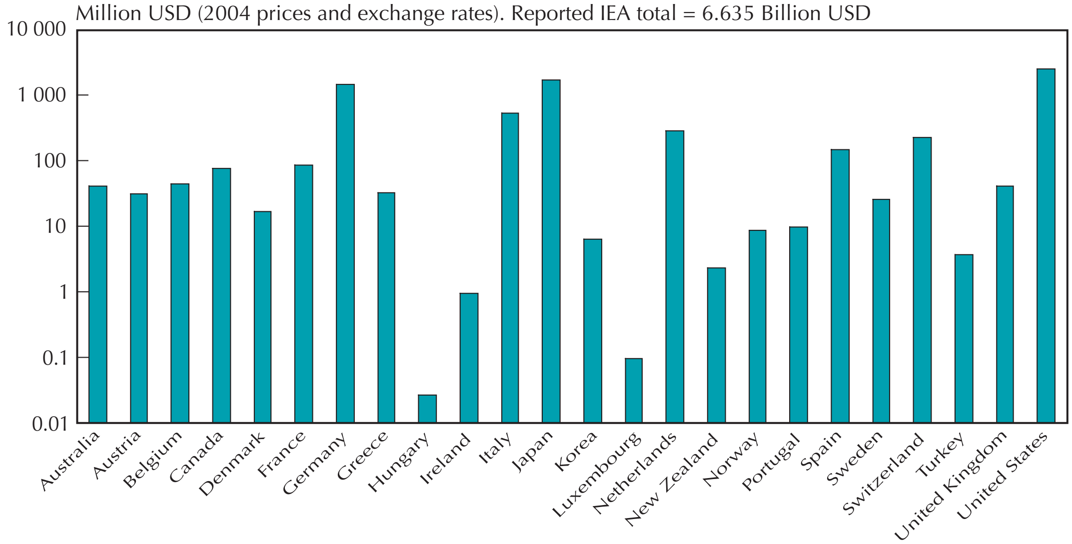
PV offers several advantages including:

- Complementarities with other energy sources, both traditional and renewable.
- Flexibility in terms of implementation. PV systems can be integrated into consumer goods or into buildings, installed as separate mobile or non-mobile modules, or used in central electricity generating stations.
- Environmental advantages. PV produces electricity with no greenhouse gas or other emissions and no noise.

Even though the amount of electricity produced using PV has increased rapidly year after year, it is still at a very low level compared to other renewables such as wind or biomass. The major barrier preventing uptake in today's market is the capital cost of PV, which makes the electricity produced too expensive for many applications. The industry must become more competitive; it needs to develop more efficient manufacturing processes and conversion devices. The regulatory framework often hinders installation and effective standardisation would yield many advantages. Current markets perceive the technology as being suitable for niche applications, but not for general use. However, as various countries (*e.g.,* Japan and Germany) reach GW levels of installed capacities, PV should gain wider recognition and acceptance. Fully coordinated research efforts could help overcome some of these barriers, but all stakeholders must also engage in other actions to realise broader deployment.

From 1974-2003, IEA member countries allocated about USD 6.6 billion (2004 prices and exchange rates) for RD&D on PV technology (Figure 1). The United States, Japan, Germany and Italy accounted for about 85% of reported governmental RD&D funding, whereas other IEA member countries contributed small or not even one-digit percentages of total PV RD&D budgets. In recent years, a number of countries have increased their PV RD&D efforts, including the Netherlands, France, the UK, and Korea.

Figure 1. **Reported government solar photovoltaic RD&D budgets in IEA member countries, 1974-2003**



Current technology status

A brief history of photovoltaics

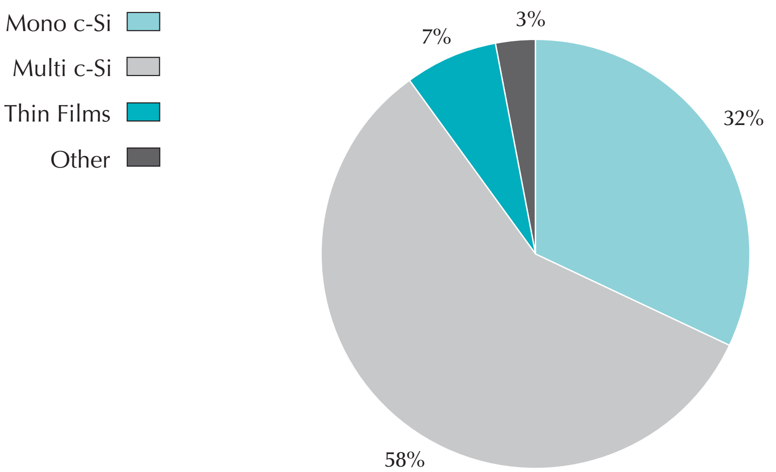
The direct relation between light and electricity was demonstrated by Antoine Henri Becquerel in 1839. However, it was not until the development of diodes in 1938 and transistors in 1948 that the creation of a solar cell became possible.

The foundation for modern PV technology was laid in the early 1950s, when researchers at Bell Telephone Laboratories discovered and developed crystalline silicon (c-Si) solar cells, which they patented for the first time in 1955 and successfully used in space applications in 1958. Despite early attempts to commercialise silicon solar cells on a larger scale, the technology was not developed enough to warrant large-scale production until the 1980s. Since then, laboratory and commercial development has progressed steadily, creating a portfolio of available PV technology options at different levels of maturity - and experience that can be expressed by a robust learning curve (price reduction vs. cumulative production of commercial PV technology) (ECN, 2004).

Photovoltaic modules

A PV system consists of a module (array of cells generating the electricity) and a Balance-Of-System (BOS) including (if applicable) the cabling, battery, charge controller, and DC/AC inverter, as well as other components and support. Most systems are the "flat-plate" variety, which operate by collecting solar energy directly on the module. Flat-plate systems are usually static (*i.e.,* having a fixed orientation) but they may also use sun-tracking components. A distinctly different type of system, known as PV concentrators, combines sun-tracking with an optical system to concentrate sunlight onto a small-area, high-efficiency solar cell.

Figure 2. **Production by technologies, 2003**



Source: EC, 2005.

Commercial PV modules

As indicated above, PV modules are generally divided into two broad categories:

- Wafer-based crystalline silicon (c-Si).
- Thin films, which include thin-film silicon, copper-indium/gallium-selenide/sulphide (CIGS), amorphous silicon (a-Si) and cadmium telluride (CdTe).

Wafer-based crystalline silicon is currently the dominant technology for several reasons: it is widely available; it has proven reliability; and it is well understood – indeed, it is founded on the knowledge and technology originally developed for the electronics industry. Crystalline silicon modules (single crystal or multi-crystalline) are typically produced by growing ingots of silicon, in a manner similar to that used for electronics devices. The ingots are sliced to make wafers, which are then processed into solar cells and electrically interconnected. The final step involves encapsulating strings of cells to form a module. The fabrication process creates challenges for the PV industry. First, it is necessary to begin with very high quality feedstock but overall silicon utilisation is still relatively low as a large fraction of the silicon is lost during processing. Thus, material costs for c-Si wafers are high compared to thin-film modules. In addition, manufacturing is often not yet optimally automated. Finally, current silicon feedstock production is energy intensive. These factors lead to a module energy pay-back time of several years, although it is now substantially lower than the module lifetimes of 20 to 30 years.

In contrast, thin-film modules are produced by coating and patterning entire sheets of substrate, usually glass or stainless steel, with micron-thin layers of conducting and semiconductor materials, followed by encapsulation. This process can be highly efficient in materials utilisation, has relatively low labour requirements, and uses comparatively little energy from start to finish.

Total area stable efficiencies of thin-film modules are in the range of 5% to 17%, which are, in principle, high enough to enable large-scale use. Nevertheless, it is still critical to improve efficiency without increasing costs in order to reduce module manufacturing costs per Watt-peak. This is the first step needed to realise lower system costs (the savings will be primarily in the reduction of area-related BOS-costs) and enable efficient use of scarce or expensive space, which may become an issue in densely populated regions.

Estimates suggest that efficiencies of current technologies could be increased to 15% to 20%, or slightly higher (further increases are possible but would require a fundamentally different approach). The range of commercial module efficiencies is expected to increase to 10% to 30% - or higher - by 2030, while also fulfilling cost reduction requirements. These figures may refer to very different technologies and applications, such as polymer-based module "foils" or super high-efficiency, sun-tracking concentrator systems.

Even though its reliability and performance underpin crystalline silicon's current domination of the market (a 90% share), there is still potential for further improvement in terms of manufacturing costs and efficiency. The learning curve of PV modules has been fully determined by c-Si in the past; this driving force is expected to continue for the next 10 to 15 years.

In contrast, the market share of thin films has remained at very modest levels over the past decades - even decreasing from 15% in 1995 to 5% today as c-Si production rose. However, as an emerging technology, thin films have important potential to extend the PV learning curve beyond the limits of c-Si technology. Existing thin films (*e.g.,* amorphous/micro-crystalline silicon or CIGS) could eventually compete with c-Si, but further development and scaling up of manufacturing is necessary. Thin-film technologies also have the advantage of allowing for specific applications such as flexible modules, semi-transparent modules, etc. To realise the potential of thin films, the PV industry and research sectors must collaborate closely to solve both fundamental and technological problems. Given the progress to date, the market share of thin-film technologies is expected to increase after 2010.

The current investment necessary for production equipment for wafer-based c-Si is approximately USD 0.6/W of annual production capacity; additional investments for building, infrastructure, electricity and gas supply, waste management and recycling, etc. bring the total investment requirement to USD 1.9/W. This represents approximately USD 93 million for a 50 MW manufacturing plant.

To date, no active manufacturing plant has successfully proven the cost-benefit potential of thin films in practical terms. Both processes and equipment remain at an immature stage, and material and energy costs are not yet optimised. The major cost element for thin films is the capital for equipment and materials. Thus, reducing material costs will be key to achieving low overall module costs in the long term.

PV concentrator technologies

There is a third technology that captures a small share of the commercial PV market. Concentrator technologies are made up of very high-efficiency, small-area solar cells used in combination with large-area, optical concentrators. Although the solar cells may be expensive per unit area, the overall technology provides an important alternative route to low generation costs. Concentrator systems effectively substitute expensive solar cells elements with less-expensive optical elements. Higher total system costs – associated with optics, tracking, cooling, etc. - are compensated for by higher efficiency. However, because of their reliance on direct solar radiation, application of concentrator systems is restricted to clear sky locations.

Technology applications

PV technology and applications are characterised by their modularity: PV can be implemented on virtually any scale and size. Overall efficiency of systems available on the market varies between 5% and 15%, depending on the type of cell technology and application. The expected life span of PV systems is between 20 and 30 years. The solar modules are the most durable part of the system, with failure rates of only one in 10,000 per year. Some components, *e.g.,* the inverter and battery, must be replaced more regularly.

Experts expect c-Si to continue dominating the market in the coming years but also predict that thin-film solar cells will become considerably less expensive in the medium to long term. It is certain that different cell technologies can exist side by side. Some applications require high efficiency in a small space (c-Si); others need less expensive material to cover a larger area (thin-film cell technologies). Therefore, speaking of different cell generations does not adequately reflect current understanding of the wide range of photovoltaic technologies.

Stand-alone or off-grid PV systems are particularly well suited for areas that are not easily accessible, that have no access to electricity mains, or where grid connection is uneconomic or unnecessary. A typical stand-alone system consists of a PV module or modules, a battery and a charge controller. An inverter may also be included to convert the direct current (DC)

Table 1. **Examples of PV applications according to size**

Size class	Applications
up to 10W	Pocket calculators, radios, remote wireless sensors, small chargers, electric fences
10W to 100W	Small illumination systems, call boxes, traffic signals, parking meters, navigation lights, small communication systems, weather stations, solar home systems, medical refrigeration, cathodic protection, small stand-alone systems for isolated huts
0.1kW to 1kW	Medium-sized pumping systems and irrigation systems, desalination plants, propulsion of smaller recreation boats, stand-alone systems for isolated buildings, small rooftop systems, small hybrid systems
1kW to 10kW	Medium-sized, grid-connected building and infrastructure-integrated systems; large stand-alone systems for isolated buildings; medium-sized hybrid systems
10kW to 100kW	Large grid-connected systems - either building- and infrastructure-integrated or ground-based
0.1MW to 1MW and above	Very large grid-connected systems - either building-integrated or ground-based

Source: NET Ltd., Switzerland.

generated by the PV modules into the alternating current (AC) required by many appliances. Stand-alone system applications can be subdivided into industrial (telecommunications, water pumping, street illumination, etc.) and rural domestic (isolated housing).

PV systems can also be connected to local electricity networks. Electricity generated can be used immediately (*e.g.,* in homes or commercial buildings) and/or can be sold to an electricity supply company. When the solar system is unable to provide the electricity required (*e.g.,* at night), power can be bought back from the network. In this way, the grid acts as a kind of "energy storage system" for the PV system owner, eliminating the need for battery storage. Grid-connected systems can be subdivided into building-integrated applications and grid-support power.

Investment costs for on-grid systems

PV system prices vary widely and depend on system size, location, customer type, grid connection and technical specifications.

Average installation prices for building-integrated, grid-connected PV systems range from about USD 5/W to USD 9/W. The lowest prices on record – of approximately USD 4.5/W to USD 5.0/W – were realised primarily within specific projects including: the Danish Sol-300 programme; the American Sacramento District Pioneer programme; during the second phase of the Dutch City of the Sun project; and the German 1.5 MW large-scale installation in Relzow. Japan has also achieved similarly low prices in household systems.

Examples of the price structure for flat-roof, sloped-roof and façade-integrated PV systems in Western Europe are shown in Table 2. Prices vary according to the maturity of the local market and specific conditions. For example, installation costs are now relatively low in Germany due to the 100,000 Roofs Programme and the Renewable Energy Sources Act. Furthermore, system prices vary significantly depending on whether the system is part of a retrofit or is integrated into a new building.

Table 2. **Typical prices (USD) of small (1 kW to 5 kW) building-integrated photovoltaic systems in urban areas of Switzerland, 2002**

Cost Category	**Flat Roof**		**Sloped Roof**		**Façade**	
USD/kW	**min**	**max**	**min**	**max**	**min**	**max**
Project development, engineering and other costs	400	1 800	400	1 800	500	1 800
Modules	3 300	4 500	3 300	5 500	3 300	6 000
Inverters	500	800	500	800	500	800
Cabling	250	350	300	500	400	600
Module support structure	350	450	400	600	600	1200
Mounting and installation	1 200	1 600	1 400	2 000	2 000	2 500
Total Investment	6 000	9 500	6 300	11 200	7 300	12 900

Source: NET Ltd., Switzerland.

Prices of on-grid systems can be lower for land-based installations; however, such installations also need adequate sub-structure, which limits cost-reduction potential.

Investment costs for off-grid systems

For off-grid systems, investment costs depend on the type of application and the climate. System prices in the off-grid sector up to 1 kW vary considerably from USD 10/W to USD 18/W. Off-grid systems greater than 1 kW show slightly less variation and lower prices. This wide range is probably due to country and project-specific factors, especially the required storage capacity. For example, in the Southwest United States, DC systems with four to five days of storage capacity can be installed. A local retailer can profitably install a simple system with PV arrays, mounting hardware, a charge controller and a lead-acid, deep-cycle battery bank for USD 10/W to USD 13/W. In a moderate climate, an AC system with ten days of storage capacity, a stand-alone inverter and ground-mounted hardware can be installed for USD 13/W to USD 17/W. High-reliability systems for industrial uses in moderate climates with 20 days of storage, all-weather mounts, battery enclosures and system controllers cost at least USD 20/W.

Generation costs

Investment costs are one of the most important factors determining the cost of the electricity generated from PV installations. Operation and maintenance costs are relatively low, typically between 1% and 3% of investment costs, and the lifetime of PV modules is 20-30 years. However, inverters and batteries must be replaced every five to ten years, more frequently in hot climates.

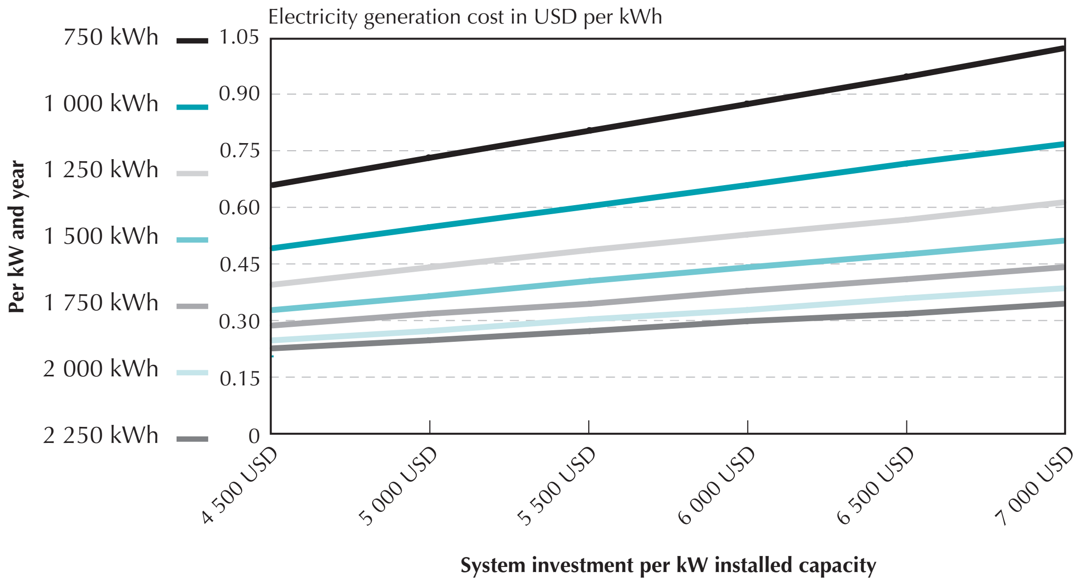
While "harmonised" investment costs (same components and systems in different areas) are relatively similar, kWh costs depend greatly on the solar irradiation level. Electrical output is roughly proportional to the incident light reaching the active area. If located in most areas of Germany, an efficient PV system that receives 1 100 kWh of solar irradiation /m^2/year may produce 110 kWh of electricity /m^2/year. The same system located in some areas of California, receiving 1 900 kWh of solar irradiation /m^2/year may produce 190 kWh of electricity /m^2/year. Electricity costs 40% less in the second case, where irradiation is about 70% greater. Electricity output also depends on other factors such as operating temperature, reflectivity and share of diffuse light. In Japan, a system cost level of USD 3 000 is projected to be reached in four to six years. Cost-competitiveness is greatest where high solar irradiation coincides with daily (peak) power demand.

Based on system investment and annual electrical output, generation costs can be estimated for a range of applications (Figure 3). Today's lowest generation costs (USD 0.20/kWh to USD 0.30/kWh) occur with installations having low investment costs (around USD 4 500) and high energy output (more than 1 500 kWh/kW/year). In the best locations, these costs can fall below USD 0.20/kWh over the lifetime of the system.

To show the full introduction potential of the photovoltaic technology, it is interesting to compare its electricity generation costs with electricity prices paid by households (Figure 4).

In Figure 4 levelised electricity cost (LEC) has been determined assuming a total installed photovoltaic system cost of USS 6 700/kWp in 2005 linearly decreasing to USD 5 000/kWp in 2010 and to USD 2 500/kWp in the year 2020. A system lifetime of 25 years and a real (above the inflation) interest rate of 3% have been assumed to calculate the LEC at an annual

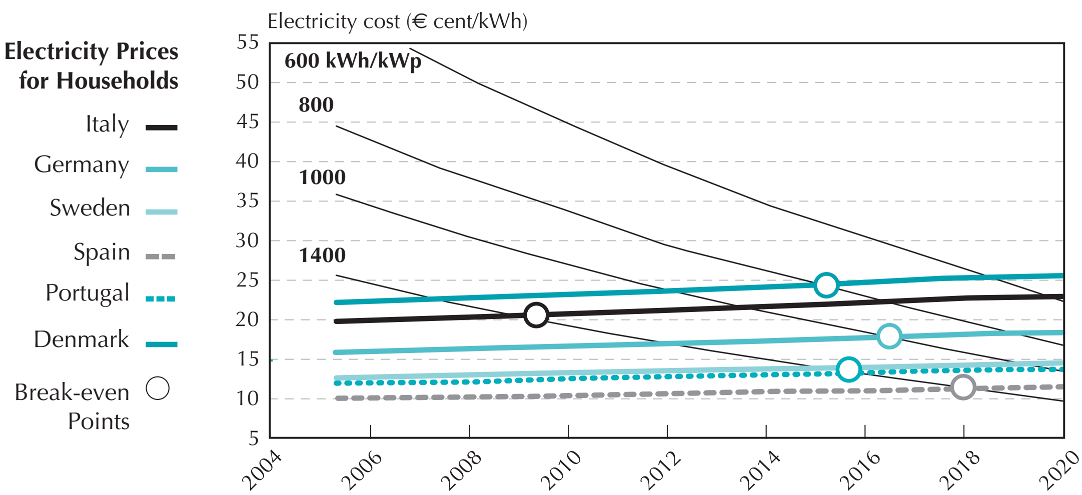
Figure 3. **Approximated generation costs for solar photovoltaics**



Source: NET Ltd., Switzerland.

Note: Based on system investment and annual electrical output, O&M costs are assumed to be 2% of system investment. Amortisation period is 15 years, and discount rate is 6%.

Figure 4. **Projected electricity generation costs of photovoltaics and electricity prices in some European countries**



Source: Pietro Menna, EC-DG TREN, unpublished results 2005.

system yield changing in the range from 600 kWh/kWp to 1 400 kWh/kWp, representing most of the European countries. Examples of household electricity prices (including all taxes) in some European countries are also shown. Using annual average value paid in 2003, the electricity price is escalated assuming a real increase of 1% per year until 2020.

It is interesting to note that, for the same system yield, the break-even point is quite different. For instance, the fact that the break-even is reached earlier in Italy than in Spain and Portugal (assuming the three countries have the same yield of 1 400 kWh/kWp) depends solely on the higher electricity price paid by Italian households. Similarly, the break-even in Denmark (at 800 kWh/kWp yield) and in Germany (at 1 000 kWh/kWp) is earlier than in Portugal and Spain, respectively, despite much higher system yields shown by photovoltaic systems installed in the latter countries. This analysis also relies on the assumption that the grid cost is paid by the other electricity generators, without any burden for photovoltaic electricity producers. This assumption is acceptable for low PV penetration, however it should be modified once the PV electricity fed into the grid becomes a relevant share (5% to 10%) of the total electricity utilising the grid.

Despite all the given assumptions, the above analysis provides a different perspective to assessing the penetration potential of PV electricity. It can be used to help devise policy instruments that must be very country-specific, as the country framework is very relevant for its economic viability.

Environment

Replacing fossil fuel-based electricity generation with PV can yield significant environmental benefits. However, two issues bear noting. First, PV consumes a relatively large amount of electricity in its production. While PV's current energy payback time is on the order of two to five years, the energy used today is almost always from the grid. Thus, renewables "inherit" the emissions of the supply. Second, PV arrays are quite large and require space for their deployment. Where these arrays can be integrated into roofs, or where marginal or rural lands can be used, this is not a problem and can even generate savings. Indeed, a study identified a large potential for building integrated photovoltaics on existing buildings (IEA PVPS, 2002). However, the future concept of large arrays near urban load centres carries a possible conflict for land use. Other issues include:

- Manufacturing and substances of concern: Depending on cell technologies, PV manufacturing processes use toxic and flammable/explosive gases such as silane, phosphine or germane, and toxic metals including cadmium. Current control technologies appear sufficient to manage wastes and emissions in today's production facilities (these emissions are typically orders of magnitude lower than for coal-based generation). Recycling technologies are being developed for cell materials. In addition, the development of thinner layers and better deposition processes can make materials use more efficient. The use of cadmium and other "black list" metals in PV components is controversial, though there are no indications of immediate risks.

- Energy payback times: As mentioned above, the effective energy payback time (EPT) of PV systems depends on the technology used, the type of application and energy yield in different climates. Regardless of these variances, the payback time is much shorter than the 20- to 30-year expected lifetime of a PV system. For crystalline silicon modules, most of the energy is needed for silicon production; for thin-film modules the encapsulation materials (*e.g.,* glass) and processing represent the largest energy requirements. Large potential remains for reducing energy use in production, which will also reduce the inherited emissions. Recently, the energy yield factor (EYR) has been proposed as a parameter to describe this issue (Richards and Watt, in press).

- Operation and emissions: PV systems operate with virtually no harmful emissions. They work silently and do not emit any gases. Electromagnetic interference may cause technical problems, but it is not harmful to humans.
- Land use: Large-scale, ground-based PV arrays may become an issue in the future, particularly where land is scarce. However, small-scale PV systems can be easily integrated into buildings, an advantage in comparison to other power plants.

Price evolution and technology learning curve

It is interesting to consider the evolution of prices (in current USD) for photovoltaic power systems in selected IEA member countries (Figure 5), as well as the historic learning curve for PV modules, which shows a 20% price reduction for each doubling of accumulated sales (Figure 6).

The price of standard PV modules is currently approximately USD 3.7/Wp. This could be reduced to USD 2.5/Wp by 2010, USD 1.2/Wp in 2020 and USD 0.6/Wp in the long term (a price reduction to below USD 1.2/Wp probably requires a transition from crystalline silicon to thin-film technology). This scale of cost reduction can only be achieved through continued market growth combined with focused research efforts, and with cross-fertilisation and spin-offs from other high-tech industry sectors (*e.g.,* flat panel displays, micro-electronics, nanotechnology, the automotive industry and the space sector).

Current RD&D

Classification of RD&D

Photovoltaic RD&D can be divided into two broad categories:

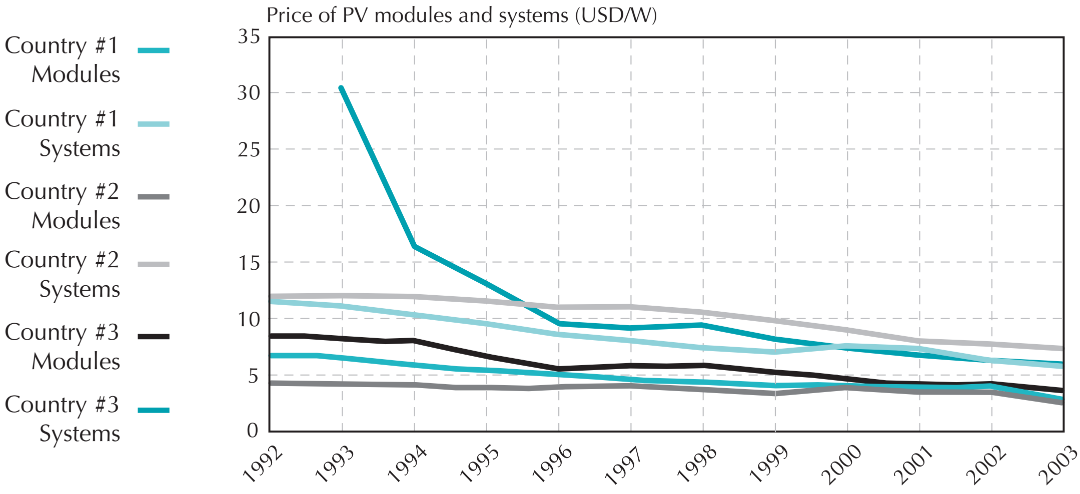
- **Fundamental RD&D** focuses on developing or improving PV solar cells and modules. Efforts are directed towards: new materials and processes; new thin-film technologies; higher performance multi-layer and concentrating cells; improving efficiency and reducing cost of crystalline silicon cells; better measurement and characterisation; and basic research into photon and materials interaction.
- **Applied RD&D** is oriented more towards manufacturing and systems and aims to: find ways to reduce costs and improve manufacturing; develop new concepts of wafer, cell or module production; maximise PV's value in grid support; improve access to new products; foster synergies and partnerships; provide consumer information and collate feedback, etc.

Emerging and new technologies

A variety of PV technologies and conversion concepts currently being pursued focus on achieving lower costs or higher efficiency - or a combination of the two. New technologies are at various stages of development, from proof-of-principle to pilot production. Most still require fundamental research to demonstrate their basic potential for commercial use.

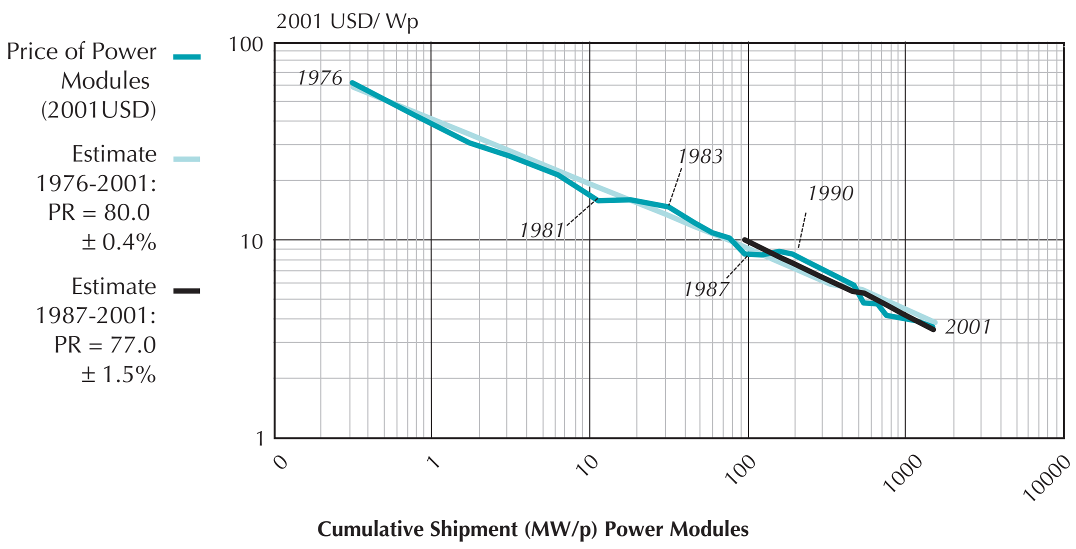
Manufacturing processes are a key factor in decreasing module costs. There is considerable interest in replacing single crystalline or polycrystalline semiconductor layers by nano-structured layers, which may be deposited very cheaply, using experience gained from other sectors.

Figure 5. **Evolution of price of PV modules and systems in selected reporting countries (current USD/W) - 1992-2003**



Source: IEA-PVPS, 2004.

Figure 6. **Price (in USD 2001) versus cumulative shipment (MWp) power modules**



Source: Strategies Unlimited, 2003.

New technologies for PV can be categorised as follows:

- Technology options primarily aimed at very low cost (while optimising efficiency):
  a. Sensitised oxide cells.
  b. Organic solar cells.
  c. Other nano-structured materials.

- Technology options primarily aimed at very high efficiency (while optimising cost):
  a. Multi-junction cells for use in concentrators.
  b. Novel conversion concepts.

Some technologies, such as sensitised oxide and multi-junction cells, are more mature and are gradually moving out of the laboratory phase; others are still in the early stages of development. Organic ("plastic") PV is often considered a high-risk, high-potential option. Working devices have been demonstrated, but efficiencies are still low and sufficient stability has yet to be proven. Finally, a number of novel conversion concepts, based on a variety of new principles, are still at the fundamental research stage.

It is very difficult to estimate future manufacturing costs for technologies that are not yet in production or pilot production and, indeed, virtually impossible to predict for laboratory concepts. The current focus for fundamental research is on efficiency, stability and lifetime.

RD&D expenditures

Figures from the IEA Photovoltaic Power Systems Programme (PVPS) show that Japan invests significantly more public funds in support of PV development than the EU or the United States (Tables 3 and 4). A full 90% of European public support comes from national PV Renewable Technology Deployment (RTD) programmes; Germany's investment alone accounts for 38% of the European financial effort in this technology.

RD&D activities: from components to systems

Worldwide, the main goal of photovoltaics RD&D – for both the public and private sectors – is continued and substantial cost reduction of the delivered energy service. Thus, primary efforts focus on areas such as: increasing efficiencies of PV components and the PV system as a whole; advanced manufacturing techniques of all PV components; raising the performance and reliability of PV power systems; decreasing energy payback time; and reducing environmental impacts. This range of subjects creates a vibrant worldwide RD&D activity, pursued in academic institutions, public research laboratories and, increasingly, within the rapidly growing PV industry.

Approximately one-third of current worldwide PV shipment (estimated to > 1000 MW in 2004) already goes to cost-competitive solutions; a cost reduction of the order of three can be expected over the next 25 years. Because of the low starting point in absolute energy contribution, markets and competitive applications are expected to grow rapidly over the next years. However, it will require considerable time before PV contributes to the energy supply at significant levels. Therefore, continuous public RD&D efforts will be required over the next two decades to deploy the huge potential of photovoltaics in the future energy supply. As PV enters into more and more competitive solutions for a broad range of applications – from small scale to multi-megawatt; grid-connected and stand-alone; in developed and developing countries; – it will be critical to develop a variety of interfaces with other energy technologies and advanced building technologies, and to address electrical grid and storage issues.

As is evident, RD&D in photovoltaics is particularly broad in its disciplinary approach, spanning materials science, device physics and chemistry, electronics, robotics, building technologies, electrical transmission systems, storage of electricity as well as modelling

Table 3. **Public expenditure on PV research and market deployment in 2003**

Annual Budget – Thousand USD				
Country[1]	**RD&D**	**Demonstration/ Field Trials**	**Market Stimulation**	**Total**
AUS	3 614	3 294	12 639	19 547
AUT	1 695		8 588[2]	10 283
CAN	4 714	643	743	6 100
CHE	11 136	1 114	2 301	14 551
DNK	3 797	759		4 556
DEU	33 559		757 062[3]	(790 621)
FIN	531		5	536
FRA	5 763	0	22 600	28 363
GBR	4 885	9 443		14 328
ISR	228			228
ITA	5 424	226	22 599	28 249
JPN (METI)	84 469	32 442	90 595	207 506
KOR	4 032	15 553	821	20 406
MEX	927		1 344	2 271
NLD	2 373	169	84 746	87 288
NOR	1 088	14	0	1 102
PRT[4]				
SWE	2 104			2 104
USA[5]	65 700	0	273 700[6]	339 400

Source: IEA-PVPS, 2004.

1. ISO country codes.
2. Not including feed-in tariffs, which are funded by all electricity consumers and amounted to USD 7 596 thousand in 2003.
3. In the form of loans, therefore not directly comparable with other market stimulation figures.
4. Data are not PV specific.
5. FY2003 (Oct 2002-Sept 2003).
6. Including USD 200 million of state tax credits.

within these different areas. Moreover, as PV systems enter into diverse markets, non-technical issues will become increasingly relevant subjects.

Depending on the diverse disciplinary origin, photovoltaic RD&D frequently focuses on specific components, processes and applications and the possible improvements thereof. This is a natural and adequate approach to the key issues on all individual levels. However, as market opportunities emerge, two particular aspects arise:

- The need for a more comprehensive approach on the system level.
- The potential for further interaction with existing technologies and industries.

Photovoltaic RD&D programmes should therefore explore the potential to assess, measure and manage programme outcomes on the system level. Fostering synergies with other technology sectors and industries, as well as collaborating on cross-cutting issues, could significantly accelerate the outcomes of photovoltaic RD&D.

Table 4. **Public expenditure on PV research 1998-2003 in million USD**

1998	R&D	Demo	Total RD&D
Japan	81.1	21.4	102.5
Europe	198.0	403.6	601.6
USA	35.0		35.0
ROW	12.3	70.2	82.5
Total	326.4	495.2	821.6

2001	R&D	Demo	Total RD&D
Japan	51.0	9.5	60.5
Europe	311.4	403.6	715.0
USA	35.0		35.0
ROW	43.8	70.2	114.1
Total	441.2	483.3	924.5

1999	R&D	Demo	Total RD&D
Japan	90.7	23.6	114.2
Europe	208.6	403.6	612.2
USA	35.0		35.0
ROW	11.6	70.2	81.9
Total	345.9	497.4	843.2

2002	R&D	Demo	Total RD&D
Japan	59.1	35.9	95.0
Europe	325.8	515.5	841.3
USA	35.0		35.0
ROW	60.6	87.8	148.3
Total	480.4	639.2	1119.6

2000	R&D	Demo	Total RD&D
Japan	85.7	36.6	122.2
Europe	249.2	465.7	714.9
USA	35.0		35.0
ROW	9.3	46.1	55.4
Total	379.2	548.4	927.6

2003	R&D	Demo	Total RD&D
Japan	84.5	32.4	116.9
Europe	274.0	524.7	798.8
USA	65.1		65.1
ROW	119.7	143.6	263.2
Total	543.3	700.7	1244.0

(Note: All figures are based on current expenditures in each year, using the exchange rates of that year.)

Source: IEA-PVPS, 1999-2004.

RD&D and market deployment

In recent years, market deployment of photovoltaics experienced very dynamic growth rates exceeding 30% per year, mainly due to supportive frameworks in a limited number of countries (Table 5). At the same time, rapid development in technology and manufacturing development triggered strong investments by the PV industry. In fact, RD&D efforts by the private sector clearly surpassed public expenditures; it is estimated that the private sector now bears a two-thirds share of total photovoltaic RD&D. In addition, the largest manufacturers are rapidly extending their production capacities.

Still, it is crucial to strengthen public RD&D efforts in order to adequately balance market deployment activities and to continue supporting development on the technology side, with the aim of realising potential for further substantial cost reductions. Although it is difficult to determine on an absolute scale, it is clear that an adequate balance between RD&D and market deployment will maximise the learning rate. Public RD&D funding is vital at the early stages of technology development. But public support is also needed where market failures arise to avoid situations in which cost signals are not transparent and market access is restricted by existing technologies and infrastructure.

Table 5. **Installed PV capacity in IEA member countries**

	Cumulative Installed PV Power (MW)											
Country	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
AUS	7.3	8.9	10.7	12.7	15.7	18.7	22.5	25.3	29.2	33.6	39.1	45.6
AUT	0.6	0.8	1.1	1.4	1.7	2.2	2.9	3.7	4.9	6.5	10.3	16.8
CAN	1.0	1.2	1.5	1.9	2.6	3.4	4.5	5.8	7.2	8.8	10.0	11.8
CHE	4.7	5.8	6.7	7.5	8.4	9.7	11.5	13.4	15.3	17.6	19.5	21.0
DNK		0.1	0.1	0.1	0.2	0.4	0.5	1.1	1.5	1.5	1.6	1.9
DEU	5.6	8.9	12.4	17.8	27.9	41.9	53.9	69.5	113.8	194.7	277.3	410.3
ESP	4.0	4.6	5.7	6.5	6.9	7.1	8.0	9.1	11.6	16.0	20.0	28.0
FIN	0.9	1.0	1.2	1.3	1.5	2.0	2.2	2.4	2.6	2.7	3.1	3.4
FRA	1.8	2.1	2.4	2.9	4.4	6.1	7.6	9.1	11.3	13.9	17.2	21.1
GBR	0.2	0.3	0.3	0.4	0.4	0.6	0.7	1.1	1.9	2.7	4.1	5.9
ISR	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.4	0.4	0.5	0.5	0.5
ITA	8.5	12.1	14.1	15.8	16.0	16.7	17.7	18.5	19.0	20.0	22.0	26.0
JPN	19.0	24.3	31.2	43.4	59.6	91.3	133.4	208.6	330.2	452.8	636.8	859.6
KOR	1.5	1.6	1.7	1.8	2.1	2.5	3.0	3.5	4.0	4.8	5.4	6.4
MEX	5.4	7.1	8.8	9.2	10.0	11.0	12.0	12.9	13.9	15.0	16.2	17.1
NLD	1.3	1.6	2.0	2.4	3.3	4.0	6.5	9.2	12.8	20.5	26.3	45.9
NOR	3.8	4.1	4.4	4.7	4.9	5.2	5.4	5.7	6.0	6.2	6.4	6.6
PRT	0.2	0.2	0.3	0.3	0.4	0.5	0.6	0.8	1.1	1.3	1.7	2.1
SWE	0.8	1.0	1.3	1.6	1.8	2.1	2.4	2.6	2.8	3.0	3.3	3.6
USA	43.5	50.3	57.8	66.8	76.5	88.2	100.1	117.3	138.8	167.8	212.2	275.2
Total	110	136	164	199	245	314	396	520	728	990	1 333	1 809

Source: IEA-PVPS, 2004.

Table 6. **Cost-reduction opportunities for solar photovoltaics (%)**

R&D	**Economy of Scale I (components size)**	**Economy of Scale II (manufacturing volume)**	**Economy of Scale III (plant size)**
Up to 20 – 25	Up to 5	Up to 15	Up to 5

Note: Cost reduction in % within a decade, based on expected technology learning and market growth.

Source: NET Ltd., Switzerland.

Experts estimate that about half of future cost decreases for PV will result from RD&D directed toward improving materials, processes, conversion efficiency and design. Substantial cost reductions can also be gained through increased manufacturing volume and economies of scale, as well as by increasing the size of components and plants and by streamlining installation procedures.

Additional RD&D priorities

Technical RD&D areas

RD&D is especially important to generate support for new cell technologies to enter the manufacturing sector and markets, particularly because there are a number of PV cell technologies, each of which offers unique characteristics. RD&D allows new cell technologies to evolve but is also necessary to the process of acquiring the manufacturing experience to make the technologies commercial. Because PV cell manufacturing requires large investments, market and manufacturing volume is very important.

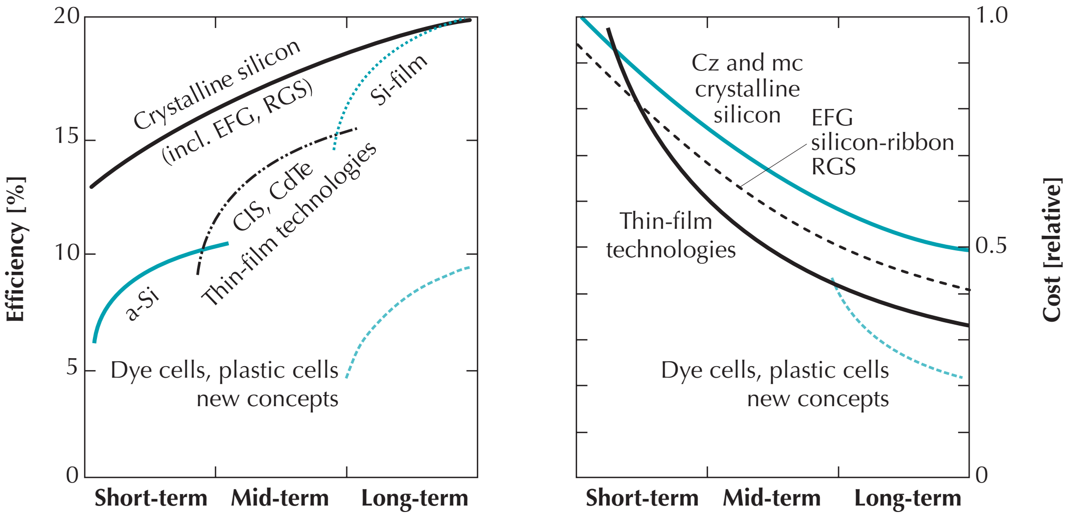
Feedstock

Until recent years, feedstocks were abundant with no short-term supply limitations. However, as production levels increase, demand from the PV industry versus world market supply of crystalline silicon is becoming a serious issue. In order to resolve this bottleneck, new feedstock production must be developed quickly. This will require significant investment by industry, which previously relied on silicon from the semi-conductor industry.

Solar cell technology

Manufacturing approaches for solar cell technologies are diversifying and many varieties of materials are being investigated. A number of technologies are in the industrial stage; many others are still in the pilot manufacturing or even laboratory phases. It is likely that different technologies will continue to co-exist for different applications for some time. It would be valuable to undertake an early assessment of production processes, industrial compatibility and costs, including an assessment of generic issues faced by thin-film manufacturing processes.

Figure 7. **A conceptual road map for photovoltaic cell technology**



Source: Hoffmann W., RWE Solar GmbH.

Balance-of-system (BOS)

Both grid-connected and stand-alone applications need better BOS components. A variety of reliable components are available, but the efficiency, lifetime and operation of some components can be further improved, especially inverters and batteries. In addition, standardisation and quality assurance are crucial – for components as well as for the entire system. Ultimately, building integrated photovoltaic systems (BIPV) should be treated like almost any other building construction component, with similar lifetimes and installation requirements.

Long-term RD&D

As with other technologies, cost reduction potential through learning in PV technology should lead to major cost reductions over time. However, they are unlikely to lead to full cost-competitiveness for on-grid power generation. Thus, long-term RD&D should focus on how to improve solar technologies with new and more cost-effective technologies and integrated products. The time horizon of this RD&D effort extends well beyond 2010.

Long-term RD&D is very important for PV, particularly for the solar cell. New manufacturing techniques and large investments are needed to bring new concept cells and modules to production; it typically takes five to ten years to move from laboratory research to industrial production. Over the next decade, thin-film technologies are expected to demonstrate their potential for cost reduction and improved performance, and, hence, to grow to significant shares of the shipped volume.

Novel concepts for PV can be found in some of today's most promising scientific fields, including nanotechnology, organic thin films and molecular chemistry. Such developments – ultimately aimed at imitating photosynthesis artificially – are likely to be characterised by ever closer relationships amongst various scientific disciplines (*e.g.,* physics, chemistry, etc.). The challenge will be to develop such devices with high conversion efficiencies and long-term stability in order to match the expected life-time of 25 years and more.

Non-technical issues

A number of non-technical issues can greatly affect the potential cost reduction and market growth of PV. For example, partnerships and networking can create vital synergies that bring together different skills to enhance efforts in RD&D, manufacturing and marketing. Mainstream industries, such as glass, display manufacturing, and the building and electronics sectors, can contribute complementary skills that benefit PV. Such synergies will become more important as market volume increases.

PV offers many environmental benefits, but it also inherits emissions from its consumption of grid electricity, particularly if that electricity is generated by fossil-fuels. There are several ways to reduce this drawback such as using: 1) lower energy intensity processes; 2) materials with less environmental impact; and 3) renewable electricity sources. Decreasing energy payback time is another key future goal, which will also reduce pollution in situations where fossil plants provide the electricity for cell and module production.

Standards and codes help create confidence and improve handling of PV products. Quality assurance is important and continued market observations as well as professional education are needed. Planning and connection restrictions should be avoided and regulations should favour the integration of PV in the built environment.

Several important stakeholder groups still lack information and understanding of PV technology, particularly electric utilities, the building industry, local governments and the finance sector. Thus, it is important to communicate best practices, promote appropriate applications, and develop sector-specific marketing strategies. The goal is to encourage all interested parties to make PV an integral part of the energy portfolio and of building and urban planning. Dissemination activities should convey the added values of PV and the specific issues to be addressed.

As with any other relatively new technology, and particularly for applications that require sizeable early investment, appropriate financing solutions must be developed. Confidence-building in the finance sector is crucial to increase investment volumes.

General RD&D issues

In addition to the topical areas of photovoltaic RD&D, a number of more general issues should be considered in setting priorities. The following issues are cited from the Photovoltaic Technology Research Advisory Council (PV-TRAC) vision report for 2030; the issues are formulated for Europe but most are equally valid on a global scale (EC, 2005).

Increasing RTD efforts

A considerable amount of research funds are currently directed towards the development of cost-effective PV components and systems. However, the level of effort needs to be increased to create a balance with current market growth and the potential of the technology. In order to account for the long term and strategic nature of these research expenditures, dedicated research and development programmes should be designed. Action is particularly necessary in countries where national research efforts for PV are scarce.

Alignment of strategies and goals

It is crucial to position PV adequately over time with respect to its future contribution to energy supply and to environmental and social benefits. Strategies and goals should be clearly formulated and separated into the short term (until 2010), the medium term (2011-2020) and the long term (beyond 2020).

Continuity and long-term action

Given the timescales needed to realise the full potential of PV, continuity of action is essential. Technology development and falling costs are a reality; with support this trend can be expected to continue, thereby enabling progressive developments of new competitive markets. Together with the liberalisation in the energy sector, this will provide new business opportunities.

Addressing the barriers

Aside from the obvious issue of high cost, several other barriers hinder large-scale deployment of PV including: technical issues, manufacturing issues, the structure of the electricity sector, standardisation, financing, education and training of installers and market awareness/public acceptance. These various barriers need to be systematically clarified and addressed, with the involvement of all stakeholders – including those outside the PV community.

Improving technology transfer

One of Europe's weaknesses, although not specific to PV, is the difficulty of rapid transfer of technology from research to application. Over the past decade, various attempts were made to improve the structural, institutional and financial approach favouring technology transfer. Many positive results were achieved and there is now greater support for the "spirit of entrepreneurship, risk-taking attitudes and focus on success".

Nevertheless, the relationships and co-operation between science and industry can still be improved to favour more rapid technology transfer. Technology transfer is known to benefit strongly from close co-operation between professionals from different environments.

Emphasising manufacturing issues

When it comes to the competitiveness of the PV industry, it is not sufficient to have excellent or even record results in the research laboratory. Technological solutions need to be compatible with industrial processing and up-scaling. In application-oriented research, these aspects should be addressed at an earlier stage, in full co-operation with industry. Moreover, manufacturing-related issues need to be better addressed in technology development programmes. For example, in the United States, the programme PVMAT[6] was seen by industry as the single most important support scheme.

Enabling critical mass

Europe's PV activities, both in academia and industry, are characterised by a wide range of projects, research groups and companies, some of which are small in size or scope. This situation developed naturally and favours healthy competition as well as a broad set of different technology options. But at the same time, it can hamper formation of the critical mass needed to successfully penetrate the market. By clustering different activities more effectively, overlap can be reduced in favour of building upon complementary strengths.

Joining forces and competencies

The PV sector can benefit from stronger exchange and co-operation with other sectors from research (*e.g.,* materials, chemistry, and nanotechnology), industry (*e.g.,* electronics, building industry, equipment manufacturers) and the energy sector (*e.g.,* other renewable energy technologies, decentralised generation, grid design, and electricity storage). Proactive dialogue can result in new synergies in which different competencies foster promising new partnerships. By more intensely combining the use of PV with other energy technologies (*e.g.,* in the building sector or in hybrid systems), PV can benefit and resolve some of its inherent weaknesses.

6. PVMAT: PV Manufacturing RD&D Project (www.nrel.gov/pvmat).

Roadmaps and research agendas

Over the past year, all major PV regions – namely Japan, the United States, Europe, and Australia – either developed or updated their own PV roadmaps (NEDO, 2004; SEIA, 2004; EC, 2004; BCSE, 2004; EPIA, 2004). Although these roadmaps differ in their approach, individual priority setting and detailed numbers, they all emphasise the important role of future photovoltaic RD&D in general, and the need for strong co-operation between public and private RD&D in particular.

As part of its recent vision report for PV in 2030 – and in the context of the initiative for a European Photovoltaic Technology Platform – the PV-TRAC formulated a comprehensive list of research areas that provide the framework of a strategic research agenda for photovoltaics (EC, 2005) (Table 7).

Costs and benefits of additional RD&D

The overall picture (Table 4) shows a tendency of increasing photovoltaic RD&D budgets in recent years. Yet it should be noted that public RD&D budgets were under considerable pressure prior to the indicated period, *i.e.,* before 1996. At present, an increasing number of countries are indicating either further budget restrictions for photovoltaic RD&D and/or considerable fluctuations in their RD&D budgets. Both elements work against the urgent need for continuous build-up of know-how, research capacity and technology transfer.

Given these observations, it is crucially important to develop a more strategic approach and create continuity into photovoltaic RD&D efforts. Providing sufficient budgets for photovoltaic RD&D is critical to build upon the current dynamics of the technology and ensuring the most rapid and cost-effective delivery of cheaper photovoltaic solar electricity.

In order for PV to rapidly realise its enormous potential as an important sustainable energy option, RD&D efforts need to be further increased. However, it is equally important to leverage public RD&D efforts with those of the private sector. Countries with strong photovoltaic RD&D programmes should – at least – maintain current RD&D efforts; countries with more variable or smaller RD&D activities should develop more strategic and substantial approaches.

Several elements must be pursued concurrently to allow photovoltaic technology to continue along its current technology learning rate in the most cost-effective manner. It is important to recognise the benefits of defining appropriate strategies for PV RD&D through system orientation, maximising synergies with other technology sectors and allocating sufficient and continuous RD&D funds. Combined with well-planned market deployment efforts, this comprehensive approach will allow photovoltaics to expand from the current competitive niche markets to the large markets of building-integrated, grid-connected applications where solar electricity is expected to become broadly competitive over the next 15 years (depending on geographical latitude and solar irradiation). Successful dissemination will require technical, market, societal and customer focussed efforts.

The markets for photovoltaics have appealing features: they are very large, continually expanding, and evenly distributed markets. Moreover, the benefits of this RD&D investment will include economic and social welfare and, ultimately, a growing contribution to a sustainable energy supply. Providing competitive energy services for a wide range of applications over the next two decades, photovoltaic markets will continue to grow substantially throughout the 21st century.

Table 7. **Strategic research agenda for photovoltaics**

Category			Contents
Current PV technologies	Wafer-based crystalline silicon technologies	Materials	• Availability, quality and price of silicon feedstock (including the development and understanding of solar grade silicon). • Wafer equivalents (MG-Si or alternative material) for epitaxial cell structure approaches (also implies reactor development for high-throughput epitaxial deposition). • Substitution of critical materials, for cost (silver) or environmental (lead, etc.) reasons; design for recycling.
		Equipment	• Crystallisation and wafer-manufacturing processes (including ribbons) for strongly reduced silicon and energy use per Wp. • Develop lower cost, standardised and fully automated process equipment.
		Device concepts and processes	• Optimise processes originally developed for laboratory uses; adapt to industrial scale. • Process development for thin-large area wafers, including low waste processes. • Reduce energy consumption of processes (including feedstock production). • New module designs for easy assembly, low cost and 25- to 40-year lifetimes. • Advanced cell designs and processing schemes for high efficiencies (up to 22% on a cell level; 20% on a module level).
	Thin-film technologies	Materials and devices	• Increase module efficiencies from the current 5 to 12% to >15%. • Understand fundamental properties of materials and devices, especially interfaces. • Develop new multijunction structures. • Develop low-cost, high-performance TCO materials for thin-film cell designs. • Reduce materials consumption (layer thickness and yield); use low-cost, low-grade materials. • Reduce or avoid the use of critical materials, substitution of scarce or hazardous materials and recycling options. • Alternative module concepts (new substrates and encapsulation). • Ensure stable module operation for 20 to 30 years with < 10% efficiency decrease.

Table 7. **Strategic research agenda for photovoltaics** (continued)

Category			Contents
Current PV technologies	Thin-film technologies	Processes and equipment	• Develop processes and equipment for high yield, low-cost, large-area manufacturing. • Ensure the uniformity of film properties over large areas and understand the efficiency gap between laboratory cells and large area modules. • Increase stability of the process and yield. • Develop process monitoring. • Adopt successful techniques to industrial conditions in view of productivity and labour. • Reduce energy consumption in relation to energy-pay-back-time of modules (from the current 1.5 yrs to 0.5 yrs under Central EU climatic conditions).
	Highly Efficient Cells for use in concentrators	Multijunction compound semi-conductor cells	• Increase efficiency from 40% to 50%. • Reduce manufacturing costs.
		Silicon cells	• Develop designs for concentrator systems, including advanced design concepts.
New and emerging technologies	Sensitised-oxide-based and other nano-structured solar cells and modules	Organically sensitised cells and modules	• Stability (from months or a few years (estimated) to >10 years). • Efficiency (from 5 to 10% for modules). • Fully solid state devices.
		Inorganically sensitised cells	• Efficiency (from very low to 5 to 10%).
		Other nano-structured devices with potential for very low cost	• Efficiency (from very low to 5 to 10%).
	Polymer and molecular solar cells		• Efficiency (from 3 to 5% to 10%). • Stability (from very low to >10 years).
	Development of stable, high quality transparent conductor and encapsulant materials		

Table 7. **Strategic research agenda for photovoltaics** (continued)

Category			Contents
New and emerging technologies	Novel conversion concepts for super-high efficiency and full spectrum utilisation		• Spectrum conversion. • Multi-band semiconductors. • Hot-carrier devices.
	Cells for low light level applications		• Device designs for integration. • Use of flexible, low-cost substrates. • Ultra low-cost approaches.
Balance-of-System (BoS)	Grid-connected PV systems	Power conditioning and interconnection	• Inverter design and manufacturing concepts aimed at low cost (≤ USD 0.31/W) combined with excellent reliability and long lifetime (20 + years). • Innovative module-integrated electronics for power conditioning, monitoring and control. • Design multifunctional, low-cost grid interfaces to ensure safe and reliable system operation.
		Grid integration aspects	• New concepts for stability and control of electrical grids at high penetration levels of PV to ensure that networks are operated effectively and economically. • Control and communication strategies and interfaces for PV systems, including energy storage. • Develop power electronics to improve power quality at high penetration levels of PV. • Interactive energy management systems for optimising the value of PV electricity in grid-connected systems (including supply/demand matching).
		Concentrator systems	• Low-cost, high-efficiency optical systems for high and low concentration factors, including compact, ultra-thin options. • Reliable, low-cost tracking systems.
	Stand-alone PV systems	Components	• Theft protection for at risk PV-modules. • New power electronics and control devices, allowing for flexible system reconfiguration and growth. • Improved energy storage in the form of robust battery designs, charging strategies, algorithms etc.

Table 7. **Strategic research agenda for photovoltaics** (continued)

Category			Contents
Balance-of-System (BoS)	Stand-alone PV systems	Systems technology	• Energy management of complex (hybrid) multi-user systems, billing and customer management systems, all being well adapted to the respective business models that have been proven suitable for the given local conditions and the cultural context. • Integration of these functionalities into power electronic components.
		Socio-economics	• RD&D on specific local and regional solutions for capacity building, business and financing models etc. as a vital pre-requisite for successful implementation.
Building integration	Building integration and mechanical mounting of modules		• Options for reduced materials and labour costs. • Options for increased installation safety, easy repair & replacement.
	Combination and integration of functions		• PV & shading, PV/thermal systems, ventilation, etc.
	Total energy concepts		
Manufacturing issues			• In-line processes and equipment for thin, large-area crystalline silicon cells and the corresponding modules. • Advanced concepts and equipment for handling and logistics. • High throughput and yield, large-area deposition systems for thin-film solar modules. • Process and equipment innovations to reduce energy and materials consumption in manufacturing. • Standardisation of equipment. • In-process quality control and feedback systems. • Manufacturing and assembly equipment for concentrator PV (adapted from electronics and optics industry). • Development of low-cost, highly reliable and efficient optical and mechanical components for concentrator applications, including operation and maintenance schemes.

Table 7. **Strategic research agenda for photovoltaics** (continued)

Category	Contents
Supportive research	• Quality assurance and standardisation: These issues have been largely neglected, causing a threat to a rapid development of PV. "Standardisation" refers to module-features, mounting techniques and electrical aspects, etc. Development of faster and lower cost qualification tests should be addressed. • Environmental aspects: The drive towards low cost and high efficiency does not yet lead to an optimum environmental profile. Replacement of critical materials with environmentally benign alternatives should be assessed in relation to meeting the targets. Life-cycle analyses and integrated impact assessments should be promoted. • Socio-economic research: Financial support to bring the sector to maturity needs consideration in relation to added benefits, e.g. jobs. • Learning curves for PV: Understanding the factors which influence the learning curve for PV is essential to direct the efforts to the most relevant areas.

Current activities of IEA Photovoltaic Power Systems Implementing Agreement

The IEA Photovoltaic Power Systems (PVPS) Implementing Agreement is a collaborative R&D Agreement conducting projects on the application of solar photovoltaic electricity. The PVPS operates worldwide via a network of national teams in participating countries.

The mission of the PVPS programme is "To enhance the international collaboration efforts through which photovoltaic solar energy becomes a significant renewable energy source in the near future."

The underlying assumption is that the market for PV systems will gradually expand from the present niche markets of remote applications and consumer products, to the utility market, through building-integrated and other diffused and centralised PV generation systems. This market expansion requires the availability of and access to reliable information on the performance of PV systems, design guidelines, planning methods, etc. to be shared with the various actors defined above.

The PVPS programme aims to realise its mission by adopting the following objectives related to reliable PV power system applications for target groups including utilities, energy service providers and other public and private users:

- Contribute to the cost reduction of their applications.
- Increase the awareness of their potential and value.
- Foster their market deployment by removing technical and non-technical barriers.
- Enhance technology co-operation with non-IEA member countries.

Currently the Programme actively pursues eight research projects, or so-called Tasks (Table 8). In 2005, the PVPS comprised 23 Participants.

Table 8. **Current projects of IEA Photovoltaic Power Systems Implementing Agreement**

Project	Outline
Exchange and Dissemination of Information on PV Power Systems	Facilitate exchange and dissemination of information on the technical, economic and environmental aspects of PV power systems.
Operational Performance, Maintenance and Sizing of Photovoltaic Power Systems and Subsystems	Improve design, construction and operation of PV systems and subsystems by collecting, analysing and disseminating information on technical performance; provide basis to measure performance in consistent format; develop design recommendations.

Table 8. **Current projects of IEA Photovoltaic Power Systems Implementing Agreement** (continued)

Project	Outline
Use of Photovoltaic Power Systems in Stand-Alone and Island Applications Operating Agent	Advance state of the art for the use of PV systems that are isolated from a large electric grid, such as stand-alone PV systems for telecommunications, rural electrification and water pumping and island PV systems for small communities.
Grid Interconnection of Building Integrated and Other Dispersed Photovoltaic Power Systems	Develop and verify technical guidelines for roof-mounted and other dispersed PV systems that can be safely and reliably linked with the electric grid at the lowest possible cost.
Photovoltaics Power in the Built Environment	Enhance the architectural and technical quality, and the economic viability of PV systems in the built environment.
Study on Very Large Scale Photovoltaics Power Generation Systems	Examine and evaluate the potential of very large scale PV power generation systems by identifying key system feasibility factors and clarifying benefits to neighbouring regions.
Deployment of Photovoltaic Technologies: Co-operation with Developing Countries	Increase the rate of successful deployment of PV systems in developing countries through increased co-operation and information exchange between bilateral and multilateral donors and the PVPS Programme.
Urban Scale PV Applications	Enhance opportunities for wide-scale, solution-oriented application of PV power electricity production in the urban environment as part of an integrated approach to maximise building energy efficiency and solar thermal and photovoltaic usage.

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Chapter 3 • Technologies

Solar heating and cooling

Highlights

- More than one-third of global energy use is for heating. Solar heating and cooling (SHC) technologies are logical and valuable substitutes to the oil and gas currently used for heating.
- Solar heating and cooling covers a broad spectrum of technologies, including solar water heating, active solar space heating, and passive solar heating and cooling, all of which have been commercially available for more than 30 years. More recently, combi-systems, which combine water and space heating, emerged on the market.
- The worldwide contribution of solar thermal heat to the overall energy supply is significant. An overall capacity of 92.7 GWth of solar thermal collectors was installed (Weiss, Bergmann and Faninger, 2005). The worldwide market for glazed solar collectors has greatly increased over the last decade to approximately 10 million m^2 installed per year. Almost all growth in this market occurred in China.
- The cost reduction history for solar water heating systems and for the newer combi-systems shows that, over the past ten years, each doubling of the market led to a 20% reduction in installation costs.
- Government funding for SHC was estimated at approximately USD 75 million in 2000 and USD 69 million in 2001. During the same years, industry-funded RD&D is estimated to have been at least half the amount put forth by government. RD&D projects that are not pre-competitive usually require an industry cost share of 50% or higher.
- A comprehensive and ambitious programme of applied research, development and demonstration is needed to generate competitive, advanced SHC systems. These systems could cost-effectively provide 5% to 10% of the overall low-temperature heat demand of the IEA Member countries.
- RD&D efforts need to focus on technical advances in materials and components, storage, scaling up and increasing efficiency of SHC systems. Architectural aspects also need to be taken into consideration: solar thermal collectors need to become an integral part of buildings, ideally becoming standard construction elements.
- Steady funding at an increased level would allow various SHC technologies and designs to better achieve cost and performance goals more rapidly. It would also facilitate their growing presence in the market and their associated environmental benefits.

Introduction

Solar heating and cooling (SHC), as defined here, comprises technologies and designs for solar water heating, solar space heating and cooling, using both active technologies and passive system designs, daylighting, and agricultural and industrial process heating.

Solar water heating, including pool heating, has been commercially available for more than 30 years. While still needing further improvements, it can be considered a mature technology. Active solar space heating, which has been commercially available for almost as long, lags significantly behind in the market, primarily because of its relatively higher cost. In recent years, systems that combine water and space heating, called combi-systems, emerged on the market and show great promise for further success.

Active solar cooling was developed in the 1980s but was never able to compete economically with conventional air conditioning systems. In recent years, the combination of advanced solar cooling systems coupled with changing market conditions created an opportunity for active solar cooling to enter the market in a significant way. Other technologies are experiencing renewed interest. Although its current market share is insignificant, solar crop drying is now commercially available for specific crops in specific locations. Solar process heat for industrial processes, initially investigated in the 1980s, is once again under study.

Passive solar heating, and to a lesser degree, passive solar cooling (or perhaps more accurately, passive cooling load reduction) has also been commercially available for about 30 years. These systems can reduce the heating and cooling load by 50% with no additional cost; some systems can reach 75% heating and cooling load reduction with modest additional cost. Daylighting designs have matured to the point where they can provide significant economic benefits and are expected to become more widely used in new commercial buildings.

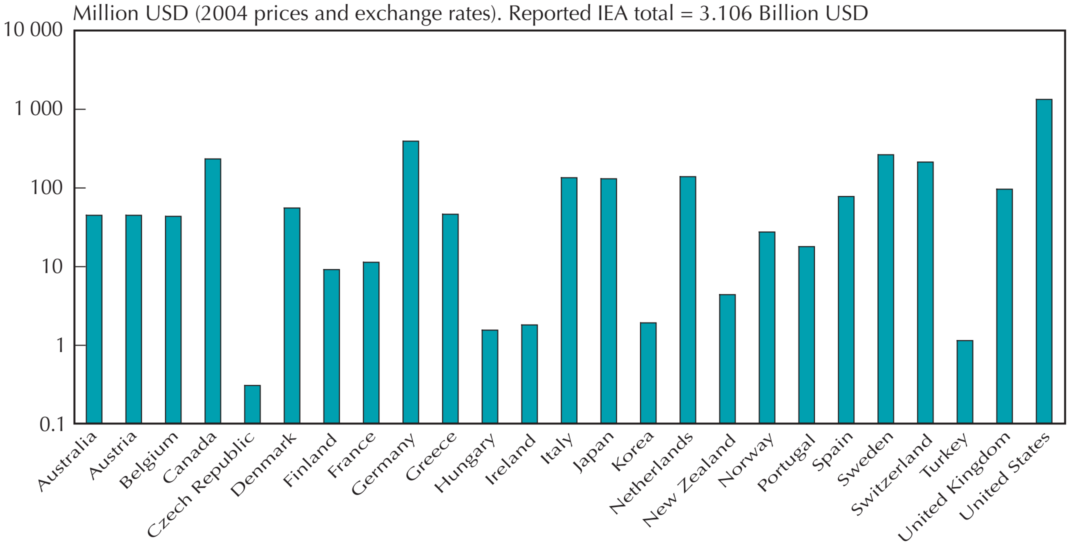
In addition to their capabilities to meet heating, cooling and lighting loads, SHC technologies can improve energy security and energy services at the point of end use. They can also reduce peak demand on electricity systems.

Continued RD&D on solar heating and cooling is highly justified. Solar heat is the logical successor of oil and gas used for heating. More than one-third of global energy use is for heating. Bioenergy and geothermal energy (in some geographic regions) are the main renewable alternatives in this segment of market demand. However, in coming years, bioenergy sources will also be used increasingly to generate electricity and fuels in vehicles and geothermal energy will be used to generate electricity. The implied competition for resources emphasises the importance of improving capacity to utilise solar heat.

Solar heat has a high cost-effectiveness for RD&D funding as a number of applications are already close to the market. Furthermore, use of solar heat will, as with other renewable energy sources, provide significant local and global environmental benefits while contributing to energy security, promoting employment and supporting sustainable economic development of nations.

IEA member countries allocated approximately USD 3.1 billion (2004 prices and exchange rates) for RD&D on solar heating and cooling technology from 1974-2003 (Figure 1). The United States accounted for about 40% of this spending; Sweden, Canada, Switzerland, Germany, the Netherlands, Italy and Japan dedicated three-digit numbers of million USD to RD&D budgets, amounting to approximately 45% of the reported total solar heating and cooling RD&D budgets of IEA member countries.

Figure 1. **Reported government solar heating and cooling RD&D budgets in IEA member countries, 1974-2003**



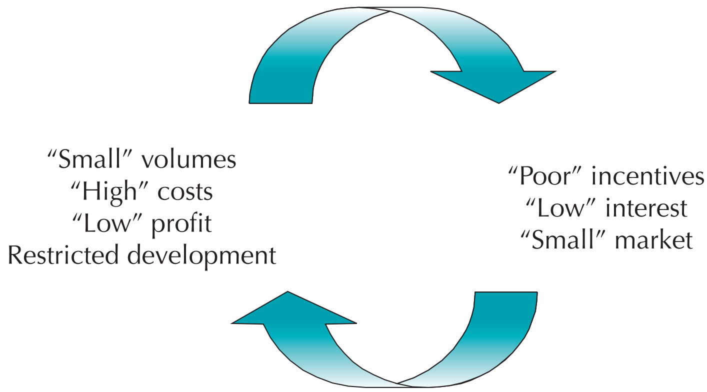
Current technology status

A large variety of solar-thermal components and systems, mostly for residential applications, are available on the market. The products are reliable and show a high technical standard in the low temperature regime. However, technical and economic barriers and obstacles prevent wider use of solar thermal components and systems. Market growth is not yet stable and still is very much dependant on public support, as is often the case with other non-renewable and renewable energy technologies.

Industry and market deployment

SHC applications have a low penetration in countries where business is carried out mainly by small and medium enterprises with partly manual fabrication and no established technical-scientific RD&D divisions. The industry-market situation can be simplified according to Figure 2. There has been, however, rapid market growth in recent years for small solar domestic hot water (SDHW) systems in countries moving towards partly automatic or semi-automatic fabrication of solar-thermal components. Over the past 20 years, specific costs of SDHW systems decreased by a factor of two (Figure 4 shows the learning curve for solar water heating systems). Nevertheless, "solar heat" is not yet seen as fully competitive with fossil alternatives. Some national and international programmes exist (*e.g.,* the EU target of 100 million m² solar collectors installed by 2010), but most countries lack strong support for solar applications.

Figure 2. **Industry and market situation in the majority of IEA member countries**

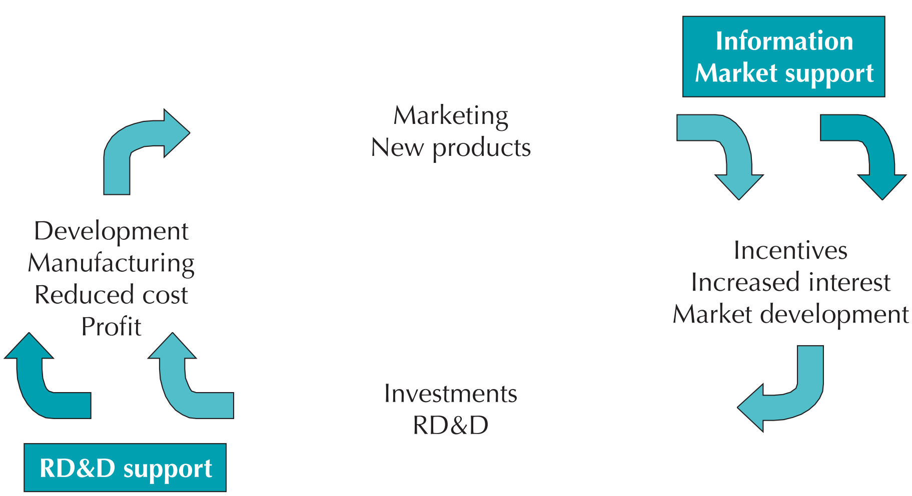


RD&D in solar heating and cooling

Three key elements are required to achieve the desired boost in SHC contributions to meeting energy demands: initial government support for RD&D, information dissemination and market development (Figure 3). A basic justification for continued RD&D support is that this very RD&D is a basic and fundamental aspect of technology and market development. Continued RD&D will also support the early development phase of a number of SHC technologies and bolster the solar industry, which is admittedly small in comparison to most other energy technologies.

That said, it is important to emphasise that RD&D and RD&D support are not the only criteria for creating a mature market for SHC technologies. Market stimulation is another essential element; in fact, one without the other does not provide best value for the money invested in either. Policies, economics and cultural aspects also have a significant impact on the market development for SHC.

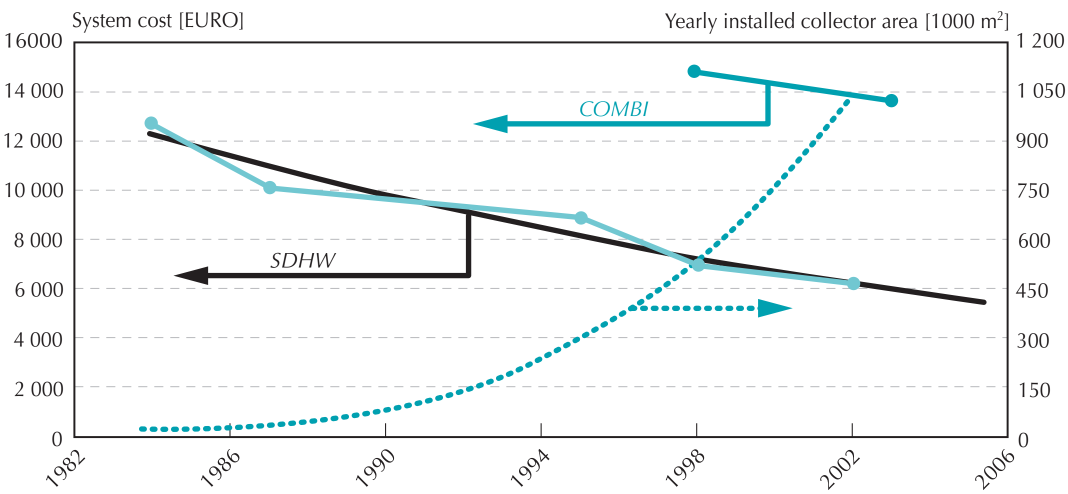
Figure 3. **Industry and market situation commonly found in many countries**



During the past two decades, market development has been positive but this is only as a result of a few major successes. The worldwide market for glazed solar collectors has increased to the order of 10 million m²/year (equivalent to an installed thermal capacity of ~7 000 MWth/year) during the last decade. However, outside of China, sales are the same now (about 2.5 million m²/year) as in the early 1980s. Over the same time period, the European (EU15) market for glazed solar collectors increased to the order of 1.5 million m²/year (~ 1 000 MWth/year), but outside Austria and Germany, sales are also the same today (about 0.3 million m²/year) as in the early 1980s (ESTIF, 2003).

The cost reduction history for solar water heating systems and for the newer combi-systems shows average values of system costs (including VAT and installation) for solar domestic hot water systems (SDHW) and solar combi-systems (COMBI) (Figure 4). These numbers are based on German and Austrian installations, which represent almost 75% of the European market for these systems. This learning curve demonstrates that, over the past ten years, each doubling of the market led to a 20% reduction in the installed cost.

Figure 4. **Development of average costs for solar thermal systems in Germany (incl. VAT and installation)**



Source: Stiftung Warentest.

Price reductions observed in the past for SDHW systems are now also evident for solar combi-systems. Although solar thermal systems are usually not sold in order to save money, (especially with regard to single- and double-family houses), it is interesting to note that the average price of one kWh of solar-heated water is about USD 0.19/kWh; for combined water and space heating, the price is about USD 0.37/kWh. This cost accounting was performed for a 20-year life, with 4% interest and without subsides. Even lower specific solar costs can be achieved in large-scale, centralised heating plants with collector areas larger than 100 m².

In some countries that offer subsidies, such as Germany with a present subsidy of USD 136.65[7] /m² collector area, this results in heat prices of approximately USD 0.12/kWh. In some countries, this price is close to the current price of heat generated with individual oil

7. The subsidy was changed in July 2005 to USD 167.7.

Table 1. **Current cost of typical solar heating and cooling systems**

Technology	Current Cost	Performance Indicator
Solar Water Heating	3 100 - 7 500 USD/system	60-70% solar fraction
Solar Combi-system	17 300 USD/system	20-40% solar fraction
Solar Cooling	1.5 – 3 times conventional cooling system cost	30-50% primary energy savings
Passive Heating	No additional cost	50% of the building heating load is typical
Daylighting	n.a.	n.a.

or gas boilers. In other countries, as is currently the case in Germany, it is still higher by a factor of two. It is interesting to examine estimates of current costs of typical SHC systems, along with an indication of their typical performance (Table 1).

The cost/unit energy input for SHC systems is strongly dependent on site and application; this sensitivity is evident in the following figures for solar cooling. A cost assessment of the first realised projects performed in the SHC Programme showed values between USD 1 900/kW of installed cooling and USD 6 200/kW. This was due to large system variations in terms of size, hardware (air handling units, chillers, chilled water networks, type of backup, type of solar collector, etc.) and level of development (pilot plants, RD&D plants, or commercial projects).

Typical initial costs were 1.5 to three times higher for a solar-assisted A/C compared to conventional solutions, largely due to the extra installations (mainly solar). Cost savings depend strongly on: site (duration of cooling season, solar gains), application (number of cooling hours, coincidence between load and solar gains) and - of course - the cost of conventional energy. In most cases, annual operating costs are 10% to 50% higher for solar cooling solutions compared to conventional.

In the case of well-designed systems in the best applications, cost break-even can be achieved with subsidies in the range of USD 124/m^2 to USD 186/m^2 of collector. Cost reductions can be expected for large systems by standardised solutions with reduced design effort, standardised and optimised control. Further cost reductions are also expected for large collector fields with increased experience on the construction of large collector fields.

Regarding design of the system of solar cooling, well-designed systems should be able to meet about 70% to 90% of the cooling load, which is possible in most cases, although thermal storage may be needed for some hours in some cases (*e.g.,* diurnal mismatch between gains and load). Primary energy savings in the range of 30% to 50% can be achieved.

Worldwide contribution of solar thermal heat to the total energy supply is significantly underestimated. According to the IEA Solar Heating and Cooling Programme's 2005 publication Solar Heating Worldwide 2003, an overall capacity of 92.7 GWth of solar thermal collectors was installed in 2003. Installed capacity in the EU15 was approximately 10 GWth.

Despite this considerable capacity, most of solar thermal systems are used for swimming pool heating, domestic hot water preparation and, to some extent, for space heating. Use of solar thermal energy in large-scale residential buildings, for cooling and industrial applications or drying, is currently insignificant.

The target set in the European Commission (EC) 1997 White Paper on renewable energy is 100 million m^2 of solar collector area installed by 2010. This target clearly will not be reached. However, it is apparent that solar thermal energy has the potential to meet a significant portion of the heating and cooling demand in the residential sector and make a large contribution to the energy supply of the commercial and tertiary sector. Of course, it is equally important that better efficiencies are used to reduce these heating and cooling demands.

To reach the EC's target and retain the leading technological position in the field of solar thermal technology, an ambitious fundamental and applied RD&D programme is required. The objective should be to develop competitive, advanced SHC systems that can cover 5% to 10% of the overall low-temperature heat demand of IEA member countries by 2020.

Current RD&D

In its 2002 National Programme Review, the IEA SHC Programme estimates government funding for solar heating and cooling to be approximately USD 75 million in 2000 and USD 69 million in 2001. Industry-funded RD&D during those years is estimated to be about 50% as much as that provided by governments; RD&D projects that are not pre-competitive usually require an industry cost share of 50% or higher.

The current status of SHC technologies raises a number of important questions: What programmes should be supported in order to further advance "mature" technologies in the markets? Is there a point where government should stop funding mature technology RD&D? A more in-depth examination of the RD&D needed to advance these SHC technologies is described in the following section, along with the RD&D needed to advance newer (*i.e.,* less mature) SHC technologies and applications. It is legitimate for government to stop funding mature technologies, when industry is able to support continued technology development. That said, solar pool heating has an established market that can, and does, compete with fossil fuels across a wide range of pool sizes. Further RD&D is not envisioned as necessary.

Another valid question is this: What programmes can best ensure market entry of "new" technologies? Experts identify two vital means of support:

- Properly designed and consistent government policies – with targets and incentives – can have the greatest impact on ensuring continued market growth of SHC.
- Continued government RD&D that addresses improved cost and performance – and that demonstrates and confirms the need for cost and performance measures.

Finally, there is the question of how government RD&D investments can spur on additional private sector investment? Once RD&D is successfully completed, industry needs to invest in tooling to enter the market with a product. This investment is usually much larger than that of the initial government-funded RD&D.

Additional RD&D priorities

A comprehensive and ambitious applied RD&D programme is needed to develop competitive advanced SHC systems that would eventually be able to cost-effectively provide 5% to 10% of overall low-temperature, heat demand of the IEA member countries. As suggested above, there are four key areas in which RD&D efforts are most needed: advanced materials and components; advanced solar heating and cooling systems; building and design integration; and standards, regulations and test procedures. Specific aspects of each area are discussed in more detail below.

Advanced materials and components

High performance and cost-efficient materials for improved solar thermal systems

Fundamental and applied research is needed to develop:

- Cost-effective optical coatings on surfaces interacting with solar irradiation in order to enhance reflection, transmission or absorption of light in highly effective ways.
- Low-cost, anti-reflective and self-cleaning glazing materials (*e.g.,* new synthetics, embossing of suitable micro-structures into the surfaces of panels and tubes).

Material research is needed on the thermal side of solar thermal energy conversion:

- Materials and components are needed that can withstand high stagnation temperatures of high-efficiency solar thermal collectors without decreasing efficiency in the required temperature range, or breaking down and thereby shortening the 20-year service life
- Plastic materials for collectors, particularly plastics with high thermal and optical performance, could significantly reduce the costs of solar thermal systems.
- To address the issue of solar thermal energy storage, there is a need for advanced insulation materials and for energy storage materials with a higher energy density than water. Promising technologies are based on phase change materials or thermo-chemical storage processes (*e.g.,* sorption). Specific RD&D needs are described below.

Advanced solar thermal components

There is a need for further innovation in the design of collectors, specifically:

- Advanced flat-plate collectors specifically designed for roof and façade integration.
- New collectors for medium-temperature applications (up to temperatures of approximately 250°C) are necessary for new and challenging applications such as solar cooling and solar heat for industrial processes.
- Photovoltaic-thermal (PVT) collectors.

Thermal energy storage

The potential for solar thermal applications in the housing sector and in industry will increase dramatically once suitable technical solutions are available to store heat for the medium (daily) to longer (seasonal) term. Such advanced storage systems could utilise chemical and physical processes to reduce total storage volume and related costs. The general aim should be to develop materials, components and systems that allow a reduction of storage volume by at least a factor of three compared to water. With current phase change materials (PCM), only a factor of 1.5 to two can be expected, relative to hot water systems.

Water tanks will achieve a good method for heat storage. However, when it comes to high solar fraction for solar homes, they show limits due to the required size and the heat losses. New materials and new types of storage concepts are necessary. These could be based on PCMs or chemicals, or on a combination of water tanks and those materials adequately encapsulated. PCM materials can also be incorporated into structural elements of buildings. In order to produce cold when the sun is available and deliver cold water on demand, solar-assisted air conditioning and cooling systems need both hot and cold storage. This is another promising application for PCM materials.

RD&D activities should be planned to fulfil the need to develop and/or test:

- New materials for storing thermal energy at >0°C to 200°C.
- New and cost-effective storage solutions for combi-systems. This should be done in conjunction with manufacturers and industry.
- Advanced concepts and materials for thermal insulation of storage units.
- Simulation programmes in order to describe the thermal performance of advanced storage systems.
- Real installations – and disseminate the results.

Advanced solar heating and cooling systems

Large-scale solar combi-systems for water and space heating

Solar heating systems for combined domestic hot water preparation and space heating (so called "solar combi-systems") are increasing their market share in many European countries. However current designs are mainly focused on single-family houses. It is necessary to develop and demonstrate solar combi-systems with several hundred kW for multi-family houses, as well as both large-scale applications for housing estates and solar-assisted district heating systems with several MW.

Special attention should be placed on stagnation behaviour, net optimisation and net management with respect to solar thermal heat integration (reduction of the temperature levels in the supply and return pipe) and optimised storage concepts (aquifers, bore holes, new materials, etc.). In addition, more research is required on the combining of solar thermal systems with central biomass heating plants and on the integration into conventional district heating networks.

Development of cost-efficient, solar-only heating systems

All solar combi-systems on the market to date need a back-up boiler. This creates a situation in which the additional cost of a solar combi-system can be amortised only through fuel savings. To reduce the cost of the overall heating system, it is necessary to develop cost-effective, solar-only heating systems. In combination with well-insulated houses and high energy-density storage tanks, solar thermal systems will be able to provide 100% of the space heating demand of a building.

Solar thermal systems for industrial applications

The industrial sector is the largest energy consumer in EU countries at approximately 30%, followed closely by the transportation and household sectors. The major share of the energy, which is needed in commercial and industrial companies for production, processes and for heating of the production halls, is below 250 °C. Appropriate system designs and controls are needed to meet industrial requirements. Furthermore, design tools, medium temperature collectors and high performance storage tanks are needed for the efficient integration of solar energy into industrial processes.

Solar cooling applications

With increasing demand for higher comfort levels in offices and houses, the market for cooling rose steadily in recent years. The obvious solution, to provide prime energy for these cooling applications through solar thermal systems, is still under development. In the small capacity range, component development of cooling equipment needs further RD&D in order to achieve higher performance, lower prices and more industrialised production. For all systems – small capacity for residential application and in small commercial buildings, as well as in the large-capacity range for large buildings and industrial applications - RD&D is required in the following areas:

- Cooling machines for low capacities and machines able to adjust to the solar thermal heat supply.
- System design, integration and control.
- Providing best-practice solutions via demonstration projects.

Systems for combined space heating and cooling

The combination of solar space heating, hot water preparation and cooling has not been addressed since the initial RD&D done in the 1980s. Such systems have a high market potential: by extending the operational period of the collectors to the full year, they will dramatically increase the competitiveness of solar thermal technology through the combination of heating and cooling.

Building design and integration

To achieve broad market introduction of solar thermal systems, architectural aspects must also be taken into consideration. Solar thermal collectors need to become an integral part of the building, ideally becoming standard construction elements. Furthermore, the impact of solar thermal systems on the building physics (*i.e.,* façade collectors) and HVAC-systems are important factors that merit detailed investigation.

As buildings come to require less and less energy, in northern countries the effective heating season is shortened to a few months of the year. These months correspond exactly to the months with the least solar radiation. Thus, issues related to superior insulation and passive solar gains become less important. This does not consider the option of using passive solar gains during the spring and autumn to eliminate auxiliary energy demand while increasing the quality of life within buildings all year around. Further investigation is needed on the interaction between windows, the degree of insulation and the use of ventilation heat recovery in high performance buildings.

Comfort of building occupants is a critical aspect, especially because the solar fraction is increased by means of passive solar design. Sun and glare protection reduce the passive solar heat contribution while the losses remain constant. Accordingly, the balance between comfort and energy savings requires careful analysis of occupant behaviour and of the various types of shading/glare control devices used, including options for automation. As "smart" houses gain a larger share of the housing market, the opportunity arises to maximise useful solar gains without compromising comfort. Types of devices, control systems and window systems could be investigated and compared in the context of highly insulated houses with and without mechanical ventilation with heat recovery.

Standards, regulations and test procedures

Standards, regulations and test procedures are all necessary to support the larger market uptake of SHC technologies. Test procedures are needed to understand the likely performance of products in the field, in terms of energy supplied or saved, durability and reliability – all of which are vital for market acceptance. Some new products, such as combi-systems, do not yet have accepted energy performance evaluation procedures. Others, such as evacuated tubes, are not yet fully covered by existing standards; for example, more work is needed on test method of hail resistance. Once test methods are developed, they can be standardised and can facilitate international trade in SHC products and components. For products with sufficient ‘proof-of-product’ performance, governments concerned with energy security and environment are beginning to regulate that cost-effective products must be used in all new buildings (*e.g.,* solar hot water in Israel and Spain).

To support further development and market introduction of solar thermal energy, it is necessary to do more than promote the technology itself; it is equally important to provide appropriate boundary conditions. These include methods of testing and assessing the thermal performance, as well as durability and reliability of systems and components. Tools and education packages for practicing architects are also needed. Furthermore, it is necessary to develop methods to assess the environmental benefits of solar thermal systems and to include solar thermal in current building standards and regulations, as has been done in the European Building Performance Directive.

Costs and benefits of additional RD&D

The first section of this paper gives numerous justifications to show the capacity of industry to absorb additional funding. Steady funding at increased levels would allow the various SHC technologies and designs to reach better cost and performance goals, thereby fostering their growing presence in the market – and their associated environmental benefits. The following table provides a breakdown of the most critical areas of RD&D and proposed budgets required.

Table 2. **Ten-year RD&D programme and the budget on solar heating and cooling**

Area	Ten-year RD&D Budget, Millions (USD)
Advanced materials	62
Advanced solar thermal collectors	75
Advanced thermal energy storage	149
Large-scale solar heating systems	87
Solar industrial processes systems	186
Solar cooling systems	99
Combined solar heating and cooling systems	186
Building integration and passive solar	124
Standards, regulations and test procedures	143
Total Ten-year RD&D Programme	**1111**

Current activities of IEA Solar Heating and Cooling Implementing Agreement

The IEA Solar Heating and Cooling Implementing Agreement (SHC) was one of the first IEA Implementing Agreements to be established. Since 1977, its 21 members have collaborated to advance active solar, passive solar and photovoltaic technologies, and their application in buildings. A total of 33 Tasks were initiated, 25 of which are now completed. Eight Tasks remain ongoing in 2005 (IEA SHC, 2005) (Table 3).

Table 3. **Current projects of IEA Solar Heating and Cooling Implementing Agreement**

Project	Outline
Performance of Solar Façade Components	Determine performance of materials and components, such as advanced glazing; promote their increased use by developing and applying appropriate methods for assessment of durability, reliability and environmental impact.
Solar Sustainable Housing	Address cost optimisation of the mix of concepts aimed at reducing energy losses, increasing usable solar gains and efficiently providing back-up to achieve high performance.
Solar Crop Drying	Address barriers by providing technical and commercial information and experience gained from the design, construction and operation of full working demonstration systems for a variety of crops and a number of geographical regions.

Table 3. **Current projects of IEA Solar Heating and Cooling Implementing Agreement** (continued)

Project	Outline
Daylighting Buildings in the 21st Century	Make daylighting the typical and preferred design solution for lighting buildings in the 21st century; integrate human response with the application of daylighting systems; shading and electric light control strategies.
Advanced Storage Concepts for Solar Thermal Systems in Low Energy Buildings	Contribute to the development of advanced storage solutions in thermal solar systems for buildings that lead to high solar fraction (up to 100% in a typical 45N latitude climate).
Solar Heat for Industrial Process	Improve conditions for market introduction of solar heating systems for industrial applications in order to promote reduced fossil energy consumption; develop environmentally friendly mechanisms for industrial production.
Testing and Validation of Building Energy Simulation Tools	Investigate the availability and accuracy of building energy analysis tools and engineering models to evaluate the performance of solar and low-energy buildings. The scope of the project is limited to building energy simulation tools, (including emerging modular type tools) and to widely used solar and low-energy design concepts. Activities include development of analytical, comparative and empirical methods for evaluating, diagnosing and correcting errors in building energy simulation software.
PV/Thermal Solar System	Catalyse development and market introduction of high quality and commercially competitive PV/Thermal Solar Systems; increase general understanding and contribute to internationally accepted standards on performance, testing, monitoring and commercial characteristics of PV/Thermal Solar Systems in the building sector.

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Chapter 3 • Technologies

Concentrating solar power

Highlights

- Solar radiation is the largest renewable resource on Earth. Solar thermal power is logically one of the main candidates to provide a major share of the renewable, clean energy needed in the future.
- The only commercial-scale projects employing this specific technology were installed in California, USA, between 1984-90. In total, 354 MW of solar trough plants were constructed, and remain in operation.
- In 2003, solar thermal electricity production in OECD member countries was 548 GWh.
- Solar thermal power is among the most cost-effective renewable energy technologies and the lowest-cost solar electricity in the world. Power generation costs are expected to be in the range of USD 0.075/kWh to USD 0.19/kWh, promising cost-competitiveness with fossil fuel plants in the future.
- Concentrating solar power (CSP) technologies are flexible. They are appropriate for a wide range of applications including dispatchable central-station power plants (in which they can meet peak-load to near-base-load needs of a utility) and distributed modular power plants (for both remote and grid-connected applications).
- Another inherent advantage of CSP technologies is their unique ability to integrate into conventional thermal plants. As such, solar thermal systems are essentially the only renewable power plants that will neither cause grid perturbations nor disturb the operation of other existing fossil plants in the entire power park. This makes CSP technologies a likely candidate for large-scale emissions reduction at reasonable cost.
- Current CSP technology systems are implemented in the cost range of USD 0.19/kWh to USD 0.25/kWh. Sustainable market integration can only be achieved if the cost can be reduced to a competitive level in the next 10 to 15 years. Competitiveness is affected not only by the cost of the technology itself, but also by potential price increases of fossil energy and the internalisation of associated social costs, such as carbon emissions.
- Estimates suggest that approximately half of the cost-reduction potential for CSP will be attributed to scaling up to larger plant sizes and volume production effects; the other half will be attributed to technology RD&D efforts. Scaling reduces unit investment cost and unit operation and maintenance costs, while also increasing performance. Technological improvements, especially in concentrator performance and cost, would most dramatically affect levelised electricity cost (LEC) figures. Storage systems are a second key factor in reducing the cost of solar power plants.
- Additional RD&D efforts must be supported by significant deployment efforts, which are needed to make the most of renewable electricity incentive schemes, especially where there are significant solar resources. Scaling up CSP to larger

power block sizes is an essential step in reducing electricity costs. Thus, it may be sufficient if incentive schemes avoided limiting upper power levels, to ensure the possibility of fully exploiting the cost-reduction potential.

- RD&D may also contribute to developing CSP technologies, particularly if the European market considers importing solar electricity from Northern Africa. High solar resource levels may more than make up for the additional transport costs.
- Legal frameworks should allow more flexibility in the adoption of hybrid operations of CSP systems.

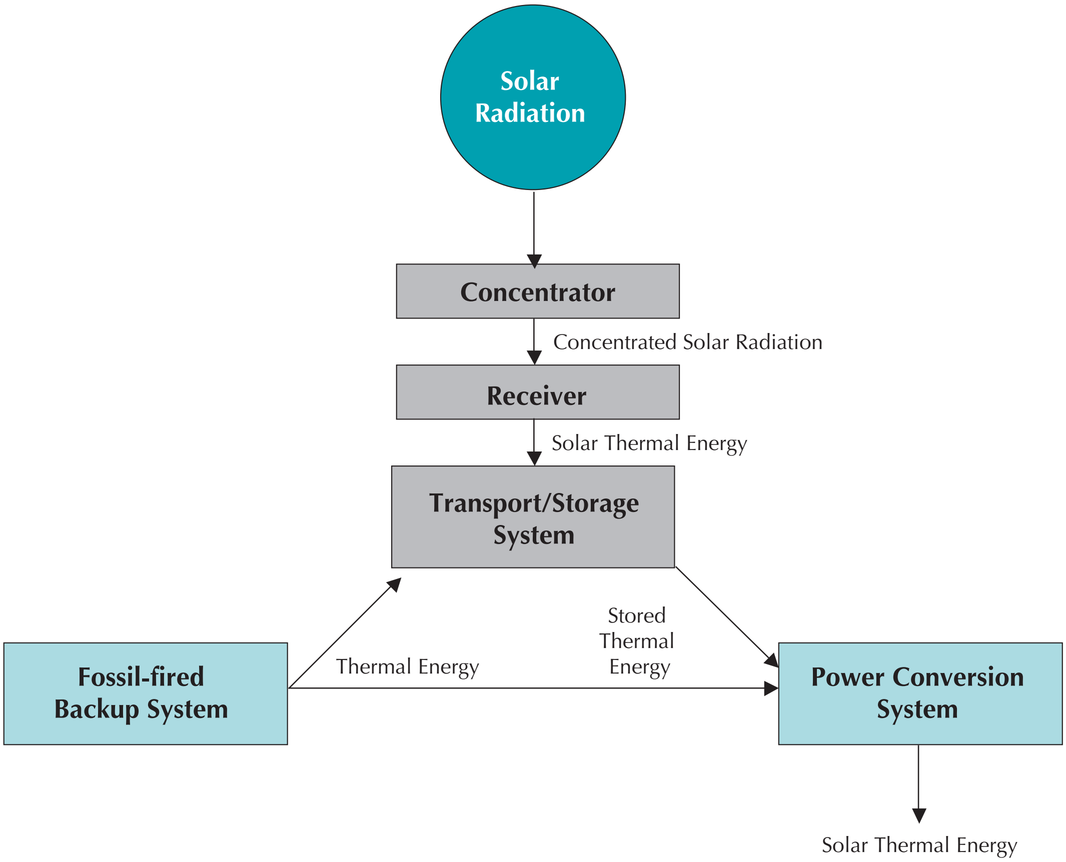
Introduction

Solar thermal power is one of the main candidates to provide a major share of the renewable clean energy needed in the future. The appeal of solar radiation is evident in that it is:

- The largest renewable resource on Earth. Solar thermal power is logically one of the main candidates to provide a major share of renewable, clean energy needed in the future.
- More evenly distributed in the sunbelt of the world than wind or biomass, allowing for more site locations.
- Among the most cost-effective renewable power technologies and the lowest-cost solar electricity in the world. Power generation costs are expected to be in the range of USD 0.075 kWh to USD 0.19/kWh, promising cost-competitiveness with fossil fuel plants in the future.
- A proven and demonstrated technology. More than 100 years of accumulated operating experience demonstrate the soundness of the concept. Since the earliest plant was installed in 1985 (California, USA), nine solar thermal power plants (of the parabolic trough type) have fed more than 8 billion kWh of solar-based electricity into the California grid.

Regarding technical features, the conversion path of all concentrating solar power technologies relies on four basic elements: concentrator, receiver, transport-storage, and power conversion (Figure 1). The concentrator captures and concentrates solar radiation, which is then delivered to the receiver. The receiver absorbs the concentrated sunlight, transferring its heat to a working fluid. The transport-storage system passes the fluid from the receiver to the power-conversion system; in some solar-thermal plants a portion of the thermal energy is stored for later use. Several solar thermal power conversion systems have been successfully demonstrated including Rankine, Brayton, combined or Stirling cycles. Three emerging solar thermal power generation concepts – namely the parabolic trough (or 'solar farm'); the solar central power receiver (or 'power tower'); and the parabolic dish system – will be described in more detail under Current Technology Status.

Figure 1. **Conversion path from solar radiation to solar electricity**



Each technology can be integrated into conventional thermal cycles as "a solar burner" in parallel to a fossil burner. This makes it possible to provide thermal storage or fossil fuel backup firm capacity without the need for separate back-up power plants and without stochastic perturbations of the grid.

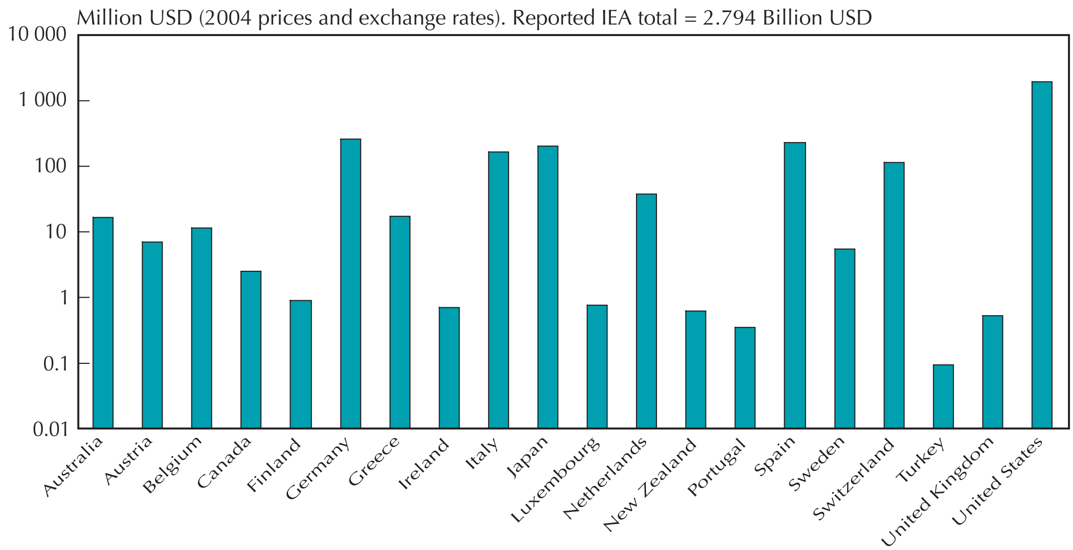
These features make CSP technologies a strong candidate for large-scale emissions reduction at reasonable cost. CSP technologies are appropriate for a wide range of applications, including dispatchable central-station power plants (in which they can meet peak-load to near-base-load needs of a utility) and distributed modular power plants (for both remote and grid-connected applications). The availability of storage and the ability to share generation facilities with biomass suggest good potential to provide a replacement for high-capacity, factor fossil fuel plants.

It is believed that CSP can contribute significantly to a truly sustainable energy system and the sector has adopted a vision to see this achieved in the medium to long term in Europe. The European Commission (EC) thus adopted a co-ordinating action, the European concentrated solar thermal road-mapping (ECOSTAR) (Pitz-Paal, Dersch and Milow, 2005; Pitz-Paal et al., 2005), to harmonise the fragmented research methodology previously in place in Europe – which led to competing approaches on how to develop and implement CSP technology. Cost-targeted innovation approaches, as well as continuous implementation of this technology, are needed to realise cost-competitiveness in a timely manner.

IEA member countries allocated approximately USD 2.8 billion (2004 prices and exchange rates) for RD&D on CSP from 1974-2003 (Figure 2). The United States accounted for about 64% of governmental RD&D funding. Other member countries, such as Spain, Japan, Italy and Switzerland, reported three-digit numbers of million USD on RD&D for CSP, amounting to about 23% of RD&D budgets for this technology.

In 2003, solar thermal electricity production in OECD member countries was 548 GWh.

Figure 2. **Reported government concentrating solar thermal power RD&D budgets in IEA member countries, 1974-2003**



Current technology status

Concentrating solar power systems can be sized for village power (10 kW) or grid-connected applications (up to 100 MW). Some systems use thermal storage during cloudy periods or at night. Others are combined with natural gas and the resulting hybrid power plants provide high-value, dispatchable power. These attributes, along with "world record" solar-to-electric conversion efficiencies, make concentrating solar power an attractive renewable energy option in the southwest United States and other sunbelt regions worldwide.

For each of the three technologies discussed in the preceding pages, various designs and configurations exist. The amount of power generated by a CSP power plant depends on the amount of direct sunlight. As with concentrating photovoltaic concentrators, these technologies use only direct-beam sunlight rather than diffuse solar radiation.

The parabolic trough or 'solar farm' consists of long parallel rows of identical concentrator modules, typically using trough-shaped glass mirrors. Tracking the sun from east to west by rotation on one axis, the trough collector concentrates the direct solar radiation onto an absorber pipe located along its focal line. A heat transfer medium, typically oil (at temperatures of up to 400°C), circulates through the pipes and evaporates water. The resulting steam drives the steam turbine generator of a conventional power block. Individual commercial plants will be sized from 50 MW to 200 MW to produce electricity. To date, the only commercial-scale projects employing this specific technology were installed in California, USA, between 1984-90. In total, 354 MW of solar trough plants were constructed, and remain in operation.

The solar central receiver or 'power tower' is surrounded by an array of two-axis tracking mirrors, called heliostats, that reflect direct solar radiation onto a fixed receiver located on the top of the tower. Within the receiver, a fluid – water, air, liquid metal and molten salt have been tested – transfers the absorbed solar heat to the power block, where it is used to heat a steam generator. Advanced high temperature power tower concepts are now under investigation, which heat pressurised air up to more than 1 000°C. The hot air is then fed into the gas turbines of modern combined cycles. Early power towers utilised steam as the heat transfer fluid; current designs utilise molten nitrate salt because of its superior heat transfer and energy storage capabilities. (Figure 3a) Current European designs use air as the heat-transfer medium because of its high temperature and its good handling characteristics.

Parabolic dish systems consist of a parabolic-shaped point-focusing concentrator, in the form of a dish that reflects solar radiation onto a receiver mounted at the focal point. These concentrators are mounted on a structure with a two-axis tracking system to follow the sun. Collected heat is typically utilised directly by a heat engine mounted on the receiver. Stirling and Brayton cycle engines are currently favoured for decentral power conversion; central Rankine cycles are being studied for use in large fields of such dishes. Projects of modular systems have been realised with total capacities up to 5 MW_e. The modules have maximum sizes of 50 kW_e and have achieved peak efficiencies of up to 30% net.

The inherent advantage of CSP technologies is their unique capacity for integration into conventional thermal plants. Each technology can be integrated as "a solar burner" in parallel to a fossil burner into conventional thermal cycles. This makes it possible to provide thermal storage or fossil fuel backup firm capacity without the need for separate back-up power plants and without stochastic perturbations of the grid.

With a small amount of supplementary energy from natural gas or any other fossil fuel, solar thermal plants can supply electric power on a firm, secure basis. Thus, solar thermal concepts have the unique capability to internally complement fluctuating solar burner output with thermal storage or a fossil back-up heater. This makes solar thermal systems the only renewable power plants that will neither cause grid perturbations nor disturb the operation of other existing fossil plants within the entire power park.

Current CSP technology systems are implemented in the cost range of USD 0.19/kWh to USD 0.25/kWh. In the conventional power market, CSP competes with mid-load power in the range of USD 0.037/kWh to USD 0.05/kWh. Sustainable market integration, as different scenarios predicted, can only be achieved if costs can be reduced to competitive levels in the next 10 to 15 years. Competitiveness is affected not only by the cost of the technology itself, but also by potential price increases of fossil energy and by the internalisation of associated social costs, such as carbon emissions. Therefore, it is assumed that in the medium to long term, competitiveness will be achieved at a level of USD 0.05/kWh to USD 0.075/kWh for dispatchable mid-load power.

Estimates suggest that approximately half of the cost-reduction potential for CSP will be attributed to scale-up to larger plant sizes and volume production effects; the other half will be attributed to technology RD&D efforts (Sargent & Lundy, 2003). Scenario approaches estimate cost-reduction potential and the total market incentives needed to achieve full compositeness with conventional choices. However, they do not help to identify specific innovations that may enable these reductions.

A recent ECOSTAR evaluation analysed current costs and the total cost-reduction potential of CSP technology. In addition, all systems labelled as 'technical innovations' were identified and defined by a component cost and performance estimate to calculate the levelised electricity cost (LEC). It found that current investment and generation cost data for each of the reference CSP systems (Figures 3a and 3b), although relatively close, vary due to different levels of maturity in the technology and different technological approaches. The costs range from USD 0.21/kWh to USD 0.22/kWh (for a parabolic trough system of 50 MW_e units that uses thermal oil as a heat transfer medium) and from USD 0.24/kWh to USD 0.35/kWh (for smaller pilot scale systems of up to 15 MW_e). Assuming that several of the smaller systems are built at the same site to achieve a power level of 50 MW and benefit from similar O&M efforts as the larger plants, the LEC estimates of all of the systems would range between USD 0.19/kWh and USD 0.25/kWh.

One significant exception is the hybridised system, in which solar energy is integrated into a gas turbine/combined cycle. Currently, this technology provides a solar capacity factor of only 11% and requires significant fossil fuel (20% to 25% annual solar share depending on load curve). However, it offers an LEC of less than USD 0.11/kWh for the hybrid operation (equivalent to USD 0.17/kWh for solar LEC). Thanks to the low specific investment cost of the gas turbine/combined cycle – coupled with high efficiency – the system is especially attractive for hybrid operations. Further development of the receiver technology would increase the solar share significantly in the future.

Current RD&D

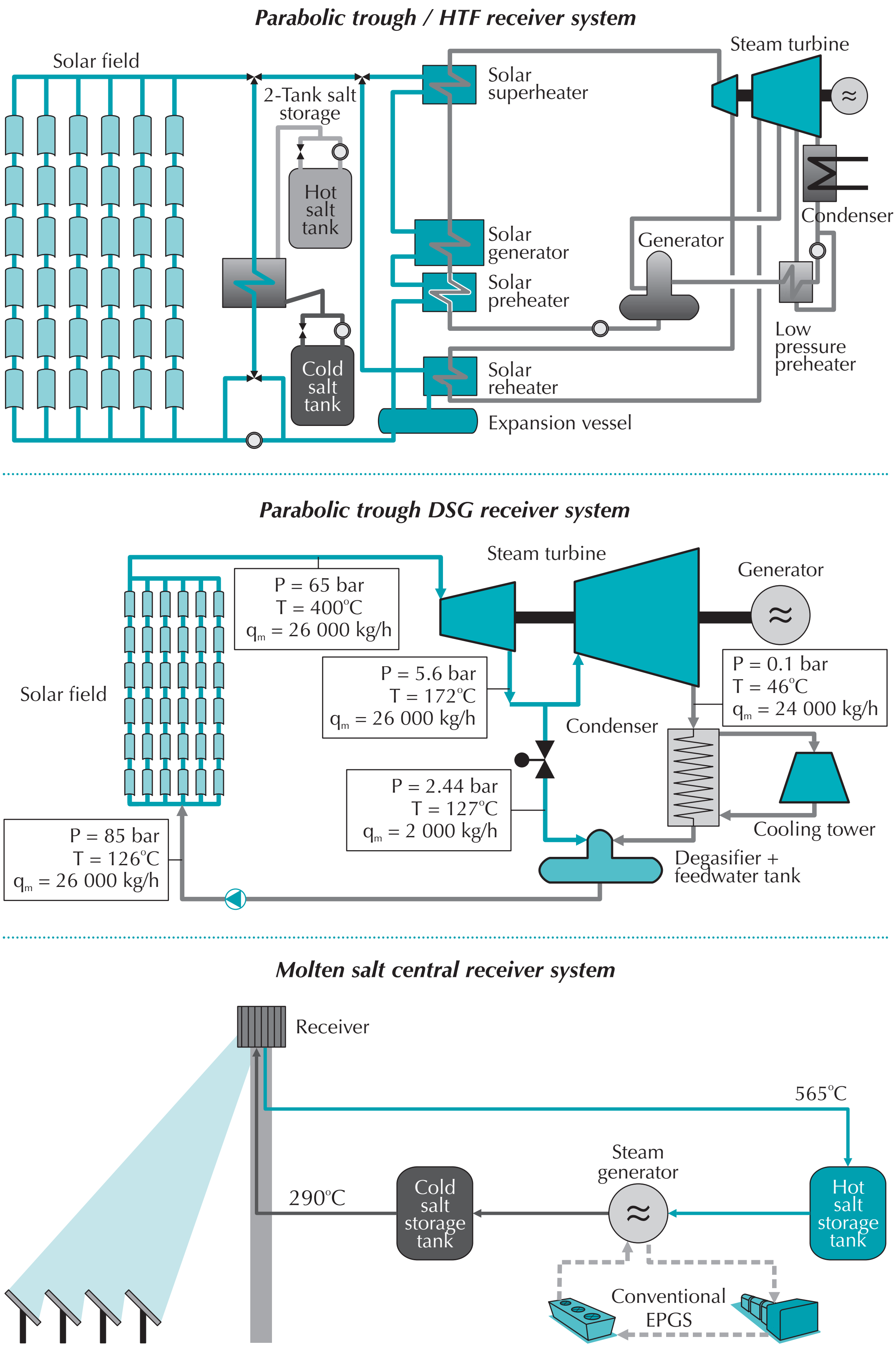
As already mentioned above, RD&D efforts play a major role in both scaling up technology and in achieving further cost reductions for CSP systems. The evaluation of ECOSTAR identified major cost reduction drivers for each of the considered reference systems (Figures 3a and 3b), as well as the potential impact of technical innovations. As mentioned, all systems labelled as 'technical innovations' were identified and defined by a component cost and performance estimate to calculate the levelised electricity cost (LEC). For example, the utilisation of thin glass mirrors in parabolic trough collectors has the following impacts (the first parameter value listed is the pessimistic estimate; the second is the optimistic estimate):

- Mean reflectivity is left unchanged at 0.88 / increases to 0.89.
- Specific investment costs are reduced to 95% / 90% of the reference value.
- O&M equipment cost percentage is increased to 1.1% / left unchanged at 1%.

These figures are used in the annual calculation model to define boundary values for the LEC reduction (Figure 4).

The evaluation combined the most promising options to estimate the overall cost-reduction potential. Based on the limited number of approaches suggested in the scope of this study, one could expect cost reductions of 25% to 35% due to technical innovations and scaling.

Figure 3a. **Reference CSP systems**

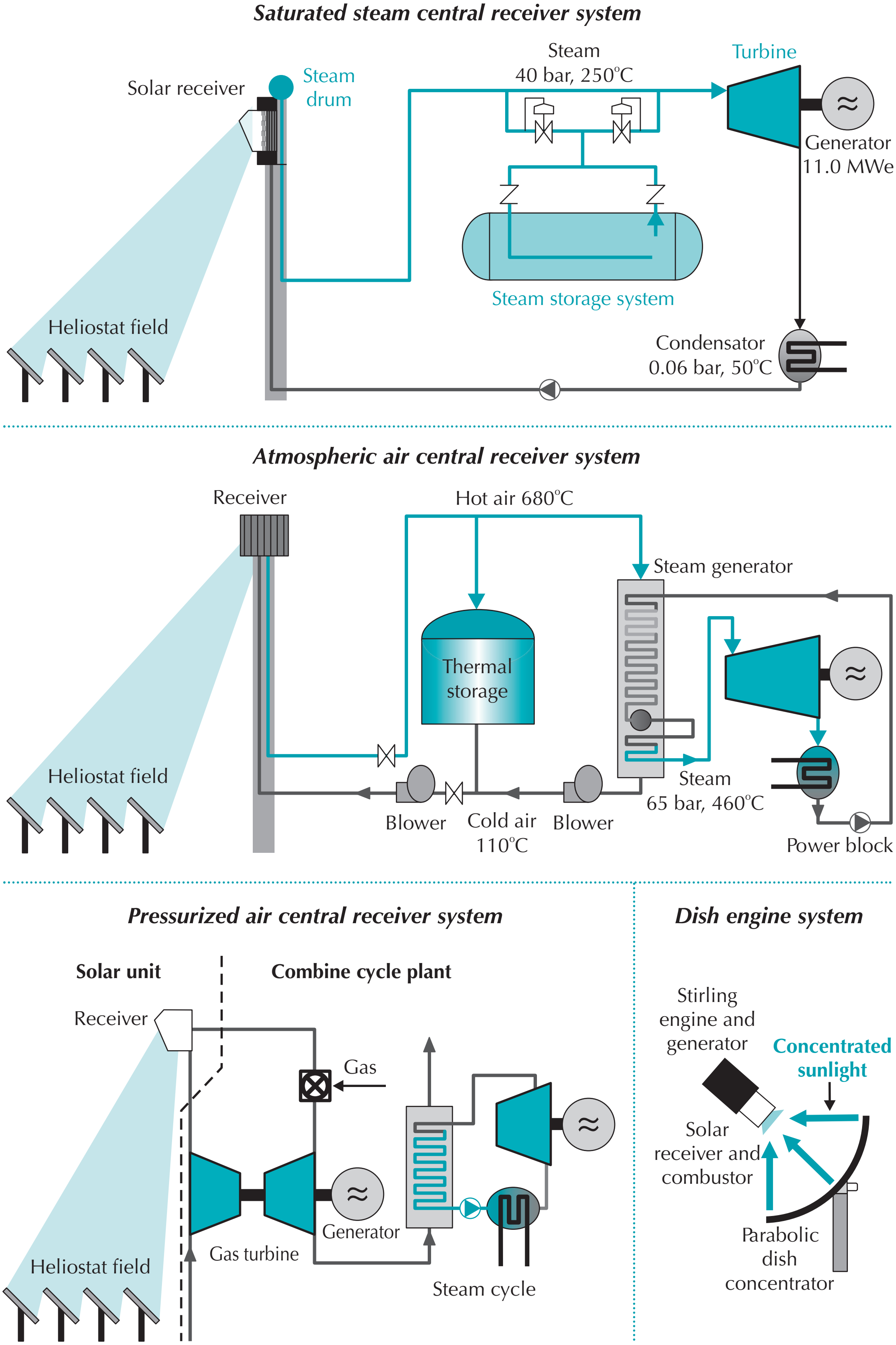


Technology	Parabolic trough / HTF receiver system	Parabolic trough DSG[4] receiver system	Molten salt central receiver system
Technical design parameter			
Collector	Parabolic trough	Parabolic trough	Heliostat field
Receiver	Linear receiver (tubes)	Linear receiver (tubes)	Molten salt receiver
Storage system	2-tank-molten-salt storage	No storage system available	2-tank-molten-salt storage
Cycle	Rankine steam cycle	Rankine steam cycle	Rankine cycle
Planed / built power size	50 MW Andasol I & II under preparation, Spain	4.7 MW INDITEP study	Solar Tres (17MW), planed, Spain
Maturity	Several commercial units up to 80 MWe are in operation in southern USA	Single row experimental plant in Spain	Solar 2 (11 MW) experimental plant in California in the 1990s
Temperature	393°C	411°C	565°C
Size of the reference system	50 MW_e	10 x 4.7 MW_e	3 x 17 MW_e
Solar capacity factor	29%	22%	33%
LEC for a single ECOSTAR reference system, solar-only	0.214 USD/kWh_e	0.232 USD/kWh_e	0.227 USD/kWh_e
LEC for a power plant park consisting of several reference systems with total capacity of 50 MW, solar-only	0.214 USD/kWh_e	0.201 USD/kWh_e	0.193 USD/kWh_e

4. The linear Fresnel collector has been considered as innovation for the parabolic trough DSG system in the subsequent analysis.

Source: Pitz-Paal, Dersch and Milow, 2005.

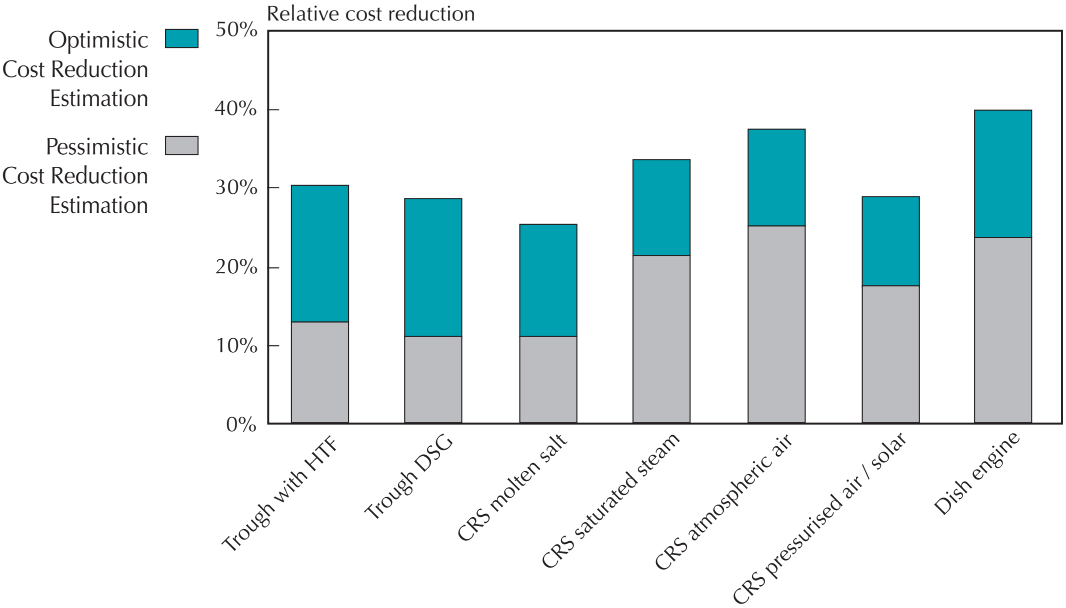
Figure 3b. **Reference CSP systems**



Technology	Saturated steam central receiver system	Atmospheric air central receiver system	Pressurized air central receiver system	Dish engine system
Technical design parameter				
Collector	Heliostat field	Heliostat field	Heliostat field	Parabolic dish
Receiver	Saturated steam receiver	Volumetric atmospheric air-cooled receiver	Pressurized air receiver	Cavity receiver with tube bundle
Storage system	Water/steam buffer storage	Ceramic thermocline thermal storage	No storage system available up to date	No storage system available up to date
Cycle	Rankine cycle	Rankine cycle	Combined cycle	Stirling engine
Planed / built power size	PS 10 (11MW), under construction, Spain	PS 10 conceptual design study	Solgate study 14.6 MW_e	22 kW_e
Maturity	Several experimental plants up to 2 MW_{th} have been tested	2.5 MW_{th} experimental plant tested in Spain in 1993	2 x 200 kW_e under construction in Italy	About 30 units up to 25 kW_e are in operation at different sites
Temperature	250°C	750°C	800°C	800°C
Size of the reference system	5 x 11 MW_e	10 x 4,7 MW_e	4 x 14.6 MW_e	2 907 x 25 kW_e
Solar capacity factor	26%	33%	11% (55%)[5]	22%
LEC for a single ECOSTAR reference system, solar-only	0.299 USD / kWh_e	0.291 USD / kWh_e	0.183 USD / kWh_e (0.124 USD / kWh_e)	0.349 USD / kWh_e
LEC for a power plant park consisting of several reference systems with total capacity of 50 MW, solar-only	0.210 USD / kWh_e	0.222 USD / kWh_e	0.173 USD/ kWh_e (0.102 USD / kWh_e)	0.240 USD / kWh_e

5. Values in brackets are for hybrid operation.

Figure 4. **Innovation-driven cost-reduction potential for CSP technologies**



For seven technologies investigated based on LEC for 50 MWe reference system and assuming a combination of selected innovations for each system.

Source: Pitz-Paal, Dersch and Milow, 2005.

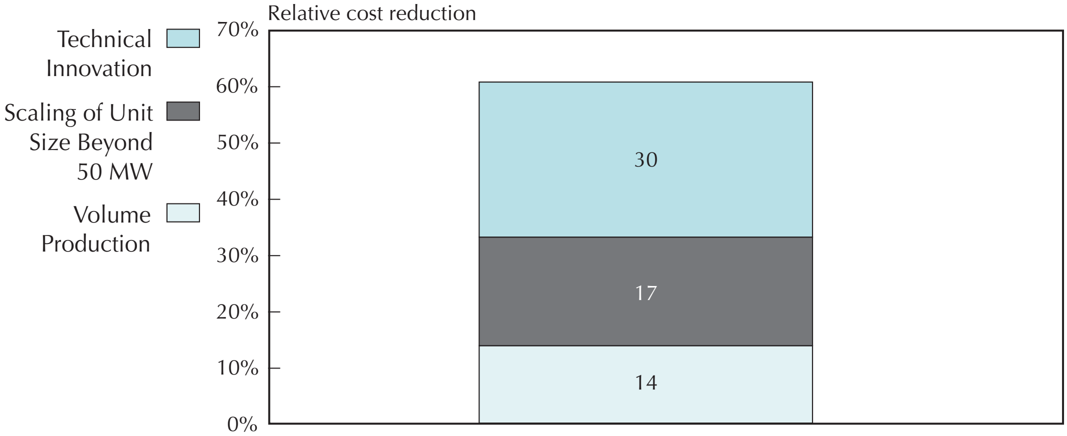
A fuel price of USD 18.6/MWh for up to 50 MW_e is feasible for most of the technologies. These figures do not include effects of volume production or scaling of the power plants beyond a unit size of 50 MW, which would result in further cost reductions.

For parabolic trough technology, there is an estimated cost reduction of 14% from using larger power blocks (400 MW) and 17% as a result of volume production effects when installing 600 MW/year (Sargent & Lundy, 2003). Assuming similar figures for other technologies, an overall cost reduction of 55% to 65% can be estimated in the next 15 years. This accumulated potential has been illustrated for the parabolic trough high temperature fluid (HTF) system (Figure 5); very similar figures appear feasible for the other six systems investigated.

Cost reductions in the technology would lead to a levelised cost of electricity – for example, in the region of USD 0.08/kWh in Southern Spain and down to USD 0.06/kWh in high solar resource areas such as the southern shore of the Mediterranean Sea by 2020 (Figure 6) – and would represent competitive cost for mid-load power.

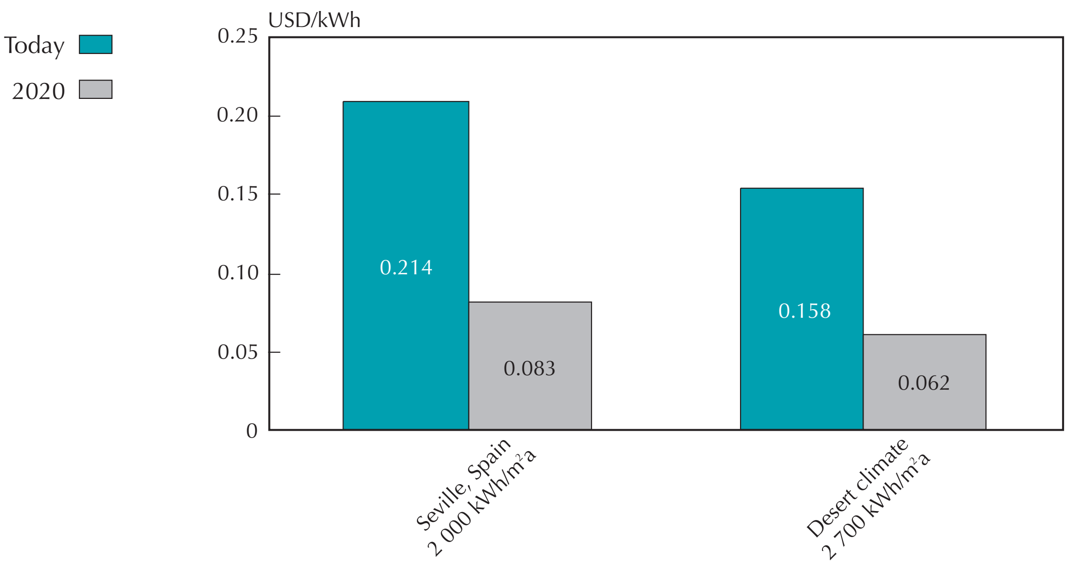
In addition to cost, several scenarios describe the potential deployment of CSP systems. The Athene Study (DLR/WI/FhG-ISE, 2003) uses a scenario technique to quantify worldwide deployment of CSP through to 2025 (Figure 7). This analysis accounts for learning and scaling effects, and estimates the overall investment cost and the average LEC. The Athene study estimates that by 2025 more than 40 GW of CSP technology will have been installed worldwide.

Figure 5. **Potential relative reduction of LEC by innovations, scaling and series production through 2020 for parabolic trough/HTF system compared to today's LEC**



Source: Pitz-Paal, Dersch and Milow, 2005.

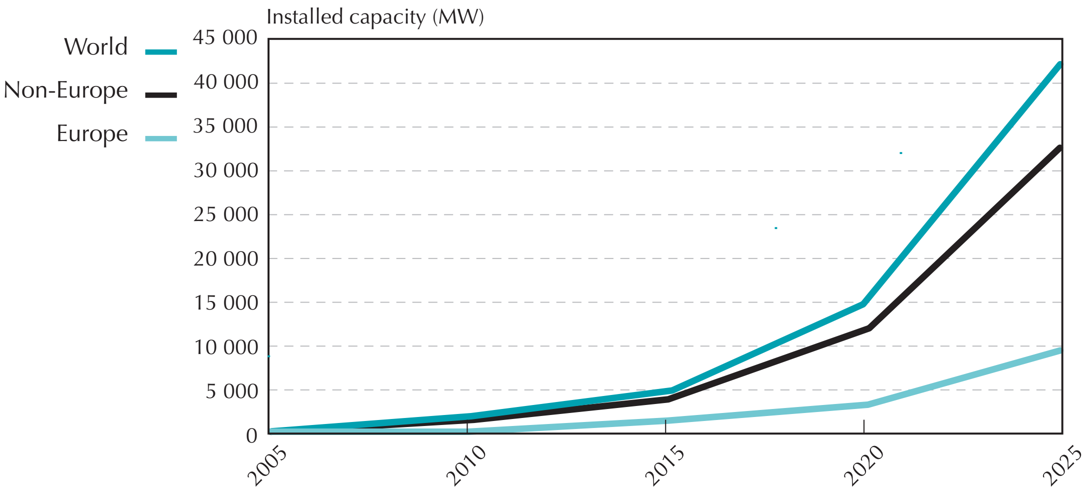
Figure 6. **CSP cost-reduction for the parabolic trough/HTF system**



Source: Pitz-Paal, Dersch and Milow, 2005.

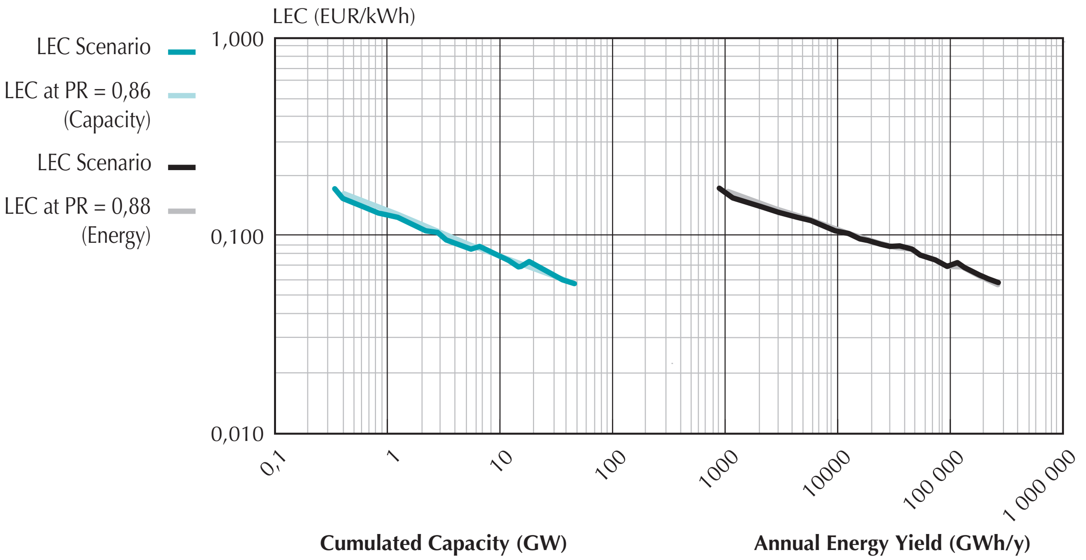
The Athene study also provides an overview of the possible cost of CSP in the medium to long term, based on a progress ratio of 86% for cumulative installed capacity and 88% for annual energy yield. This approach predicts a significant cost reduction: At a total installed capacity of 40 GW, the cost is driven down to USD 0.06/kWh, achieved between 2020-25 (Figure 8).

Figure 7. **Athene scenarios on the deployment of concentrated solar power systems**



Source: DLR/WI/FhG-ISE, 2003.

Figure 8. **Athene scenario of LEC reduction predicted by the learning curve approach**



Source: DLR/WI/FhG-ISE, 2003.

Additional RD&D priorities

The relatively small difference in investment and generation costs between the CSP technologies makes it difficult to define RD&D priorities based on technology (*e.g.,* trough vs. towers). However, various innovation aspects have different impacts on LEC reduction for the seven systems investigated in the ECOSTAR evaluation. The innovation potential with the highest impact on CSP cost reduction was identified for each technology (Table 1).

Summarising the detailed findings for individual systems, it is clear that improvements in the concentrator performance and cost have the most dramatic impact on LEC figures. As the

Table 1. **Innovation potential with the highest impact on CSP cost-reduction**

Technology	Priority A	ΔLEC	Priority B	ΔLEC	Priority AC	ΔLEC
Trough Using Oil	Concentrator structure and assembly	7-11%	Low cost storage system Advanced reflectors and absorber	3-6 % 2-6%	Increase HTF temp Reduce parasitics	1-3% 2-3%
Trough DSG	Scale increased to 50 MW system Concentrator structure, and assembly	14% 7-11%	Advanced storage Advanced reflectors and absorber	3-6% 2-6%	Increase HTF temp Reduce parasitics	1-3% 2-3%
SCR Salt	Scale increased to 50 MW Heliostat size, structure	3-11% 7-11%	Advanced mirrors	2-6%	Advanced storage	0-1%
SCR Steam	Scale increased to 50 MW Heliostat size, structure	6-11% 7-11%	Superheated steam Advanced storage	6-10% 5-7%	Advanced mirrors	2-6%
SCR Atmosph. Air	Scale increased to 50 MW Heliostat size, structure	8-14% 7-11%	Advanced storage Increased receiver performance	4-9% 3-7%	Advanced mirrors	2-6%
SCR Hybrid GT	Heliostat size, structure, Include thermal storage	7-11% 7-10%	Scale increased to 50 MW	3-9%	Advanced mirrors Increased receiver performance	2-6% 1-2%
Dish	Mass production for 50 MW	38%	Improve availability and red. O&M Brayton instead of stirling Increased unit size	8-11% 6-12% 5-9%	Increased engine efficiency Reduced engine cost Advanced mirror and tracking	2-6% 2-6% 0-1%

Source: Pitz-Paal, Dersch and Milow, 2005.

concentrator is a modular component, it is possible to adopt a straightforward strategy that couples development of prototypes and benchmarks of these innovations in parallel with state-of-the-art technology – in real solar power plant operation conditions. Modular design also makes it possible to focus on specific characteristics of individual components, including reflector materials and supporting structures, both of which would benefit from additional innovation.

New reflector materials should be low cost and have the following traits:

- Good outdoor durability.
- High solar reflectivity (>92%) for wave lengths within the range: 300 nm to 2 500 nm.
- Good mechanical resistance to withstand periodical washing.
- Low soiling co-efficiency (<0.15%, similar to that of the back-silvered glass mirrors).

New supporting structures should fulfil the following requisites:

- Lower weight.
- Higher stiffness.
- More accurate tracking.
- Simplified assembly.

Scaling to larger power cycles is an essential step for all technologies (except for parabolic trough systems using thermal oil, which have already undergone scaling in the nine solar electric generation stations (SEGS) in California starting at 14 MW_e and ending at 80 MW_e). Scaling reduces unit investment cost, unit operation and maintenance costs, and increases performance. The integration into larger cycles, specifically for power tower systems, creates a significant challenge due to their less modular design. Here the development of low-risk scale-up concepts is still lacking.

Storage systems are a second key factor for cost reduction of solar power plants. Development needs are very much linked to the specific system requirements in terms of the heat-transfer medium utilised and the necessary temperature. In general, storage development requires several scale-up steps linked to an extended development time before market acceptance can be achieved. A particular challenge lies in the development of storage systems for high pressure steam and pressurised, high temperature air, which would lead to a significant drop in electricity costs.

Requirements for storage systems are:

- Efficiency in terms of energy and exergy losses.
- Low cost.
- Long service life.
- Low parasitic power requirements.

In many cases, higher temperatures lead to higher system performance. However, the current status of receiver technology does not exploit the full performance potential. Significant improvements in the performance of high temperature receivers are possible, whereas potential for performance improvements in the temperature range below 400°C is relatively small (cost improvements are possible).

Costs and benefits of additional RD&D

Detailed analysis identifies a number of innovations most relevant for cost reduction. In order to transfer this knowledge – first into products, then into a continuous deployment of CSP technology – a number of key issues must be addressed.

Increasing RD&D efforts

The amount of RD&D funds dedicated to CSP was small compared to other renewable energy technologies such as wind, photovoltaics and biomass. However, the funds have been sufficient to support a new start-up of CSP technology, for example, in Europe (specifically in Spain and Italy). Several hundred MWs of installed capacity appear likely by 2010. If, as desired, the cost reductions triggered by technical innovations are to pay off their full potential in the next 15 years, an increase in RD&D efforts should take place.

Alignment of RD&D strategies and goals

ECOSTAR sets a good example in its aim to initialise a much stronger, long-term European integration effect achieving more than is possible through co-operation on a project-by-project basis. All European research centres involved in ECOSTAR manage a significant institutional (or sometimes even national) budget for CSP research. A joint European roadmap will provide a starting point against which countries can adjust their current programme goals and priorities – and thereby help to achieve the highest collective impact with individually limited resources. This will be the basis to implement the existing European facilities of various powers and concentration factors. It will also support more efficient use of existing tools and human resources in future projects and help to streamline national development activities by setting common priorities and goals. One important result is the formation of the SOLLAB alliance, comprising members from leading CSP research organisations.

Involving further excellence

It is important that many entities with different expertise and a variety of research institutions should be involved in RD&D projects in this field. Further expertise is required in the following areas:

- Large companies from the power sector that are capable of – and have experience in – leading engineering, procurement and construction (EPC) contracts could contribute better market knowledge and address more thoroughly the question of solar system integration with the power cycle.
- Companies specialised in glass, reflectors, light weight structures, drives, outdoor plastic etc. could provide expertise in concentrators.
- The chemical industry could support the development of improved high temperature fluid (HTF) or storage media.
- Large construction companies could assist in designing and building storage containers that are able to handle and transport hot fluids.
- Companies specialised in mass production and logistics (such as car manufacturers) could optimise production processes and minimise manufacturing costs.

- Technical supervising companies could suggest strategies to achieve a high quality control to reduce risks specifically in the scaling process.

Building a global market

CSP is currently emerging in many countries of the world; the situation in Spain is one of the most developed. One key to success is to build a sustainable market. In many of the countries, current progress is slow partly due to non-technical barriers. In order to generate a global market, it is important to take the lessons learned in the countries where CSP deployment is successful and transfer them to other countries. This would promote faster market growth, attract larger global companies, and lead to costs that are increasingly competitive with conventional sources. The CSP Global Market Initiative (GMI; www.solarpaces.org/gmi.htm) is a significant reference to be accessed.

In order to achieve the range of goals described above, there is a strong need to set the political framework for CSP RD&D. The current reality is that:

- Countries that have significant solar resources should consider opening their incentive schemes to CSP technologies.
- Existing resources are not evenly distributed; therefore, it may be logical to consider opening market for the import of solar electricity (*e.g.,* European countries can import from Northern Africa). Higher solar resource levels may more than compensate for additional transport costs while deployment of the technology may help to support political stability in this region.
- Legal frameworks create barriers to optimal use of CSP technologies. Hybrid operation of CSP systems is highly beneficial for both the cost of the solar electricity and for stability of the electrical grid. Legal frameworks should be more flexible to allow this option.
- Incentive schemes do not always span the full range of activities required to achieve RD&D goals. Scaling up CSP to larger power block sizes is an essential step to reduce electricity costs. To ensure that it is possible to fully exploit the cost-reduction potential, incentive schemes should not limit the upper power level.

Current activities of IEA SolarPACES Implementing Agreement

The IEA Solar Power and Chemical Energy Systems (SolarPACES) Implementing Agreement is an international co-operative organisation bringing together teams of national experts to focus on the development and marketing of concentrating solar thermal power systems. Currently the Programme actively pursues four research projects (Table 2). They are focusing on concentrating solar electric power systems, solar chemistry research, and solar technology and applications. Solar heat for industrial processes is a collaborative research project of the IEA Solar Heating and Cooling Programme and the IEA SolarPACES Programme. It brings together experts and industries from the fields of residential solar heating and high temperature solar power. In 2005, the SolarPACES comprised of 15 Participants.

Table 2. **Current projects of IEA SolarPACES Implementing Agreement**

Project	Outline
Solar Thermal Electric Power Systems	Design, testing, demonstration, evaluation and application of solar thermal electric systems, including parabolic troughs, power towers and dish/engine system.
Solar Chemistry Research	Develop engineering aspects of pre-commercial and demonstrational solar chemical systems projects, and basic research on solar-specific chemical reactions and processes
Concentrating Solar Technology and Applications	Develop/test solar components and subsystems; refine computation/measurement techniques and facilities; advance specific solar technology areas.
Solar Heat for Industrial Processes (SHIP)	Collaborative research project of the IEA Solar Heating and Cooling Programme.

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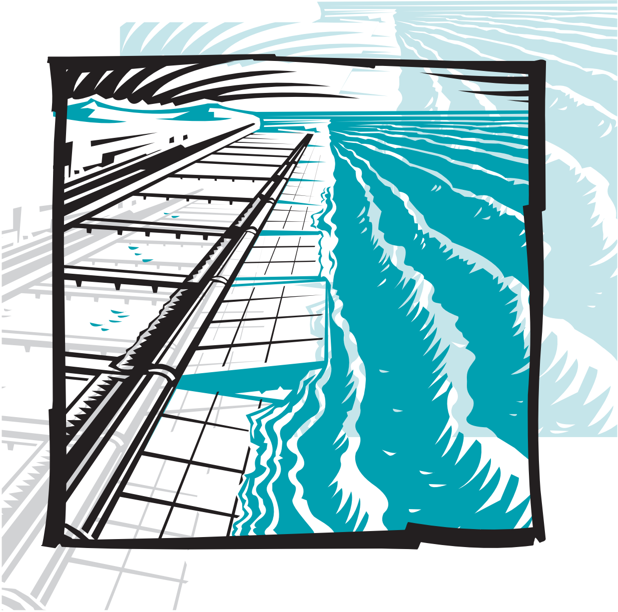
Chapter 3 • Technologies

Ocean energy systems



Highlights

- The oceans contain a huge amount of power that can be drawn from different sources and exploited for generating useful energy. The most developed conversion systems utilise tidal energy, thermal energy, marine currents and ocean waves. Collectively, these renewables are often referred to as 'ocean energy'.
- Tidal energy results from the gravitational fields of the sun and moon. Thermal energy (ocean thermal energy conversion or OTEC) derives directly from solar radiation. Marine currents are caused by thermal and salinity variances as well as by tidal effects. Winds blowing over the ocean surface generate ocean waves, which are another source of energy. All of these marine characteristics represent untapped power sources. Other technologies, namely salinity gradient devices, are at a much lower level of development.
- There is no commercially leading technology amongst ocean energy conversion systems. However, three tidal barrages currently operate as commercial power plants, amounting to a worldwide total of 260 MW of installed capacity.
- Ocean energy systems confront the marine environment in its most energetic location, implying that devices must be able to withstand strong wave climate and/or strong currents. At the same time, ocean energy technologies must fulfil basic economic and environmental requirements including: low cost, safety, reliability, simplicity and low environmental impact.
- Concerted RD&D efforts are needed to tackle a range of technical barriers that stand in the way of ocean energy concepts reaching their full potential. Each concept has its own list of specific technical barriers. Nevertheless, there are also common denominators amongst similar types of concepts. These barriers can be categorised into three technology areas: wave, tidal and salinity gradient.
- A number of non-technical barriers can also slow – or even stop – the maturation of emerging technologies. Again, many common barriers exist that also require co-ordinated RD&D efforts. These can be classified as concerning resource assessments, energy production forecasting, simulation tools, test and measurement standards, and environmental impact.
- Additional RD&D is critical to advancing the development of ocean energy systems. Ocean energy technologies must solve two major problems concurrently: proving the energy conversion potential and overcoming very high technical risks associated with a harsh environment. Additional RD&D would help to mitigate the substantial technical and financial risks faced by device developers daring to harness the energy of the marine environment.

Introduction

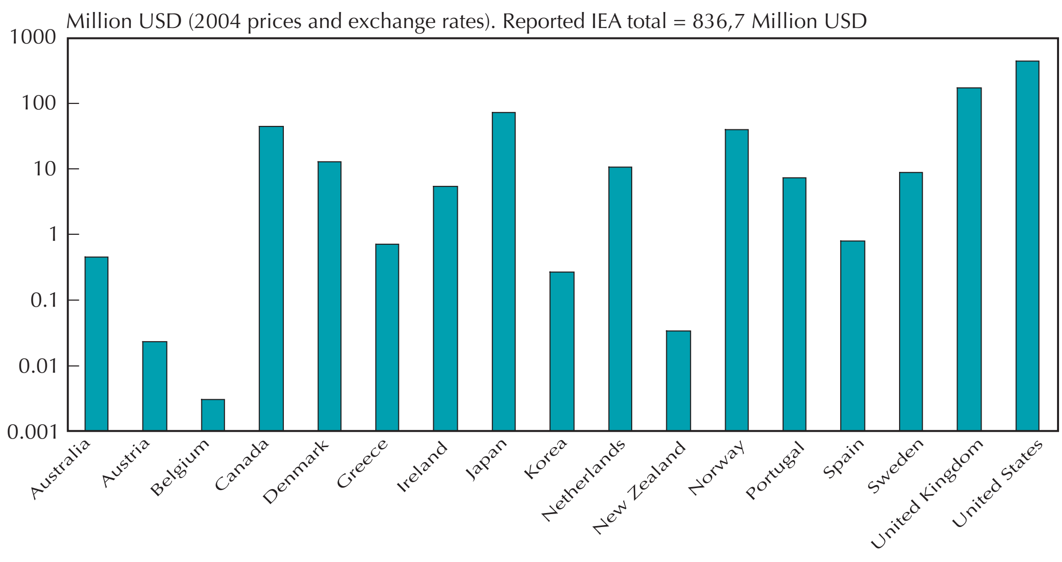
The oceans contain a huge amount of power that can be drawn from different sources and exploited for generating useful energy. Compared to other renewable energies, technologies to extract energy from this resource are in an early stage of development. Investment in ocean energy RD&D captured a small fraction of the total renewable RD&D budgets in IEA member countries over the past 30 years. However, the resource is theoretically much greater than world energy demand.

The most developed conversion systems concern tidal energy, thermal energy, marine currents and ocean waves. Tidal energy results from the gravitational fields of the moon and the sun. Winds blowing over the ocean surface generate ocean waves. Thermal energy (ocean thermal energy conversion or OTEC) derives directly from solar radiation, drawing energy from the thermal gradient of temperature differences between surface water and cold deep water. Marine currents are caused by thermal and salinity differences, as well as by tidal effects. Salinity gradient utilises the pressure difference arising between fresh water and sea water. All of these characteristics of the marine environment represent untapped power sources. Other technologies, namely salinity gradient devices, also show potential but are at a much lower level of development.

IEA governments allocated about USD 0.8 billion (2004 prices and exchange rates) for RD&D on ocean energy from 1974-2003 (Figure 1). The United States accounted for about 53% of reported governmental RD&D funding. Significant expenditures by the United Kingdom, Japan, Canada and Norway equalled about 41% of ocean technology RD&D budgets in IEA member countries.

In the near term, ocean energy technologies will continue focus on executing prototype deployments and on investigating multi-device, large-scale deployments. In the medium term, these technologies may become significant contributors to those markets adjacent to

Figure 1. **Reported government ocean energy RD&D budgets in IEA member countries, 1974-2003**



the resource. In the longer term, when hydrocarbon scarcity becomes a more serious constraint and new forms of energy transmission are required, ocean energy could become a much more important part of the world's energy portfolio.

Current technology status

Three tidal barrages currently operate as commercial power plants, amounting to a worldwide total of 260 MW_e of installed capacity. In addition, two wave power installations – also commercially run – accumulate around 750 kW_e of peak power. As yet, tidal current systems, OTEC installations and salinity gradient concepts have been tested only as prototypes.

Aside from the tidal barrages (in which there is little interest in future development), there are no purely commercial ocean energy plants in operation. Thus, learning curves and cost figures for ocean energy systems do not reflect existing experience, but rely instead on estimates. For example, wave energy systems have seen 20 years of slow development. Three studies, summarised in the final report of the European Wave Energy Thematic Network (WAVENET, 2002), show that estimated electricity cost for oscillating water columns have decreased by a factor of four, from USD 0.5/kWh to USD 0.12/kWh. These estimates assume bulk production of components and perfect power plant behaviour, both of which have yet

Table 1. **Types of ocean energy**

	Resource	Technologies	Estimated global resource	Near term cost Estimates
Ocean Wave	Onshore, nearshore and offshore waves	OWCs, overtopping, point absorbers	8 000-80 000 TWh/y[(1),(2)]	99-137 USD/MWh[(2)]
Tidal	Tidal basins	Barrage, trad. Hydro turbines	200 TWh/y[(4)]	
Marine Current	Tides, topography, salinity and thermal diff.	Turbines, reciprocating wing	Up to 5 TW[(1)] 800 + TWh/y[(3)]	56-168 USD/MWh[(5)]
Salinity	Pressure differential fresh and sea water	Semi-permeable osmotic membrane	2 000 TWh/y[(6)]	
OTEC	Temperature differential surface and deep sea	Thermo-dynamic Rankine cycle	10 000 TWh/y[(7)]	

1. Isaacs and Seymore, 1973.
2. WEC, 1993.
3. DTI Renewable Innovation Review, 2004.
4. ATLAS, http://europa.eu.int/comm/energy_transport/atlas/htmlu/worldwide_market_and_potential.html.
5. Boud, 2003.
6. Aaberg, 2004.
7. Saga University, 2003.

to be obtained. Available estimates of power cost for energy from off-shore wave devices are in the range of USD 0.10/kWh to USD 0.14/kWh (WEC, 1993). However, it should be noted that these estimates are not current; more recent figures place prices for tidal and marine current energy in the range of USD 0.055/kWh to USD 0.16/kWh (Boud, 2003).

Current RD&D

A great deal of research and technological development needs to be done to bring ocean energy technologies to maturity. Ocean energy systems confront the marine environment in its most energetic location, implying a need for devices that can withstand strong wave climate and/or strong currents while also fulfilling basic economic and environmental requirements such as low cost, safety, reliability, simplicity and low environmental impact.

Tidal barrage technology is not considered in this text for two reasons. Firstly, the concept is based on mature hydropower components requiring limited research development to adapt to the marine environment. Secondly, their environmental impact on local ecosystems prevents widespread deployment. However, an in-depth analysis of the three existing installations would provide crucial information to help policy makers assess proposals when developers come forward with new project ideas.

Economic viability

Economic viability is essential to attract investors and energy producers. It derives from the best compromise between an inexpensive design, a reliable design and the economic situation of a particular site. Predictability of power generation also plays a strong role. The most attractive combination is a good design that delivers reliability and ease of manufacture and deployment.

Lowering costs will improve the economic viability and acceptability of emerging ocean energy technologies. This aim is achieved through efficient design, the use of low-cost and readily available materials and components, and economies of scale. Safety is a crucial issue for any device in a marine environment and must concern both the device itself and all the sea users – human and non-human. To ensure security, deployment and construction procedures and accident prevention systems must be efficient, reliable and safe. Reliability is necessary to minimise the need to access the site for repairs and inspections, thereby helping to decrease the cost of operation.

Low environmental impact

Ensuring that ocean energy technologies have low environmental impact is a fundamental requirement to preserve the fragility of marine ecosystems and to truly be a clean energy source. All ocean energy systems must be designed with consideration of how the system will influence the environment in which it is placed – including the fact that ocean energy devices can have positive environmental impacts. An ocean energy farm consisting of multiple devices over a specified area could help create a wildlife sanctuary by restricting access to the site. In addition, marine life is known to thrive on man-made structures and wave energy systems could be integrated into coastal protection strategies.

Additional RD&D priorities

The following summary describes the research needs for ocean energy systems in terms of technical barriers for specific technologies on wave, tidal current, salinity and thermal gradients and non-technical barriers common to all ocean energy technologies.

Technical barriers

Technical barriers are hurdles that must be solved by research activities to bring a concept to its full potential. Each concept has its own list of specific technical barriers. Nevertheless, there are common denominators amongst similar types of concepts. For simplification, these barriers will be categorised into three technology areas: wave, tidal and salinity gradient. The following section highlights various challenges under each technology type, as well as a range of cross-cutting aspects.

Wave energy systems

Wave energy systems are divided into two main categories, fixed devices and floating devices.

A fixed device has a solid foundation. This foundation can be incorporated either in the coastline, in a breakwater structure, or on an off-shore platform that is fixed on the seafloor. Today's most advanced concepts are installed on the shoreline. A floating device is a completely floating structure, like a ship, that can be linked to the shore via a high voltage power cable. Such devices are kept in position with either mooring systems or motors.

Within each group there is a range of wave energy technologies under development. Because their specificities are so wide ranging, defining all RD&D needs would lead to a large list of small details important for individual concepts. The focus here is on common concerns and needs including: wave behaviour and hydrodynamics of wave absorption; structure and hull design method; mooring; power take-off systems; and deployment methods.

Wave behaviour and hydrodynamics of wave absorption

Basic knowledge on subjects such as wave behaviour and hydrodynamics of wave absorption is needed to allow engineers to design the best devices for specific concepts. At present, general knowledge and data available are primarily concerned with only deep water wave climate, although some countries are now mapping the near-shore resource as well. Coastal wave forecasting and behaviour are also needed – even for off-shore devices that will be installed in 50 m+ water depth where bottom effects are not that strong and the shelter effect of coastlines and islands plays a significant role. Hydrodynamics of wave absorption models must be improved in order to include non-linear effects known to be important.

Design with confidence in reliability and survivability

The off-shore oil exploration industry has a strong knowledge base that can provide information useful for the development of off-shore floating prototypes and reduce risks during early sea trials. Thus, knowledge transfer from existing off-shore industries to ocean energy development is needed. While some devices may appear to be similar to ocean vessels – and hull design must exhibit seaworthiness – a wave energy device is not a ship.

There is a need to develop a common set of parameters and requirements specific to wave energy, to which every device should adhere in order to provide confidence of reliability and survivability.

Generic mooring techniques

Mooring is an important element of any off-shore wave device; it is a means of keeping the system safely in one position no matter what the weather conditions. Ship-building and off-shore industries have a strong knowledge base in this domain. However, wave energy systems will typically be installed in deep water (50 m to 400 m) and face strong wave climates most of the time – not the usual conditions faced by moored ships or off-shore platforms. Each device will need a complete and independent mooring design, but a broad investigation of mooring techniques will make it possible to expand current codes of practices and engineering standards to include the specific requirements of wave energy systems.

Power take-off systems

Power take-off systems also need a strong research effort to investigate performance optimisation, seaworthiness and cost reduction. As the component that converts incoming energy into electricity, they are the most important part of any ocean energy plant. These systems can be based on hydrodynamic, mechanical or even magnetic conversion concepts. For example, air turbines are commonly used in oscillating water columns, yet there is still potential to improve their performance and reduce cost. This can be done through new turbine concept development, blade optimisation, and variable-pitch control systems. A particular area of concern is efficiently reducing noise from airflow with low influence on turbine performance.

Deployment methodology and decommissioning

Deployment methodology must be reliable, replicable and cost-effective. Method reliability provides confidence in the installation process and, therefore, lowers risk-based costs such as insurance premiums. Methods that are replicable across many sites and under variable conditions will also reduce installation cost and increase confidence. Decommissioning, the reverse process, should also be addressed. The deployment method is closely related to the supporting structure of the wave energy systems, which should be designed to account for these requirements and to deliver best performance in all sea climates. The three phases of operation requiring access – deployment, maintenance and repair, and decommissioning – will have different technical requirements and each will have an impact on total system costs.

Tidal stream current systems

Research and development needs for tidal stream current systems are closely related to the problems faced by other recently developed devices. These systems are based on the concept of underwater turbines converting energy from the flowing water into electrical power, following principles similar to wind turbines in the atmosphere. The turbines can have a horizontal rotating axis or a vertical rotating axis, or could even use reciprocating foils. RD&D carried out to date has not yet shown which system is best. Typical research needs can also be divided into basic knowledge, such as water stream flow pattern and cavitations, and applied science, such as supporting structure design, turbines, foundations and deployment methods.

Transfer of knowledge to an underwater environment

Knowledge transfer is an important element of research for tidal stream current devices. Horizontal rotating axis turbines will benefit from developments in the wind industry; experience gained in ship and submarine propellers should be also taken into account. Research efforts could focus on adapting relevant technologies such as these to an underwater environment.

Basic knowledge of the current speed along the water column

Tidal stream current turbines in the megawatt size will operate at depth below 20 m, with rotor diameter of ~12 m for horizontal axis systems. Maritime charts provide only surface current speed. Knowledge of the current speed along the entire water column is essential to choose the correct turbine and rotor sizes, and to design the supporting structure to resist stresses and vibrations. This information is also important during the installation phase. Knowledge of the water flow patterns and reaction to the turbines is important for assessing the impact on sedimentation patterns. Development of adequate measuring instrumentation is linked to these research activities.

Structure must be water tight

Contrary to wave energy devices, the supporting structure of a tidal stream current system has very restrictive requirements that influence turbine design, installation procedures and operation and maintenance demands. Above all, the structure must be water tight. Seals should support pressures in water depths of 10 m to 20 m, be able to withstand pressure changes due to tidal variation and resist the abrasive properties of sea-water and sediment flow. The structure should also allow easy access for maintenance and facilitate the deployment process. Turbines must be reliable to minimise access requirements, thereby reducing operation and maintenance costs.

Cost-efficiency, reliability and maintenance

Research efforts on turbines and rotors should focus on cost-efficiency, reliability and ease of maintenance. Both components should be manufactured using materials designed to resist marine environments. Special attention should be given to bearings to ensure that they function safely and reliably in the marine environment. Control systems for turbine speed and rotor pitch will also be important to maximise power output.

Foundation and installation methods

Foundation and installation methods are critical: research is needed to make them safe, easily replicable and cost-effective. Tidal current systems require very stringent reliability parameters. Firstly, systems will be installed in currents with speed between 2 m/s,7.2 km/h, and 4 m/s, 14.4 km/h (due to the density of water, this is equivalent to wind speeds of between 70 km/h and 140 km/h). Secondly, while there will be tidal variation, these current speed levels are always present. Thus, tidal stream system foundations must be robust and deployment methods must be safe for the equipment and for the workforce. Several solutions are being developed and research actions are needed.

Salinity gradient

Being a new technological development in the field of ocean energy systems, salinity gradient systems need to overcome several hurdles. The main challenge is to develop functioning and efficient membranes that can generate sufficient energy to make an energy system competitive. The complementary development required is the means to support system integration into a power generation plant. The EC project, SALINITY POWER, estimates that the first commercial power plants would need membranes capable of power production of at least 6 W/m^2 and could have a size of approximately 10 MW_e, corresponding to around 1 700 000 m^2 of membranes. Future developments would lead to industrial-scale production at reduced costs.

Functioning and efficient membranes

The scope of research in membrane development should cover performance improvement, manufacturing potential and cost reductions. A membrane's primary purpose is to "generate" power: to do so, it must be resistant to biological and chemical contaminations, and be strong physically and enduring. The best performing membranes have been measured at 1.5 W/m^2, but have a power potential of 5 W/m^2. Basic research and technical development are needed to fulfil – and eventually increase – this potential. The manufacturing potential of membranes is the capacity for large-scale production without loss of performance. A high power potential can be obtained relatively easily on a centimetre-scale sample, but maintaining the same performance at much larger dimensions requires further research.

Ocean thermal energy conversion

Research needs in this area are closely linked to the nature of ocean thermal energy conversion (OTEC) systems. Many advances were made during the past decades, but obstacles to achieving the full exploitation of ocean thermal energy remain. Three main research areas can be identified: thermal cycles, environmental influence and floating applications.

Thermal cycle

OTEC systems use small temperature differential cycles, which must be carefully controlled to maintain high conversion efficiency. Therefore, research actions should address the development of power technologies, integrated systems and control strategies adapted to the marine environment and to ocean thermal applications.

Influence of the environment

Environmental impacts of OTEC systems must be addressed more fully. The marine environment has direct impacts (*e.g.,* corrosion and marine growth) on the materials and equipment used. Research focused on reducing these impacts should also aim to minimise the systems' influence on marine ecosystems.

Floating systems

Applications using OTEC on floating structures offer a wider scope for deployment, from using the produced energy in on-site applications through to facilitating artificial fishery (the introduction of the mineral-rich deep water at sea level attracts plankton). The wide range of possible uses creates demands for research to solve the particular problems associated with each device. At the same time, RD&D related to floating structures will also need to resolve issues similar to off-shore wave and tidal structures, such as mooring and survivability. In addition, the mechanical resistance and stability of an OTEC installation, deep water piping and positioning, should also be addressed with respect to the transport of energy from the production site to the site of energy use.

Non-technical barriers

Non-technical barriers are hurdles that have the capacity to slow – or even stop – the maturation of emerging technologies. For example, lack of knowledge and understanding may prevent local authorities from issuing permits for the installation of prototype devices. Uncertainties surrounding power generation, in terms of power quality and availability, can delay granting of permits to generate electricity. Poor understanding of device behaviour predictions can create difficulties in securing financing for projects. Challenges inherent in comparing different systems can make it difficult for power distributors to determine which systems best fit their needs. In addition, environmental impacts not identified prior to deployment can be a barrier to technology development.

Such concerns are of interest to all stakeholders in a given technology and are therefore prime topics for common research activities. In total, five non-technical barriers that cross multiple ocean energy systems are identified as requiring additional research: resource potential assessments, energy production forecasting, simulation tools, test and measurement standards, and environmental impact.

Resource potential assessment

Resource potential assessment provides information about how much energy is available and where it is accessible – and is the first step in enabling decision-making for device developers, deployment project sponsors, and policy makers. But the tool needs to be refined and extended. Past estimates for wave and tidal current technologies (1992) and for a wave energy resource atlas of Europe (1996), gave numbers for off-shore applications and according to the measurement and exploitation technologies available at the time. Coupled with previous knowledge, these estimates allowed developers to promote devices such as LIMPET[8], PICO[9] and SEAFLOW[10]. However, a number of developments during the past decade suggest that updated resource assessments are now necessary. The recent developments include:

- Improved measurement technologies and deeper knowledge in oceanography.
- New ocean energy concepts and devices that open new exploitation possibilities.

8. *Land Installed Marine Powered Energy Transformer (LIMPET) is a 500 kW shore-based Oscillating Water Column (OWC) generator. The project is a joint venture between Queens University, WAVEGEN, Instituto Superior Técnico (Portugal), the EU and Charles Brand Engineering. Limpet has been operating for several years.*
9. *In 1991 the EC (JOULE programme) started a series of Preliminary Actions in Wave Energy R&D and one of these actions was an European PilotPlant Study for a shoreline pilot plant. The final choice was a natural gully at Porto Cachorro, in the island of Pico at the Azores Archipelago.*
10. *An offshore tidal current turbine with a rated power of 300kW has been successfully installed approximately 3km to the NE of Lynmouth in North Devon, UK. This project known as "Seaflow" is being conducted by an industrial consortium of UK and German companies and supported by the UK DTI, the EC and the German government.*

- Enhanced Earth observation satellites that dramatically improve capacity to measure the height (with one-metre precision) and physical properties of waves.
- Weather forecasting and climate change models that simulate patterns in wave generation and current behaviour.
- The advent of remote-sensed wave measurements for wave energy resource assessment, which promises to become a very important tool – particularly when coupled with mathematical modelling of waves.

To fully exploit the potential of these new technologies, ocean energy experts require more detailed knowledge of waves and tidal currents. They also need access to a database or an atlas showing energy available and including the following:

- Wave energy or current speed (depending on the device).
- Availability of grid connections.
- Availability of harbour facilities.
- Presence of natural reserves or restricted areas.
- Status of access to the site.

A new methodology may be needed to adapt currently available databases and new expertise may be required to complement existing knowledge on ocean energy. Such databases are now being compiled at the national level and should be expanded on a regional basis. The scope and universality of the proposed assessment will be limited only by the ambition applied and the resources assembled.

Energy production forecasting and design simulation tools

Energy production forecasting and design simulation tools are closely inter-related and are needed by device developers, electricity system operators, investors and insurance brokers. A device developer may know intuitively how a given concept should behave in real sea conditions. Nevertheless, the developer needs to provide energy production data – that can confidently predict the device interaction with the marine environment – to relevant stakeholders. Simulation and predictive tools should be designed and certified so that all stakeholders identified above can take rational decisions.

Test and measurement standards

Test and measurement standards complement the previous topic in that they are a means by which stakeholders can make comparisons between systems and come to decisions on which concept best fits a particular development plan. Such standards must be valid across technologies and independent of site testing. At the same time, they need to be specific for particular resource types (*e.g.,* wave will require a different set of standards than tidal). The standards will need to be clearly defined so that lay-persons can understand and choose the system best suited to their needs.

Environmental impacts

Contrary to common understanding, environmental impacts are not limited to the impact of systems on the environment. It is also necessary to consider how the environment affects the systems. This duality is very specific to ocean energy systems, in which the marine environment has a strong influence on the device design and performance (a similar impact is seen in ship-building design). Here again, different technology areas will require specific technological solutions. Nevertheless, the study of these impacts could be undertaken in a global analysis. For example, impacts from the marine environment might be caused by marine growth (*e.g.,* algae, shells, etc.), seabirds nesting, corrosion or sedimentation flow on the devices. On the other hand, impacts to the marine environment could include oil leakage from engines, noise from power take-off systems or debris from sunken devices. Both aspects are intertwined and will have an impact on system design.

Arrays or farms of ocean energy systems

As with wind energy, the unit size of a wave energy device – usually not more than a few megawatts – will make it necessary to consider operating in arrays of systems or farms in order to achieve economies of scale. Thus, there is a need to address and document the impact of unit interaction on power generation efficiency and quality, the impact of large-scale energy extraction on the environment, and the potential benefits of scale economies

Dual-purpose plants

Dual-purpose ocean energy plants are a longer term means of decreasing costs and improving the economic viability of ocean energy systems. For example, incorporating a wave concept into a breakwater will reduce costs by using the wave breaker as a supporting structure for the wave energy device (and possibly requiring less material for the breakwater). Similarly, incorporating a wave concept with an off-shore wind turbine could lead to savings by using the same high-power cable to shore and increasing production capacity on a typical site. Preliminary technical and economic assessments, followed by scaled prototype testing, are needed to further advance these innovative, cross-cutting concepts.

Costs and benefits of additional RD&D

Over the last 20 years, ocean energy developers received some 10% of photovoltaic projects RD&D funding.

Increasing RD&D funds will accelerate the rate of development. The effort and financing put forward in the United Kingdom is already showing an increase in technical progress. Several concepts envisage full-scale demonstration prototypes around the British coast in the near future.

Additional RD&D is critical to advancing the development of ocean energy systems. But ocean energy technologies must solve two major problems concurrently: proving the energy conversion potential and overcoming very high technical risks associated with a harsh environment. No other renewable energy technology faces such demands. Each time they deploy their prototypes, device developers confront the possibility of losing five years of development and investment in the space of a few hours. Furthermore, the majority of the developers are small- and medium-sized enterprises (SMEs) for whom such losses can be overwhelming. Additional RD&D would help to mitigate the substantial technical and non-technical risks faced by device developers daring to harness the energy of the marine environment.

Current activities of IEA Ocean Energy Systems Implementing Agreement

The IEA Implementing Agreement on Ocean Energy Systems began in October 2001. The Agreement's mission is to enhance international collaboration to make ocean energy technologies a significant energy option in the mid-term future. The Agreement's objective is to lead to the deployment and commercialisation of ocean energy technologies through the promotion of research, development and demonstration, as well as through information exchange and dissemination. The most pressing technology priorities are ocean waves and marine current systems; two Tasks related to these technologies are currently being pursued (Table 2).

Table 2. **Current projects of IEA Ocean Energy Systems Implementing Agreement**

Project	Outline
Review, exchange and dissemination of information on ocean energy systems	Collate, review and facilitate the exchange and dissemination of information on the technical, economic, environmental and social aspects of ocean energy systems.
Development of recommended practices for testing and evaluating ocean energy	Develop recommended practices for testing and evaluating ocean energy systems and, thereby, improve the comparability of experimental results.

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Chapter 4
Conclusions

Synthesis of technical RD&D and policy needs

Based on the information collected during the studies on RD&D priorities, it is possible to draw some conclusions as to the major technology policy issues and trends.

- The physical and technical potential of each and all technologies is very large. There are, of course, geographical influences on the choice of option and technology.
- Emerging renewable energy technologies show significant progress in efficiency, reliability and lower costs. The cost of delivered energy from renewable sources has decreased dramatically through technology development and economies of scale. The current cost of generating electricity is comparable with conventional forms of energy in the case of hydropower, many forms of bioenergy and geothermal, and in niche markets for other technologies. However, there is overall agreement that more effort towards cost-effectiveness is still the most important issue.
- Certain renewable energy technologies have inherently diurnal and seasonal fluctuations and intermittency. It is necessary to address integration of new technologies into electricity and heating grids, including specific technologies for storage and grid management.
- Flexible, reliable and low-cost energy storage continues to be a barrier to deployment of most renewable energy technologies. These issues can be addressed through collaborative efforts within the framework of the IEA.
- Assistance is needed to strengthen manufacturing capability and the infrastructure for emerging technologies.
- Trends show significant and growing private sector investment, especially in hydropower, wind, PV and bioenergy.
- While sometimes criticised, technology demonstrations advance technology development, for example in the case of concentrating solar power, ocean energy, novel bioenergy technologies and other options. They can serve to test new findings and act as a precursor to market deployment.
- Environmental and social issues associated with some bioenergy technology, hydropower, geothermal, wind energy and ocean energy need to be addressed, along with challenges related to public acceptance and capacity build-up.

A number of policy issues must also be addressed to support the technical RD&D needs described above. Specifically, there is a need for:

- Long-term and stable policies that credit renewable energy for its environmental and sustainable benefits. This merits the attention of governments.
- Stability and predictability of funding for technology and industry development. This is a must for proper planning and development of expertise.

- Successful policies for the commercialisation of emerging renewable energy technologies – including capital assistance, premium prices for green energy generated, tax incentives, quota systems, etc.
- Access to public lands, siting of projects, permitting and royalties, and other socio-economic and environmental concerns. This needs to be addressed if renewable energy sources are to be fully exploited and harnessed.
- Assistance in the adoption of new technologies in appropriate sectors of the economy (*e.g.,* energy generation and transmission, zero-energy buildings, etc.).
- Guidance in expediting major projects for mature renewable energy technologies.
- Efforts to improve information dissemination regarding the opportunities and challenges of renewable energy.

General observations and conclusions

There is a general consensus that RD&D and market deployment complement each other and result in faster and more meaningful technology learning. Governments have a consistent role to play in this respect, particularly in terms of developing new deployment policies that facilitate market growth for renewables. At the same time, RD&D and policy strategies need to differentiate among technologies, in order to address diverse problems of specific and unique technical challenges.

The key impediment to wide commercialisation of renewable technologies is their higher cost compared to conventional technologies and, in several cases, their intermittent character. Reducing energy production costs remains the top priority in order to improve market deployment potential. This can be achieved through technology advances and also through improvement in manufacturing and production processes, which are themselves affected by targeted market deployment and active investments by the private sector.

The issue of renewable energy integration into the electricity and heating grids of intermittent renewable sources remains a challenge and should be addressed via technology advances and adjustments in policy and regulatory frameworks. Interconnection safety, codes and standards that address the intermittent nature of renewables have made great strides in the last decade but more work remains. RD&D is also needed to address the reliability and efficiency of wind turbines, solar panels, and other emerging technologies. Demonstration trials are needed to field test and verify technology compatibility and safety. Consistent and balanced technology policies and regulatory environments that recognise the contributions of renewable energy sources have proven to be an effective means to advance deployment of renewable energy.

Access to public lands, siting of projects, permitting and royalties, and other socio-economic and environmental concerns need to be addressed if renewable energy sources are to be fully exploited and harnessed. The geothermal, wind and hydropower communities have grappled with these issues for decades. Demonstration projects can help overcome these barriers but they can also add to public unease as the landscapes of some IEA member countries are littered with renewable energy projects that are broken, outdated or undesirable. Emerging technologies, such as ocean energy or concentrating solar power, may benefit from additional demonstration projects.

There is growing interest in distributed energy systems as an adjunct or partial replacement of traditional electricity and heating grids. Distributed energy systems directly address the growing need for energy security, economic prosperity and environmental protection. These systems are often located closer to the consumer and are more efficient and reliable.

Integrated building systems that combine cutting edge renewable energy technologies are being embraced by architects, engineers, builders and consumers.

RD&D must lead to market-related products and services. This link is particularly important in the context of justifying RD&D in policy messages and requests for additional resources. There must be a clear distinction between wide-ranging 'long-term scientific research' and well-focused 'near market RD&D'. In this context, international technology collaboration has provided proof that it can substantially contribute to the process of technological innovation. Many of the identified technology issues can be – and are being – addressed through collaborative effort within the framework of the IEA.

Renewable energy has made very significant progress over the last three decades. Through RD&D, a number of technologies have advanced and are gaining a growing market share, while contributing significantly to energy supply. Today, hydro-electricity provides almost 20% of global electrical generation, while bioenergy and geothermal contribute significant amounts of both electricity and heat. Newer technologies, such as wind and photovoltaics, are becoming important global industries with annual sales of several billion USD.

Energy security, climate and environmental concerns are strong drivers of national energy policies. This was underlined at the May 2005 IEA Ministerial meeting and the G8 Summit at Gleneagles in July 2005. Technology experts stress that the potential for renewable energy supply offers significant opportunities for further growth. Drawing on the experience of the last few decades and the lessons learned, it is clear that renewable energy can play a very important role in transitioning to a global sustainable energy supply by the middle of this century.

Each country has its own RD&D priorities based on their particular resource endowment, technology expertise, industrial strengths and energy markets. Recent IEA analysis demonstrates consensus that RD&D in renewable energy must be strengthened, but with a caveat that priorities must be well selected in order to address priority policy objectives, especially as they relate to prospective cost-effectiveness. Intelligent choice of such priorities will invariably facilitate market deployment of new and improved technologies.

RD&D priorities by technologies

RD&D priorities identified by each IEA Renewable Energy Implementing Agreement are briefly outlined in the following tables.

Table 1. **Bioenergy**

Title	Content
Current RD&D	Current research efforts in bioenergy include technology development and reliability in areas such as: • Gasification (for biofuels, IGCC). • Biological conversion (for ethanol, biogas, etc.). • Anaerobic digestion (for biogas). • Municipal solid waste incineration (for electricity and heat). • Co-firing applications (for electricity and heat). • Flash pyrolysis (for bio-oil). • Production of bioethanol and biodiesel from sugar, oil-based crops and lignocellulosics. • Production of biohydrogen. Current research efforts in feedstock technology reliability in areas such as: • Short Rotation Forestry (SRF). • Woody biomass (state-of-art forest management techniques). • Grasses (all pre-treatment operations). • Straw (seasonable availability, problems of fluidising bed gasifier). • Refuse-derived fuel (RDF) (feeding systems for fluff RDF). • Sewage and other industrial sludges (for thermochemical energy applications). • Efforts to increase the energy density per unit volume of biomass fuels focus primarily on pelletising.
Additional RD&D Priorities	Primary objectives of additional RD&D are to: • Promote market deployment of technologies and systems for sustainable energy production from biomass. • Actively encourage the maintenance and development of networks of participants involved in RD&D and education, and to provide for the effective dissemination of information on bioenergy. Short-term technology needs include: • Increasing the relative availability of cheap feedstocks in large quantities; the development of fuel quality standards. • Improving the efficiency of some basic processes while reducing their costs; innovative approaches in materials. Medium-term needs include: • Further development of the biorefinery concept for biomass feedstocks. • Production of ethanol from lignocellulosics. • Development of dedicated crops tailored to the requirements of biorefineries. Long-term needs include: • Development of pathways for bioenergy to start playing an important role in the evolving hydrogen economy through gaseous and liquid biofuels.

Table 2. **Hydropower**

Title	Content
Current RD&D	The main issues facing hydropower are grouped below: **Large Hydropower** The technical challenges are already mostly covered by the few manufacturers of major equipment and the numerous suppliers of auxiliary components and technology. While no major breakthroughs have occurred in machinery, the advent of computers has led to vast improvements in monitoring, diagnostics, protection and control technologies, as well as in many other areas. **Small Hydropower** The technical challenges are both a by-product of the large hydro industry and the application of appropriate technology by small manufacturers, organisations and agencies. Small hydropower has a huge variability of designs, layouts, equipment types and material types. It can be said that there is no "state of the art" in small hydropower, but rather a huge body of knowledge and experience in designing and building projects to fit the site and the resources of the developer. **Additional energy at existing power plants and dams** One of the greatest opportunities for hydropower is to maximise the energy produced from existing projects through modernisation. Gains of 5% to 10% are not an excessive target for most hydropower owners; where there are significant numbers of dams without generation, the numbers could be much higher. **Extension of asset life** provides an additional opportunity through the identification of aging and improved maintenance practices, risk assessment, asset management and improvements in surveillance systems. **Integration of non-firm renewables** including wind-hydro and hybrid systems (*e.g.,* hydrogen) is another area that shows potential.
Additional RD&D Priorities	Additional RD&D can be classified under the categories: technology, implementation and development, as well as public acceptance and project approval. **Technology** • Improvements in efficiency. • Reductions in equipment costs. • Reductions in operating and maintenance costs. • Improvements in dependability (reliability and availability). • Integration with other renewables. • Development of hybrid systems, including hydrogen. • Development of innovative technologies. • Environmental technologies. • Education and training of hydropower professionals.

Table 2. **Hydropower** (continued)

Title	Content
Additional RD&D Priorities	**Public acceptance and project approval** • Identification and implementation of appropriate mitigation measures for environmental and social impacts. • Reinforcement of acceptance of hydropower as renewable and sustainable. • Establishment of renewable premiums and credits for all hydropower. • Streamlining legal and financial procedures for hydropower development and the approval process. • Conducting impact assessments, including both western and indigenous peoples' approaches. • Implementation of certification of sustainable energy sources. • Identification of new hydro sites which meet sustainability criteria. • Improvements in public relations. **Implementation and development** • Exploration of innovative financing, including sharing of costs for multiple uses. • Understanding of the true cost of hydropower compared with other energy sources. • Establishment of development mechanisms (CDM etc.). • Address integration issues with wind and thermal. • Address integration into distribution systems. • Increase understanding of the risks of decision-making in plant modernisation. • Develop approaches to add hydro plants to existing dams. • Pursue a systematic approach to development that fulfils sustainability requirements.

Table 3. **Geothermal**

Title	Content
Current RD&D	Some of the current priorities being addressed are: • Environmental impacts of geothermal energy. • Enhanced geothermal systems such as hot dry rock. • Advanced geothermal drilling techniques. • Direct use of geothermal energy, including geothermal heat pumps, space heating, etc. • Encourage use of rural electrification and mini-grid power systems.
Additional RD&D Priorities	Some of the specific priorities for additional RD&D could include funding to expedite the completion of current priorities, as well as new topics, and increased production and dissemination of information to support: • Development of better exploration, resource confirmation and management tools. • Commercial development of enhanced geothermal systems (EGS). • Development of deep (>3,000 m) geothermal resources. • Increased geothermal co-generation (power and heat). • Reduction of costs of geothermal well drilling, logging and completion. • Increased direct use of geothermal resources for space/district heating and multi-purpose "cascading". • Improved understanding and mitigation of environmental effects. • Dissemination of appropriate information to stakeholders. **More general priorities being proposed include:** • Life-cycle analysis of geothermal power generation and direct use systems. • Sustainable production from geothermal resources. • Power generation by improved conversion efficiency cycles. • Shallow geothermal resources for small-scale individual users. • Induced seismicity related to geothermal power generation (conventional and enhanced geothermal systems (EGS)).

Table 4. **Wind energy**

Title	Content
Current RD&D	During the last five years, industry RD&D has put emphasis on developing larger and more effective wind turbine systems, using knowledge gained from national and international generic RD&D programmes. Continued RD&D is essential to ensure the necessary reductions in cost and uncertainty, to realise the anticipated and desired level of deployment, and to improve understanding of how extreme wind situations, aerodynamics, and electrical generation affect wind turbine design. The challenge is to try to find the evolutionary steps which will further improve wind turbine technology, including, • Large-scale integration of wind turbines into electric grids. • Elimination of uncertainties by incorporating wind forecasting results and information on grid interaction with other energy sources.
Additional RD&D Priorities	RD&D priorities in the mid- and long-term time frame in wind energy include: Increase value and reduce uncertainties in areas such as: • Forecasting power performance (target of uncertainty of power output 5% to 10%). • Reduce uncertainties related to engineering integrity, improvement and validation of standards in terms of providing better understanding of extreme environmental conditions, safety, power performance and noise. • Storage techniques. Continue cost reductions through: • Improved models for aerodynamics/aeroelasticity. • Improved site assessment including off-shore. • New intelligent structures/materials and recycling. • More efficient generators and converters. • New concepts including devices such as highly flexible down-wind machines and diffuser-augmented turbines. • Improved stand-alone and hybrid systems that integrate PV or diesel generating systems for remote locations where grid connection is not feasible. Enable large-scale use through: • Electric load flow control and adaptive loads. • Improved power quality (especially in weak grids). Minimise environmental impacts by addressing issues related to: • Compatible use of land and aesthetic integration (*e.g.*, visual impact). • Noise studies. • Flora and fauna.

Table 5. **Photovoltaics**

Title	Content
Current RD&D	New technologies for PV can be divided into two categories: • Primarily aimed at very low cost (while optimising efficiency): a. Sensitised oxide cells. b. Organic solar cells. c. Other nano-structured materials. • Primarily aimed at very high efficiency (while optimising cost): d. Multi-junction cells for use in concentrators. e. Novel conversion concepts. These technologies are still in the early stages of development, except for a and d. Organic ("plastic") PV is often considered a high-risk, high-potential option. Working devices have been demonstrated, but efficiencies are still low and sufficient stability has yet to be proven. Primary efforts for further cost reduction focus on areas such as: increasing the efficiency of PV components and the PV system as a whole, advanced manufacturing techniques of all PV components, raising the performance and reliability of PV power systems, decreasing energy payback time and reducing environmental impacts. RD&D in PV is particularly broad in its disciplinary approach, spanning materials science, device physics and chemistry, electronics, robotics, building technologies, electrical transmission systems, and storage of electricity as well as modelling within these different areas. As market opportunities emerge, two particular aspects arise: • The need for a more comprehensive approach on the system level. • The potential for further interaction with existing technologies and industries. About half of the future cost reduction for PV may result from RD&D in improving materials, processes, conversion efficiency and design. Substantial cost reductions can also be gained through increased manufacturing volume and economies of scale. Increasing the size of components and plants will also reduce costs.
Additional RD&D Priorities	Additional RD&D priorities can be categorised as follows: • New feedstock production to meet the demand of world market c-Si. • Early assessment for immature solar cell technologies, including thin-film manufacturing processes. • Better balance-of-system (BOS) components in terms of the efficiency, lifetime and operation of some components, especially inverters and batteries. • Performance improvement and further cost reduction of thin-film technologies.

Table 5. **Photovoltaics** (continued)

Title	Content
Additional RD&D Priorities	• Exploration into scientific fields, including nanotechnology, organic thin films and molecular chemistry for novel concepts regarding PV. • Develop devices with high conversion efficiencies and long-term stability in order to match the expected lifetime of 25 years and more. • Building integration, manufacturing issues, quality assurance and standardisation.

Table 6. **Solar heating and cooling**

Title	Content
Current RD&D	The priority areas for solar heating and cooling RD&D include: • Performance of solar façade components. • Sustainable solar housing. • Solar crop drying. • Daylighting in buildings. • Advanced storage concepts. • Solar for industrial process. In addition, more effort should be directed towards RD&D projects that are not yet pre-competitive.
Additional RD&D Priorities	A comprehensive and ambitious applied RD&D programme is needed to develop competitive advanced solar heating and cooling systems that can cost-effectively provide 5% to 10% of the overall low temperature heat demand of the IEA member countries. The proposed research priorities are outlined below. Advanced materials and components including: • High performance and cost-efficient materials (*e.g.*, improvement of optical coating technologies, development of low-cost anti-reflective, self-cleaning glazing, and materials with over 20-year durability, including plastic). • Advanced solar thermal components (*e.g.*, flat-plate collectors for roof and façade integration, new collectors for medium-temperature applications (<250°C), photovoltaic-thermal (PVT) collectors). • Advanced thermal energy storage (*e.g.*, development of new materials for storing thermal energy of >0°C to 200°C, including PCMs to allow a reduction of storage volume by at least a factor of three compared to water). Advanced systems including: • Large-scale solar combi-systems for water and space heating (*e.g.*, development and demonstration of solar combi-systems with several hundred kW for multi-family houses, as well as large-scale applications for housing estates and solar-assisted district heating systems with several MW). • Solar thermal systems for industrial applications (*e.g.*, more efficient integration of solar energy into industrial processes). • Solar cooling applications (*e.g.*, cooling machines for low capacities and machines able to adjust to the solar thermal heat supply, system design, integration and control). • Combined solar heating and cooling systems. • Building design and integration (*e.g.*, better design integration of solar thermal systems on the building physics – *i.e.*, façade collectors – and HVAC-systems, careful analysis of occupant behaviour, improvement of control shading, glare and window systems). Standards, regulations and test procedures should also be developed.

Table 7. **Concentrating solar power**

Title	Content
Current RD&D	Current development needs and perspectives for significant further cost reductions were identified for: • Parabolic trough technology using high temperature fluid (HTF) or direct steam generation (DSG). • Central Receiver Systems (CRS) using: - molten salt - saturated steam - atmospheric air - pressurised air receiver and dish Stirling systems.
Additional RD&D Priorities	The key priority for RD&D should be to focus on improvements of modular components such as concentrators, heliostats or modular receivers, which are essential cost drivers. New reflector materials should be low cost and have the following traits: • Good outdoor durability. • High solar reflectivity (>92%) for wave lengths within the range: 300 nm to 2 500 nm. • Good mechanical resistance to withstand periodical washing. • Low soiling co-efficiency (<0.15%, similar to that of the back-silvered glass mirrors). New supporting structures should fulfil requirements such as lower weight, higher stiffness, more accurate tracking and simplified assembly. Storage systems are the second key factor for cost reduction. Development needs are very much linked to the specific system requirements in terms of the heat-transfer medium utilised and the necessary temperature. A particular challenge lies in the development of storage systems for high pressure steam and pressurised, high temperature air, which would lead to a significant drop in electricity costs. Requirements for storage systems are: • Efficiency in terms of energy and exergy losses. • Low cost. • Long service life. • Low parasitic power requirements. Significant improvements in the performance of high temperature receivers are possible, whereas potential for performance improvements in the temperature range below 400°C is relatively small (cost improvements are however possible). Scaling to larger power cycles (except for parabolic trough systems using thermal oil) is also an important factor reducing unit investment cost, unit operation and maintenance costs, and realising increased performance.

Table 8. **Ocean energy systems**

Title	Content
Current RD&D	Ocean energy systems confront the marine environment in its most energetic location, implying a need for devices that can withstand strong wave climate and/or strong currents, while also fulfilling basic economic and environmental requirements such as low cost, safety, reliability, simplicity and low environmental impact. Current RD&D includes: • More efficient design, the use of low-cost and readily available materials and components, and economies of scale. • Better management in the process of deployment and construction to ensure safety. • Development of devices that are maintenance free or require low site access for repairs and inspections. • Development of low environmental impact devices, including positive environment-impact devices such as an ocean energy farm consisting of multiple devices to help create a wildlife sanctuary. (Marine life is known to thrive on man-made structures, and wave energy systems could be integrated into coastal protection strategies).
Additional RD&D Priorities	Additional RD&D to support individual technologies includes: • Wave energy systems (*e.g.*, further research in wave behaviour and the hydrodynamics of wave absorption, to allow engineers to design the best devices for specific concepts, incorporating reliability and survivability into design; development of reliable mooring techniques for devices installed in deep water (50m to 400m); and improvement of power take-off systems). • Tidal stream current systems based on underwater turbines (*e.g.*, further research into the basic knowledge of current speed along the water column in deep water; development of water tight structures; improvement of turbines and rotors that are more cost efficient and reliable; further research of foundation and installation methods to make them safe, easily replicable and cost-effective; encouragement of further knowledge transfer from the wind energy and shipbuilding industries to improve the efficiency of tidal stream current devices). • Salinity gradient (*e.g.*, development of functioning and efficient membranes). • Ocean thermal energy conversion (OTEC) (*e.g.*, development of power technologies, integrated systems and control strategies adapted to the marine environment and to ocean thermal applications; further research on the influence of the environment; development of reliable floating systems including mooring techniques, deep water piping and positioning).

Table 8. **Ocean energy systems** (continued)

Title	Content
Additional RD&D Priorities	Non-technical issues to research include: • Resource potential assessment. • Energy production forecasting and design tools. • Test and measurement standards. • Environmental impacts. • Feasibility study of ocean energy system farms in order to achieve economies of scale. Dual-purpose plants that combine energy and other structures (*e.g.,* incorporating a wave concept into a breakwater).

Chapter 5
Annex

National renewable energy RD&D trends in IEA member countries

Australia

The government total budget for energy RD&D was USD 687 million (in 2002 prices and exchange rates) between 1979-97. In this period, 12% of the total RD&D budget was allocated to renewable energy RD&D.

Government RD&D expenditures for renewables peaked in the early 1980s and declined notably after 1985, except for a slight boost in 1993. The government RD&D budget for renewables in 1997 was approximately USD 5 million.

Among the renewable technologies, solar heating and cooling received the highest level of funding at USD 28.43 million, or 33%, over 1979-97. Biomass was funded at USD 20.23 million, representing 24% of renewable energy RD&D. Solar PV was the third largest area with 22% of the renewable RD&D expenditures from 1979-97.

Prior to 1978, the main form of government support for renewable energy in Australia was direct investment by government-owned utilities, notably in hydropower. In 1978, the National Energy Research, Development and Demonstration Council (NERDDC) was established, beginning an era in which support for RD&D was the primary form of policy support for renewables in Australia. This phase lasted until 1997. Of the USD 172 million committed under the NERDDC to 1990, 11% was devoted to renewable energy, while the bulk of the funds supported various forms of coal research. This programme, renamed the Energy Research & Development Corporation (ERDC), continued until 1997, and partially funded RD&D and commercialisation efforts in the renewable energy field, including small equity investments.

The Australian government will provide funding of USD 26.9 million over four years to encourage ongoing investment in the development, demonstration and deployment of smaller-scale low emissions technologies, and other cost-effective abatement activities.

A programme of Advanced Electricity Storage Technologies is designed to increase the attractiveness of intermittent electricity generation sources such as wind and solar, and their ability to contribute to the electricity system. It is anticipated that projects demonstrating batteries, electro-mechanical and chemical storage technologies in either on-grid situations, or in off-grid situations that could lead to on-grid usage, will be considered for support.

The Australia-USA Climate Action Partnership (CAP) aims to foster the exchange of scientific expertise, technology and innovation between government, businesses and scientists of the two countries. The Partnership focuses on the field of climate change mitigation and greenhouse emissions abatement. The initial work programme for the CAP was announced in Washington (2002) by the Australian Minister for the Environment and Heritage and US

Under Secretary of State for Global Affairs. The work programme includes 19 projects under six areas of co-operation. The key areas of focus for the initial work programme are: Climate change science and monitoring; Stationary energy technologies; Engaging with business - Technology development; Engagement with business - Policies, tools and approaches; Collaboration with developing countries to build capacity to deal with climate change; and Greenhouse accounting in the forestry and agriculture sector.

Australia participates in international collaborative Renewable Energy RD&D in Bioenergy, Geothermal, Hydrogen, Photovoltaic Power Systems, Solar Heating and Cooling, SolarPACES and Wind Turbine Systems through the IEA Implementing Agreements.

Austria

Austria spent a total of USD 785 million (2002 prices and exchange rates) on government energy RD&D between 1977-2002. Energy research and development expenditures averaged USD 40 million to USD 45 million from 1977-85, after which they dropped to a low of about USD 12 million in 1990. Funding rebounded to about USD 25 million in 1994; it has since remained relatively stable.

In Austria, 20% of the total RD&D budget in the 1977-2002 period was allocated to renewable energy RD&D. From 1977-2002, 56% of the total renewables RD&D budget was allocated to biomass technologies. Total funding was approximately USD 95.2 million. Solar heating and cooling accounted for some 19%, followed by solar photovoltaics with 13%. Funding for hydropower and geothermal is minimal.

Austria participates in international collaborative Renewable Energy RD&D in Bioenergy, Photovoltaic Power Systems, Solar Heating and Cooling, and Wind Turbine Systems through the IEA Implementing Agreements.

Belgium

Government energy RD&D budgets in Belgium totalled USD 2.6 billion (in 2002 prices and exchange rates) between 1974-99. In this period, USD 135.8 million was allocated to renewable energy RD&D. While overall energy RD&D budgets decreased as a result of general budget cuts, the bulk of the decrease between 1990-93 is attributed to data deficiencies and to a lack of reconciliation between regional and federal RD&D budgets, which occurred during the regionalisation process.

The regionalisation process of 1988 transferred responsibility of Belgian renewable energy policy to the three regional administrations (Flanders, Wallonia, and Brussels). Regional investments in RD&D are partly made through research centres. Together with market deployment policies, regional renewable energy RD&D constitutes the main policy to increase renewable electricity generation.

No RD&D expenditure data are available for Belgium in 1990. Additionally, government energy RD&D expenditures for nuclear research are unavailable between 1990-94. According to Belgian authorities, RD&D budgets actually increased by an additional USD 8.19 million between 1991-94, with a concomitant increase of USD 2.02 million between 1991-94 for renewable energy RD&D.

Government RD&D expenditures for renewables peaked in the early and mid-1980s and then declined in the late 1980s, coinciding with the expansion of nuclear power. Government renewable RD&D expenditures averaged some USD 2 million throughout the 1990s.

Among the renewable technologies, solar heating and cooling and PV received the highest level of funding. Geothermal was a priority in the early 1980s, but funding decreased significantly in 1985. Solar thermal and PV followed a similar trend although renewed interest, particularly in the Flemish region, brought about new funding, albeit at lower levels. Increased funding was also made available for biomass starting in 1994. Budget outlays for solar heating and cooling were steady over the period.

Government energy RD&D expenditures increased after the oil price shocks of the 1970s and focused primarily on nuclear energy and natural gas as substitutes for oil. Federal expenditures specifically targeted nuclear fission (fuels, materials, reactors, waste, and safety) and fusion, while university laboratories and research centres concentrated RD&D efforts on wind, biomass and solar technologies.

A policy known as Tax Deduction for Environment-Friendly Investments was introduced in 1992. This policy makes incentives available for environmentally sound investments by industry. It provides capital grants of up to 13.5% of investment costs. Investments are considered eligible if they deal either with energy efficiency or energy resulting from non-polluting treatment of industrial and urban waste. The policy covers projects dealing with solar, wind, hydro energy, biomass (including biofuels) and geothermal energy technologies, as well as RD&D activities that promote environmentally sound technologies. Tax payers are allowed to spread the deductions out over several years. The policy also offers grants totalling 20.5% of the investment and 25.5% for especially innovative companies.

Regional government research and development trends

The renewables that receive policy attention and the measures implemented vary according to the natural resource endowments of the specific region. Throughout the 1990s, the Flemish region focused the majority of its renewable RD&D activities on solar PV. Flemish RD&D funding for renewable energy, characterised by the VLIET and VLIET bis programmes, provided grants for research projects totalling 50% to 100% of total costs, although the primary aim was energy efficiency. Development projects were entitled to a refundable loan of 50% of investment costs. Loans were partially converted to grants, with the level depending on the success of the project. The Walloon region funds research on solar thermal technology through the Soltherm Programme, which began in 2000. Biomass also received sustained attention from the RD&D institutions in the Flemish and, especially, in the Walloon region.

Belgium participates in international collaborative Renewable Energy RD&D through the Bioenergy and Solar Heating and Cooling IEA Implementing Agreements.

Canada

Canada spent a total of USD 8.79 billion (2002 prices and exchange rates) on government energy RD&D between 1974-2002. In this period, 7.4% of its total RD&D budget was allocated to renewable energy.

The overall trend of government RD&D expenditures for renewables peaked in the early 1980s and declined notably after 1985. Since 2000, additional programmes related to climate change have been instituted, increasing federal government energy RD&D budgets, including renewables.

Among the renewable technologies, biomass received the highest level of funding at USD 254 million, or 40%, in the 1974-2002 period. Solar heating and cooling was funded at USD 178 million, representing 28% of renewable energy RD&D. Wind was the third largest recipient with 13% of the renewable RD&D expenditures from 1974-2002.

Assistance programmes for research and development in renewable energy have been in place for more than 30 years. The main funding organisation is Natural Resources Canada through the federal Programme of Energy Research and Development (PERD). The main component of this RD&D effort is the Renewable Energy Technologies Programme (RETP). It supports efforts by Canadian industry to develop and commercialise advanced renewable energy technologies such as active solar, wind power, bioenergy and small hydro that can serve as cost-effective and environmentally responsible alternatives to conventional energy generation. In the mid-1980s, at the peak of energy RD&D expenditures, the governments' total budget (federal and provincial) for renewable energy was in excess of USD 60 million per year. Current government support for renewable energy RD&D is in the order of USD 23 million annually.

Under its climate change initiatives, the federal government has announced a number of programmes in support of renewable energy technologies. In 2000, the federal government invested about USD 15 million over five years to help develop technologies that would reduce GHG emissions, including renewable energy technologies such as biogas production.

The main support programme for demonstration is Technology Early Action Measures (TEAM). Its objective is to help accelerate the demonstration and commercial deployment of new technologies.

Sustainable Development Technology Canada was founded in 2000. This government-funded not-for-profit foundation aims to stimulate the development and demonstration of Canadian technologies related to climate change, clean air, water quality and soil. This foundation has an investment fund of USD 423 million.

The Industrial Research Assistance Program (IRAP) is a generic technology development programme administered by the National Research Council. It provides assistance to small- and medium-sized companies to advance their technologies.

Another major generic technology development programme that often provides assistance to renewable energy projects is Technology Partnerships Canada (TPC) administered by Industry Canada. It provides repayable financial assistance for the development of technologies directly associated with improved industrial processes. Support for environmental and sustainable alternatives is a programme priority.

Announced in 2003, the Climate Change Technology and Innovation Initiative supports long-term development of greenhouse gas reduction technologies in five areas, three of which address renewable energy: decentralised energy production, biotechnology and the hydrogen economy. It has a total budget of USD 192 million over five years.

Additional funds were allocated in 2005 for specific investments aimed at reducing GHG emissions. A total of USD 154 million over four years will contribute to the development and implementation of a Sustainable Energy Science and Technology Strategy, of which renewable energy will form an integral part. An additional USD 154 million over five years will help to further stimulate the use of wind power through the renewal of the Wind Power Production Incentive. Finally, USD 75 million over five years will go to the Renewable Power Production Incentive to encourage the use of other renewable energy technologies such as small hydro, biomass and landfill gas.

In addition, Canada participates in international collaborative Renewable Energy RD&D in Bioenergy, Hydrogen, Hydropower, Ocean Energy Systems, Photovoltaic Power Systems, Solar Heating and Cooling, and Wind Turbine Systems through the IEA Implementing Agreements.

Czech Republic

The National Research and Development Programme provides funding for projects selected from all sectors of the national economy. Although there is no special budget for energy projects, the programme's priorities include nuclear safety, the use of coal, renewable energy sources and energy efficiency. The total amount spent on research and development in the area of renewable energy is not known, but it is estimated to have been used largely for demonstration projects.

Denmark

The Danish Government spent a total of USD 890 million (2002 prices and exchange rates) on energy RD&D between 1975-2002. In this period, 33.3% of its total RD&D budget was allocated to renewable energy RD&D. The overall trend of government RD&D expenditures for renewables increased significantly from 1989 and retained a fairly stable level from 1991-2002 when RD&D spending declined notably, reflecting the priority changes of the new government. However, government funds for RD&D increased again in 2004.

In addition, funds from the Public Service Obligation, which are not considered government funds, have recently been applied to renewables RD&D, for example in several large biomass demonstration projects.

Among the renewable technologies, wind received the highest level of funding at USD 134 million, or 45.3%, from 1975-2002. Biomass was funded at USD 79.6 million, representing 26.9% of renewable energy RD&D.

The Energy Research Programme supports the implementation of Danish energy policy. It supports energy projects with strategic/practical perspectives over a two- to three-year time frame. Areas of focus include oil and natural gas, environmentally benign heat and power production, wind, buildings and solar energy, energy and society, and energy efficiency in products and industrial processes. Financial support of up to 100% is available, though the average support level is about 50% of eligible costs.

Denmark participates in international collaborative renewable energy RD&D in Bioenergy, Hydrogen, Ocean Energy Systems, Photovoltaic Power Systems, Solar Heating and Cooling, and Wind Turbine Systems through the IEA Implementing Agreements.

Finland

Finland spent a total of USD 777 million (in 2002 prices and exchange rates) on government energy RD&D between 1990-2002. In that period, 10.7% of the total energy RD&D budget was allocated to renewable energy. Government energy RD&D expenditures peaked in the late 1990s and declined after 1999. The RD&D budget for renewables gradually increased in the 1990s with a peak in 1997.

Among the renewable technologies, biomass received the highest level of funding at USD 65.4 million, or 78%, from 1990-2002. Wind was funded at USD 6.6 million, representing 10% of renewable energy RD&D. Solar heating and cooling was the third largest recipient with 8% of the renewable RD&D expenditures from 1990-2001. A relatively smaller portion of RD&D spending was allocated for the deployment of small hydropower plants.

RD&D funding for renewable energy is focused primarily on developing competitive renewable energy technologies through technology development. In the past, funding was aimed at improving the efficiency of boilers and biomass systems; today biomass technologies in Finland are highly efficient. The objective of current funding is to lower the costs of harvesting wood and wood wastes and to improve the logistics of transporting biomass. Considerable work is also being done on lowering the costs of combustion and gasification technologies for both large and small-scale heat and co-generation facilities.

Current RD&D programmes involved with renewable energy sources include: Wood Energy (1999-2003), concentrating on small-scale production and use of wood fuels; Streams (2001-2004), on recycling technologies and waste management; and Densy (2003-2007), on distributed energy systems.

In addition, Finland participates in international collaborative Renewable Energy RD&D in Bioenergy, Hydrogen, Hydropower, Photovoltaic Power Systems and Wind Turbine Systems through the IEA Implementing Agreements.

France

France reports having spent a total of USD 9.8 billion (2002 prices and exchange rates) on government energy RD&D between 1985-2002 (data not available prior to 1985). The share of renewable energy RD&D in total energy RD&D was less than 2% over the period. Government RD&D expenditures for renewables declined steadily from 1985-98, but increased to 2002.

Among the renewable technologies, biomass received the highest level of funding at USD 65.2 million, or 34.4%. Solar photo-electric was funded at USD 63.8 million, or 33.6% of renewable energy RD&D funding. Geothermal was the third largest recipient with 16.9% of the renewable RD&D expenditures.

The main research institutions include the laboratories at the French Atomic Energy Commission (CEA), the French National Center for Scientific Research (CNRS), universities, L'Institut français du pétrole (IFP), le Bureau de recherches géologiques et minières (BRGM), and the Agency for Environment and Energy Management's (ADEME). Renewable energy research and development focuses on solar energy, wind, biomass, hydrogen and fuel cells, and geothermal (hot dry rock at Soultz site in Alsace). Research on renewables is often structured in networks.

In 2002, research institutions had an overall budget for energy of USD 1 167 million (including government budgets and industrial contracts). The budget was allocated as follows: USD 720 million for nuclear; USD 286 million for fossil fuels; USD 62 million for renewables; USD 50 million for energy efficiency; and USD 50 million for hydrogen and fuel cells. The government contribution to this budget was about USD 745 million.

In addition, France participates in international collaborative Renewable Energy RD&D in Bioenergy, Hydrogen, Hydropower, Photovoltaic Power Systems, Solar Heating and Cooling, and SolarPACES through the IEA Implementing Agreements. Much of France's research on renewables is conducted in the context of the European framework programmes.

Germany

During the last 10 years, Germany spent a total of USD 3.55 billion (in 2004 exchange rate) on government energy RD&D. About 25% of this budget was allocated to RD&D on renewable energies. During this period, government RD&D expenditures for renewables built a solid and noticeable baseline for innovation. The budget for renewable energy RD&D averaged USD 87 million, annually.

Among the renewable technologies, photovoltaic power production (PV) received the highest level of funding from 1995-2004 with a share of 42% of the budget. Wind energy represents 25% of renewable energy RD&D. Solar Thermal heating and cooling was the third largest recipient with 14% of the renewable RD&D expenditures from 1995-2004. The 4th Energy Research Programme, established in 1996, set the framework for public RD&D support for energy technologies. A successor, the 5th Energy Research Programme was published in June 2005.

While funds available at the federal level or due to federal law have been the main driver for the deployment of renewable energy technologies, the federal states (Länder) have also provided considerable support.

In addition, Germany participates in international collaborative Renewable Energy RD&D in Geothermal, Photovoltaic Power Systems, Solar Heating and Cooling, SolarPACES and Wind Turbine Systems through the IEA Implementing Agreements.

Greece

Greece spent a total of USD 373 million (in 2002 prices and exchange rates) on government energy RD&D between 1977-2002. In this period 41.1% of its total RD&D budget was allocated to renewable energy.

Government RD&D expenditures for renewables peaked in the early 1980s and declined notably in the 1990s. Among the renewable technologies, geothermal received the highest level of funding at 33% in the 1977-2002 period. Solar heating and cooling was funded at USD 32 million, representing 22% of renewable energy RD&D. Solar PV and wind each accounted for about 16% of the renewable RD&D expenditures from 1977-2002.

Funding for research and development has not played a significant role in developing and deploying renewable energy technologies in Greece. However several studies and pilot applications regarding the exploitation of renewable energies have been carried out since 1999 by the Centre for Renewable Energy Sources (CRES), which is the official coordinating body for the promotion of renewable energies in Greece.

In addition, Greece participates in international collaborative Renewable Energy RD&D in Wind Turbine Systems through the IEA Implementing Agreements.

Hungary

In 1995, Hungary initiated efforts to develop and promote renewable energy sources with the adoption of official energy policies. Government energy RD&D budgets in Hungary amounted to USD 7.7 million (in 2002 prices and exchange rates) between 1995-2002. Renewable energy has received the bulk of the government energy RD&D budget almost every year since 1995, with notable exceptions from 1997-99. Additional RD&D funding for conservation and fossil fuels was provided in 2000. Renewables retained the largest share of government RD&D funding in 2002 with more than 50% of the total funding.

Government RD&D expenditures for renewables followed the same overall trend as for total energy budgets. Government RD&D budgets for renewables started in 1995, and then dropped to very low levels until 2000 and increased significantly in 2001/02.

From 1995-2002, approximately 46% of the total government energy RD&D budget (USD 3.57 million) was allocated to renewables RD&D. Biomass retained the largest share almost every year, except between 1996-99 when overall government budgets decreased and government RD&D funding was redistributed. Solar heating and cooling also commanded consistent funding over this period. Geothermal received some RD&D funding in 1996. Wind energy was allotted 14% of the total renewable RD&D budget in 2002.

Historically, RD&D activities received little financial or institutional support from the government. Early efforts in renewable RD&D were hampered by other competing national priorities. Until recently, no coherent or comprehensive RD&D plan existed to develop renewable energy technology and market priorities.

The government responded to this need and emphasised a new commitment to RD&D as a policy measure to define clear technology and market priorities to promote the use of renewables. The National Energy Saving and Energy Efficiency Improvement Programme was established in 1995 in the framework of the Energy Policy Concept, the Energy Saving Credit Programme and the Energy Saving Action Plan.

This programme offered support to RD&D activities in the form of interest-free loans. This was followed by the 1999 Energy Saving and Energy Efficiency Improvement Action Programme, which specifically prescribed the involvement of renewable energies in RD&D programmes to ultimately facilitate the establishment of renewable energy facilities.

Ireland

Ireland spent a total of USD 94.5 million (in 2002 prices and exchange rates) on government energy RD&D between 1974-2002. Approximately 32% of the total RD&D budget in this period was allocated to renewable energy RD&D. The overall trend of government RD&D expenditures for renewables peaked in the early 1980s and declined notably after 1983. There was no significant funding between 1990-2001.

Among the various renewable technologies, biomass received the highest level of funding at USD 13.6 million, or 46%, in the 1974-2002 period. Wind was funded at USD 8.4 million, representing 28% of renewable energy RD&D.

The Sustainable Energy Act of 2002 gave Sustainable Energy Ireland (SEI), formerly the Irish Energy Centre, the remit to promote and assist renewable energy RD&D activities. The government noted that the historically low rate of provision for RD&D in Ireland had contributed to a relative failure to exploit the full range of sustainable energy opportunities, on both the demand and supply sides. New RD&D programmes administered by SEI aim to address this failure, primarily by supporting exposition and development of a least-cost path to reducing CO_2 emissions in a more sustainable energy economy.

SEI's Renewable Energy Research, Development and Demonstration Programme (RE RD&D) explicitly focuses on renewable energy R&D, while two other programmes – the House of Tomorrow Programme and the Public Sector Investment Programme – have aspects of renewable energy R&D.

Renewable Energy Research, Development and Demonstration Programme (RE-RDD)

The main aims of the Renewable Energy Research, Development and Demonstration Programme (RE-RDD) are to stimulate deployment of renewable energies that are close to market, and to assess and develop technologies that have prospects for the future. The Programme also addresses the need for information and education, which are required to raise the awareness and willingness of all relevant players to actively engage in the market.

The programme strategy was developed in 2001 and was the subject of public consultation prior to its launch in July 2002. It was refined in 2004 to better match government policy objectives and market demand.

The Programme has an indicative budget of USD 15 million from 2000-06 and is supporting projects in all aspects of renewable energy technologies and systems including: wind, biomass, solar, ocean, small hydro, ambient heat (heat pumps) and geothermal energy. It also includes provisions for hybrid or cross-sector RD&D activities and for community renewable energy schemes.

Priority is given to supporting:

- Research aimed at: developing policy options; defining the market structure; reducing costs; and improving reliability and/or opening new markets.
- Feasibility studies for renewable energy projects.
- Demonstration of new technologies aimed at high-risk, high-reward projects or non-technical innovation.
- Investigation of core areas common to many renewable technologies.
- Commissioned research directed at informing government policy and regulation, and informing the market, institutions and public understanding.

A renewable energy R&D programme overview, launched in March 2005, aims to disseminate best-practice projects that have been supported under the programme. The programme saw expenditure of USD 7.18 million, with total commitments of USD 9.73 million. The ocean energy strategy, developed in co-operation with the Marine Institute, is an example of an area developed in partnership with related government agencies.

SEI's House of Tomorrow and Public Sector Investment Programmes support the objectives of renewable energy research and development related to solar thermal, PV, heat-pumps, and biomass applied in the built environment.

The House of Tomorrow Programme

The House of Tomorrow Programme, launched in 2001, offers support for RD&D projects aimed at generating and applying technologies, products, systems, practices and information leading to greater use of sustainable energy in Irish housing. The programme has a budget of approximately USD 12 million for 2000-2006. The main focus of the programme, for the period 2000-2006, is on stimulating widespread uptake of superior energy planning, design, specification and construction practices in markets for both new home building and home improvement.

The research component of the House of Tomorrow guides policy and identifies deficiencies and barriers to energy performance improvement. It models demonstration projects – for new build, refurbishment or retrofit – with the potential for market influence and replication. Sixty-three projects (48 of which are demonstration projects) have been supported to date, with a total of 2 300 dwellings. A total of eight public good research projects and six international collaboration projects were also funded. A total of USD 13.2 million has been committed, with expenditure to date (September 2005) of USD 4.67 million.

The Public Sector Investment Programme

The Public Sector Investment Programme aims to stimulate application of improved energy efficiency design strategies, technologies and services in public sector building construction and retrofit projects. It facilitates the delivery of significant energy efficiency improvements in the design and specification of new-build and refurbishment construction. It acts as both an exemplar for good practice and as a demand leader for the services and technologies involved.

As of September 2005, expenditure was USD 10.53 million, with commitments of USD 16.19 million. To date, the programme has supported 79 design studies, 71 model solutions and three energy management bureaux. In addition to the design studies and model solutions, a number of studies were commissioned including: an evaluation of ten model solution projects; an assessment of low carbon technologies; an energy manager's guide; and the development of Irish building energy performance indicators.

In April 2005, the Irish government launched an energy consultation document with a view to enabling a more co-ordinated and structured approach to energy RD&D in Ireland. Two public fora were held in July 2005 to discuss the results of the consultation. This process is ongoing.

In addition, Ireland participates in international collaborative Renewable Energy RD&D in Wind Turbine Systems, Bioenergy and Ocean Energy Systems through the IEA Implementing Agreements.

Italy

Italy allocated approximately USD 14 billion (2002 prices and exchange rates) to energy RD&D from 1977-2002. Budget outlays in 2002 were USD 270 million. Funding for RD&D fell considerably in the late 1980s, due primarily to a decline in funding for nuclear research. The share of funding for renewable energy RD&D, however, increased considerably. The share averaged between 3% and 5% in the 1970s and 1980s, but rose to 15% in the mid-1990s. There was no budget data reported for energy RD&D in 1992 and 1999.

In Italy, the budget for renewable energy RD&D was USD 49 million in 2002. Approximately USD 890 million was allocated to renewable energy RD&D from 1977-2002. During this period, RD&D for solar PV was 42% of the budget. Another 18% was budgeted for wind research and some 17% for biomass research. The RD&D renewable budget increased substantially in 1984, mostly because funding for solar PV research quadrupled: Italy has the fourth-largest budget among IEA member countries for solar PV. More recently, budget outlays for RD&D of solar-thermal electric technologies have increased. In 2002, RD&D on solar-thermal electric received more than 62% of the renewable energy RD&D budget.

Legislative Decree 387/03 entered into force on 15 February 2004 and sets out, in 20 articles, a national framework for the promotion of renewable energy sources and particularly for their use in micro-generation plants. The Decree adopts a definition of renewable energy sources and electricity produced from renewables contained in article 2 of the EC Directive 2001/77/EC. Consistent with the Directive, the Decree sets a timetable for the periodic reporting, review and monitoring – by the Ministry of Productive Activities (MPA) – of progress towards the implementation of the objectives. It also sets, for the period 2005-07, a 0.35% annual rate of increase for the minimum share of electricity produced from renewable energy sources feeding into the national grid. The Decree also identifies deadlines for the MPA to plan further increments over the periods 2007-09 and 2010-12. Sanctions are established for non-compliance and applied by the Regulatory Authority (AEEG[11]) based on the reports of the grid manager (GRTN[12]).

To assess the exploitable energy potential from biomass, an ad-hoc experts committee was created to help design appropriate legislation. A six-month deadline is also set for the adoption of legislation and criteria (*e.g.,* minimum requirements; possibility to accumulate incentives; preferential tariffs; capacity targets; use of green certificates; etc.) for granting incentives to power produced from solar energy. The Decree includes specific provisions that favour biomass and hybrid plants (*i.e.,* those producing part of their power from renewables) over fossil fuel plants in dispatching.

A five-year programme agreement between the MPA and ENEA[13] on RD&D measures to support renewables and energy efficiency was established. Regional targets for renewable-based electricity are encouraged and regional governments can establish their own plans for renewables support. Specific articles address the issue of certification of origin for electricity produced from renewables, which can be requested for plants producing more than 100 MWh per year from GRTN. Conditions under which the electricity produced can be sold in the power market or purchased by GRTN are indicated. Specific rules are set for the streamlining of authorisation procedures for plants and infrastructure devoted to power production from renewables.

Article 17 of the Decree extends the benefits granted to renewables to waste and fuels derived from waste, including the non-biodegradable fraction of urban, agricultural and industrial waste mentioned in articles 31 and 33 of the legislative Decree no. 22 of

11. The Italian Regulatory Authority for Electricity and Gas (L'Autorità per l'energia elettrica e il gas).
12. Gestore della Rete di Transmissione Nazionale S.p.A.
13. ENEA, the Italian National Agency for New Technologies, Energy and the Environment (Ente per le Nuove tecnologie, l'Energia e l'Ambiente).

5 February 1997. This is subject to another Decree (to be adopted by MPA in the future) specifying the exact types of waste admitted and the allowable emission limits from plants that use them as fuels. However, the energy sources assimilated to renewables in Law 10/91 and the goods, products and substances originating in production of energy are excluded from the benefits of DLGS 387. This removes a peculiarity of earlier legislation that granted the same subsidies as those given to renewables to CHP (whatever the fuel used and including refinery waste such as tar).

In addition, Italy participates in international collaborative Renewable Energy RD&D in Bioenergy, Geothermal, Hydrogen, Photovoltaic Power Systems, Solar Heating and Cooling, and Wind Turbine Systems through the IEA Implementing Agreements.

Japan

In 2001, Japan had the largest energy RD&D budget among IEA member countries, USD 3.4 billion (in 2002 prices and exchange rates). This represented about 40% of total IEA funding for energy RD&D. From 1974-2001, Japan spent more than USD 77 billion on energy RD&D. Funding for renewables, however, has represented a small share over the past three decades (Figure 5). On average, from 1974-2001, RD&D spending for renewable energy technologies was 4.1% of total energy RD&D funding. The renewable share of the total energy RD&D budget peaked in 1982, but still only represented some 6%.

From 1974-2001, Japan allocated USD 3.2 billion to renewable energy RD&D. On average over the period, PV received 43% of funding and geothermal benefited from 37% of the total renewables RD&D expenditure.

In 2001, Japan allocated USD 128 million for renewable energy RD&D, of which 62% was for PV, 15% for geothermal and 12% for biomass technologies. The RD&D budget for biomass technologies averaged USD 40 million throughout the 1990s.

Following the first oil price shock of 1973, the Ministry of International Trade and Industry, which is now the Ministry of Economy, Trade and Industry (METI), launched the Sunshine Project. It presented a long-term plan for RD&D of renewable energy technologies. Japan focuses primarily on public-private collaboration for RD&D, mostly for PV and wind power.

As a response to the second oil price shock, the Japanese government enacted the Law Concerning Promotion of Development and Introduction of Oil Alternative Energy in 1980. It boosted funding for renewable energy technologies from USD 81 million in 1979 to USD 193 million in 1980. The law established the New Energy Development Organization (NEDO), which was renamed the New Energy and Industrial Technology Development Organization in 1988. NEDO has actively implemented various RD&D projects, including PV and wind, and has played an important role in reducing costs and improving the efficiency of renewable technologies. Funding for renewable energy RD&D increased dramatically in the 1980s, especially for geothermal and solar thermal.

Launched in 1993, the New Sunshine Programme set out a comprehensive long-term RD&D plan for renewable energy. It aimed to develop PV technology that could produce electricity at a cost that was competitive with conventional sources by 2000. The New Sunshine Programme expired in 2000. Moving away from the comprehensive approach, renewable energy RD&D is now more technology-specific with separate guidelines and goals for each technology.

The current RD&D budget structure is three-pronged: technical development; field tests; and promotion and implementation. For 2005 the requested budget for new energy sources (excluding hydrogen and fuel cells) was USD 629 million. This is proportioned at about 15% for RD&D and 85% for field tests and demonstration projects. In addition, USD 415 million has been requested to provide subsidies to companies and municipalities for the purchase of new energy systems.

Recent support for biomass technologies

Eleven projects have been allocated funding by METI through NEDO, seven in 2001 and four in 2003. These projects focus on RD&D for co-firing technology, small-scale distributed power generating systems, biomass gasification, and biodiesel fuel and fuel ethanol production from cellulosic biomass. NEDO contracts these projects to private entities. In fiscal year (FY) 2003, about USD 26.5 million was allocated for these projects. Biomass for energy is generally used in small-scale operations, as Japan's mountainous terrain makes it difficult to collect large amounts of wood. Biomass for energy is promoted through technological development of small-size, high-efficiency conversion applications.

At present, biomass makes only a very minor contribution to total electricity generation in Japan, but its role is expected to expand in order to meet the government's renewable energy targets. Biomass-fired generation is included in the 2002 Special Measures Law concerning the Use of New Energy by Electricity Retailers (RPS Law), which obliges electricity suppliers to supply 1.35% of electricity from renewables. In addition to the RPS Law, support for biomass is provided for pilot generation plants, field tests for biomass co-generation systems, and the installation of biomass energy systems and full-scale facilities.

In 2002, the Biomass Nippon Strategy was initiated to promote the use of biomass. Under the strategy, concerned government authorities co-operate to take measures to prevent global warming, establish a recycling–oriented society, encourage new industries and stimulate the agriculture, forestry and fishery sectors.

Japan participates in international collaborative Renewable Energy RD&D in Bioenergy, Geothermal, Hydrogen, Hydropower, Ocean Energy Systems, Photovoltaic Power Systems, and Wind Turbine Systems through the IEA Implementing Agreements.

Korea

The government of Korea has provided both financial and administrative support to research institutes and universities for renewable energy RD&D. Early programmes focussed on general RD&D efforts. More recent programmes narrowed the RD&D focus to specific technologies such as photovoltaics (PV), fuel cell and wind power, including market deployment strategies.

The Republic of Korea's first concerted attempt to reduce dependence on imported fossil fuels was the Promotional Law of New and Renewable Energy Development (1987), introduced by the Ministry of Commerce, Industry and Energy (MOCIE). It provided the initial framework for the development, through RD&D funding, of new and renewable energy technologies in Korea. The law encouraged the installation of waste-incineration facilities to generate heat and power, residential solar water heaters, small hydroelectric plants and facilities to use methane gas extracted from agricultural and livestock manure. A plan developed in the framework of the law established a target for new and renewable energy to contribute 3% to

TPES by 2006. The target is to be achieved through government-funded RD&D activities and demonstration and dissemination projects.

Between 1988-2004, USD 0.34 billion was invested in RD&D and dissemination of new and renewable energy technologies. Investments were made in 560 projects in eleven research areas, including PV, fuel cells, wind power, bioenergy and waste energy. As a result, the supply of new and renewable energy in Korea increased on average by about 15% per year over the period (according to the Yearbook of New and Renewable Energy). The majority of this growth was in the capture of waste heat produced from municipal and industrial waste. Energy production from municipal and industrial waste accounts for slightly more than 92% of total renewable energy. RD&D efforts continued to be promoted through the establishment of the New and Renewable Energy Development Centre (NREDC) in 1989 (renamed the RD&D Supporting Centre for Energy Resources in 1992).

The financial crises of 1997/98, combined with the devaluation of Korea's currency, led to a doubling of energy prices and exacerbated the country's dependence on imported energy sources. In order to develop domestic energy sources, the Korean government renewed its efforts in RD&D activities for renewable energy technologies. A renewed framework gave rise to the New and Renewable Energy RD&D Basic Plan in 2002. Wind, PV power and fuel cells were selected as top-priority technologies for RD&D support. Other technologies targeted include solar thermal, waste and biomass. The Korean government projected to invest approximately USD 800 million to help deploy renewable technologies. Preferential tax treatments were offered to encourage RD&D activities for specific technologies.

The mid- and long-term goal of new and renewable energy supply in Korea is to develop and deploy eleven new and renewable technologies with the overall aim of increasing the percentage contribution of renewable energy in the energy mix to 3% in 2006 and 5% in 2011. This plan comprises both RD&D and market deployment components. The RD&D component consists of a two-tiered strategy of selection and concentration. Technologies with comparative advantage will be selected and government support will be concentrated on the chosen technologies.

Three technologies – wind, PV and fuel cells – have been chosen from eleven competing technologies, all of which received support under the 1987 Act. Solar thermal, biomass and waste to energy are included in the category of significant consideration for dissemination support. A total of USD 7.6 billion is planned for investment through the government budget between 2004-11. Financial and tax supports are offered as incentives through: low-interest loans offered to companies that employ renewable energy technologies, processes and equipment; a 10% investment tax credit for companies investing in energy RD&D projects; priority in receiving tax credits for companies reserving funds to invest in renewable energy RD&D; plans to strengthen mandatory fixed-price purchases of renewables electricity; and plans to provide RD&D grants for renewable technologies of up to 70% of capital cost for PV and 25% for wind power. In addition, a green pricing programme is under review and the private sector is encouraged to undertake RD&D activities through project-based business centres that provide grants and credits.

Korea's Local Energy Plan is financed by KEMCO[14] and is managed by local governments to facilitate the use of new and renewable energies. The Local Energy Plan consists of an

14. Korea Energy Management Corporation.

Infrastructure Build-Up Programme and a Demonstration Programme. Loans are available for the production and purchase of facilities using new and renewable energy, at 4.75% interest with a three-year grace period and a five-year repayment period. Production incentives are available in which renewables-based electricity is purchased by a government-owned utility at the rate equivalent to the average retail price set by the Electricity Law.

The plan provides financial support for the dissemination of renewable energy technologies via the following mechanisms:

- Low-interest rate loans for companies that install renewable energy technologies.
- Requirements that utilities (only Korea Electric Power Corporation (KEPCO)) purchase electricity from renewable energy sources at feed-in tariffs (per kWh): USD 0.63 for PV, USD 0.094 for wind, USD 0.064 for small hydropower and USD 0.54 for landfill gas electricity.
- Requirements that new public buildings install renewable energy equipment, with a value of 5% of total building construction cost.
- Reducing local taxes imposed on new and renewable energy facilities.
- Plans to establish a net metering programme in which surplus electricity generated by renewable energy will be sold to KEPCO at rates considered sufficiently high to make renewable energy projects viable.

Tax incentives are offered in the form of income tax credits and compensate 10% of the total investment. From 1988-2004, the Korean government invested USD 0.18 billion in RD&D of new and renewable energy technology. In addition to government-supported RD&D activities, Korea participates in international collaborative Renewable Energy RD&D through the Photovoltaic Power Systems IEA Implementing Agreement.

Luxembourg

Luxembourg has devoted few financial resources to energy RD&D. The only RD&D activity that commanded funds consistently for the past 20 years is the European fusion research programme, which received some USD 62 100 per year. The majority of government funds for renewable energy RD&D were directed toward demonstration projects, at between USD 62 100 and USD 124 200 per year.

Government budgets for renewable energy RD&D totalled USD 1.6 million (in 2002 prices and exchange rates) between 1991-2000. The overall trend of government RD&D expenditures for renewables was minimal in the early 1990s; there was some increase in the latter half of the decade.

Among the renewable technologies, wind received the highest level of funding at USD 0.62 million, 39% of the total renewable RD&D budget over 1991-2000. Solar thermal-electric was funded at USD 0.53 million (33%) and biomass at 24% of the renewable RD&D expenditures during the period.

Netherlands

The Netherlands spent a total of USD 4.88 billion (in 2002 prices and exchange rates) on government energy RD&D between 1974-2001. In this period, 15.4% of the total energy RD&D budget was allocated to renewable energy RD&D.

Among the renewable technologies, wind power received the highest level of funding at USD 243.8 million, or 33%, in the 1974-2001 period. Solar photo-electric was funded at USD 184 million, representing 25% of renewable energy RD&D. Biomass was the third-largest recipient with 20%.

Prior to 2000, the Ministry of Economic Affairs managed 25 technology-specific, multi-annual programmes covering short- and long-term research and development, as well as demonstration and market introduction.

The programmes, and the specific projects funded, were determined by the Ministry and the Netherlands Agency for Energy and Environment (NOVEM). NOVEM reviewed the programmes annually, and an external evaluation was held upon programme completion. Such evaluations found that targets, (*e.g.*, technology uptake, energy conservation, etc.) were often not met, leading to the continuation of programmes with larger budgets. The programmes were deliberately broad, covering an extensive range of energy technologies.

In 2001, the government decided that it should not be dictating specific technologies to achieve general energy goals, and the programmes were changed to two broad themes: EDI, the programme for energy efficiency through innovation; and DEN, the programme for renewable energy. In the same year a White Paper, entitled *Energie Onderzoek Strategie (EOS),* established a framework for clarifying which key technologies should form the focus of RD&D policy.

In 2002, the RD&D programme was reviewed and changed to better reflect this new framework. Short-term RD&D is generally left to the private sector or supported through innovation policy measures. Long-term (commercialisation after 2010) energy RD&D and demonstration projects are established by the Ministry of Economic Affairs, in consultation with a range of stakeholders.

In addition, the Netherlands participates in international collaborative Renewable Energy RD&D in Bioenergy, Hydrogen, Photovoltaic Power Systems, Solar Heating and Cooling and Wind Turbine Systems through the IEA Implementing Agreements. The Netherlands actively participates in the EU Framework Programmes for Research and Technological Development.

New Zealand

New Zealand, with a population of 4 million, invested a total of USD 182 million (2002 prices and exchange rates) on government energy RD&D between 1975-2002. In this period, 31% of its total RD&D budget was allocated to renewable energy.

The overall trend of government RD&D expenditures for renewables peaked in the early 1980s and declined notably after 1985. Government RD&D budgets for renewables increased somewhat since 2001 and reached approximately USD 6 million in 2004.

Among the renewable technologies, geothermal received the highest level of funding at USD 34 million, or 60%, in the 1975-2002 period. Biomass was funded at USD 16.3 million, or 29%, of renewable energy RD&D. Wind was the third-largest recipient with only 4.5%, but has since proved to be the fastest growing renewable energy technology.

The oil price shocks in the 1970s led to higher public RD&D investment. However, once the crude oil price dropped in the early 1980s, both major energy funding agencies – the New Zealand Energy Research and Development Committee and Liquid Fuels Trust Board – were closed. The Ministry of Energy became part of the Ministry of Commerce soon after. In the 1990s, the Foundation of Research Science and Technology was established and funded a series of research programmes for renewable energy, particularly geothermal and biomass, and more recently, wave energy and distributed generation. In recent years, higher levels of investment in fossil fuels were made to support oil and gas exploration due to lower than expected natural gas reserves. This competed with investment in renewables.

New Zealand's first National Energy Efficiency and Conservation Strategy (NEECS) was prepared as a requirement of the Energy Efficiency and Conservation Act 2000. The Strategy's purpose is to promote energy efficiency, conservation and renewable energy, and to move New Zealand towards a sustainable energy future. It promotes practical ways to make energy efficiency, conservation and renewable energy mainstream solutions and is organised around policies, objectives and targets, supported by a set of measures. The Strategy outlines five separate action plans – for government, energy supply, industry, buildings and appliances, and transport – to help achieve its targets. The Strategy's overall plan is to improve New Zealand's energy efficiency by at least 20% by 2012 and to increase the current 150PJ consumer supply of renewable energy by 30 PJ by 2012, including 2PJ of biofuels. Policies within the NEECS will take effect through various renewable energy programmes designed to support renewable energy development by engaging with stakeholders and working to minimise barriers that inhibit the realisation of renewable energy's full potential. The expanded programme aims to cover:

- Planning and policy processes.
- Information and communication.
- Education and training in renewable energy systems.
- Identifying and prioritising research needs.
- Supporting pilot projects/demonstrations.
- Standards setting, where appropriate.
- Market development, capacity enhancement and business development opportunities.
- Government leadership.

Renewable energy RD&D is mostly applied research, though some support has been given to new organic solar capture systems based on poryphyrins. Large hydropower is deemed a mature technology.

New Zealand participates in international collaborative Renewable Energy RD&D in Bioenergy, Geothermal, Solar Heating and Cooling, and Hydrogen through the IEA Implementing Agreements.

Norway

Norway spent a total of USD 1.37 billion (2002 prices and exchange rates) on government energy RD&D between 1974-2002. During this period, 10.7% of Norway's total energy RD&D budget was allocated to renewable energy RD&D.

The overall trend of government RD&D expenditures for renewables peaked in the late 1980s to early 1990s, followed by a notable decline in 1995 when renewables RD&D funding levelled out at about USD 5 million annually until 2000. The trend shows a further decline in public investment in renewable energy RD&D in recent years.

Among the renewable technologies, ocean/wave energy received the highest level of funding as it was a priority in the 1980s (it still receives a little support, but is no longer a priority). Biomass has received the most sustained funding levels over the last two decades, totalling USD 33 million, or 23%, of the renewables RD&D expenditures between 1974-2002.

RD&D Programmes

Clean energy for the future (RENERGI, 2004-2013) is a broad energy RD&D programme administered by the Research Council of Norway. RENERGI encompasses all energy research except petroleum, and includes basic and socio-economic research in the energy field. The primary research areas are renewables (hydro, bioenergy, wind, photovoltaics, thermal solar and ocean energy), energy usage, energy system (including distribution and transmission), biofuels and hydrogen. RENERGI has a budget for 2005 of USD 20 million.

The project funds for 2005 are allocated as follows: 32% to hydrogen; 9% for energy usage; 12% for socio-economic research; 28% for energy systems; and 19% for renewables.

Projects in the renewables area include:

- Bioenergy: Small combustion systems with low emissions; electricity and heat production from biomass; biofuels for engines; small- to medium-size combustion of municipal solid waste (MSW). Support for biomass research is strong, particularly in relation to wood wastes produced by Norway's substantial forest industry.
- Solar: Solar energy systems integrated into buildings; photovoltaic cells; silicon metal; wafer production.
- Wind: Focus on subcontractor market (turbine blades, controlling electronics, generators); methods for mapping wind resources; off-shore wind turbines.
- Ocean energy: Overtopping wave energy devices and reverse osmosis (salinity differential).

In addition, Norway participates in international collaborative Renewable Energy RD&D through the Bioenergy, Hydrogen, Hydropower, Photovoltaic Power Systems, Solar Heating and Cooling, and Wind Turbine Systems IEA Implementing Agreements.

Portugal

Expenditures on energy RD&D were USD 150 million (2002 prices and exchange rates) from 1980-2002. Since the early 1990s, funding for energy RD&D has declined dramatically. The budget for renewable energy RD&D, however, has not exhibited as dramatic a decline as the overall energy budget; its share of total energy RD&D increased from 17% in 1980 to more than 40% in 2001.

Portugal's renewables RD&D budget has hovered around USD 0.5 million since 1994. In the 1980s, the focus was on solar thermal, PV and biomass. For the past several years, the focus was primarily on biomass. Funding for ocean technologies was USD 5.1 million from 1980-2002, averaging some USD 220 000 per year over the period.

Portugal participates in international collaborative Renewable Energy RD&D through the Photovoltaic Power Systems, Solar Heating and Cooling, Ocean Energy Systems and Wind Turbine Systems IEA Implementing Agreements.

Spain

Spain spent a total of USD 2.7 billion (in 2002 prices and exchange rates) on government energy RD&D between 1974-2002. Funding peaked in 1984 at USD 288 million. Spain allocated USD 47.9 million to energy RD&D in 2001.

The share of renewable energy expenditures in total energy RD&D was about 20% over the past two decades, averaging USD 13.4 million per year from 1985-2002. Spain has spent considerable funds on researching concentrating solar power – more than half the renewable energy RD&D budget since the early 1980s – although, as yet, there is no commercial use of this technology. Some 27% of budget outlays for renewable energy RD&D went to solar-thermal electric technology from 1974-2002. The remainder of funding has been directed to biomass technologies (22.4%), with smaller shares going to solar PV (18.3%), wind (11.6%) and solar heating (9.5%) technologies. Funding for renewable energy was USD 15.5 million in 2002.

The National RD&D Plan was in effect from 2000-03. The budget for the programme was USD 62 million over four years, and was used for the development of cleaner energy systems, including renewables.

Spain participates in international collaborative Renewable Energy RD&D in Hydrogen, Photovoltaic Power Systems, Solar Heating and Cooling, SolarPACES and Wind Turbine Systems through the IEA Implementing Agreements.

Sweden

Sweden spent a total of USD 2.73 billion (2002 prices and exchange rates) on government energy RD&D between 1974-2001. In that period, 25% of its total energy RD&D budget was allocated to renewable energy RD&D.

The overall trend of government RD&D expenditures for renewables peaked in the early 1980s, then declined notably after 1984 except for a boost in 1992. Government RD&D budgets for renewables increased considerably in 2000/01.

Among the renewable technologies, biomass received the highest level of funding at USD 323 million, or 47%, over 1974-2001. Solar heating and cooling was funded at USD 186.6 million, representing 27% of renewable energy RD&D. Wind was the third-largest recipient with 20%.

Government-funded energy research and development programmes date back to 1975. Sweden uses RD&D to promote commercial applications where possible, particularly for new technology with higher efficiency and lower environmental effects. Areas highlighted by the parliament include: combined heat and power production using biomass and waste; biofuel production; new processes for the production of ethanol from woody biomass; large-scale use of on-shore and off-shore wind; photovoltaics; and efficient use of energy in buildings, industry and transport.

The energy policy programme was established in 1997 to compensate for the closure of nuclear power stations by promoting the production of electricity from renewable energy sources. It includes measures aimed at reducing the consumption of electricity for heating purposes, making more efficient use of the existing power system and increasing the supply of electricity and heating from renewable energy sources. It consists of a short-term programme, which focuses on ways to increase the supply of renewable electricity and reduce electricity consumption, and a long-term programme that is more research-directed.

Swedish government RD&D activity takes place mainly in the following renewable energy technologies:

- Hydropower: Two major programmes aim to create general improvements in hydropower technology and in the water environment used for hydropower generation.
- Photovoltaic cells: One major programme seeks to develop thin-film solar cells, Grätzel solar cells and smart windows; another focuses on user-oriented development of complete solar cell systems.
- Wind power: A number of research programmes focus on how to integrate wind plants into the Swedish energy system without negatively impacting the environment.
- Biomass: The government spends about 16% of its annual total energy RD&D funds in the field of biomass. Various programmes look at fuels from agricultural lands, carbon balances, biomass and the environment, and refined solid biomass.
- Solid waste (including biogas): One research programme focusing on energy production with minimal environmental consequences.
- Geothermal: One programme examines possibilities for geothermal energy in Skåne; another looks at deep drilling for geothermal energy in Lund.

There are many programmes related to renewable energy in the Swedish RD&D programme. Apart from the ones listed above, there are efforts on: biofuel-fired CHP (bio-IGCC); large-scale biofuel-fired heat plants; renewable-based production of hydrogen; gasification of black liquor from the pulp and paper industry for power generation or transport fuel production; and small-scale heating using wood or pellets.

Sweden participates in international collaborative Renewable Energy RD&D in the Bioenergy, Hydrogen, Hydropower, Photovoltaic Power Systems, Solar Heating and Cooling and Wind Turbine IEA Implementing Agreements.

Switzerland

Switzerland spent a cumulated total of USD 3.1 billion (in 2002 prices and exchanges rates) on local and federal governments energy RD&D between 1974-2002. In this period, 20% of the total energy RD&D budget (USD 633.39 million) was allocated to renewable energy RD&D.

Governments RD&D expenditures for renewables peaked in 1993. Expenditures declined after 1999, when renewables RD&D funding levelled out at approximately USD 25 million annually until 2002.

Among renewables, solar heating and cooling and solar photovoltaic technologies received the highest level of funding. Solar photovoltaic received the most sustained funding, totalling USD 177.216 million, or 28%, of the renewables RD&D cumulated expenditures between 1974-2002. Most of the remaining renewable technologies, apart from hydropower, began receiving funding in 1977/78. Hydropower has received the least amount of funding at 4.9%.

The Swiss Energy Research Strategy includes funding distribution. Approximately 15% to 20% of funding for RD&D originates from the federal government, which directs and coordinates the publicly funded RD&D programmes and activities. The general decrease in funding for RD&D is a result of general federal budget cuts in the federal and local funding offices, as well as in public research institutions.

More than half of the Energy2000 programme (1990-2000) budget was targeted at pilot and demonstration projects related to renewables. The new programme SwissEnergy (2001-2010) has a smaller budget, which is reflected in the decrease in government renewable energy RD&D expenditures since 2000.

Switzerland participates in international collaborative Renewable Energy RD&D in the Bioenergy, Geothermal, Hydrogen, Photovoltaic Power Systems, Solar Heating and Cooling, SolarPACES and Wind Turbine IEA Implementing Agreements.

Turkey

Turkey spent a total of USD 107.2 million (2002 prices and exchange rates) on government energy RD&D between 1980-2002. In this period, 15.3% of its total energy RD&D budget (USD 16.4 million) was allocated to renewable energy.

Government RD&D expenditures for renewables followed the general trend in overall energy RD&D expenditures, rising in the late 1980s and then falling in the early 1990s. Public funding increased substantially in 1997.

Among the renewable technologies, geothermal received the most sustained funding over the past two decades and the highest level of funding, equivalent to USD 6.1 million, or 37%, of the renewables RD&D expenditures between 1980-2002. In addition, Turkey participates in international collaborative Renewable Energy RD&D in Hydrogen and Photovoltaic Power Systems through the IEA Implementing Agreements.

United Kingdom

The United Kingdom spent a total of USD 14.6 billion (2002 prices and exchange rates) on government energy RD&D between 1974-2002. In this period, 4.7% of its total energy RD&D budget (USD 688 million) was allocated to renewable energy RD&D.

The overall trend of government RD&D expenditures for renewables peaked in 1981. There was a notable decline through the mid- and late-1990s. From this lowered level, the renewables RD&D budget doubled from 2001-02, with increased RD&D focus on solar photo-electric.

Among the renewable technologies, wind power received the highest level of funding (USD 189 million) equalling 27% of renewables RD&D budget over 1974-2002. Geothermal RD&D was funded at USD 164 million, or 24%, of overall RD&D spending, and was a focus in the 1980s but support declined to zero in the 1990s. Ocean energy received approximately 20% of the renewable RD&D spending, concentrated in the late 1970s and early 1980s, with minimal support until the early 1990s.

In 2000, the UK government announced a USD 476 million package for measures over 2001-04 to stimulate renewable energy, comprising: USD 163 million towards capital grants to help develop off-shore wind, energy crop power generation projects and small-scale biomass heating projects, through the New Opportunities Fund; grants for energy crops (short rotation coppice and miscanthus) of USD 3.6 million; an initial funding of USD 18.3 million to kick-start a major solar PV demonstration scheme; a further USD 183 million for new generation renewable energy technologies; and an expanded renewable energy research and development programme of USD 101.6 million. These measures are in addition to the substantial boost for renewable energy coming from the renewables Obligation and exemption from the Climate Change Levy.

The government's policy is to stimulate the development of renewable and sustainable energy technologies that show strong prospects of being economically beneficial and environmentally attractive. The Sustainable Energy Programme, which supports the promotion of appropriate technology, was funded at USD 25.6 million for 2000/01. Its principal role is to support and encourage innovation by industry of those technologies that have the prospect of becoming competitive.

The Department of Trade and Industry (DTI) is responsible for the programme; the process for defining priorities is overseen by an advisory group. In consultation with the main players, the DTI is preparing a series of roadmaps to help determine RD&D priorities, covering the time frame up until 2020.

In addition, the United Kingdom participates in international collaborative Renewable Energy RD&D in Bioenergy, Hydrogen, Ocean Energy Systems, Photovoltaic Power Systems, Solar Heating and Cooling, and Wind Turbine Systems through the IEA Implementing Agreements.

United States

The United States spent a total of USD 106 billion on government energy RD&D between 1974-2002. In this period, 10.4% of the total RD&D budget was allocated to renewable energy RD&D.

Since 1974, energy RD&D has been dominated by funding for nuclear energy, followed by funding for fossil fuels. Funding for energy technologies peaked in 1979, when the budget reached more than USD 7.7 billion, of which just over USD 1.2 billion went to renewables. The share of renewable energy RD&D has varied considerably since 1974, but has been in the range of 20% since 1992.

Among the renewable technologies, solar photovoltaic received the highest level of funding at USD 2.6 billion, or 23%, over 1974-2002. Geothermal was funded at USD 2.2 billion, or 20%, of renewable energy RD&D. Solar heating and cooling and biomass were the next largest recipients with approximately 13% each.

In response to the oil price crises, the United States instituted aggressive RD&D programmes for renewables in 1974, including: the Solar Energy Research Act, which authorised funding for solar and wind research and development; the Geothermal Energy Research, Development and Demonstration Act; and the Solar Heating and Cooling Demonstration Act. In 1978, the solar programme was re-organised and funding was increased for solar technologies. The Wind Energy Systems Act of 1980 provided funding for wind RD&D; its re-authorisation included funding to support demonstration projects, which was a key factor in promoting the early wind power projects in California.

After the peak in 1980, funding for renewable energy technologies dropped significantly from about USD 1.3 billion in 1980 to USD 560 million in 1981, then to just under USD 140 million in 1990. Since then, funding has stabilised at more than USD 200 million, although there have been shifts in priorities between the different technologies.

The legislation of Energy Efficiency & Renewable Energy Development provides for increased funding for RD&D of renewable energy technologies. It also included an investment package of nearly USD 1.4 billion to research, develop, and deploy clean energy technologies. The programme augments existing initiatives such as the Bioenergy Initiative to develop advanced bioenergy technologies, under which was announced USD 13 million in financial assistance to promote the growth of the biomass industry.

The United States participates in international collaborative Renewable Energy RD&D in Bioenergy, Geothermal, Hydrogen, Photovoltaic Power Systems, Solar Heating and Cooling, SolarPACES and Wind Turbine Systems through the IEA Implementing Agreements.

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