Technical and economic features of renewable electricity technologies

P. Lako

ECN-E--10-034

May 2010

Acknowledgement/Preface
This study provides an analysis of the potential for cost reduction for a number of key renewable energy technologies. The study was initiated to investigate the potential impact of technological learning on renewable electricity generation technologies and has been performed in the framework of an international project with a long-term view. Valuable comments have been received from Joost van Stralen (co-reader) and incorporated to the maximum extent. The study has been registered at ECN under project number 5.0368.

Abstract
Renewable energy technologies show a steady growth both in Europe and on a global scale. In this study, the potential for cost reduction of renewable energy technologies is investigated, based on assumed learning effects. These learning effects may involve cost reductions of 5-20% for each doubling of the cumulative installed capacity for a specific renewable energy technology. The extent to which the investment costs (and also the operation and maintenance costs) of a technology may be reduced, depend therefore on two main variables, i.e. on the one hand the learning effect that is representative for that technology and on the other hand the potential expansion of the global (or European) capacity of the technology of interest. In this way, future investment costs and operation and maintenance costs of key renewable energy technologies are estimated.

Contents

List of tables

List of figures

Summary

This study provides an overview of technical-economic data of renewable technologies for electricity generation from the point of view of future deployment and based on assumed learning effects. Learning effects for (renewable) energy technologies are mainly determined by two variables:

- A so-called Progress Ratio (PR). The Progress Ratio is a number, e.g. 0.9, which determines that the investment cost - specific investment cost, in €/kW installed - of a technology decreases by 10% for each doubling of the cumulative installed capacity. This PR is generally applied to the global installed capacity of a renewable energy technology. However, it may also be applied to the European capacity of, e.g. offshore wind, particularly if a technology is not (yet) applied elsewhere. The most realistic results, however, apply to a global context.
- The other variable is the (global) expansion to be expected for a specific renewable energy technology. It has been argued that global scenarios are preferred above European scenarios. However, in this study both European and global expansion scenarios are considered. It may be preferable to consider relatively optimistic scenarios in order to investigate the potential cost reduction for several renewable energy technologies.

Therefore, this study considers a number of renewable energy technologies and their potential for cost reduction in the timeframe 2008-2030 (and beyond). This is performed in the following way:

- The technology is characterised in terms of currently installed capacity, current electricity generation, capacity factor (number of full-load hours), availability, etc.
- The investment cost and the current operation and maintenance (O&M) costs are presented.
- The global and European potential of the technology is presented, starting with the technical potential of the technology but including constraints from environmental protection, etc.
- The future investment cost (in €/kW installed) is determined based on a learning curve that may be representative for a technology. A progress ratio (PR) is defined. The cost of operation and maintenance (O&M) is assumed to decrease proportionally with the investment cost.

The investment costs and operation and maintenance costs are expressed in € of the year 2008.

Onshore wind

In 2008, the onshore wind capacity in the EU, Norway, Switzerland and Turkey stood at 64.5 GW_e. On the one hand, the EU capacity is assumed to be increased to 149 GW_e in 2020 and 210 GW_e in 2030. On the other hand, it is assumed that the global onshore wind capacity may be increased from 119.4 GW_e in 2008 to 488 GW_e in 2020 and 1,028 GW_e in 2030. Furthermore, it is assumed that the Progress Ratio (PR) for onshore wind is 0.9, which means that the investment cost decreases by 10% for each doubling of the cumulative capacity. For the operation and maintenance costs of onshore wind a similar cost reduction is assumed.

Based on these scenarios for onshore wind in the EU27(+) and the world and a PR of 0.9, it turns out that the specific investment cost may come down as follows:

- € 1,350/kWe in 2008.
- € 1,090-1,190/kWe in 2020.
- € 970-1,130/kWe in 2030.

Therefore, the investment cost may be reduced by 20-25% in the period 2008-2030. Representative operation and maintenance costs are € 12/MWh in 2008, € 10-11/MWh in 2020, € 8-10/MWh in 2030.

Offshore wind
In 2008, the offshore wind capacity in the EU stood at 1,400 MW_e. On the one hand, the EU capacity is assumed to be increased to 43.1 GW_e in 2020 and 124.6 GW_e in 2030. On the other hand, it is assumed that the global capacity may be increased from 1,400 MW_e in 2008 (there are no offshore wind farms outside the EU until this date) to 50.7 GW_e in 2020 and 275.7 GW_e in 2030. Also, a default Progress Ratio (PR) of 0.95 is assumed for offshore wind (5% cost reduction for each doubling of cumulative capacity), both for specific investment costs and the operation and maintenance costs.

Based on these scenarios for offshore wind in the EU27(+) and the world and a PR of 0.95, it turns out that the specific investment cost may come down as follows:
- € 3,000-3,400/kWe in 2008.
- € 2,300-2,640/kWe in 2020.
- € 2,030-2,440/kWe in 2030.

Therefore, the investment cost may be reduced by 30% in the period 2008-2030. Representative operation and maintenance costs are € 33/MWh in 2008, € 24-27/MWh in 2020, € 21-25/MWh in 2030.

Geothermal power
In 2008, the total geothermal capacity in the EU27 was approximately 840 MW_e. On the one hand, the EU capacity is assumed to be increased to 4.2 GW_e in 2020 and 9.7 GW_e in 2030. On the other hand, it is assumed that the global geothermal capacity may be increased from 9.0 GW_e in 2008 to 29.8 GW_e in 2020 and 80.9 GW_e in 2030. Furthermore, it is assumed that the Progress Ratio (PR) for geothermal power is 0.95 (5% cost reduction for each doubling of cumulative capacity).

Based on these scenarios and learning rates, the specific investment cost may come down as follows:
- € 4,000-10,000/kWe in 2008.
- € 3,550-9,150/kWe in 2020.
- € 3,350-8,500/kWe in 2030.

Therefore, investment costs may be reduced by 15% in the period 2008-2030. Representative operation and maintenance costs are € 10-25/MWh in 2008, € 9-23/MWh in 2020, € 8.5-22/MWh in 2030.

Concentrating Solar Power (CSP)
In 2008, the capacity of CSP in the EU27 was approximately 175 MW_e. On the one hand, the EU capacity is assumed to be increased to 14.0 GW_e in 2020 and 62.3 GW_e in 2030. On the other hand, it is assumed that the global capacity of Concentrating Solar Power (CSP) may be increased from 675 MW_e in 2008 to 17.6 GW_e in 2020 and 139.4 GW_e in 2030. Furthermore, it is assumed that the Progress Ratio (PR) for CSP is 0.925 (7.5% cost reduction for each doubling of cumulative capacity).

Based on these scenarios and learning rates, the specific investment cost may come down as follows:
- € 4,500/kWe in 2008.
- € 2,440-3,350/kWe in 2020.
- € 2,065-2,655/kWe in 2030.

Therefore, investment costs may be reduced by approximately 48% in the period 2008-2030. Representative operation and maintenance costs are € 47/MWh in 2008, € 26-35/MWh in 2020, € 22-28/MWh in 2030.

Photovoltaic power (PV)
In 2008, the capacity of PV in the EU27 was approximately 9.4 GW_e. On the one hand, the EU capacity is assumed to be increased to 116 GW_e in 2020 and 392 GW_e in 2030. On the other hand, it is assumed that the global capacity of photovoltaic power (PV) may be increased from 14.7 GW_e in 2008 to 189 GW_e in 2020 and 716 GW_e in 2030. Furthermore, it is assumed that the Progress Ratio (PR) for PV is 0.82 (18% cost reduction for each doubling of cumulative capacity).

Based on these scenarios and learning rates, the specific investment cost may come down as follows:
- € 3,600-4,500/kWe in 2008.
- € 1,730-2,190/kWe in 2020.
- € 1,180-1,550/kWe in 2030.

Therefore, investment costs may be reduced by approximately 67% in the period 2008-2030. Representative operation and maintenance costs are € 18-19/MWh in 2008, € 8-10/MWh in 2020, € 5-7/MWh in 2030.

Hydropower
In 2008, the capacity of small hydropower in the EU27 was approximately 12.8 GW_e. On the one hand, the EU capacity is assumed to be increased to 16.7 GW_e in 2020 and 19.0 GW_e in 2030. On the other hand, it is assumed that the global small hydropower capacity may be increased from 85 GW_e in 2008 to 116.8 GW_e in 2020 and 145.3 GW_e in 2030. Furthermore, it is assumed that the Progress Ratio (PR) for small hydropower is 0.95 (5% cost reduction per doubling of the cumulative capacity).

Based on these scenarios and learning rates, the specific investment cost may come down as follows:
- € 2,500-4,220/kWe in 2008.
- € 2,440-4,130/kWe in 2020.
- € 2,400-4,100/kWe in 2030.

Therefore, investment costs may be reduced by 5% in the period 2008-2030. Representative operation and maintenance costs are € 13-21/MWh in 2008, € 12-21/MWh in 2020, € 12-21/MWh in 2030.

1. Introduction

1.1 General

This study provides an overview of technical-economic data of a number of renewable energy technologies for electricity generation that are available today and may play an increasingly important role inside and outside Europe. These renewable electricity generation technologies are covered in the following way:
- The technology is characterised in terms of currently installed capacity, current electricity generation, capacity factor (number of full-load hours), availability, etc.
- The investment cost and the current operation and maintenance (O&M) costs are presented.
- The global and European potential of the technology is presented, starting with the technical potential of the technology but including constraints from environmental protection, etc.
- The future investment cost (in €/kW installed) is determined based on a learning curve that may be representative for a technology. First, a progress ratio (PR) is defined. For instance, a PR of 0.9 means that the investment cost (in €/kW installed) decreases by 10% for each doubling of the cumulative capacity of the technology. Then, the potential of the technology in Europe and the world in the period 2010-2050 is tentatively determined. Finally, the future investment cost is determined based on these global and European scenarios and taking into account the progress ratio of the technology. Also, the cost of operation and maintenance (O&M) is generally assumed to decrease proportionally with the investment cost.

The renewable electricity generation technologies covered in this study are:
- Onshore wind (Chapter 2).
- Offshore wind (Chapter 3).
- Geothermal power (Chapter 4).
- Concentrating Solar Power, CSP (Chapter 5).
- Photovoltaic power, PV (Chapter 6).
- Hydro power (Chapter 7).

1.2 Scenarios for deployment of renewable electricity technologies

In order to give insight in the scenarios for renewable energy options for Europe (the EU27, Norway, and Switzerland) and the world, the main assumptions in terms of capacities are summarised below.

Onshore wind

For onshore wind, the scenario for Europe may be as follows (the numbers refer to the maximum capacity in a year):
- 2008: 64.5 GWe.
- 2010: 79.5 GWe.
- 2020: 149.1 GWe.
- 2030: 210.3 GWe.
- 2050: 297.5 GWe.

Figure 1.1 shows the maximum capacity of onshore wind in Europe and on a global scale. More explanation about these maximum capacities will be provided in Chapter 2.

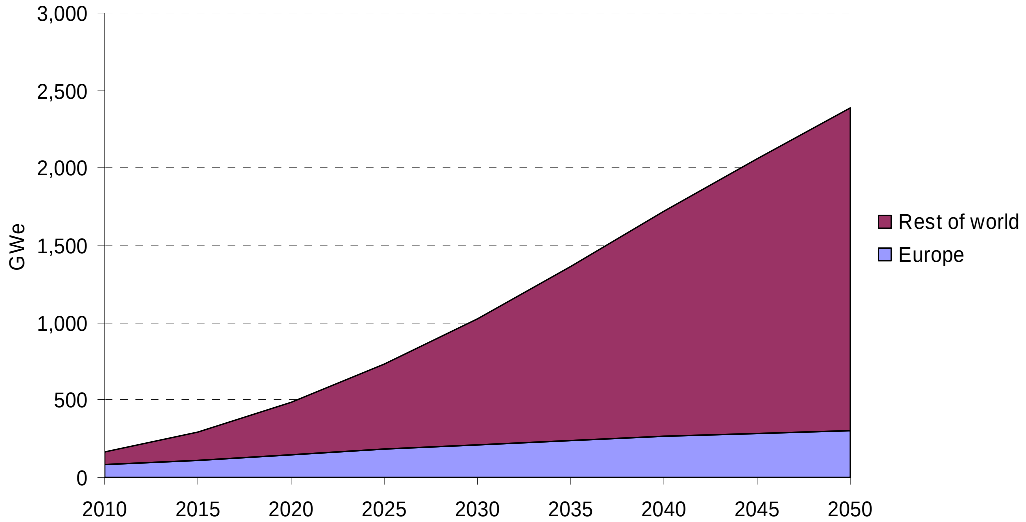

Figure 1.1 *Maximum capacity of onshore wind in Europe and on a global scale*

Offshore wind
For onshore wind, the scenario for Europe may be as follows (the numbers refer to the maximum capacity in a year):
- 2008: 1.4 GWe.
- 2010: 3.7 GWe.
- 2020: 43.1 GWe.
- 2030: 124.6 GWe.
- 2050: 260 GWe.

Figure 1.2 shows the maximum capacity of offshore wind. The offshore wind capacity of the EU in 2020-2030 is based on (Tambke and Michalowska-Knap, 2010), as will be explained in Chapter 3.

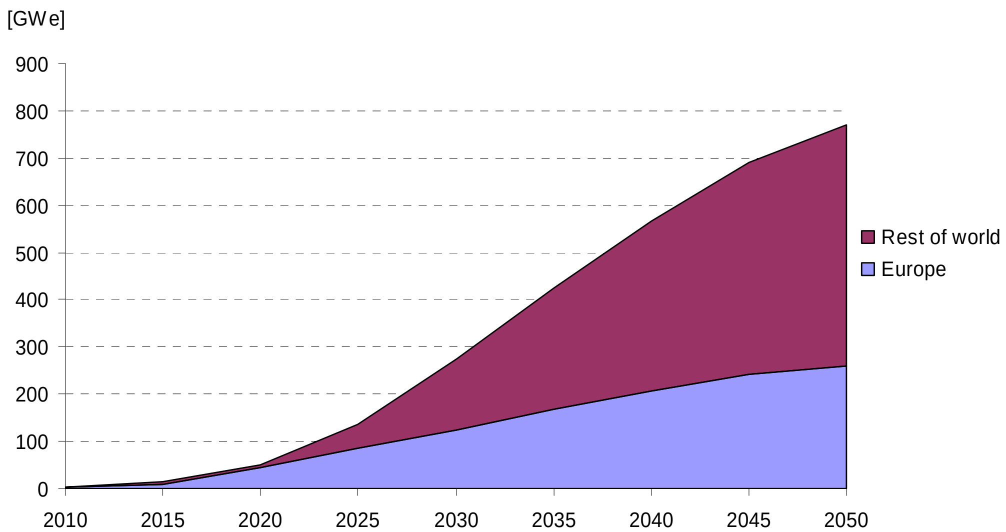

Figure 1.2 *Maximum capacity of offshore wind in Europe and on a global scale*

Geothermal power
For geothermal power, the scenario for Europe may be as follows (the numbers refer to the maximum capacity in a year):
- 2008: 0.8 GWe.
- 2010: 1.2 GWe.
- 2020: 4.2 GWe.
- 2030: 9.7 GWe.
- 2050: 16.7 GWe.

Figure 1.3 shows the maximum capacity of geothermal power in Europe and on a global scale. More explanation about these maximum capacities will be provided in Chapter 4.

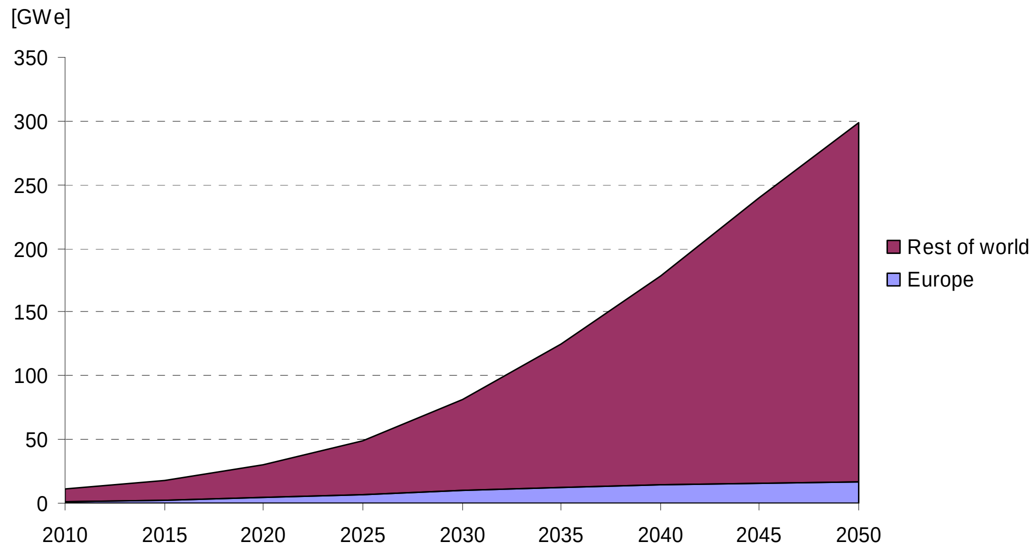

Figure 1.3 *Maximum capacity of geothermal power in Europe and on a global scale*

Concentrating Solar Power (CSP)
For Concentrating Solar Power (CSP), the scenario for Europe may be as follows (the numbers refer to the maximum capacity in a year):
- 2008: 0.2 GWe.
- 2010: 0.4 GWe.
- 2020: 14.0 GWe.
- 2030: 62.3 GWe.
- 2050: 100 GWe.

Figure 1.4 shows the maximum capacity of Concentrating Solar Power in Europe and on a global scale. More explanation about these maximum capacities will be provided in Chapter 5.

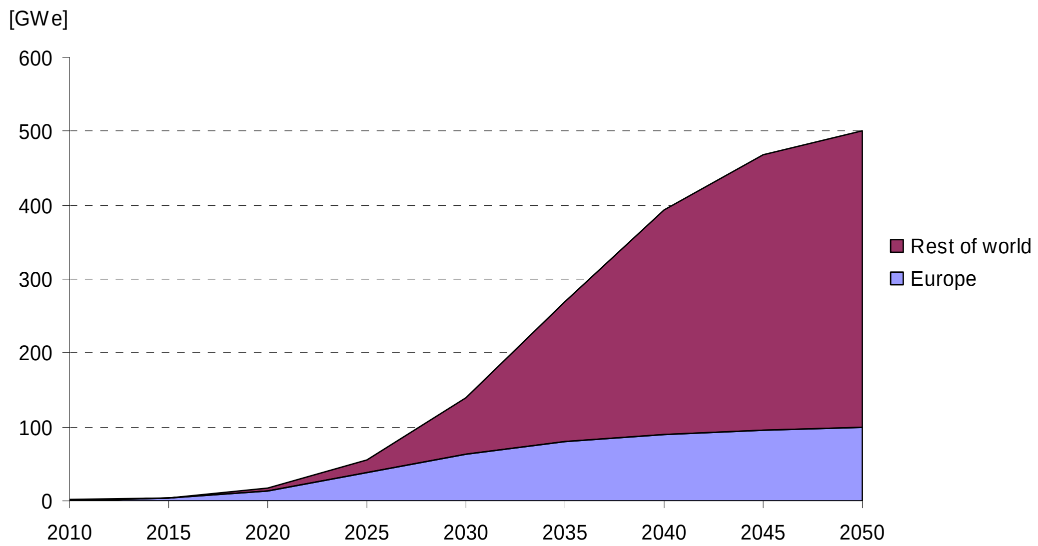

Figure 1.4 *Maximum capacity of geothermal power in Europe and on a global scale*

Photovoltaic power (PV)

For photovoltaic power (PV), the scenario for Europe may be as follows (the numbers refer to the maximum capacity in a year):

- 2008: 9.4 GWe.
- 2010: 15.9 GWe.
- 2020: 115.8 GWe.
- 2030: 392 GWe.
- 2050: 988 GWe.

Figure 1.5 shows the maximum capacity of photovoltaic power in Europe and on a global scale. More explanation about these maximum capacities will be provided in Chapter 6.

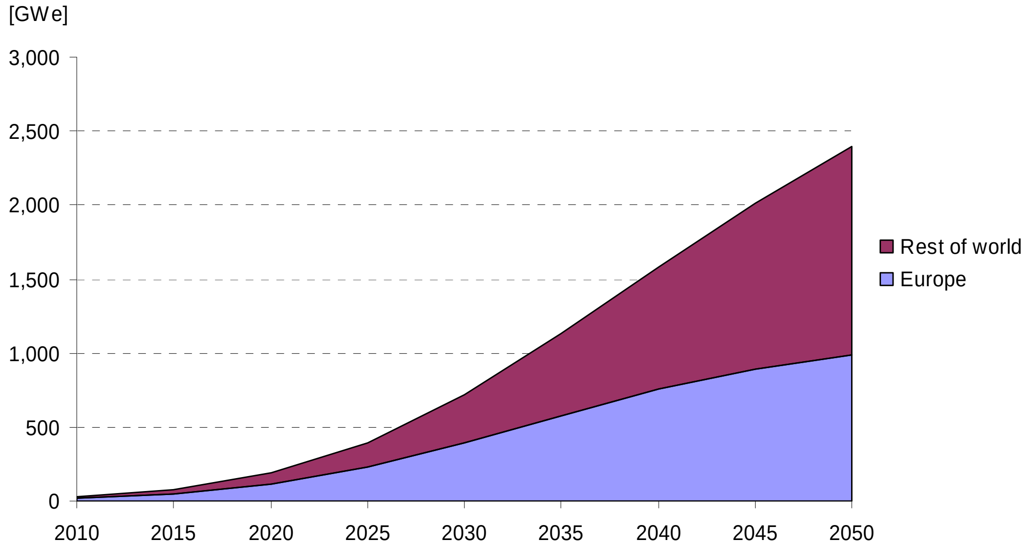

Figure 1.5 *Maximum capacity of photovoltaic power (PV) in Europe and on a global scale*

Hydro power
With regard to hydro power, a scenario for *small hydro power* for Europe (EU25 with Norway and Switzerland) may be as follows (the numbers refer to the maximum capacity in a year):
- 2008: 12.6 GWe.
- 2010: 13.3 GWe.
- 2020: 16.7 GWe.
- 2030: 19.0 GWe.
- 2050: 20.3 GWe.

Figure 1.6 shows the maximum capacity of small hydro in Europe and on a global scale. More explanation about these maximum capacities will be provided in Chapter 7.

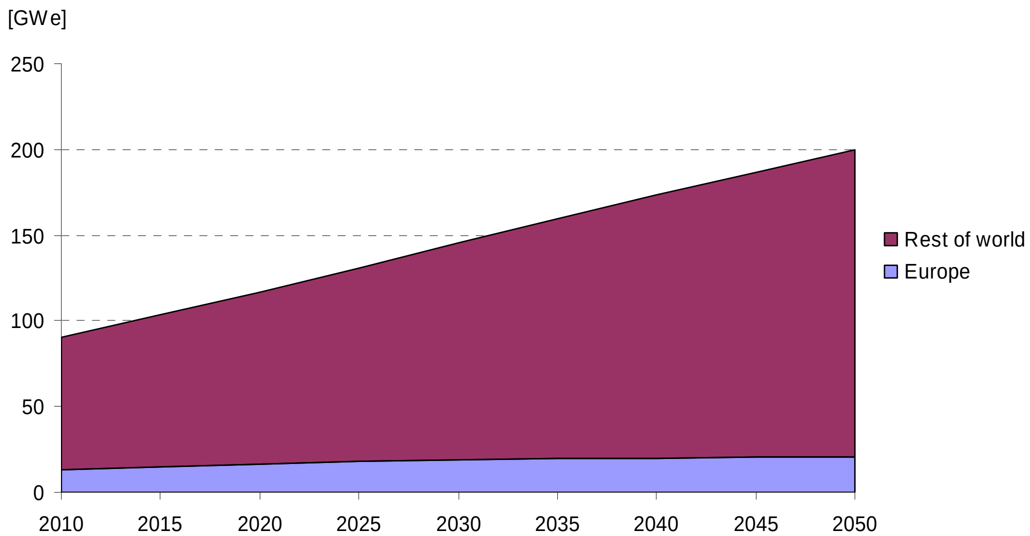

Figure 1.6 *Maximum capacity of small hydro power in Europe and on a global scale*

2. Onshore wind

The start of onshore wind, with relatively small wind turbines, may be characterised as the year 1985. In 2008, the capacity of onshore wind in the EU, Norway, Switzerland and Turkey stood at 64.5 GW_e (Table 2.1). Figure 2.1 shows the share of wind in power generation in a few key countries. It is assumed that the realistic potential of onshore wind in Europe is 261 GW_e in 2040 (Table 2.1), corresponding to an amount of electricity of approximately 441 TWh per year, based on estimates of the *realistic potential* for countries of interest[1] (Beurskens, 2010). Table 2.2 presents technical, environmental, and economic characteristics of onshore wind. Wind farms have capacities from 20 to 200 MW_e, with a construction period of 3-13 months (average 8 months). The capacity factor ranges from 14 to 28% (average 25%).

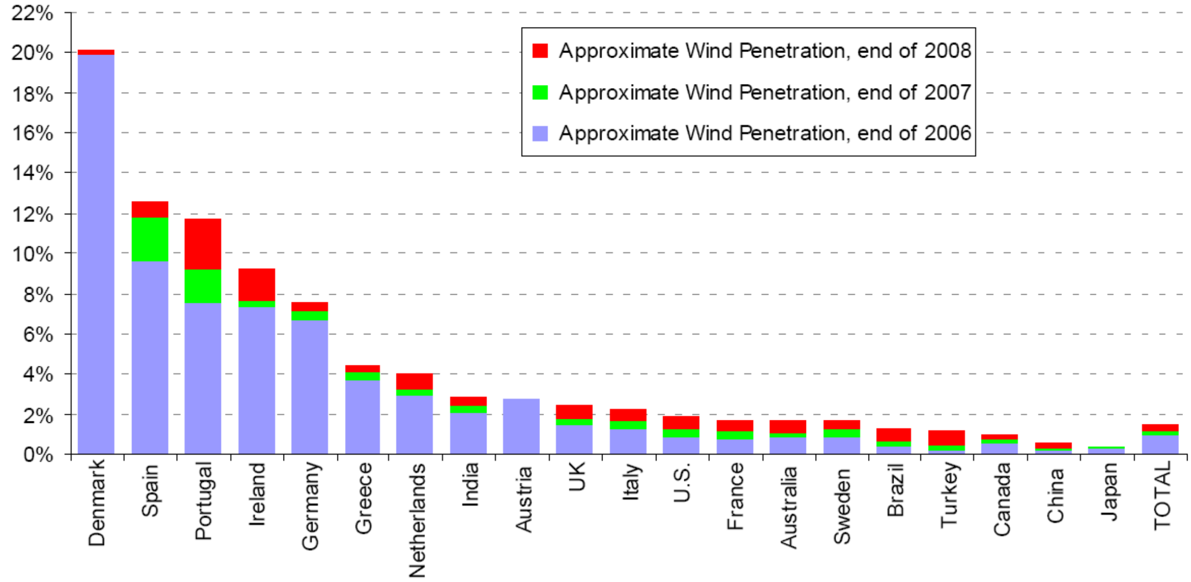

Figure 2.1 *Approximate wind power penetration in a number of countries*
Note: Estimates of Berkeley Lab based on data from BTM Consult and others.
Source: NREL, 2009.

In the USA, the investment cost was $1,915/kW (≈ € 1,300/kW) in 2008 (NREL, 2009). In Europe, Lensink et al (2009) put the cost at € 1,350/kW ($€_{2010}$) in 2010. BTM Consult (2009) gives a figure of € 1,380/kW ($€_{2009}$) for 2009-2010. In the present study, a range is assumed of € 1,200-1,500/kW - on average € 1,350/kW - in $€_{2008}$ for 2008. The operation and maintenance (O&M) costs are estimated at 2% of the investment cost per year. The economic lifetime is 25 years, equal to the technical lifetime.

The progress ratio (PR) has been reported for different world regions and countries and different timeframes. Junginger reported a PR of 0.91-1.01 for Germany in the period 1991-2001, and a PR of 0.81-0.85 for the world in the period 1990-2001 (Junginger, 2005; Junginger et al, 2008). According to the latter literature source, PR's have been reported from as low as 0.83 for Denmark (1981-2000)

1 The realistic wind potential is the technical potential with exclusion of areas protected for reasons of nature conservation, natural beauty, safety, noise, etc. A realistic potential includes social constraints, but not economical constraints.

to as high as 0.92-0.94 for wind turbines produced in Denmark and Germany (until about 2003). Therefore, the PR of onshore wind is put at 0.9, which means that the investment cost decreases by 10% for each doubling of the cumulative capacity. The investment costs depend on future capacities. There are two scenarios: a global scenario ending up at 2,390 GW_e in 2050, and a European scenario ending up at approximately 300 GW_e in 2050 (Beurskens, 2010). Table 2.2 shows the development of the specific investment costs. The investment cost may come down to € 860/kW or € 1,070/kW in 2050, depending on the scenario.

Table 2.1 *Realistic potential of onshore wind in the EU27 region including Norway, Switzerland, and Turkey*[a]

Country	Unit	Potential capacity						Unit	Potential generation					
		2008	2010	2020	2030	2040	2050		2008	2010	2020	2030	2040	2050
Austria	[MWe]	997	1,247			2,904		[GWh]					4,243	
Belgium & Lux.	[MWe]	376	486			2,085		[GWh]					3,824	
Bulgaria	[MWe]					632		[GWh]					2,950	
Cyprus	[MWe]	138	238			1,983		[GWh]					1,074	
Czech Republic	[MWe]	2,761	2,934			4,882		[GWh]					1,938	
Denmark	[MWe]	67	167			1,433		[GWh]					10,216	
Estonia	[MWe]	113	248			7,570		[GWh]					1,933	
Finland	[MWe]	3,671	6,966			35,558		[GWh]					13,331	
France	[MWe]	23,933	27,273			33,250		[GWh]					65,211	
Germany	[MWe]	1,102	1,502			4,566		[GWh]					54,209	
Greece	[MWe]	162	312			2,932		[GWh]					8,374	
Hungary	[MWe]	990	1,415			4,561		[GWh]					2,584	
Ireland	[MWe]	3,731	5,031			12,504		[GWh]					10,876	
Italy	[MWe]	29	129			1,062		[GWh]					17,655	
Latvia	[MWe]	71	171			1,773		[GWh]					1,142	
Lithuania	[MWe]					632		[GWh]					1,938	
Malta	[MWe]					13		[GWh]					21	
Netherlands	[MWe]	1,994	2,525			4,500		[GWh]					9,032	
Norway	[MWe]	385	885			25,590		[GWh]					57,481	
Poland	[MWe]	472	1,072			10,000		[GWh]					9,233	
Portugal	[MWe]	2,829	4,729			4,800		[GWh]					6,256	
Romania	[MWe]	76	276			7,000		[GWh]					14,160	
Slovenia	[MWe]					1,068		[GWh]					1,043	
Slovakia	[MWe]	3				255		[GWh]					224	
Spain	[MWe]	16,453	20,453			35,414		[GWh]					45,194	
Sweden	[MWe]	891	1,761			13,015		[GWh]					24,303	
Switzerland	[MWe]	13	93			1,047		[GWh]					1,194	
Turkey	[MWe]	512	1,062			20,066		[GWh]					26,853	
UK	[MWe]	2,675	5,047			18,000		[GWh]					44,602	
Total EU27+	[MWe]	64,510	86,213			261,368		[GWh]					441,094	

a The realistic wind potential is the technical potential with exclusion of areas protected for reasons of nature conservation, natural beauty, safety, noise, etc.

Source: Beurskens, 2010.

Table 2.2 *Technical and economic features of onshore wind in the EU*

Technical performance	Unit	Typical ranges									
Technology		Onshore wind									
Efficiency	[%]	Not applicable									
Construction period	[month]	3-13; average 8									
Technical lifetime	[year]	25									
Capacity factor	[%]	14-28; average 25									
Maximum availability	[%]	98									
Environmental impact		Typical ranges									
GHG emissions	[kg/MWh]	Not applicable									
SO_2	[g/MWh]	Not applicable									
NO_x	[g/MWh]	Not applicable									
Particulates	[g/MWh]	Not applicable									
Solid waste	[g/MWh]	Not applicable									
Costs		[$€_{2008}$]									
Investment cost including IDC [a] (2008)	[€/kW]	1,200-1,500; average 1,350									
Fixed & variable O&M cost	[% of inv.]	2									
Fuel cost	[€/MWh]	Not applicable									
Economic lifetime	[year]	25									
Progress ratio	[]	0.9									
Data projections		2010			2020			2030			2050
Variant		Low	Average	High	Low	Average	High	Low	Average	High	Average
Capacity factor	[%]	25	25	25	25	25	25	25	25	25	25
Investment cost including IDC [a]	[€/kW]	1,147-1,163	1,290-1,308	1,433-1,453	969-1,057	1,090-1,189	1,211-1,321	865-1,003	973-1,128	1,081-1,253	856-1,070
Operation and maintenance	[€/MWh]	10.5-10.6	11.8-11.9	13.1-13.3	8.8-9.7	10.0-10.9	11.1-12.1	7.9-9.2	8.0-10.3	9.9-11.4	7.8-9.8
Capacity Europe (realistic potential)	[GWe]	79.5	79.5	79.5	149.1	149.1	149.1	210.3	210.3	210.3	297.5
Capacity world (realistic potential)	[GWe]	160.7	160.7	160.7	487.7	487.7	487.7	1,028.4	1,028.4	1,028.4	2,390

a IDC = Interest during construction.

3. Offshore wind

Offshore wind farms were built from 1990, starting with a single turbine in Sweden. In 2009, thirty wind farms are operational with a combined capacity of approximately 2,000 MW_e (Table 3.1).

Table 3.1 *Characteristics offshore wind farms in the EU*

Wind farm	Country	On line	Capacity Turbine [MW]	Capacity Farm [MW]	Capacity factor []	Investment cost [$M€_{2006}$]	Investment cost [€/kW]	Reference (IS = Internet Source)
Nogersund	S	1990	0.22	0.22				
Vindeby	DK	1991	0.45	5.0	0.26	13.3	2,679	IS 1
Lely	NL	1994	0.5	2.0	0.22	5.5	2,770	IS 2
Tuno Knøb	DK	1995	0.5	5.0	0.30	12.3	2,485	Madsen, 1996
Bockstigen	S	1998	0.55	2.75	0.38	4.5	1,635	IS 3-4
Utgrunden	S	2000	1.425	10.5	0.40	20.6	1,962	IS 5
Blyth	UK	2000	2	4	0.30	6.3	1,570	IS 6
Middelgrunden	DK	2001	2	40	0.28	52.6	1,315	Larsen et al, 2005
Yttre Stengrund	S	2001	2	10	0.34	14.6	1,462	IS 5 and 7
Horns Rev I	DK	2002	2	160	0.43	291.3	1,821	Frandsen et al, 2004
Samsø	DK	2003	2.3	23	0.34	37.4	1,628	IEA, 2005
Rønland	DK	2003	2.3	17.2	0.47			
Nysted I	DK	2003	2.3	165.6	0.38	287.6	1,737	IEA, 2005
Frederikshavn	DK	2003	3	10.6	0.23			
Arklow Bank	IRL	2003	3.6	25.2	0.43			
North Hoyle	UK	2003	2	60	0.38	123.3	2,055	IS 8
Scroby Sands	UK	2004	2	60	0.33	114.1	1,901	IS 9
Kentish Flats	UK	2005	3	90	0.36	158.6	1,762	IS 10-11
Rostock Breitling	D	2006	2.5	2.5	0.41			
Barrow	UK	2006	3	90	0.39	146.7	1,630	IS 12
Egmond aan Zee	NL	2006	3	108	0.38	203.6	1,885	IS 13
Grenaa-harbour	DK	2007	2.75	8.25				
Lillgrund	S	2007	2.3	110	0.34	190.2	1,723	IS 14
Moray Firth	UK	2007	5	10	0.46			
Burbo Bank	UK	2007	3.6	90	0.40	153.5	1,706	IS 15
Princess Amalia	NL	2008	2	120	0.38	376.3	3,136	IS 16
Thornton Bank I	B	2008	5	30				
Kemi A jos	FIN	2008	3	24				
Lynn-Inner Downsing	UK	2008	3.6	193	0.39	434.8	2,237	IS 17-18
Robin Rigg	UK	2009	3	180	0.40	465.0	2,583	IS 19-20
Horns Rev II	DK	2009	2.3	200	0.46	456.2	2,281	IS 21
Rhyl Flats	UK	2009	3	90		272.1	3,023	IS 22

Sources: Junginger et al, 2008; Madsen, 1996; Kühn et al, 2001; Lako, 2002; Frandsen et al, 2004; SEI, 2004; Junginger, 2005; IEA, 2005; Larsen et al, 2005; Shell, 2005; Isles, 2006; REW, 2007; Moll, 2007; Internet Sources 1-22.

Table 3.1 shows that the specific investment cost of offshore wind decreased from € 2,500-2,800/kW ($€_{2006}$) in the early 1990s to as low as € 1,820/kW for Horns Rev I (Denmark), commissioned in 2002. After that, prices started to rise, jumping to a level in excess of € 3,000/kW ($€_{2006}$) for the wind farms Princess Amalia (formerly known as Q7 WP, the Netherlands, 2008) and Rhyl Flats (UK, 2009). Several factors among which lack of competition between wind turbine manufacturers (Isles, 2006), risk aversion by manufacturers that were able to choose between supply of on- and offshore wind turbines, and fast increasing prices of steel and copper caused price increases of approximately 50%. After a period of rising prices, it is highly probable that prices of offshore wind farms will come down again. Junginger et al. (2008) argue that a number of factors cause long-term cost reduction:

- Increasing capacity of wind turbines, from 500 kW in the early 1990s to 2 MW in 2000, and 5 MW and more today (economies of scale of offshore wind turbines).
- Increasing numbers of turbines and correspondingly increasing capacity of wind farms, which may be up to 400 MW around 2010 (economies of scale by series production).
- Fewer platforms/foundations needed as wind turbine capacities increase: for example, Thornton Bank (Belgium) will have 60 turbines of 5 MW each, compared to 100 turbines of 3 MW for Thanet (UK). However, the anvil, the connecting piece between piling hammer and pile, reaches its limit at a diameter of six metres. The pile diameter for a 5-MW machine in water 30 metres deep would surpass that limit (Mathis, 2006; Internet Source 23).
- Economies of scale with regard to lifting equipment, reported by Söger et al. (2006).
- Reduced cost of cables, transformers, and grid connection (Junginger, 2005), which may be a function of the size of the wind farm. It is acknowledged that High Voltage Direct Current (HVDC) appears to be optimal for large, relatively far offshore wind farms (400-1,000 MW).
- Significant learning by doing occurring during turbine installation, e.g., the time to install an offshore wind turbine was reduced from over 48 to less than 8 eight hours (Junginger, 2005).
- Dedicated offshore turbines, which may reduce Operation and Maintenance (O&M) costs.

Table 3.2 shows the potential capacity and generation of offshore wind for the EU27 and Norway, Switzerland, and Turkey, and for the period 2008-2050, based on an assessment of the realistic potential of each European country (Beurskens, 2010). It is reiterated that the *realistic potential* is defined as the technical potential with exclusion of areas protected for reasons of nature conservation, natural beauty, safety, noise, etc. The *realistic potential* of offshore wind in Europe is estimated at approximately 212 GW_e in 2040, corresponding to an amount of electricity of approximately 655 TWh per year. For the years 2020 and 2030, a projection of the offshore wind capacity in the North Sea and the Baltic Sea of Tambke and Michalowska-Knap (2010) has been used. Their data for Belgium in 2030 has been corrected: the maximum capacity of Belgium is estimated at 2,625 MW_e, and data of Russia has been omitted it as we focus on EU27+ countries. Taking into account that wind turbines become larger and more efficient, it appears to be realistic to assume an offshore wind capacity of 260 GW_e in 2050.

Table 3.3 provides typical technical, environmental, and economic characteristics of offshore wind farms. At the end of 2008, the cumulative capacity amounted to 1,400 MW_e. The typical size of an offshore wind farm is approaching 400 MW_e. The corresponding construction period of offshore wind farms is 18-32 months (average 24 months). The capacity factor is 34-46% (average 40%).

The investment cost of offshore wind ranges from typically € 3,000/kW, as assumed by BTM Consult (2009), up to € 3,400/kW - average € 3,200/kW - in $€_{2008}$ in 2008. Operation and maintenance (O&M) costs are estimated at 3.6% of the investment cost per year. The economic lifetime is put at 25 year (equal to the technical lifetime). For offshore wind, Progress Ratios (PR's) have been reported from as low as approximately 0.9 for offshore wind farms in Europe until 2005 to as high 0.90-1.13 for the second period distinguished from 1991 to 2007 (Isles, 2006; Junginger et al, 2008). Therefore, the PR of offshore wind is estimated at 0.95. Specific investment costs decrease by 5% for each doubling of the cumulative capacity. Based on these data, the specific investment cost may come down as shown in Table 3.3. It turns out that the investment cost may come down to approximately € 2,000/kW or € 2,175/kW around 2050, depending on the scenario.

Table 3.2 *Realistic potential of offshore wind in the EU27 region including Norway, Switzerland, and Turkey* [a]

Country	Unit	Potential capacity						Unit	Potential generation					
		2008	2010	2020	2030	2040	2050		2008	2010	2020	2030	2040	2050
Austria	[MWe]							[GWh]						
Belgium & Lux.	[MWe]	30	450	1,994	2,625	2,625		[GWh]					8,537	
Bulgaria	[MWe]					1,998		[GWh]					4,463	
Cyprus	[MWe]					2,916		[GWh]					8,046	
Czech Republic	[MWe]							[GWh]						
Denmark	[MWe]	398	850	2,329	3,799	15,000		[GWh]					51,087	
Estonia	[MWe]				1,600	1,860		[GWh]					4,839	
Finland	[MWe]		15	590	3,190	4,500		[GWh]					11,826	
France	[MWe]		105	2,510	4,914	30,540		[GWh]					92,255	
Germany	[MWe]		60	10,249	26,553	34,755		[GWh]					125,831	
Greece	[MWe]					4,740		[GWh]					11,062	
Hungary	[MWe]							[GWh]						
Ireland	[MWe]	25	25	1,055	3,780	6,600		[GWh]					21,967	
Italy	[MWe]					17,010		[GWh]					35,780	
Latvia	[MWe]				900	1,860		[GWh]					3,910	
Lithuania	[MWe]				1,000	600		[GWh]					1,261	
Malta	[MWe]					60		[GWh]					140	
Netherlands	[MWe]	228	228	4,622	12,122	16,000		[GWh]					58,756	
Norway	[MWe]			957	9,667	486		[GWh]					1,488	
Poland	[MWe]			500	5,300	9,000		[GWh]					26,351	
Portugal	[MWe]					2,400		[GWh]					5,889	
Romania	[MWe]					4,398		[GWh]					11,491	
Slovenia	[MWe]							[GWh]						
Slovakia	[MWe]							[GWh]						
Spain	[MWe]					7,800		[GWh]					18,802	
Sweden	[MWe]	133	163	2,983	10,522	7,734		[GWh]					20,782	
Switzerland	[MWe]							[GWh]						
Turkey	[MWe]					3,000		[GWh]					7,332	
UK	[MWe]	588	1,816	15,303	38,146	35,640		[GWh]					123,487	
Total EU27+	[MWe]	1,402	3,712	43,092	124,118	211,522	259,500	[GWh]					655,382	

a The realistic wind potential is the technical potential with exclusion of areas protected for reasons of nature conservation, natural beauty, safety, noise, etc.

Source: Beurskens, 2010.

Table 3.3 *Technical and economic features of offshore wind in the EU*

Technical performance	Unit	Typical ranges									
Technology		Offshore wind									
Efficiency	[%]	Not applicable									
Construction period	[month]	18-32; average 24									
Technical lifetime	[year]	25									
Capacity factor	[%]	34-46; average 40									
Maximum availability	[%]	97									
Environmental impact		Typical ranges									
GHG emissions	[kg/MWh]	Not applicable									
SO_2	[g/MWh]	Not applicable									
NO_x	[g/MWh]	Not applicable									
Particulates	[g/MWh]	Not applicable									
Solid waste	[g/MWh]	Not applicable									
Costs		[$€_{2008}$]									
Investment cost including IDC [a] (2008)	[€/kW]	3,000-3,400; average 3,200									
Fixed & variable O&M cost	[% of inv.]	3.6									
Fuel cost	[€/MWh]	Not applicable									
Economic lifetime	[year]	25									
Progress ratio	[]	0.95									
Data projections		2010			2020			2030			2050
Variant		Low	Average	High	Low	Average	High	Low	Average	High	Average
Capacity factor	[%]	40	40	40	40	40	40	40	40	40	40
Investment cost including IDC [a]	[€/kW]	2,793	2,979	3,165	2,301-2,328	2,454-2,483	2,607-2,638	2,030-2,153	2,165-2,296	2,300-2,440	2,006-2,174
Operation and maintenance	[€/MWh]	28.7	30.6	32.5	23.6-23.9	25.2-25.5	26.8-27.1	20.8-22.1	22.2-23.6	23.6-25.1	20.6-22.3
Capacity Europe	[GWe]	3.7	3.7	3.7	43.1	43.1	43.1	124.6	124.6	124.6	260.1
Capacity world	[GWe]	3.7	3.7	3.7	50.7	50.7	50.7	275.7	275.7	275.7	770

a IDC = Interest during construction.

4. Geothermal power

Table 4.1 shows the geothermal capacity in countries around the globe. In 2007, a few EU countries had operational geothermal power plants[2]: Italy (711 MW_e), Austria (0.7 MW_e), and Germany (8.4 MW_e). In 2007, Iceland had an operational geothermal capacity of 421 MW_e, and Turkey 29.5 MW_e. However, Iceland is not included in the subset of European countries. According to (Bertani, 2007), Europe's geothermal capacity amounts to 750 MW_e in 2007, and approximately 1,000 MW_e in 2010.

Table 4.1 *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 (F)	14.7	102	14.7	35	2F
Germany	0.2	1.5	8.4	8	B
Guatemala	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.
Sources: Bertani, 2006-2007; DiPippo, 1999; Lako, 2008 ; Internet Source 24.

2 The installed geothermal capacity at the Azores is not accounted for in the capacity of Europe.

On average, the temperature of the earth increases by about 3 °C for every 100 meters of depth. Geothermal energy conversion has small and manageable environmental effects compared to other energy conversion technologies. It is a reliable and predictable energy source suited to provide base load power, and it is also easy to regulate and can therefore act as peak power (Figure 4.1).

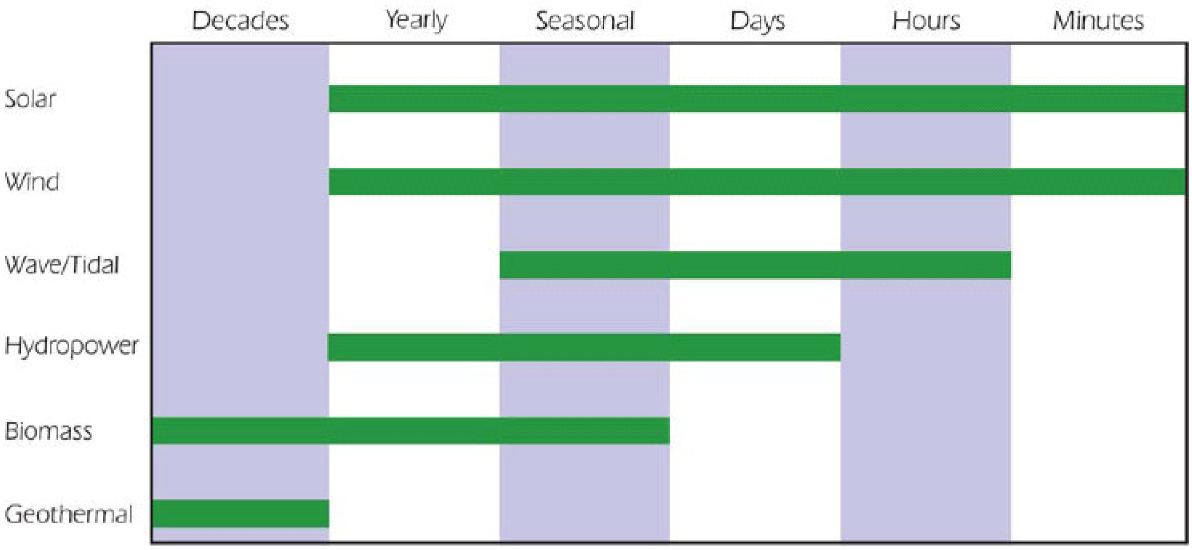

Figure 4.1 *Timescales of natural variability of renewable energies*
Source: Lundin et al, 2006.

Figure 4.2 presents the range of temperatures in the underground at 5 km depth in Europe.

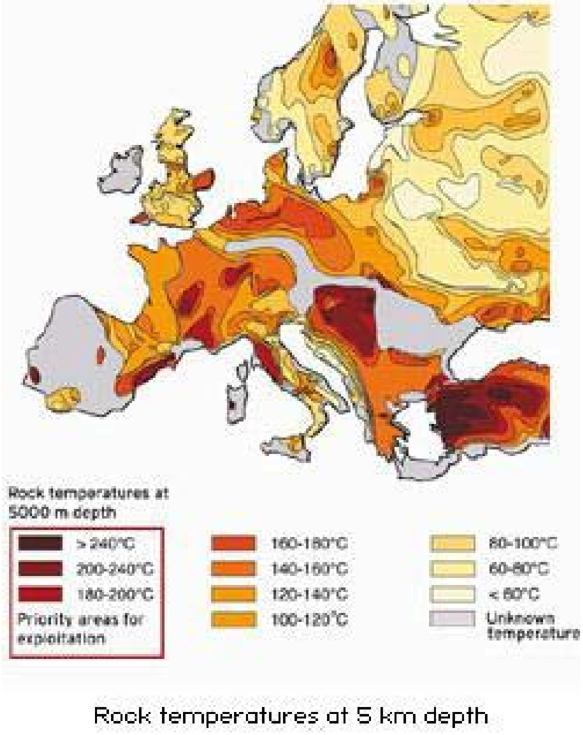

Figure 4.2 *Temperatures in the underground at 5 km depth*
Source: SPG, 2008.

Table 4.2 presents data of geothermal power and the potential thereof for European countries, based on (Gawell et al, 1999; Lundin, 2008; Bertani, 2006-2007; Gawell and Greenberg, 2007; BP, 2009). According to Lundin et al (2008), the geothermal capacity of Europe, excluding Croatia, could amount to 1,600 MW_e in 2010. The difference between the potentials presented in Tables 4.1 and 4.2 for 2010 is explained by a higher growth of geothermal power in Turkey assumed by Lundin et al. With regard to the realistic potential of geothermal power, Lundin et al (2008) present only scarce data: 380 MW_e for Croatia, 3,400 MW_e for the Czech Republic, and 500-2,000 MW_e for Turkey.

Table 4.2 *Geothermal capacity, generation, and potential by European country*

Country	Capacity 2005 (2008) [MW_e]	Generation 2005 [GWh]	Capacity 2010 (proj.) [MW_e]	Generation 2010 (proj.) [GWh] [a]	Potential Technical [MW_e]	Potential Realistic [MW_e]
Austria	1.1 (1.2)	3.2	6	15		
Belgium						
Bulgaria						200
Croatia			4.4	34.3		380
Czech Republic						3,400
Cyprus						
Denmark						
Estonia						
Finland						
France [b]	14.7 (16.0)	102	33	*231*		
Germany	0.23 (6.6)	1.5	8.4	*60*	35,500 [c]	1,600
Greece			20	*140*		900
Hungary			80	600		800
Italy	699 (711)	5,340	910	6,190		2,000
Latvia						
Lithuania						
Luxembourg						
Malta						
Netherlands						
Portugal [b]	13 (23)	90	35	275		
Poland						300
Romania						200
Slovakia			6	40		200
Slovenia						
Spain						
Sweden						
Switzerland						
Turkey	18 (83)	105	500	3,500	31,500	1,400
UK						
Total [d]	746 (841)	5,642	~ 1,600	~ 11,000		

a Figures in italics have been calculated by assuming 7,000 full load hours.
b France includes Guadeloupe, and Portugal refers to the Azores.
c Based on a technical potential of 280 TWh/a (TAB, 2003).
d Excluding Croatia.
Sources: Gawell et al, 1999; TAB, 2003; Lundin, 2008; Bertani, 2006-2007; Gawell and Greenberg, 2007; BP, 2009.

In Europe, geothermal power is assumed to have a *realistic potential* of 16,700 MW_e in 2050, which is 13 times the current installed capacity and 50% more than the *realistic potential* of the European countries of which potentials have been estimated in Table 4.2. Today, there are hardly any studies that give clues about the experience curve for geothermal power. This is because geothermal power generation is based on various technologies. In the USA, the levelized cost of geothermal power generation based on a double-flash geothermal power plant ranges between \$68/MWh and \$118/MWh with an average of \$89/MWh (Sener et al, 2009). However, this literature source does not provide a view of future cost reductions. On a global scale, the *realistic potential* is estimated at approximately 300 GW_e. Table 4.3 presents technical and economic data of geothermal power. The specific investment cost of new geothermal power plants in 'average European conditions' (e.g., Germany, Czech Republic, Hungary, etc) may come down from € 7,000/kW on average in 2008 to € 5,400-5,600/kW in 2050, based on a PR of 0.95.

With regard to the assumed specific investment cost in 2008, a range of € 4,000/kW (low) to € 10,000/kW (high), a number of literature sources give some background. There are a few regions in Italy and Iceland that have excellent geological characteristics for geothermal power, where geothermal power is a commercial option for decades. Most of Europe does not possess such favourable geological characteristics. Therefore, it is commonly assumed that geothermal power in other regions (Germany, Austria, Turkey, etc.) will be based on relatively deep geothermal power extraction making use of an Organic Rankine Cycle (ORC) plant. Typical characteristics are water of approximately 100°C from a depth of 2,500 m, e.g. the German Neustad-Glewe project, making use of water of 95-98°C from a depth of 2,250 m. These conventional geothermal power projects are costly. The electricity generation cost amounts to 12-18 €ct/kWh or more, which is comparable to offshore wind.

A more distant geothermal power technology that is still under development, formerly denoted as Hot Dry Rock (HDR), is the Enhanced Geothermal Systems (EGS) technology. This technology is developed in the USA, France, and Australia. For modelling purposes, it does not make much sense to model 'conventional' geothermal power (based on ORC technology) separate from EGS. It may simply be assumed that the specific investment cost of geothermal power will come down as a function of the cumulative capacity, just like in case of onshore wind, offshore wind, geothermal power, Concentrating Solar Power (CSP), Photovoltaic power (PV), and (small) hydro power.

'Conventional' geothermal power generation in European countries, except Iceland and Italy, are characterised by capacities ranging from 250 kW_e to several MW electric. An example is the geothermal power (CHP) project in Austria (Pernecker and Uhlig, 2002), with a total cost of € 4,511,000 ($€_{2000}$). Considering that the electric capacity was 500 kW_e, the investment cost amounted to € 9.000/kW ($€_{2000}$). Thus, the upper bound of geothermal power in 2008 is put at € 10.000/kW ($€_{2008}$).

A strong indication that the total specific investment cost of 'conventional' ORC- based geothermal power generation is at least € 4,000/kWe (in $€_{2008}$) is derived (Duvia and Gaia, 2002), who describe application of the ORC for small-scale biomass power generation projects.

- Net capacity 450 kWe: € 2,988/kWe (in $€_{2002}$).
- Net capacity 600 kWe: € 2,477/kWe (in $€_{2002}$).
- Net capacity 1,100 kWe: € 1,788/kWe (in $€_{2002}$).
- Net capacity 1,500 kWe: € 1,605/kWe (in $€_{2002}$).

Table 4.3 *Technical and economic features of geothermal power in the EU*

Technical performance	Unit	Typical ranges									
Technology		Geothermal									
Efficiency Single Flash / Binary cycle	[%]	30 / 6-18									
Construction period	[month]	18-36									
Technical lifetime	[year]	80									
Capacity factor	[%]	90									
Maximum availability	[%]	97									
Environmental impact		Typical ranges									
GHG emissions	[kg/MWh]	Not applicable									
SO_2	[g/MWh]	Not applicable									
NO_x	[g/MWh]	Not applicable									
Particulates	[g/MWh]	Not applicable									
Solid waste	[g/MWh]	Not applicable									
Costs		[€$_{2008}$]									
Investment cost including IDC [a] (2008)	[€/kW]	4,000-10,000; average 7,000									
Fixed & variable O&M cost	[% of inv.]	2									
Fuel cost	[€/MWh]	Not applicable									
Economic lifetime	[year]	25									
Progress ratio	[]	0.95									
Data projections		2010			2020			2030			2050
Variant		Low	Average	High	Low	Average	High	Low	Average	High	Average
Capacity factor	[%]	90	90	90	90	90	90	90	90	90	90
Investment cost including IDC [a]	[€/kW]	3,906-3,941	6,835-6,897	9,764-9,853	3,551-3,661	6,214-6,406	8,877-9,151	3,337-3,400	5,840-5,950	8,343-8,500	5,403-5,611
Operation and maintenance	[€/MWh]	9.9-10.0	17.3-17.5	24.8-25.0	9.0-9.3	15.8-16.3	22.5-23.2	8.5-8.6	14.8-15.1	21.2-21.6	13.7-14.2
Capacity Europe	[GWe]	1.16	1.16	1.16	4.2	4.2	4.2	9.7	9.7	9.7	16.7
Capacity world	[GWe]	11.0	11.0	11.0	29.8	29.8	29.8	80.9	80.9	80.9	298

a IDC = Interest during construction.

5. Concentrating Solar Power

5.1 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 from, e.g. natural gas based Combined Cycle systems as well as by storing surplus heat (IPCC, 2007).

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. By 2008, the global capacity of CSP stood at approximately 0.5 GW_e (REN21, 2009).The *technical potential* of CSP appears to range from 630 GW_e by 2040 up to 4,700 GW_e by 2030 (IPCC, 2007). In the following an estimate will be presented of the *realistic potential* of Europe and North Africa[5].

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. 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.

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.

5.2 Mirror-based systems

There are three types of mirror-based concentrated solar power plants:
- Parabolic trough.
- Solar tower.
- Solar dish.

Parabolic trough technology is a 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

---
[3] The term 'suns concentration' refers to the concentration factor compared to normal sunlight.
[4] Integration of CSP in, e.g., a combined cycle (CC) based on natural gas may increase the capacity factor to 70% in 2020, which is equivalent to approximately 6,100 full-load hours.
[5] The realistic potential is the technical potential with exclusion of areas protected for reasons of nature conservation, natural beauty, safety, noise, etc.

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, and into electrical power with a steam turbine.

Since the 1980s, nine commercial-scale CSP plants were built - the first in 1984 - and operated in the California Mojave desert with capacities ranging from 14 to 80 MW_e, and a combined capacity of 354 MW_e. Large fields of parabolic trough collectors supply thermal energy to power a steam cycle (Figure 5.1). Another 400 MW_e are under construction and 6 GW_e is planned (Internet Source 25).

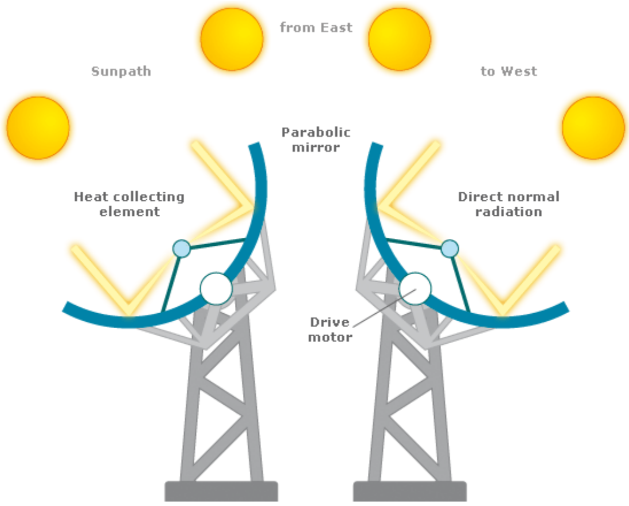

Figure 5.1 *Operating scheme for parabolic through technology*
Source: Internet Source 25.

Solar tower systems are next in line with regard to technology development. 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, which drives the generator (Figure 5.2). CSP plants (e.g., based on a *solar tower*) may be equipped with the added capability of 15 hours heat storage which gives them an estimated operating time of 6,500 hours/a.

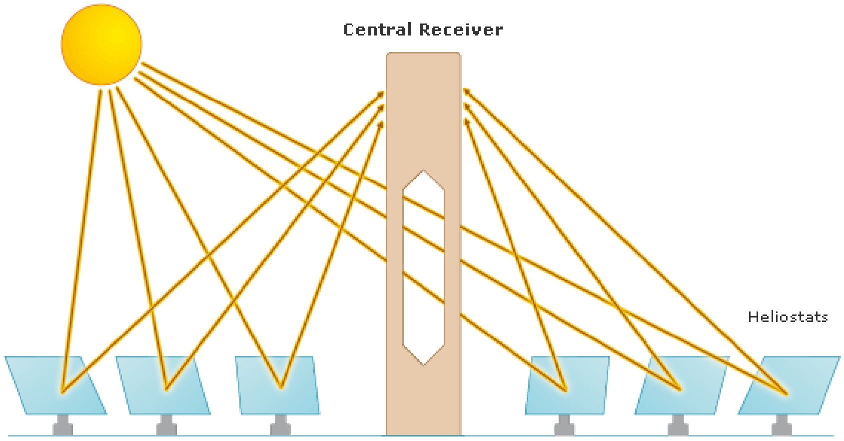

Figure 5.2 *Operating scheme for tower technology*
Source: Internet Source 25.

In terms of development, *solar dish* CSP (Figure 5.3) is slightly behind other technologies. A CSP plant of Stirling Energy Systems (SES) (Internet Sources 26-27) is characterised as follows:

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

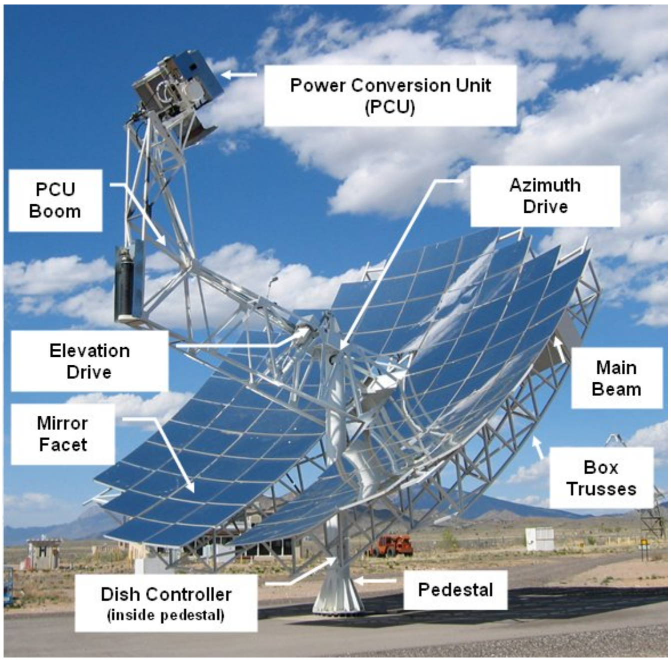

Figure 5.3 *Example for solar dish technology (25 kW_e SES SunCatcher)*
Source: Internet Sources 26-27.

5.3 Fresnel-lens based systems

Ausra and SkyFuel develop technology based on the *Fresnel lens*[6], with a system of a Compact Linear Fresnel Reflector (CLFR) solar collector and steam generation of Ausra, and one based on molten salt-filled tubes and heat exchangers to power the steam turbines of SkyFuel (Figure 5.4).

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 28-30).

Figure 5.4 *Visualisation of 177 MW_e plant based on Fresnel-lens at the Carrizo Plain, CA*
Source: Internet Sources 28-30.

5.4 Industrial activity

Currently, the following companies design, engineer, and manufacture these plants (Table 5.1). Most of the companies are headquartered in the USA, Spain, Germany, and Israel.

[6] 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.

Table 5.1 *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	Solar-Reserve USA	Solel Israel	Stirling Energy Systems USA
Parabolic trough								
Reflector	√			√	√		√	
Receiver	√			√	√		√	
Sun-tracking	√			√	√		√	
Support structure	√			√	√		√	
Rankine steam cycle	√			√	√		√	
Solar tower								
Heliostat	√		√			√		
Central receiver	√		√			√		
Tower	√		√			√		
Rankine steam cycle	√		√			√		
Solar Dish								
Reflector								√
Stirling engine								√
Fresnel lens								
Reflector		√		√				
Rankine steam cycle		√		√				

Sources: Internet Source 25 (Abengoa); Internet Source 26 (Stirling Energy Systems); Internet Sources 28-30 (Ausra); Internet Source 31 (Brightsource Energy); Internet Source 32 (SkyFuel); Internet Source 33 (Solar Millennium); Internet Source 34 (SolarReserve); Internet Source 35 (Solel).

5.5 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 36). 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).

5.6 Current state of the art

CSP plants have been built or are constructed in the USA, Spain, Morocco, and Algeria (Table 5.2).

Table 5.2 *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 27-40; RER, 2008.

Figure 5.5 gives a corresponding view of CSP plants that are under construction or planned (Internet Source 41). Based on this data, CSP projects 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.

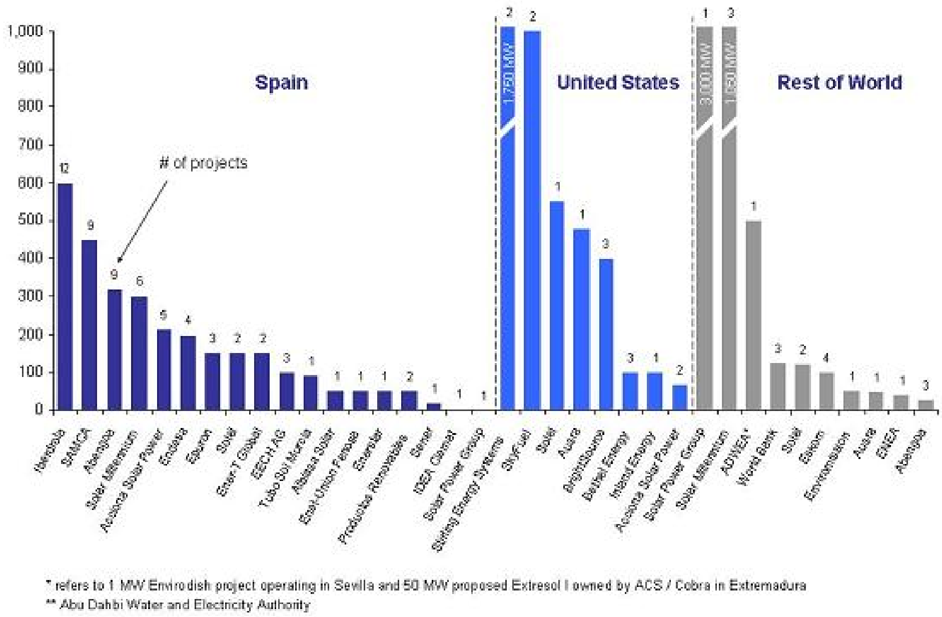

Figure 5.5 *Concentrating solar power (CSP) projects under construction or planned*
Source: Internet Source 41.

5.7 Main technical and economic data for southern Europe

The specific investment cost of CSP *with thermal storage* (see below) is estimated at € 4,000-5,000 per kW for southern Europe (Spain, Portugal, Italy, and Greece), based on (Schott, 2009). Thermal storage based on molten salt may provide for a few hours of additional operation and a load factor of 32.5% (Kelly, 2008; Internet Source 42). Extension of the operation of a CSP plant *with thermal storage* comes at a price. In the following, also a CSP plant *without thermal storage* is described that is assumed to be representative of North Africa. The operation and maintenance (O&M) cost is put at 3% of the specific investment cost per year. Table 5.3 shows the outlook for CSP with respect to potential and cost.

The *realistic potential* of CSP in southern Europe (Spain, Portugal, Italy, and Greece) is estimated at 100 GW_e. This potential is based on publications on CSP in North Africa for export to Europe, viz. (Desertec, 2009; Trieb et al, 2009; Richter et al, 2008). These literature sources put the *realistic global potential* at 28 GW_e in 2020, 140 GW_e in 2030, and 500 GW_e in 2050. Richter et al (2008) present the following data for the *realistic potential* of Europe: 4 GW_e (11 TWh/a) in 2012, 30 GW_e (85 TWh/a) in 2020, and 60 GW_e (170 TWh/a) in 2030 (Table 5.3). For Concentrating Solar Power, Progress Ratios may vary between as low as 0.80-0.85 and as high as 0.90-0.95, based on (Junginger et al, 2008) and (Younger, 2008). However, Younger (2008) cautions for too optimistic views on cost reductions. Therefore, the investment cost is based on these scenarios and a progress ratio of 0.925. Table 5.3 shows that the investment cost of *CSP with a limited thermal storage* may come down from € 4,000-5,000/kW ($€_{2008}$) in 2008, to € 2,070/kW or € 2,200/kW in 2050, depending on the scenario.

Table 5.3 *Technical and economic features of Concentrating Solar Power (CSP) in the EU*

	Unit	Typical ranges									
Technology		CSP									
Efficiency	[%]	10-20									
Construction period	[month]	18-36									
Technical lifetime	[year]	25									
Capacity factor (with storage)	[%]	32.5									
Maximum availability	[%]	98									
Environmental impact		Typical ranges									
GHG emissions	[kg/MWh]	Not applicable									
SO_2	[g/MWh]	Not applicable									
NO_x	[g/MWh]	Not applicable									
Particulates	[g/MWh]	Not applicable									
Solid waste	[g/MWh]	Not applicable									
Costs		[$€_{2008}$]									
Investment cost including IDC[a] (2008)	[€/kW]	4,000-5,000; average 4,500									
Fixed & variable O&M cost	[% of inv.]	3									
Fuel cost	[€/MWh]	Not applicable									
Economic lifetime	[year]	25									
Progress ratio	[]	0.925									
Data projections		2010			2020			2030			2050
Variant		Low	Average	High	Low	Average	High	Low	Average	High	Average
Capacity factor (with storage)	[%]	32.5	32.5	32.5	32.5	32.5	32.5	32.5	32.5	32.5	32.5
Investment cost including IDC[a]	[€/kW]	3,599	4,049	4,499	2,443-2,679	2,748-3,014	3,053-3,349	2,066-2,124	2,324-2,389	2,582-2,654	2,069-2,204
Operation and maintenance	[€/MWh]	37.9	42.7	47.1	25.7-28.2	29.0-31.8	32.2-35.3	21.8-22.4	24.5-25.2	27.2-28.0	21.9-23.2
Capacity Europe (realistic potential)	[GWe]	0.45	0.45	0.45	14.0	14.0	14.0	62.3	63,3	63.3	100
Capacity world (realistic potential)	[Gwe]	1.3	1.3	1.3	17.6	17.6	17.6	139.4	139.4	139.4	500

a IDC = Interest during construction.

5.8 Main technical and economic data for North Africa

Some assumptions with regard to the development of CSP in southern Europe (Spain, Portugal, Italy, and Greece) may also be applied to North Africa. The main difference between these regions is the more abundant solar resource of North Africa. It is assumed that the same capacity factor of 32.5% that was used for southern Europe *with limited thermal storage* may be used for North Africa *without thermal storage*. The investment cost of CSP, representative of North Africa, is assumed to vary from € 3,750/kW to € 4,250/kW - average € 4,000/kW - in 2010. The CSP potential of North Africa is conservatively estimated at 1.5 GW_e in 2020, 23.1 GW_e in 2030 and 100 GW_e in 2050. Table 5.4 shows that the investment cost of CSP *without storage* may decline from € 3,750-4,250/kW ($€_{2008}$) in 2010 to € 1,680/kW in 2050, but the aforementioned figure of € 2,070/kW or € 2,200/kW appears to be more representative, as the current capacity (45 MW_e) in North Africa is almost negligible.

Table 5.4 *Technical and economic features of Concentrating Solar Power (CSP) in North Africa*

Technical performance	Unit	Typical ranges									
Technology		CSP									
Efficiency	[%]	10-20									
Construction period	[month]	18-36									
Technical lifetime	[year]	25									
Capacity factor (without storage)	[%]	32.5									
Maximum availability	[%]	98									
Environmental impact		Typical ranges									
GHG emissions	[kg/MWh]	Not applicable									
SO_2	[g/MWh]	Not applicable									
NO_x	[g/MWh]	Not applicable									
Particulates	[g/MWh]	Not applicable									
Solid waste	[g/MWh]	Not applicable									
Costs		[$€_{2008}$]									
Investment cost including IDC [a] (2010)	[€/kW]	3,750-4,250; average 4,000									
Fixed & variable O&M cost	[% of inv.]	3									
Fuel cost	[€/MWh]	Not applicable									
Economic lifetime	[year]	25									
Progress ratio	[]	0.925									
Data projections		2010			2020			2030			2050
Variant		Low	Average	High	Low	Average	High	Low	Average	High	Average
Capacity factor (without storage)	[%]	32.5	32.5	32.5	32.5	32.5	32.5	32.5	32.5	32.5	32.5
Investment cost including IDC [a]	[€/kW]	3,750	4,000	4,250	2,512	2,679	2,846	1,859	1,983	2,107	1,681
Operation and maintenance	[€/MWh]	39.5	42.1	44.8	26.5	28.2	30.0	19.6	20.9	22.2	17.7
Capacity North Africa	[Gwe]	0.05	0.05	0.05	1.5	1.5	1.5	23.1	23.1	23.1	100
Capacity world (realistic potential)	[Gwe]	1.3	1.3	1.3	17.6	17.6	17.6	139.4	139.4	139.4	500

a IDC = Interest during construction.

6. Photovoltaic power

6.1 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, modules, and systems are considerably improved compared to some years ago, witnessed by increased efficiency and reduced replacement of, e.g., inverters (Internet Source 43).

Photovoltaic solar energy is estimated to have a technical potential of at least 450,000 TWh/year, equivalent to 16,000 EJ/year (IPCC, 2007). However, realising this potential will be limited by land, energy-storage, and investment constraints. In 2008, global capacity of photovoltaic power (PV) stood at 14.73 GW_e (9.16 GW_e in 2007) (EPIA, 2009). On a global scale, photovoltaic power exhibits a growth rate of its cumulative installed capacity of 30-50% per year. Due to the global recession, growth in 2009 will be much lower (expectedly 17%) than in 2008 (60%). DuPont anticipates that the PV market will (continue to) grow by double digits over the next several years, driving demand for existing and new materials that are more cost effective (Internet Source 44). 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 capacity addition increased from approximately 2,400 MW_e in 2007 to 5,600 MW_e in 2008, and for 2009 an addition of 5,000-6,800 MW_e for the cumulative PV capacity is expected (EPIA, 2009).Germany and Spain are among the world market leaders, together with Japan, the USA, South Korea and other countries (see Figure 6.2).

Most commercial PV modules are based on crystalline silicon cells. Mono-crystalline modules show efficiencies of up to (nearly) 20% efficiency, and had a share of 33% in the world market in 2007. Multicrystalline modules, with efficiencies of up to 15%, are cheaper per W_p (peak Watt) and had a 56% market share in 2007. Cost reductions will continue, partly depending on the future world price for silicon; efficiency improvements for PV cells as a result of R&D; mass production; and learning through project experience - see, e.g. Lensink et al. (2009).

Thinner cell materials have potential for cost reduction, including thin-film Si cells, thin-film copper indium di-selenide cells, cadmium telluride cells, photoelectrochemical cells, and polymer cells. Commercial modules based on thin-film cells have efficiencies up to 12%. Concentrating PV modules based on multilayer cells have efficiencies up to 25% today, but their costs are still relatively 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 more effective use of the surface (roofs) of houses and buildings. PV technology and applications are characterised by their modularity: they can be implemented on virtually any scale and size. The overall (AC) efficiency of PV systems is approximately 5-15%, depending on the module type used. The expected life span is 20-30 years. Solar modules are the most durable part of the system, with failure rates of only once in 10,000 per year. Inverters still have a shorter lifetime (10-15 yrs), but the industry strives to equal the lifetimes of modules and inverters.

6.2 Types and main components

PV cells that are the base of *PV modules* operate in general in the following way. The photovoltaic effect is based on a two-step process. Firstly, absorption of light (consisting of light particles; photons) in a suitable (usually semiconductor) material, by which negatively charged electrons are excited and literally mobilized. The excited electrons leave behind positively charged 'missing electrons', called holes, which can also move through the material. Secondly, the spatial separation (collection) of generated electrons and holes at a selective interface, which leads to a build-up of negative charge on one side of the interface and positive charge on the other side. As a result of this charge separation a voltage (an electrical potential difference) builds up over the interface. In most solar cells the selective interface (junction) is formed by stacking two different semiconductor layers: either different forms of the same semiconductor (so-called "p" and "n" type) or two different semiconductors. The first case is referred to as (p-n) homojunction solar cells, the second case as heterojunctions solar cells. Homojunctions can be formed by adding different types of impurities (dopants) to the layers on both sides of the junction (Sinke, 2009).

PV modules generally consist of two types (Figure 6.1), viz.:

- Modules based on silicon PV cells (monocrystalline or multicrystalline).
- Alternatively, thin-film solar cells may be made from amorphous silicon, copper indium diselenide (CIS) or cadmium telluride (CdTe). They require very little material and can be (generally) easily manufactured on a large scale (with the exception of CIGS cells). Manufacturing lends itself to automation and the fabricated cells can be flexibly sized and incorporated into building components. Thin-film PV is currently less energy efficient than silicon-based PV. However, it becomes more efficient and cost competitive over time. Thin-film cells may attain a market share of 20 % in the short term (Internet Source 45).

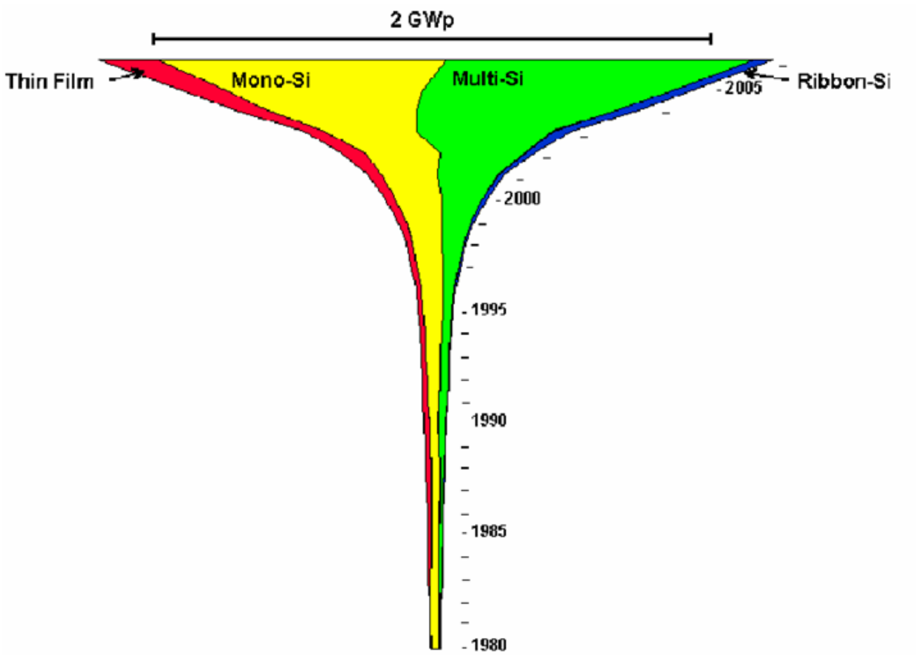

Figure 6.1 *Development of the global photovoltaic market, 1980-2006*
Sources: Zahler, 2007; Internet Source 46.

The 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.
- Etc.

6.3 Markets of different PV technologies and applications

Crystalline silicon is by far the most common solar cell material, because:
- It is used for more than 50 years, and its manufacturing processes are well known.
- The raw material silicon is very abundant - the second most abundant element in the Earth's crust.

PV has various applications and markets with a market share of up to 85-90% in 2008-2009 for *grid-connected* PV. Developing countries generally apply off-grid PV, with or without power storage.

In the medium term, the market will see both wafer-based crystalline silicon *and* thin-film PV. Thin-film cells provide the possibility of semi-transparency, although this is still a niche market. Also, if they are not based on a glass carrier material, thin-film modules offer flexibility and low weight. However, this still remains a small market until this date. It is possible to make semi-transparent panels that substitute for window panes on facades, roofs, etc. In specific cases, modules based on thin-film cells may be 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 or black multicrystalline silicon cells (Internet Source 47).

Figure 6.2 shows the world market of PV systems by country or world region (Arp, 2009).

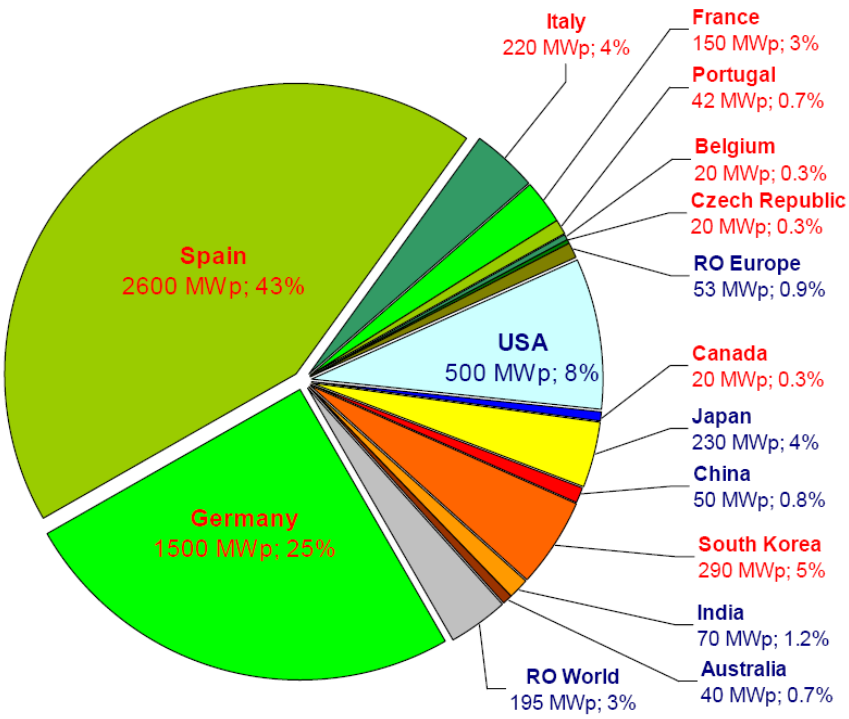

Figure 6.2 *The global market of PV systems by country or region in 2008*
Source: Arp, 2009.

The WorldWatch Institute states that China is emerging as a dynamic solar manufacturing industry. 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 48). 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.

6.4 Main technical and economic data

PV systems experience not only high growth rates on a global scale, but also substantial cost reductions. These are interrelated through the learning rate. The progress ratio (PR) of PV is estimated at 82%, i.e. 18% cost reduction for each doubling of the cumulative capacity, based on (Junginger et al, 2008). Because of these characteristics, the investment cost (€/W_p or €/kW, see Table 6.1) and the generation cost (€/MWh) will come down. Table 6.1 shows the expected capacity growth and the cost reduction of PV. The growth is expected to continue, both worldwide and in Europe.

The specific investment cost of PV is estimated at € 3,600-4,500/kW - average € 4,050/kW - in $€_{2008}$ in 2008, based on (Lensink et al, 2009). The average cost of € 3,420/kW ($€_{2008}$) in 2010 corresponds to an average of € 3,600/kW ($€_{2010}$) projected by Lensink et al (2009) for 2010. Operation and maintenance costs are estimated at 0.6% of the investment cost per year. Table 6.1 shows the potential and cost of PV. Growth in Europe is assumed to be slightly lower than on a global scale. The lowest cost level corresponds to a *realistic* global *potential* of 2,395 GW_e, and the highest to a European potential of 988 GW_e. The specific investment cost could come down to € 940-1,070/kW in 2050, based on an economic lifetime of 25 years and a PR of 0.82. It should be noted that such deep cost reductions depends on the extent to which costs of solar cells, modules, and balance of system may be reduced at the same rate, which is questionable.

Table 6.1 *Technical and economic features of photovoltaic power (PV) in the EU*

Technical performance	Unit	Typical ranges									
Technology		PV									
Efficiency	[%]	Not applicable									
Construction period	[month]	0.1-12									
Technical lifetime	[year]	25									
Capacity factor Central / South Europe	[%]	10 / 15									
Maximum availability	[%]	99									
Environmental impact		Typical ranges									
GHG emissions	[kg/MWh]	Not applicable									
SO_2	[g/MWh]	Not applicable									
NO_x	[g/MWh]	Not applicable									
Particulates	[g/MWh]	Not applicable									
Solid waste	[g/MWh]	Not applicable									
Costs		[€$_{2008}$]									
Investment cost including IDC [a] (2008)	[€/kW]	3,600-4,500; average 4,050									
Fixed & variable O&M cost	[% of inv.]	0.6									
Fuel cost	[€/MWh]	Not applicable									
Economic lifetime	[year]	25									
Progress ratio	[]	0.82									
Data projections		2010			2020			2030			2050
Variant		Low	Average	High	Low	Average	High	Low	Average	High	Average
Capacity factor southern Europe [b]	[%]	15	15	15	15	15	15	15	15	15	15
Investment cost including IDC [a]	[€/kW]	3,098	3,485	3,872	1,733-1,755	1,950-1,974	2,167-2,193	1,184-1,237	1,332-1,392	1,480-1,547	943-1,068
Operation and maintenance	[€/MWh]	14.2	15.9	17.7	7.9-8.0	8.9-9.0	9.9-10,0	5.4-5.7	6.1-6.4	6.8-7.1	4.3-4.9
Capacity Europe	[Gwe]	15.9	15.9	15.9	115.8	115.8	115.8	392.3	392.3	392.3	988
Capacity world	[Gwe]	24.9	24.9	24.9	189.0	189.0	189.0	715.5	715.5	715.5	2,395

a IDC = Interest during construction.

b For central European, the production cost has to be increased by approximately 50% based on a solar radiation of 1,100 kWh/m^2 compared to up to 1,700 kWh/m^2 for southern Europe.

7. Hydro power

7.1 Introduction

At present, approximately 19% of global electricity comes from hydro power. The current global generation of approximately 3,000 TWh/yr based on a hydro power capacity of 945 GW_e corresponds to 37% of the economically feasible potential and 23% of the technical potential. In general, a distinction is made between large, small, mini, and micro hydro power (Internet source 49):

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

The EU regards 'small' hydro power as <10 MW_e, and plants ≥10 MW_e as 'large-scale' (Internet Source 50). 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).

Large hydro power plants may be huge, e.g., the Three Gorges project in China, with a capacity of 22,500 MW_e. In China and India, where large hydro power is expanded, 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. In 2008, the global capacity of large-scale hydro power was 860 GW_e, and that of small-scale hydro approximately 85 GW_e (REN21, 2009).

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 (Lako et al, 2003). In developing countries, however, hydro is expected to be the fastest-growing renewable energy source. Untapped hydro potential is identified in South and Central Asia, Latin America, and Africa, but also in Canada, Turkey, and Russia. In Europe, additional potential is limited, *inter alia* due to reasons of protection of nature and landscape. However, in some regions, among which the USA, modernisation of hydro plants could add considerable amounts of electricity - a figure of 12-35% is found in literature - compared to the current hydro generation.

7.2 Environmental issues

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 the past, environmental issues have surfaced at large hydro power projects (Internet source 51):

- 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., 1.13 million people for the Three Gorges Dam.
- Oxygen reduction in the water by rotting of flooded vegetation killing fish and plants.
- Methane emission after rotting. CH_4 is a strong GHG gas, 21 times more effective 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).

7.3 Types

There are basically four types of hydro power plants (Internet Source 52):

- *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*, used for low and medium height projects, normally for a head of <15 m.

7.4 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 specific investment costs of small hydro power vary between € 2,500/kW and € 4,220/kW - on average € 3,360/kW - ($€_{2008}$) in 2008 (Table 7.1), a range which has been checked and proved to be consistent with a ‘Technical Brief’ (Beurskens and Lako, 2010). This range is used for calculations of future investment costs, based on a global scenario for small hydro power, ending up at 200 GW_e, and a European scenario, ending up at 20.3 GW_e in 2050. Cost reductions are based on a PR of 0.95 (Table 7.2).

Table 7.1 *Economic characteristics of small hydro power in Europe*

	Investment cost			O&M	Generation cost		
	Low [€/kW]	Medium [€/kW]	High [€/kW]	cost [€/MWh]	Low [€/MWh]	Medium [€/MWh]	High [€/MWh]
Austria	3,758	4,665	5,572	5.2	46.6	117.3	187.9
Belgium	4,794	5,611	6,427	23.3			
Czech Republic	855	1,723	2,592		25.9	32.4	38.9
Finland	2,851	3,088	3,326		38.9	42.1	45.4
France	1,555	2,721	3,887				
Germany	5,183	6,479	7,775			64.8	
Greece	1,296	1,944	2,592		31.1	42.8	54.4
Ireland	1,944	3,401	4,859		48.6	83.3	117.9
Italy	1,944	2,916	3,887		64.8	97.2	129.6
Lithuania	2,851	3,045	3,240		32.4	35.6	38.9
Poland	648	1,101	1,555			38.9	
Portugal	1,685	2,462	3,240				
Spain	1,296	1,944	2,592	10.6	45.4	68.0	90.7
Sweden	2,332	2,592	2,851	16.4	51.8	58.3	64.8
UK	2,592	4,406	6,220		64.8	77.7	90.7
Average	2,495	3,357	4,218	13.9	45.0	65.4	85.9

Sources: ESHA, 2004 and 2006.

Table 7.2 *Technical and economic features of small hydro power in the EU*

Technical performance	Unit	Typical ranges									
Technology		Small hydro power									
Efficiency	[%]	Not applicable									
Construction period	[month]	12-24									
Technical lifetime	[year]	80									
Capacity factor	[%]	45									
Maximum availability	[%]	99									
Environmental impact		Typical ranges									
GHG emissions	[kg/MWh]	Not applicable									
SO_2	[g/MWh]	Not applicable									
NO_x	[g/MWh]	Not applicable									
Particulates	[g/MWh]	Not applicable									
Solid waste	[g/MWh]	Not applicable									
Costs		[$€_{2008}$]									
Investment cost including IDC [a] (2008)	[€/kW]	2,500-4,220; average 3,360									
Fixed & variable O&M cost	[% of inv.]	2									
Fuel cost	[€/MWh]	Not applicable									
Economic lifetime	[year]	25									
Progress ratio	[]	0.95									
Data projections		2010			2020			2030			2050
Variant		Low	Average	High	Low	Average	High	Low	Average	High	Average
Capacity factor	[%]	45	45	45	45	45	45	45	45	45	45
Investment cost including IDC [a]	[€/kW]	2,489	3,345	4,201	2,442-2,449	3,282-3,291	4,122-4,133	2,403-2,425	3,229-3,259	4,055-4,093	3,154-3,243
Operation and maintenance	[€/MWh]	12.6	17.0	21.3	12.4	16.7	20.9-21.0	12.2-12.3	16.4-16.5	20.6-20.8	16.0-16.5
Capacity EU25 + CH + N	[Gwe]	13.3	13.3	13.3	16.7	16.7	16.7	19.0	19.0	19.0	20.3
Capacity world	[Gwe]	90.2	90.2	90.2	116.8	116.8	116.8	145.3	145.3	145.3	200

a IDC = Interest during construction.

8. Conclusions

This study provides an overview of technical-economic data of a number of renewable energy technologies for electricity generation that are available today and may play an increasingly important role in Europe and on a global scale. First, the study focuses on the way in which specific investment costs of renewable energy technologies may come down based on a so-called Progress Ratio (PR) that is deemed to be representative of that technology. For instance, a PR of 0.9 means that the specific investment cost will be reduced by 10% for each doubling of the cumulative capacity. In this study, it is assumed that the operation and maintenance cost will come down correspondingly.

For *onshore wind*, a PR of 0.9 is applied. In case of relatively optimistic deployment scenarios for onshore wind, the specific investment cost may come down from € 1,350/kWe (€$_{2008}$) in 2008 to € 1,090-1,190/kWe in 2020, and € 970-1,130/kWe in 2030. This is tantamount to a cost reduction of 20-25% in the period 2008-2030. If the operation and maintenance would come down at the same rate, they would be reduced from € 12/MWh in 2008 to € 10-11/MWh in 2020, and € 8-10/MWh in 2030.

For *offshore wind*, a PR of 0.95 is applied. For optimistic deployment scenarios for offshore wind, the specific investment cost may come down from € 3,000-3,400/kWe in 2008 to € 2,300-2,640/kWe in 2020, and € 2,030-2,440/kWe in 2030. This is tantamount to a cost reduction of 30% in the period 2008-2030. If the operation and maintenance would come down at the same rate, they would be reduced from € 33/MWh in 2008 to € 24-27/MWh in 2020, and € 21-25/MWh in 2030.

For *geothermal power*, a PR of 0.95 is used, although hardly any data is available. For optimistic deployment scenarios for geothermal power, the specific investment cost may come down from € 4,000-10,000/kWe in 2008 to € 3,550-9,150/kWe in 2020, and € 3,350-8,500/kWe in 2030. This is tantamount to a cost reduction of 15% in the period 2008-2030. If the operation and maintenance would come down at the same rate, they would be reduced from € 10-25/MWh in 2008 to € 9-23/MWh in 2020, and € 8.5-22/MWh in 2030.

For *Concentrating Solar Power* a PR of 0.925 is applied. For optimistic deployment scenarios for Concentrating Solar Power (CSP), the investment cost may come down from € 4,500/kWe in 2008 to € 2,440-3,350/kWe in 2020, and € 2,065-2,655/kWe in 2030. This is tantamount to a cost reduction of approximately 48% in the period 2008-2030. If the operation and maintenance would come down at the same rate, they would be reduced from € 47/MWh in 2008 to € 26-35/MWh in 2020, and € 22-28/MWh in 2030.

For *photovoltaic power (PV)* a PR of 0.82 is applied based on experience until this date. For optimistic deployment scenarios for PV, the investment cost may come down from € 3,600-4,500/kWe in 2008 to € 1,730-2,190/kWe in 2020, and € 1,180-1,550/kWe in 2030. This is tantamount to a cost reduction of approximately 67% in the period 2008-2030. If the operation and maintenance would come down at the same rate, they would be reduced from € 18-19/MWh in 2008 to € 8-10/MWh in 2020, and € 5-7/MWh in 2030.

Finally, for *small hydropower* a PR of 0.95 is applied. In case of optimistic deployment scenarios for small hydropower, the investment cost may come down from € 2,500-4,220/kWe in 2008 to € 2,440-4,130/kWe in 2020, and € 2,400-4,100/kWe in 2030. This is tantamount to a cost reduction of 5% in the period 2008-2030. If the operation and maintenance would come down at the same rate, they would be reduced from € 13-21/MWh in 2008 to € 12-21/MWh in 2020, and € 12-21/MWh in 2030.

References

Arp, J. (2009): *Photovoltaic Market in Germany*. German Day, May 21st, 2009, Bangkok, Thailand. Http://www.german-renewable-energy.com/Renewables/Redaktion/PDF/en/Vortraege-2009/en-Renewable-Energy-Asia-2009-Arp,property=pdf,bereich=renewables,sprache=en,rwb=true.pdf

Bertani, R. (2006a): World Geothermal Power Generation 2001 - 2005. RC Bulletin, May/June 2006, pp. 89-111. http://www.geothermal.org/articles/worldpower05.pdf

Bertani, R. (2006b): World Geothermal Power Generation 2001-2005. International Geothermal Development, May/June 2006, pp. 89-111. http://www.geothermal.org/articles/worldpower05.pdf

Bertani, R. (2007): World Geothermal Generation in 2007. GHC Bulletin, September 2007, pp. 8-19. http://geoheat.oit.edu/bulletin/bull28-3/art3.pdf

Beurskens, L.W.M. (2010): Private communication L.W.M. Beurskens and J. Van Stralen. ECN, May 2010.

Beursksen, L.W.M., and P. Lako (2010): Hydropower - Technology Brief (draft). IEA-ETSAP, Paris, March 23, 2010.

BP (2009): *BP Statistical Review of World Energy - Renewables*. BP, UK, June 2009.

BTM Consult (2009): *International Wind Energy Development - World Market Update 2008*. BTM Consult ApS, Ringkøbing, Denmark, March 2009.

Desertec (2009): *Clean Power from Deserts - WhiteBook 4th Edition*. Desertec Foundation, Bonn, Germany, February 2009. http://www.desertec.org/downloads/articles/trec_white_paper.pdf

DiPippo, R. (1999): Small Geothermal Power Plants: Design, Performance and Economics. GHC Bulletin, June 1999, p 1. http://geoheat.oit.edu/bulletin/bull20-2/art1.pdf

Douglas Westwood (2007): *POWER: Pushing Offshore Wind Energy Regions. Trans-national Offshore Wind Supply Chain Study - Update June 2007*. Douglas Westwood, UK, June 2007.

DTI (2007): *Study of the costs of offshore wind generation*. DTI, UK, 2007, URN 07/779.

Duvia, A., M. Gaia (2002): *ORC plants for power production from biomass from 0.4 to 1.5 Mwe: Technology, efficiency, practical experiences and economy*. 7th 'Holzenergie Symposium', ETH Zurich, Zurich, Switzerland, 18 October 2002. http://www.Econergy.ltd.uk/downloads/Turboden%20CHP%20Paper.pdf

EPIA (2009): *Global market outlook for photovoltaics until 2013*. European Photovoltaic Industry Association (EPIA), Brussels, Belgium, March 2009.

ESHA (2004): *Current situation of small hydropower in the EU15 according to ESHA's members*. European Small Hydropower Association (ESHA), Brussels, Belgium, March 2004. http://www.esha.be/fileadmin/esha_files/documents/publications/position_papers/ESHA_contributionDGTREN.pdf

ESHA (2006): *State of the art of small hydropower in EU25*. ESHA, Brussels, Belgium, 2006. http://www.esha.be/fileadmin/esha_files/documents/publications/publications/State_of_the_Art.pdf

EWEA (2007): *Delivering Offshore Wind Power in Europe*. European Wind Energy Agency (EWEA), Brussels, Belgium, December 2007.

Frandsen, S., et al (2004): *Offshore Wind Power: Easing a Renewable Technology out of Adolescence*. 19th World Energy Congress, Sydney, Australia September 5-9, 2004.

Gawell, K., et al (1999): *Preliminary Report: Geothermal Energy, the Potential for Clean Power from the Earth*. US Geothermal Energy Association (GEA), Washington DC, USA, April 7, 1999. http://www.geo-energy.org/publications/reports/Geothermal%20Potential%20Preliminary%20Report%20April%201999.pdf

Gawell, K., and G. Greenberg (2007): *2007 Interim Report Update on World Geothermal Development*. US Geothermal Energy Association (GEA), Washington DC, USA, 2007. http://www.geo-energy.org/publications/reports/GEA%20World%20Update%202007.pdf

IEA (2005): *Offshore wind experiences*. IEA, Paris, June 2005, p. 13.

IPCC (2007): *Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Intergovernmental Panel on Climate Change (IPCC), 2007.

Isles, L. (2006): *Offshore Wind Farm Development - Cost Reduction Potential*. Lund University, Sweden, October 2006.

Junginger, H.M. (2005): *Learning in Renewable Energy Technology Development*. PhD Thesis Utrecht University, the Netherlands, 13 May 2005, ISBN: 90-393-0486-6.

Junginger, M., P. Lako, S.M. Lensink, W. van Sark, and M. Weiss (2008): *Climate Change Scientific Assessment and Policy Analysis: Technological learning in the energy sector*. Netherlands Environmental Assessment Agency, Bilthoven, the Netherlands, 2008.

Kelly, B. (2008): *Past, present, and future of solar thermal generation*. Abengoa Solar, Inc., Berkeley, California, USA, June 2008. http://www.ewh.ieee.org/r6/san_francisco/pes/pes_pdf/256,1,Past, Present, and Future of Solar Thermal Generation

Kühn, M., et al. (2001): *Utgrunden offshore wind farm - first results of design certification by measurements*. EWEC 2001, Copenhagen, pp 545-548.

Lako, P. (2002): *Learning and diffusion for wind and solar power technologies*. ECN, Petten, April 2002, ECN-C-02-001.

Lako, P., et al. (2003): *Hydropower Development with a focus on Asia and Western Europe*. ECN and Verbundplan (Austria), ECN, Petten, July 2003, ECN-C-03-027.

Larsen, J.H.M. et al. (2005): *Experiences from Middelgrunden 40 MW Offshore Wind Farm*. Copenhagen Offshore Wind, 26-28 October 2005. Http://www.middelgrunden.dk/projektinfo/mg-pjece_300dpi_rgb.pdf.

Lensink, S.M., et al. (2009): *Eindadvies basisbedragen 2010 voor elektriciteit en groen gas in het kader van de SDE-regeling*. ECN/KEMA, Petten/Arnhem, September 2009, ECN-E-09-058. http://www.ecn.nl/docs/library/report/2009/e09058.pdf

Lundin, J., et al (2006): *EUSUSTEL WP3 Report - Geothermal power production*. Uppsala University, Sweden, 2006. http://eusustel.be/public/documents_publ/WP/WP3/WP3_Geothermal_energyFINAL.pdf

Madsen, P.S. (1996): *Tuno Knøb offshore wind farm*. EWEC 1996, Goteborg, Sweden, 20-24 May 1996, pp 4-7.

Mathis, H. (2006): *Offshore-Fundamente in Beton - Neue Baumethoden für die Zukunft*. DEWEK, 2006.

Mills, D.R., et al (2006): *First Results from Compact Linear Fresnel Reflector Installation*. 1Solar Heat and Power Pty Ltd, Sydney, Australia, 2006. http://solarheatpower.veritel.com.au/MILLS_CLFR_ANZSES_FINAL.pdf

Moll, M. (2007): *The East of England hub for offshore* *enewable*. Pushing Offshore Wind Energy Regions (POWER). Suffolk County Council, UK, 2007. http://www.offshore-power.net/Files/Billeder/2007-03-01%20esbjerg%20event%20-%20east%20of%20england.pdf

Musial, W. (2005): *Overview: Potential for Offshore Wind Energy in the Northeast*. Offshore Wind Energy Collaborative Workshop, Resolve, Washington D.C., USA, February 10-11, 2005.

Normark, B., E.K. Nielsen (2005): *Advanced power electronics for cable connection of offshore wind*. Copenhagen Offshore Wind 2005, Copenhagen, 2005.

NREL (2009): *2008 Wind Technologies Market Report*. National Renewable Energy Laboratory NREL, Colorado, USA, July 2009.

Pernecker, G., S. Uhlig (2002): Low-enthalpy power generation with ORC-turbogenerator - The Akltheim project Upper Austria. GHG Bulletin March 2002, p. 26-30. http://geoheat.oit.edu/bulletin/bull23-1/art6.pdf

REN21 (2009): Renewables Global Status Report - 2009 Update. Renewable Energy Policy Network for the 21st Century, REN21, 2008.

RER (2008): Renewable Energy Report, 155, May 12, 2208, p. 20-21.

REW (2007): Renewable Energy World, May-June, 2007, pp. 102-115.

Richter, C., et al (2008): *Concentrating Solar Power - Status and Perspectives*. German Renewable Energy Day, Solar Power 2008, San Diego, Califonia, USA, October 15, 2008. http://www.german-renewable-energy.com/Renewables/Redaktion/PDF/de/Vortraege-2008/de-Solar-Power-2008-Richter,property=pdf,bereich=renewables,sprache=de,rwb=true.pdf

Schott (2009): *Memorandum on solar thermal power plant technology*. Schott, Germany, 2009. http://www.schott.com/newsfiles/20061109160336_SCHOTT_Memorandum_E.pdf

SEI (2004): *Offshore Wind Energy and Industrial Development in the Republic of Ireland*. Sustainable Energy Ireland (SEI), Dublin, Ireland, October 2004. http://www.sei.ie/getFile.asp?FC_ID=1721&docID=65

Sener, A.C. et al (2009): Perspectives on the Economics of Geothermal Power. GRC Transactions, Vol. 33, 2009, pp. 29-36. http://www.icfi.com/docs/geothermal-power.pdf

Shell (2005): Shell Venster, eptember — oktober 2005, pp. 6-9.

Sinke, W.C. (2009): *PV in the urban environment*. ECN Solar Energy, Petten, the Netherlands, 2009, ECN-B—09-001.

Söger, H., et al (2006): *Offshore wind energy in the North Sea. Technical possibilities and ecological considerations - a study for Greenpeace*. Deutsches Windenergie-Institut GmbH (DEWI), Wilhelmshaven, Germany, October 2006.

SPG (2008): *The Netherlands Country Report - Legal Framework & Geothermal Policy Issues*. Stichting Platform Geothermie, the Hague, the Netherlands, August 2008.

TAB (2003): *Möglichkeiten geothermischer Stromerzeugung in Deutschland*. Büro für Technikfolgen-Abschätzung beim Deutschen Bundestag (TAB), Germany, October 24, 2003.

Tambke, J., and K. Michalowska-Knap (2010): *OffshoreGrid - D3.2b Time Series of Wind Power Output*. 3E, Belgium, IEE/08/780/S12.528573, January 31, 2010.

Trieb, F., et al (2009): *Global Potential of Concentrating Solar Power*. SolarPaces Conference, Berlin, Germany, September 2009. http://www.trec-uk.org.uk/reports/DNI-Atlas-SP-Berlin_20090915-04-Final.pdf

Younger, D.R. (2009): *Concentrating Solar Power (CSP) financing and the Clean Technology Fund*. International Finance Corporation (IFC), 2009. http://siteresources.worldbank.org/INTCC/Resources/CSP_Overview_CTF.pdf

Internet Sources

1. Http://www.seas-nve.dk
2. Http://lib.kier.re.kr/cadet/retb/no61.pdf
3. Http://www.windenergy.foi.se/main.html
4. Http://www.vindkompaniet.se
5. Http://www.vindkraft.nu
6. Http://www.blyth-offshore.co.uk
7. Http://www.stem.se
8. Http://www.npower-renewables.com/northhoyle/statistics.asp
9. Http://www.berr.gov.uk/files/file34791.pdf
10. Http://www.offshore-power.net/Files/Billeder/2007-03-01%20esbjerg%20event%20-%20east%20of%20england.pdf
11. Http://www.offshore-power.net/Files/Billeder/2007-03-01%20esbjerg%20event%20-%20east%20of%20england.pdf
12. Http://www.centrica.com/index.asp?pageid=995&newsid=931
13. Http://www.seas-nve.dk
14. Http://www.vattenfall.se/www/vf_se/vf_se/518304omxva/518334vxrxv/521964aktue/522474lillg/522564vindk/index.jsp
15. Http://www.liverpooldailypost.co.uk/liverpool-news/regional-news/tm_headline=wind-farm-ready-for-harvest&method=full&objectid=19257644&siteid=50061-name_page.html
16. Http://www.q7wind.nl/en/nieuwsarchief01.htm
17. Http://www.centrica-energie.de/pdf/pr-2007-03-05-wind-farm.pdf
18. Http://www.azom.com/details.asp?newsID=7967
19. Http://www.eon-uk.com/downloads/Humber_gateway_national_PR_Aug07.pdf
20. Http://www.contractorsunlimited.co.uk/news/061207a-E.ON.shtml
21. Http://www.dongenergy.com/en/ir/releases/2007/data/DONG+Energy+to+proceed+with+Horns+Rev+2.htm
22. Http://www.rwe.com/generator.aspx/konzern/verantwortung/aktuelles/2007/0711/language=en/id=486766/page.html
23. Http://www.newenergy.info/index.php?id=874
24. Http://iga.igg.cnr.it/geoworld/geoworld.php?sub=elgen
25. Http://www.solucar.es/sites/solar/en/tec_ccp.jsp
26. Http://www.stirlingenergy.com/pdf/2009-05-06_Calico-(Solar-One)-Project-Application-Achievement.pdf
27. Http://www.stirlingenergy.com/technology/suncatcher.asp

28. Http://www.ausra.com
29. Http://www.pge.com/about/news/mediarelations/newsreleases/q4_2007/071105.shtml
30. Http://www.ausra.com/pdfs/ausra_usgridsupply.pdf
31. Http://www.brightsourceenergy.com/PGEPressReleaseApril12008.pdf
32. Http://www.skyfuel.com
33. Http://www.solarmillennium.de
34. Http://www.solar-reserve.com
35. Http://www.solel.com
36. Http://www.abengoasolar.com/sites/solar/en/sparaelectricas_iscc.jsp
37. Http://www.solarelectricpower.org/docs/Virtual%20Spain%20CSP%2012-2007%20low%20res.pdf
38. Http://renewableenergydev.com/red/solar-energy-andasol-1-2-3/
39. Http://renewableenergydev.com/red/solar-energy-solar-tres-power-tower-csp/
40. Http://earth2tech.com/2007/12/12/skyfuel-heats-up-solar-thermal
41. Http://www.renewableenergyworld.com/rea/partner/story?id=50827
42. Http://www.renewableenergyworld.com/rea/news/article/2009/05/concentrating-solar-energy-technologies-explained
43. Http://www.solarelectricpower.org/index.php?page=basics&subpage=pv&display=facts
44. Http://www.printedelectronicsnow.com/news/2009/03/18/dupont_expects_continued_revenue_growth_in_global_photovoltaic_market
45. Http://www.solarserver.de/solarmagazin/index-e.html
46. Http://web.mit.edu/mit_energy/resources/iap/MIT-IAP-Jan2007_PVin2012_Buonassisi-Lecture-2.pdf
47. Http://www.wtc-consult.com/cms/cms/upload/PDF/Press_Releases/solar_cells-DB_new.pdf
48. Http://economictimes.indiatimes.com/News_by_Industry/Moser_Baer_to_invest_15_bn_in_solar_power/articleshow/2771966.cms (11 Feb, 2008)
49. Http://www.shakti.hypermart.net/articles/re/smallhydro.htm
50. Http://www.esha.be/fileadmin/esha_files/documents/publications/publications/Doc_Strat_TNSHP_2005.pdf
51. Http://www.ucsusa/clean_energy/renewable_energy/
52. Http://powermin.nic.in/JSP_SERVLETS/jsp/Hydro_faq.htm#1