ICTSD Programme on Trade and Environment

Mapping Climate Mitigation Technologies and Associated Goods Within the Renewable Energy Supply Sector

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Acknowledgement/Preface

This study provides an analysis of the state-of-the-art of renewable energy technologies not only to reduce greenhouse gas emissions but particularly to develop into mainstream technologies for industrialised and developing countries alike. The study was performed on behalf of and in close cooperation with the International Centre for Technological Development and Trade (ICTSD), in particular with Mahesh Sugathan.

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Abstract

On behalf of and in close cooperation with the International Centre for Trade and Sustainable Development (ICTSD) (Switzerland), this study analyses the state-of-the-art of renewable energy (RE) technologies not only to reduce greenhouse gas emissions, but particularly to develop into mainstream technologies for industrialised and developing countries alike. In order to give a broad view of technologies that are (becoming) commercially available today as well as technologies that need 5 to 10 years before commercialisation, the technologies of interest were listed and characterised in accordance with ICTSD. This was accomplished with the goal of detailed mapping studies in order to enable ICTSD to identify issues related to international trade. In general, a large number of renewable energy technologies show high grow rates and corresponding cost reductions. However, there are also several renewable energy technologies that need another 5 to 10 years before they may become commercial. Even then, some renewable options may not yet be commercial, as they are still in a very early stage of R&D or lack sufficient government R&D spending until this date. Besides renewable energy options, also a few options for electricity storage and some options of CO_2 capture and storage (CCS) are shortly addressed.

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Summary

This study presents an overview of climate-mitigation technologies/goods within the energy supply sector, focusing on renewable energy technologies. The study was instituted by the International Centre for Trade and Sustainable Development (ICTSD). These energy supply technologies/goods not only offer substantial perspective for reduction of greenhouse gas (GHG) emissions, but are also suitable to develop into mainstream technologies for industrialised and developing countries alike. In order to give a broad view of technologies that are commercially available today as well as technologies that need 5 to 10 years before commercialisation, the technologies of interest were listed in accordance with ICTSD.

In September 2007, IPCC's Working Group III published a report on *inter alia* energy supply technologies, with the aim to assess the potential of options for mitigating climate change. Several aspects link climate change with development issues. The report explores these links in detail, and illustrates where climate change and sustainable development are mutually reinforcing. Pacala and Socolow (2004) published the article 'Stabilization wedges: solving the climate problem for the next 50 years with current technologies'. Their focus is global reduction of GHG emissions. They distinguish various appropriate options or technologies that may provide 'wedges' to reduce emissions of GHGs. A wedge is defined as a technology or group of technologies that enable a GHG emissions reduction of 1 GtC-eq/yr[1] (giga-tonne carbon equivalent per year) by 2054, starting from zero in 2004. Cumulatively - based on a linear development - a wedge would equate 25 GtC. On a global scale, wind may reduce GHG emissions by 1,000 MtC (1 GtC) per year in 2050. The same approximately holds for photovoltaic power.

Many renewable energy (RE) technologies are currently commercially available or just starting to be applied on a more or less commercial base, e.g. in demonstration projects followed by diffusion to the market. Other RE technologies are still less mature and deserve perhaps another 5 to 10 years before commercialisation (or less than that in case of concerted action by governments and private companies). Starting with commercially available technologies, *concentrating solar power* (CSP) or 'solar thermal power' has been around for about 25 years (with a combined capacity of approximately 400 MW_e) and is just now gathering momentum as a 'new' RE technology. Another 400 MW_e are under construction and 6 GW_e is in the stage of planning. There are two technologies that are relatively mature, viz. solar trough and solar tower systems. These are still further developed in conjunction with a number of commercial plants that are built or planned. Two other technologies are less mature, viz. solar dish (based on Stirling engine) and Fresnel-lens based CSP. These technologies are advancing fast, which is facilitated by the favourable financial incentives for such CSP plants in Spain, the USA, and a number of other countries.

Solar heating and cooling in the built environment, particularly solar heating for hot water in dwellings and offices (reducing the amount of fossil energy needed for water heating by 40 to 50%), becomes a mainstream RE technology. Used predominantly for hot water and space heating, solar thermal collectors are typically mounted on roofs of buildings, and as solar thermal installations are quite visible, this has lead to developments in both technology and architecture. The maturity of this technology is witnessed by steady growth in collector area in both industrialised countries (e.g., the EU, which mainly uses flat plate collectors) and developing countries (e.g., China, which mainly uses evacuated tube collectors).

Photovoltaic power (PV) is used for grid-connected systems and off-grid systems (the latter predominantly in developing countries). PV is based on photovoltaic modules (based on PV

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[1] 1 GtC is equivalent to 3.664 Gt CO_2.

cells) and the balance of system (BOS) which includes *inter alia* the inverter, battery, electronics, and other components. PV is experiencing high growth rates in Europe (Germany, Spain), Japan, and the USA. As a consequence, costs are in general coming down correspondingly. China is emerging as a dynamic solar manufacturing industry, and also India shows a relatively fast transition. The technology is becoming more diverse, with various options of silicon, thin-film and other forms of PV cells. Thin-film PV could grow ten-fold from 250 MW_e per year to approximately 2 GW_e per year in 2010 with a market size of US$ 5 billion. Developing countries including emerging economies like China and India are becoming significant producers of PV cells and modules.

Wind energy is now a mainstream technology. In 2007, investments in on- and offshore wind amounted to an estimated € 27.5 billion. There are several 'multinational' wind turbine manufacturers, but also a number of wind turbine manufacturers that have a more regional (e.g., European) scope. Wind turbines consist of various components like blades, gearbox, generator, etc. Numerous original equipment manufacturers (OEMs) produce the aforementioned components. The production of wind turbines and wind turbine components is becoming more and more international, with two Chinese and one Indian wind turbine manufacturer in the global 'top 10' based on commercial production capacity. Know-how with regard to (onshore) wind turbine manufacturing is spreading fast. With regard to offshore wind, much experience exists in a number of European countries. However, also the USA and a number of other countries in South East Asia are developing offshore wind farms.

With respect to *ocean energy technologies*, wave power and tidal stream power technologies are entering the commercial stage. At least four *wave power* technologies are being developed and demonstrated with the medium-term perspective of commercial application. These are deemed to be in the pre-commercial stage. They are being demonstrated in EU countries such as Portugal, England and Scotland with a favourable Atlantic wave climate[2]. Also, there is much interest in wave power from the USA and countries in South East Asia. Besides tidal range power (based on a barrier) which is already relatively mature, there are (at least) three *tidal stream power* technologies in stages of R&D and demonstration. It is likely that these technologies may become commercial in the same timeframe as wave power. Interest in tidal stream power is not limited to Europe, but is also apparent in North America and elsewhere.

For *geothermal energy*, there are three main applications, viz. power generation, direct heat, and ground source heat pumps. Commercial *geothermal power* plants range from those based on dry steam to organic Rankine cycle (ORC). Concepts relating to deep geothermal heat and small-scale applications are under development, with prospects for rapid commercialisation. *Direct use of heat* for buildings and industry is a commercial technology. *Ground source heat pumps* (using shallow geothermal heat) are experiencing a fast growth and cost reduction.

With regard to *hydro power*, a distinction is made between large (>10 MW_e), small (1-10 MW_e), and micro (<1 MW_e) hydro power. Where expansion of large hydro power is occurring, major social disruptions, ecological impacts on existing river ecosystems and fisheries and related evaporative water losses are stimulating public opposition. Land-use and environmental concerns may mean that obtaining resource permits is a constraint. Hydro power is commercial, although there is still significant development potential for micro hydro. Large hydropower turbines and other components are manufactured in Europe (Voith Siemens, Alstom), the USA (GE), Canada, China, India, and other countries. The manufacturing base for small hydro power turbines is broader, encompassing the OECD, FSU, China, India, Brazil, and others.

Biomass is currently the most important renewable energy source in terms of primary energy supply on a global scale. There is much experience with commercial medium- and large-scale biomass-based combustion systems to produce power and heat and combined heat and power

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[2] The wave climate is determined inter alia by the latitude and the prevailing winds at that latitude.

(CHP). Also, gasification systems for power and CHP are developing into the commercial stage, at least on a medium scale. They are being used in industrialised and developing countries alike. Anaerobic digestion of wet biomass streams is also commercially available in many (e.g., agricultural) applications. As these applications increase, the technologies become more competitive, with the biogas being used for small-scale power generation, CHP, etc. In addition to more or less established applications of biomass, the production of so-called first-generation biofuels mainly for transportation (vehicles) is gaining momentum in numerous countries around the globe. Some technologies offer prospects to become main second-generation technologies for biofuels, making use of ligno-cellulosic biomass, though these remain mainly at the RD&D stage with some pilot-plant and pre-commercial scale demonstrations in place or under development.

There are several RE (and other) technologies that are largely in the R&D stage, but have strong prospects of near to medium term deployment in 5-10 years from now. These are:

- Solar heating with seasonal storage (in the shallow underground) and solar cooling
- PV systems based on modules with nanotechnology-based PV cells
- Floating offshore wind
- Ocean thermal energy conversion (OTEC)
- Salinity gradient based power
- Small-scale geothermal power
- *Hot dry rock* (HDR) geothermal power
- Biomass integrated gasification combined cycle (BIGCC)
- Pyrolysis of biomass
- Torrefaction of biomass
- Cellulosic ethanol
- Second generation biodiesel and algae
- Di-methyl ether (DME) from biomass
- Biorefinery.

Many of these technologies may be commercial before or soon after 2015. It has been noted that concerted action of governments and private companies in the stages of research, development, and demonstration may shorten the period until commercialisation. Some technologies may take a longer period of time for commercialisation as they are still in a very early stage of R&D or lack sufficient government R&D spending until this date. Technologies related to electricity storage, which may become important for renewable electricity generation, are in different stages of development, demonstration, and market introduction. Also, there are some options of CO_2 capture and storage (CCS) that deserve support from governments in the R&D stage and for demonstration.

1. Introduction

This study presents an overview of climate-mitigation technologies/goods within the energy supply sector, focusing on renewable energy technologies. The study was instituted by and performed in close cooperation with the International Centre for Trade and Sustainable Development (ICTSD) in Switzerland. The study includes:

- An overview of the key findings of the Working Group III report (IPCC, 2007) of the IPCC (Intergovernmental Panel on Climate Change) with regard to mitigation measures within energy supply sector. In addition, this Chapter (Chapter 2) also provides an overview of the 'wedge' approach as proposed by Pacala and Socolow (2004) as pertaining to renewable electricity and fuels where the GHG mitigation efforts would yield results.
- A characterisation of the critical goods and technologies related to renewable energy within the energy supply sector that would be relevant to climate change mitigation that have already been commercialised or are pending immediate commercialisation. This characterisation may be useful for the ICTSD because of its relation with trade issues. A short technical description of these goods is provided (Chapter 3).
- A broad description of types of energy supply technologies/goods that would be relevant to climate change mitigation under each sector where significant public or privately-funded research initiatives are already underway and there is a strong likelihood that the technologies will be commercially deployed within a reasonable time horizon of 5-10 years (Chapter 4).

Figure 1.1 presents the stages of R&D, demonstration, and commercialisation of technologies, based on (EPRI, 2007). Commercialisation will generally start when the technology is mature. In the footnote below the Table, the position of nano-structured PV in the Figure is explained.

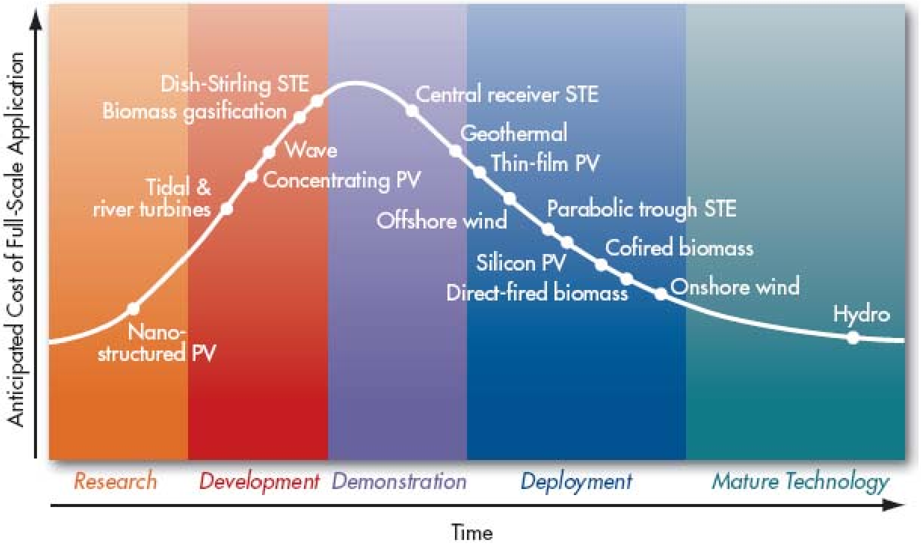

Figure 1.1 *Stages of R&D, demonstration, and commercialisation of RE technologies*

Note: The example of nano-structured PV may be used to explain this Figure. Nowadays, the technology is at the research stage. After this stage, the technology will enter the development stage, which will require a higher financial investment, and after that the demonstration stage which may be even more costly in terms of overall investments. Then, the technology will 'come down the hill', and become more and more competitive when being deployed. At the end, nano-structured PV may become competitive (2015-2020?).

Source: EPRI, 2007.

In Chapter 2, the focus is on characteristics of renewable energy (RE) technologies based on the IPCC Fourth Assessment Report (IPCC, 2007). Chapter 3 gives an in-depth overview of commercially available RE technologies, and their medium term prospects. Chapter 4 focuses on RE technologies that are largely in the R&D stage, but have strong prospects of near to medium term deployment, notably in a period of 5-10 years from now. This aims to determine a probable timeframe for commercialisation of the technologies. Appendix B provides a *disaggregation of the main components* of RE technologies (climate mitigation goods) available on a commercial basis of Chapter 3. Likewise, Appendix C provides such a *disaggregation* for RE technologies undergoing R&D with strong prospects for commercialisation based on Chapter 4. Appendix D provides a brief overview of technologies for electricity storage in various stages of development. Finally, Appendix E gives a comparable view of CCS technologies in the stages of RD&D.

2. Overview of Findings of IPCC Working Group III on Energy Supply for Mitigation and the ‘Wedges’ Analysis

2.1 Introduction

In September 2007, IPCC’s Working Group III published a report (IPCC, 2007) on *inter alia* energy supply technologies, with the aim to assess the potential of options for mitigating climate change. Several aspects link climate change with development issues. This report explores these links in detail, and illustrates where climate change and sustainable development are mutually reinforcing.

The report covers the following subjects:
- Issues related to mitigation in the long-term context
- Energy supply
- Transport and its infrastructure
- Residential and commercial buildings
- Industry
- Agriculture
- Forestry
- Waste management
- Mitigation from a cross-sectoral perspective
- Sustainable development and mitigation
- Policies, instruments and cooperative agreements
- Gaps in knowledge.

Section 2.2 addresses the Chapter on ‘Energy supply’ in IPPC’s Working Group III report, and 2.3 provides (a) a concise overview of an article by Pacala and Socolow on ‘stabilization wedges’ in 2004 (in ‘Science’) and (b) a view on the greenhouse gas (GHG) emissions reduction potential of renewable energy technologies, which are described and characterised in the present study.

2.2 Energy supply

With regard to the global availability of renewable energy sources (a subject with relevance for this study), IPCC Working Group III report gave an overview (Table 2.1). The main renewable energy sources used today are biomass (aggregated share of traditional and modern biomass to world’s primary energy supply in 2004: 9.4%) and hydropower (share 5.3%). Three renewable energy sources have a global theoretical potential in excess of the world’s current total energy use of approximately 500 EJ/year, viz. solar energy (PV), geothermal energy, and wind (Table 2.1). Thus, the availability of renewable energy on a global scale is abundant. There are, however, a few drawbacks if ‘renewables’ would be exploited on a massive scale:
- Most renewables are not uniformly distributed around the globe: geothermal energy for example (with the exception of ground-source heat pumps) can only be used economically in regions with a geothermal gradient that is above-average.
- Some renewables like wind and solar PV are variable by nature, which limits their possible share in electricity generation, unless a flexible power supply system, possibly including economically competitive energy storage is available.
- Some renewables are still in an early stage of development, and are relatively expensive.
- Several renewables have environmental constraints (Table 2.1).

Although the theoretical potential of renewables does not pose a problem in view of the current and envisioned worldwide energy demand, the development and large-scale application of renewable energy technologies is not without difficulty, leading to a much smaller market potential. In the short term, economic problems may prevail, e.g. with regard to financial support for market introduction and sustained growth. In the longer term, environmental issues may surface that are not so evident in the early stage of development. For instance, the potential contribution of onshore wind may be constrained by (perceived) visual obtrusion, particularly in landscapes characterised by natural beauty.

Table 2.1 *Generalised data for global renewable energy resources*

Renewable energy source	Estimated energy resource [EJ/year]	Rate of use in 2005 [EJ/year]	% of primary energy supply 2005 [%]	Comments on environmental impacts
Hydro (>10 MW)	60	25	5.1	Land-use impacts
Hydro (< 10 MW)	2	0.8	0.2	
Wind	600	0.95	0.2	
Biomass (modern)	250	9	1.8	Land-use for crops
Biomass (traditional)		37	7.6	Air pollution
Geothermal	5,000	2	0.4	Waterway contamination
Solar PV	1,600	0.2	<0.1	Toxics in manufacturing
Concentrating solar power (CSP)	50	0.03	0.1	Small
Ocean (all sources)	7 [a]	<1	0	Land and coastal issues

a Exploitable energy resource.
Source: IPCC, 2007.

The IPCC report states that in areas where the industry is growing, many sites with good wind, geothermal, biomass, and hydro resources have already been utilised. Nevertheless, the potential of PV, geothermal energy, and wind on a global scale is far from fully exploited. Therefore, the main issue is to put in place sufficient financial incentives to support market introduction and sustained growth of renewables. The IPCC report stresses that the cost of renewable energy technologies comes down with increased cumulative capacities installed (learning curve). Therefore, financial support for technologies that are becoming more mature like wind energy may be reduced over time. And gradually, financial support may be shifted to those technologies that are still in an early stage of market introduction like solar PV and ocean energy.

The IPCC report signals that there has also been increasing support for renewable energy deployment in developing countries, not only from international development and aid agencies, but also from large and small local financiers with support from donor governments and market facilitators to reduce their risks. As one example, total donor funding pledges or requirements in the Bonn Renewables 2004 Action Programme amounted to around US$ 50 billion. The total investment in new renewable energy capacity in 2005 was $ 38 billion, excluding large hydro power (defined below), which represented $ 15-20 billion. A recent estimate (REN21, 2008) for the global investment in renewable energy (including large hydro power) is $ 71 billion in 2007.

With regard to renewable energy sources, Table 2.2 provides a brief overview of the state of the art of renewable energy sources. The Table shows that some renewable energy sources are (partly) commercial, others are (partly) deployed and a few others are still largely in the stage of research, development, and demonstration (RD&D).

Table 2.2 *State of the art of renewable energy sources*

Renewable energy source	Conversion technology	Operational capacity 2007 [MW_e / MW_{th}]	Stage of development	Main trends
Concentrating solar power (CSP)		354 [a]	Deployment	Renewed interest with accelerating growth
Solar heating & cooling			Commercial (partially)	Rapid commercialisation
Photovoltaic power (PV)		9,100	Deployment (partially)	Rapid growth
Wind energy		90,520	Largely commercial	Rapid commercialisation
Ocean energy	Tidal range	260	Deployment	Feasibility investigated (UK)
	Tidal stream	< 5	Demonstration	Early deployment
	Wave power	< 5	Demonstration	Early deployment
	Ocean thermal energy conversion (OTEC)		R&D	Needs demonstration
	Saline gradient		R&D	Needs further R&D
Geothermal energy	Geothermal power	8,590	Commercial (partially)	Small-scale and deep geothermal needs R&D
	Geothermal heat	15,145 [b]	Commercial	Further growth
	Ground-source heat pump		Deployment	Rapid commercialisation
Hydro power	Mini hydro (< 1 MW_e)	~73,000[a]	Commercial	Further growth
	Small hydro (1-10 MW_e)			
	Large hydro (> 10 MW_e)	~870,000[a]	Commercial	Further growth
Biomass	Combustion	> 9,700	Commercial (partially)	Rapid commercialisation
	Gasification		Deployment (partially)	Needs further RD&D
	Digestion		Commercial (partially)	Rapid commercialisation
	Biofuels		Deployment (1st generation)	Needs further RD&D (2nd generation)

a At the end of 2006.
b At the end of 2000.

2.3 'Stabilization wedges'

Pacala and Socolow (2004) published the article 'Stabilization wedges: solving the climate problem for the next 50 years with current technologies'. Their focus was global reduction of GHG emissions. Therefore, they distinguish various appropriate options or technologies, viz.:

- Improve fuel economy
- Reduced reliance on cars
- More efficient buildings
- Improved power plant efficiency
- Decarbonisation of electricity and fuels
- Substitution of natural gas for coal

- Carbon capture and storage
- Nuclear fission
- Wind electricity
- Photovoltaic electricity
- Biofuels.

These options or technologies may provide ‘wedges’ to reduce emissions of GHGs. A wedge is defined as (group of) technology/technologies that enable a reduction of GHG emissions equal to 1 GtC-eq/yr (giga-tonne carbon equivalent per year) in 50 years from 2004. Cumulatively - based on a linear development - a wedge would equate to 25 GtC.

Furthermore, they take consider two options that are available to use natural sinks of CO_2, viz.:

- forest management,
- agricultural soils management.

They consider that these two options are already available at large scale but could be scaled up.

The potential for reduction of GHG emissions of these options and technologies is reviewed. A view is given on the potential for GHG emissions reduction of wind and photovoltaic power, examples of renewable energy technologies that are currently growing very fast.

2.3.1 Decarbonisation of electricity and fuels

Shifting from coal to gas

Carbon emissions per kWh of electricity are half as large for power plants based on natural gas compared to plants based on coal. In order to realise one wedge, the amount of gas-fired power (substitituted for coal-fired power) should be should be four times as large as the total current gas-based power.

Carbon dioxide capture and storage

One wedge is achieved by providing CCS at 800 GW_e of baseload coal-based power plants or 1600 GW_e of natural gas based power.

Nuclear fission

Adding 700 GW_e (twice the current capacity) of *nuclear capacity* equates to one wedge, though issues involved are nuclear proliferation, terrorism, safety, and nuclear waste treatment and storage.

Wind energy

A wedge is achieved by about 2,000 GWe of wind power capacity displacing coal-based power by 2054.

Photovoltaic electricity

Similarly, *photovoltaic electricity* may be used to significantly reduce GHG emissions. A wedge is achieved by about 2,000 GW_e of photovoltaic power displacing coal-based power in 2054.

Biofuels

Shifting to biofuels for transportation by production of 34 million barrels per day of ethanol to replace gasoline in 2054 avoids emissions of 1 GtC (though this is very dependent on the source of biomass feedstock and the conversion process).

2.3.2 GHG emissions reduction potential of renewable energy technologies

With a view on the ‘Stabilization wedges’ of Pacala and Socolow, the potential of wind and photovoltaic power to reduce GHG emissions is briefly addressed below.

Wind energy

Roadmaps for the development of wind power in Europe and the USA have been made by the European Wind Energy Technology Platform (TPWind, 2008), and the US Department for Energy (DoE, 2008), respectively. The roadmaps project a total wind capacity of approximately 300 GW_e in Europe in 2030, and approximately 305 GW_e in the USA. Although the European Wind Technology Platform is not a government organisation, it is striking that their projection for Europe’s wind capacity in 2030 is almost equal to that of the US Department of Energy for the USA. This seems to indicate that the European Platform’s projection is rather solid. The proportion between onshore wind and offshore wind is straightforward for the USA, but less clear-cut for the EU27:

- In 2030, onshore wind in the USA could stand at 255 GW_e, and offshore wind at 55 GW_e.
- In 2030, onshore wind in the EU27 could stand at 185 GW_e, and offshore wind at 115 GW_e.

It is assumed that from 2030 onwards the total wind capacity in the EU27 will grow by 25% until 2050, ending up at 375 GW_e. For the USA, a similar growth of 25% until 2050 is assumed, resulting in approximately 382 GW_e in 2050. For the rest of the world (ROW), the following is assumed:

- Wind in ROW will grow proportionally to the USA, with a capacity of 167 GW_e in 2030. After 2030, growth is assumed to decline, with a capacity of 1,023 GW in 2050.
- The ratio between on- and offshore wind in ROW is presumed equal to that of Europe.

Based on these assumptions, a possible development of wind power in the EU, the USA, and the rest of the world can be assessed (Figure 2.1). The total wind capacity (onshore and offshore) could be up to 960 GW_e in 2030 and possibly 1,780 GW_e in 2050.

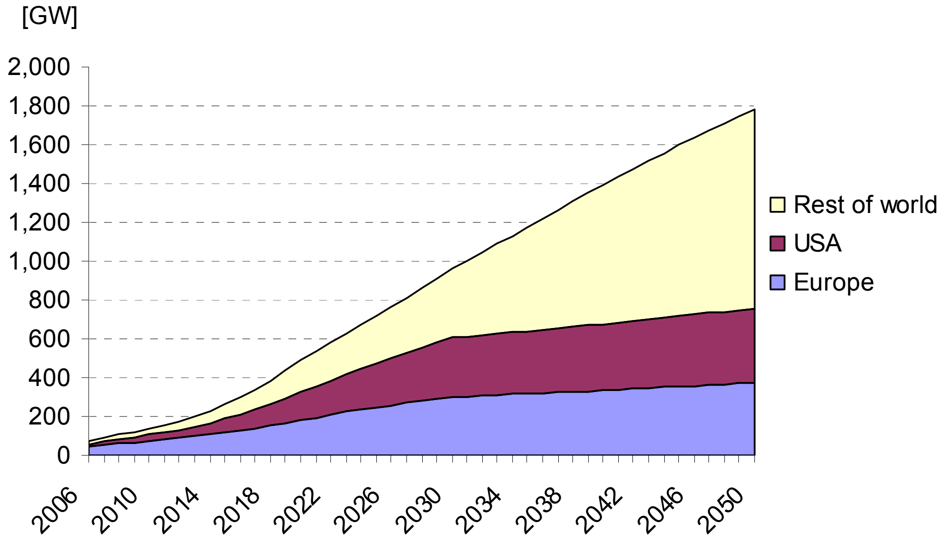

Figure 2.1 *Possible development of global wind capacity until 2050 based on projections for the EU and the USA up to 2030*

Sources: TPWind, 2008; DoE, 2008.

Electricity generation based on wind may amount to 2,945 TWh in 2030 and 5,235 TWh in 2050. (DoE, 2008) assumes that one wind TWh is equal to a GHG emission reduction of 0.7 Mt

CO_2. Based on this assumption, wind power could have a GHG emission reduction potential of 1 Gt C in 2050 (Figure 2.2) if substituting for coal-fired power.

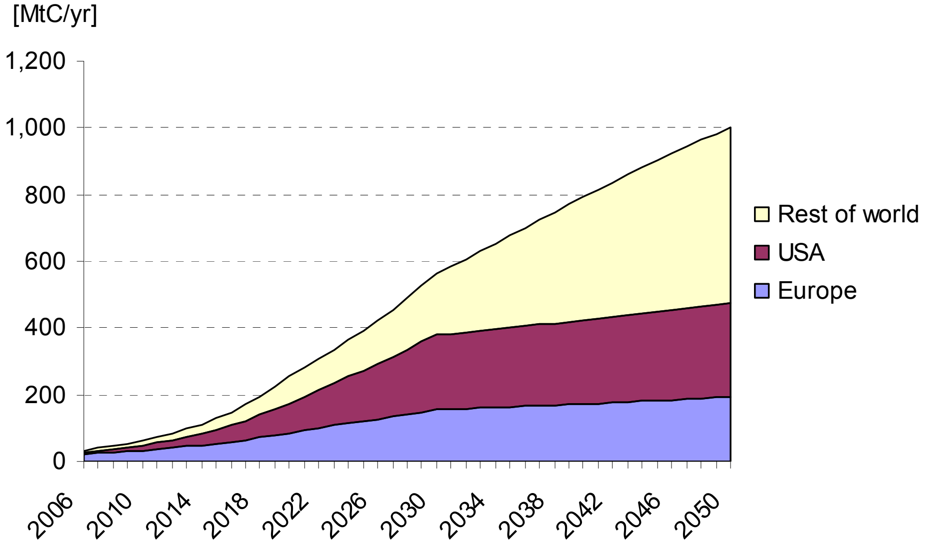

Figure 2.2 *Possible development of GHG reduction from wind power until 2050 based on projections up to 2030*
Sources: TPWind, 2008; DoE, 2008.

Wind may reduce GHG emissions by 1 GtC/yr in 2050, which means that the assumption of Pacala and Socolow (2004) with respect to wind may prove to be correct.

Photovoltaic power
There are a few global scenarios, e.g., (EREC, 2007) and - to a lesser extent (with more focus on Europe) - (EPIA, 2008). Without too much detail about growth rates in world regions until 2050 (to 2012 for EPIA), Figure 2.3 gives an idea of the global potential of PV, in particular until 2050, based on the study of EREC/Greenpeace (2007) giving a global PV capacity of approximately 2,030 GW in 2050.

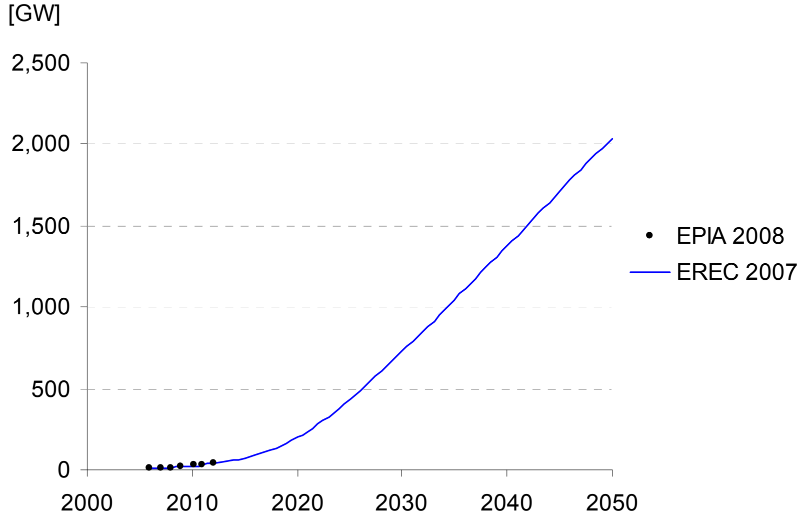

Figure 2.3 *Possible development of global PV capacity until 2050 based on (EREC, 2007)*
Sources: EPIA, 2008; EREC, 2007.

In order to achieve the GHG emissions reduction that is equal to one wedge (1 GtC per year in 2050) it seems that besides photovoltaic power also an additional, albeit relatively small, amount of concentrated solar power or CSP has to be assumed. CSP is an alternative to PV in regions with a high direct insolation. Figure 2.4 shows the solar power generation corresponding with one wedge (GHG emissions reduction of 1 GtC per year in 2050). Just as has been explained for on- and offshore wind in the present study (Figures 2.1 and 2.2), the power generated in 2050 could exceed 5,000 TWh which is deemed equal to one wedge (1 GtC emission reduction in 2050). This short analysis confirms that the assumption of Pacala and Socolow with respect to photovoltaic power is plausible.

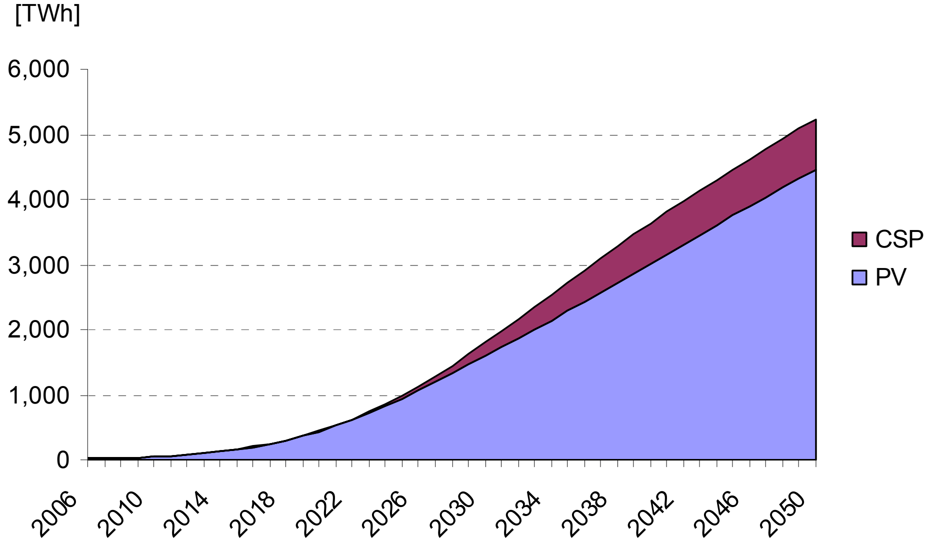

Figure 2.4 *Possible power generation based on PV and CSP until 2050 corresponding with one wedge (1 GtC per year of GHG emission reduction in 2050)*

Note: It was assumed that CSP makes up for the deficit that would arise if the 2,030 GW of PV according to EREC (2007) would be installed in 2050.

Sources: EPIA, 2008; EREC, 2007.

3. Key mitigation technologies/goods within the energy supply sector that are commercially available

3.1 Introduction

This Chapter sets out to provide an overview of 'key mitigation technologies/goods within the energy supply sector that are commercially available'. This description is specified as follows:

- *Technologies (or goods) are assumed to be commercially available if they are mature or if they are in the pre-commercial stage after having been demonstrated.* This specification is meant as a demarcation from technologies that are currently not mature, viz. assumed to become commercially available about 5-10 years from now: Chapter 4. It is acknowledged that this demarcation is not straightforward. Some technologies may be in the demonstration stage, but are hampered by economic feasibility and may therefore not be commercial on short notice. Other technologies may not yet be considered as commercial or sufficiently demonstrated and still turn out to enter the commercial stage within a couple of years.
- Technologies that are covered in this Chapter are renewable energy technologies:
    - Solar energy
    - Wind energy
    - Ocean energy
    - Geothermal energy
    - Hydro power
    - Biomass.

For renewable energy technologies several categories of potentials are used. These categories may be explained for hydro power:

- The (gross) theoretical potential based on computations of the potential of water flows, without taking into account technical, economical, and environmental constraints.
- The technically feasible potential or the net exploitable potential is the amount of hydro power that can be developed from a technical point of view. The technical potential does not consider economic or environmental factors that may curtail the potential.
- The economically feasible potential is the amount of hydro power that could be developed based on economical constraints like competition with fossil fuel based power generation including the price of CO_2 emissions. Environmental constraints are not considered.

A short overview of the technologies of interest and their current geographical base is given in Section 3.2, followed by the state-of-the-art of renewable technologies with a focus on technological characterisation and disaggregation in Section 3.3, and an overview of the current and future (2020) cost of renewable energy for power generation and biofuels in Section 3.4.

3.2 Technologies of interest: an overview

The six main categories of renewable energy technologies - solar, wind, ocean, geothermal, hydro, biomass - may be disaggregated into components (Table 3.1). The Table shows in which world regions the respective technologies have been applied to a significant extent or only marginally. *Now*, a characterisation is given of the technologies of interest and their applications:

- Solar energy
    - Solar thermal power (CSP) is a group of technologies making indirect use of solar energy (in contrast with solar PV) for power generation, based on mirrors or on the so-called Fresnel lens. Mirror-based CSP plants have been built and are operated particularly in the USA and Spain, and are under construction in, e.g., Morocco.

Table 3.1 *Overview of renewable energy technologies in the (pre-)commercial stage and worldwide application (X = significant; M = marginal)*

Energy source	Main application	Technology/Good	Europe	North America	Former Soviet Union	Middle East	China	India	Other Asia and Pacific	Latin America	Africa
Solar	Solar thermal	Solar concentrator, mirror based	X	X							X
		Fresnel lens based									
	Solar heating & cooling	Heating: hot water & room heating	X	X	(M)	X	X	X	X	(M)	(M)
		Cooling									
	Photovoltaic power (PV)	Current types of PV	X	X	(M)	X	X	X	X	(M)	(M)
		Thin-film based	X	X				X	X		
Wind	Onshore wind		X	X	X	X	X	X	X	X	X
	Offshore wind		X								
Ocean	Wave power	Pelamis energy converter	(M)								
		Other, e.g. Archimedes Wave Swing	(M)	(M)				(M)			
	Tidal power	Tidal barrier	X	X							
		Tidal stream	(M)	(M)							
Geothermal	Geothermal power		X	X			X		X	X	X
	Geothermal heat		X	X	X		X	X	X	X	
	Geothermal heat pump		X	X					X		
Hydro power	Hydraulic turbines	Less than 1 MW	X	X	X	X	X	X	X	X	X
		1-10 MW	X	X	X	X	X	X	X	X	X
		In excess of 10 MW	X	X	X	X	X	X	X	X	X
Biomass	Biomass-based power/heat	Combustion	X	X	X		X	X	X	X	X
		(Small-scale) gasification	X	X			X	X			
		Digestion (anaerobic)	X	X	X	X	X	X	X	X	X
		Co-combustion/co-gasification	X	X			X	X			
	First-generation biofuels	Pure Plant Oil (extraction)	X	X			(M)	(M)	(M)	(M)	(M)
		Bio-ethanol	X	X			X		X	X	
		Bio-diesel	X	X			X	X	X	X	(M)

Note: In some regions, application of specific technologies is marginal until this date, which is denoted by (M).

  - Solar heating for hot water is becoming widely applied in OECD countries, China, India, and other world regions. Solar heating for room heating and solar cooling are in the pre-commercial stage and therefore addressed in Chapter 4.
  - Photovoltaic power (PV) directly converts solar energy into electricity on a modular scale (Watts, kWs). The technology is becoming more and more mature and is gaining a foothold in OECD countries, and to a lesser extent - because of its relatively high cost until this date - in other world regions, although solar home systems are becoming a mainstream technology in developing countries.
- Wind energy
  - Onshore wind is being applied (on a significant scale) in Europe, the USA, India, and China. This technology may be disaggregated into a number of main components, viz. blades, gearbox, generator, tower, etc. Onshore wind turbines are also applied in other regions: Latin America (e.g., Brazil), Asia (Japan), Africa (Morocco), and Australia.
  - Offshore wind is a new application of wind power, with its origin in Europe. For offshore wind, the main components are blades, gearbox, and tower, but also the support structure (below the surface of the sea). Offshore wind projects are also developed in other world regions: the USA, Asia, etc.
- Ocean energy
  - Wave power
    There are a few wave power devices - the Pelamis energy converter - that are entering the (pre-)commercial stage. Demonstration projects are under way in Europe and the USA, and there are concrete plans in other regions.
  - Tidal power
    There are a few tidal power plants in operation in the world, among which in France (la Rance, dating from the 1960s). The most common type is based on a tidal barrier, which enables operation during ebb and flood. Alternatively, one may make use of a tidal stream. The latter application is in the demonstration stage. Tidal barrier-based and tidal stream-based prototypes are demonstrated or planned in several European countries, the USA, and other world regions. It is acknowledged that it is doubtful whether wave and tidal power plants are already mature enough to be categorised as technologies in the (pre-)commercial stage.
- Geothermal energy
  - Geothermal power
    There are a few world regions which make use of geothermal energy for power generation on a significant scale, viz. Europe (Iceland, Italy), the USA, and other countries like the Philippines, Indonesia, Kenya, etc.
  - Geothermal heat
    Geothermal heat is already widely applied in Iceland (hot water and room heating) and to a much lesser extent in other countries in the world (Europe).
  - Ground source heat pump
    Another relatively recent application of geothermal energy is the ground source heat pump which makes use of available heat in the ground in winter and stores heat in the ground when cooling in summer to heat buildings and apartments. This application is of recent date. Ground source heat pumps are more and more used in OECD countries.
- Hydro power
  - Hydraulic turbines < 1 MW_e
    Hydraulic turbines of less than 1 MW_e (mini hydro) are widely applied.
  - Hydraulic turbines 1-10 MW_e
    Many hydraulic turbines have a capacity of 1-10 MW_e (‘small hydro’).
  - Hydraulic turbines > 10 MW_e
    Hydro power plants of > 10 MW_e are generally denoted as ‘large hydro’. Their capacity may range up to GW_es. They are widespread in OECD countries, but also in China, India, Brazil, and other world regions.
- Biomass
  - Biomass based power or heat

Biomass (or the organic fraction of municipal solid waste) may be used to fuel plants providing heat (e.g., for district heating) or producing power or combined heat and power (CHP). Alternative options are (small-scale) gasification and anaerobic digestion (wet manures). Combustion plants and anaerobic digestion are widely applied.

- First-generation biofuels
  First-generation biofuels are pure plant oil (PPO, based on extraction of plants oils), bioethanol, and biodiesel. These biofuels are applied in significant amounts in OECD countries (notably the USA, and increasingly in Europe) and in Latin America (notably Brazil). They are generally based on crops that also are used for food and feed. Therefore, there is a need for more efficient 'second-generation' biofuels that do not compete with food production.

With regard to the electric generating capacity of renewables among world regions, (Bertani, 2007) presents the following concise overview (Figure 3.1), showing that today, hydro power is by far the most important renewable source of electricity. Also, the most important regions with regard to hydro power are Europe, Asia, North America, and Latin America. The data shown refer to capacities in 2004. They do not present a representative view of potentials.

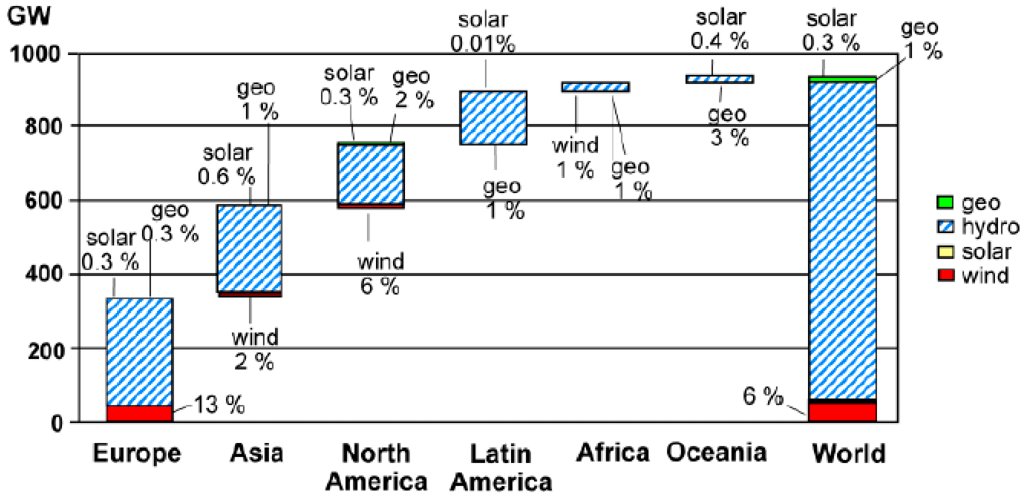

Figure 3.1 *Distribution of the current renewable energy capacity among world regions*
Source: Bertani, 2007.

3.3 Technological characterisation and disaggregation

3.3.1 Solar thermal power

Introduction

Concentrating solar power (CSP) plants are categorised according to whether the solar flux is concentrated by parabolic trough-shaped mirror reflectors (30-100 suns concentration[3]), central tower receivers requiring numerous heliostats (500-1000 suns), or parabolic dish-shaped reflectors (1000-10,000 suns). The receivers transfer the solar heat to a working fluid, which, in turn, transfers it to a thermal power-conversion system based on Rankine, Brayton, combined or Stirling cycles. To give a secure and reliable supply with capacity factors at around 50% rising to 70% by 2020[4], solar intermittency problems can be overcome by using supplementary energy

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[3] The term 'suns concentration' for concentrating solar power as well as concentrating PV refers to the concentration factor compared to normal sunlight.

[4] Integration of CSP in, e.g., a combined cycle (CC) based on gas may increase the capacity factor to 70% in 2020, which is equivalent to approximately 6,100 full-load hours.

from associated natural gas, coal or bioenergy systems as well as by storing surplus heat (IPCC, 2007). By 2006, the global capacity of CSP stood at approximately 0.4 GW_e (REN21, 2008).

Solar thermal power-generating plants are best sited at lower latitudes in areas receiving high levels of direct insolation. In these areas, 1 km^2 of land is enough to generate around 125 GWh/year from a 50 MW_e plant at 10% conversion of solar energy to electricity. Thus about 1% of the world's desert areas (240,000 km^2), if linked to demand centres by High Voltage Direct Current (HVDC) cables, could, in theory, be sufficient to meet total global electricity demand as forecast out to 2030. Estimates for the global *technical* potential of CSP range from 630 GW_e installed by 2040 up to 4,700 GW_e by 2030 (IPCC, 2007).

The most mature of CSP technologies is solar troughs with a maximum (peak) efficiency of 21% (conversion of direct solar radiation into electricity). CSP tower technology has been successfully demonstrated by two 10 MW_e systems in the USA with the prospect of giving long-term levelised electricity costs similar to trough technology. Advanced technologies include troughs with direct steam generation, Fresnel collectors that may reduce costs by 20%, energy storage including molten salt, integrated combined-cycle systems and advanced Stirling dishes. The latter are getting renewed interest and may provide opportunities for further cost reductions.

CSP is usually based on *mirrors*. Alternatively, *Fresnel lenses* are used for power generation. Also, *mirror-based systems* or *Fresnel-lens systems* may be integrated into a natural gas-fired combined cycle (CC) power plant, resulting in a hybrid solar/natural gas-based power plant.

Mirror-based systems

There are three types of mirror-based concentrated solar power plants:

- Parabolic trough
- Solar tower
- Solar dish.

Parabolic trough technology is the most proven type of mirror-based systems. A parabolic trough is a solar concentrator that follows or tracks the sun around a single rotational axis. Sunlight is reflected from parabolic-shaped mirrors and is concentrated onto the receiver tube at the focal point of the parabola. Synthetic heat transfer oil is pumped through the receiver tube and is heated to approximately 400°C. The oil transports the heat from the solar field to the power block where the energy is converted to high-pressure steam in a series of heat exchangers. This steam is converted into electrical energy using a conventional steam turbine.

Since the 1980s and 1990s, nine commercial-scale CSP plants were built (the first of which in 1984) and operated in the California Mojave desert. Their capacity ranges from 14 to 80 MW_e and their combined capacity is 354 MW_e. Another 400 MW_e are under construction and 6 GW_e is in the stage of planning (Internet Source 1). Large fields of parabolic trough collectors supply thermal energy used to produce steam for a Rankine steam turbine cycle (Figure 3.2).

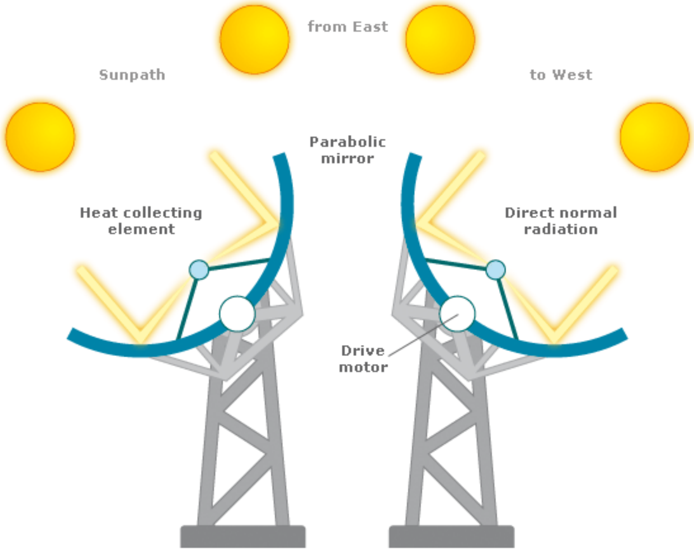

Figure 3.2 *Operating scheme for parabolic through technology*
Source: Internet Source 1.

The main components of parabolic trough technology are (Internet Source 1):

- The parabolic trough reflector: The cylindrical parabolic reflector reflects incident sunlight from its surface onto the receiver at the focal point. Typically, the reflector is made of thick glass silver mirrors formed into the shape of a parabola. Alternatively, mirrors can be made from thin glass, plastic films or polished metals.
- The receiver tube or heat collection element: The receiver tube consists of a metal absorber surrounded by a glass envelope. The absorber is coated with a selective coating to maximize energy collection and to minimize heat loss. The glass envelope is used to insulate the absorber from heat loss, and may be coated with an anti-reflective surface to increase the transmittance of light to the absorber. For high temperature CSP applications, the space between the absorber and glass tube is evacuated to form a vacuum.
- The sun-tracking system: An electronic control system and associated mechanical drive system is used to focus the reflector onto the sun.
- The support structure: Typically made of metal, the collector support structure holds the mirrors in accurate alignment while resisting the effects of the wind.

Also infrastructure is necessary, consisting of foundations, grid connection, and access roads.

Solar tower systems are next in line with regard to technology development in mirror-based systems. On tower systems, a heliostat field comprised of movable mirrors, is oriented according to the solar position in order to reflect the solar radiation concentrating it up to 600 times on a receptor located on the upper part of the tower. This heat is transferred to a fluid in order to generate steam expanding in a steam turbine, coupled to a generator to produce power (Figure 3.3). CSP plants (e.g., based on a *solar tower*) may be equipped with the added capability of 15 hours energy (heat) storage which gives them an estimated operating time of 6,500 hours/year.

Solar thermal power based on *solar dish* technology (Figure 3.4) is slightly behind the other two mirror-based systems. Yet, (U.S.) Stirling Energy Systems (SES) intends to build a 500 MW_e CSP plant based on *solar dish* technology. Characteristics of the project are (Internet Sources 2-3):

- Capacity: 500 MW_e with expansion option to 850 MW_e.
- 20,000 - 34,000 solar dish Stirling systems.
- 20-Year Power Purchase Agreement with Southern California Edison Company.
- Sited in the Mojave Desert east of Barstow, California.

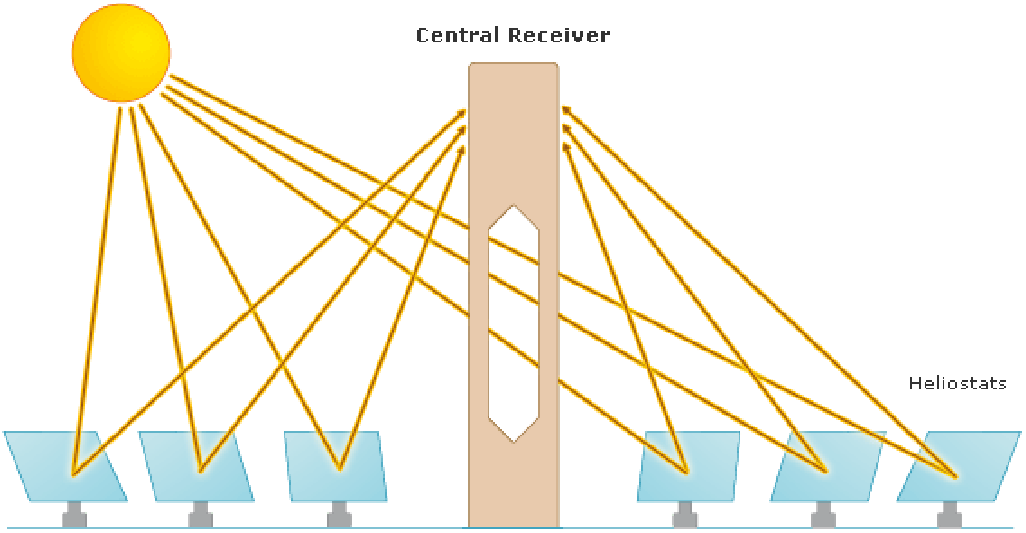

Figure 3.3 *Operating scheme for tower technology*
Source: Internet Source 1.

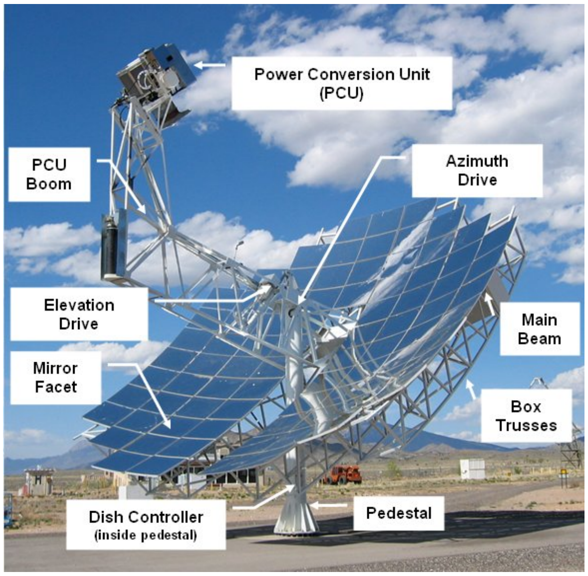

Figure 3.4 *Example for solar dish technology (25 kW$_e$ SES SunCatcher)*
Source: Internet Source 6.

Fresnel-lens based systems

Ausra and SkyFuel develop technology based on the *Fresnel lens*[5]. Ausra's technology is a Compact Linear Fresnel Reflector (CLFR) solar collector and steam generation system. SkyFuel develops a system based on the *Fresnel lens* (Figure 3.5) and molten salt-filled tubes and heat exchangers to power the steam turbines. In November 2007, Pacific Gas and Electric (USA) entered into a contract to buy electricity from a *Fresnel lens* based 177 MW$_e$ power plant, built by Ausra in San Luis Obispo county, central California (Mills et al, 2006; Internet Sources 4-5).

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[5] French physicist and engineer Fresnel is most often given credit for the development of this lens for use in lighthouses. Cheap Fresnel lenses can be stamped or moulded out of transparent plastic and are used in overhead projectors, projection televisions, etc. Now, they are also introduced for CSP.

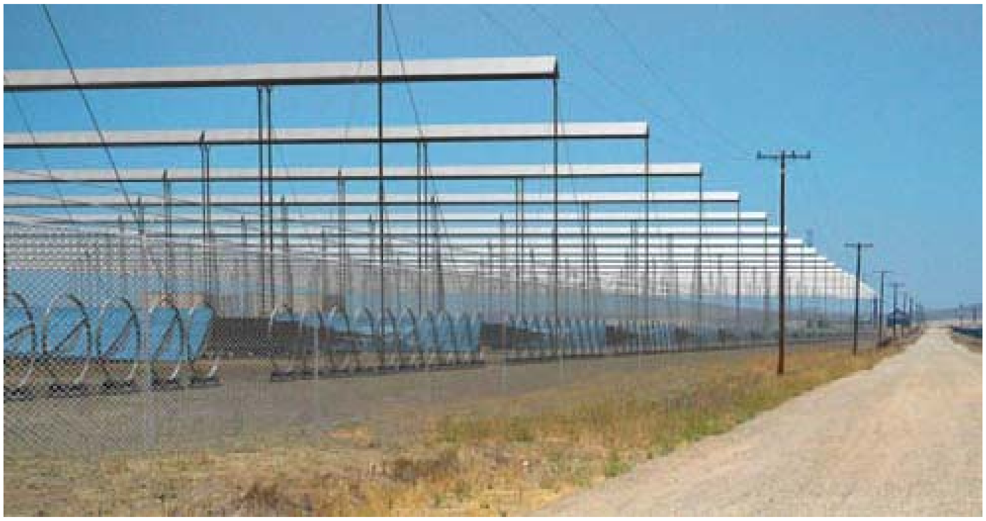


Figure 3.5 *Visualisation of 177 MW_e plant based on Fresnel-lens at the Carrizo Plain, CA*
Source: Internet Source 13.

Industrial activity

Currently, the following companies design, engineer, and manufacture these plants (Table 3.2). Most of the companies are headquartered in the USA, Spain, Germany, and Israel.

Table 3.2 *Firms engaged in design, engineering, and manufacturing of solar thermal power*

Type	Abengoa Solar Spain	Ausra USA	Bright-source Energy USA/Israel	SkyFuel USA	Solar Millennium Germany	SolarReserve USA	Solel Israel	Schott Solar Germany	Stirling Energy Systems USA
Parabolic trough									
Reflector	√			√	√		√		
Receiver	√			√	√		√	√	
Sun-tracking	√			√	√		√		
Support structure	√			√	√		√		
Rankine steam turbine cycle	√			√	√		√		
Solar tower									
Heliostat	√		√			√			
Central receiver	√		√			√			
Tower	√		√			√			
Rankine steam turbine cycle	√		√			√			
Solar Dish									
Reflector									√
Stirling engine									√
Fresnel lens									
Reflector		√		√					
Rankine steam turbine cycle	√		√						

Sources: Internet Source 1 (Abengoa); Internet Source 2 (Stirling Energy Systems); Internet Source 4 (Ausra); Internet Source 7 (Brightsource Energy); Internet Source 8 (SkyFuel); Internet Source 9 (Solar Millennium); Internet Source 10 (SolarReserve); Internet Source 11 (Solel); Internet Source 12 (Schott Solar).

Integrated Solar (gas-fired) Combined Cycle (ISCC) plant

Spanish Abengoa agreed with Morocco-based ‘Office National de l’Électricité’ to build an integrated solar combined cycle (ISCC) plant at Ain Beni Mathar, combining solar trough technology with a natural-gas based combined cycle power plant. The power plant has a capacity of 472 MW_e, of which 20 MW_e based on solar troughs (Internet Source 14). A second ISCC plant will be built by Algeria’s Sonatrach. The 150 MW_e ISCC plant - of which 25 MW_e is based on solar cylinder technology - is called ‘Híbrido Gas-Solar de Hassi R’Mel’ and is due to be operational in 2010 (RER, 2008).

Current state of the art

CSP plants have been or are in the stage of being built in the USA, Spain, Morocco, and Algeria (Table 3.3).

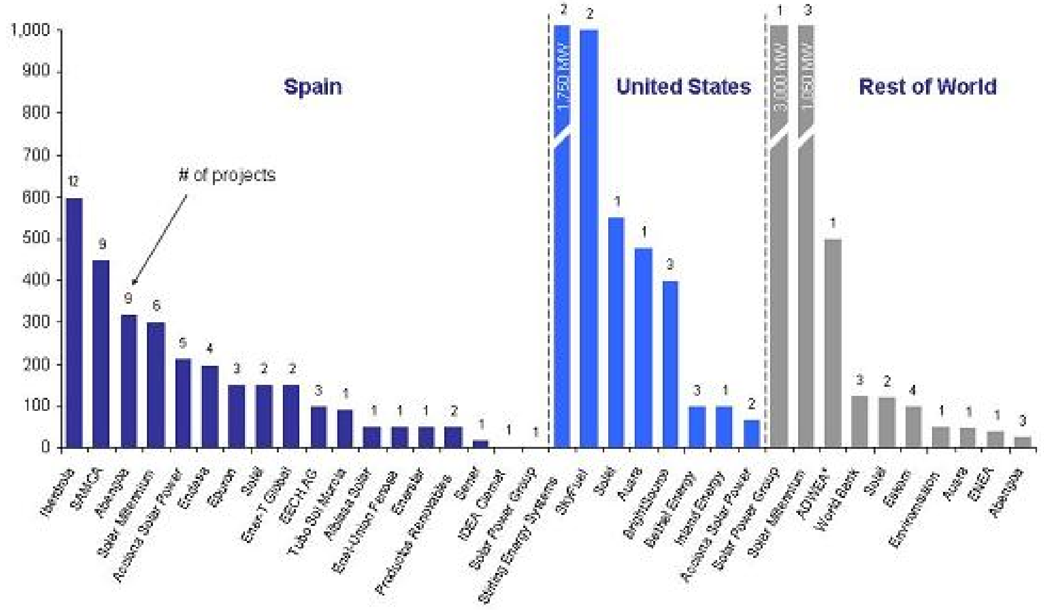
Table 3.3 *Concentrating solar power (CSP) plants based on mirrors and the Fresnel lens*

Project	Country	State/Site	On-line	Technology	Solar capacity [a] [MW_e]
SEGS	USA	Nevada	1984-	trough	354
Saguaro	USA	Arizona	2006	trough	1
Nevada Solar 1	USA	Nevada	2007	trough	64
PG&E	USA	California	2010	Fresnel lens	177
PG&E	USA	California	2011	trough	731
SCE	USA	California	2012	Stirling	500
SDG&E	USA	California	2012	Stirling	300
SW Initiative	USA	AZ/NV	2012	to be decided	200-250
PS10 (Sanlúcar la Mayor)	Spain	Seville	2008	central receiver	11
Solar Tres	Spain	Seville	2009	central receiver	17
Andasol I	Spain	Grenada	2008	trough	49.9
Andasol II	Spain	Grenada	2009	trough	49.9
Andasol III	Spain	Grenada	2008	trough	49.9
Sanlúcar la Mayor	Spain	Seville	2013	trough & central receiver	289
Ain Beni Mathar	Morocco		2009	trough	20 [a]
Híbrido Gas-Solar de Hassi R’Mel	Algeria		2010	cylinder	25 [a]

a Integrated Solar Combined Cycle (ISCC) plant. Only the solar capacity is shown in the rightmost column.

Sources: Internet Sources 15-18; RER, 2008.

Figure 3.6 gives a corresponding view of CSP plants that are under construction or planned (Internet Source 19).



* refers to 1 MW Envirodish project operating in Sevilla and 50 MW proposed Extresol I owned by ACS / Cobra in Extremadura
** Abu Dahbi Water and Electricity Authority

Figure 3.6 *Concentrating solar power (CSP) projects under construction or planned*
Source: Internet Source 19.

Based on these sources CSP capacities to the tune of 5,000 MW_e will be developed up to 2015:

- USA: 354 MW_e built in the 1980s, 3,800 MW_e under construction and announced;
- Spain: 437 MW_e built or under construction, approximately 1,400 MW_e announced;
- Algeria: 20 MW_e built/under construction;
- Morocco: 20 MW_e built/under construction
- etc.

3.3.2 Solar heating

Introduction

Technologies for solar hot water are fully commercial and in operation in many countries all over the world. A solar heating system transforms the energy of the sun to heat, typically in a single, closed circuit. The solar collector consists of a black plate, which picks up the energy of the sun and heats up a mixture of water and antifreeze, which is pumped to a special hot-water tank in the house, where it emits the heat and runs back to the solar collector. Solar collectors are typically used for heating up domestic water, but more and more people also use solar-heated water for floor heating and other space heating. The system is adapted to the size of the house and the heating requirements.

Solar heating and cooling of buildings can reduce conventional fuel consumption and reduce peak electricity loads. Buildings can be designed to use efficient solar collection for passive space heating and cooling, active heating of water and space using glazed and circulating fluid collectors, and active cooling using absorption chillers or desiccant regeneration (IPCC, 2007). Solar thermal technology converts part of the energy content of the insolation into heat. The main technologies and applications include flat plate collector systems[6] typically for dwellings and offices. Typical solar thermal conversion efficiencies range from about 25-60% (reducing the amount of fossil energy needed for water heating by 40 to 50%) and other low temperature

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[6] Solar heating systems are either based on the thermo-siphon principle or on forced circulation.

applications such as space heating or large scale district heating, and parabolic troughs/evacuated tube collectors for higher temperature applications such as industrial process heat (Ahm, 2006).

Active systems of capturing solar energy for direct heat are used mainly in small-scale, low-temperature, domestic hot water installations; heating of building space; swimming pools; crop drying; cook stoves; industrial processes; desalination plants and solar-assisted district heating. The estimated annual global solar thermal-collector yield of domestic hot water systems alone is around 80 TWh (0.3 EJ) with the capacity growing by 20% per year. Annual solar thermal energy use depends on the area of collectors in operation, the solar radiation levels available and the technologies used including both unglazed and glazed systems.

In 2005, approximately 125 million m^2 (88 GW_{th}) of active solar hot-water collectors existed, excluding swimming pool heating. The energy contribution from this technology can be calculated using the IEA adopted conversion factor of 1 $m^2 = 0.7$ kW_{th}. China is the world's largest market for glazed domestic solar hot-water systems with 80% of annual global installations and existing capacity of 79 million m^2 (55 GW_{th}) at the end of 2005. Most new installations in China are now evacuated-tube in contrast with Europe (the second-largest market), where most collectors are flat-plate. Domestic solar hot-water systems are also expanding rapidly in other developing countries. Estimated annual energy yields for glazed flat-plate collectors range from 400 kWh/m^2 in Germany to 1,000 kWh/m^2 in Israel. In Austria, annual solar yields were estimated to be 300 kWh/m^2 for unglazed, 350 kWh/m^2 for flat-plate, and 550 kWh/m^2 for evacuated tube collectors (IPCC, 2007).

Furthermore, a new and promising use of solar heating is being developed - solar cooling. By attaching a solar collector that can heat water to 80 to 100°C to an absorption cooler, it is possible to create refrigeration, which for example can be used in air-conditioning systems. As the world uses more energy for cooling than for room heating, great energy-saving perspectives in the solar cooling area become available.

Current development stage

With regard to the technologies applied, it is estimated that about 25% is unglazed collectors, mainly serving swimming pools, and 75% is flat-plate and evacuated-tube collectors, predominantly for preparing hot water and for space heating. The average market growth rate has been 17-20% in recent years. The most dynamic market areas are China and Europe. By 2004, China has 65 million m^2 installed capacity corresponding to 50 m^2/1000 inhabitants. At the end of 2006, the EU exhibits 19 million m^2 installed capacity with wide variation from country to country (Table 3.4).

The presently installed solar thermal capacity provides around 0.2% of the requirements for hot water and space heating of the entire EU27. Used predominantly for hot water and space heating, solar thermal collectors are typically mounted on roofs of buildings, and as solar thermal installations are quite visible, this has lead to developments in both technology and architecture.

As system costs decrease with the size of the system, solar heating systems connected to a district heating network are more cost-effective than for single family houses. In practice, short-term storage is included in a solar thermal system of 50-75 l per m^2 collector area. Seasonal storage with a capacity of approximately 2,000 l per m^2 collector is not state-of-the-art today, but in the demonstration stage.

Table 3.4 *Solar thermal heating systems in Europe (EU27 + CH), 2003-2006*

Country	Capacity addition [m^2]			Cumulatively installed in 2006 [m^2]
	2004	2005	2006	
Austria	182,594	233,470	292,669	1,611,627
Belgium	14,700	20,234	35,636	104,118
Bulgaria	1,800	2,000	2,200	25,100
Switzerland (CH)	31,160	39,132	51,863	443,548
Cyprus	30,000	50,000	60,000	560,200
Czech Rep.	12,250	15,550	22,030	106,730
Germany	750,000	950,000	1,500,000	8,054,000
Denmark	20,000	21,250	25,300	362,280
Estonia	250	250	300	1,120
Spain	90,000	106,800	175,000	702,166
Finland	1,630	2,383	3,400	16,493
France	52,000	121,500	220,000	615,600
Greece	215,000	220,500	240,000	3,287,200
Hungary	1,500	1,000	1,000	6,250
Ireland	2,000	3,500	5,000	15,790
Italy	97,738	127,059	186,000	855,230
Lithuania	500	500	600	2,750
Luxembourg	1,700	1,900	2,500	15,900
Latvia	500	1,000	1,200	3,850
Malta	4,215	4,000	4,500	23,860
Netherlands	26,300	20,248	14,685	318,441
Poland	28.900	27,700	41,400	167,520
Portugal	10,000	16,000	20,000	180,950
Romania	400	400	400	69,100
Sweden	20,058	22,621	28,539	236,929
Slovenia	1,800	4,800	6,900	109,300
Slovakia	5,500	7,500	8,500	72,750
UK	25,000	28,000	54,000	250,920
EU27 + CH	1,627,495	2,049,297	3,003,622	19,219,722

a In 2007, 940,000 m^2 was added in Germany.

Sources: ESTIF, 2007; BSW-Solar, 2008.

3.3.3 Solar photovoltaic (PV)

Introduction

Photovoltaic (PV) systems consist of *modules* (based on PV cells) and the '*Balance of System*' (BOS). The evolution of PV modules has paralleled the successes of PV cells. '*Module*' is the term used to identify a grouping of interconnected PV cells into an enclosed, environmentally sealed package. Modules utilise a transparent front material, a cell and cell encapsulant, and a back cover material. Current PV cells and modules are considerably improved compared to some years ago, witnessed by increased efficiency and reduced replacement of, e.g., inverters (Internet Source 20).

Solar photovoltaic is estimated to have a technical potential of at least 450,000 TWh/year. However, realising this potential will be limited by land, energy-storage, and investment constraints. At the end of 2007, the global capacity of photovoltaic power (PV) stood at 10.5 GW_e - 7.8 GW_e (5.1 GW_e in 2006) grid-connected, and 2.7 GW_e off-grid (REN21, 2008). Grid-connected PV represents 75% of the total, primarily in Germany, Japan, and the USA, and grows at annual rates of 50-60% in contrast to 15-20% for off-grid PV (IPCC, 2007).

Expansion is taking place at around 30% per year in developing countries where around 20% of all new global PV capacity was installed in 2006, mainly in rural areas where electricity from the grid is either not available or unreliable. Decentralised generation by solar PV is already economically feasible for villages with long distances to a distribution grid and where providing basic lighting, radio, and PC is socially desirable. Annual production of PV modules grew from 740 MW_e in 2003 to 1.9 GW_e in 2006 (REN21, 2008), with new manufacturing plant capacity built to meet growing demand. Germany is currently the world market leader. Until this date solar PV generation remains modest, with only approx. 0.01% of global electricity generation.

Most commercially available solar PV modules are based on crystalline silicon cells with monocrystalline at up to 18% efficiency, and a share of 33% of the global market. Polycrystalline cells at up to 15% efficiency are cheaper per W_p (peak Watt) and have 56% market share. Modules costing 3-4 US\$/W_p can be installed for around 6-7 US\$/W_p from which electricity can be generated for around 250 US\$/MWh in high sunshine regions. Cost reductions are expected to continue, partly depending on the future world price for silicon; solar-cell efficiency improvements as a result of R&D investment; mass production of solar panels and learning through project experience. Costs in new buildings can be reduced where PV systems are designed to be an integral part of the roof, walls or even windows (IPCC, 2007).

Thinner cell materials have prospects for cost reduction, including thin-film silicon cells (8.8% of market share in 2003), thin-film copper indium di-selenide cells (0.7% of market share), photochemical cells and polymer cells. Commercial thin-film cells have efficiencies up to 8%, but 10-12% should be feasible within the next few years. Experimental multilayer cells have reached higher efficiencies but their cost remains high. Work to reduce the cost of manufacturing, using low-cost polymer materials, and developing new materials such as quantum dots and nano-structures, could allow the solar resource to be more fully exploited.

Combining solar thermal and PV power generation systems into one unit has good potential as using the heat produced from cooling the PV cells would make it more efficient. Photovoltaic (PV) technology and applications are characterised by their modularity: they can be implemented on virtually any scale and size. The overall efficiency of current PV systems is generally approximately 12-15%[7]. The expected life span is 20 to 30 years. Solar modules are the most durable part of the system, with failure rates of only once in 10,000 per year. Some components, e.g., the inverter and (if applicable) battery, have to be replaced more regularly (IEA, 2003).

Types and main components

PV cells that are the base of *PV modules* generally consist of two types (Figure 3.7), viz.:

- To create a photovoltaic cell, a material such as silicon is doped with atoms from an element with one more or less electrons than occurs in its matching substrate (e.g., silicon). A thin layer of each material is joined to form a junction. Photons, striking the cell, cause this mismatched electron to be dislodged, creating a current as it moves across the junction. Through a grid of physical connections, the current is gathered. Various currents and voltages can be supplied through series and parallel arrays of cells. ‘Mono-crystalline’ and ‘multi-crystalline’ (silicon) PV is currently most widely applied.
- Alternatively, thin-film solar cells are used. Thin films are made from amorphous silicon, copper indium diselenide or cadmium telluride. Thin-film solar cells require very little material and can be easily manufactured on a large scale. Manufacturing lends itself to automation and the fabricated cells can be flexibly sized and incorporated into building components. Thin-film PV technology is currently less energy efficient than silicon-based PV. However, it becomes more efficient and cost competitive over time. Thin-film PV cells may attain a market share of 20 % within a few years (Internet Source 21).

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[7] The range of 12-15% efficiency for solar modules is the state of the art described in (IEA, 2003). New solar PV systems may achieve higher efficiencies.

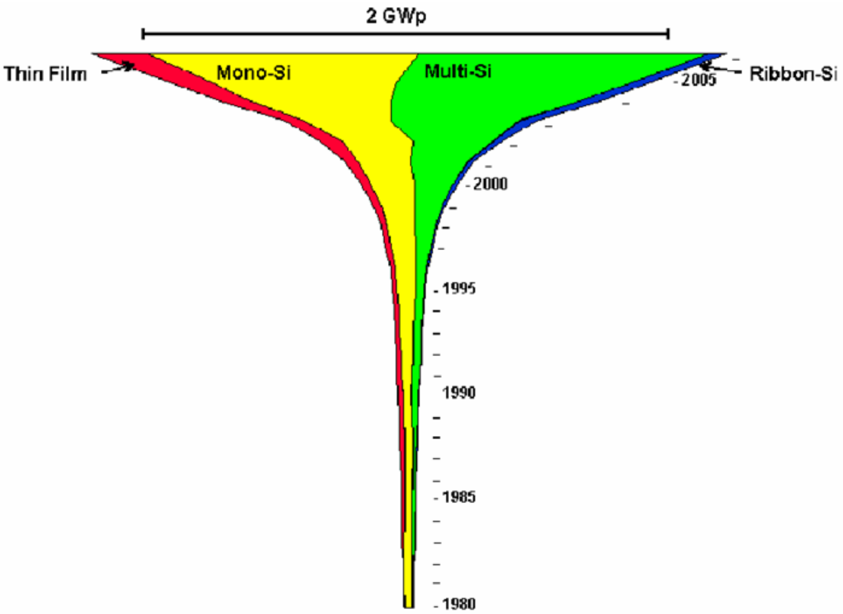

Figure 3.7 *Development of the global photovoltaic market, 1980-2006*
Sources: Zahler, 2007; Internet Source 22.

Balance-of-System - equipment other than the actual PV modules - consists of:

- Inverter (power conditioning unit)
- Electrical Wiring
- Structure
- Foundation (including tracking systems, if applicable)
- Electrical Interconnection & Metering
- Data Monitoring
- Communications & Control
- Engineering & Design
- Siting & Permitting
- Procurement
- Installation
- Electrical Protection & Safety Equipment
- Project Management
- Other equipment/services (construction management, site facilities, start-up testing, training, operation and maintenance if applicable).

Markets of different PV technologies and applications

Crystalline silicon is by far the most common solar cell material (Figure 3.7), because:

- It is used for more than 50 years, and its manufacturing processes are well known.
- The raw material used, silicon, is very abundant (the second most abundant element in the Earth's crust - second only to oxygen).

In the medium term, the global market will most likely see both mono-/poly-crystalline *and* thin-film PV. Thin-film cells provide advantages over mono-/poly-crystalline cells such as semi-transparency, flexibility, and low weight. It is possible to make semi-transparent panels that substitute for window panes on facades, roofs, etc. Thin-film modules are light and easy to combine with steel plates for roofs or reservoirs, and also offer a varied range of appearances, some more aesthetically attractive than deep blue poly-crystalline silicon wafers (Internet Source 23).

PV has various applications and markets with today 75% market share for *grid-connected* PV. Developing countries generally apply off-grid PV, with or without power storage (Figure 3.8).

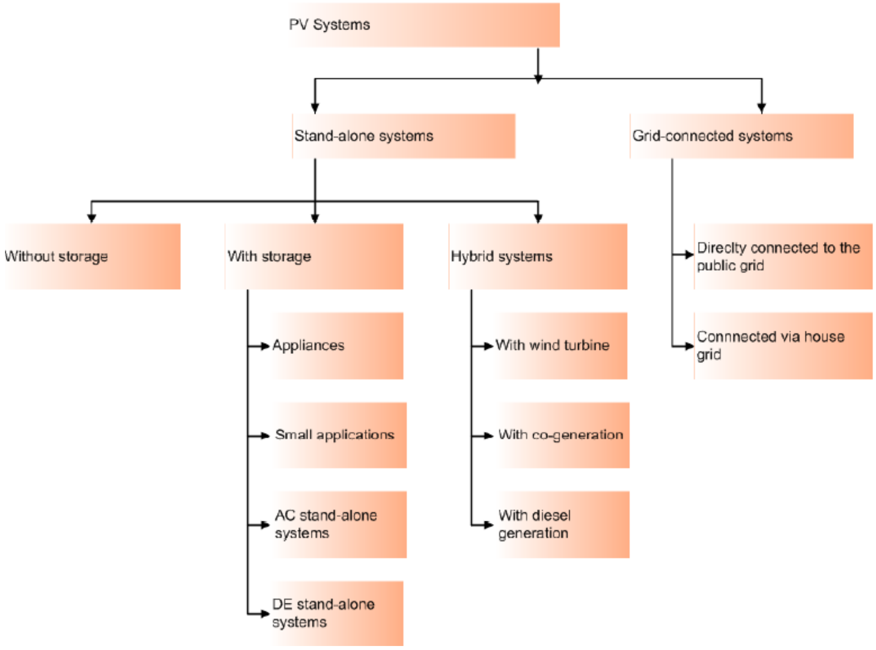

Figure 3.8 *Photovoltaic power (PV) applications*
Source: Korman, 2006.

PV cell and module production

Figure 3.9 shows the PV cell production (in MW_e) in 2006 by country (Watt, 2007). In 2006, the largest producers of solar cells were Japan, (increasingly) Germany, and the USA.

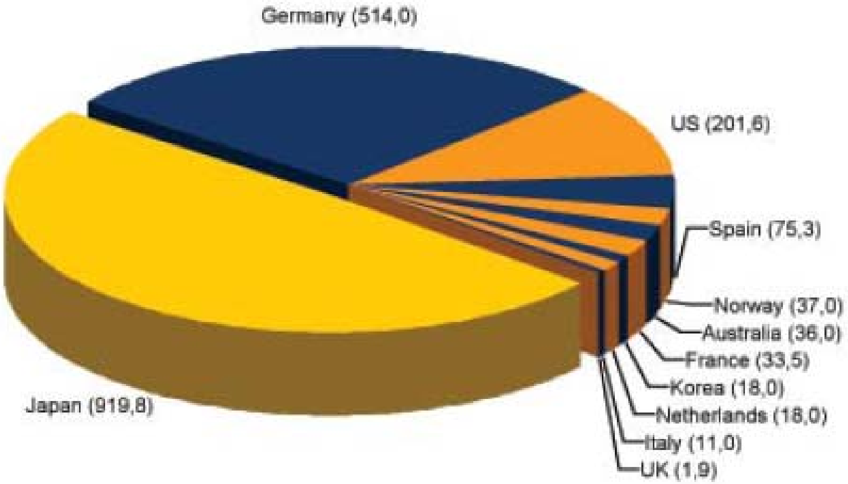

Figure 3.9 *PV cell production in the IEA PVPS countries in 2006 [MW_e]*
Note: The market of PV cells depicted is limited to IEA countries, and therefore exclusive of China, India, etc.
Source: Watt, 2007.

(REN21, 2008) puts the global PV capacity in 2007 at approx. 10.5 GW_e (Figure 3.10).

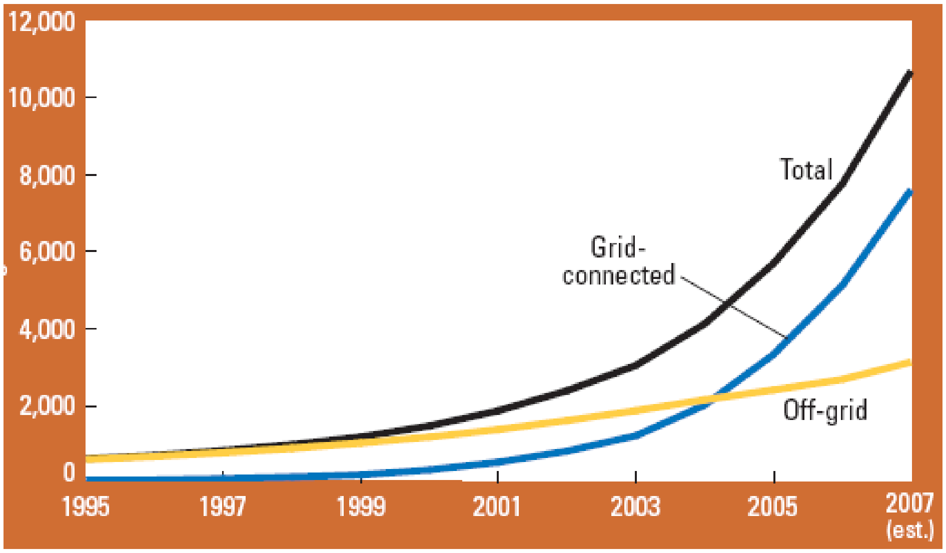

Figure 3.10 *Global cumulative installed PV capacity 1995-2007 [MW$_e$]*
Sources: REN21, 2008.

The WorldWatch Institute states that China is emerging as a dynamic solar manufacturing industry, with a solar module production (note: not solar cell production, compare Figure 3.9) of more than 1,500 MW$_e$ per year in 2007. India shows a relatively fast transition, too. In January 2008, PV Technologies India Ltd - parent company Moser Baer India Ltd - signed a Memorandum of Understanding (MoU) with a leading global equipment supplier to secure supply of critical equipment for a phased expansion of its thin-film PV modules manufacturing capacity amounting to 565 MW$_e$ (Internet Source 24). Together with its current production capacity of 40 MW$_e$, the modules production capacity will be over 600 MW$_e$ by 2010. Thin-film solar modules have large emerging applications and a robust demand. Thin-film PV could even grow ten-fold from 250 MW$_e$ to approximately 2 GW$_e$ per year in 2010 with a market size of US$ 5 billion (Internet Source 25). Developing countries including emerging economies like China, India, etc. seem to become significant producers of PV cells and modules.

3.3.4 Onshore wind energy

By 2007, wind energy represented a capacity of 94 GW$_e$, equivalent to an electrical output of 194 TWh (BTM Consult, 2008), or 1% of global electricity generation. To supply over 20% of total electricity would require more accurate forecasting, regulations that ensure wind has priority access to the grid, demand-side response measures, more extensive use of operational reserves in the power system, or development of energy storage systems[8] (IPCC, 2007). However, the costs for back-up power decrease drastically with larger grid area, larger area containing distributed wind turbines, and a greater share of flexible hydro and natural-gas-fired power plants.

A number of technologies are under development in order to maximise energy capture for lower wind-speed sites. These include: optimised turbine designs; larger turbines; taller towers; the use of carbon-fibre technology to replace glass-reinforced polymer in longer wind-turbine blades; more accurate aero-elastic models, and more advanced control strategies to keep the wind loads within the turbine design limits.

The production of wind turbines and components for wind turbines, in particular for onshore application, is a fast growing industry. This industrial sector may best be characterised as one

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[8] The U.S. Department of Energy regards 20% of wind energy in the generation mix in 2030 as feasible (DoE, 2008).

with a regional base: wind turbine manufacturers are mainly focused on a number of countries. Only few large wind turbine companies have developed or are developing into ‘global players’.

According to (BTM Consult, 2008), political support for wind power is growing for a host of reasons. The key drivers include climate change, the Kyoto Protocol, the industry’s job creation potential and a desire for greater energy self-sufficiency. As a result, wind power has become accepted as a mainstream technology by utilities all over the world, particularly onshore wind.

Regarding equipment and activities related to onshore wind farms, there are several types of equipment or activities for onshore wind. Wind turbine or component manufacturers may deploy various production activities:
- Blades
- Gearbox
- Generator
- Bearings
- Towers
- Electronic Control Equipment
- Cast Iron - items
- Forged - items
- Assembly.

Wind turbine manufacturers may choose to buy equipment from original equipment manufacturers (OEMs), or they may buy some components and manufacture others themselves. For OEMs, it is the other way around: they are active in production of components like blades, gearboxes, generators, towers, etc, or combinations of them, e.g. towers and gearboxes. Wind turbine companies may also be specialised in assembly of wind turbines. This kind of companies is mainly restricted to the category of medium-scale (< 1 MW_e) turbines.

Focusing on the ten largest wind turbine manufacturers - in MW_e sold - in 2007, their market shares are presented in Figure 3.11. The largest wind turbine manufacturers originate from OECD countries, India, and China, with the share of capacity *installed* in 2007:
- Vestas Wind Systems A/S (Denmark): 22.8%
- GE Energy (GE Wind, USA): 16.6%
- Gamesa Eólica (Spain): 15.4%
- Enercon GmbH (Germany): 14.0%
- Suzlon Energy (India): 10.5%
- Siemens Wind Power (Denmark): 7.1%
- Acciona Windpower (Spain): 4.4%
- Goldwind, Xinjiang Wind Energy (China): 4.2%
- Nordex AG (Germany): 3.4%
- Sinovel Wind Co. Ltd (China): 3.4%.

Figure 3.11 shows the capacity *supplied* of 22,207 MW_e in 2007 (BTM Consult, 2008). This exceeds the *installed* capacity of 19,791 MW_e, as some capacity was not yet in operation (criterion for ‘installed’) by yearend 2007. The aforementioned percentages refer to the *installed* capacity.

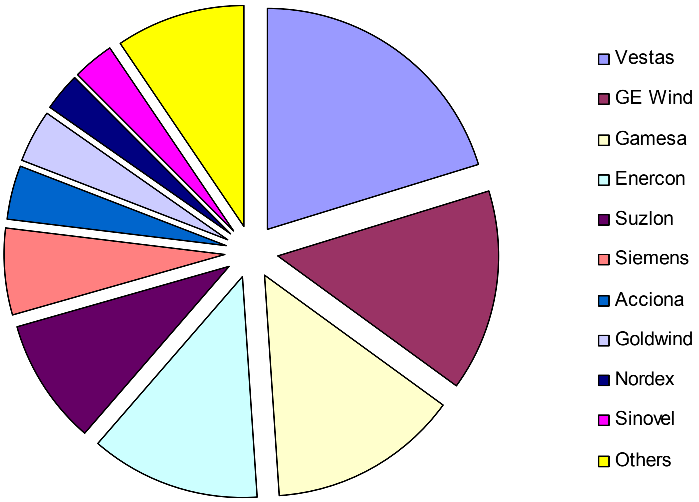

Figure 3.11 *Wind turbine market by wind turbine supplier in 2007 [fraction of MW_e sold]*

Notes: Wind turbines supplied are for onshore as well as offshore application (offshore «1% of the total market). The capacity *supplied* in 2007 was 22,207 MW_e; the capacity *installed* was 19,791 MW_e.

Source: BTM Consult, 2008.

Wind turbine manufacturers such as Vestas and GE Energy have developed or are developing into global players, considering their market shares in world regions (BTM Consult, 2008). The market is becoming more diverse with entrance of wind turbine manufacturers from India (Suzlon, which acquired REpower of Germany in 2007) and China (Goldwind and Sinovel):

- Many of the aforementioned wind turbine suppliers have diversified or are diversifying their manufacturing base with plants (e.g., for key components) in other world regions.
- There are numerous OEMs, not only in OECD countries, but also in India, China, etc.

Figure 3.12 shows revenues reported or inferred for the top-10 wind turbine companies and Ecotècnia (Spain, currently Alstom Ecotècnia). Internet Sources 26-30 show that revenues in 2007 ranged from M€ 4,862 for Vestas to about M€ 350 for Ecotècnia. How revenues of six out of 11 wind turbine companies have been estimated is explained in the notes below Figure 3.12. The revenues reported signal the importance of this fast growing renewable energy industry, considering the related employment, opportunities for import reduction, export, etc.

The published or estimated revenues of the top-10 wind turbine companies plus Ecotècnia may be put in perspective in the following way: the *wind turbine blades* manufacturer LM Glasfiber (Denmark) reports revenues of M€ 578 (DKK 4,310 mln) in 2007 (Internet Source 32), which is comparable to revenues of wind turbine company Nordex. As sales corresponded to a wind turbine capacity of 4,950 MW_e, *wind turbine blades* represent a *value* of approx. € 117/kW.

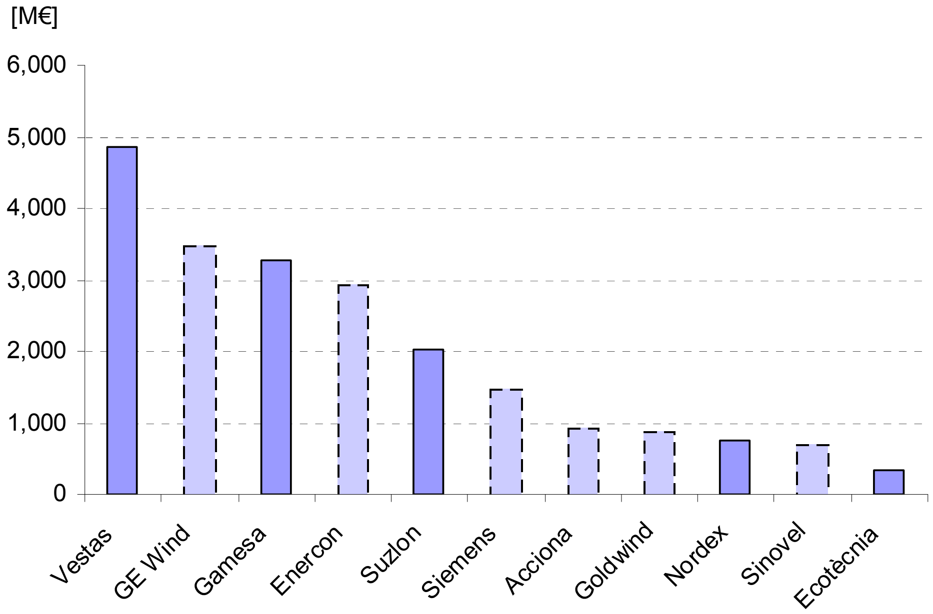

Figure 3.12 *Revenues of top-10 wind turbine companies plus Ecotècnia (6 inferred)*

Notes: Vestas, Gamesa, Suzlon, and Nordex report revenues in 2007. (Internet Source 30) provides a figure for revenues of Ecotècnia. (Windpower Monthly, 2008a) provides Ecotècnia's capacity installed (341 MW_e). Revenues are divided by capacities *installed* from (BTM Consult, 2008), shown in Figure 3.11. The resulting figure of *€ 1,058/kW* is the base for other companies' revenues. Apparently, revenues of Goldwind are overestimated as they were approximately M€ 311, according to (Internet Source 31), rather than M€ 878.

Sources: Vestas, 2008; Nordex, 2008; Windpower Monthly, 2008a; BTM Consult, 2008; Internet Sources 26-31.

According to (Internet Source 33), revenues from manufacturing *gearboxes* for wind turbines by Hansen Transmissions of Belgium - acquired by Suzlon (India) - are M€ 339 in the financial year 2007 (ending March 31, 2008). This puts Hansen in the same league as Ecotècnia. Production capacity stood at 3,795 MW_e per year (Windpower Monthly, 2008b). Based on 100% capacity utilisation, *gearboxes* represent a *value* of approximately € 89/kW. (Hansen, 2008) puts this figure at € 81/kW (fiscal year 2008). The figure of € 89/kW has been retained in this study.

With regard to the *price of wind turbines*, it is noted that the estimate of *€ 1,058/kW* (see notes Figure 3.12) pertains to wind turbines from Vestas, Gamesa, Suzlon, Nordex, and Ecotècnia. (BTM Consult, 2008) gives an estimate of the *total investment cost* of onshore wind to the tune of *€ 1,380/kW*. The balance of € 322/kW (23%) is attributed to other investment costs, notably:

- Foundation
- Electrical infrastructure and grid connection
- Civil works
- Operation and Maintenance (O&M) facility (if applicable).

Based on these data with regard to wind turbine components, investments, and investment costs per kW installed (for onshore wind) may be estimated as follows (Table 3.5). It is estimated that the investments in on- and offshore wind amounted to approximately € 27.5 billion in 2007. It is noteworthy that a country like China required that 75% of the wind turbine components were sourced domestically. As a capacity of 3,287 MW_e was installed in 2007, supplies in China may have been *worth* approximately € 2.5 billion (~ € 750/kW). This figure may be compared to the *potential value* of the combined capacity that Goldwind and Sinovel supplied, viz. € 1.6 billion.

Table 3.5 *Investment cost on- & offshore wind and investment per kW onshore wind 2007*

	Total investment 2007 [M€]	Investment per kW onshore wind 2007 [$€_{2007}$/kW] [a]	[%]
Wind turbine blades	2,287 [b]	117	8.5
Wind turbine gearboxes	1,503 [c]	89	6.5
Other main components	16,938	852	61.7
Total onshore wind turbines	20,727	1,058	76.7
Balance	6,758	322	23.3
Total	27,486	1,380	100.0

a The right column in $€_{2007}$/kW reflects investment per kW for onshore wind of € 1,058/kW, based on published revenues and capacities of Vestas, Gamesa, Suzlon, Nordex, and Ecotècnia (see notes Figure 3.12). Investment costs for *blades* and *gearboxes* refer to published data of LM Glasfiber, and Hansen Transmission, respectively. The balance (€ 852/kW) refers to *other main components*, viz. rotor, nacelle, including main shaft, generator, and brakes, I&C, and tower. The *balance* (€ 322/kW) results from the *investment cost* according to BTM Consult (€ 1,380/kW) diminished by the *turbine price* (€ 1,058/kW).

b The left column shows investments in wind power: ~ M€ 2,290 for *blades* (€ 117/kW), ~ M€ 1,500 for *gearboxes* (€ 89/kW), ~ M€ 20,730 for onshore wind (€ 1,058/kW), and M€ 27,486 for the combined on- and offshore investments - M€ 27,036 (€ 1,380/kW and 19,591 MW_e) refers to onshore wind, and M€ 450 (€ 2,250/kW and 200 MW_e) to offshore wind. The row 'Balance' includes offshore wind.

c Enercon supplies gearless 'Direct Drive' turbines. For a representative figure for investments in *gearboxes*, the onshore wind capacity in 2007 (19,591 MW_e) has been diminished by Enercon's supplies (2,769 MW_e).

Sources: Vestas, 2008; Nordex, 2008; Internet Sources 26-30, and 32-33; BTM Consult, 2008.

3.3.5 Offshore wind energy

Offshore wind farms have been built from 1990, starting with a single wind turbine in Sweden. In the '*demonstration stage*', wind farms with turbines up to 2 MW_e and up to 10 turbines each were built. Around 2000, a period of *commercialisation* started based on wind farms with large turbines of 2 MW_e and more. Today, 24 *operational* offshore wind farms[9] have a total capacity of approximately 1,228 MW_e. The following countries have *operational* offshore wind farms:

- Denmark (9)
- UK (7)
- Sweden (4)
- The Netherlands (2)
- Ireland (1)
- Germany (1, a single turbine at Rostock-Breitling).

Table 3.6 shows that two dismantled[10] and 24 operational offshore wind farms are recorded until June 2008. For 19 of them, investment costs have been reported. Investments have been made comparable using Producer Price Indexes (PPIs), and (if applicable) and by conversion to a common currency ($€_{2006}$):

1. A producer price index (PPI) is used to convert an investment to a corresponding value for the year 2006 in the same currency in which the investment costs are reported - e.g., Danish Crown (DKK), Swedish Crown (SEK), British Pound (£) or Euro (€).
2. The aforementioned currencies (2006) are converted to the common currency of $€_{2006}$.

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[9] Some wind farms consist of one or a few wind turbines, and may therefore be qualified as demonstration projects.

[10] Two wind farms have been decommissioned: 'Lely' (the Netherlands) in 2006 and 'Norgersund' (Sweden) in 2007.

Table 3.6 *Investments offshore wind farms installed in the period 1990 through June 2008*

№	Country	Project	On line	Capacity [MW$_e$]	Cumulative capacity [MW$_e$]	Investment cost [M€$_{2006}$]	Specific investment cost [€$_{2006}$/kW]
1	S	Nogersund († 2007)	1990	0.22	0.22	-	-
2	DK	Vindeby	1991	5.0	5.2	13.3	2,679
3	NL	Lely (offline 2006)	1994	2.0	7.2	5.5	2,770
4	DK	Tuno Knøb	1995	5.0	12.2	12.4	2,485
5	S	Bockstigen	1998	2.75	14.9	4.5	1,635
6	S	Utgrunden	2000	10.5	25.4	20.6	1,962
7	UK	Blyth	2000	4	29.4	6.3	1,570
8	DK	Middelgrunden	2001	40	69.4	52.6	1,315
9	S	Yttre Stengrund	2001	10	79.4	14.6	1,462
10	DK	Horns Rev	2002	160	239.4	291.3	1,821
11	DK	Samsø	2003	23	262.4	37.4	1,628
12	DK	Rønland	2003	17.2	279.6	-	-
13	DK	Nysted	2003	165.6	445.2	287.6	1,737
14	DK	Frederikshavn	2003	10.6	455.8	-	-
15	IRL	Arklow Bank	2003	25.2	481.0	-	-
16	UK	North Hoyle	2003	60	541.0	123.3	2,055
17	UK	Scroby Sands	2004	60	601.0	114.1	1,901
18	UK	Kentish Flats	2005	90	691.0	158.6	1,762
19	D	Rostock - Breitling	2006	2.50	693.5	-	-
20	UK	Barrow	2006	90	783.5	146.7	1,630
21	NL	Egmond aan Zee	2006	108	891.5	203.6	1,885
22	DK	Grenaa-harbour	2007?	8.25	899.8	-	-
23	S	Lillgrund	2007	110	1,010.2	190.2	1,723
24	UK	Moray Firth	2007	10	1,020.2	-	-
25	UK	Burbo Bank	2007	90	1,110.2	153.5	1,706
26	NL	Q7 (IJmuiden)	2008	120	1,230.2	376.3	3,136

Notes: The literature sources included below refer to the offshore wind farm № in the leftmost column. The data in this Table is based on (Junginger et al, 2008), who subsequently refer to literature sources presented below.

Sources: Junginger et al, 2008; Internet Source 34 (2); Internet Source 35; IEA, 2005 (3); Madsen, 1996 (4); Internet Sources 36-37 (5); Kühn et al, 2001; Internet Source 38 (6); New Energy, 2001; Internet Source 39 (7); Larsen et al, 2005 (8); Internet Sources 40-41 (9); Frandsen et al, 2004 (10); IEA, 2005 (11); IEA, 2005; SEI, 2004 (13); Internet Source 42 (16); Internet Source 43 (17); Internet Sources 44-45 (18); Internet Source 46 (20); Shell Venster, 2005; Internet Source 47 (21); Internet Source 48 (23); Internet Source 49 (25); REW, 2007; Internet Source 50 (26).

The investment costs range from € 1,315/kW (€$_{2006}$) for the (near-shore) wind farm Middelgrunden in Denmark (2001) to € 3,136/kW for the offshore wind farm Q7 IJmuiden in the Netherlands (2008). However, it is noted that only a few offshore wind farms show investment costs in excess of € 3,000/kW. The majority of offshore wind farms completed in 2006-2007, or due for completion in 2008-2009 shows specific investment costs between € 2,000 and € 2,500/kW. According to (BTM, 2008), a representative price for offshore wind is € 2,380/kW.

Figure 3.13 shows the *operational* offshore wind capacity by wind turbine manufacturer based on total 1,228 MW$_e$ (June 2008). Vestas and Siemens combined supplied 96% of this capacity. There are at least six wind turbine companies active in offshore wind turbine manufacturing:

- Vestas with 2 and 3 MW$_e$ turbines.
- GE Energy with 3.6 MW$_e$ turbines for ‘Arklow Bank’ (Ireland).
- Siemens with 2.3 and 3.6 MW$_e$ turbines.
- Nordex with 2.3 and 2.5 MW$_e$ turbines.
- REpower with 5 MW$_e$ turbines.
- Multibrid with 5 MW$_e$ turbines.
- BARD Engineering GmbH with 5 MW$_e$ turbines (Internet Source 51).

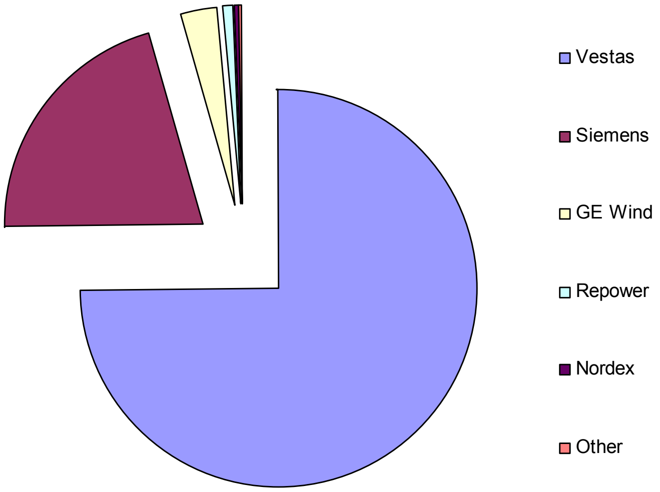

Figure 3.13 *Distribution of cumulative offshore wind capacity by manufacturer (June 2008)*
Note: The shares by 'offshore wind manufacturers' refer to 24 *operational* offshore wind farms in Table 3.7.
Source: (based on) Junginger et al, 2008.

According to (Internet Source 52), the specific investment cost of offshore wind farms in France would range from € 1,930/kW in Bretagne to € 3,020/kW in Languedoc (Figure 3.14) - these investment costs do not include grid connection, and the currency used is $€_{2004}$.

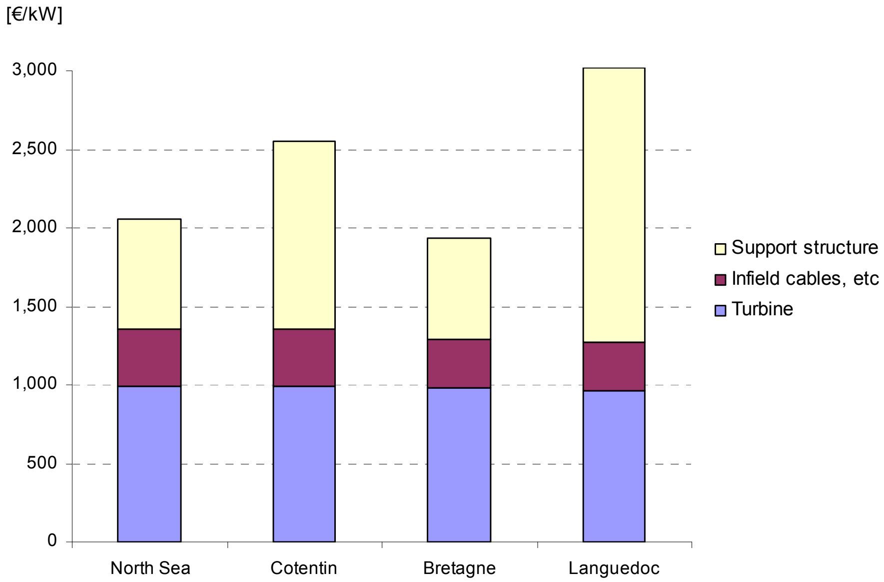

Figure 3.14 *Specific investment cost offshore wind excl. grid connection [$€_{2004}$/kW]*
Notes: 'Infield cables etc' includes transformers (converter stations for High Voltage Direct Current, HVDC).
Source: Internet Source 52.

Table 3.7 provides more insight in the investments cost of offshore wind based on (Wind-kraft Journal, 2007), (Internet Sources 53-61), and (Lako, Van Stralen and Beurskens, 2008). Usually, one company supplies infield cables, transformers (or converter stations in case of HVDC), and grid connection. Another may supply the support structures and perform the installation work. Also, one (or two) contractor(s) may be responsible for Engineering, Procurement, and Construction (EPC), as occurred for the Dutch offshore wind farm Q7 IJmuiden[11] (De Vries, 2007).

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[11] Q7 IJmuiden has been renamed as the 'Princess Amalia' offshore wind farm.

Table 3.7 *Main cost determining factors and investment costs of offshore wind farms*

Wind farm (Country)		Middelgrunden[a] (DK)	Horns Rev I[b] (DK)	Barrow[cd] (UK)	Burbo Bank[e] (UK)	Q7[f] (NL)	Lynn & Inner Dowsing[g] (UK)	Robin Rigg[h] (UK)	Horns Rev II[i] (DK)	Rhyl Flats[j] (UK)
On-line		2001	2002	2006	2007	2008	2009	2009	2009	2009
Turbine manufacturer		Siemens	Vestas	Vestas	Siemens	Vestas	Siemens	Vestas		Siemens
Rotor diameter	[m]	76	80	90	107	80	107	90		107
Turbine capacity	[MW$_e$]	2	2	3	3.6	2	3.6	3		3.6
Number of turbines		20	80	30	25	60	54	60		25
Total capacity	[MW$_e$]	40	160	90	90	120	194	180	200	90
Distance to shore	[km]	2-3	14-20	7	10	23	5	9	42	8
Main cable length	[km]		21	27				13.5	42	
Water depth	[m]	2-6	6-14	15-23	1-8	19-24	6-13		6-14	
Hub height	[m]	64	70	75	88	59	80.5			
Foundation type		caisson	monopile	monopile	monopile	monopile	monopile	monopile	monopile	monopile
Annual electricity generation	[GWh/a]	101	600	305	315	400	659	631	800	
Capacity factor	[%]	29	43	39	40	38	39	40	45.7	
Wind speed	[m/s]	7.2	9.7		> 9				9.7	
1. Total investment cost	[€$_{2006}$ mln]	53.1	291.3	146.7	153.5	376.3	434.8	465	456.2	272.1
Specific investment cost	[€$_{2006}$/kW]	1,327	1,821	1,630	1,706	3,136	2,237	2,583	2,281	3,023
2. Investment wind turbines	[€$_{2006}$ mln]	28.9 [a]			87.4[e]					
Specific investment cost	[€$_{2006}$/kW]	723			972					
3. Investment support structures	[€$_{2006}$ mln]	14.0 [a]	60.7 [b]		35.0[e]					
Specific investment cost	[€$_{2006}$/kW]	351	379		389					
4. Construction and installation	[€$_{2006}$ mln]			30.2[c]						
Specific investment cost	[€$_{2006}$/kW]			336						
5. Investment transformer station	[€$_{2006}$ mln]							30.2 [h]		
Specific investment cost	[€$_{2006}$/kW]							168		
6. Investment **M**ain/**I**nfield cables	[€$_{2006}$ mln]		6_{I} 14.7	$6_{M\&I}$ 8.2 [d]			$6_{M\&I}$ 10 [g]		6_{M} 30 [i]	$6_{M\&I}$ 10.7 [j]
Specific investment cost	[€$_{2006}$/kW]		6_{I} 92	$6_{M\&I}$ 92			$6_{M\&I}$ 52		6_{M} 150	$6_{M\&I}$ 119
7. Transformer station & cables	[€$_{2006}$ mln]	5+6_{I} 4.9 [a]	5+6 61.6 [b]			5+6 26.3 [f]				

a Internet Source 53.
b Internet Source 54.
c Internet Source 55.
d Internet Source 56.
e Wind-kraft Journal, 2007.
f Internet Source 57.
g Internet Source 58.
h Internet Source 59.
I Internet Source 60.
j Internet Source 61.

3.3.6 Ocean energy

Introduction

The potential of ocean energy is huge, although the economical potential is more modest. Ocean energy consists of:

- marine-energy resource of wind-driven waves,
- gravitational tidal ranges,
- marine currents,
- thermal gradients between warm surface water and colder water at depths of >1000 m,
- salinity gradients.

Technologies that are near to commercialisation

Three *tidal-range barrages* with a combined capacity of 260 MW_e are in commercial operation. Due to the harsh environment, installed costs are usually high. The marine energy industry is now in a similar stage of development to the wind industry in the 1980s. Since oceans are used by a range of stakeholders, siting devices will involve considerable consultation. The best *wave energy* climates have deepwater power densities of 60-70 kW/m, but power densities fall to approximately 20 kW/m at the foreshore. Around 2% of the world's 800,000 km of coastline exceeds a power density of 30 kW/m, representing a technical potential of around 500 GW_e, presumed that offshore wave-energy devices have an efficiency of 40%. The total economic potential is estimated to be well below this, with generating cost estimates around 80-110 US$/MWh remaining highly uncertain, since no truly commercial-scale plant exists (IPCC, 2007).

Extracting electrical energy from *marine currents* could yield in excess of 10 TWh/year (0.4 EJ/year) if major estuaries with large tidal fluctuations could be tapped. A 1 km-stretch of permanent turbines built in the Agulhas current off the coast of South Africa, for example, could give 100 MW_e of power. In order for these new technologies to enter the market, sustained government and public support is needed.

Technologies that are more distant

Other technologies may be considered as '*ocean power*' too, viz., *Ocean Thermal Energy Conversion* (OTEC) and *Saline Gradient based power*. However, such technologies are predominantly in the RD&D stage. They may have prospects for commercialisation (see Chapter 4).

Wave power

Wave power is a technology of the '*ocean power*' family that is most advanced, witnessed by:

- *Pelamis*, developed and introduced on the market by Pelamis Wave Power Ltd, UK;
- *Archimedes Waveswing*™ with a linear generator, product of AWS Ocean Energy Ltd;
- *Permanent Magnet Linear Generator Buoy*, developed by Columbia Power Technologies, or 'Columbia Power' (parent company Greenlight Energy Resources, Inc., USA). 'Columbia power' develops wave power devices optimised for use one to three miles offshore, with the greatest energy potential (Internet Sources 62-63; Szabó et al, 2007);
- *Limpet*, a wave power device developed and brought on the market by Wavegen, a subsidiary of Voith Siemens Hydro Power Generation, Germany (Internet Sources 64-65).

The current state-of-the-art of wave power technology may be summarised as follows:

- The 750 kW_e Pelamis - three Power Conversion Modules of 250 kW_e each - is the result of extensive testing, modelling, and development by Pelamis Wave Power Ltd. A 750 kW_e *module* contains a complete electro-hydraulic power generation system. It is moored in waters approximately 50-70 m in depth (5-10 km from the shore) where the high energy levels found in deep swell waves can be accessed. In October 2006, the world's first commercial wave power plant off the north Portugal coast was put in operation (Figure 3.15), based on three Pelamis modules totalling 2.25MW_e (Internet Sources 66-68). Phase 2 of the project would add an additional 28 Pelamis converters to the farm, and increase the generating capacity to 22.5 MW$_\text{e}$ (Internet Source 69).

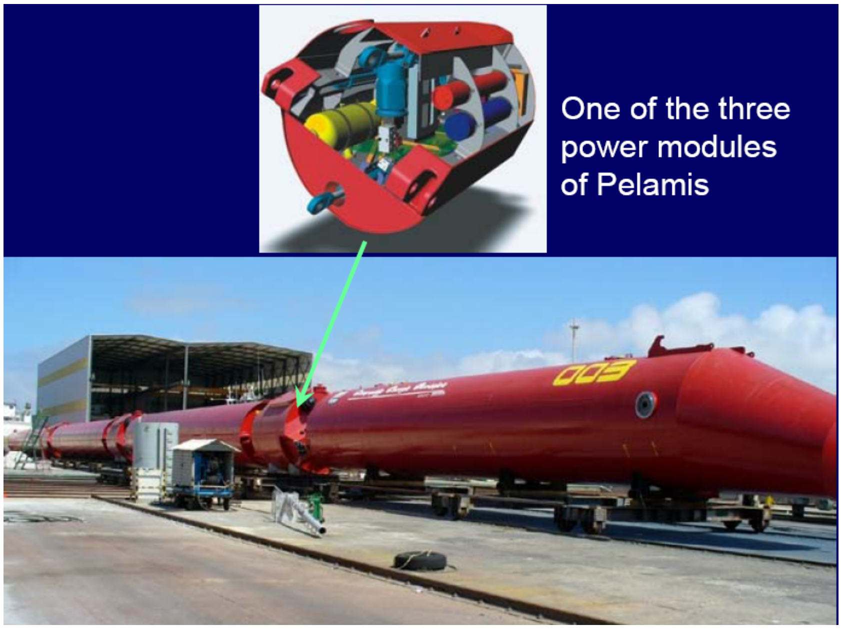


Figure 3.15 *One of three sections of a Pelamis module (Aguçadura, Portugal)*

- In 2004, the first Archimedes Waveswing™ pilot plant - a 1.25 MW$_\text{e}$ unit developed by AWS Ocean Energy (Hamilton, 2006; Internet Source 68) - was moored off the coast of Portugal (Figure 3.16). AWS Ocean Energy Ltd, UK, plans to deploy a 250 kW$_\text{e}$ demonstrator in 2009, with commercialisation a few years later (Internet Source 70).

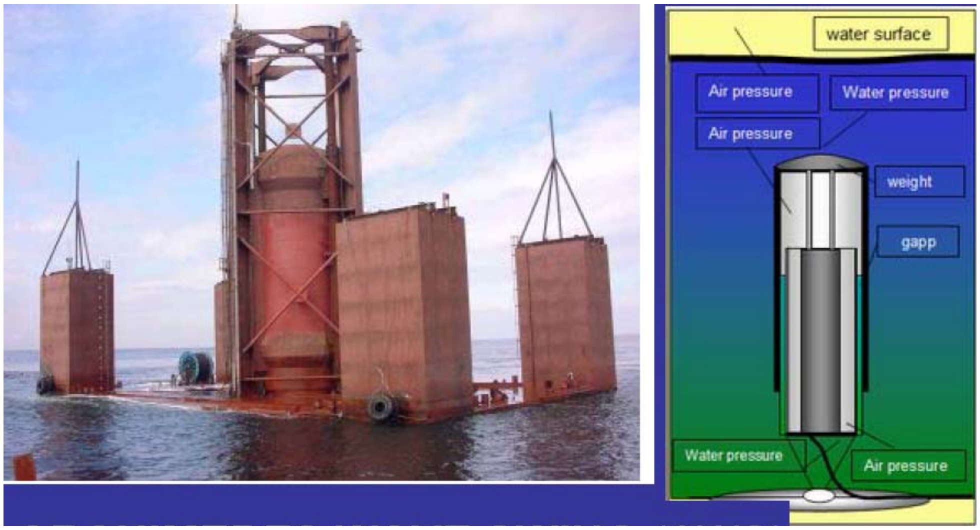
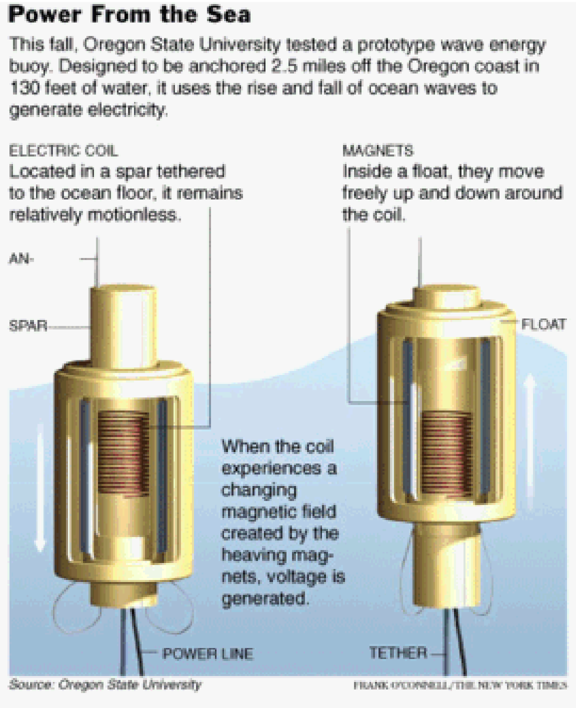


Figure 3.16 *1.25 MW$_\text{e}$ pilot plant Archimedes Waveswing™, Portugal*
Source: Internet Source 68.

- A Permanent Magnet Linear Generator Buoy consists of an electric coil surrounding a magnetic shaft inside the buoy. While the coil is secured directly to the buoy, the magnetic shaft is anchored to the sea floor. When the coil is moved up and down relative to the fixed magnetic shaft, voltage is induced and power is generated (Figure 3.17). Each buoy could potentially produce 250 kW$_e$. This wave power technology is developed by ‘Columbia Power Technologies, LLC’, Columbia, USA (Internet Sources 62-63).



Power From the Sea

This fall, Oregon State University tested a prototype wave energy buoy. Designed to be anchored 2.5 miles off the Oregon coast in 130 feet of water, it uses the rise and fall of ocean waves to generate electricity.

ELECTRIC COIL
Located in a spar tethered to the ocean floor, it remains relatively motionless.

MAGNETS
Inside a float, they move freely up and down around the coil.

When the coil experiences a changing magnetic field created by the heaving magnets, voltage is generated.

Source: Oregon State University

FRANK O'CONNELL/THE NEW YORK TIMES

Figure 3.17 *Permanent Magnet Linear Generator Buoy (‘Columbia Power’)*

- Limpet (Land Installed Marine Powered Energy Transformer) is a wave power device developed by Wavegen, optimised for near-shore application given a suitable wave climate and topography: the water depth at the entrance to an Oscillating Water Column (OWC) is 7 m (Figure 3.18). The water column feeds a pair of counter-rotating turbines driving a 250 kW$_e$ generator, generating a total of 500 kW$_e$ (Internet Sources 64-65).

Figure 3.18 *Limpet sited on the island of Islay, off Scotland’s west coast*

A comparable wave power concept - an overtopping wave power device - and other wave power concepts are developed and tested by WAVEenergy AS of Norway (Internet Source 71).

Tidal power

Tidal power consists of two related technologies. Worldwide, there are three operative tidal power plants based on '*tidal-range barrages*' (combined capacity 260 MW$_e$). Tidal power based on a *tidal barrage* is a prospective technology for the UK, in particular the Severn estuary. This technology is more or less mature, although its application so far is limited (comparable to the global capacity of CSP). More attention is paid to *tidal stream power* (Figure 3.19).

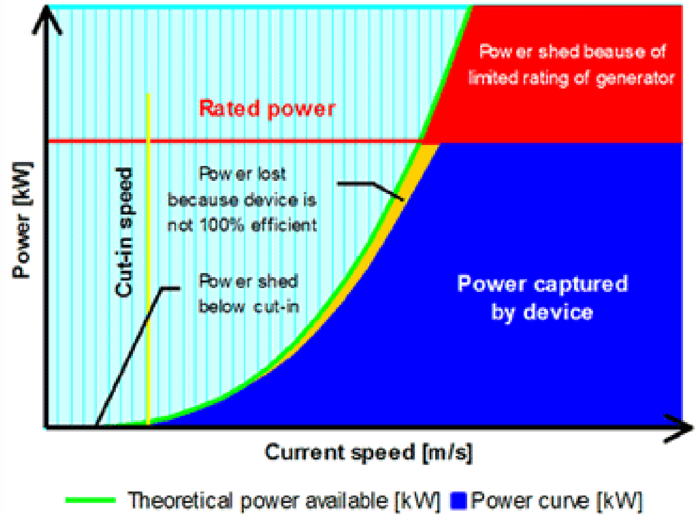


Figure 3.19 *Example of power curve of a tidal stream power device*
Source: Internet Source 72.

Until this date, three technologies for *tidal stream power* seem to offer commercial perspectives:

- SeaGen, a technology developed by Marine Current Turbines Ltd, a subsidiary of Marine Current Turbines Ltd, UK (Internet Sources 73-74). In 2008, a 1.2 MW$_e$ tidal stream unit was moored at the southern shore of Strangford Lough, UK (Figure 3.20).

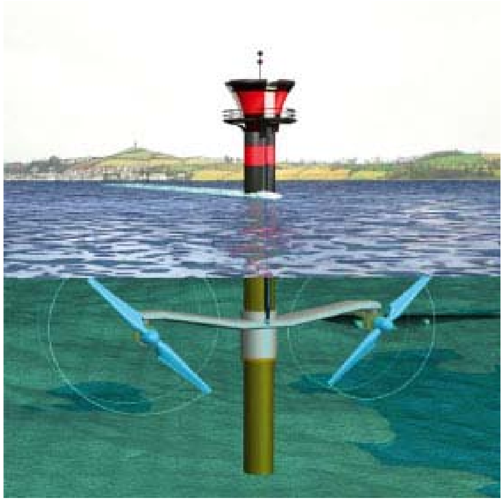


Figure 3.20 *SeaGen tidal power (artist impression), Marine Current Turbines Ltd*
Source: Internet Source 73.

- In 2003, a tidal stream technology developed by 'Hammerfest Strøm' - largely owned by the company Statoil (Norway) - created a 'worlds-first' by installation of a 300 kW$_e$ prototype tidal turbine, at 50 metres depth in Kvalsundet off Hammerfest (Figure 3.21). In 2007, Hammerfest Strøm signed a contract with Scottish Power to further develop the technology for tidal power in Scotland (Internet Sources 75-76).

Figure 3.21 *Prototype tidal stream unit Hammerfest Strøm (parent company Statoil)*
Source: Internet Source 75.

- In March 2008, UK-based Lunar Energy announced an agreement with Korean Midland Power Co (KOMIPO) to build a 300-turbine tidal stream power plant in the Wando Hoenggan Water Way off South Korea. The plant will provide 300 MW$_e$ to Korean Midland Power Co by the end of 2015 (Internet Source 77). Fabrication and installation of the tidal turbines will be carried out by Hyundai Samho Heavy Industries (HSHI). Figure 3.22 shows a scheme of a tidal stream power unit of Lunar Energy.

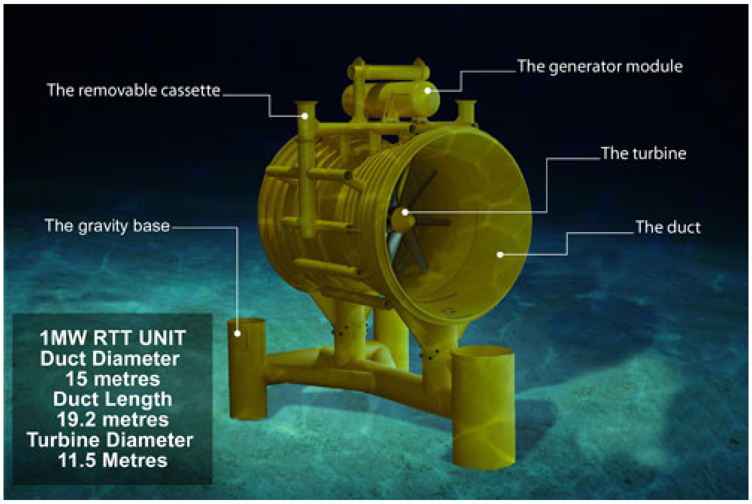


Figure 3.22 *Scheme of tidal stream power unit Lunar Energy (UK)*
Source: Internet Source 77.

It has been noted that it is a question mark whether wave and tidal stream power may be categorised as 'commercial', given the limited experience gathered in demonstration projects. Also, it should be acknowledged that there are still questions about connection to the shore, possible conflict with commercial fishing, environmental impacts, corrosion, materials, etc.

3.3.7 Geothermal energy

Geothermal resources from low-enthalpy fields have long been used for direct heat extraction for district heating, industrial processing, domestic water and space heating, etc. High-quality high-enthalpy fields (with high-temperature natural steam reached by drilling at depths less than 2 km) where temperatures are above 250ºC allow for direct power generation using binary power plants (with low boiling-point transfer fluids and heat exchangers), Organic Rankine Cycle (ORC) systems or steam turbines. Capacity factors range from 40 to 95% (71% on average) with some therefore suitable for base load. On a global scale, heat and power produced is approximately 2 EJ/year. In 2007, the operational geothermal capacity was 8.6 GW_e (Table 3.9).

Fields of natural steam are rare: only two geothermal fields in the world, Larderello, Italy, and The Geysers, United States, *are vapour-dominated* (Renner, 2002). Most are a mixture of steam and hot water requiring single- or double-flash systems to separate out the hot water, which can then be used in binary plants (*approximately 12% of global capacity*) or for direct use of the heat. Sustainability concerns relating to land subsidence, heat-extraction rates exceeding natural replenishment, chemical pollution of waterways (e.g. with arsenic), and associated CO_2 emissions have resulted in some permits for geothermal plants being declined. This could be partly overcome by re-injection techniques. For environmental aspects, see e.g. (Lundin et al, 2006).

Deeper drilling up to 8 km to reach molten rock magma resources may become technically feasible, which does not necessarily imply that it will be cost-effective. Deeper drilling technology may be the key to develop widely abundant *hot dry rocks* (HDR), currently denoted as enhanced geothermal systems (EGS) - water injected into artificially fractured rocks and heat extracted as steam. In addition, ground-to-air heat pumps (*geothermal heat pumps*) for heating buildings may show increasing growth. Geothermal energy may be subdivided in three main applications, which are addressed below:

- Geothermal power (including CHP)
- Geothermal heat
- Geothermal heat pump.

Geothermal power

Table 3.8 presents a view of global geothermal power generation (Bertani, 2006-2007; DiPippo, 1999). Figure 3.22 gives a corresponding view presented as a graph based on (Sanner, 2007).

Table 3.8 *Operational and projected geothermal power generation by country*

Countries with geothermal power	Operational capacity 2005 [MW_e]	Annual energy produced [GWh/year]	Operational capacity 2007 [MW_e]	Projected capacity 2010 [MW_e]	Plant types [a] (DiPippo, 1999)
Australia	0.1	0.5	0.1	0.2	B
Argentina	(0.7)	N/A	-	-	B
Austria	1.1	3.2	0.7	1	B
China	18.9	96	18.9	28	1F, 2F, B
Costa Rica	162.5	1,145	162.5	197	1F
El Salvador	119	967	189	204	1F, 2F
Ethiopia	7.3	0	7.3	7	H
Guadeloupe	14.7	102	14.7	35	2F
Germany	0.2	1.5	8.4	8	B
Guatemala (F)	29	212	49.0	53	2F
Iceland	202	1,483	420.9	580	1F, 2F, H
Indonesia	838	6,085	991.8	1,192	DS, 1F
Italy	699	5,340	711.0	910	DS, 2F, H
Japan	530.2	3,467	530.2	535	DS, 1F, 2F
Kenya	128.8	1,088	128.8	164	1F
Mexico	953.0	6,282	953.0	1,178	1F, 2F, H
New Zealand	403	2,774	373.1	590	1F, 2F, H
Nicaragua	38	271	52.5	143	1F
Papua New Guinea	6	17	56.0	56	N/A
Philippines	1,838	9,253	1,855.6	1,991	1F, 2F, H
Portugal (Azores)	13	90	23.0	35	1F, H
Russia	79	85	79.0	185	1F
Thailand	0.3	1.8	0.3	0.3	B
Turkey	18	105	29.5	83	1F
United States	1,935	17,917	1,935.0	2,817	DS, 1F, 2F, B, H
Total	8,035	56,786	8,590	10,993	

a DS = Dry steam, 1F = Single flash, 2F = Double flash, B = Binary, H = Hybrid; explained in the following.

Sources: Bertani, 2006-2007; DiPippo, 1999.

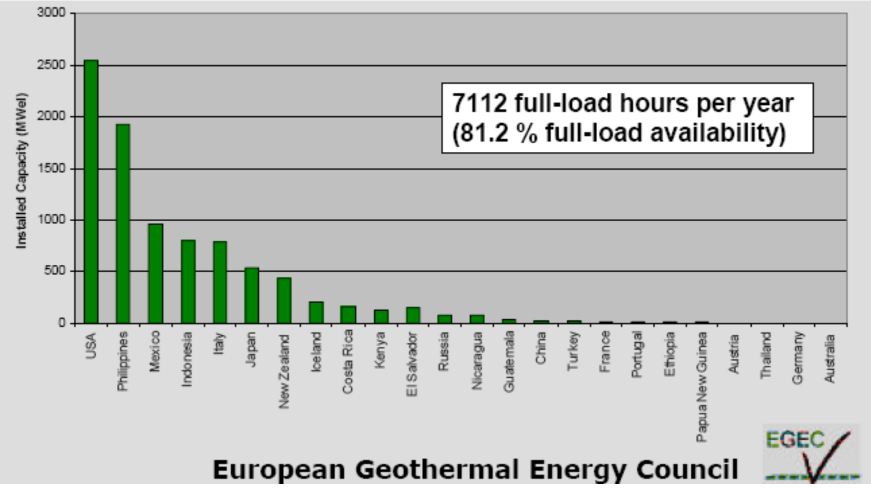


Figure 3.23 *Geothermal power generation capacity (installed) by 2007 [MW_e]*

From 2000 through 2005, geothermal power generation tripled in France, Russia, and Kenya. Austria, Germany, and Papua New Guinea are relatively new countries producing geothermal power (Internet Source 78). Also, a geothermal power plant (≤100 MW_e) is prepared for Canada (Internet Source 79). There are three main geothermal power technologies (Internet Source 80):

- *Dry Steam Power Plants*

In Dry Steam power plants, hot steam goes directly to a turbine/generator (Figure 3.23).

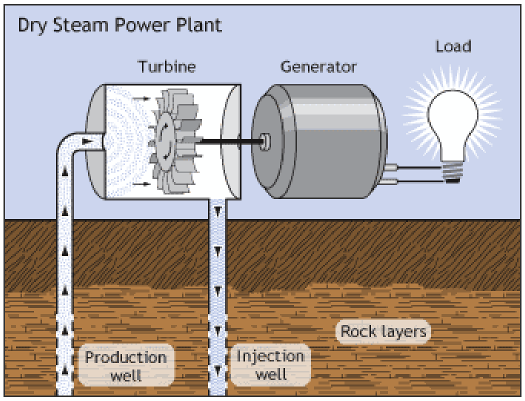


Figure 3.24 *Scheme of Dry Steam Power Plant*

- *Flash Steam Power Plants*

Flash Steam power plants require hydrothermal fluids in excess of 150°C (Figure 3.24).

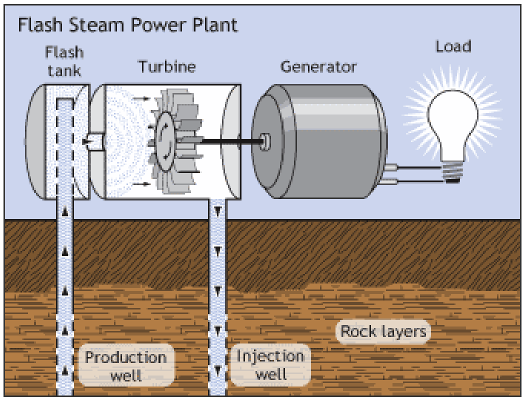


Figure 3.25 *Scheme of Flash Steam Power Plant*

- *Binary-Cycle Power Plants*

Most geothermal areas contain moderate-temperature water, viz. of 80-150°C. Energy is extracted from these fluids in Binary-Cycle power plants (Figure 3.25).

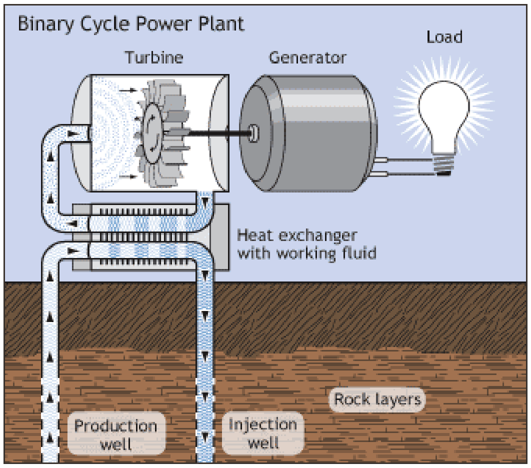


Figure 3.26 *Scheme of Binary-Cycle Power Plant*
Source: Internet Source 80.

Table 3.9 summarises characteristics of three geothermal power options. Ormat, headquartered in the USA, supplies Binary-Cycle power plants. Ormat has successfully supplied in excess of 950 MW_e of geothermal power plants, based on its proprietary technology[12] (Internet Source 81).

Table 3.9 *Comparison between three options for geothermal power*

Type of plant	Temperature needed [°C]	Unit size (installed capacity) [MW_e]	Average power rating of unit [MW_e]
Dry Steam	180-300+	15-120	39
Double-Flash	240-320	5-110	30
Single-Flash	200-260	3-90	28
Binary Cycle	85-200	1-10	2

Source: Lundin et al, 2006.

Also small-scale geothermal power projects (up to 5 MW_e) draw much attention (Kutscher, 2001; Rybach, 2008). Geothermal power projects of a few 100 kW_e are developed in Europe - Germany, Austria, and France - as well as in the USA and elsewhere. In 2007, a 225 kW_e Binary-Cycle power plant was put in operation in central Alaska (Internet Source 82). The production temperature from the wells is as low as 74°C[13]. The low temperature difference of 49°C and the location favour Binary-Cycle technology. In Germany, a feed-in tariff for geothermal power (CHP) favours small-scale geothermal projects (Sanner, 2007) (Figure 3.26).

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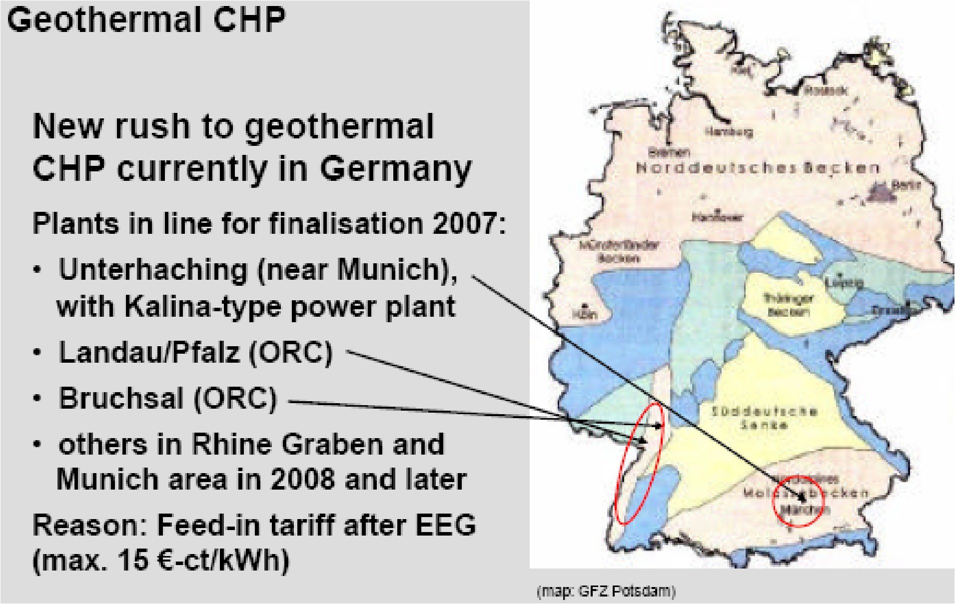
[12] This is equivalent to approximately 12% of the (operational) global geothermal capacity.

[13] In Germany, a comparable project in Neustadt-Glewe shows a primary water temperature of 98°C (Sanner, 2007).



Geothermal CHP

New rush to geothermal CHP currently in Germany

Plants in line for finalisation 2007:

- **Unterhaching (near Munich), with Kalina-type power plant**
- **Landau/Pfalz (ORC)**
- **Bruchsal (ORC)**
- **others in Rhine Graben and Munich area in 2008 and later**

Reason: Feed-in tariff after EEG (max. 15 €-ct/kWh)

(map: GFZ Potsdam)

Figure 3.27 *Geothermal power generation in Germany*
Source: Sanner, 2007.

(MIT, 2006) and (Rybach and Mongillo, 2006) indicate that 'Enhanced/Engineered Geothermal Systems' offer additional potential for the USA. There is ample potential for development of geothermal power (Lundin et al, 2006): the global geothermal potential is 22,400 TWh/year, of which 3,700 TWh/year is in Europe. According to Bertani, the worldwide geothermal capacity may increase from 8,590 MW_e in 2007 to approx. 11,000 MW_e in 2010 (Table 3.9).

Geothermal heat (direct use) and geothermal heat pump
With regard to *direct use* of geothermal, Table 3.10 presents an overview of geothermal heat.

Table 3.10 *Worldwide direct use of geothermal heat (2000)*

Country	Operational capacity [MW_{th}]	Energy produced annually [GWh_{th}/a]	Capacity factor []
China	2,282	10,531	0.53
France	326	1,360	0.48
Georgia	250	1,752	0.80
Hungary	473	1,135	0.27
Iceland	1,469	5,603	0.44
India	80	699	1.00
Italy	326	1,048	0.37
Japan	1,167	7,482	0.73
Mexico	164	1,089	0.76
New Zealand	308	1,967	0.73
Romania	152	797	0.60
Russia	308	1,707	0.63
Serbia	80	660	0.94
Slovak Rep.	132	588	0.51
Sweden	377	1,147	0.35
Switzerland	547	663	0.14
Turkey	820	4,377	0.61
USA	3,766	5,640	0.17
Other	2,118	4,731	0.25
Total	15,145	52,976	0.40

Source: Stefansson, 2007.

Geothermal heat pumps are ground-coupled heat pumps, operating with subsurface heat exchanger pipes (horizontal or vertical) or groundwater boreholes (Rybach and Mongillo, 2006). It is deemed likely (Grímsson, 2007) that heat pumps will become competitive where water above 50°C is not found. In such places, heat pumps can be used instead of direct electrical heating to raise the temperature of warm spring water. Figure 3.27 shows the components of a geothermal heat pump: the heat pump, earth connection, and heat distribution system (RETScreen, 2005).

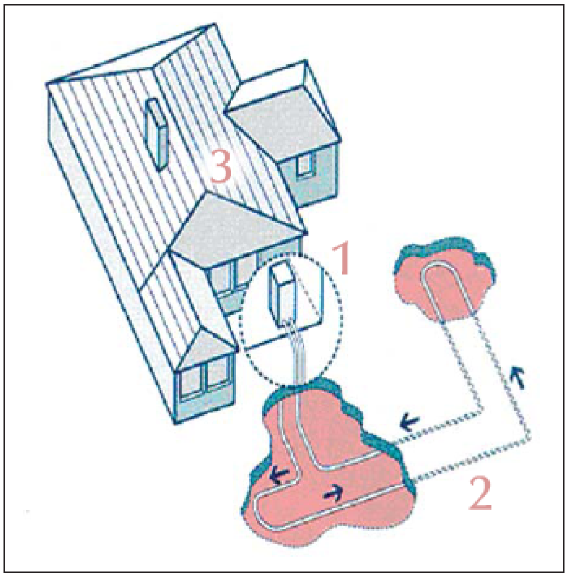


Figure 6:

The three GSHP System Major Components:
(1) Heat Pump,
(2) Earth Connection, and
(3) Heating/Cooling Distribution system.

Figure 3.28 *Main components of geothermal heat pumps*
Source: RETScreen, 2005.

According to (Internet Source 83), the heat generated directly from geothermal sources and by geothermal heat pumps is as shown in Table 3.11. Until recently, almost all of the geothermal heat pump installations have been in North America and Europe. China, however, is the most significant newcomer. According to the Geothermal China Energy Society (February 2007), space heating with ground-source heat pumps expanded from 8 million m^2 in 2004 to 20 million m^2 in 2006. Conventional geothermal space heating in China had grown from 13 million m^2 in 2004 to 17 million m^2 in 2006 (Internet Source 84).

Table 3.11 *Direct heat from geothermal sources and geothermal heat pumps, 2005*

	Direct geothermal heat [TJ/year]	Geothermal heat pumps [TJ/year]	Total geothermal heat [TJ/year]
Australia	2,712	30	2,741
Austria	780	1,450	2,230
Belgium	54	324	378
Canada	26	2,160	2,186
Czech Republic	-	1,130	1,130
Denmark	460	3,940	4,400
Finland	-	1,950	1,950
France	4,030	469	4,499
Germany	604	2,200	2,804
Greece	14	39	53
Hungary	1,017	23	1,039
Iceland	17,900	20	17,920
Ireland	-	84	84
Italy	1,711	500	2,211
Japan	1,410	22	1,432
South Korea	-	12	12
Mexico	13	-	13
The Netherlands	-	685	685
New Zealand	700	-	700
Norway	-	3,085	3,085
Portugal	13	-	13
Spain	102	-	102
Sweden	7,560	36,000	43,560
Switzerland	134	2,854	2,988
Turkey	8,530	-	8,530
United Kingdom	-	46	46
United States	9,024	22,215	31,239
Total	56,794	79,237	136,031

Source: Internet Source 83.

3.3.8 Hydro power

Introduction

Generally, a distinction is made between large (>10 MW_e), small (1-10 MW_e), and micro (<1 MW_e) hydro power. Where expansion of large hydro power is occurring, particularly in China and India, major social disruptions, ecological impacts on existing river ecosystems and fisheries and related evaporative water losses are stimulating public opposition. Land-use and environmental concerns may mean that obtaining resource permits is a constraint. At the end of 2006, the global capacity of large-scale hydro power stood at approx. 870 GW_e (REN21, 2008).

Small (or micro) hydro power does not raise so many environmental concerns, as many schemes are based on run-of-river power plants without (large) dams. The global technical potential of small and micro hydro is around 150-200 GW_e with many unexploited resource sites available. About 75% of water reservoirs in the world were built for irrigation, flood control and urban water-supply schemes and many could have small hydro power generation retrofits added. In 2006, the global capacity of small-scale hydro power stood at approx. 73 GW_e (REN21, 2008).

(Lako et al, 2003) summarise the development of hydro power in the world. Whereas hydro showed substantial growth in OECD countries in the 20th century, most of the growth of renewables in the next decades is expected to come from wind and biomass. In developing countries, however, hydro is expected to be the fastest-growing renewable energy source (IEA, 2002).

River power plants and high-pressure systems with reservoirs and dams convert the kinetic energy with turbines and generators into electrical energy. Hydro power systems are also used for flood control and irrigation. Storage systems with pumps allow storage of energy for different time horizons (daily, weekly, or seasonally).

At present, approximately 19% of global electricity generation comes from hydro power. The current global generation of 2,700 TWh/yr based on a total hydro power capacity of 715 GW_e corresponds to 33% of the economically feasible potential and 19% of the technical potential. That would mean that - theoretically - the world electricity demand could be met by hydro power[14].

Untapped hydro power potential is identified in developing countries of South and Central Asia, Latin America, and Africa, but also in Canada, Turkey, and Russia. In Europe and the USA, the additional hydro power potential is limited, because of advanced development but also due to environmental and political reasons. However, in these countries (notably in the USA) modernisation of hydro power stations could add considerable amounts of electricity - a figure of 12-35% is found in literature - compared to the current generation of hydro power.

Worldwide, there are many and sometimes huge projects under construction or planned (Table 3.12). In Central and Eastern Europe the focus is on modernisation of hydro power plants. In the USA and in Europe, new large-scale hydro power plants are generally not accepted for environmental reasons. The focus is on upgrading of hydro power plants and on relatively small hydro projects that are assumed to be more environmentally benign than large hydro plants.

Table 3.12 *Hydro capacity under construction or planned in selected world regions (2003)*

Region or country	Commissioning date	Under construction or planned [GW_e]
Canada	2003-2012	6.6
Mexico	2007-2012	5.7
Central America	2003-2016	4.4
South America	2003-2010 (and beyond)	34.9
China	2002-2020	77.7
India	2003-2014	>11.6
Nepal	2003-2010 and beyond	20.5
Pakistan	2003-2010 and beyond	>7.1
Myanmar	2003-2010 and beyond	4.5
Vietnam	2003-2016	5.7
Africa	2003-2010 and beyond	9.0
Turkey	2003-2009 and beyond	>3.6

Note: The capacities presented refer to 2003.

Comment: Around 2003, the installed electricity generation capacity in China was 0.25 kW per capita. The generation was 1,064 kWh/capita (compared to 2,200 kWh/capita for the world). The total power generated in China amounted to 1,500 TWh from 355 GW. By that time, the additional installed capacity was about 20 GW/yr. The power generation was expected to consist of 72.4% thermal power generation, 24.5% hydro, 2.4% nuclear, and 0.7% ‘new energy’ in 2005.

Sources: Lako et al, 2003; Internet source 85.

Classification

There are several classifications related to dimensions of hydro power, e.g. (Internet source 86):

- Micro hydro: <100 kW_e;
- Mini hydro: 100 - 500 kW_e;
- Small hydro: 500 kW - 50 MW_e;
- Large hydro: >50 MW_e.

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[14] Reference is made to several categories of potentials addressed in Section 3.1.

The EU regards 'small' hydropower as less than 10 MW_e. This definition has been adopted by the European Small-Hydropower Association (ESHA), according to (Internet Source 87). Hydro power plants larger than 10 MW_e are 'large-scale'.

Environmental issues

The past has shown that hydroelectric power plants especially in large-scale projects can induce several environmental issues (Internet source 88):

- Blocking fish moving up the river to the spawning grounds.
- Decreasing of wildlife in river grounds and former rain forests by flooding.
- Dislocation of people for dam projects, e.g. in case of Three Gorges Dam (China) 1.13 million people.
- Oxygen reduction in the water by rotting of flooded vegetation killing fish and plants.
- Emission of methane after rotting. Methane is a strong greenhouse gas that has 21 times more effect than CO_2.
- Dissolving of natural metals from stones and soils (e.g. mercury) after flooding.
- Water quality (oxygen reduction) and sedimentation problems (filling) by reducing the flow speed.
- Problems for fish population as a result of flushing for clearing sedimentation.
- Stranding fish in shallow water areas by power plant operation.
- Potential dam breaking (war, earthquakes).

Types and main components

There are basically four types of hydro power plants (Internet Source 89):

- *Pelton turbine*. This is an impulse turbine which is normally used for more than 250 m of water head.
- *Francis turbine*. This is a reaction turbine which is used for a water head varying between 2.5 and 450 m.
- *Kaplan turbine*. It is a propeller type of plant with adjustable blades which are used for water heads varying between 1.5 m to 70 m.
- *Propeller turbine*. This type is used for a water head between 1.5 to 30 m.
- *Tubular turbine*. This type is used for low and medium height projects, normally for a water head of less than 15 m.

The main components of hydro power based on dams are (Internet Source 90):

- The reservoir, storing water from a natural water body like a river. This reservoir is built at a level higher than the turbine.
- The dam, which obstructs the flow of water stored in the reservoir by huge walls (the dam), thereby harnessing the energy present in the water stored. The dam has gates present at its bottom, which can be lifted to allow the flow of water through them.
- The penstock, connecting the reservoir with the turbine propeller and running in a downward inclined manner. When the gates of the dam are lifted, gravity makes the water flow down the penstock and reach turbine. As the water flows through the penstock, the potential energy of water stored in the dam is converted into kinetic energy.
- The turbine, of which the blades are turned by the kinetic energy of the running water. The turbine can be either a Pelton Wheel Model or a Centrifugal type. The turbine has a shaft connected to the generator.
- The generator, which is connected to the turbine by a shaft. When the blades of the turbine rotate, the shaft drives a motor which produces electric current in the generator. If needed, the generator can be designed to act as a motor: hydro pumped storage.
- Power lines, which connect the hydro power plant with power distribution stations.

Run-of-river hydro power plants show similar components, except the reservoir and dam.

Construction and generation costs
A key feature of investments in hydroelectric power generation is that they require long-term loans with extensive grace periods because they are capital-intensive, have a long construction phase with significant risks and have a long useful life. The average construction costs of hydro power are between US$ 1,100/kW[15] (China, Latin America) and US$ 1,400-1,800/kW (Africa, India, Turkey), with exceptions both of higher and lower construction costs. The generation costs may be very low, especially for existing hydro power. On average, the cost of electricity of existing hydro power is less than a third of that of coal- or gas-fired power or nuclear power.

Global potential and manufacturing base
In countries with a presently high share of small-scale hydro power plants, this share is expected to stagnate or even decline. Only in areas dominated by large hydro power projects, the future could bring an increased market penetration of small hydro (Table 3.13). In Europe (including Turkey), an additional 45 TWh/a (11 GW_e) of small-scale hydro and 400 TWh/a (127 GW_e) of large-scale sites could be exploited in the period 2003-2014 (Internet Sources 90-91). On the global scale, the relation between small hydro (including mini/micro) and large hydro power was 1:20 (115 and 2,260 TWh, respectively) in 1995. For 2010, this relation is expected to be 1:18 (220 and 3,990 TWh, respectively) based on (Internet source 92).

Large hydropower plants are produced in Europe (Voith Siemens, Alstom), the USA (GE), Canada, China, India, and other countries. The manufacturing base for small hydro power plants is broader, encompassing the OECD, FSU, China, India, Brazil, and others (Internet Source 91).

3.3.9 Biomass

Biomass continues to be the world's major renewable resource for use as heat, electricity, liquid fuels and chemicals. Woody biomass and straw can be used as materials, which can be recycled for energy at the end of their life. Biomass sources include forest, agricultural and livestock residues, short-rotation forest plantations, dedicated herbaceous energy crops, the organic component of Municipal Solid Waste (MSW), and other organic waste streams. These are used as feedstocks to produce energy carriers in the form of solid fuels (chips, pellets, briquettes, and logs), liquid fuels (methanol, ethanol, biodiesel, etc), gaseous fuels (biogas, synthesis gas, and hydrogen), power, and heat.

Globally, biomass currently provides around 43.6 EJ of bio-energy in the form of combustible biomass and wastes, liquid biofuels, renewable MSW, solid biomass/charcoal, and gaseous fuels (2005). This share is estimated to be over 10% of global primary energy, but with over two thirds consumed in developing countries as traditional biomass for household use (IEA, 2007). In 2001, combustible renewables and waste contributed 6.7 EJ/year to the energy supply of IEA countries, mainly for heat and power generation (IEA, 2004). In developing countries, use of biomass entails inefficient combustion, often combined with significant local and indoor air pollution and unsustainable use of biomass resources such as native vegetation. Digestion of wet biomass streams is a commercially available technology with many (e.g., agricultural) applications. As these applications increase, the technologies become more competitive.

The potential of residues from industrialised farming, plantation forests, and food- and fibre-processing operations that are currently collected worldwide and used in modern bio-energy plants is difficult to quantify but probably supply approximately 6 EJ/year. They can be classified as primary, secondary, and tertiary. Current combustion of over 130 Mt of MSW provides more than 1 EJ/year though this includes plastics, etc. Landfill gas also contributes to biomass supply at over 0.2 EJ/year.

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[15] The specific investment costs quoted refer to cost figures in US$ of 2003 in (Lako et al, 2003).

A wide range of conversion technologies is under continuous development to produce bio-energy carriers for small- and large-scale applications. Organic residues and wastes are often cost-effective feedstocks for bio-energy conversion plants, resulting in niche markets for forest, food processing, and other industries. Industrial use of biomass in OECD countries was 5.6 EJ in 2002, mainly in the form of black liquor in pulp mills, biogas in food processing plants, and bark, sawdust, rice husks etc. in process heat boilers (IPCC, 2007).

Combustion for heat and steam generation remains state of the art, but advancing technologies include second-generation biofuels, Biomass Integrated Gasification Combined Cycle (BIGCC), co-firing (with coal or gas), and pyrolysis. Many are close to commercial maturity but awaiting further technical breakthroughs and demonstrations to increase efficiency and reduce costs.

Biochemical conversion using enzymes to convert lingo-cellulose in sugars that, in turn can be converted in bioethanol, biodiesel, di-methyl ether (DME), hydrogen and chemical intermediates in bio-refineries is not yet commercial. Biochemical- and Fischer-Tropsch based thermochemical synthesis processes can be integrated in a single bio-refinery such that the biomass carbohydrate fraction is converted in methanol or biodiesel and the lignin-rich residue gasified and used to produce heat for process energy, electricity and/or fuels, thus greatly increasing the overall system efficiency to 70-80%.

Biomass is considered the renewable energy source with the highest potential to contribute to the energy needs of modern society for both the developed and developing economies worldwide (Maniatis, 2002). There is much interest in application of biomass with a sustainable origin and in biomass-based RD&D. Bio-energy technologies can be divided into five categories, viz.:

- Medium and large-scale power (20-250 MW_e) or combined heat and power (CHP).
- Small-scale CHP or bio-power (defined here as <20 MW_e).
- Biomass-based heat generation.
- Digestion of wet biomass streams (manure).
- Biofuels (mainly) for transport.

In order to put solid biomass technologies in perspective, Figure 3.27 - based on (Cobb, 2007) and (Obernberger and Biedermann, 2005) - shows the development of biomass technologies compared to technologies based on waste, coal, or lignite. Figure 3.27 characterises the stage of development of a technology, but the timescale is tentative. Some technologies, e.g., coal- or biomass-based IGCC (Integrated Gasification Combined Cycle) are not completely commercial. Technologies based on waste or coal became commercial before comparable biomass-based technologies. A few biomass-based technologies may be considered as commercial, viz. small-scale heat generation, power generation and CHP on a medium or large scale (20-250 MW_e), and some technologies for production of biofuels.

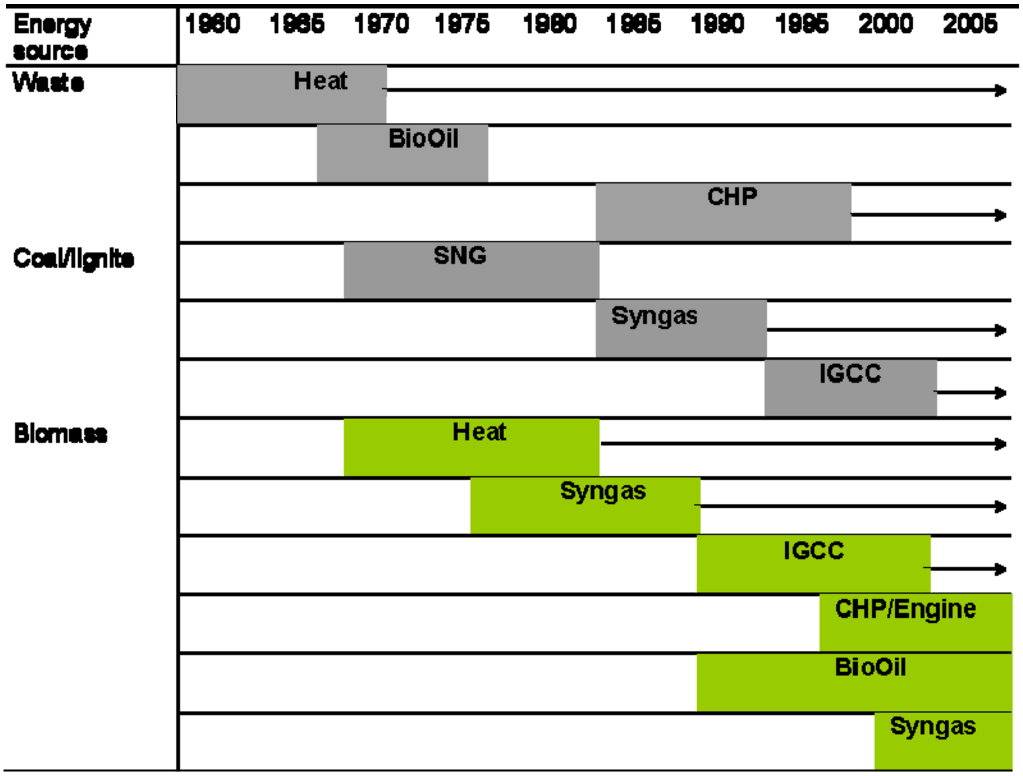

Figure 3.29 *Solid biomass technologies compared to waste- or coal-based technologies*

Notes: CHP = Combined Heat and Power, IGCC = Integrated Gasification Combined Cycle (power generation), SNG = Substitute Natural Gas.
Some technologies are commercially available (CHP from waste and biomass), others are in the pre-commercial stage (biomass IGCC) or under development (second generation 'BioOil'), denoted by arrows.

Note: Based on (Cobb, 2007) and (Obernberger and Biedermann, 2005).

Medium- and large-scale power or CHP

There are various technologies for medium- and large-scale power - defined as 20-250 MW$_e$[16] - or Combined Heat and Power (CHP) based on biomass. For this type of power plants, mainly Bubbling Fluidised Bed (BFB) boilers (maximum capacity 120 MW$_e$) and Circulating Fluidised Bed (CFB) boilers (maximum capacity 240 MW$_e$) with steam cycle are used (Kinni, 2006). Such power plants have a generating efficiency of approx. 30-34% and are utilised in the pulp and paper industry or based on local biomass or urban wood waste (Wiltsee, 2000). BFB boilers are in use since 1974 and CFB boilers since 1980 (Kinni, 2006). Thus, biomass-fuelled power or CHP based on fluidised bed combustion - BFB or CFB - is a mature commercial technology.

Alternatively, gasification may be used to produce gas from biomass and subsequently burn it in a gas turbine/generator or combined cycle power plant. This technology is used since the 1990s and is still developed further (Ståhl et al, 2004; Kwant and Knoef, 2004). Integrated gasification combined cycle (IGCC) plants based on biomass may have a capacity of approx. 50 MW$_e$. IGCC plants are in operation in the USA and Europe. Problems encountered are related to gas-cleaning and process integration (Stevens, 2001). Biomass-based IGCC offers higher generating efficiencies - up to 40-45% - than plants based on fluidised bed boilers. If integrated with an existing pulverised coal-fired power or IGCC plant, the generating efficiency may be approximately 35-40% (e.g., if based on application of a separate biomass gasifier). IGCC technology may also be used for gasification of waste (Belgiorno et al, 2003; Lundberg and Morris, 1999).

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[16] The range up to 20 MWe is denoted as 'small-scale CHP/ bio-power', based on (Savola, 2005) and (Savola, 2007).

Small-scale CHP or bio-power

Similar considerations apply to small bio-power plants, viz. <20 MW_e. Biomass-based combustion or gasification plants with a capacity of 5-20 MW_e are relatively mature, but smaller bio-power plants (<5 MW_e) based on gas engines or Stirling engines deserve further development (Lilley, 2006). There is much experience with fluidised bed gasification (Bruno, 2006). Figure 3.28 shows several bio-power systems (Sims, 2003). Many options, e.g., based on fuel cells, are still in the stage of RD&D. Very small-scale bio-power (<5 MW_e) is still on the learning curve.

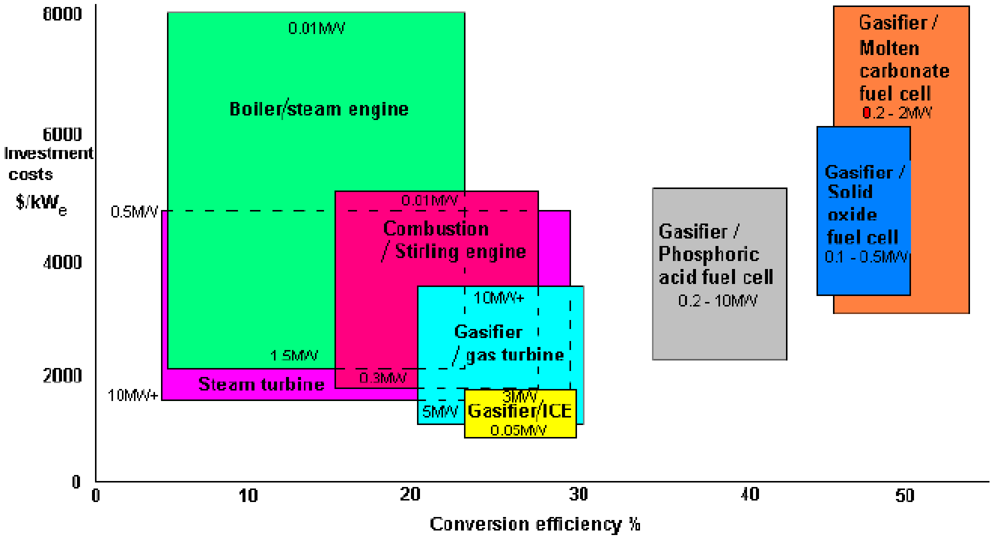

Figure 3.30 *Small-scale power generation options based on solid biomass*

Note: Investment costs (in $/kW) are higher for small boiler/steam engine combinations and combustion/Stirling engines than for larger ones.

Source: Sims, 2003.

Digestion of wet biomass streams

Digestion is a more or less commercial technology used to produce biogas - and subsequently CHP or power - from wet biomass: wet manure, waste-water, the organic fraction of municipal solid waste, etc (Duff, 2007). There are several types of digesters. The technology is relatively mature, but there is still room for further development (Verma, 2002; Chynoweth, 2006). Power plant capacities of anaerobic digestion plants range from hundreds of kW_e to about 10 MW_e.

For these and other aforementioned (commercial) biomass technologies, manufacturers are found in OECD countries, Asia (China, India) and others like South Africa (Internet Source 92).

Biofuels

Bioethanol, biodiesel, and Pure Plant Oil (PPO) are important biofuels. Bioethanol can be produced from raw materials containing fermentable sugars as sugar cane and beet that are rich in sucrose. It may also be produced from polysaccharides that can be hydrolysed for obtaining sugars convertible into ethyl alcohol. Starch contained in grains is the major polymer used for ethanol production. Ligno-cellulosic biomass (a complex comprised of several polysaccharides) is the most promising feedstock considering its great availability and low cost, but large-scale production from ligno-cellulosic materials is not yet commercial (Cardona and Sánchez, 2007).

Biodiesel is produced from 'virgin' vegetable oils (soy, Canola, corn, mustard, palm, refined tall oil, peanuts, olive, sesame, hemp, etc. [17]), animal fats, or recycled grease. Pure plant oil (PPO) may be produced from, e.g., rapeseed, sunflower, or Jatropha. Normally, only after inter-

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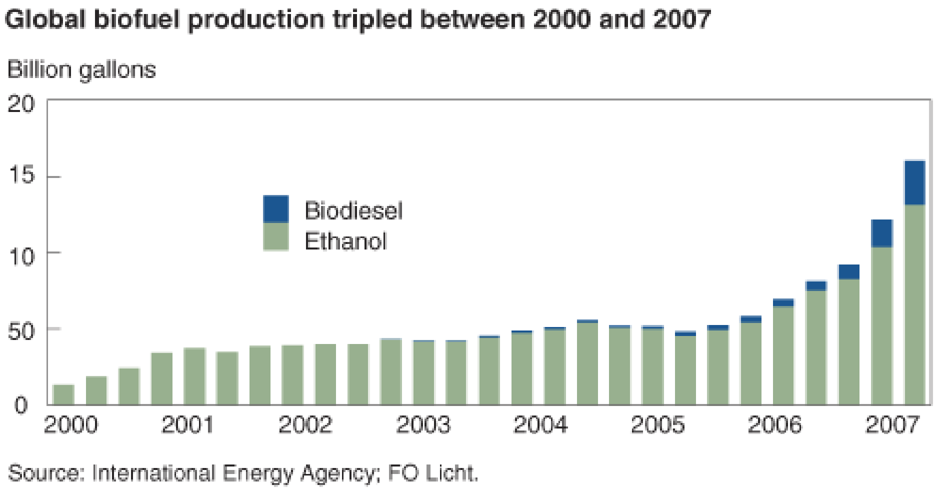
[17] Today, between 75 and 90% of U.S. biodiesel production is based on production of soybean oil (CARD, 2007).

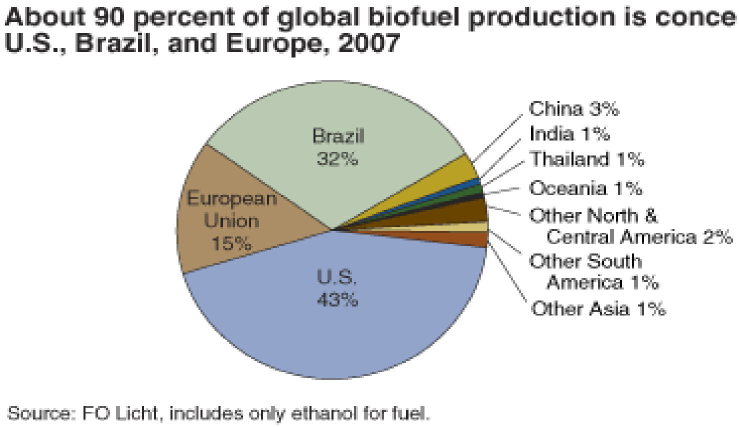
esterification, it may substitute diesel (Internet Source 94). Figure 3.29 presents the growth of global biofuel production (Internet Source 95). Biofuel production more than tripled between 2000 and 2007. In 2007, biofuels had a modest share of only 1.3% in global road transport fuel consumption (Suzuki, 2008).


Global biofuel production tripled between 2000 and 2007

Source: International Energy Agency; FO Licht.

Figure 3.31 *Global biofuel production*
Source: Internet Source 95.

With regard to the distribution of global biofuel production, Figure 3.30 shows that approximately 90% of the global biofuel production is concentrated in the USA, Brazil, and Europe.


About 90 percent of global biofuel production is concentrated in U.S., Brazil, and Europe, 2007

Source: FO Licht, includes only ethanol for fuel.

Figure 3.32 *Distribution of global biofuel production*
Source: Internet Source 95.

Continued growth of biofuel production - see Figure 3.31 (Suzuki, 2008) - raises concern from, e.g., the FAO[18] due to competition with food and feed production. For first-generation biofuels produced in EU it is stated by (Enguídanos, 2002) that 'in the long run and considering the agricultural yields, bio-diesel is not likely to supply a two-digit percentage share of the EU road transport fuel needs'. Also, (Righelato and Spracklen, 2007) compared the greenhouse gas efficiency of biomass and biofuels with carbon retention by forest stocks. They conclude that only conversion of woody biomass may be compatible with retention of forest carbon stocks. Woody biomass can be used directly for fuel or converted to liquid fuels. Biofuels' implications are addressed by (ICTSD, 2006) and (Torre Ugarte et al, 2006), and may be alleviated by second-

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[18] FAO = Food and Agricultural Organization of the United Nations.

generation biofuels. Figure 3.32 gives another striking example of the forecasted growth of bioethanol production (Zhuang, 2007).

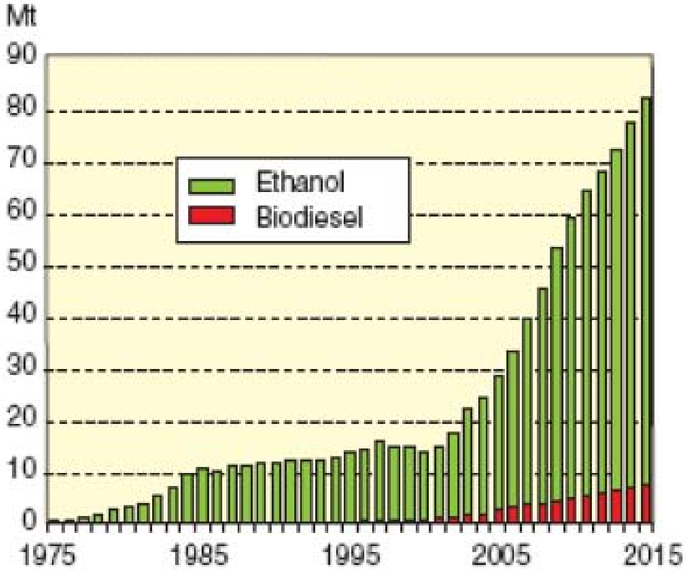

Figure 3.33 *Global biofuel production, predicted worldwide growth until 2010*
Note: Based on presentation F.O. Licht, Christoph Berg, at World Biofuels, Seville, 2006.
Source: Zhuang, 2007.

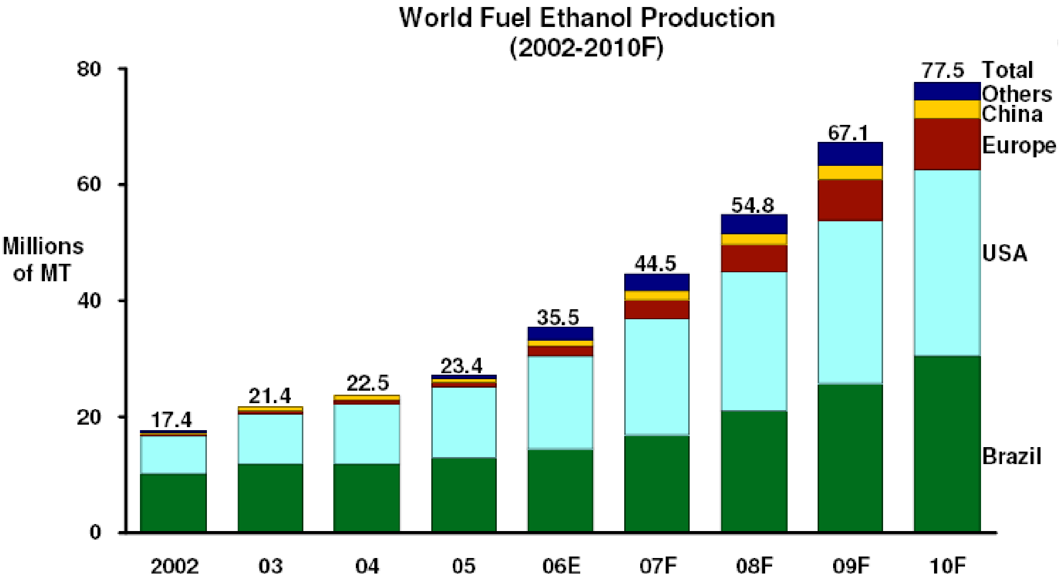

Figure 3.34 *Global bioethanol production, projected worldwide growth until 2015*
Notes: Based on F.O. Licht, Novozymes Analysis.
E (2006) = Estimate, F (2007 through 2010) = Forecast.
Source: Zhuang, 2007.

Today, several processes for production of bioethanol and biodiesel are commercially available (Schumacher, 2007). Worldwide, there are only few initiatives (e.g., from Iogen Corporation, Canada) to produce bio-ethanol at a commercial scale using wheat straw and corn stover instead of corn (Chandel et al, 2007). From the perspective of reduction of GHG emissions, and reduced competition with food and feed, second-generation processes for bioethanol and biodiesel are necessary. In Chapter 4, the perspectives of these second-generation biofuels are addressed.

3.4 Current cost and medium-term cost projection

It is deemed relevant to show the costs today and in the medium term, viz. 2020, of renewable energy technologies that are commercially available or are pending immediate commercialisation - the RE technologies considered in Chapter 3 - and technologies related to CO_2 capture and storage (Appendix E) that need further RD&D before commercialisation (around 2015). Table 3.13 shows the costs of power generation based on renewables or coal-fired power with CCS, today and in the future (2020).

Table 3.13 *Current and future (2020) specific investment cost and generation cost of renewable energy options and selected CCS options*

	Specific investment cost [$\$_{2007}$/kW$_e$]			Generation cost [$\$_{2007}$/MWh]			Source [a]
		2007	2020		2007	2020	
Concentrating Solar Power [b]	[$/kW$_e$]	4,100	2,500-3,000	[$/MWh]	150-170	100-125	IS 96
Photovoltaic	[$/kW$_e$]	8,000	2,850-3,250	[$/MWh]	450-550	175-225	Borenstein, 2008
Onshore wind	[$/kW$_e$]	1,900	1,200-1,300	[$/MWh]	80-110	50-80	Lako et al, 2008
Offshore wind	[$/kW$_e$]	3,250	2,000-2,400	[$/MWh]	160-180	100-125	Lako et al, 2008
Wave	[$/kW$_e$]	4,875	2,000-2,500	[$/MWh]	275-325	125-150	IS 97-99
Tidal range	[$/kW$_e$]	3,750	2,400-2,800	[$/MWh]	175-225	125-150	IS 100
Tidal stream	[$/kW$_e$]	3,250-5,750	2,000-2,500	[$/MWh]	225-275	100-125	DTI, 2004; Davidson, 2007
Conventional geothermal	[$/kW$_e$]	1,750-2,750	1,500-2,250	[$/MWh]	60-90	50-75	Lundin et al, 2006
Hot Dry Rock	[$/kW$_e$]	-	2,250-3,250	[$/MWh]	-	75-100	Lundin et al, 2006
Micro hydro (< 1 MW$_e$)	[$/kW$_e$]	2,250-3,500	2,000-3,000	[$/MWh]	54-84	48-72	Lako et al, 2003
Small hydro (1-10 MW$_e$)	[$/kW$_e$]	2,000-3,000	1,750-2,750	[$/MWh]	48-72	42-66	Lako et al, 2003
Large hydro (> 10 MW$_e$)	[$/kW$_e$]	1,500-2,500	1,500-2,500	[$/MWh]	35-60	35-60	Lako et al. 2003
Biomass combustion				[$/MWh]			
Medium scale (5-20 MW$_e$)	[$/kW$_e$]	3,500-4,250	2,750-3,750	[$/MWh]	65-95	55-85	Mozaffarian and Lako, 2008
Large scale (> 20 MW$_e$)	[$/kW$_e$]	2,500-3,250	2,250-2,750	[$/MWh]	45-75	40-70	Mozaffarian and Lako, 2008
Biomass gasification							
Medium scale (5-20 MW$_e$)	[$/kW$_e$]	3,750-6,500	3,000-3,750	[$/MWh]	70-115	55-85	Mozaffarian and Lako, 2008
Large scale (> 20 MW$_e$)	[$/kW$_e$]		2,750-3,500	[$/MWh]		40-70	Mozaffarian and Lako, 2008
Coal-fired power with CCS [c]							
Post combustion	[$/kW$_e$]		2,100-2,400	[$/MWh]		60-80	Lako, 2004
Pre-combustion (IGCC)	[$/kW$_e$]		2,100-2,400	[$/MWh]		55-80	Lako, 2004
Oxy-fuel	[$/kW$_e$]		2,000-2,500	[$/MWh]		60-80	Black, 2008

[a] IS = Internet Source.

[b] Under solar conditions prevailing in southern California and Nevada.

[c] Investment cost of pulverised coal-fired power without CCS typically $ 1,500/kW$_e$ (Dalton, 2004). According to (Davis, 2007), a CCS-ready, IGCC plant would cost at least 16.9% more than a supercritical pulverized coal plant, which is therefore approximately $ 1,750/kW$_e$.

Sources: Internet Source 96 (CSP); Borenstein, 2008 (PV); Lako et al, 2008 (wind) ; Internet Sources 97-100; DTI, 2004; Davidson, 2007 (wave and tidal) ; Lundin et al, 2006 (geothermal); Lako et al, 2003 (hydro); Mozaffarian and Lako, 2008 (biomass power); Dalton, 2004; Lako, 2004; Davis, 2007; Black, 2008 (coal-fired power).

Also, the costs today and in the medium term, viz. 2020, are shown of biofuel technologies that are commercially available or are pending immediate commercialisation. Table 3.14 gives a view of their current and future (2020) cost. First generation biofuels have costs ranging from \$18/GJ up to \$40/GJ, whereas 2nd generation biofuels could have costs of \$13-20/GJ in 2020.

Table 3.14 *Current and future (2020) cost of biofuels*

		Production cost [$/l]			Production cost [$/GJ][a]		Source
		2007	2020		2007	2020	
Corn ethanol (1st generation)	[$/l]	0.46		[$/GJ]	21.0		Williams et al, 2007
Corn ethanol (1st generation)	[$/l]	0.40-0.50		[$/GJ]	18-23		IS 101
Wheat or sugar beet ethanol (1st generation)	[$/l]	0.81-0.90		[$/GJ]	37-41		Chacón, 2004
2nd generation bioethanol	[$/l]		0.29-0.31	[$/GJ]		13.3-14.0	Torre Ugarte, 2006
2nd generation bioethanol	[$/l]		0.33-0.43	[$/GJ]		15-20	Williams et al, 2007
Soybean biodiesel (1st generation)	[$/l	0.613	0.573	[$/GJ]	18.7	17.5	Pruszko, 2007
Biodiesel, 1st generation	[$/l]	0.61-0.82		[$/GJ]	18.5-25.0		Shaine Tyson, 2006
Biodiesel, 1st generation	[$/l]	0.76		[$/GJ]	23.3		Enguídanos et al, 2002
Rapeseed biodiesel (1st generation)	[$/l]	0.75-0.81		[$/GJ]	23.0-24.7		Chacón, 2004

a The energy content (lower heating value) of ethanol is 21.823 MJ/l (EUBIA, 2008) and of biodiesel 32.8 MJ/l (Enguídanos et al, 2002). The conversion ratio of the Euro is 1 Euro = 1.3705 US\$ (2007).

Sources: Williams et al, 2007; Internet Source 101; Chacón, 2004 ; Torre Ugarte, 2006 ; Pruszko, 2007 ; Shaine Tyson, 2006 ; Enguídanos et al, 2002; EUBIA, 2008.

4. Technologies/goods within the energy supply sector subject to R&D but with strong prospects for commercialisation

This Chapter addresses renewable energy technologies that are (largely) in the R&D stage, but have strong prospects of near to medium term deployment, notably in a period of 5-10 years from now. In general, the technologies described have not been demonstrated on a commercial scale until this date. However, the stage of development is such that commercialisation in 5-10 years from now may be expected. In some cases, however, technologies may be in a very early stage of R&D or lack sufficient government R&D spending until this date. Then, it does not seem probable that those technologies will be commercial in 5-10 years from now.

4.1 Technologies of interest

Table 4.1 presents an overview of technologies that are (largely) in the R&D stage, but have strong prospects of near to medium term deployment in a period of 5-10 years from now. These technologies are decomposed in main components in Appendix C. In the following, the technologies and the projected timeframe of commercialisation are described.

Solar heating and cooling

Solar heating with seasonal storage is in the stage of development and demonstration rather than being commercially available. The option may be crucial for regions with a cold winter climate. (Internet Sources 102-103) suggest commercialisation after 2015. Solar heating for hot water is already competitive in regions around the Mediterranean Sea and comparable latitudes around the world and may be commercial elsewhere before 2015.

For solar cooling - or air-conditioning - somewhat different considerations apply (Internet Sources 104-105). Figure 4.1 shows air-conditioning based on solar cooling. Based on recent data, (IEA, 2007) and (ESTIF, 2007), it is likely that the technology will be commercial in 2015[19].

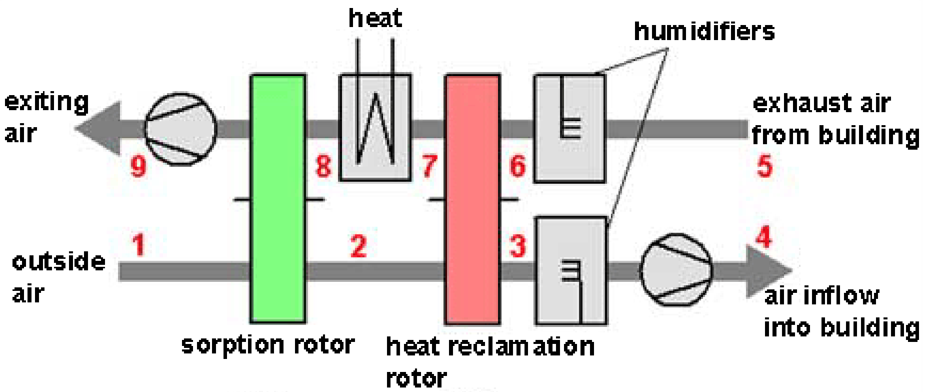

Figure 4.1 *Air-conditioning system based on solar cooling (sorption)*
Source: Internet Source 104.

It has been noted in Section 3.3.1 that CSP plants may be equipped with the added capability of energy (heat) storage. A company active in this field is SolarReserve (USA). Appendix D shows the development stage of various electricity storage technologies

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[19] PV may also be used to power cooling or air-conditioning systems. This technology may be closer to market penetration, as the insolation in future markets of interest like developing countries is very high (Rudischer et al, 2005).

Table 4.1 *Renewable energy technologies/goods currently in the R&D stage but with strong prospects for commercialisation in the near to medium term*

Energy source/technology	Main application	Technology/Good	Commercialisation (projected) Before 2015	Commercialisation (projected) Beyond 2015	Main components
Solar	Solar heating & cooling	Solar heating systems & seasonal storage [a]	X		Solar collectors & seasonal storage
		Cooling	X		Solar collectors & cooling system
	Photovoltaic power (PV)	PV based on nanotechnology	X		Nanotechnology PV
Wind	Floating offshore wind		X		Offshore wind turbines based on floating structures
Ocean	Ocean Thermal Energy Conversion (OTEC)			X	Piping system, turbine-generator set, floating structure
	Salinity gradient power			X	Piping systems, membranes, and electric generators.
Geothermal	Geothermal power	Small-scale geothermal power	X		Drilling technology, Organic Rankine or Kalina Cycle
		Hot Dry Rock		X	Drilling and electrical conversion
Biomass	Biomass-based power/heat	(Large-scale) gasification	X		Gasifier, adapted combined cycle system
		Pyrolysis	X		Pyrolysis process, upgrading of oil and gas
		Torrefaction	X		Feed system and torrefaction reactor
	Second-generation biofuels	Cellulosic ethanol (CELEtOH)	X		New enzymes and ethanol production processes
		Second-generation biodiesel	X		Biomass gasification and Fischer-Tropsch synthesis
		DME (based on gasification)		X	Biomass gasification and DME synthesis
		Bio-refinery		X	Bio-refinery processes
		Algae		X	Reactors

a Appendix D provides an overview of electricity storage technologies.

PV based on nanotechnology

Chapter 3 has evidenced that thin-film cells provide advantages over mono-/poly-crystalline cells such as semi-transparency, flexibility, and low weight. It is possible to make semi-transparent panels that substitute for window panes on facades, roofs, etc (Internet Source 23). There are many companies in the world that are engaged in development of thin-film solar cells. Based on projections from the PV industry (Internet Sources 106-107), it is probable that PV based on nanotechnology will capture a significant share of the PV market before 2015[20].

Floating offshore wind power

A new option is 'floating offshore wind'. (Bulder et al, 2003) showed that a so-called tri-floater could be designed for water depths of 50 m and more. However, it could also be used in water depths of 40-45 m. In July 2007, the Norwegian start-up SWAY raised NOK 150 million (€ 18.7 million) from Statoil (Internet Source 109). For SWAY, building of full-scale pilots for testing will be central in the further process. A first pilot project based on SWAY's proprietary technology is expected to be completed in 2010, and commercialisation is expected by 2012. Also, a company called 'Blue H' is developing technology for offshore wind turbines floating on stable platforms based on adapted proven deepwater technology from the oil and gas industry (Internet Source 110).

Statoil itself is working on a 2.3 MW_e floating wind turbine that will be attached to the top of 'Spar-buoy' and moored to the seabed by three anchor points. It is anticipated by Statoil that the 80 meter diameter, 65 meter high Siemens turbine will have lower deep-water installation costs when compared to traditional wind installations. The company plans to have the first prototype ready by fall of 2009, when they will begin feasibility tests to assess how it stands up to high winds. A 3 metre high scale model has already been tested in a wave tank simulator (Internet Source 111).

In the USA, building offshore wind farms in, e.g., offshore of the San Francisco Bay Area will most probably require development of floating turbine support structures for large scale offshore turbine development (Dvorak, Jacobsen and Archer, 2007). Based on these developments and (Internet Source 112), it is assumed that floating offshore wind will enter the commercial stage around 2015.

Ocean Thermal Energy Conversion (OTEC)

OTEC generates electricity by using the temperature difference of 20°C or more between warm tropical waters and colder waters drawn from depths of about 1000 m. The warm water is used to heat and vaporise a liquid, which will drive a turbine-generator set. There are basically three basic types of OTEC power plants: closed-cycle, open-cycle, and various combinations of the two. They can be built on land, on offshore platforms fixed to the seafloor, or on floating platforms anchored to the seafloor (Internet Source 113). Considering the limited effort that has been done to develop OTEC and its technical rate of progress, it is assumed that it will not be commercially available before 2015.

Salinity gradient power

There are basically two methods to produce energy from salinity gradient power. One is based on the osmotic pressure. This technology goes back to a breakthrough by the American Sidney Loeb who produced a semi-permeable membrane that separates salt. Production of fresh water by Reverse Osmosis (RO) is now a major industry, especially in the Middle East. The same membranes can be used in an installation for producing electricity by *pressure retarded osmosis* (see Figure 4.2). In Norway, this technology is under investigation by Statkraft (Ende and Groenman, 2007).

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[20] It is noted that nanotechnology may also be used for (energy) applications (Internet Source 108).

A second technology for salinity gradient power is based on reverse dialysis and acts as a power cell. It requires two types of membranes, viz. one that is selectively permeable for positive ions and one that is selectively permeable for negative ions (see Figure 4.3). Salt water separated from fresh water between two such membranes will lose both positive ions and negative ions. This charge separation produces a potential difference that can be utilized directly as electrical energy. The voltage obtained depends on the number of membranes in the stack, the absolute temperature and the ratio of the concentrations of the solutions, the internal resistance and the electrode properties.

Up to now only small pilot installations (lab scale) have been built. Therefore, it is expected that salinity gradient power will not be commercial available by 2015.

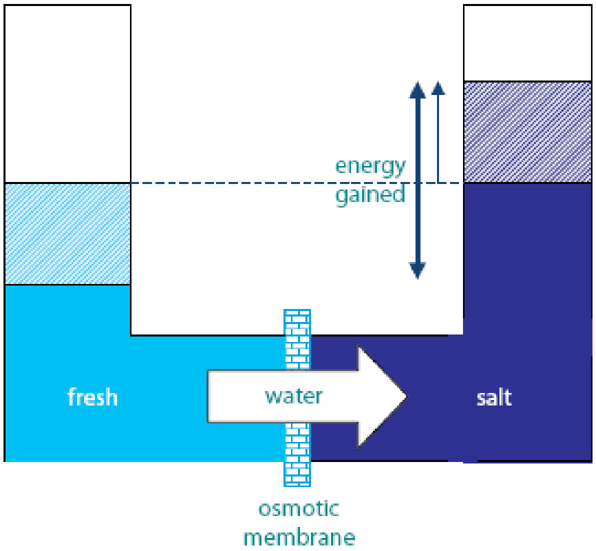

Figure 4.2 *Electricity generation based on pressure retarded osmosis*

Note: When fresh water permeates the semi-permeable membrane to the other seawater compartment, nature tries to equalise the salt concentration on both sides. As a result a hydrostatic pressure is built up, which can be harvested for electricity generation.

Source: Ende and Groenman, 2007.

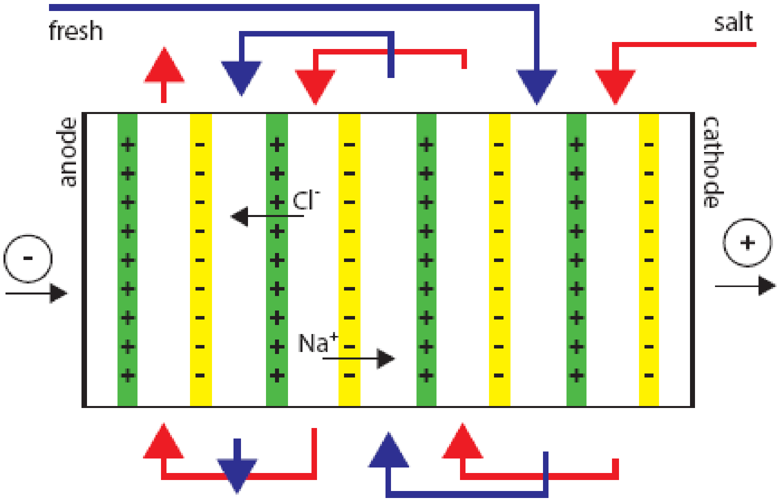

Figure 4.3 *Electricity generation based on reverse electrodialysis*

Note: Using a pair of ion exchange membranes positive and negative ions from the salt solution are separated. At the electrodes direct electrical energy can be generated.

Source: Ende and Groenman, 2007.

Small-scale geothermal power

There is limited experience with small-scale (up to 5 MW$_e$) geothermal power plants based on an Organic Rankine Cycle (ORC). Most of these units have been built in the USA, in a number of countries in Europe - Germany, Austria, and France - and elsewhere. There is still a large potential for small-scale geothermal power or CHP. However, development of this potential will require further development and innovations for a number of technologies, viz.:

- New deep drilling systems (Internet Source 114).
- Optimised Organic Rankine Cycle systems (TAB, 2003).
- More efficient energy conversion systems, e.g., the Kalina Cycle (Internet Source 115), demonstrated so far only a few times, among which in Iceland (Mlcak et al, 2002)[21].

As there is much interest in geothermal power (and CHP) generation, it is assumed that small-scale geothermal power (hundreds of kW$_e$ up to 5 MW$_e$,) will become commercial before 2015.

Hot Dry Rock geothermal power

Companies in Europe, the USA, and Australia are developing so-called ‘hot dry rock’ (HDR) technology for electricity or combined heat and power (CHP). South Australia has potential in naturally occurring hot rock geothermal resources (Internet Source 117; Chopra and Wyborn, 2003). A high temperature gradient means that in order to obtain the same energy output, shallower and therefore less costly boreholes can be drilled than with low temperature gradients (BTT, 2007) (Figure 4.4).

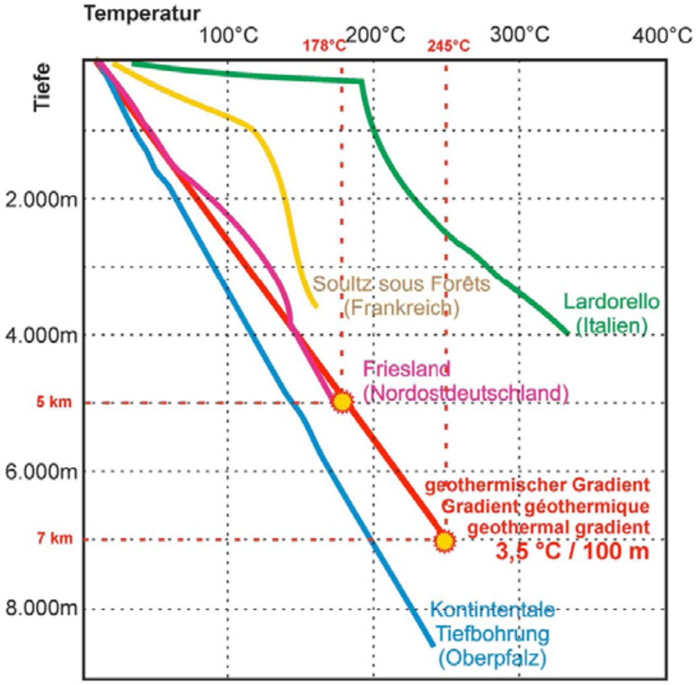

Figure 4.4 *Geothermal power generation based on ‘Hot Dry Rock’ technology*

Note: Larderello (Italy) is an example of conventional (‘Dry Steam’) geothermal power generation. Soultz sous Forêts (France), Friesland and ‘Kontinentale Tiefbohrung (Oberpfalz)’ (Germany) are examples of HDR.

Source: BTT, 2007.

(Internet Source 118) suggests that commercialisation of HDR technology will take about 20 years. However, Australia’s Research Institute for Sustainable Energy (RISE) indicates that the HDR technology may become commercial sooner, but not before 2015 (Internet Source 119).

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[21] In July 2004, Geodynamics of Australia reported to have lodged a provisional patent application in Australia for a new Kalina Cycle design (Internet Source 116).

Biomass gasification (Integrated Gasification Combined Cycle, IGCC)

According to the technical research centre of Finland, VTT, large-scale integrated gasification combined cycle (IGCC) power plants based on biomass need further RD&D before they will become commercially available (VTT, 2002). According to (Internet Source 120), significant economies of scale and improvements in generation efficiency can be gained by going to 50 or 75 MW_e output. Biomass-fuelled IGCC power plants of 50-75 MW_e capacity will take another 5 years for commercialisation, which suggests that they could be commercial before 2015.

Pyrolysis of biomass

Pyrolysis of biomass generates three different energy products in different quantities: coke, gas, and oils. Flash pyrolysis gives high oil yields, but the technical efforts needed to process pyrolytic oils mean that this energy generating system does not seem very promising at the present stage of development. However, pyrolysis as a first stage in a two-stage gasification plant for straw and other agricultural biomass does deserve consideration. In the typical biomass gasification process, air is used as the gasifying agent and hence the gas has a low calorific value (3-5 MJ/m^3). After cleaning it can be used in gas-fired engines or gas turbines.

Combined cycle power plants will burn medium calorific value gas (12-15 MJ/m^3) more favourably than low calorific gas. The use of steam injection into the gas turbine combustion chamber (Cheng process) requires at the very least medium calorific value gas. Integration of biomass-fuelled gasifiers in coal-fired power stations has certain advantages over stand-alone biomass gasification plants (Internet Source 121). A priority in case of pyrolysis of biomass is process development to improve product quality and reduce costs. The timeframe of commercialisation of biomass pyrolysis may be similar as that of biomass IGCC, viz. before 2015.

Torrefaction of biomass

Torrefaction is thermal pre-treatment- involving heating of biomass without oxygen in a closed reactor to 250-300°C for ~ 60 minutes (Mitchell et al, 2007) - practised for biomass with poor grindability or to reduce the weight of biomass before further transport. For co-firing of biomass in a coal-fired power plant or gasification, torrefaction may be attractive to improve the fuel properties of biomass (wood, straw) prior to power generation (Prins, 2005). ECN developed a torrefaction process ‘BO2’ (Kiel et al, 2008). ECN teams up with two industrial parties, Econcern and Chemfo, to bring the technology to the market. BO2GO aims to realise the first commercial plant with a capacity of 70 ktonnes/a BO2pellets at Delfzijl (the Netherlands) with start-up scheduled for late 2009. Torrefaction of biomass can be commercially available before 2015.

Cellulosic ethanol

Figure 4.5 presents an overview of pilot plants and demonstration plants for bioethanol based on ligno-cellulosic biomass, started up in the period from 2004 through 2007 (Malatesta, 2008).

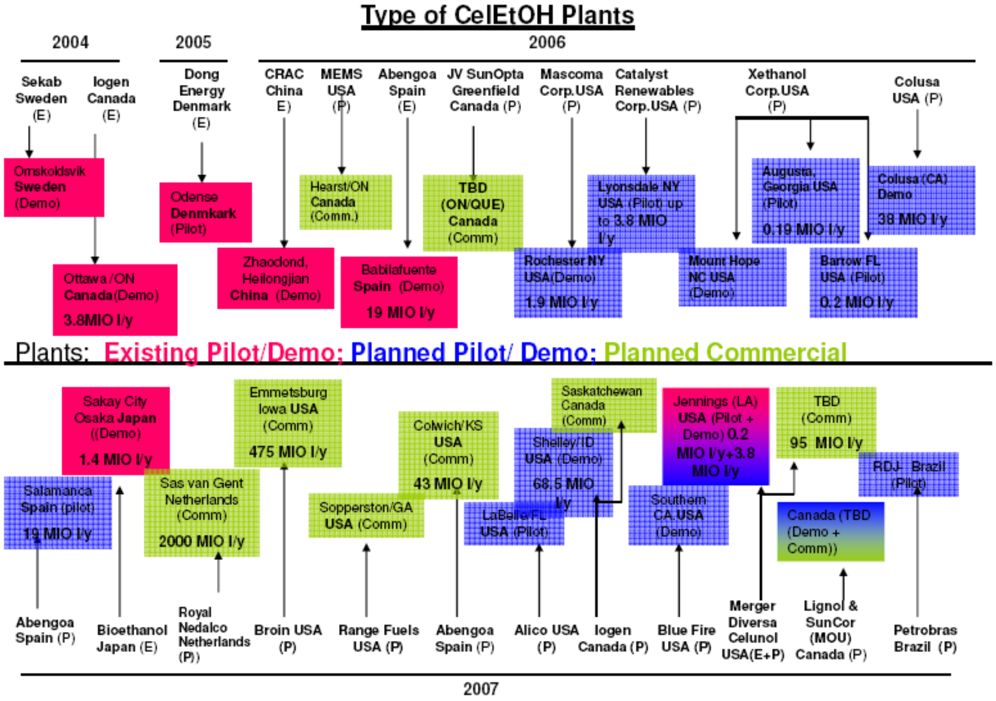

Figure 4.5 *Pilot plants and demonstration bioethanol plants for ligno-cellulosic biomass*
Source: Malatesta, 2008.

Cellulosic ethanol is a transportation fuel based on agriculture residues - cereal straws (e.g., wheat and barley straw) or corn stover - or energy crops such as switchgrass and miscanthus. Several companies and research institutes are engaged in RD&D of cellulosic ethanol:

- IOGEN Corporation of Canada started demonstration in 2004 (Internet Source 122).
- In February 2007, Range Fuels, Inc. (California, USA), announced that it will build its first ethanol plant in Treutlen County, Georgia. Range Fuels is at the forefront of new proprietary technology based on cellulosic ethanol (Internet Source 123).
- In October 2007, Abengoa (Spain) opened a pilot plant for conversion of biomass in Nebraska, USA. The plant - investment more than US$ 35 million - is solely dedicated to R&D of biofuel production from lignocellulosic biomass (Internet Source 124).
- AE Biofuels (USA) plans to integrate their technology for cellulosic bioethanol - based on Ambient Temperature Starch Hydrolysis (ATSH) enzymes - into existing corn-based ethanol plants (Internet Source 125).
- Royal Nedalco plans to build a cellulosic ethanol production plant at Sas van Gent (the Netherlands) with a capacity of 200 Ml of bioethanol per year (Internet Source 126).

(Wännström, 2008) expects that cellulosic ethanol may become commercial around 2015.

Second-generation biodiesel and algae

Second-generation biodiesel and algae are different ways to diversify the feedstocks that can be used for production of biodiesel. According to (Nieminen, 2007), the timeframes are as follows:

- Second-generation biodiesel (Fischer-Tropsch based) may be commercial before 2015.
- Production of biodiesel from algae would need a longer RD&D timeframe (Figure 4.6).

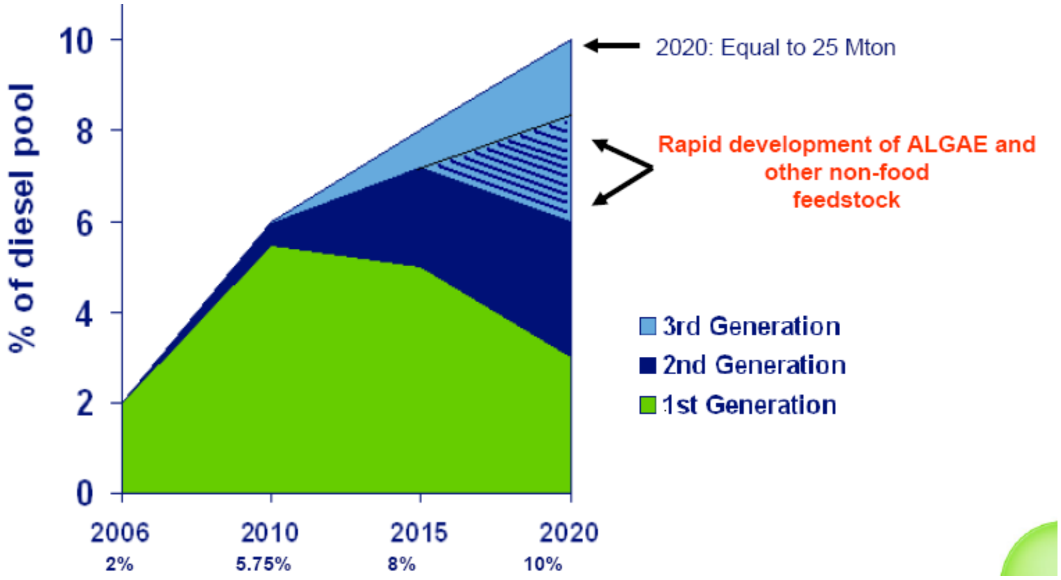

Figure 4.6 *Development of biodiesel technologies in the timeframe 2006-2020*
Source: Nieminen, 2007.

Therefore, it is expected that second-generation biodiesel production may become commercially available before 2015, but that biodiesel from algae will become commercial after 2015.

Di-Methyl Ether (DME) from biomass
With regard to production of di-methyl ether (DME) from biomass, which is comparable to 2nd generation biodiesel, the focus is on gasification of biomass and synthesis of DME (Figure 4.7).

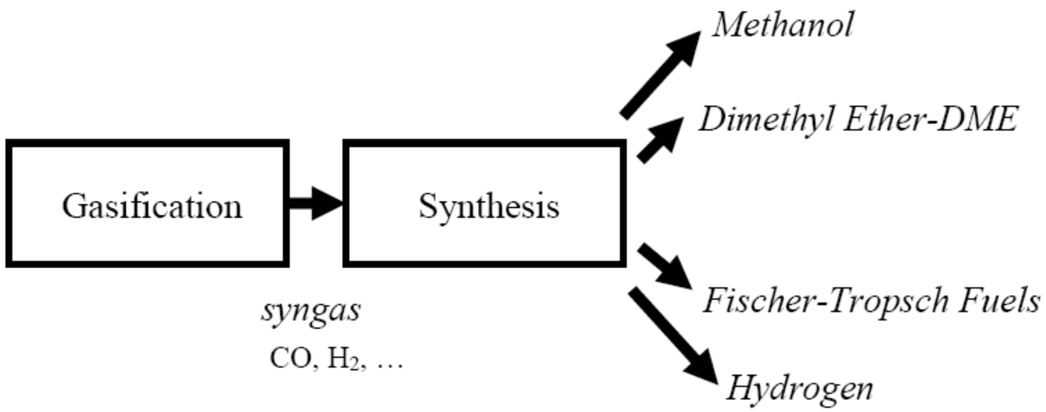

Figure 4.7 *Production process for Di-Methyl Ether (DME)*
Source: Internet Source 127.

The conversion efficiency of DME from biomass could be between 55 and 60%, whereas that of Fischer-Tropsch fuels (2nd generation biodiesel) is approximately 45% (Towers, 2005). Therefore, production of DME from biomass could be superior to 2nd generation biodiesel in terms of energy efficiency and possibly too in terms of economics. However, DME is still not used on a significant scale as a transportation fuel. Therefore, it is expected that DME from biomass will become commercially available after 2015.

Bio-refinery
According to (Zwart, 2006), a bio-refinery is similar in concept to the petroleum refinery, except that it is based on conversion of biomass feedstocks rather than crude oil. Bio-refineries in

theory would use multiple forms of biomass to produce a flexible mix of products, including fuels, power, heat, chemicals and materials. In a bio-refinery, biomass would be converted into high-value chemical products and fuels (both gas and liquid). By-products and residues, as well as some portion of the fuels produced, would be used to fuel on-site power generation or cogeneration facilities.

In the USA, several companies are developing a bio-refinery concept based on switch grass (Internet Source 128), as part of a programme of the government to develop bio-refinery concepts (Internet Source 129). Similar developments take place in European countries, and elsewhere. As development of the bio-refinery concept is as complex as that of production of DME from biomass, 2nd generation bio-refineries are not expected to be commercial before 2015.

In the preceding section, a broad view has been presented of renewable energy technologies that are in the state of research and development, and therefore not yet mature enough to enter the commercial stage. Appendix C presents a decomposition of these technologies in main components. Furthermore, Appendix D provides an overview of electricity storage technologies that may become important for renewable electricity generation. Whereas research, development, and demonstration with respect to these technologies are very important, also RD&D on other technologies like CO_2 capture and storage (CCS) deserves attention. Therefore an Appendix has been added on CCS Technologies Undergoing R&D with Strong Prospects for Commercialisation (Appendix E).

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Appendix A Abbreviations and acronyms

AWS	Archimedes Wave Swing
BFB	Bubbling Fluidised Bed
BIGCC	Biomass Integrated Gasification Combined Cycle
BOS	Balance Of System
CAES	Compressed Air Energy Storage
CC	Combined Cycle
CCS	Carbon Capture and Storage
CFB	Circulating Fluidised Bed
CHP	Combined Heat and Power
CLFR	Compact Linear Fresnel Reflector
CSP	Concentrating Solar Power
DLR	German Aerospace Center
DME	Di-Methyl Ether
ECHX	Earth Coil Heat Exchanger
ESHA	European Small-Hydropower Association
FAO	Food and Agricultural Organisation
GHG	Greenhouse Gas
GSHP	Ground-Source Heat Pump
HDR	Hot Dry Rock
HVDC	High Voltage Direct Current
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
ISCC	Integrated Solar Combined Cycle
Limpet	Land Installed Marine Powered Energy Transformer
MDEA	Methyl Di-Ethanol Amine
MoU	Memorandum of Understanding
MSW	Municipal Solid Waste
OEM	Original Equipment Manufacturer
OHVS	Offshore High Voltage Station
ORC	Organic Rankine Cycle
OTEC	Ocean Thermal Energy Conversion
OWC	Oscillating Water Column
PPO	Pure Plant Oil
PV	Photovoltaic power
R&D	Research and Development
RE	Renewable Energy
RO	Reverse Osmosis
ROW	Rest of World
SES	Stirling Engine System
SMES	Superconducting Magnetic Energy Storage
SNG	Substitute Natural Gas

Appendix B Characterisation of Climate Mitigation Goods available on a Commercial Basis

Table B.1 *Characterisation of Climate Mitigation Goods available on Commercial Basis*

Sector	Technology	Sub-category	Main components	HS-Code/Ex-out
RENEWABLE	Solar Energy	Solar Thermal		
		Solar Trough	Parabolic trough reflectors Receiver tube or heat collection element Sun-tracking system Support structure Steam turbine/generator system	
		Solar Tower	Heliostats Central receiver Steam turbine/generator system	
		Solar Dish	Mirrors Elevation and azimuth drives Main beam Pedestal with dish controller Power Conversion Unit (Stirling engine)	
		Fresnel-lens	Fresnel reflector modules Absorber lines Space frame Steam turbine/generator system	
		Solar Heating	Flat plate collector; or Evacuated tube collector (Auxiliary heat source)	
		Photovoltaic		
		Mono-cryst. Si	PV module Inverter (Support structure)	
		Poly-cryst. Si	PV module Inverter (Support structure)	
		Thin-film PV	PV module Inverter (Support structure)	
	Wind Energy	Onshore Wind	Wind turbine blades Gearbox Generator Bearings Tower Electronic Control Equipment	
		Offshore Wind	Wind turbine blades Gearbox Generator Bearings Tower Electronic Control Equipment Infield and export cables Offshore High Voltage Station Support structure (monopole or tripod & transition piece)	
	Ocean Energy	Wave Power	Wave power converter	

Sector	Technology	Sub-category	Main components	HS-Code/Ex-out
			Infield and export cables	
			Offshore High Voltage Station (OHVS)	
		Tidal Stream Power	Tidal stream power converter	
			Infield and export cables (& OHVS)	
	Geothermal Energy	Geothermal Power		
		Flash Steam Power Plant	Pipes	
			Heat exchangers	
			Steam turbine/generator	
		Binary-Cycle Power Plant	Pipes	
			Heat exchangers	
			Organic Rankine Cycle (ORC) system	
		Geothermal Heat	Pipes	
			Heat exchangers	
		Geothermal heat pump	Earth coil heat exchanger (ECHX)	
			Ground Source Heat Pump (GSHP)	
	Hydro Power	Large hydro (> 10 MW$_e$)	Dam (concrete)	
			Pelton, Francis, or Kaplan turbine	
			Generator	
			High Voltage Transformer Station	
		Small hydro (1-10 MW$_e$)	Dam (concrete)	
			Kaplan, propeller, or tubular turb.	
			Generator	
		Micro hydro (<1 MW$_e$)	Propeller or tubular turbine	
			Generator	
	Biomass	Biomass-based Power or CHP		
		Fluidised bed combustion	Boiler	
			Steam turbine	
			Generator	
			Gas cleaning	
		(Small-scale) gasification	Gasifier	
			Gas cleaning	
			Gas turbine or gas engine	
			Generator	
		Digestion (biogas)	Anaerobic digester	
			Gas cleaning (CO_2)	
			(Gas engine)	
		Pure Plant Oil	Oil mill based on cold pressing	
			Filtering	
		Bio-ethanol (1st generation)	Fermentation	
			Distillation	
			Purification (mol sieve)	

Sector	Technology	Sub-category	Main components	HS-Code/Ex-out
		Biodiesel (1st generation)	Crushing Transesterification Refining Drying	

Appendix C Characterisation of Climate Mitigation Goods Undergoing R&D with Strong Prospects for Commercialisation

Table C.1 *Characterisation of Climate Mitigation Goods with strong Prospects for Commercialisation*

Sector	Technology	Technology sub-category	Main components (in italics new or different components)	HS-Code/Ex-out
RENEWABLE	Solar Energy	Solar heating & seasonal storage	Flat plate collector (Evacuated tube collector) *Heat storage device*	
		Photovoltaic Nanotechnology	PV module *based on ‘nanotechnology PV cells’* Inverter (Support structure)	
	Wind Energy	Floating Offshore Wind	Wind turbine blades Gearbox Generator Bearings Tower Electronic Control Equipment Infield and export cables Offshore High Voltage Station *Floating support structure*	
	Geothermal Energy	Small-scale Geothermal Power	Pipes Heat exchangers Organic Rankine Cycle system	
		Hot Dry Rock	*Drilling equipment* and pipes Heat exchangers Steam turbine/generator / Organic Rankine Cycle (ORC) system	
	Biomass	Biomass-based Power or CHP		
		(Large-scale) gasification	Gasifier (*large-scale*) Gas cleaning Gas turbine or *Combined Cycle* Generator	
		2nd generation bio-ethanol	(Fermentation) *Conversion of lignocellulose* Distillation Purification (mol sieve)	
		2nd generation bio-diesel	Gasifier (*large-scale*) Gas cleaning Syngas reactor (*large-scale*) Liquids purification	

Appendix D Characterisation of electricity storage technologies

As the contribution of electricity generated from renewal sources (wind, wave, solar) grows, the inherent intermittency of supply from such generating technologies requires electricity storage for high penetration rates. Also, increasing use of solar heating, not only for solar hot water but also for room heating, requires storage of solar heat at affordable costs. The decision to use an energy storage system depends both on the requirements of the application and the cost of competing solutions. For renewable electricity options (wind, wave, PV, CSP), for instance, the use of fossil fuel based back-up generation and large-scale interconnection capacity may enable renewables to penetrate. Also, hydro power plants with their fast start-up capability may be used.

Hall and Bain (2008) present a view of electricity storage options and a comparison of the technologies in terms of lifetime and efficiency (Figure D.1). When the discharge period is short, devices that can deliver high power are required, for example, in overcoming fluctuations in the output of a wind turbine. Conversely, if conditions are such that there is no energy generation (calm day, solar at night), there is a requirement for a device that can store large amounts of energy and release it over what may be a long time. Such devices are largely in the R&D stage.

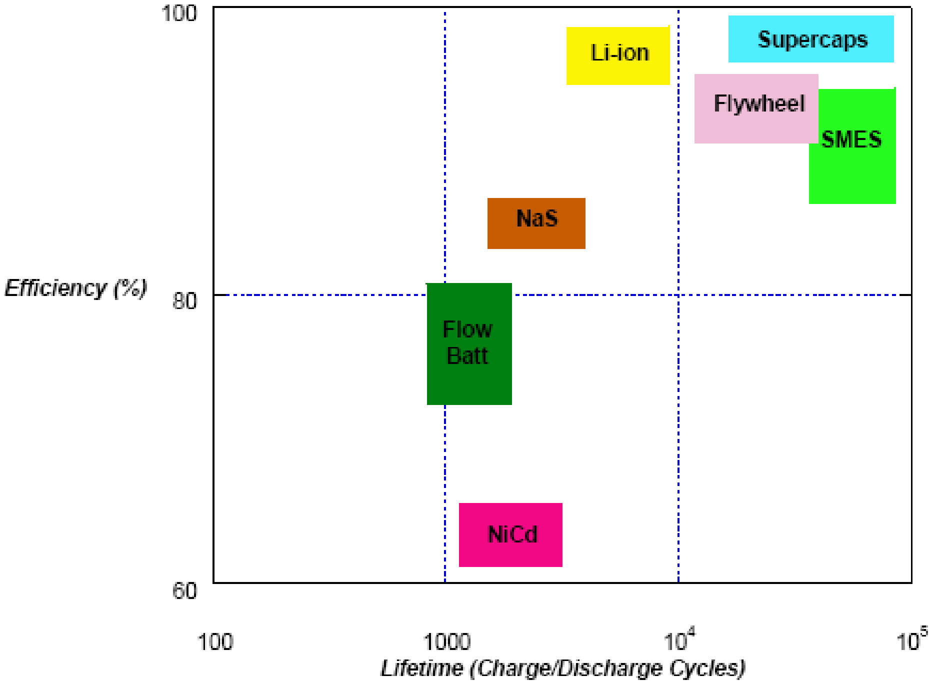

Figure D.1 *Efficiency/lifetime properties of technologies for electricity storage*
Note: The acronyms are explained in Appendix A and Table D.1.
Source: Hall and Bain, 2008.

Table D.1 provides an overview of electricity storage technologies, their stage of development, and their development potential. The already widely applied technology of pumped hydro storage is not included, as it is already commercial for a long period of time. Also, only a number of electricity storage technologies is addressed, not all the technologies that are known today.

Table D.1 *Characteristics energy storage techniques for renewable electricity generation*

Sector	Technology	Sub-category	Main characteristics	Stage	Development potential
Electricity storage	High-power-density battery	NiCd, Ni-MeH and Pb-acid	Can supply excellent pulsed power; large and heavy compared to Li-ion.	Commercial	Relatively small?
		NaS and zebra (Na-$NiCl_2$)	Much smaller and lighter than NiCd and Ni-MeH batteries. Energy-storage efficiency ~85%. Operate at 300°C and require constant heat input.	Commercial	Relatively small?
		Lithium-ion	Small in size and light in weight (suited to portable applications). Energy-storage efficiency close to 100%. Drawbacks are high cost and detrimental effect deep discharging.	Commercial	Relatively large? R&D aimed at optimisation of ancillary components such as packaging and overcharge protection circuitry for reduced cost.
	Flow battery	Polysulphide bromide (PSB), vanadium redox (VRB) and zinc bromine (ZnBr)	Energy-storage efficiency 75–85%. Series and parallel combination of individual cells allow design of high-current and high-voltage solutions. Isolated storage of electrolytes in charged state mitigates self-discharge.	More or less commercial	Limited? ZnBr has increased capital and running costs (pump system to circulate bromine complexes).
		Cerium zinc (CeZn)	Are relatively new to the market and offer larger cell potentials and increased power density.	More or less commercial	Medium? Aim higher power and energy density for increased versatility technology.
	Supercapacitor	Carbon-based supercapacitors	High-power-density energy-storage technology. Very high energy-storage efficiencies (>95%), can be cycled hundreds of thousands of times. Susceptible to self-discharge depending on nature of the carbon electrodes. Applied in portable electronics and automotive industries.	More or less commercial	Relatively large? Focus on electrode, electrolyte, and package development. Besides automotive and portable electronics industries, applied in medicine, defence, consumer goods?
	Kinetic energy storage	Flywheels	Flywheels with a long working lifetime (>20 years) available, but no commercial applications in power management. High cost of stored energy, largely demonstration stage.	Demonstration (largely)	Medium? Cheap devices where space is not restricted (e.g., land-based wind), high-performance where space is at a premium (marine-based wind).

Sector	Technology	Sub-category	Main characteristics	Stage	Development potential
	Superconducting magnetic energy storage (SMES)		To maintain superconducting state, device cooled to temperature at which superconductivity is attained. For low-temperature superconductors liquid helium, for high-temperature superconductors liquid nitrogen.	Micro-SMES devices (1–10 MW) are commercially available	Medium? Aim devices capable of 100 MW with efficiencies of 99% and a lifetime of 40 years based on high-temperature superconductors. Could be a realistic goal by 2050.
	Pumped storage	Compressed Air Energy Storage (CAES)	Peaking gas turbine power plant consuming less than 40% of the gas used in conventional gas turbine to produce same amount of power.	Commercial	Limited?
	Regenerative hydrogen fuel cells	Lithium Oxide (Li_2O)/ Lithium Nitride (Li_3N)	Focus is on fuel cells for vehicles although there is potential for other applications. Also hydrogen/bromine is patented (Internet Source 132).	RD&D	Possibly large? US provisional patent applications filed February, 2004, for Lithium Oxide (Li_2O)/ Lithium Nitride (Li_3N).
Thermal energy storage for CSP	Molten-salt heat transfer		ENEA (Italy) has proven the technical feasibility of using molten-salt in a parabolic trough solar field.	RD&D	Unknown
	Concrete etc.		German Aerospace Center (DLR) is examining high temperature concrete for use with parabolic trough plants.	R&D	Unknown
	Phase-Change Materials		DLR is evaluating phase-change thermal energy storage for application in parabolic trough solar power plant.	R&D	Unknown

Sources: Hall and Bain, 2008; Internet Source 130 (NREL) - 132.

Appendix E Characterisation of CCS Technologies Undergoing R&D with Strong Prospects for Commercialisation

According to the IPCC (2005), CCS may give a significant contribution to mitigating climate change, or 'As a result of the 2002 IPCC workshop on CO_2 capture and storage (IPCC, 2002), it is now recognized that the amount of CO_2 emissions which could potentially be captured and stored may be higher than the value given in the Third Assessment Report. Indeed the emissions reduction may be very significant compared with the values quoted above for the period after 2020. Wider use of this option may tend to restrict the opportunity to use other supply options. Nevertheless, such action might still lead to an increase in emissions abatement because much of the potential estimated previously (IPCC, 2001a) was from the application of measures concerned with end uses of enegy. Some applications of CCS cost relatively little (for example storage of CO_2 from gas processing as in the Sleipner project (Baklid *et al.*,1996) and this could allow them to be used at a relatively early date. Certain large industrial sources could present interesting low-cost opportunities for CCS, especially if combined with storage opportunities which generate compensating revenue, such as CO_2 Enhanced Oil Recovery (IEA GHG, 2002)'.

ECN Policy Studies characterised the state of affairs of CCS in Europe for a 'WRI Issue Brief' on Carbon Capture and Sequestration of the World Resources Institute. Table E.1 provides an overview of pilot CCS projects for Europe.

Table E.1 *Pilot CCS projects focusing on CO_2 Storage or CO_2 Capture in EU countries*

Project (country)	Feedstock	Size	CO_2 capture capacity (or CO_2 captured)	CO_2 Capture Process	CO_2 use / storage	Duration
		[MW_e/] (MW_{th})	[t CO_2/a] (t CO_2 cum)			
RECOPOL Silesia (Poland)	Fertilizer industry	-	(760)	(Pre)	ECBM [a]	November 2001 - May 2005
CO2SINK Ketzin (Germany)	Hydrogen production	-	30,000 (60,000)	(Pre)	Storage	2008-2010
CASTOR Esbjerg (Denmark)	Coal	420 (slipstream)	8,000 (24,000)	Post	-	2006-2008
Fortum Värtan (Sweden)	Coal	112(e)/288(th)	N/A	Post	-	2007-2008
E.ON Karlshamn (Sweden)	Oil & Gas	Slipstream	1,500	Post	-	2008-2009
Total Lacq (France)	Gas & Oil	(35)	(150,000)	Oxy	Storage	2008-2010
E.ON Maasvlakte (Netherlands)	Hard coal	500 (slipstream, ~ 1 MW_{th})	2,000	Post	-	2008-
Nuon Buggenum (Netherlands)	Hard coal	Slipstream	N/A	Pre	-	2008-2011

a (CO_2) Enhanced Coal Bed Methane.

Sources: WRI, 2008; Van Bergen, 2007; Thiez, 2008; Solie, 2008; Aimnard, 2007; Lindman, 2008; Lundström, 2007; Internet Sources 133-136.

As Table E.1 shows, there is limited experience with CO_2 capture. However, a few large CCS projects with CO_2 separation in conjunction with natural gas production are operational, such as the Sleipner project (offshore Norway). Some pilot projects are based on 'post-combustion' CO_2 capture from coal-fired power plants, e.g. CASTOR (Esbjerg, Denmark) and E.ON (Maasvlakte, the Netherlands). So-called 'oxy-fuel combustion' and 'pre-combustion' CO_2 capture could offer advantages with regard to efficiency and possibly cost over 'post-combustion' (Figures E.1-E.2)

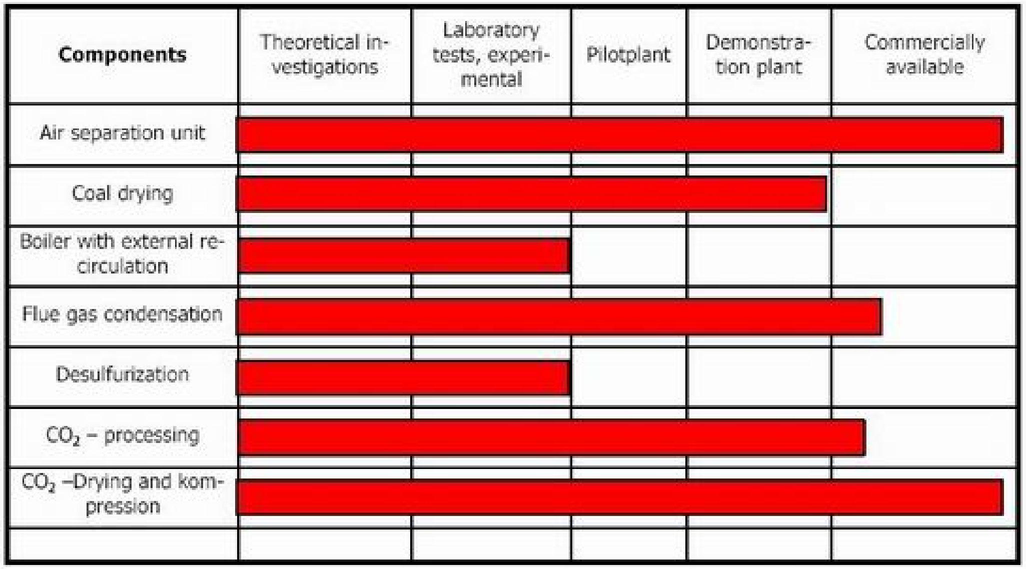

Figure E.1 *Market-readiness of oxy-fuel combustion for coal-fired power plants*
Source: Internet Source 137.

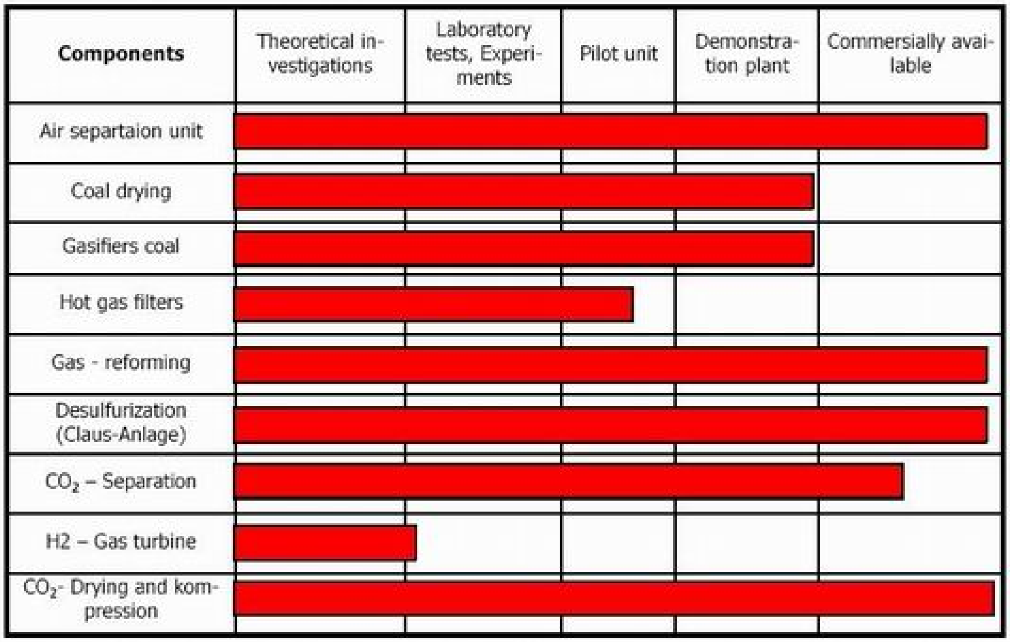

Figure E.2 *Market-readiness of pre-combustion for coal-based IGCC power plants*
Source: Internet Source 137.

Generally, it is assumed that CCS - in applications other than natural gas production - could be commercial around 2015 (Strömberg, 2003). Table E.2 provides insight in the disaggregation of the three aforementioned coal-based CCS technologies into main components.

Table E.2 *Characterisation of Climate Mitigation Goods related to CCS with strong Prospects for Commercialisation*

Sector	Technology	Technology sub-category	Main components	HS-Code/Ex-out
Carbon Capture and Storage	Post combustion	Post combustion at coal-fired power plant	Conventional (supercritical or ultrasupercritical) coal boiler	
			Desulphurisation	
			CO_2 separation (chemical, e.g. by means of aMDEA)	
			CO_2 drying and compression	
	Oxy-fuel combustion	Oxy-fuel at coal-fired power plant	Air separation plant	
			Coal drying	
			Boiler with external recirculation	
			Flue gas condensation	
			Desulphurisation	
			CO_2 processing	
			CO_2 drying and compression	
	Pre-combustion	Pre-combustion at IGCC power plant	Air separation plant	
			Coal drying	
			Coal gasifier	
			Hot gas filters	
			Gas reforming (water-gas shift reaction)	
			Desulphurisation (Claus plant)	
			CO_2 separation (physical)	
			H_2 gas turbine	
			CO_2 drying and compression	

Note: Conventional components common in these applications, like steam turbines and generators are excluded.