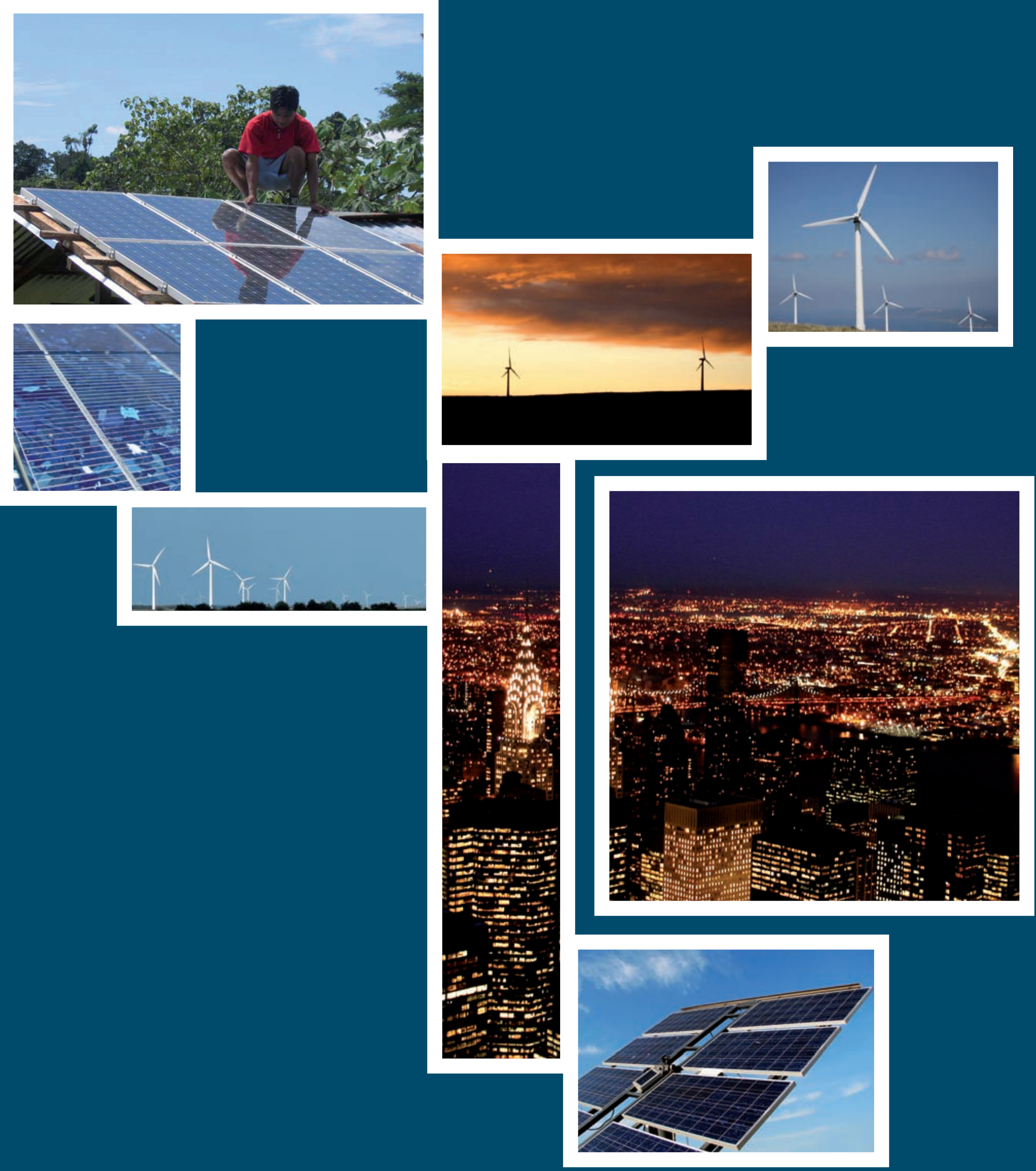

Research and Development on Renewable Energies

A Global Report on Photovoltaic and Wind Energy

ISPRE

International Science Panel on Renewable Energies

ISPRE

The International Science Panel on Renewable Energies was established in 2007 by the International Council for Science (ICSU) and the International Council of Academies of Engineering and Technological Sciences (CAETS). The central mission of ISPRE has been to provide analysis and strategic guidance for renewable energy research and development (R&D) efforts worldwide. It aims to help improve the intensity, effectiveness and coherence of R&D programmes being implemented at national, regional, and international levels. Generous financial support has been provided by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, under the contract 0329971A.

ICSU

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Research and Development on Renewable Energies

A Global Report on Photovoltaic and Wind Energy

December 2009

Foreword

Coherent R&D programmes for renewable energies are key elements in designing political strategies, not only for renewable energies but also for carbon mitigation. Enhancing the dialogue between science and policy is essential to achieve a consistent global approach which takes into account the maturity of the different renewable energy technologies.

This ISPRE report discusses two selected renewable technologies: photovoltaic and wind energy. Along with biomass, these are the technologies that are currently considered to have the greatest sustainable potential and widest applicability. Biomass is the subject of a separate preliminary report prepared by ISPRE. It is recognised that other renewable technologies, such as solar thermal power plants, solar thermal heating and cooling, geothermal energy, hydropower and marine energy (wave and tidal power) will also make a contribution to future global energy supplies.

This report (i) highlights the importance of R&D in renewable energy technologies, (ii) addresses the potential of the two selected technologies to contribute to a global sustainable energy supply system and (iii) gives detailed directions for further research and development.

The report shows how unevenly R&D activities in renewables are distributed worldwide. It argues that strong national and international efforts are necessary to establish and foster R&D in renewable energies in almost every country or region of the world.

ISPRE members, 2007–2009 and authors of this report

Andrew BLAKERS
Centre for Sustainable Energy Systems
The Australian National University, Canberra

Patrick DEVINE-WRIGHT
School of Environment and Development
The University of Manchester, United Kingdom

Decio Luiz GAZZONI
Empresa Brasileira de Pesquisa Agropecuária,
Centro Nacional de Pesquisa de Soja, Londrina, Brazil

Anne Grete HESTNES (Vice Chair)
Faculty of Architecture and Fine Art
Norwegian University of Science and Technology, Trondheim

Evans KITUYI
Industrial Ecology Group
University of Nairobi, Kenya

Jan KRETZSCHMAR
University of Antwerp, Belgium
International Council of Academies of Engineering and Technological Sciences (CAETS)

Joachim LUTHER (Chair)
Solar Energy Research Institute of Singapore (SERIS)
National University of Singapore

James MANWELL
Wind Energy Center
University of Massachusetts, USA

H.S. MUKUNDA
Department of Aerospace Engineering
Indian Institute of Science, Bangalore

Carlos ROLZ
Academia de Ciencias de Guatemala
Universidad del Valle

Jim SKEA
UK Energy Research Centre, London

Eduard VOLKOV
Russian Academy of Sciences, Moscow

WANG Zhifeng
Solar Energy Laboratory
Chinese Academy of Science, Beijing

Masafumi YAMAGUCHI
Toyota Technological Institute
Nagoya, Japan

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Executive Summary and Recommendations

1. Renewable energy sources have a huge contribution to make in creating a sustainable energy system. They help to mitigate climate change, increase the security of our global energy supply system and give developing countries access to affordable energy in support of the UN Millennium Development Goals.

2. Renewable energy could meet almost half of global energy demand by 2050 according to the International Energy Agency's ambitious BLUE MAP scenario published in Energy Technology Perspectives 2008. Under this scenario, world greenhouse gas (GHG) emissions are halved. By the end of the century, it is conceivable that global energy needs could be supplied mainly from renewable sources, although their contribution would vary from one region to another.

3. Research and development (R&D) has a vital role to play if the potential of renewable energy is to be fully exploited. Policy measures, such as taxes, cap and trade schemes, obligations and feed-in tariffs, which take into account environmental impacts and, in particular, the social cost of carbon dioxide emissions, will contribute to faster deployment. However, investment in R&D will not be delivered by market signals alone; extensive support at the national and international levels is needed to accelerate the development of renewable technologies.

4. R&D targeted at different stages of the innovation chain will yield benefits in the short-term (up to five years), medium-term (5–15 years); and in the longer term (15 years plus).

5. R&D with a short-term focus is needed to improve technologies that are already technically proven. More mature technologies include wind energy and the standard silicon-based conversion of solar energy to electricity in photovoltaic (PV) cells. Strong industries are already associated with these technologies and government deployment measures in several countries are helping to drive rapid market growth.

6. Much R&D with a short-term perspective will be provided by industry itself. But research activity in publicly-funded institutions (universities, laboratories and institutes) will also be needed. This will provide basic scientific insights and respond to the more fundamental science, engineering and socio-economic challenges that are inevitably thrown up in the process of demonstrating and deploying new technologies.

7. R&D with a medium and long-term perspective is needed to underpin long-term improvements in renewable technologies and enable breakthroughs that could give such technologies a decisive advantage in energy markets. The medium-term goal must be to ensure that renewables can compete successfully, without subsidy, once external environmental costs and other contributions to social goals (e.g. access, security) are taken into account. Medium- or long-term R&D efforts in this area will largely be developed through public sector support.

8. Regardless of whether R&D is conducted with a long or short-term perspective, it must contribute to improved performance and cost reductions or otherwise help to reinforce the role of renewable energy in a sustainable energy system. Areas of focus for R&D activity should be:

- improved performance, including conversion efficiency, reliability, durability and lifetime;
- advanced manufacturing techniques for components;
- reduced material requirements, especially for toxic materials;
- sustainable production processes that minimise life-cycle environmental impacts through manufacturing, use, recycling and final disposal;
- improved methods for integrating renewable energy into buildings, electricity grids and other distribution systems;

- socio-economic research aimed at developing effective policy measures that will encourage the deployment of renewables and enhance public acceptability of new energy technologies; and
- capacity-building aimed at developing new generations of trained scientists, engineers and others.

9. The deployment of renewable energy is distributed very unevenly round the world. The distribution of R&D in renewables is similarly uneven. R&D is dominated by a small number of industrialised countries (Japan, USA, Germany), though developing countries such as China, India, and Brazil are playing an increasingly important role. The current pattern of activities in terms of industries, markets and R&D could become a main obstacle to the widespread take-up of renewable energy technologies.

10. Fostering competences in the deployment and development of renewable energy technologies across a wide range of countries is a prerequisite if ambitious visions for future sustainable energy systems are to be realised. This will ensure that countries at a critical stage of development do not have to suffer the financial burden of importing knowledge and necessary hardware. R&D has a particular role to play in helping to adapt technology to local needs and build capacity through the fostering of skills and local enterprise. Thus, all countries can share the economic benefits associated with a transition to a sustainable energy system.

Recommendations

11. To underpin the long-term contribution of renewable energy to a sustainable energy system, R&D activities need to be accelerated. There is a particular need to ensure that efforts are made across a range of countries to support the wider deployment of modern renewables technologies. Existing R&D institutions should be encouraged to undertake activities in the field of renewable energy.

12. The precise focus of enhanced R&D efforts will vary from one technology to another. Specific recommendations are made here for the two technologies covered by this report, as well as for cross-cutting R&D, crucial for establishing renewable energy as a major player in future sustainable energy systems.

13. ***Photovoltaic (PV)***. The following research directions are critical for the development of PV:

- Reduction in the consumption of silicon and other materials in conventional crystalline silicon applications.
- Novel high efficiency silicon device concepts.
- Higher efficiency modules for thin-film applications based on silicon and other materials.
- Nano-structured devices such as organic, organic/inorganic hybrid devices and dye cells.
- Development of high quality transparent conductive oxides.
- Improved power electronics to enhance output quality and the compatibility with smart grid schemes.
- Grid integration issues for high levels of penetration, including large distance DC transport.
- High throughput, high yield, integrated processing with increased automation across all module types.
- Improved sustainability of production, including the use of recycled material, supported by life cycle assessment studies.

14. ***Wind.*** The development of very large turbines and the move offshore are key research challenges. The following research directions are critical:

- Improved wind forecasting.
- Fundamental design issues for very large turbines (up to 10 MW).

- Development of support structures for offshore wind.
- Grid integration issues for high levels of penetration, including transmission options for far offshore turbines.
- Analysis of offshore wind regimes and wind characteristics within large arrays.
- Condition monitoring and remote maintenance options.
- Environmental impacts and management offshore.
- Interactions with telecommunications and radar systems.
- Storage and fuel production for isolated networks.
- Design of special purpose applications such as desalination or hydrogen production.
- Public engagement/spatial planning issues.

15. There is also an urgent need for cross-cutting R&D to support the renewable contribution to a sustainable energy system. This needs to cover the integration of renewables into energy networks, the sustainable potential for and environmental impact of renewable energy, and socio-economic issues. Priority topics include:

- The integration of 'non-dispatchable' renewables into electricity grids and other distribution networks, addressing issues such as energy storage, adaptive loads and the active management of networks.
- The integration of renewables into buildings and other structures.
- Storage and fuel production for isolated networks.
- More reliable and specific information about the sustainable potential for renewable energy globally and regionally.
- The contribution of renewables to development goals, particularly in rural areas.
- The social acceptability of renewable energy.
- The environmental impacts of renewable energy.
- The facilitation of knowledge transfer.
- The development and evaluation of decision making support tools for policy makers.
- The design of policy measures, regulatory arrangements and grid management procedures which promote and take account of the particular characteristics of renewable energy.

16. Strategic research agendas (SRAs) should be established for all types of renewable energy and linked to cross-cutting R&D. These will be essential for building capacity and making the most efficient use of resources. At the national level, these agendas will need to take account of specific local and regional characteristics. There is a need for agendas to be co-ordinated at an international level to ensure resource efficiency and effective knowledge sharing.

17. SRAs need to contain road maps and specific quantitative milestones consistent with the overall goals of energy policy. It is vital that the international scientific community, governments and the private sector are engaged in the preparation of SRAs. Coherent plans should integrate short, medium and long-term R&D needs and establish a clear path from basic research through to applied research, development, demonstration and deployment.

18. International institutions should use existing networks and, where necessary, create new networks to facilitate the exchange of knowledge and scientific personnel. Adequately resourced networks are essential if a wide range of countries, particularly those in the developing world, are fully engaged in the development and deployment of renewable energy.

1. Introduction

A transformation of the global energy system is needed to:

- Protect the global life-support system, especially by mitigating climate change.
- Eradicate energy poverty in developing countries.
- Reduce the risk of geopolitical conflicts over energy resources.
- Establish a secure energy supply system.

Alongside major improvements in energy efficiency, energy conversion and transportation systems, the extensive use of renewable energy sources such as solar and wind will make a major contribution to future sustainable energy systems (Greenpeace/EREC, 2008; REN21, 2007; REN21, 2008; WBGU, 2003).

This transformation to a sustainable global energy system is urgent and sustained policy activity is essential. This needs to take place at multiple levels, through, for example, international treaties, regulations, development mechanisms and market deployment schemes. The latter is especially important because the impact of today's energy systems on our environment and climate is not sufficiently reflected in current energy prices. This constitutes a severe market failure.

A number of studies have shown that the transformation to a sustainable energy system is technically and economically feasible. However, different studies envisage different ways of achieving this.

The BLUE Map scenario in the International Energy Agency's 2008 Energy Technology Perspectives Report (IEA, 2008a) was developed to secure a 50% reduction in global CO_2 emissions by 2050. According to the IPCC (2007), however, emissions must be reduced by 50–85% to keep global temperature increases between 2° and 2.4°C. Under the BLUE Map scenario, biomass accounts for around 23% of total world primary energy in 2050 and becomes the most important energy source. Solar power and wind provide 11% and 12% of global electricity production respectively (Figure 1.1).

The World Energy Vision 2100, developed by the German Advisory Council on Global Change (WBGU, 2003), envisaged higher levels of energy demand and consequently renewables play an even greater role. Under this scenario, solar electricity becomes the most important energy source, contributing about 20% of world energy supply by 2050 and over 60% by 2100 (Figure 1.2).

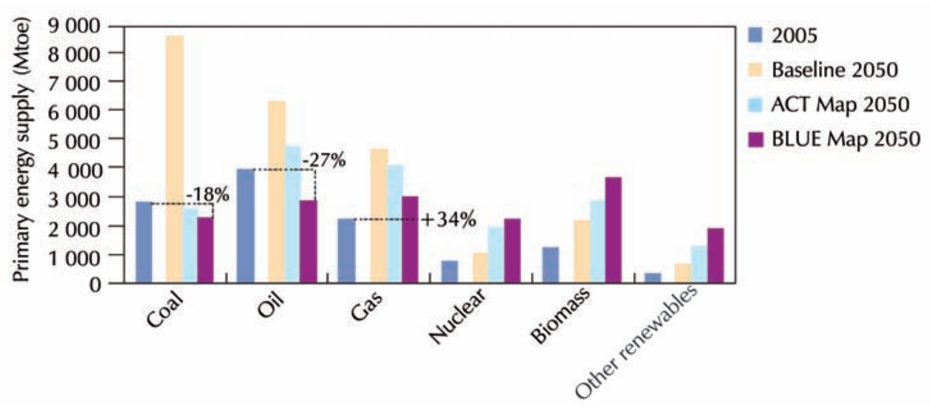


Figure 1.1: World fuel supply for Baseline, ACT Map and Blue Map, 2050 from IEA Energy Technology Perspectives 2008 (IEA, 2008b).

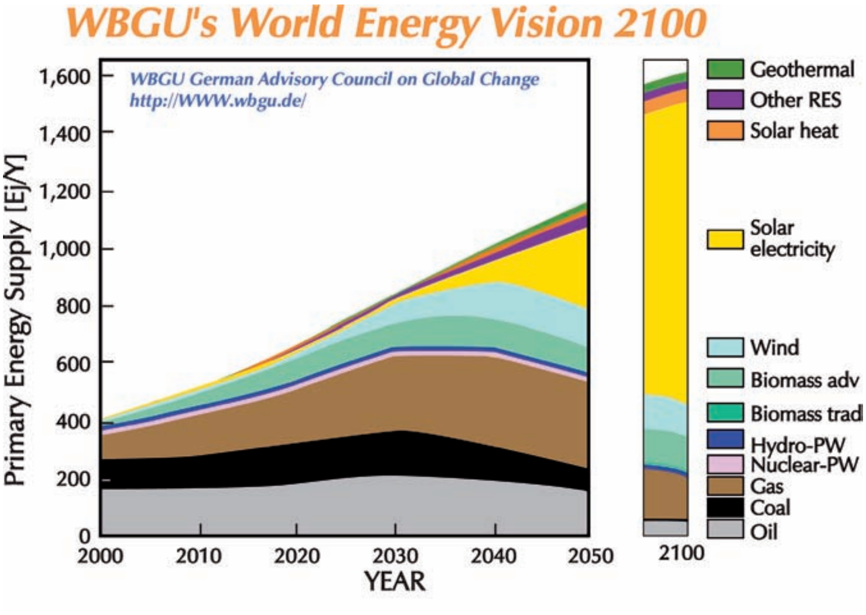


Figure 1.2: Transformation of the global energy supply system towards sustainability. Strict and comprehensive sustainability criteria are applied. This scenario provides the chance to keep global concentrations of CO_2 below 450ppm. Strong worldwide economic growth is assumed. A substantial increase in energy efficiency is implemented. Extensive use of carbon capture and sequestration is required under this scenario as a transitional technology. There is a phase-out of the use of nuclear energy. Only proven sustainable potentials for renewable energy sources are used. Traded energies are shown in this graph; non-traded energy contributions (like domestic applications of solar, biomass and geothermal sources) are accounted for under 'energy efficiency' (WBGU, 2003).

Strong and targeted activities in R&D are essential if a sustainable energy system is to be achieved. The transformation of our global energy supply system will not be successful without progress in and regional adaptation of today's proven renewable energy technologies. Cost reductions, low material consumption, recycling, new energy conversion schemes and extended technical lifetimes of the components are of key importance. In addition, research has to focus on the socio-economic aspects of this unprecedented transformation to our energy system.

In many areas such as photovoltaics (solar cells) and bioenergy fundamental research is key to finding fundamentally new ways of converting solar energy.

To date, R&D activity in most countries has been targeted on specific technologies rather than being comprehensive in scope. Such a division of activities can be seen as a characteristic of global co-operation. However, given the pressing need to transform the global energy system, enhanced R&D programmes with greater scope are needed in many—if not most—countries and regions across the world.

The establishment of sustainable energy systems calls for massive investment in renewable energy technologies and energy efficiency. If the necessary knowledge and hardware has to be imported, many countries will not be able to meet the short-term costs. Thus the evolution of energy systems needs to be associated with income and job creation. The prerequisite for this is R&D, which forms the basis for industrial activity, income and employment. R&D is particularly important for creating skilled personnel and for supporting industrial activities at the regional level.

Technology transfer from highly industrialised countries to the developing world is also urgently needed, particularly for renewable energy technologies. However, this knowledge transfer will not be sufficient to create a worldwide sustainable energy system in the near future. Local issues, as mentioned above, must first be addressed, at least in part, by local R&D, education and training. In addition, the global distribution of intellectual property rights (IPR) could represent an obstacle to the transformation of our energy supply systems. If adequate R&D platforms become more widely established this situation could be alleviated by creating partnerships between IPR holders and local technology expertise.

Of course, regional and local R&D must not be done in isolation. Global co-operation increases the effectiveness and speed of knowledge generation and facilitates scientific exchange thus fostering a shared understanding of the global challenges. By exploiting synergies, it also reduces the call on financial resources.

This report: (i) draws attention to the uneven global distribution of R&D on sustainable energy systems; (ii) underlines the consequent need for the swift and efficient transformation of today's energy system; and (iii) provides advice on critical R&D needs for the short- medium- and long-term. This advice is based upon a comprehensive review and analysis of two selected renewable energy technologies: photovoltaics and wind energy. Biomass is the subject of a separate preliminary report prepared by ISPRE.

The authors of this report believe that this report is largely unique in the sense that it focuses on: (i) research and development (including fundamental science); (ii) adopts a global view on this issue; (iii) addresses the global imbalance in R&D on sustainable energy technologies; and (iv) suggests directions for R&D at the regional and national levels not found in other reports.

The report focuses on publicly-funded R&D but acknowledges the considerable efforts of industry especially in technology development. At the same time, it recognises that industry is unlikely to undertake significant amounts of technology development in countries or regions with low levels of publicly-funded R&D. To stimulate innovation, i.e. transfer technologies based on applied R&D to the market, it is imperative that strong partnerships and co-operation between academia and industry are established. This will be most effective if industrial and academic activities are conducted in close proximity to each other.

Photovoltaics and wind energy have been selected as the main topics for the ISPRE report. Together with biomass, solar thermal power generation and solar heating, these two technologies have the highest sustainable potential of all renewable energy sources. Other technologies such as geothermal energy, wave and hydropower also have important roles to play.

The integration of renewable energy sources into energy supply and distribution structures must be analysed. This report does not cover this in-depth, although we recognise that issues such as large area grids (super-grids), grid stability, power quality, load management, energy storage, control of solar and wind energy conversion systems, energy weather forecasting and the merging of power and information grids (smart grids) are of utmost importance for an efficient integration of energy from sustainable sources into regional and eventually global energy systems.

Furthermore, appropriate energy supply structures for developing regions have to be designed. Solar home systems, small biomass systems, local wind turbine applications, micro hydro installations and optimised integrated village power systems also have to be developed and applied.

The two chapters comprising the main part of this report concentrate on the two example technologies namely photovoltaics (solar cells) and wind energy. Each of the chapters analyse the following points from a global perspective: (i) technologies, (ii) renewable potential, (iii) R&D activity and (iv) industrial activity. On the basis of this information, directions for future R&D are suggested. These recommendations represent the views of the authors of this report but are firmly based on the evidence available. The directions identified could help to define and focus new R&D activities worldwide.

2. Photovoltaics

Summary

Solar energy, including solar photovoltaics (PV), has a vast sustainable energy potential in comparison to global energy demand. The IEA envisaged solar power accounting for 11% of global electricity production by 2050 in its BLUE MAP scenario (IEA, 2008b). In the World Energy Vision 2100, developed by the German Advisory Council on Global Change (WBGU, 2003), solar electricity contributes about 20% of the world's energy supply by 2050 and over 60% by 2100. This suggests PV could play an important role in the transition to a sustainable energy economy. However, the further development of PV science and technology is essential for PV to become a major source of electricity and energy.

The world photovoltaic market grew by more than 60% in 2007; cumulative installed PV capacity was more than 10 GW. Important drivers for this growth were the feed-in-tariff laws in Germany and Spain. The cumulative global capacity of PV systems is forecast to reach 1,600–2,000 GW by 2030, due in part to targeted R&D activities.

PV devices are mainly fabricated from semiconductor materials. At present the typical efficiency of flat-plate crystalline Si solar cell modules is around 15%. However, flat-plate PV and concentrator III-V compound multi-junction solar cells have the potential in principle to increase efficiency to almost 30% and more than 50%, respectively. To achieve the full market potential for PV, the development of high performance flat-plate PV and concentrator PV modules with efficiencies of 25% and 40%, respectively, is necessary.

Today, most major PV applications are in the building sector. Further R&D will lead to improvements in the performance and durability of PV systems and the development of low-cost manufacturing processes. In order to achieve the economically efficient deployment of PV systems, the target cost for PV power generation should be set equal to wholesale electricity prices (approximately 7 JPY/kWh, or 0.045 Euro/kWh) by 2030.

More widespread application of PV technology will be the driving force in the global PV market. Four countries—Germany, Japan, Spain and the USA—have contributed most to PV market growth. The PV budgets of other countries are an order of magnitude lower than the budgets of these four. In particular, PV R&D activity in developing countries is considerably lower than in developed countries. Countries such as China and India, which have the largest populations, and a rapidly growing energy demand, should increase PV R&D activity and the deployment of renewable energy.

Although reliable, high-performance PV systems are commercially available and widely deployed, the further development of PV science and technology is crucial to enable it to become a major source of electricity and energy. Target prices for PV systems are therefore very important for its rapid and widespread development. Very large-scale development is only feasible if PV generation costs can be drastically reduced.

Cost reductions will be achieved through the following measures: (ii) higher conversion efficiency, (ii) less material consumption, (iii) application of cheaper materials, (iv) innovations in manufacture, (v) mass production and (vi) optimised system technology. Both fundamental research and more applied R&D, are crucial for the further development of PV. Collaborative research addressing targeted issues can play an important role in achieving the critical mass and effectiveness required to meet the sector's ambitions.

Short-term R&D must focus on making the PV industry more competitive. Rapid development and high production volumes are crucial for industrial leadership. Industry generally supports investment in short-term R&D and, as the PV industry grows, this pressure may grow. Governments must, however, take a medium and long-term view. Mid- and long-term oriented scientific work will be essential even if today's PV R&D may be focused on near-term technology development.

The major PV R&D topics needing further study are summarised in this report. Priority topics include: optimisation of transparent conductive oxide for thin-film PV; optical concentrating PV; and self-organisation and alignment in solar cell production using novel concepts. There should be an increased R&D focus on PV systems, including power electronics, grids, and rural electrification. Life cycle assessment and academic education form the basis for the sustainable introduction of PV into the global energy supply system.

Introduction

PV potential

The energy potential of solar energy, including solar photovoltaics and solar thermal power plants, is vast when compared to global energy demand. The global solar power potential is about 600 TW. Assuming a solar photovoltaic system efficiency of 10%, at least 60 TW of power (Lewis, 2005) could be supplied from terrestrial solar energy resources. This report covers only photovoltaic power, not solar thermal.

Conversion routes, theoretical and possible conversion efficiencies

Photovoltaic energy conversion (PV) is the direct conversion of sunlight into electricity with devices mainly fabricated from semiconductor materials. Table 2.1 shows the theoretical and obtained conversion efficiencies of various types of solar cells. Present conversion efficiencies obtained from polycrystalline and amorphous PV cells are about 20% and 6% lower respectively than those obtained from standard single crystalline cells. Concentrator III-V compound multi-junction solar cells, using wide-band photo-response, have significant potential for efficiencies of more than 50%. Novel conversion paths, such as intermediate band hot carrier cells, are also expected to have the potential of 50–60%, however the concept has yet to be proved. Some technology routes like dye-sensitised and organic PV do not yet play a significant role in the market.

Table 2.1: Theoretical, possible and obtained conversion efficiencies of various solar cells (Private communication: Blakers, Yamaguchi, Luther, 2008)

Cells	Theoretical efficiencies (%)	Obtained laboratory efficiencies (%)
Single crystalline Si	28.9	24.7
Polycrystalline Si	28.9	20.3
Amorphous Si	22	14.7
Amorphous/microcrystalline Si	28	15.1
CIS	28	19.5
III-V multi-junction	58	33.8
III-V concentrator multi-junction	70	40.7
Dye-sensitized	22	11
Polymer	22	5.7
Novel conversion paths	70	

Installed capacities

Figure 2.1 shows cumulative PV system installations in the major countries (Maycock, 2007). More than half of this growth was due to the German market. 953 MW of capacity was introduced in 2006 alone. The driver for this growth was the German feed-in-tariff law originally introduced in 1991 but strengthened in 2000 and 2004. The cumulative installed PV capacity in Germany in 2006 reached 2.86 GW, the largest in the world.

The Japanese PV market was the second largest, with 287 MW of new installations in 2006, primarily using grid connected residential systems under the Japanese PV residential programme. The cumulative installed PV capacity in Japan reached 1.71 GW in 2006. The third largest PV market was the US with 624 MW of PV installations in 2006, and a cumulative installed PV capacity totalling 1.45 GW. Although the PV market in China is currently quite small, it is expected to grow drastically within the next five years in order to meet its targets to supply 15% of total primary energy in 2020 from renewable energy sources (NDRC, 2007).

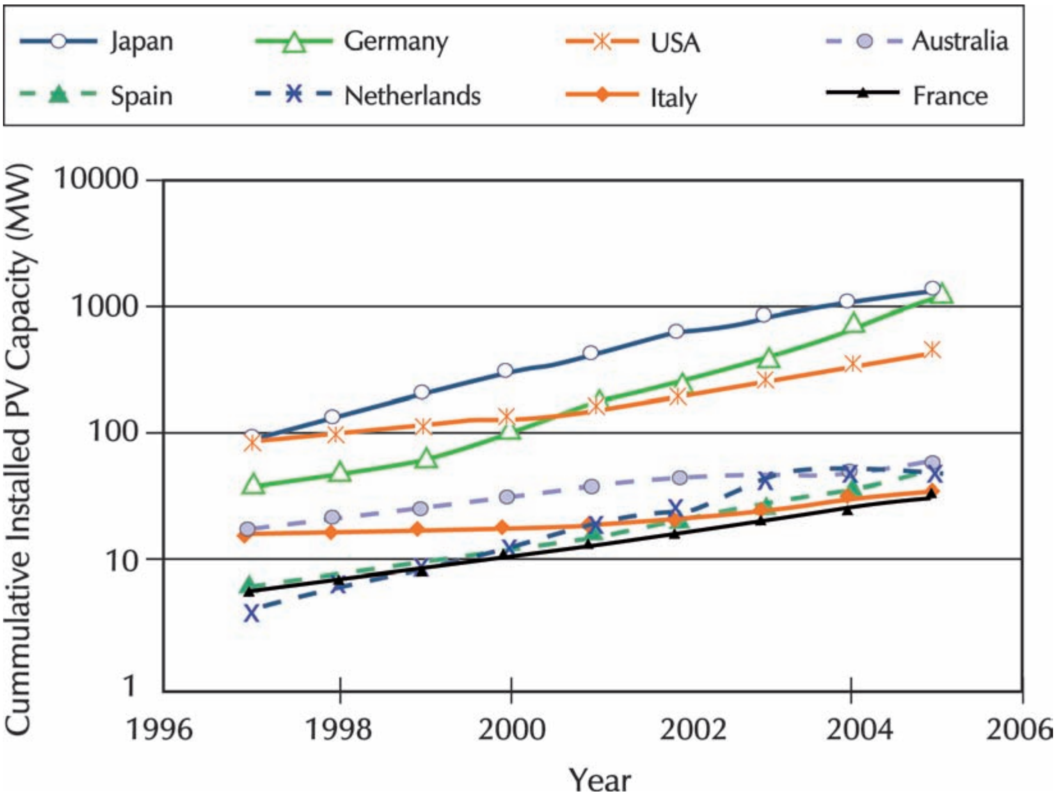


Figure 2.1: Cumulative PV system installations in selected countries. (Maycock, 2007)

According to investment analysts and industry forecasts, solar energy capacity will continue to grow at high rates in the coming years. The European Photovoltaic Industry Association (EPIA) and the European Renewable Energy Council (EREC) have developed scenarios for the future growth of PV (EPIA, 2009 and EREC, 2008). Table 2.2 synthesises roadmap targets from the EPIA (EPIA, 2009 and EREC, 2008), the US (EIA, 2009), Japan (Kurokawa and Aratani, 2004) and the Chinese Mid-Long term Development Plan for Renewable Energy, (NDRC, 2007).

Table 2.3 shows IEA projections drawn from the Energy Technology Perspectives 2008 Blue Map Scenario (IEA, 2008b).

Table 2.2: 2006 and target values of cumulative PV installed capacities shown by EPIA Roadmap, US PV-Industry Roadmap, Japanese PV 2030 Roadmap, EREC2040 scenario and Chinese Mid-Long term Development Plan for Renewable Energy. (Units = GWp)

Countries	2006	2010	2020	2030
World	5.7	14	200	1800
EU	–	>10	41	200
(Germany)	(2.9)	–	–	–
US	0.6	3.5	36	200
Japan	1.7	4.82	30	100
China	0.085	0.45	8	–

Table 2.3: IEA Projections of Installed PV Capacity in the BLUE Map Scenario.

Countries	2008	2010	2020	2030
World	14.73 GW	–	–	>150 GW
EU	9.53 GW	18 GWp	150 GWp	–
Germany	5.31 GW	–	–	–
US	1.17 GW	1.28 GW	2.43 GW	5.45 GW
Japan	2.15 GW	4.82 GWp	30 GWp	100 GWp
China	0.15 GW	0.3 GW	1.8 GW	9 GW

Under the BLUE Map scenario, the IEA foresaw that in 2030 PV installed capacity will be more than 150 GW, contributing to about 4% of the global electricity consumption. Installed PV capacity could reach 1,150 GW in 2050, or 12% of global electricity production.

The projections in Tables 2.2 and 2.3 show the huge opportunities for PV in the future. Such development will not happen by itself, but will require constant support from all stakeholders. The scenarios above will only be possible if—in parallel with the optimisation of the existing proven technologies—new solar cell and module design concepts can be developed. With current technology the demand for some materials like silver (for contacts) could exceed the available resources within the next 30 years. Research leading to solutions which will overcome such problems is underway.

Price situation and cost targets

Today, most major applications are found in the building sector, particularly in Japan and Germany. The average household electricity price of around 23 JPY/kWh (0.15 Euro/kWh) thus sets the target cost for PV in Japan. However, industrial use may require a lower cost target of 14 JPY/kWh (0.085 Euro/kWh). R&D leading to improvements in the performance and durability of PV systems and low-cost manufacturing processes could allow the wholesale electricity price of 7 JPY/kWh (0.45 Euro/kWh) to be achieved by 2030. The EPIA and the European Photovoltaic Technology platform suggest that parity with the wholesale electricity price will be achieved during the next decade and in Southern Europe during the next few years

(EPIA, 2009). More conservatively, according to the Energy Technology Perspectives 2008 Blue Roadmap (IEA, 2008b), PV will become competitive with retail electricity between 2020 and 2030.

With increasing photovoltaic electricity generation, new concepts of grid integration, grid operation and load management have to be introduced. This calls for focused R&D and for considerable investment in worldwide grid structures. In particular, large area (even intercontinental) grids have to be considered. Parallel to this, optimised autonomous rural electrification schemes (village power systems, hybrid systems) have to be developed and introduced on a large scale.

These measures would lead to mass take-up of PV systems without being constrained by grid structures. PV systems will also become more attractive through improvement in the performance of solar cells, improvement of PV system durability and the development of a wider variety of PV modules and inverters with multiple functions.

Table 2.4 shows key targets for PV system price, electricity generation costs, module efficiencies and energy pay-back time contained in the EU Strategic Research Agenda (Sinke, 2007). The quantitative targets shown were found to be roughly consistent with US (DOE, 2007) and Japanese (NEDO, 2004) scenarios.

Table 2.4: Key targets of PV system price, electricity generation costs, module efficiencies and energy pay-back time (assumed location of the systems: Europe, Mediterranean area). (European Photovoltaic Strategic Research Agenda, Sinke 2007)

Key targets	Present (2007)	2015/2020	2030	Long-term potential
Turn-key system price (Euro/Wp)	5	2.5/2.0	1	0.5
Typical PV electricity generation cost (Euro/kWh)	0.3	0.15/0.12	0.06	0.03
Typical commercial flat-plate module efficiencies	<15%	<20%	<25%	<40%
Typical commercial concentrator module efficiencies	<25%	<30%	<40%	<60%
Typical system energy pay-back time (yrs)	2	1	0.5	0.25

Research and Development Activities

Total PV budgets over a 10-year period in 10 major countries are shown in Figure 2.2 (NEDO, 2004). The 2006 public budgets for market stimulation, R&D, demonstration and field trials for IEA countries contributing to the PVPS programme are shown in Table 2.5. It is worth noting that definitions of what constitutes ‘research’, ‘development’, ‘demonstration’, ‘field trials’ and ‘market stimulation measures’ often differ from one country to another.

The USA, Japan and Germany, have contributed most to the development of PV over the past decade. Until 1995, the US led the first stage development of PV market growth and had the highest PV R&D budget. An increase in the Japanese PV budget contributed to second stage development. In the past five years, the German PV budget has increased faster than any other and Germany is the major contributor to PV’s third stage development.

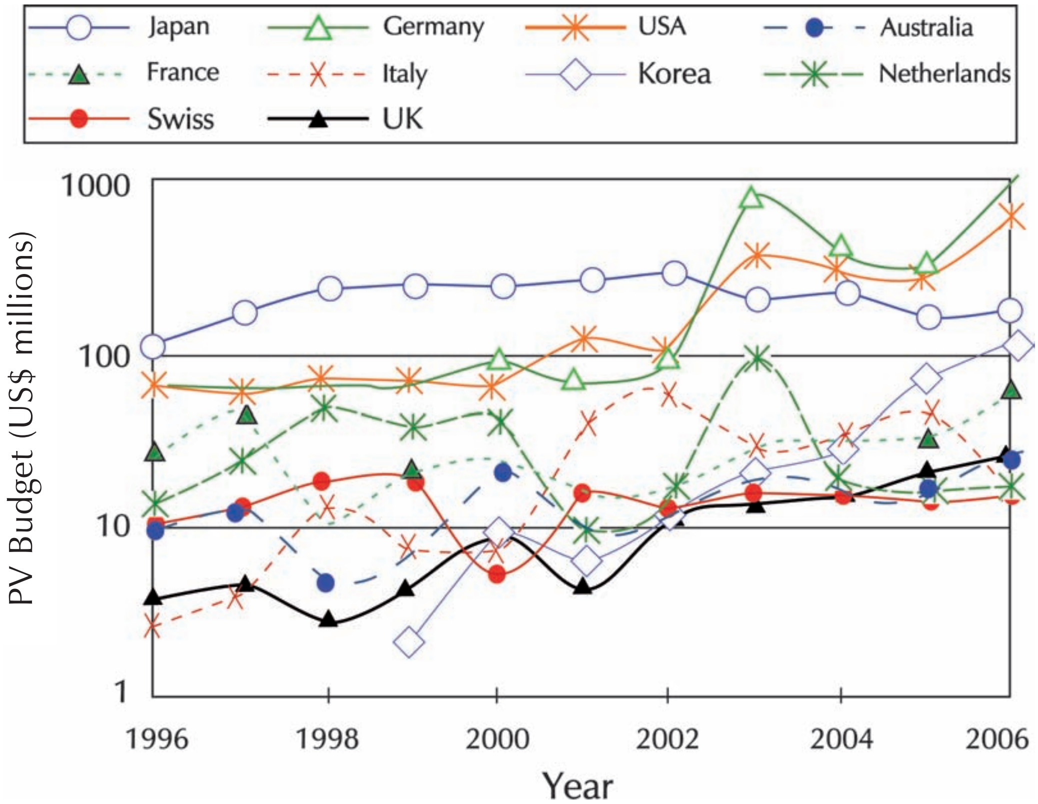


Figure 2.2: Development of the total PV budget in selected countries on a logarithmic scale. Currency conversion: 1 Yen=0.008259 US$, 1 Euro=1.3092 US$, 1 AUD=0.78 US$, 1 KRW=0.001065 US$, 1 CHF=0.804699 US$, 1 GBP=1.95 US$

Table 2.5: PV budget for R&D, demonstration and market stimulation programmes in selected IEA countries in 2006 and 2007. For certain countries demonstration is included in R&D (IEA-PVPS, 2006 and 2007).

Country	R&D (2007)	R&D (2006)		Demonstration (2006)		Market stimulation (2006)		Total (2006)
	(US$ millions)	(US$ millions)	%	(US$ millions)	%	(US$ millions)	%	(US$ millions)
Germany	61	82.5	7.6	–		1,000.0	92.4	1,082.5
US	138.3	121.8	21.5	3.0	0.5	440.0	77.9	564.8
Japan	38.9	27.2	15.1	116.9	65.0	35.7	19.9	179.8
Korea	18.4	19.7	16.2	0.3	0.2	101.6	85.6	121.6
France	12.3	32.8	56.6	–	–	25.0	43.4	57.8
UK	15.2	13.3	47.8	14.5	52.2	–	–	27.8
Australia	6.2	5.2	22.1	0.5	2.1	17.8	75.7	23.5

Total public expenditure on PV R&D and market stimulation in the IEA PVPS countries has quadrupled since the late 1990s. 2006 saw a large increase in total spending on PV compared to 2005, to over US$2 billion. While this was largely due to feed-in tariffs and other market stimulation measures, R&D spend also increased by about 17%. Nearly all countries listed in Table 2.5 reported increases in total expenditure for 2006 compared to 2005. Besides the obvious increase in Germany, the US and Korea increased funding dramatically (120% and 67% respectively).

European Union R&D funding support for PV continued under the 6th RTD Framework Programme (FP6), which reached completion in 2006. The 7th Framework Programme (FP7) has been operating since 2007; first calls for proposals were launched in December 2006. To date there have been four calls launched for PV, including:

- Efficiency and material issues for thin film photovoltaics.
- Manufacturing and product issues for thin-film photovoltaics.
- Support to the coordination of stakeholders' activities in the field of photovoltaics.
- Low/medium temperature solar thermal systems for industrial process heat.

Whether at the national or multi-national level, continuing political support for PV is required for R&D and new applications. Getting the balance right between R&D and market stimulation funding will be a challenge and will vary from country to country, but is important for long-term market development. Cost and prices must continue to come down steadily for PV to maintain public appeal and to develop and propagate the emerging interest from electricity utilities and investors.

Research and Development Institutions

Figure 2.3 shows the number of papers presented at three recent PV conferences (WCPEC–3, 19th EU–PVSEC, and PVSEC–17). Figure 2.3 shows the volume of R&D activities in photovoltaics. It is clear that R&D outputs, as measured by contributions to major conferences, have a strong correlation with R&D budgets.

It can be seen from Table 2.6 that public organisations such as universities and national research institutes have greatly contributed to PV R&D. Such organisations are able to demonstrate the potential of photovoltaics to policy makers and companies, and offer technological ideas to industry.

The roles of universities and national laboratories are categorised as follows: (1) to develop technical concepts for industry to exploit; (2) to propose national R&D projects for industry; (3) to promote national R&D projects; (4) to support industry through collaboration or contract research; and (5) to teach and educate researchers and engineers.

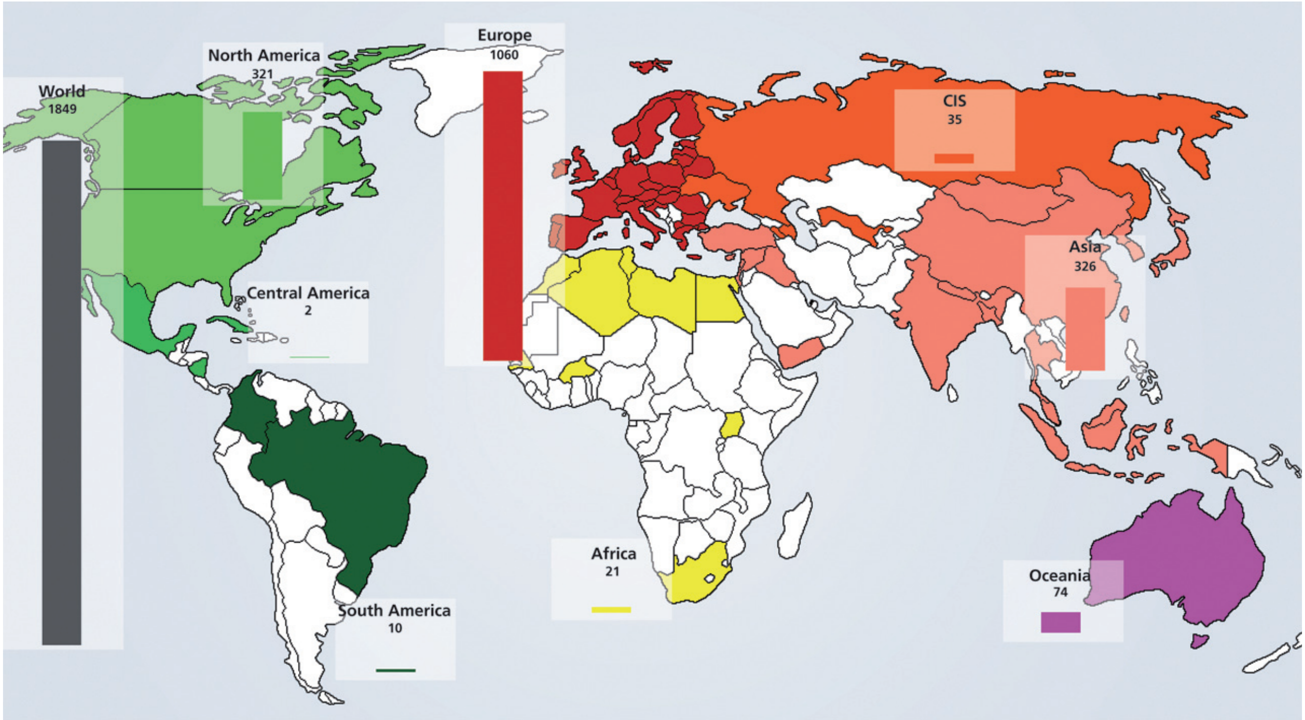


Figure 2.3: World map of contributions to three international PV conferences:
World Conference on Photovoltaic Energy Conversion (Hawaii, May 2006), 21st European Photovoltaic Solar Energy Conference (Dresden, September, 2006), International Photovoltaic Science and Engineering Conference (Fukuoka, December 2007). The number of authors who presented papers at these conferences is shown. In the compilation all authors of a paper are counted equally. Pure basic research was not strongly covered by the three conferences selected for the analysis.

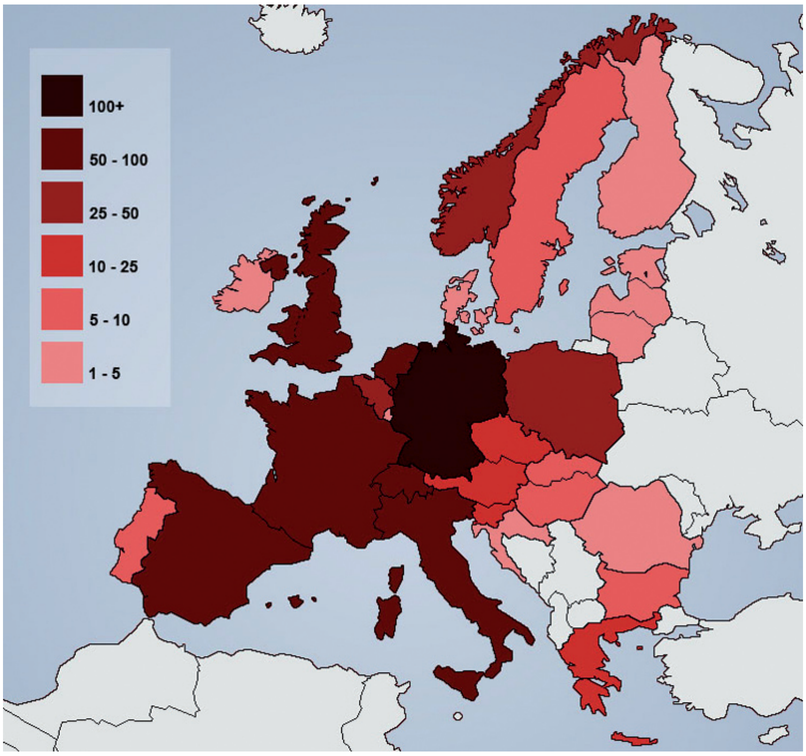


Figure 2.4: Details for Europe of the map shown in Figure 2.3.

Table 2.6: Total number of papers presented at the WCPEC–4, 19th EU–PVSEC and PVSEC–17 by R&D institutions including universities. Only the first 13 entries are shown.

Rank	Affiliation	Country	1	2	3	4	5	6	7	8	Total
1	Fraunhofer ISE	Germany	6	0	8	61	0	7	5	5	92
2	NREL	USA	8	13	8	6	4	7	4	5	55
3	AIST	Japan	14	7	1	6	15	4	5	1	53
4	Hahn-Meitner Univ.	Germany	3	12	1	16	5	0	1	0	38
5	UPM	Spain	9	0	10	7	0	6	2	2	36
6	Toyota Tech. Inst.	Japan	6	0	17	9	0	1	0	1	34
7	Univ. Konstanz	Germany	1	0	0	29	0	2	0	0	32
8	Tokyo Inst. Tech.	Japan	5	6	1	6	11	0	0	2	31
9	UNSW	Australia	9	0	0	12	1	2	2	4	30
10	IMEC	Belgium	3	0	2	21	0	2	0	0	28
11	Tokyo Univ. A. & T.	Japan	1	0	0	12	1	0	10	2	26
12	EC-JRC	EU	1	0	0	0	0	8	5	5	19
13	ENEA	Italy	0	5	0	6	4	3	0	0	18

The categories are: 1 = Fundamentals, Novel Materials and Devices, 2 = II-VI & CIGS, 3 = III-V, concentrator & Space, 4 = Crystalline Silicon, 5 = Thin Film Si, 6 = PV Modules and components, 7 = PV Systems, 8 = Programmess, Policies, Economics, Environment.

In Germany, short-term and mid-term PV R&D is well-organised. Good co-operation exists among academic and industrial groups. However, more fundamental, longer-term research is necessary to further facilitate scientific and technological development. Other European countries have contributed to more specific areas of PV research; there are several Centres of Excellence for PV across Europe.

Japanese PV R&D has focused on thin film, although its crystalline Si cell module production is the largest in the world. Its PV R&D budget has decreased in recent years but new market stimulation initiatives following the Residential PV System Dissemination Programme are expected to be introduced. There is currently no Centre of Excellence in the field of PV in Japan and relationships between Japanese industry and universities can be poor.

In the US, fundamental studies on PV are wide ranging and well-organised which should contribute to future development. There are several Centres of Excellence in the US. However, more industry-oriented R&D is thought to be necessary.

Industrial Activities

Figure 2.5 shows global solar cell module production from 1990 to 2006 (Maycock, 2007). Although the global photovoltaic market grew by more than 40% in 2006, the Japanese PV industry in particular has shown a low annual growth rate of 11.4% for solar cell module production due to silicon feedstock shortages. This suggests that effective utilisation of low-grade (solar-grade) Si is a topic suitable for further R&D. In contrast, Chinese and Chinese Taiwanese PV industries have shown higher annual growth rates of 308% and 222% respectively.

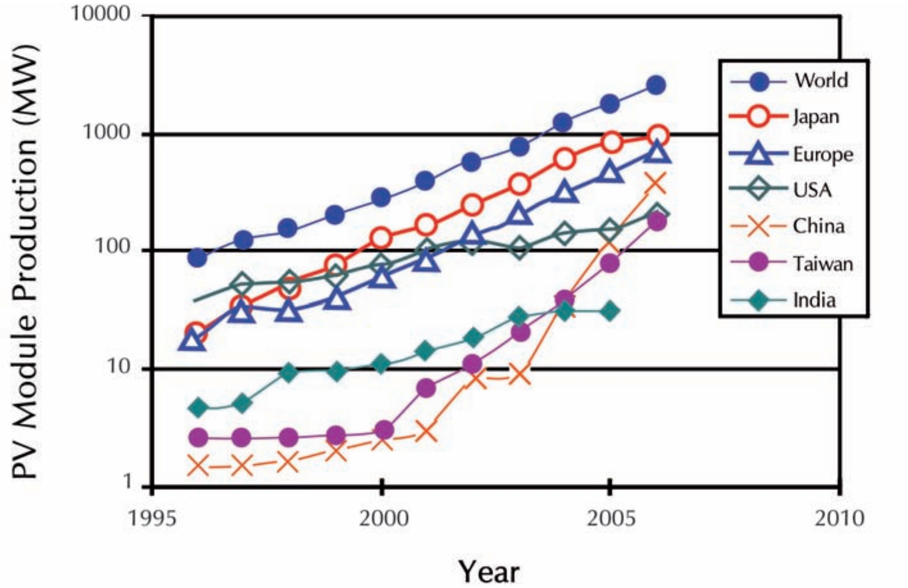


Figure 2.5: World photovoltaic module production from 1990 to 2006. (Maycock, 2007)

Figure 2.6 shows forecasts for the annual production of crystalline Si solar cell modules (Yamaguchi, 2006) in comparison with those made by EPIA/Greenpeace (2001) and Zweibel (2005). Case 1 results represent an 'optimistic' scenario and is close to Zweibel's estimate for the annual production of PV modules (7.7 GW in 2010; 120 GW in 2020; 706 GW in 2030; and 2,095 GW in 2040, respectively). Case 3 results represent a 'pessimistic' scenario and are close to the result reported by EPIA/Greenpeace for the annual production of PV modules (3 GW in 2010; 50 GW in 2020; 200 GW in 2030; and 680 GW in 2040, respectively). The results of case 2 (the 'realistic' case) are intermediate between the two.

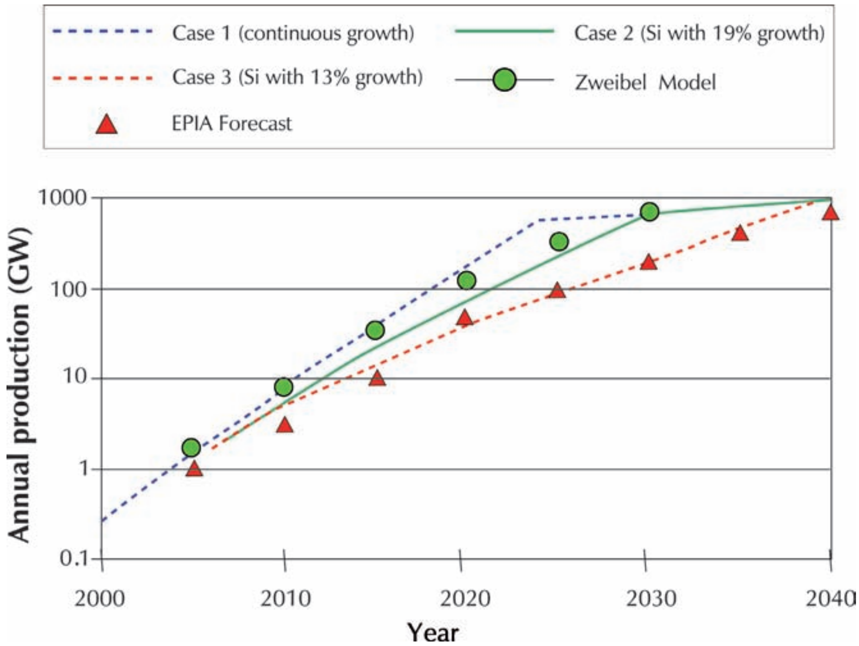


Figure 2.6: Different forecasts for the annual production of photovoltaic modules (see text for further information), (Yamaguchi, 2006).

Directions for Future Research and Development

It is apparent that further deployment of PV technology will be the driving force in the global PV market. Four countries—Germany, Japan, Spain and the USA—have invested most in the development of the PV market and account for almost 85% of the global installed grid connected PV capacity (REN21, 2009). PV R&D activity in developing countries is considerably less than that of developed countries. China and India in particular, which have the world's largest populations, and an increasing energy demand, would benefit by stepping up PV R&D activity and deploying more renewable energies.

Although reliable, high-performance PV systems are commercially available and widely deployed, further scientific and technological development will be crucial in enabling it to become a major source of electricity and energy. However, very large-scale development is feasible only if PV generation costs are drastically reduced.

R&D, including basic science, is crucial to the further development of PV. Joint (collaborative) research addressing well-chosen issues can play an important role in achieving the critical mass required to meet the sector's ambitions. Consortia such as the EU FullSpectrum project, the EU CrystalClear project and the DARPA Super High Efficiency Solar Cell project must be effective in accelerating PV R&D. Difficulties in organising consortium partners from academic, institutional and industrial sectors, especially in manufacturing dominated countries such as Japan, must be overcome. Issues can include the mismatch of interests: universities have long-term interests while industry is generally more near-term, concentrating instead on building knowledge and skills.

Generally, reducing the cost and increasing the performance of PV technologies is the primary research focus, but the importance of other drivers should also be emphasised. The lifetime of PV system components and the value of PV electricity must be considered. In addition, energy and materials consumption in manufacturing and installation is essential, as is the further shortening of energy pay-back time. Avoiding the use of scarce or hazardous materials presents significant R&D challenges. Standardisation and harmonisation as well as flexibility in system design is required. Socio-economic aspects such as public and political awareness, training and education, user acceptance and financing must also be considered. Resolving these issues will make PV more attractive while also leading to a reduction in CO_2 emissions.

Short-term R&D must focus on making the PV industry more competitive. Rapid development and high production volumes are crucial to establish industrial leadership. Industry will usually push for investment in short-term R&D and as the PV industry grows, this pressure may grow. Governments must, however, take a medium and long-term view.

Table 2.7 is a summary of discussions by the ISPRE PV Working Group and shows a summary of major PV R&D issues which need further study. The table considers EU PV (Sinke, 2007), US PV (DOE, 2007) and Japanese PV (NEDO, 2004; NEDO, unpublished) documents.

Table 2.7: Compilation of major PV R&D issues. SOG-Si = solar grade silicon, UMG-Si = upgraded metallurgical silicon, CPV = optically concentrating PV, LCA = least cost analysis, BoS = balance of system.

Cells	Short-term (2008–2013)	Mid-term (2013–2020)	Long-term (2020–2030)
Crystalline Si	• High throughput, high yield, integrated processing • Development of SOG-Si • Improved crystal growth • Thin cells • Improved wafering technologies •Characterisation	• Reduction in consumption of Si and materials • Towards utilisation of UMG-Si • New and improved materials • Safe and low-environmental – impact processing • Advanced wafering and encapsulants • Mechanism on gettering and passivation • Very high efficiency devices • Understanding of imperfections in Si • Defect engineering	• Novel and integrated device concepts • Si-based tandem devices • Effective utilisation of UMG-Si

Table 2.7: continued

Cells	Short-term (2008–2013)	Mid-term (2013–2020)	Long-term (2020–2030)
Thin-film Si	• Low cost and large area processes and equipment • High quality transparent conductive oxide • Higher efficiency in industry modules (>15%), tandem structures • Light trapping in devices • Characterisation	• Reliable, cost effective production equipment • High quality and low-cost transparent conductive oxide • Understanding of interface, material properties and light trapping • Poly crystalline cell on foreign substrates	• Overcome mechanism on light degradation of a-Si •Novel and integrated device concepts
CIGS and CdTe	• Improvement of production throughput and yield • Higher module efficiency in industry (>15%) • Highly reliable and low cost packaging • High quality transparent conductive oxide • Characterisation	• Alternative or modified material combinations • Standardisation of Equipment • High quality and low-cost transparent conductive oxide • Optimisation of materials and production with respect to sustainability issues • Understanding of materials, interface, device physics and processes	• Understanding of imperfections in CIGS and II-VI compounds • Tandem cells
III-V multi-junction and Concentrator	• New materials • Reliable and low-cost module assembly • Cheap and highly efficient optics • Tracking systems • System simulation • Testing and installations • Increasing reliability and lifetime • Characterisation	• Intensive material research • Higher effciency cells (>45%) • Reliable and low-cost optical systems • Higher concentration and analysis of optimum concentration factors • Testing and cost evaluation of CPV systems	• Understanding of imperfections in III-V compounds • Higher efficiency cells (>50%) • III-V/Si tandem cells • Novel concepts • Advanced optical systems • Environmental sustainability
Novel Devices	• Nano-structured devices (organic, dye cells) • Self organisation and alignment in novel concepts • Characterisation	• Cells based on novel concepts • Self organisation and alignment in novel concepts • Demonstration of enhanced performance • Characterisation	• Understanding of imperfections • Demonstration of enhanced performance
Electronic components	• PV inverters optimise for different modules and system technologies • Storage technologies	• Development of power electronics and control strategies for quality improvement • Storage technologies • Long distance energy transport	• Development of large scale storage technologies • Alternative storage technologies

Table 2.7: continued

Cells	Short-term (2008–2013)	Mid-term (2013–2020)	Long-term (2020–2030)
Manufacture	• In-line production control • Automation • Fully integrated production • Large scale production • Recycling	• In-line production control • Automation • Fully integrated production • Very large scale production • Entirely sustainable production • Extensive recycling • Custom-made modules	
Systems	• Technology development for high voltage systems • Smart grids for distributed electricity generation • Village systems for rural electrification • Standardisation	• New concepts for stability and control of electrical grids • New concepts for rural electrification • Very large PV systems (e.g. in deserts) • Large scale load management in grids	• Intercontinental links, very large scale distributed power generation
Socio -economic Aspects	• Integration of PV in the built environment • Market introduction schemes • LCA studies on BoS components • Financial schemes for rural PV electrification	• Acceptance of extensive PV employment • Acceptance of load management schemes • LCA studies on emerging technologies	

3. Wind

Summary

This section summarises the key issues associated with wind energy technology. It highlights the need for various types of research and development to continue in order to increase the proportion of world energy derived from wind.

Wind energy has been used for many thousands of years, but only in the past 35 has it come to be integrated into the modern energy supply on a significant scale. It is derived ultimately from sunlight. It is estimated that approximately 2% of the sunlight that falls on the earth is converted to wind energy. However, the amount of energy that is technically extractable from the wind greatly exceeds the world's electricity use at the present time. Currently wind provides approximately 1% of the world's electricity, and the amount of installed capacity is continuing to increase.

The key factors that affect the design of wind turbines and their ability to be integrated into the modern electrical systems are: (i) the low energy density of wind; (ii) the fluctuating nature of wind; (iii) the conversion of kinetic energy to electricity, via mechanical processes; (iv) the non-dispatchability of wind generation; (v) the material requirements of the turbines; and (vi) the associated material costs. Socio-political issues should also be considered; whether 'associated costs', for example, are perceived to be acceptable is a value judgment, reflected by energy policy, planning policy and public responses.

The basic topology of wind turbines, at least on land, seems to be settled: turbines consisting of a single rotor/nacelle assembly installed on a tower. The rotor axis is horizontal and the rotors themselves typically have three blades, which are located upwind of the tower. The rotor is connected to a main shaft, which drives an electrical generator, usually via a step up gearbox. Control is most often via a combination of changing the blade pitch and varying the generator torque via power electronic converters. Connection to the electrical network is presently by conventional means (transformers and switchgear). The environmental/energy contribution of wind turbines is presently primarily that of fuel saving with respect to conventional utility generators.

Future trends include: (i) adding progressively more wind generators to electrical networks (both small and large), such that the mismatch between the wind and the load must be taken into account; (ii) designing and building far larger turbines; (iii) moving increasingly into offshore generation; and (iv) designing turbines for difficult conditions (e.g. complex terrain, cold regions).

The main R&D issues are related to these new trends, as well as the general need to decrease costs, increase reliability, enhance public acceptability and ensure that the environment is not adversely affected.

Most wind energy research today is being undertaken in Europe and the US. Within Europe, Germany and Denmark are particularly active. Elsewhere around the world, significant activity is underway in Japan, India, China and Korea.

With regard to new R&D, there is a continued need to better understand the variability of wind both temporally and spatially both across the disc of individual rotors (especially very large ones) and in more difficult locations (especially offshore and in complex terrain). Significant R&D is required to develop very large wind turbines that are reliable, installable and maintainable, as well as smaller turbines that can be used effectively in isolated networks. Since ever larger turbines bring greater local environmental impacts (e.g. visual and acoustic, see Devine-Wright, 2005), the relative importance of research on institutional (land-use planning) and social-psychological (public acceptance) aspects of turbine siting is likely to increase in the future. A broad range of R&D is needed to develop wind energy technology for offshore applications, particularly in deeper water. R&D is needed on a number of electrical and grid integration questions, including improving generators and power electronic converters, designing and implementing system wide control using demand side management, energy storage and fuel production. R&D is also needed on broad range of social and environmental issues. Finally, there is a continued need to better understand the basic physics of the various processes involved in wind energy conversion.

Introduction

Wind Resource

Wind energy is derived fundamentally from solar energy via a thermodynamic process. Sunlight warms the ground causing air above it to rise. The ensuing pressure differential causes air from elsewhere to move in, resulting in air motion (wind). Different regions on earth are heated differently than others—primarily a function of latitude. Air motion is also affected by the earth's rotation. The net effect is that certain parts of the world experience higher average winds than others. The regions of highest winds are the most attractive for extracting its energy: Theoretically, the power which can be extracted from the wind is proportional to the cube of the velocity, so a good wind regime is particularly important. The power that can be extracted in practice, however, is somewhat less than proportionally related to the cube of velocity.

The total energy impinging on at the outer atmosphere, assuming a solar constant of 1,367 W/m^2, is $1.53x10^{18}$ kWh per year. The conversion of solar energy to wind has been estimated to occur at an efficiency of 2%; approximately 35% of this is in the lower boundary layer where it could potentially be extracted by wind turbines (Gustavson, 1979). According to this estimate, the maximum global wind resource is approximately $1.22x10^{15}$ kWh/yr.

Recently Hoogwijk et al. (2004) made estimates of the technical potential of onshore wind energy. These authors conclude that, with present technology, the onshore technical potential of wind is about $1.0x10^{14}$ kWh/yr. They also cite other sources which preliminarily indicate that the offshore wind energy resource at water depths up to 50 m is another $3.7x10^{13}$ kWh/yr. In comparison, the global consumption of electricity at the present time is about $1.6x10^{13}$ kWh/yr. The global distribution of wind energy potential is illustrated in Figure 3.1.

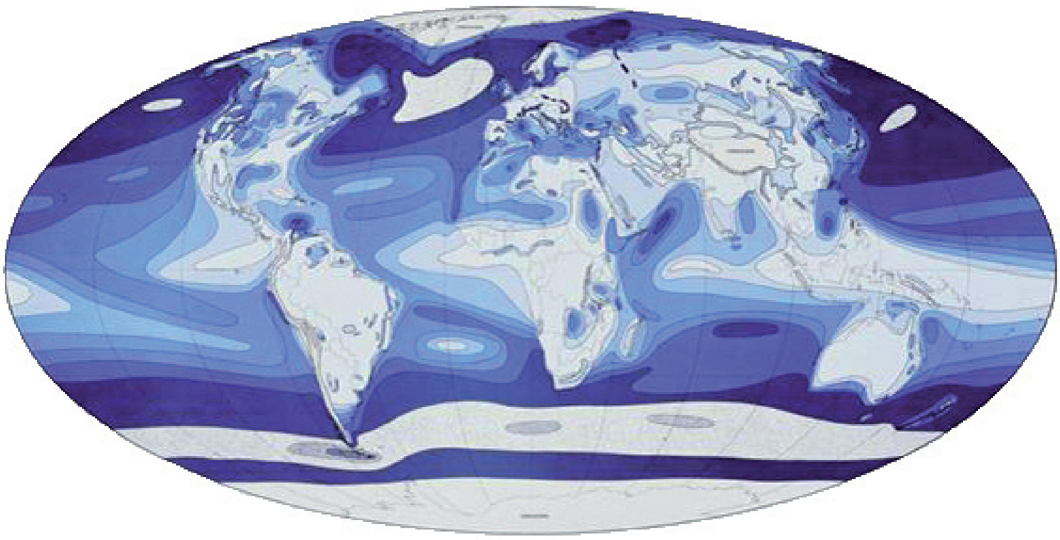


Figure 3.1: World Wind Energy Resource Distribution Estimates (NREL), the darker the colour, the higher the wind speed.

Wind Energy Technology

Wind energy has been used for transportation for at least 5,000 years, and has been used for land-based applications for at least 2000 years (Woodcraft, 1851). Mechanical applications of wind energy became widely used in Europe in the Middle Ages before falling out of favour with the advent of coal-based steam power in the 1700s. Wind energy continued to be used for water pumping into the mid-1900s and was used for electricity generation in some locations from the late-1800s to the mid-1900s.

Wind energy experienced a resurgence beginning in the early 1970s. Over the last 35 years, turbine rotors have grown in size from approximately 10 m to more than 120 m. Power ratings of individual turbines have increased from tens of kW to more than 5 MW. As of 2006, an estimated capacity of 73.9 GW was installed worldwide (WWEA, 2007). Also according to the World Wind Energy Association, this capacity produces more than 1% of the world's electricity and in the case of one country (Denmark) produces an amount equal to 20% of its consumption (www.wwea.org, accessed 20 March 2008). Figure 3.2 illustrates a typical wind turbine.

Figure 3.2: Typical Wind Turbine.

Wind Energy System Design

Converting the energy in wind into a socially useful electrical or mechanical form involves many types of processes which all have their own particular characteristics. Some of these processes are well developed, others less so. Modern turbines have evolved primarily from what is known as the 'Danish concept'. This design was based on a three bladed, upwind, stall-controlled rotor which drove an induction generator via a gearbox. Today's turbines have extended that concept; many of them now incorporate blade pitch control, power electronic converters and use different types of generators. Some of the key features of modern wind turbines are summarised below and are illustrated in Figure 3.3 (for more details see Manwell et al. 2001).

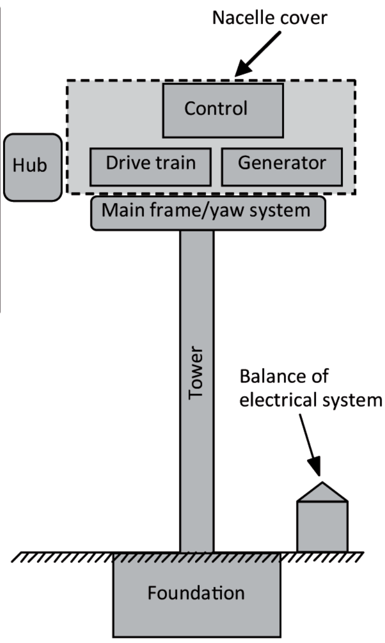


Figure 3.3: Schematic of typical wind turbine (Manwell et al, 2001)

The first step in the extraction of energy is converting the kinetic energy of wind to mechanical energy in a rotor via an aerodynamic lift. Rotors nowadays typically have three blades, but having more or fewer is possible. Blades are constructed primarily of composite material. Most rotors have a horizontal axis of rotation, although a vertical axis is also possible. The rotor is generally oriented such that the blades are upwind of the tower, although downwind orientation has sometimes been used.

Positioning of the rotor is provided by a yaw system (which turns the entire nacelle, see below). The rotor, which turns relatively slowly (the more so for larger rotors), is connected to a main shaft which in turn connects (typically) to a gearbox. The gearbox provides an increase in speed such that the speed of the gearbox's output shaft is matched to the speed requirements of the generator. The generator, which is the next step in the process, performs the conversion of mechanical energy to electrical energy. The shafts, gearbox, generator and associated equipment are contained in a nacelle which is located on top of a tower.

The tower keeps the rotor nacelle assembly well up into the air where the wind speed is higher and less turbulent than it would be closer to the ground. The tower, which is normally made of steel, is attached to a foundation (reinforced concrete for onshore turbines) or to a more extensive support structure (as in the case of offshore turbines). Electricity is carried down the tower via a droop cable. A control system, portions of which may be in the nacelle or on the ground, performs a variety of functions. These include starting and stopping the rotor and protecting the machine during extreme winds or faults. Most turbines today incorporate blade pitch control where the blade may be turned about its long axis to change its aerodynamic properties. Other devices may also play a significant role in the process. These include in particular power electronic converters, which may facilitate variable speed operation of the rotor, while allowing the output electricity to be of essentially constant voltage and frequency.

The electrical output of most turbines nowadays is directed into a conventional electrical network. The voltage may be at the distribution level or higher, depending on the situation. In any case, a transformer is normally used to convert the generator's output (low voltage) to the electrical line voltage (medium or high voltage). Various other electrical devices and switchgear are also used to allow safe connection to the network and protection in the case of faults.

In some applications, such as where the grid is isolated or weak, or where there is large amount of wind energy generation installed, the interconnection process may be more involved. Such applications can benefit from the use of short-term storage and supervisory control systems. As an increasing amount of wind generation is added to grids of whatever type, more attention must be given to the issues associated with interconnection. These could include demand side management, longer-term storage or even fuel production (e.g. hydrogen via the electrolysis of water).

There are a number of characteristics of wind energy technology which are distinctive and which affect the design of wind turbines and their use:

1. Low energy density of the resource
2. Fluctuating nature of the resource
3. Social acceptance
4 Non-dispatchability of wind generation
5. Material requirements
6. Costs

These characteristics have been taken into account in the recent development of wind turbines, and will have to be taken into account in the future. It should be noted that offshore wind energy has a number of additional issues which need to be considered in the design of turbines and systems.

Low energy density

In most sites considered for wind energy development, the average wind power density is in the range of 200–800 W/m^2 (vertical area). The implication is that rotors must be physically quite large (in comparison, for example, to steam turbines or hydroelectric turbines) to produce a given amount of power. A secondary effect is that turbines are imposing in the landscape and so public reaction to their appearance is a factor that must be taken into account.

Fluctuating wind resource

The wind itself is highly variable both spatially and temporally and on many lengths and time scales. These fluctuations affect all aspects of the design, siting and operation of the wind turbines. Wind speed measurements are typically averaged over ten minute intervals for use in performance and economic assessments. These long-term averages vary sufficiently over the day and from one season to another that the average power from wind turbines is typically between 20% and 40% of their rated maximum.

Wind naturally exhibits occasional extremes. These extremes result in very high forces on the turbines, even when they are not running. These extremes must be considered in the design process. The magnitude of the extremes is typically closely related to the long-term average wind speed at a site, but not always so (as in the case of regions prone to hurricanes). In any case, it is desirable to utilise a turbine whose design is suited to its location ensuring that the turbine does not have either too much or too little material.

Short-term fluctuations (known as turbulence) have major influence on the design of the turbines. In particular, fluctuations in wind speed and direction contribute to material fatigue in many of the wind turbine's components. These fluctuations must be taken into account in the sizing of the components, choice of materials, control strategies and maintenance schedules.

Social acceptance

Due to the relatively large size of wind turbines and the need to site them in exposed locations, public acceptance of wind energy development has sometimes been problematic. The need has arisen to address public concerns through education or by mitigating the impact.

Non-Dispatchability

Due to the nature of the wind itself and the technology used for its extraction, energy derived from wind is inherently non-dispatchable. That means that generation cannot be turned on at will. When the wind turbines provide a relatively small portion of a network's requirements this is not an issue. When turbines are intended to supply a large fraction of the energy, then the overall system must be configured differently. In this case, the wind turbines need to operate in concert with a suitable control system and possibly storage.

Material requirements

Material requirements of wind turbines relate directly to the low power density of wind and its fluctuating nature. The low power density requires large heavy rotors. As the rotor rotates there are large reversing forces which contribute to fatigue along with the fluctuations in the wind.

Costs

To a significant extent, wind turbines can be designed that will work adequately and survive a sufficiently long period of time. There is still an issue of cost, however, both in terms of resources and required financial outlay. High costs are associated with the material requirements of the wind turbine. Long-term operation and maintenance costs are also important. There is a need for continuing work to drive down the costs of the turbines while maintaining and improving their reliability. Cost reductions will benefit from improved understanding of the fundamental physics of the conversion process, as well as of the failure mechanisms. Continuous monitoring of the wind turbines and design and implementation of structural health management systems should help to decrease these costs.

It may be noted that costs for wind generated electricity have decreased significantly over the last 30 years. For example, the cost of energy from wind in 1980 has been estimated to be approximately US$0.50/kWh (EIA, 1995). Presently, it is less than a fifth of that in many locations. This is largely due to experience, research and development. The resulting enhanced understanding of the interaction of the wind turbine with its environment has led to improvements and cost reductions in all aspects of the technology. Costs are moving towards parity with conventional energy generation.

Research and Development Activities

Research and development has already helped greatly to reduce the cost of wind energy, although there is scope to further lower capital costs, improve reliability, and expand the range of applicability of wind energy systems. As will be described in the next section, R&D is still active and is reported in conferences which are held every 12–18 months. In understanding the current activities it is helpful to categorise the reports into one of the following topic areas:

1. Wind resource (including meteorological analysis, siting and remote sensing)
2. Wind turbine design (including aerodynamics, mechanics and dynamics)
3. Electrical (including control, storage and integration into both conventional and other, renewable energy systems)
4. Applications (including hybrid power systems, water pumping, desalination and fuel production)
5. Offshore wind energy
6. Social/environmental aspects (including avian issues, noise and acceptance)
7. Economics, incentives and social costs of energy
8. Condition Monitoring, operation, maintenance, reliability and protection

New Areas of Focus

Wind turbines in the 1–3 MW size range are commercially produced and widely used. It may be expected that they will be gradually and incrementally improved over time, but that a significant amount of R&D will be integral to that process.

There are also certain areas which are less mature and represent significant opportunities for new development. These include:

1. Wind energy systems for high penetration applications

2. Very large wind turbines (for open inland sites or offshore)

3. Offshore wind energy technology in general

4. Wind turbines for special conditions, such as difficult climates or locations (e.g. arctic, complex terrain)

Some of these areas are described in more detail below.

Wind energy systems for high penetration applications

Over the past 35 years, the majority of wind energy systems development has focused on turbines that were intended to be integrated into large central grids, where the issue of penetration (defined here as ratio of wind generation to electrical load) was not really significant. As time goes on, there will be an increasing need to design more comprehensive systems, in which the wind turbine itself is just one of the components. There will be need for more comprehensive control systems and storage.

Very large wind turbines

There are a variety of factors that impel manufacturers to produce ever larger wind turbines. This is particularly true for offshore applications. The cost to build the support structures is so great each must produce of a large amount of electricity. At the same time, there are many challenges to design, manufacture, transport, install and maintain such large turbines. To a certain extent, large rotors can be scaled up versions of smaller ones. There may be limitations to that, however. For example, simple scaling laws predict that the mass of a rotor should increase with the cube of the diameter, while the power will increase with the square. At some point this would clearly result in an unacceptably heavy and costly rotor.

Actual experience has been that the weight to power relation was more positive (on the order of D2.5) but the effect will be progressively more significant as larger rotors are constructed. One possibility is to use multiple smaller rotors rather one single large rotor. This old concept has never been investigated to any significant degree.

There are also some other possibilities to consider, such as trying two, or even one blade rotors again, or re-examining the pros and cons of vertical axis turbines.

The wind conditions may also vary significantly over the rotor disc. For example, the average wind will almost always be lower at the lower part of the rotor's swept area. In addition, the turbulence intensity will decrease with increasing height. The spectral characteristics of the wind and the correlation between gusts will also vary across the rotor. There may be relatively discrete low level jets to contend with. Due to the Eckman spiral effect, the average wind direction will also change over the height of the rotor. All these factors will need to be considered in the design process.

Design for special conditions

Over the past 30 years, the design of turbines has focused on sites that can be considered relatively benign. The ideal sites are relatively flat, with minimal surface roughness (trees, buildings etc.) and climatic conditions that are not extreme (i.e. not too hot, too cold, or too humid). Design standards that have been developed are best suited to these types of conditions. As the more benign sites are used up, there will be greater interest in using some of the less benign sites. There will be a need to develop turbines for these conditions and the results of these designs must be incorporated into the standards process.

There is also the need for improved designs for smaller turbines, which would be suitable for isolated network or off-grid applications. The small wind turbine designs of the future should be able to integrate much of the experience of the larger turbines, so they can be easily integrated with the electrical system they are connected to.

Offshore wind energy systems

The offshore resource areas provide a host of new issues to consider, beyond that of turbine size. To some degree, for example, use of large turbines is simplified in the water, since transport of the blades can be done by ship or barge. Similarly, large floating cranes can be constructed for installing and maintaining the turbines.

On the other hand, the marine environment presents many challenges. Waves, and to a lesser extent currents, and in some cases floating ice, are found in the environment where the turbines are to be located and must be considered in the design process. Other topics that are of importance include condition monitoring, integrated system operation and maintenance methods, and corrosion mitigation. A new offshore technology area is just beginning to emerge, namely that of special purpose turbine and support structure designs. These are likely to include floating or semi-submersible concepts for deeper water.

Research and Development Institutions

The main R&D activities in the wind energy sector are undertaken in Europe and the USA. Within Europe, R&D takes place both at the EU level and in individual countries. EU activities are under the auspices of the Directorate General for Transport and Energy (DG TREN) and DG Research. In the US, most R&D is under the aegis of the US Department of Energy (DOE), although some more applied work is supported by state governments. There is also significant international cooperation in wind energy R&D. This cooperation is facilitated through the International Energy Agency. Some other bodies, such as the International Electro-technical Commission (IEC), through its standards process, provide impetus to R&D, but the IEC does not in general undertake R&D on its own. There is also R&D undertaken by industry, but typically the results of such studies are not publicly available. In some cases, R&D is undertaken as part of a national education and research consortium, such as the Danish Academy of Wind Energy. Other countries that engage in wind energy R&D also typically do so under the guidance of a national agency, such as National Resources Canada.

Research expenditures are difficult to quantify. According to the IEA database, US expenditures for wind energy research were approximately US$49 million in 2007, while European expenditures were in the order of US$160 million. The details of R&D budgets for countries are listed in Table 3.1.

Table 3.1: R&D expenditures of IEA countries in 2007

Country	R&D budget 2007 (US$ millions)
Denmark	21.5
Germany	29.2
UK	29.2
US	48.7
Canada	5.5
Hungary	0.1
Ireland	0.1
Italy	4.1
Japan	2.8
Korea	18.1
New Zealand	0.06
Norway	3.5
Portugal	0.4
Spain	10.1
Sweden	1.8
Switzerland	0.8

A study was undertaken to ascertain which groups were performing wind energy research and reporting on it. For this study three conferences from 2007 were considered in detail. These were the conferences of the European Wind Energy Association (EWEA), the American Wind Energy Association (AWEA) and the World Wind Energy Association (WWEA). The papers were categorised according to nationality and company, university or institute of the first author and primary topic of the paper. There were 555 papers presented in these conferences (Figure 3.4). These represented contributions from 316 groups. Of these groups, approximately 41% were from research institutes (13%) or universities (28%). The rest were from manufacturers, consultants, non-governmental organisations or government agencies.

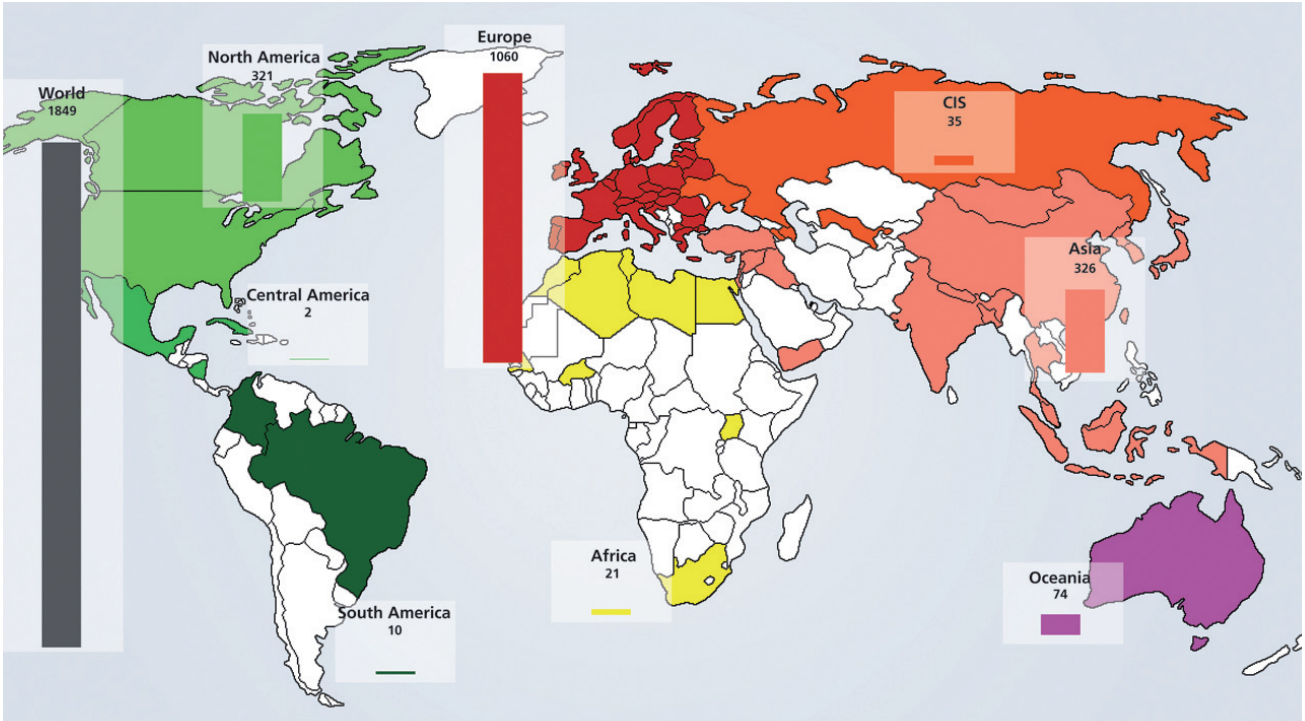


Figure 3.4: Contribution to the wind conferences EWEA, AWEA and WWEA. The total number of authors who contributed to papers presented at the three conferences in 2007 is shown.

From the total papers presented, half came from Europe. The next major contributor was the USA (24%). Within Europe the top five contributors were (in order) Germany, Denmark, Spain, the UK and the Netherlands. Outside Europe and the US, the top five contributors were Japan, India, China, Korea and Canada. Table 3.2 lists the top 14 research centres or universities based on the total number of papers presented in all three conferences mentioned (those with four or more are included).

Table 3.2: Some research institutes and universities engaged in wind energy R&D

Institute	Country
Riso National Laboratory	Denmark
Delft University of Technology	Netherlands
National Renewable Energy Laboratory (NREL)	USA
Renewable Energy National Centre of Spain (CENER)	Spain
Energy Research Center of the Netherlands (ECN)	Netherlands
Institut für Solare Energieversorgung (ISET)	Germany
Technical University of Denmark	Denmark
University of Tokyo	Japan
China Electrical Power Research Institute	China
CIEMAT	Spain
Ecole des Mines de Paris	France
ForWind - Center for Wind Energy Research	Germany
University of Massachusetts. Renewable Energy Research Laboratory	USA
University of Belgrade	Serbia

It is also of interest to see how the topic areas varied by conference. For the total, as can be seen from Table 3.3 below, the top five areas of interest (in order) were: (1) Wind resource, (2) Turbine design, (3) Electrical, (4) Economics and (5) Offshore. At the WWEA (Figure 3.5), the top five topic areas were: (1) Economics, (2) Turbine design, (3) Wind resource, (4) Electrical and (5) Applications. At the EWEA conference, the top five top were: (1) Wind resource, (2) Turbine design, (3) Electrical, (4) Offshore and (5) Operations. Finally, at the AWEA conference the main topic areas were: (1) Economics, (2) Turbine design, (3) Electrical, (4) Social/environmental and (5) Wind resource. These differences are most likely associated with the differing state of wind energy technology implementation in the various parts of the word.

Table 3.3: Summary of topic areas covered by EWEA, AWEA and WWEA conferences.

Topic	Percentage
Wind resource	26.1
Wind turbine design	22.0
Electrical	16.2
Economics and incentives	12.8
Offshore wind energy	6.7
Monitoring and operations	6.3
Applications	3.4
Social/environmental	2.9

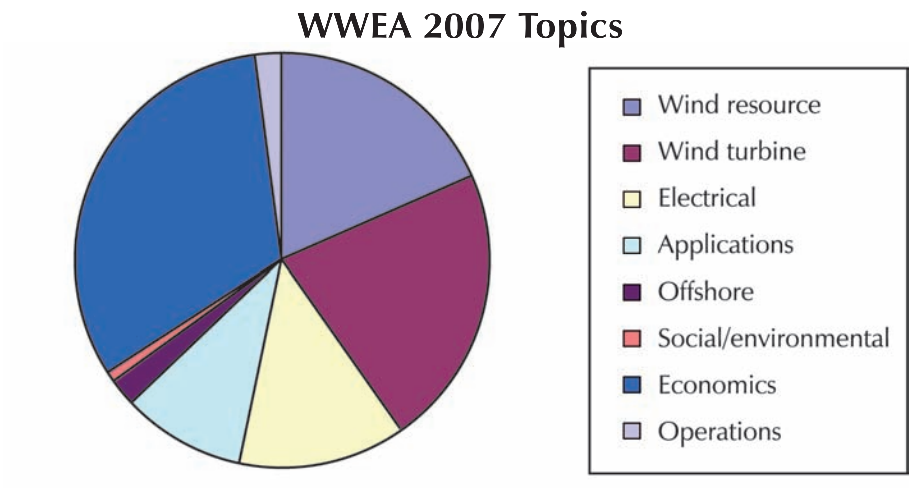


Figure 3.5: Wind energy topics covered during WWEA 2007, Mar del Plata, Argentina (Oct 2007).

Industrial Activities

The majority of the industrial wind energy activity (including both manufacture and installation) in the world is taking place in Europe, followed by the USA and India. Lists of manufacturers can be found in a variety of locations, such as the EcoBusiness links website (www.ecobusinesslinks.com/large_wind_turbines_generators_manufacturers.htm).

Today the world's largest manufacturers are in Denmark, Germany and Spain. The manufacturers with the largest market share as of 2006 (largest to smallest, with nationality in brackets) are: Vestas (Denmark), GE Energy (US), Gamesa (Spain), Enercon (Germany), Siemens (Germany), Suzlon (India), Repower Systems (Germany), Mitsubishi (Japan) and Nordex (Germany). In addition to turbine manufacturers, there is also significant other commercial activity in the wind energy sector. This includes component suppliers (e.g. blades, gearboxes, towers etc.), consultants and developers. Table 3.4 shows the extraordinarily rapid installation of wind capacity in the US and Europe starting in the late 1990s. Europe now accounts for about 75% of installed capacity in OECD countries with Germany and Spain dominating the picture.

Table 3.4: Cumulative Installed wind capacity (MWe) (IEA, 2008c).

	1990	1995	2000	2005	2006
OECD North America	1912	1755	2472	9393	12875
OECD Europe	471	2449	12766	40750	47899
Germany	48	1137	6095	18428	20622
Spain	2	98	2206	9918	11736
OECD/IEA Pacific	0	3	160	2234	2973
OECD Total	2383	4207	15398	52377	63747

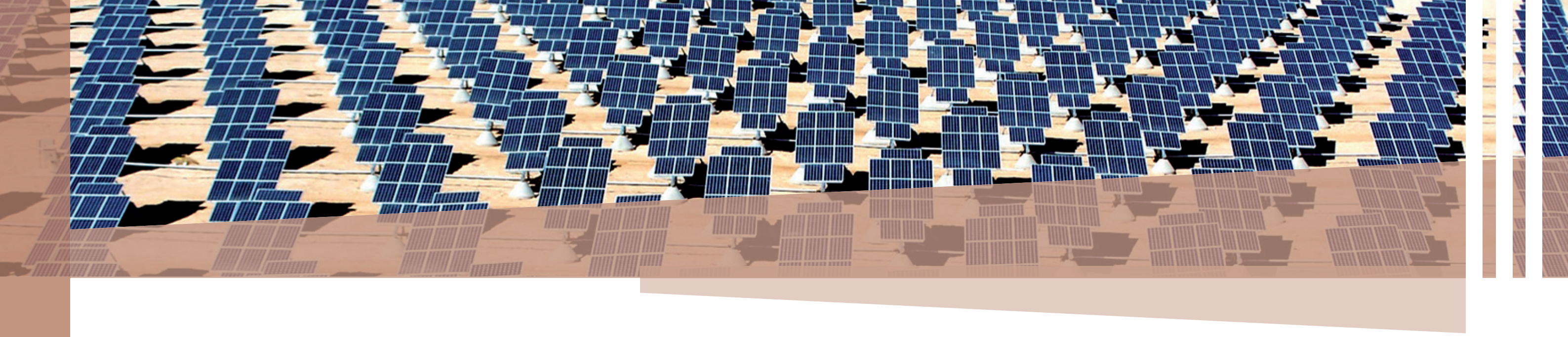
Directions for Future Research and Development

As should be apparent, there are still many areas which could benefit from additional research and development activity. Some of this R&D is already underway. Some effort has already been made by various groups, including the International Energy Agency and the USA DOE to provide recommendations on what should be done in the near future. Some of the R&D possibilities are listed below. They are organised according to the categories used previously. In general, the need for R&D is continuous, and the division between short-term and long-term is somewhat arbitrary. It is clear that short-term R&D will help to advance the technology from where it is today. The medium and long-term will advance it the point where wind turbines can be used in very difficult locations and can provide a very large fraction of the world's energy supply.

Table 3.5: Directions for future research and development in wind energy.

	Short-term (2008-2013)	Mid- and long-term (2013-2030)
Wind Resource	• Improved short-term forecasting • Improved site assessment techniques • Improved remote sensing techniques and devices • Wind flow around turbines and wake characterisation • Regional siting information databases • New remote sensing devices • Wind flow around turbines and wake characterisation	• Improved long-term forecasting • Site assessment techniques integrated with meso-scale numerical models • Impact of wind energy extraction on the micro- and meso-scale climate • Improved turbulence modeling (for inputs to design codes) • Detailed meteorological studies for world's oceans • World siting information databases • Low cost/high resolution remote sensing devices • Multiple large array interactions
Wind Turbine Design	• Investigate intelligent materials • Analyse root cause of reliability issues • Continuous advancement: advanced blades, taller towers, advanced drive trains, improved sensors, controls and structural health management • Investigate nano-materials for blades • Continuous: testing, standards development, certification • Field tests to validate existing structural dynamics codes	• Integral structural intelligence • Incorporate recyclable materials • Implement high reliability systems • Investigate new rotor concepts • Integrate computational fluid mechanics, structural dynamics and material fatigue models in design codes • Apply advanced materials in blades • Develop design standards for deep water offshore turbines • Testing centres for progressively larger components and complete systems
Electrical	• Continuous improvement of efficiency of generators and converters • Improved power quality • Investigate high penetration grid issues • Condition monitoring (CM) • Development of control systems for structural load minimisation	• New generator concepts • Electric load flow control and adaptive loads • Fully integrate distributed generation, load management, fuel production • Transmission options for far offshore turbines • Integrate CM with system health management
Economics/ Incentives	• Analysis of existing policy mechanisms	• Improved incentives and financing, both for developed and developing countries

	Short-term (2008-2013)	Mid- and long-term (2013-2030)
Offshore Wind Energy	• Establish design basis for offshore wind turbines • Investigate fundamental design issues for larger offshore turbines • Continuous: marine environment studies (oceanographic, biological, metocean design conditions) • Study wind characteristics within large offshore arrays	• Support structures for progressively deeper water • Design codes for wind/wave/ large flexible structure interactions • Modelling and prediction of winds/ waves/ currents in deep water • Advanced offshore operation and maintenance techniques • Deep water environmental issues • Very large turbines for offshore
Monitoring and Operations	• Designs for reliability • Improved access methods, especially for offshore	• Integrated condition monitoring, structural health management • Robotic maintenance for offshore
Applications	• Redesign small/medium size turbines to apply large turbine experience • Design systems for high penetration reliability • Investigate special purpose applications (e.g. desalination, hydrogen)	• Develop 'plug and play' hybrid power systems • Develop storage and fuel production for isolated networks • Perfect special purpose applications (e.g. desalination, hydrogen)
Social / Environmental	• Comparative environmental studies (e.g. local impacts vs. regional benefits) • Public engagement and involvement in land-use planning procedures	• Sound reduction and cancellation • Telecommunications and radar issues • Aesthetic integration of turbines into landscape • Potential impacts on plants and wildlife in general



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List of Abbreviations

AWEA	American Wind Energy Association
BoS	balance of system
CHP	combined heat and power
CIGS	cadmium, indium, gallium (di)selenide
CO_2	carbon dioxide
CPV	optically concentrating PV
DOE	US Department of Energy
EU	European Union
EWEA	European Wind Energy Association
GDP	Gross Domestic Product
GEF-STAP	Global Environmental Facility - Scientific and Technical Advisory Panel
GJ	gigajoule (10^9 Joule or 0.27 MWh)
ha	hectare
IEA	International Energy Agency
IEC	International Electro-technical Commission
IPCC	Intergovernmental Panel on Climate Change
JPY	Japanese yen
kg	kilogram (10^3 gram)
kl	kilolitre (10^3 litre)
kV	kilovolt (10^3 Volt)
kWe	kilowatt electric (10^3 Watt)
NL	The Netherlands
m	metre
Mtoe	millions of tonnes oil equivalent
MWe	megawatt electric (10^6 Watt)
MWth	megawatt thermal (10^6 Watt)
OECD	Organisation for Economic Co-operation and Development
Si	silicon
SOG-Si	solar grade silicon
t	tonne
TWh	terawatt hours
UMG-Si	upgraded metallurgical silicon
US	United States of America
USD	US dollar
USDA	US Department of Agriculture
V	volt
VGB	Verein für Grosskraftwerk Betreiber (Association of Large Power Plant Operators)
W	watt
WWEA	World Wind Energy Association
yr	year

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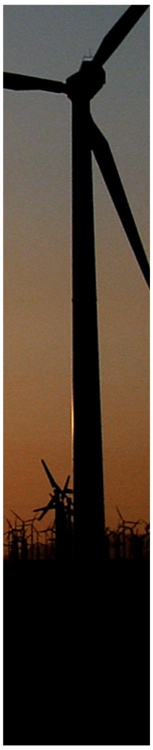

ISPRE

International Science Panel on Renewable Energies