Lecture Notes in Energy 3

Ricardo Guerrero-Lemus
José Manuel Martínez-Duart

Renewable Energies and CO_2

Cost Analysis, Environmental Impacts and Technological Trends- 2012 Edition

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3

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Cost Analysis, Environmental Impacts and Technological Trends- 2012 Edition

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This book is dedicated to Inés and Claudia,
with love.

Preface

This book is devoted to offering a one-stop source of information to engineers, economists and other professionals, as well as graduate students in renewable energy technologies and climate change activities. The book includes the main current statistics and the state of the art in the different topics related to all renewable energy technologies, carbon capture and storage, energy and electricity storage and smart grids. The most important up-to-date numerical data related to efficiencies, energy capacities and lifetimes of the systems, production costs, energy payback ratios, carbon emissions, patents and literature statistics, are exposed in 17 chapters, 247 figures and 49 tables, integrated in terms of units and methodology. All these data are also analysed in the book as a means to project future grid and fuel parity scenarios, and future technology tendencies in the different areas exposed. The book contains 405 references to books, briefings, reviews and research articles, mostly published in 2009–2012.

The book starts with an executive summary including a resume of the main data related to renewable systems and energy production costs, state of the art and environmental impact for each technology. The following chapter includes a brief description of the current use and theoretical potential of renewable and conventional energies, the evolution of the CO_2 emissions and atmospheric concentration and their influence in the climate change, generation costs of renewable fuel and electricity, the technological current status and the environmental impacts of the renewable energy technologies. The scheme followed in each of the technology chapters is identical: (1) overview of the technology and global updated energy production and capacity; (2) current status and key technologies; (3) current and future cost scenarios; (4) carbon emissions, energy payback and external costs; (5) technological trends; (6) pre-production and innovation highlights in 2009–2011 and (7) analysis of patents and literature statistics.

All values of the energy costs exposed in the book have been referred to 2011, mainly considering US and EU inflation indexes. To define the EUR/USD equivalence, we have considered the 2011 average exchange rate between both currencies. To evaluate the grid parities for the different renewable technologies, the following data have been selected: (1) the annual average electricity price forecasts in the reference scenario at nominal USD per kWh (2011–2030) (EIA); (2) the electricity prices in the Iberian trade market and (3) the retail electricity prices published in the IEA Key World Energy Statistics. The electricity prices selected to graph grid parities for decentralised renewable technologies have been the US industrial and residential end-users EIA forecasts. The electricity prices selected to graph grid parities for centralised renewable technologies have been the US prices for generating services and the linear adjustment of the average electricity price in the Iberian trade market between 2000 and 2011.

To discuss global energy figures (mainly supply, capacities and production), we use the IEA Statistics Database. We consider this source very rigorous, but the methodology employed produces 2-year delayed data with respect to present. To compensate this drawback, in many chapters more updated estimations, provided by global and prestigious associations related to the specific technology, are referred.

For the analyses of the evolution of the number of patents for the different technologies, we have considered the publication date instead of the application date.

The data and the subsequent analysis provided in the text will be annually updated, as new data from different recognised sources are continuously collected and analysed by the authors. The sources considered are only international reputed agencies, energy departments of G8 countries, recognised international energy associations and top impact index journals. The description of pre-production and innovation highlights presented in each technology chapter are always extracted from past 3-year published top impact index journals, listed in the Journal of Citations Reports and from qualified and specialised news media.

This book surges from the work produced by the authors within the programme "Energy and Climate Change" (2008–2011) of the Foundation for Applied Economic Research (FEDEA) and funded by the Focus-Abengoa Foundation. This programme had the aim to analyse the economic, technological and environmental impacts of the different renewable and associated technologies to define the role of each in the configuration of global and regional future energy mixes. Once the targets of the programme were met, the authors decided to update the information, adding also new content and publish it in book form.

We want to acknowledge the support of the Focus-Abengoa Foundation as well as the Foundation for Applied Economic Studies. We also want to acknowledge the support of the University of La Laguna and Universidad Autónoma de Madrid. We want to thank also the collaboration of the following persons: Inés Gutiérrez Toledo, Luis A. Puch, Gustavo A. Marrero, Elena Santiago, Santiago Marín, Carlos Bousono, José Dominguez-Abascal, Carlos Sebastian, Antonio Miguel Bernal, Anabel Morillo, Ricardo Arjona, José Luis Arroyo, Javier Brey, José Caraballo, África Castro, María de los Ángeles Gutiérrez, Cristina Huertas, Manuel Losada, José María Marimón, Eduard Soler, Enrique Moreno, María Victoria Sánchez, Nieves Valenzuela, Alfonso Vega, Pablo Vázquez, Bruno Díaz-Herrera, Benjamín González-Díaz, and students of the Master in Renewable Energies and Electronic

Engineering of the University of La Laguna. We also want to make special mention to our image designer, Aneliya Stoyanova.

The authors are available for readers to discuss any data or analysis published in this book and to propose any additional and recognised contents for next editions (rglemus@ull.es). Any reader who collaborates in the enrichment of the topics in future book editions will be recognised as collaborator of the edition where his/her contribution is added.

La Laguna Spain Ricardo Guerrero-Lemus
Madrid Spain José Manuel Martínez-Duart

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List of Acronyms

a-Si:H	Amorphous silicon
AFC	Alkaline fuel cells
ATES	Aquifer thermal energy storage
bbl	Oil barrel
BIGCC	Biomass integrated gasification combined cycle
BOP	Balance of plant
BPL	Broad-band power lines
BTES	Borehole thermal energy storage
c-Si	Crystalline silicon
CAES	Compressed air energy storage
CCS	Carbon capture and storage
CFB	Circulating fluidized bed
CHP	Combined heat and power
CPTD	Concentrating photovoltaics and thermal design
CRS	Central receiver systems
CSP	Concentrated solar power
DEC	Desiccant evaporative cooling
DHW	Domestic hot water
DNI	Direct component normal irradiance
DOE	US Department of Energy
EC	Electrochemical
EGS	Enhanced geothermal systems
EIA	US Energy Information Administration
EOR	Enhanced oil recovery
ETC	Evacuated tube collector
EUR	Euro
EV	Electric vehicle
FACTS	Flexible alternating current transmission systems
FAFC	Phosphoric acid fuel cells
FBC	Fluidized bed combustion

FPC	Flat plate collector
GHG	Greenhouse gases
HAPL	High average power laser
HAT	Humid air turbine
HHV	High heating value
HRSG	Heat recovery steam generator
HTS	High temperature superconductors
HVAC	High-voltage alternating current
HVDC	High-voltage direct current
IEA	International Energy Agency
IGBT	Insulated gate bipolar transistor
IGCC	Integrated gasification combined cycle
IHA	International Hydropower Association
iLUC	Indirect land use change
IPCC	International Panel on Climate Change
ITER	International thermonuclear experimental reactor
JET	Joint European Torus
LCA	Life cycle analysis
LCC	Line commuted converters
LCI	Life cycle inventory
lde	Litres of diesel-equivalent
lge	Litres of gasoline-equivalent
LIDAR	Laser imaging detection and ranging
LSIP	Large-scale integrated project
mc-Si	Multi-crystalline silicon
MCFC	Molten carbonate fuel cells
NGCC	Natural gas combined cycle
NIF	National Ignition Facility
NREL	National Renewable Energy Laboratory
NVOCM	Non-volatile organic compounds methane
PC	Pulverized coal
PCM	Phase change materials
PEMFC	Proton exchange membrane fuel cell
PF	Pulverized fuel
PM	Particulate mater
ppm	Parts per million
PSA	Pressure swing adsorption
psig	Pound per square inch
PV	Photovoltaics
RFP	Reversed field pinches
SAHC	Solar air heating collector
SAT	Single-axis tracking solar collector
SCADA	Supervisory control and data acquisition system
SHC	Solar heating and cooling

SMES	Superconducting magnetic energy storage systems
SMR	Steam methane reforming
SODAR	Sonic detection and ranging
SOFC	Solid oxide fuel cells
SSG	Seawave slot-cone generator
STP	Standard temperature and pressure
TES	Thermal energy storage
TPES	Total primary energy supply
UPS	Uninterruptible power supply
USD	US dollar
VSC	Voltage source converter
WF	Water resource footprint

I

Introduction

Chapter 1
Executive Summary

The Energy Technology Perspectives 2012 survey of the International Energy Agency (IEA) highlights that limiting global temperature rise to 2 °C above pre-industrial levels is technically feasible, if timely and significant government policy action is taken and a range of clean energy technologies are developed and deployed globally to reduce CO_2 emissions [1]. However, CO_2 emissions are steadily growing, reaching 395 ppm in March 2012 (Fig. 1.1) [2].

The IEA warned that under current policies, CO_2 emissions will nearly double in 2050 in relation to current values [3]. Moreover, more than one-third of the analyses (larger and more sophisticated than ever) for inclusion in the Fifth Climate Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) due out in 2013 have been submitted and predict very similar geographic patterns of future warming and changing precipitation around the world [4].

Renewable energies are growing rapidly, thus avoiding large amounts of CO_2 emissions per unit energy consumed. World renewable energy accounts for 12.88 % of all global energy supply [5], and global renewable energy installations have more than quadrupled from 2000 to 2010 [6]. The global economic crisis is hitting hard many of the developed countries that traditionally led the penetration of these technologies but, in 2011 for the first time global investment in new renewable power plants (USD 240 billion) surpassed fossil fuel power plant investment, which stood at USD 219 billion [7]. However, a 22 % decline has been detected in the first quarter 2012 in relation to the first quarter 1 year earlier [8]. This, in spite of the fact that investment costs in renewable technology in general have been declining, being especially impressing in PV systems, where prices in the last 3 years have been reduced a 75 % [1].

At present, more mature renewable energies are nearing competitiveness in a broader set of circumstances. Progress in hydropower, on-shore wind, solar PV and bioenergy are broadly on track and in some circumstances they have reached cost parity relative to competing conventional energy sources. Thus, large hydropower plants and biomass combustion CHP systems are plentiful competitive; on-shore wind can now compete without special financial support in electricity markets endowed with steady winds and supportive regulatory frameworks

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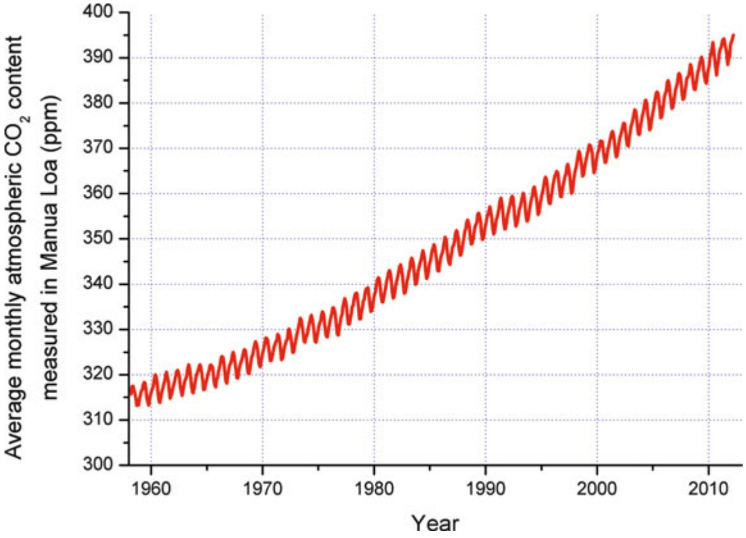

Fig. 1.1 Average monthly atmospheric CO_2 content measured in Manua Loa Laboratory (Hawaii, USA)

(e.g., New Zealand and Brazil); and PV projects with a capacity of more than 500 MW, and without any government subsidy, have been announced in 2012 to be installed in Southern Spain. Less mature renewable technologies (advanced geothermal, concentrated solar power and off-shore wind energy) are currently making progress under desired rates. A resume of the renewable electricity costs discussed in this book for the different technologies, based on official data obtained from the most relevant energy agencies and laboratories, is exposed in Fig. 1.2.

In renewable fuels, bioethanol is approaching gasoline price in future markets, mainly when the value of crude is peaking (Fig. 1.3a), and total biofuel production is planned to double in the short term, with advanced biofuel production expanding. On the other hand, biodiesel costs are not yet competitive compared to diesel (Fig. 1.3b), and production costs for hydrogen obtained from renewable resources are quite above those of competing fossil fuels. On the other hand, carbon capture and storage techniques (CCS) are not seeing the necessary rates of investment into full-scale demonstration projects and nearly one-half of new coal-fired power plants are still being built using inefficient technologies [1].

Future technology trends are focused on further reducing the energy costs from renewable technologies applying different strategies: new designs, new materials, increasing economies of scale, redefining logistics, moving factories to more attractive locations, increasing energy storage capacities, etc. But also the renewable energy systems should play an essential role in securing the whole energy system. Especially, renewable energy systems should be active energy agents in combination with smart power grids. For this purpose, energy storage systems should increase hugely in terms of capacity connected to the grid and operating at

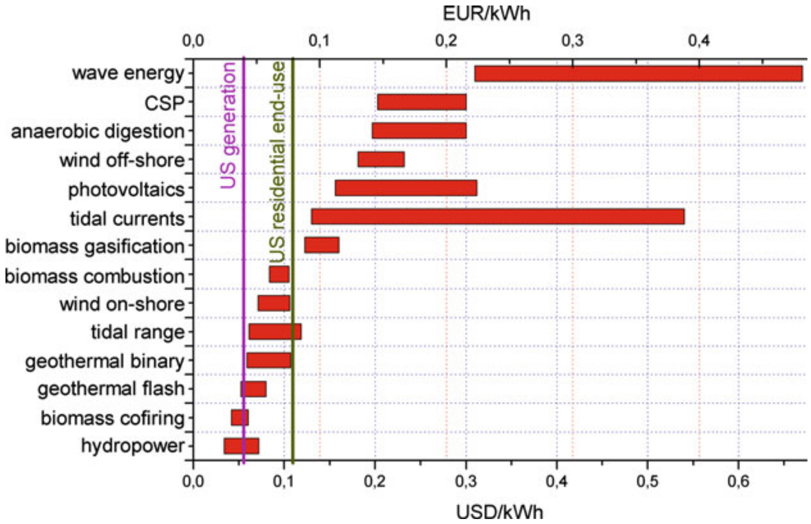

Fig. 1.2 Electricity costs in 2011 from different renewable energy resources, and compared to US average generation and residential end-use price

three different levels: (1) providing base power to the grid when needed; (2) providing distributed storage systems for distributed renewable sources and (3) improving distribution power quality. These new roles will further increase the value and attractiveness of renewable energy globally.

Consequently, the smart grid concept will be transformed into the smart energy concept, where not only transport and distribution, but also generation and storage, will increase substantially the security of the whole energy system and, at the same time, decrease its environmental impact and cost. Moreover, widespread decarbonised electrification of transport and other sectors (building, industry, etc.) will be required to reach global temperature values targeted by international agencies.

In the following chapters, we evaluate the different technologies that will make possible this evolution of the energy system, considering that renewable technologies can substantially reduce the CO_2 emissions per kWh (Fig. 1.4a) and, in the case of the transport sector, by using biofuels (Fig. 1.4b), instead of conventional fuels.

The already reduced environmental impact of renewable technologies is expected to still further decreases in the future, as their life-cycle analyses show increasing improvements. These improvements are mainly linked to more decarbonised energy mixes associated to the fabrication phase, and also the expected introduction of second- and third-generation biofuels in the near future.

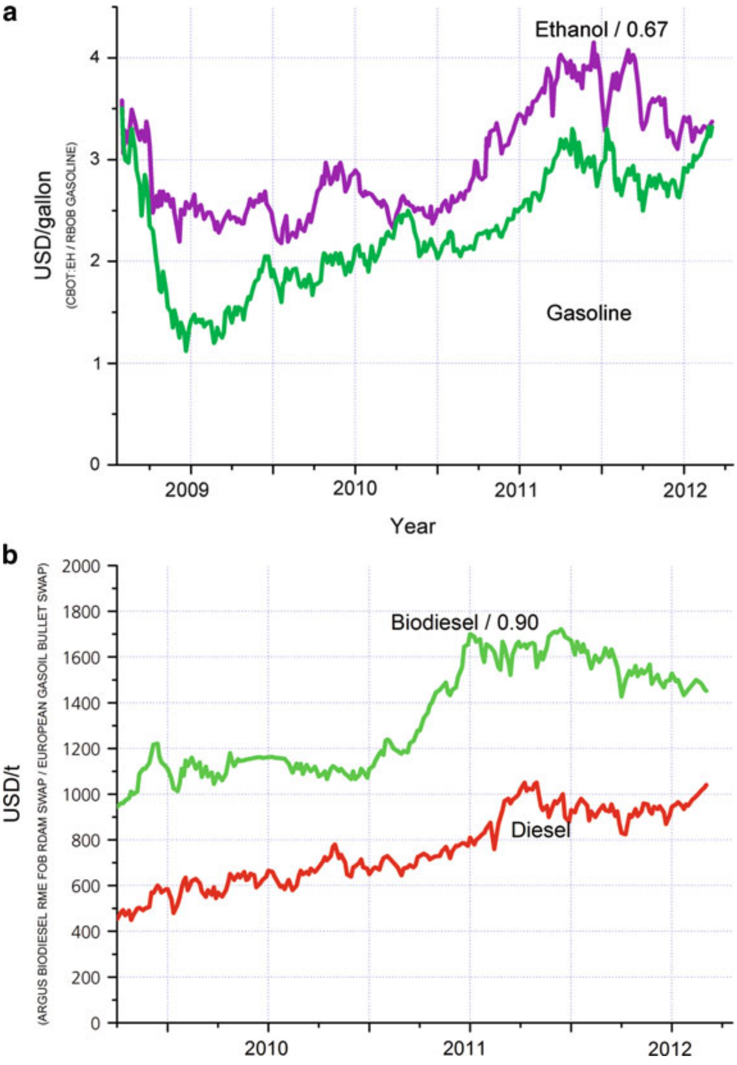

Fig. 1.3 Price evolution for different fuels in the futures market (balancing the difference in calorific values): (**a**) ethanol compared to gasoline and (**b**) biodiesel compared to diesel (source: INO)

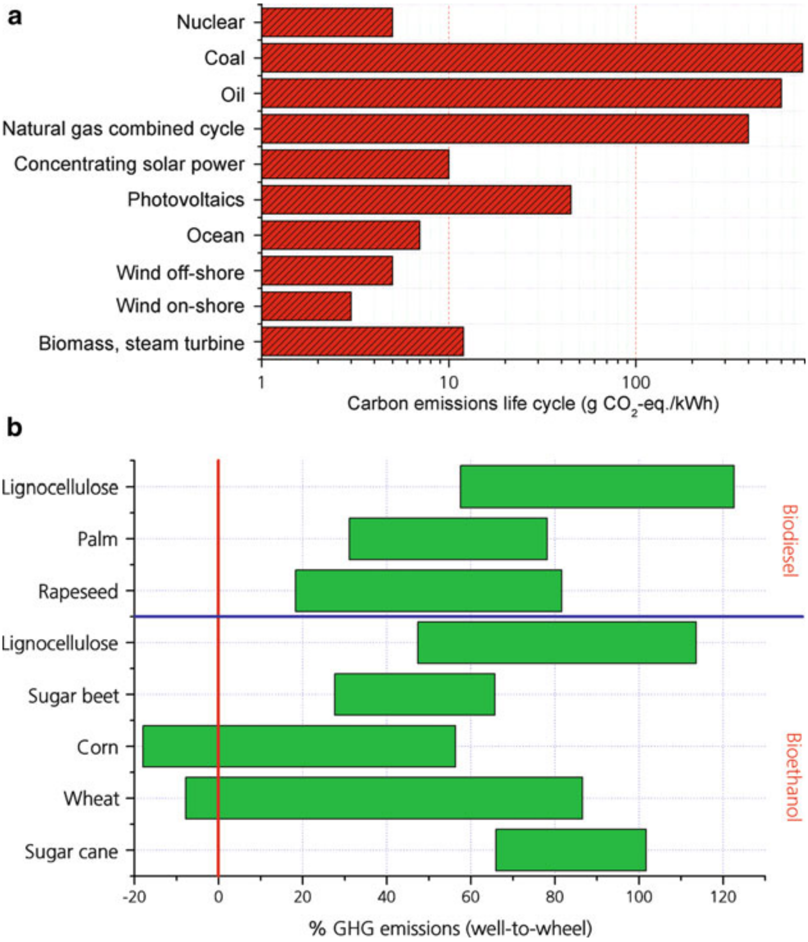

Fig. 1.4 (**a**) CO_2 emissions per kWh of electricity produced from different renewable energy technologies considering the entire lifecycle of these systems [9]; and (**b**) percentage of CO_2 well-to-wheel emissions avoided for different feedstock species for the production of bioethanol and biodiesel [10]

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Chapter 2
Renewable Energy and CO_2: Current Status and Costs

Abstract In this chapter, it is exposed a brief description of the current use and theoretical potential of renewable and conventional energies, the evolution of the CO_2 emissions and atmospheric concentration and their influence in the climate change, fuel and electricity generation costs of renewable energy technologies, the technological development status and the environmental impacts of the renewable energy technologies. Significant figures and how they have evolved in recent decades are included, and also estimation of conventional fuel reserves and leading countries in terms of renewable energy penetration.

2.1 The Current Use and Theoretical Potential of Conventional and Renewable Energies

Although it might seem surprising, the percentage of world total primary energy supply (TPES) from renewable energy technologies has remained fairly constant over the past 32 years (Fig. 2.1a) [1]. It has been a substantial growth in TPES from renewable technologies (Fig. 2.1b), but the growth rates in TPES from conventional technologies have also grown largely [1].

On the other hand, if we consider the evolution of TPES from the different renewable and conventional energy sources (Fig. 2.2), diverse behaviour can be observed between technologies. Thus, in relation to renewable technologies, ocean energy can be considered stagnant, while hydropower, geothermal energy, biomass and biofuels grow at moderate rates; photovoltaics, solar thermal energy and wind energy have grown very rapidly. Among conventional energies, nuclear energy is stabilised since the early 1990s, energy growth remains moderate for oil, but it is growing rapidly for coal and natural gas. TPES from waste is taking off, though moderately in recent years.

The evolution of the world TPES can be analysed numerically considering the data from the latest years available (2008 and 2009), shown in Table 2.1. This table also shows the TPES percentage added by each energy technology to the total and

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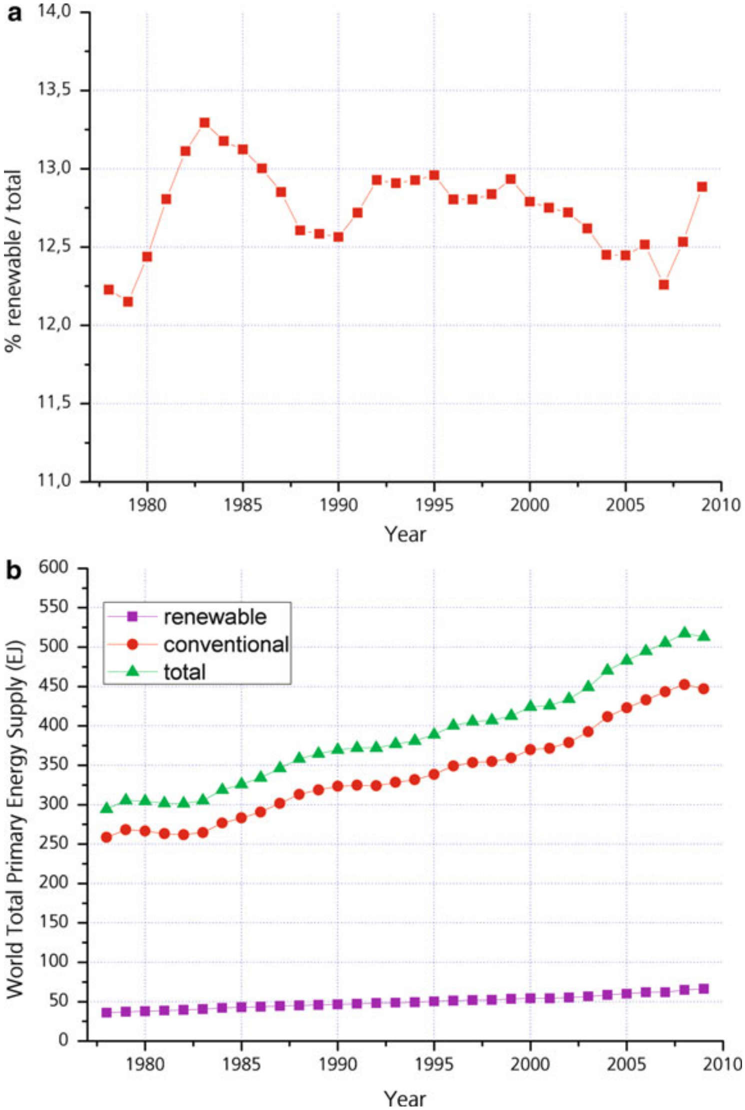

Fig. 2.1 (**a**) Percentage of world TPES from renewable technologies and (**b**) evolution of TPES from renewable and conventional energy technologies [1]

the estimated global technical potential [2] for each renewable energy resource. Then, the larger growth rates are observed for photovoltaics, solar thermal and wind power, although none of these technologies add more than a 1 % to the world TPES. On the other hand, TPES from the main conventional energy technologies have decreased from 2008 to 2009. This result is attributed to the global economic depression initiated in late 2008. It is also important to consider that the technical

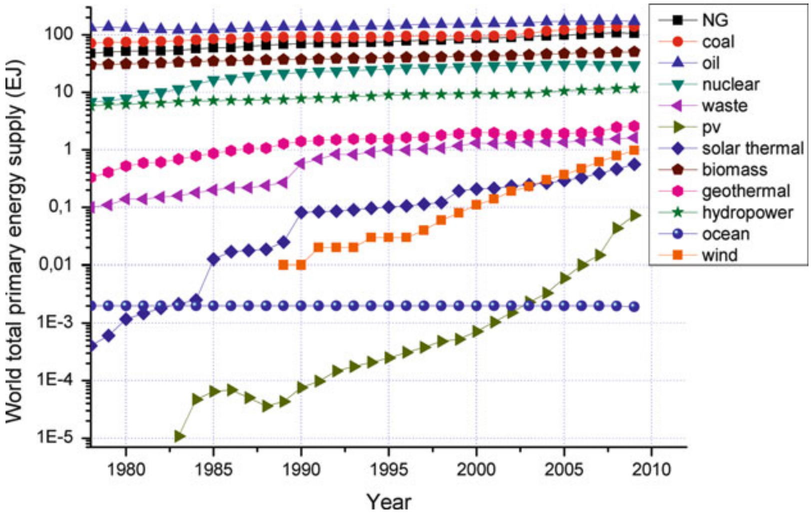

Fig. 2.2 Evolution of TPES from the different conventional and renewable energy technologies [1]

Table 2.1 TPES from renewable and conventional energy technologies in 2009 in absolute terms (EJ) and as percentage of the total, increase from 2008, estimated technical potential of renewable energy resources and current CCS capacity [1, 2]

Technology	Current use (2009) (EJ/y)	% Total (2009)	% Increment (2009/2008)	Technical potential (EJ/y)
Biomass	50.20	9.78	1.28	9,260
Hydro	11.71	2.28	1.59	463
Geothermal	2.59	0.50	4.59	4,630
Wind	0.98	0.19	23.98	92,600
Solar thermal	0.56	0.11	20.56	833,400 (continental)
Solar photovoltaics	0.07	0.01	70.24	833,400 (continental)
Ocean	0.002	0.0004	−2.93	926
Total Renewable	66.11	12.88	1.92	941,279
Oil	171.47	33.42	−1.42	
Coal	138.14	26.92	−0.43	
Natural gas	106.35	20.73	−1.99	
Uranium	29.45	5.74	−1.24	
Waste	1.62	0.32	4.19	
Total Conventional	447.04	87.12	−1.22	
CCS (Mt/year, 2011)	22.3	22.3	0.00	

potential of any renewable energy resources is larger than the TPES from conventional technologies in 2009, being especially large in solar energy. Finally, information about current (2011) carbon capture and storage (CCS) capacity (22.3 Mt/year) has been included in Table 2.1. But considering that global carbon emissions reached 28,999 Mt in 2009 [1], the CCS capacity represents only a 0.08 % of the global carbon emissions.

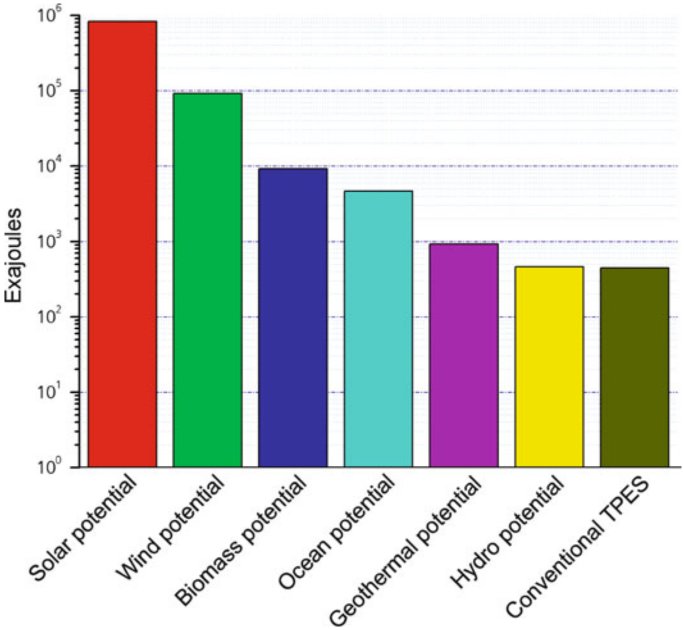

Fig. 2.3 Global technical potential for the different renewable energy resources, and compared to the world conventional annual TPES in 2009 [2]

The global technical potential for the different renewable energy resources is represented in terms of energy potential in Fig. 2.3. It can be observed that the renewable energy resource with the largest potential is solar energy (considering only the surface land above the sea level), followed by wind energy. On the other hand, the conventional global TPES is lower than any of the technical potential values for the different renewable resources but close to surpass the hydropower technical potential.

In relation to the proven reserves of the different fossil fuel resources and uranium, the most updated statistics indicate that proven reserves are 1.34e12 bbl for oil [3], 6.25e15 cubic feet for natural gas [3], 8.47e11 t for coal [4] and 5.47e6 t for uranium [5]. Using appropriate factors to convert these units to EJ in the case of natural gas, coal and oil [6, 7] and comparing uranium consumption to nuclear power produced in recent years, we can estimate the number of years that proven reserves can cover annual TPES for these resources. For these estimations, we consider two scenarios: (1) annual consumption constant and equal to the 2009 TPES from each resource and (2) adding the average annual TPES growing rates for oil (+1.01 %), coal (+4.10 %), natural gas (+2.19 %) and uranium (+0.44 %) obtained for the period 2000–2009 (Fig. 2.4). Thus, according to the results

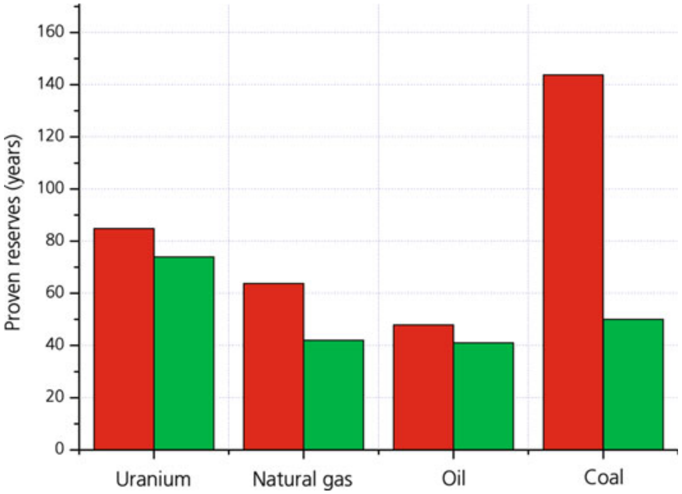

Fig. 2.4 Proven reserves of conventional energy resources in terms of years covered at 2009 TPES rates (*red bars*), and also adding the 2000–2009 average annual TPES growing rates (*green bars*)

obtained, the largest proven reserves at 2009 TPES rates are offered by coal (144 years). However, as coal shows the largest annual TPES increase in recent years, if this growth rate is maintained, proven reserves only cover the next 50 years. Equivalently, proven reserves at 2009 TPES rates cover 48 years for oil, 64 years for natural gas and 85 years for uranium. But if 2000–2009 average annual TPES growing rates are introduced, proven reserves cover 41 years for oil, 42 years for natural gas and 74 years for uranium.

Analysis about scarcity and depletion of conventional energy resources, mainly oil, are not a novelty. These analyses are increasingly more rigorous, forecasting in parallel the years when production peaks will be reached for each conventional resource and how the renewable resources will gradually replace them (Fig. 2.5) [8]. In this sense, the debate about the world future energy mix has increased momentum, particularly after the IEA concludes in its 2009 World Energy Outlook [9] that conventional oil production will peak in 2020 if demand continues at current growing rates. To obtain this conclusion, the IEA studied the historical production trends of 800 individual oil fields in 2008 [10]. More recent studies consider that non-OPEC oil production has not increased significantly from 2004, and many experts, as well as some major oil companies do not consider increasing ever again [11]. Also, new forecasts suggest that coal reserves will run out faster than many believe, and energy policies relying on cheap coal have no future [12].

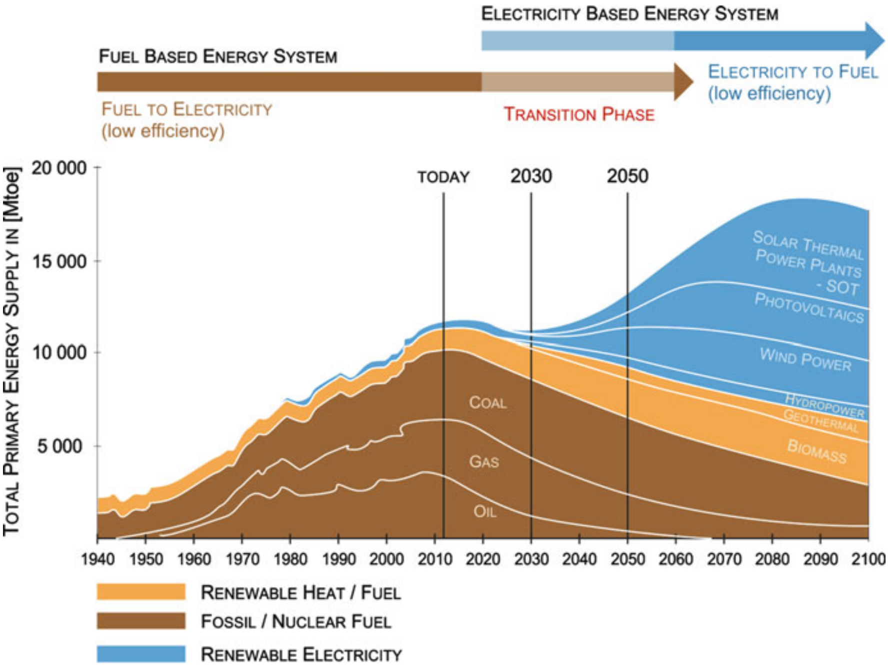

Fig. 2.5 World TPES evolution for the different energy resources and technologies, adding an example of energy mix forecast considering energy production peaks for oil, natural gas and coal proposed in the literature [8]

2.2 Evolution of CO_2 Emission Rates and Influence on Climate Change

If we consider the thermodynamic balance of a planet at a constant temperature, the amount of absorbed energy as solar radiation must equal the amount of energy emitted back to space at longer wavelengths (infrared). In Earth, re-emitted radiation reaches 239 W/m^2. According to thermodynamics, a body emitting energy with this power density would have a mean temperature of −18 °C. However, the average temperature on Earth is larger due to the presence of greenhouse gases in the atmosphere, which absorb and re-emit infrared radiation while keeping the lower atmosphere and the Earth's surface warm (Fig. 2.6) [13].

The increase in global energy consumption associated to our economic development in recent decades is also related to the increase in annual CO_2 emission rates (Fig. 2.7) [1]. In this figure, the influence of different global economic crisis in 1974, 1980–1982, 1990 and 2008–2009 can be easily correlated to small reductions in annual CO_2 emission rates.

If we consider the most recent global carbon budget published in the literature (Table 2.2) [14], it suggests that fossil fuels and cement are increasing their shares

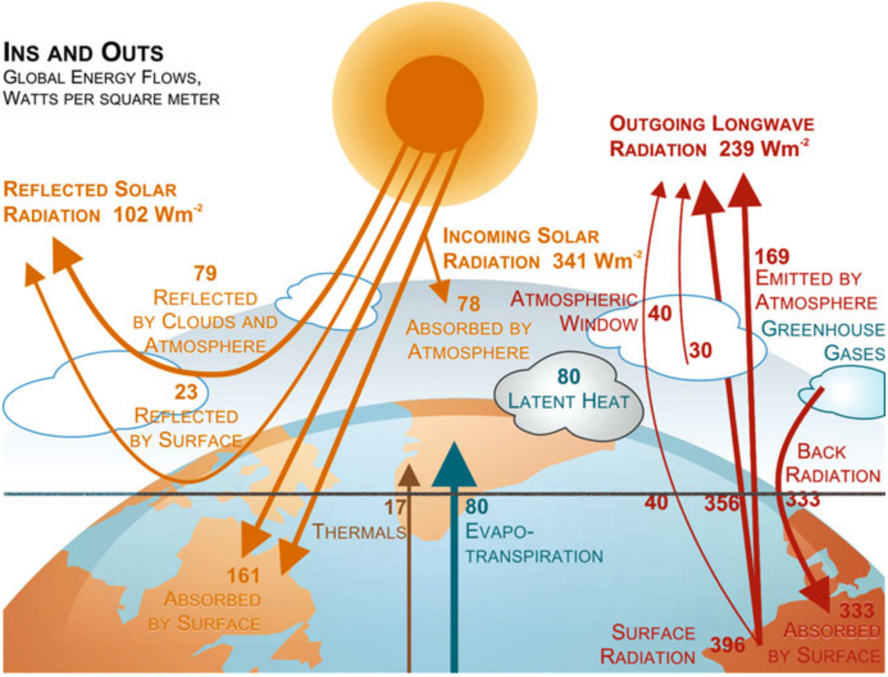

Fig. 2.6 Description of the thermodynamic balance on Earth [13]

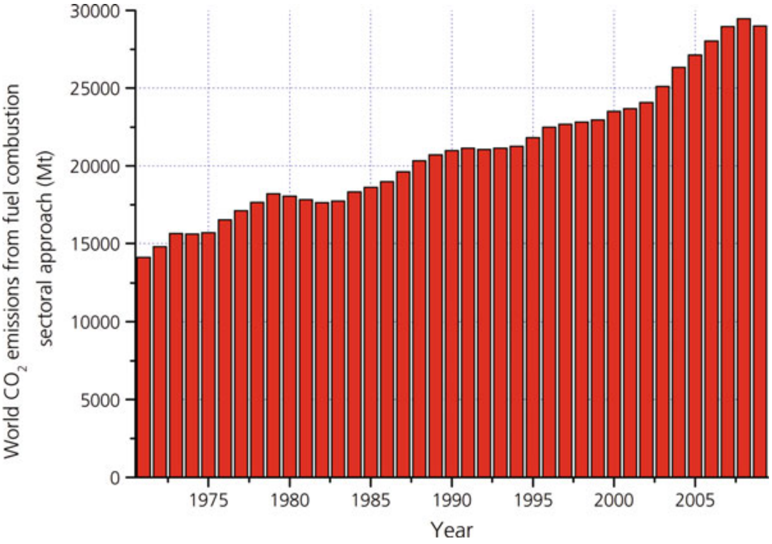

Fig. 2.7 Evolution of the world annual CO_2 emission rates in the period 1978–2009 [1]

Table 2.2 Global carbon budget decomposed in terms of sources and sinks, and calculated for the periods 1990–1999 and 2000–2007 [14]

Pg CO_2/year	1990–1999	2000–2007
Sources (C emissions)		
Fossil fuel and cement	6.5 ± 0.4	7.6 ± 0.4
Land-use change	1.5 ± 0.7	1.1 ± 0.7
Total sources	8.0 ± 0.8	8.7 ± 0.8
Atmosphere	3.2 ± 0.1	4.1 ± 0.1
Ocean	2.2 ± 0.4	2.3 ± 0.4
Terrestrial (established forest)	2.5 ± 0.4	2.3 ± 0.5
Total sinks	7.9 ± 0.6	8.7 ± 0.7
Global residuals	0.1 ± 1.0	0.1 ± 1.0

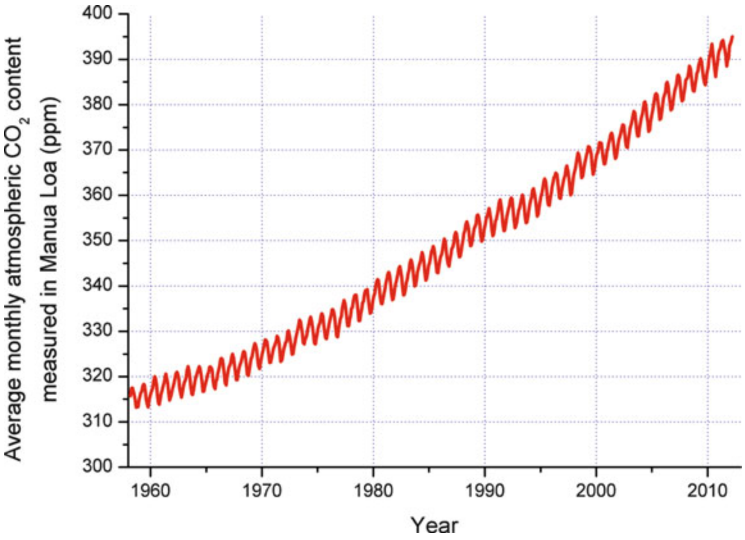

Fig. 2.8 Average monthly atmospheric CO_2 content measured at Mauna Loa Laboratory (Hawaii) [15]

in global CO_2 emissions, and established forest is decreasing its role as CO_2 sink. Consequently, the atmosphere is increasing its share in the carbon budget and, consequently, an increase in atmospheric CO_2 content is produced.

Increasing CO_2 emissions to the atmosphere is causing the average CO_2 levels in the atmosphere to rise very significantly, from the 280 ppm in the pre-industrial era to the 390 ppm currently measured (Fig. 2.8) [15].

This increase in CO_2 levels in the atmosphere is reducing the Earth's radiation of heat into space and, consequently, producing an increase in the average global temperature (Fig. 2.9) [16, 17]. Under these conditions, temperature growth around 0.15 °C per decade is estimated [17, 18].

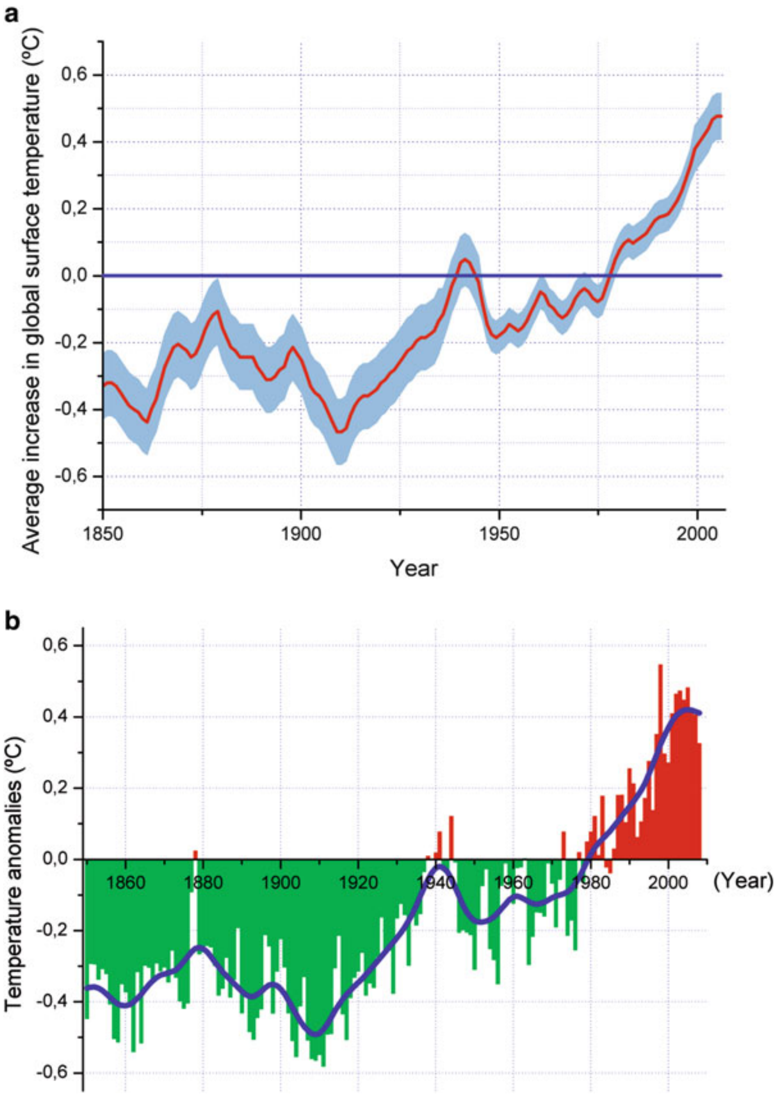

Fig. 2.9 (**a**) Increase in average global temperature over the period 1850–2007, considered by the International Panel on Climate Change [16]; and (**b**) measurement of the temperature anomalies in the period 1850–2008 according to the Met Office Hadley Centre [17]

This rise in CO_2 content in the atmosphere increases the average temperature, and also produces an increase of the average sea level (Fig. 2.10a) and a decrease in global land area covered by ice (Fig. 2.10b) [16]. It is considered that further increases in average temperature and sea level and also a further decrease in global land area covered by ice will be produced in the future as the increase of the CO_2 levels in the atmosphere are not yet stabilised [13]. Global warming is not only

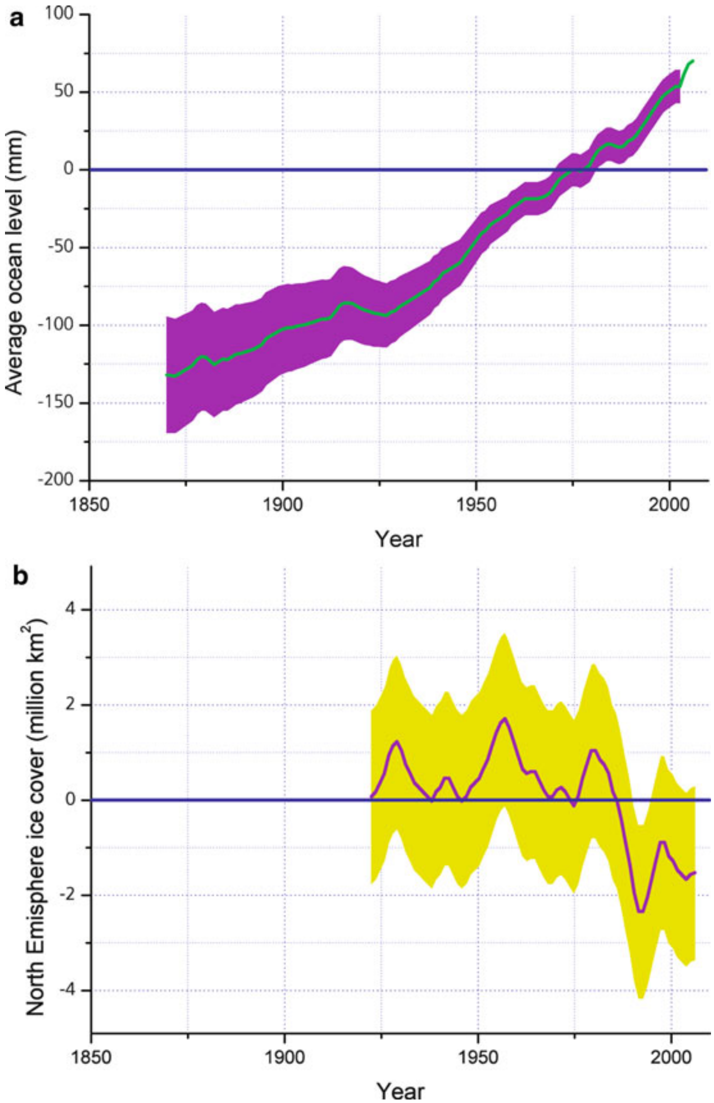

Fig. 2.10 (**a**) Increase in the average sea level in the period 1870–2007 and (**b**) changes in the extent of the Arctic ice cap in the period 1920–2007

associated to direct changes in weather conditions and subsequent food availability [19, 20] but also to the increase of extreme weather events [21, 22] and even civil conflicts [23].

Since the average CO_2 levels in the atmosphere are not stabilised, but in an upward trend, as noted above (Fig. 2.8), the future increases in temperature will depend on the CO_2 levels in which the atmospheric composition will be stabilised in the future (Fig. 2.11) [16].

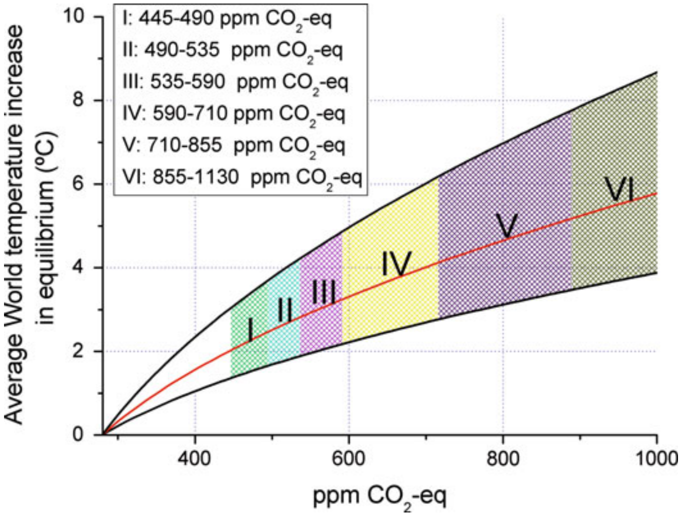

Fig. 2.11 Projected average world temperature increase in equilibrium as a function of different CO_2 concentration ranges in the atmosphere [15]

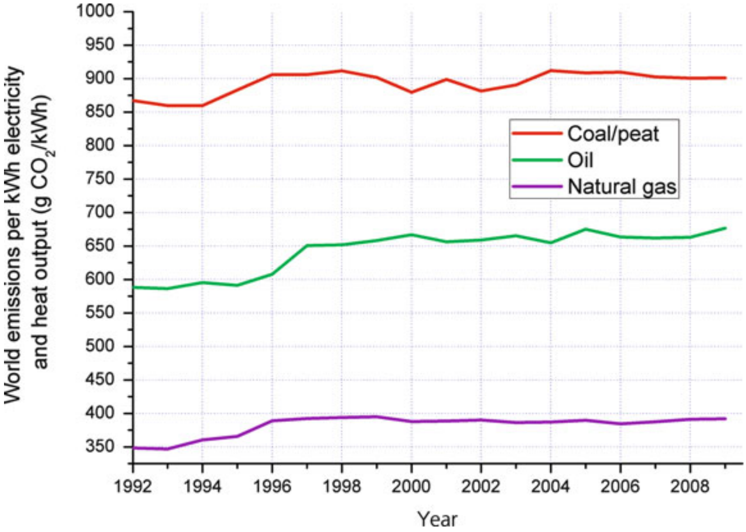

Fig. 2.12 Evolution of CO_2 emissions per kWh of electricity produced by conventional power plants fired with coal, oil or natural gas [1]

Some technological advances in the energy sector can help to reduce the CO_2 emissions to the atmosphere, as for example the replacement of coal-fired power plants by natural gas combined cycle power plants (Fig. 2.12). However, it is obvious that to rapidly reduce CO_2 emission rates from the energy sector should

Fig. 2.13 Evolution of the daily CO$_2$ emission permits price in the EU Emission Trading Scheme [18]

be achieved by a combination of improving energy efficiency, replacement of conventional by renewable energy technologies, as well as the capture and storage of CO$_2$ emitted.

To this purpose, some measures derived from the implementation of the Kyoto Protocol have been considered to encourage large industries to reduce their CO$_2$ emission rates. One of the most popular measures has been the creation of a market for carbon emission permits to incentive more efficient energy consumption and to improve the technology used in industrial processes. However, the price evolution of the emission permits in this market in the EU Emission Trading Scheme has been below initial expectations (Fig. 2.13) [18], generating very little incentive to reduce CO$_2$ emissions and even the introduction of technology to capture and storage CO$_2$ (cost above USD 40/t CO$_2$). However, it is estimated that this market has induced a CO$_2$ emissions reduction between 2 and 5 % per year compared to a scenario without this permits market [24].

2.3 Fuel and Electricity Production Costs from Renewable Energy Sources

As it has been exposed above (Table 2.1), the world TPES is mainly based on fossil energy resources. The market prices for these fossil fuels are very volatile, especially in recent years (Fig. 2.14) [25], and the prices of electricity and secondary fuels (gasoline, diesel, kerosene, etc.) are very much coupled to those markets.

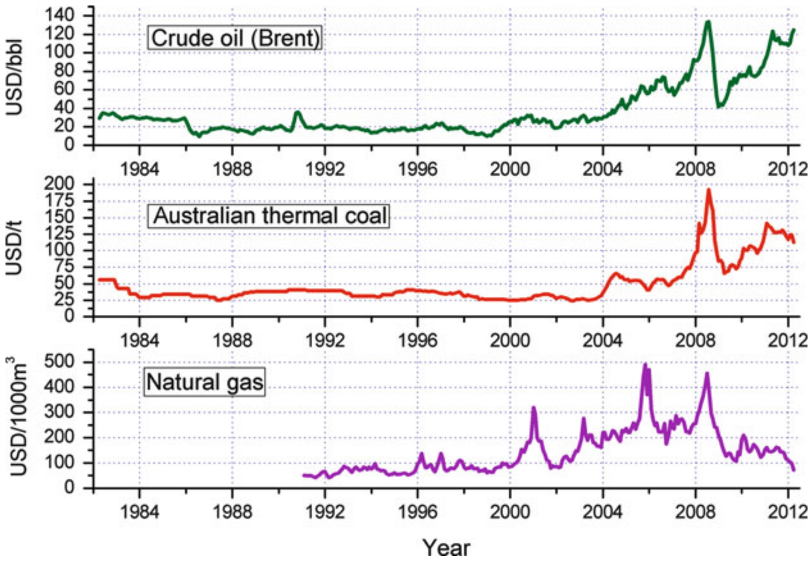

Fig. 2.14 Evolution of the oil, coal and natural gas prices in recent decades [25]

Contrary to fossil fuels, variations in the cost of energy from renewable resources are mainly coupled to the evolution of the associated technology and the cost of raw materials. Also the price of fossil fuels can influence this cost, but derived from their use in the manufacturing processes (i.e., fuel mix to produce electricity in a particular power system). This influence is predicted to decrease as the share of energy from renewable resources increases in the different energy mixes around the world.

When a cost analysis of energy production from renewable sources is calculated, it is desirable to first classify between renewable technologies that produce electricity or fuels. In the following chapters, we discuss each technology and the evolution of the production energy costs, but it is convenient to summarise in this chapter the current situation.

Thus, electricity costs for the renewable energy resources in 2011, considering the different studies, publications and technical papers analysed in the following chapters, are exposed in Fig. 2.15. These values are compared to the US generation prices and residential end-use price for 2011, published by the U.S. Energy Information Administration (EIA). Then, hydropower is the most competitive renewable technology, although restricted by the requirements of suitable sites for the location of plants, and wave energy is the most expensive technology.

On the other hand, renewable technologies that can be directly installed and exploited by end-users in residential areas have reached grid parity (geothermal and wind on-shore) or are very close to reach it (photovoltaics) in adequate locations. Moreover, if we consider the industrial and household electricity retail prices

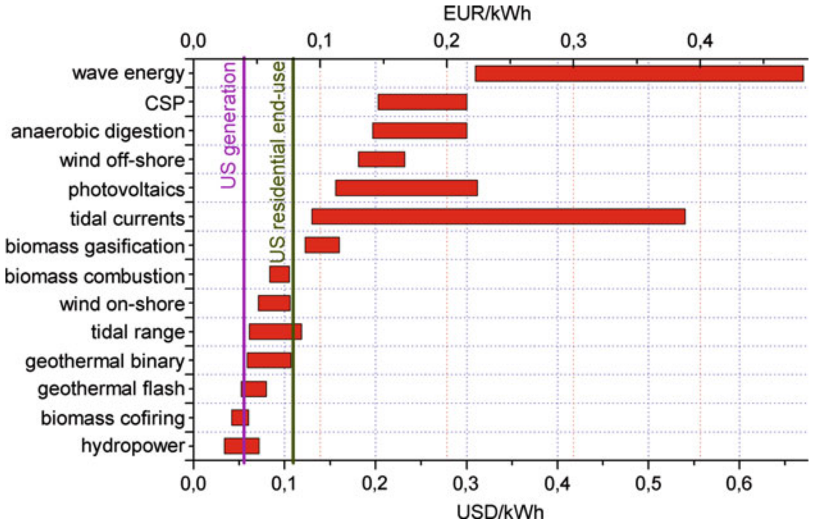

Fig. 2.15 Electricity costs in 2011 from different renewable energy resources, and compared to US average generation and residential end-use price

Table 2.3 2010 Industrial and household electricity retail prices for selected OECD countries [7]

Retail prices	Industry USD/kWh	Households USD/kWh
Canada	0,0699	0,0945
Chinese Taipei	0,0776	0,0932
Denmark	0,1144	0,3563
France	0,1056	0,1568
Germany	...	0,3248
Italy	0,2581	0,2632
Japan	0,1544	0,2322
Korea	...	0,0834
Mexico	0,1042	0,0888
Netherlands	0,1230	0,2212
Norway	0,0737	0,1758
Sweden	0,0964	0,2180
Switzerland	0,1023	0,1800
Turkey	0,1509	0,1841
UK	0,1211	0,1990
USA	0,0679	0,1158

for different OECD countries (Table 2.3), grid parity has been reached for these renewable technologies (including photovoltaics) in many locations.

For a first approximation to evaluate heating parity, we can consider the updated solar heating costs exposed in Chap. 13. Considering the average solar irradiance of Spain, stand-alone solar thermal heating systems lowest cost USD 118/MWh_{th}

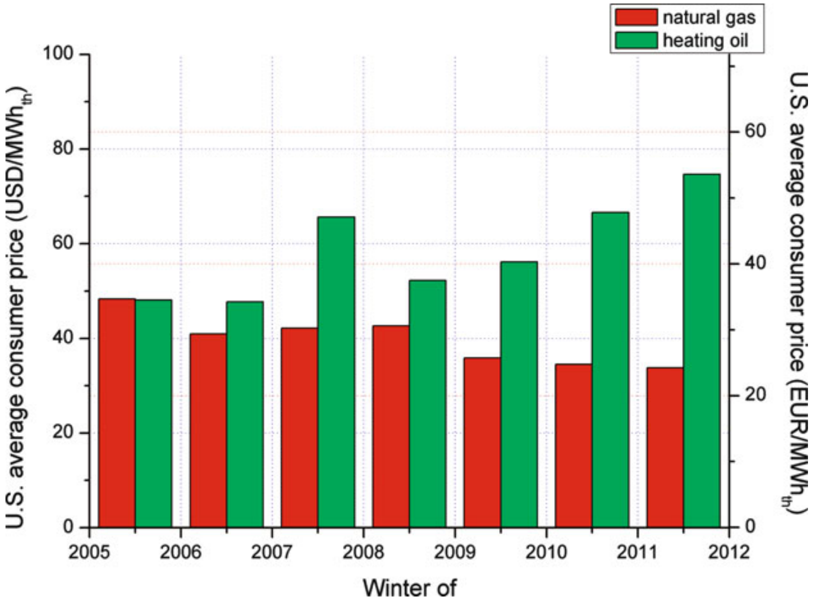

Fig. 2.16 Evolution of U.S. average consumer price for heating oil and natural gas

(EUR 85/MWh$_{th}$) usually is more expensive than heat produced from natural gas and heating oil, but competitive with retail electricity prices [26]. The average fuel prices for US consumers heating in 2010–2011 winter were USD 34.56/MWh$_{th}$ (EUR 24.83/MWh$_{th}$) for natural gas and USD 66.63/MWh$_{th}$ (EUR 47.87/MWh$_{th}$) for heating oil [16] (Fig. 2.16), but the investment and O&M costs of conventional systems should be added to compare with solar heating costs. Consequently, the use of high capacity solar heating energy for heat supply may be competitive with conventional energy sources (mainly heating oil) in highly sun irradiated areas.

As it will be exposed in the following chapters, renewable technology costs are, in general, decreasing over the years and electricity prices from conventional resources are increasing. Consequently, grid parity is being reached in many cases for the different renewable technologies, but it also depends on specific characteristics of the countries studied (solar irradiance, wind resources, grid interconnections, etc.). Then, it can be observed that in some countries, the penetration of renewable energy in the electricity grid reaches almost a 100 % (Table 2.4), mainly if the country has large hydropower capacity, as it also acts as energy storage system. If we only consider unmanageable energy (wind and solar), it can also largely penetrate in the electricity grid, mainly in countries where these resources are abundant and the technologies have been promoted.

To compare conventional and renewable fuels, the evolution of prices for ethanol [27] and gasoline [28], and biodiesel [29] and diesel [30] is exposed in Fig. 2.17a, b, respectively, considering equivalent calorific values [31] (ethanol = 67 % gasoline, biodiesel = 90 % diesel). It can be observed from Fig. 2.17a that in

Table 2.4 Top 20 countries in percentage of electricity from renewable sources in 2009 considering hydropower (countries A), without considering hydropower (countries B), and top 20 OECD countries in 2010 considering only unmanageable resources (wind and solar)

		% 2009		% 2009		% 2010
	Countries A	Hydro included	Countries B	Hydro no included	OECD country	Unmanag.
1	Paraguay	100,00	Guatemala	33,99	Denmark	20,26
2	Iceland	99,99	El Salvador	30,34	Portugal	17,54
3	Mozambique	99,92	Denmark	27,59	Spain	16,87
4	Zambia	99,69	Iceland	27,05	Ireland	9,87
5	Nepal	99,58	Kenya	24,38	Germany	7,81
6	D.R. Congo	99,55	Nicaragua	22,30	Greece	3,68
7	Albania	99,39	Portugal	19,93	New Zealand	3,65
8	Tajikistan	97,97	Costa Rica	17,37	Netherlands	3,53
9	Norway	95,99	Philippines	16,78	Italy	3,37
10	Costa Rica	95,15	Spain	16,08	Austria	2,91
11	Kyrgyzstan	89,28	New Zealand	15,92	UK	2,63
12	Brazil	89,04	Germany	12,71	Sweden	2,28
13	Ethiopia	87,63	Finland	12,50	USA	2,24
14	Georgia	86,61	Ireland	11,11	Estonia	2,14
15	Namibia	82,03	Sweden	10,21	Belgium	2,10
16	Ghana	76,77	Netherlands	9,46	France	1,80
17	Angola	76,05	Uruguay	9,30	Luxembourg	1,63
18	Togo	75,40	Austria	9,14	Australia	1,59
19	Colombia	72,84	Hungary	7,43	Hungary	1,43
20	Venezuela	72,79	Chile	7,17	Turkey	1,38

mid-2008, when oil prices reached record highs (Fig. 2.14a), the price of ethanol and gasoline overlapped, reaching a fuel parity. This overlap has been produced three times again since then, mostly coinciding with high oil prices. For biodiesel, the historical data show no overlapping and the price differential with diesel remains wide (Fig. 2.14b). Consequently, ethanol is close to fuel price parity with gasoline, but biodiesel is still far above diesel in terms of price.

Finally, to analyse costs of renewable energy, it is necessary also to consider energy storage costs, mainly to produce electricity, since mostly the sun, wind and ocean, show unpredictable behaviour and, consequently, make uneasy to couple electricity offer and demand into a certain power grid.

All electricity storage systems introduce very significant capital costs in the supply of electricity (Fig. 2.18) [32]. In a first approximation, if the priority is energy storage at the lowest cost, the best option is the metal-air batteries technology. If the priority is power management, the best option is the electrochemical capacitor technology. However, other parameters (power density, energy density, number of charging cycles, response time, etc.) need also to be considered to select the best technology for a specific application, as it will be exposed in Chap. 15.

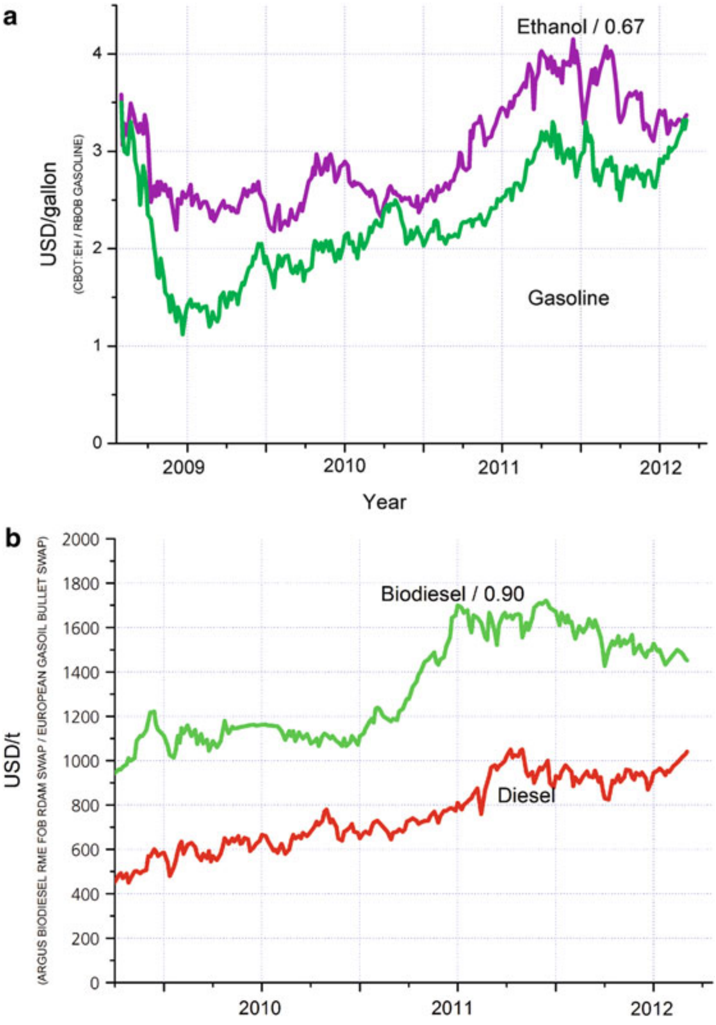

Fig. 2.17 Price evolution for different fuels in the futures market (balancing the difference in calorific values) (**a**) ethanol compared to gasoline and (**b**) biodiesel compared to diesel (source: INO)

2.4 Status of the Renewable Energy and Associated Technologies

In order to compare the status of the various technologies discussed in this book, Fig. 2.19 shows a diagram where they are classified according to the stage of development estimated after the discussions included in the different chapters. The classification distinguishes between the following stages of development [33]:

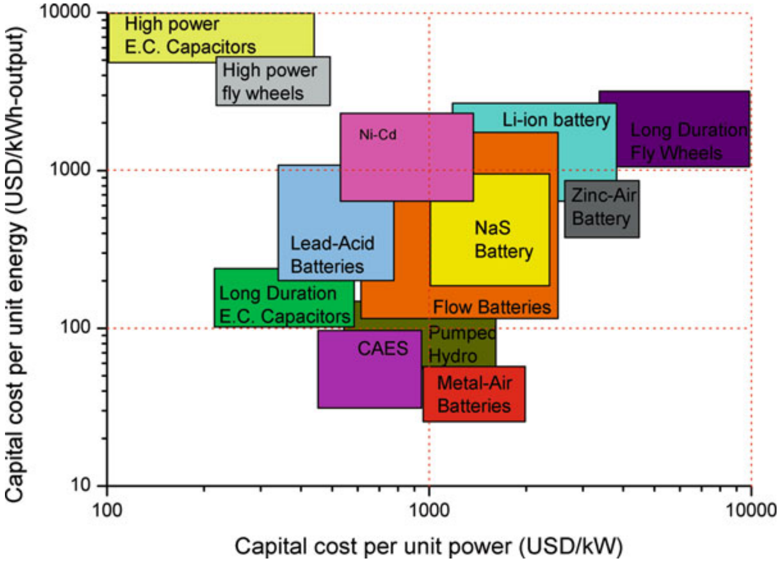

Fig. 2.18 Scheme of capital costs per unit of energy and per unit power for different storage systems [32] (CAES: compressed air energy storage, EC capacitors: electrochemical capacitors)

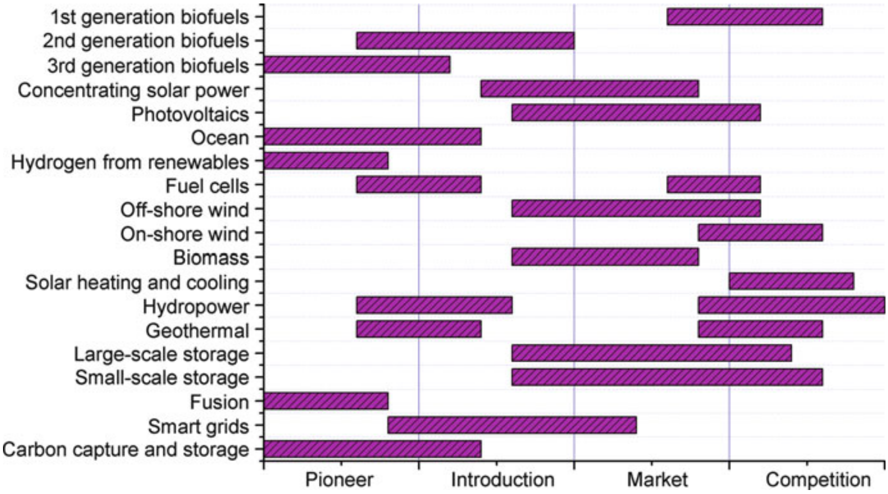

Fig. 2.19 Stage of development for each technologies discussed in this book

– Pioneer: Technology emerges as independent. This phase is characterised by a small number of companies developing the technology, mainly through radical innovations. The first barrier is to create a viable and reliable product. The greatest risk is technological.

- Introduction: The introduction of the product into the markets (primarily in niche markets). The technology is already known and there are many companies. Innovation processes are increased and the major risk is financial.
- Market: The technology is reliable, standardised and is already established in the market. Competition among companies has resulted in reducing the number of them. The greatest risk is the investor's own market risk, i.e. getting sufficient market share.
- Competition: The product is mature and has the opportunity to compete on equal terms with the conventional energy production technologies. There are few companies, but large.

The stage of development exposed in Fig. 2.19 is revised periodically, based on pre-production and innovation highlights for each technology that frequently occur on a global scale. In each chapter, we have also incorporated a similar stage of development figure for each renewable technology, including the different subtechnologies that are key topics for it.

2.5 CO_2 Emissions, Energy Payback and Other Environmental Costs

This section summarises the main values for different environmental impact parameters related to the technologies exposed in this book: CO_2 emissions, water consumption, land occupancy, energy payback and external costs. The importance of this information is increasing over the years for evaluating different impacts previously neglected in the energy sector. We consider that at present there are not well-established methodologies for their calculation, since the values for each technology are affected by external constraints such as location, energy mix, variations in the prices of raw materials, etc. However, the values shown below can serve as a guidance to estimate relative environmental impacts and further describe each technology.

On the other hand, the various literature sources used to obtain these data do not include all renewable technologies. Consequently, the reader may observe that some data is missing, which we hope to complete in new book editions.

In relation to CO_2 emissions, at present it should be noted that the production of electricity with all renewable technologies produce CO_2 emissions if we consider the whole lifecycle of the production system (Fig. 2.20) [34]. This is because the manufacture of renewable power plants requires energy, and it is normally supplied by a power grid where fossil fuels play an important role. Thus, for example, comparing renewable power plants manufactured in the USA and Europe, emissions of greenhouse gases are significantly lower in the latter case due to a higher renewable energy share supplied to the power grid. This fact must also be considered for many of the materials that integrate the renewable power plants

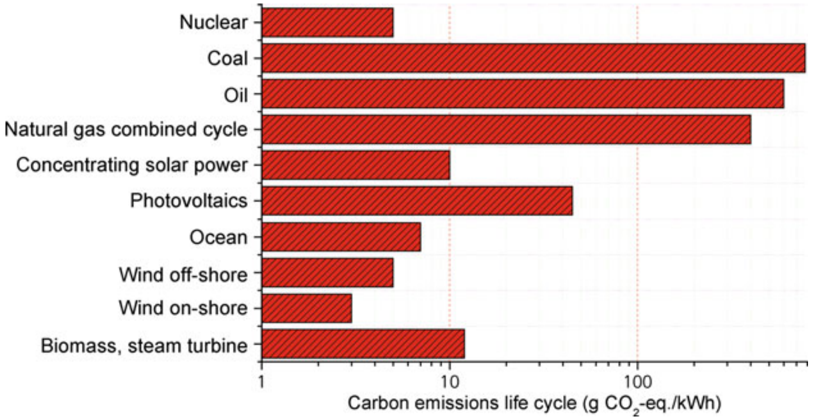

Fig. 2.20 CO_2 emissions per kWh of electricity produced from different renewable energy technologies considering the entire lifecycle of these systems [34]

(cement, steel, aluminium, etc.), as they are also produced with energy supplied from power grids or heating systems where fossil fuels play an important role.

Thus, it is expected that the increase in the contribution of renewable energy sources to total energy consumption will decrease the CO_2 emissions associated to energy obtained from renewable technologies, as the energy used for the manufacturing, construction, O&M and disposal of renewable power plants will be increasingly free from carbon emissions.

On the other hand, as it can be observed from Fig. 2.20, the larger CO_2 emitters per kWh produced are the coal-fired power plants, largely above those from renewable technologies. However, recent studies suggest that also crude oil extracted by new procedures increases air polluting with respect to established estimations, as the crude extracted from the Canadian oil sands [35].

If the reader is interested in CO_2 emissions from the production of renewable fuels (biofuels) and energy carriers (hydrogen) and comparing to fossil fuels, detailed information can be found in Chaps. 4 and 5 devoted to the corresponding technologies. The variety of raw materials and processes involved in the production of renewable fuels and hydrogen makes it impossible to define a general value or a range of CO_2 emissions for these fuels.

Another important parameter to be considered into this section is the water consumption per kWh produced by different energy technologies. As it can be observed in Fig. 2.21 [36], water consumption for wind energy and photovoltaics is almost negligible, but it is substantial for other renewable technologies, mainly hydropower and geothermal. On the other hand, conventional power plants are also important water consumers, leading the ranking the coal-fired power plants. This result, added to the fact that coal-fired power plants are the larger carbon emitters of all power plant technologies (Fig. 2.20), makes coal the leading technology in terms of environmental impact. On the other hand, recent studies conclude that the energy return from water invested for the most water-efficient fossil fuel technology is

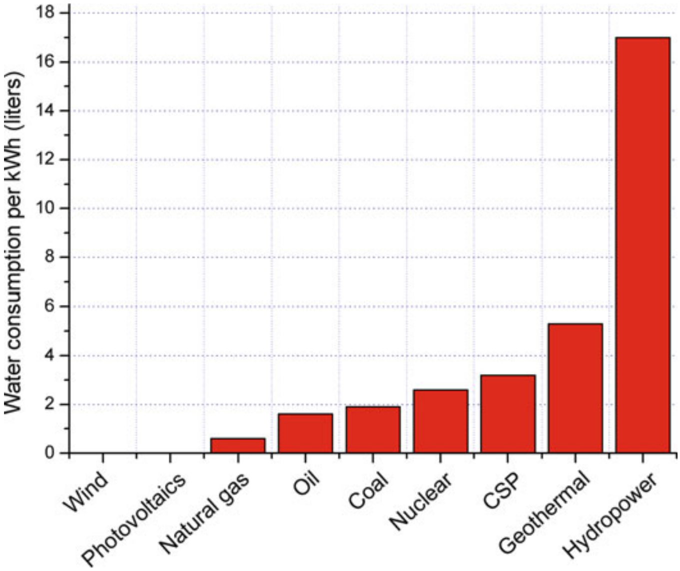

Fig. 2.21 Water consumption per kWh for different conventional and renewable energy technologies [36]

one or two orders of magnitude greater than the most water-efficient biomass technologies [37]. Then, the development of biomass energy technologies could produce or exacerbate water shortages around the globe that should be avoided.

In relation to water consumption for biofuel production, it varies substantially depending mainly on the raw material used to obtain it and the country where it is obtained. Specific information about water consumption for biofuel production can be found in Chap. 4.

Another important factor is the land occupancy to obtain energy from different resources. In this respect, there exists a significant gap between fossil fuels and renewable technology in terms of power density per unit area (Fig. 2.22) [38]. A coal mine or oil field, for instance, yields 5–50 times more power per square metre than a solar facility, 10–100 times more than a wind farm, and 100–1,000 times more than a biomass plant. Even if the energy needed to extract, transport and process coal is not considered, it still yields 50 times more energy per unit of land than ethanol from corn and ten times more than ethanol from sugar cane.

The energy payback ratio gives the ratio of net energy produced during the lifetime of the facility, divided by the energy required to build, maintain and supply the facility during all that time. Thus, the higher the energy payback ratio, the more attractive the technology is.

Works are scarce and segmented by technology in relation to energy payback ratios. Thus, we have found studies analysing PV [39], wind, nuclear, coal and natural gas [40], hydropower [41] and biomass energy [42] (Fig. 2.23). As it can be observed, the largest payback ratio is obtained by hydropower, as the dams

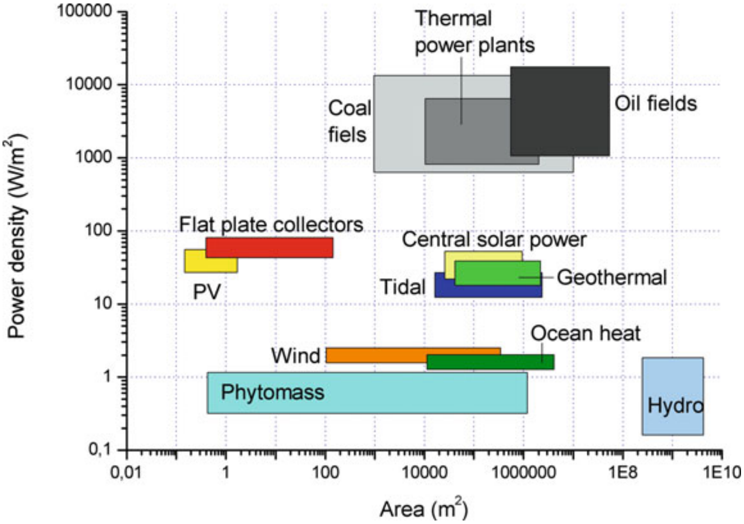

Fig. 2.22 Power density per unit area for different conventional and renewable energy resources and technologies [38]

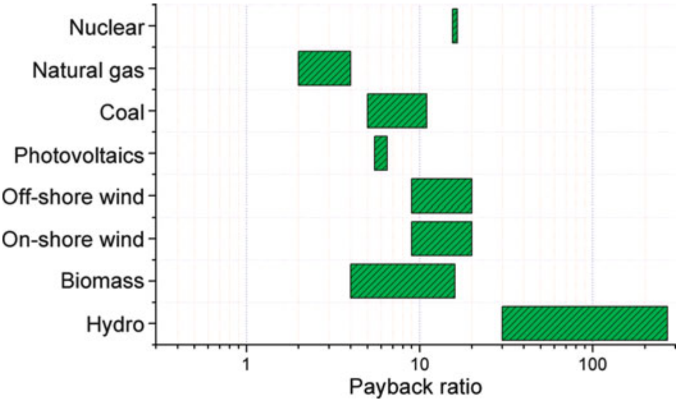

Fig. 2.23 Energy payback ratio for different conventional and renewable energy technologies [39–42]

associated to produce this energy have lifetimes of more than 100 years. Also, other renewable technologies as wind and biomass have attractive payback ratios. In relation to photovoltaics, values can be considered as outdated, as the energy required to produce crystalline silicon has been decreasing substantially in recent years. Moreover, all the values are approximate, because there are many features that are independent of the technology used but influence the energy payback ratio.

When economic or social activities of a participant in economic activities have positive or negative impacts on other participants, and these impacts are not

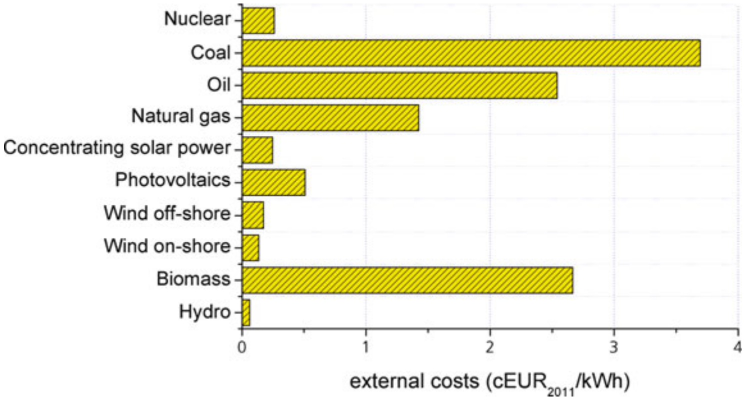

Fig. 2.24 The external costs per kWh for different renewable and conventional energy technologies [44]

counted or are compensated by the first participant, the costs generated are called "external". In this sense, there is a growing effort to account for and internalise these costs. An example of costs internalisation is the establishment of CO_2 emission rights for polluters, derived from the Kyoto Protocol.

In the energy sector, there are few studies that quantify these costs, although the political interest in establishing them is increasing. In this sense, the project ExternePol (Extension of Accounting Framework and Policy Applications) [43] can be considered as pioneering in this area. The ExternePol project has been surpassed by the NEEDS (New Energy Externalities Development for Sustainability) [44] project, both funded by the European Union. From the NEEDS project, we have obtained the external costs values for different energy production technologies exposed in Fig. 2.24. It can be observed that not only conventional energy technologies based on fossil fuels show the larger external costs but also the energy derived from biomass shows external costs comparable to fossil fuel based technologies. This can be attributed to the environmental impact that emissions and waste from biomass power plants produce.

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II
Renewable Fuels and Carriers

Chapter 3
Biomass

Abstract The energy stored in the biomass existing on the Earth can be transformed by chemical or biological processes into heat or electricity. From a certain point of view, biomass can be considered as solar energy stored in carbohydrate chemical bonds by means of the photosynthesis process. Therefore, the emitted CO_2 to the atmosphere, when biomass is burned or transformed, can be considered to be equal to the CO_2 absorbed during its previous growth, i.e., energy from biomass could in principle be considered as carbon neutral. It is important to remark that bioenergy provides about 12 % of the global energy consumption, and therefore is, together with hydropower, one of the main renewable energy resources in the world. In this chapter, we describe some of the most common energy processes for using biomass as a fuel: direct combustion, pyrolysis for the production of charcoal, gasification for obtaining synthesis or producer gas, co-firing with coal, etc. On the other hand, the production of liquid or gaseous biofuels will be treated in Chap. 4.

3.1 Overview

Biomass is any living mass, both animal and vegetable, existing on Earth, including its waste. Biomass can be converted into heat or other energy carriers such as electricity, when it reacts with oxygen in the combustion process. Biomass is almost the only type of fuel used by mankind since ancient times up to the industrial revolution, with large use in wide areas of the less developed world at present.

Biomass has a low energy density compared to fossil fuels. However, its energy density can be increased substantially by conversion to biofuels through different mechanical, chemical or biological procedures. This chapter covers the technological aspects related to solid biomass, which can be partially or totally transformed to a gaseous fuel (biogas), being its energy used as well. On the other hand, Chap. 4 is completely devoted to the technologies related to liquid biofuels.

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Table 3.1 Energy content per unit weight and volume for various types of biomass [1, 2]

Feedstock	GJ/t	GJ/m^3
Dry wood	15	10
Paper	17	9
Dry manure	16	4
Baled straw	14	1.4
Dry sugar cane	14	10
Household waste	9	1.5
Crude	42	34
Coal	18	50
Natural gas	55	0.04

Biomass can also be considered as solar energy stored in chemical bonds of carbon–hydrogen as a result of metabolic activity or photosynthesis of different organisms. Through this process, CO_2, water and some nutrients are converted into biomass, which is mainly composed of carbohydrates, fats, proteins and minerals. About 95 TW (0.05 %) of the solar power that reaches the Earth (170,000 TW) is considered to be absorbed to produce photosynthesis [1, 2].

The energy stored in biomass varies between 8 GJ/t for green wood and 15 GJ/t for dry wood, which are very low compared to 55 GJ/t for natural gas. Table 3.1 [1, 2] shows the energy content of various types of biomass, both per unit weight and volume, and are compared to those of oil, coal and natural gas.

According to statistics from the International Energy Agency [3], the supply of biomass (primary solid biomass, biogas, liquid biofuels and renewable municipal waste) has grown steadily from 26.05 EJ in 1971 to 50.20 EJ in 2009 (last available data) (Fig. 3.1). Of this amount, 93.7 % corresponds to primary solid biomass, biogas 1.9 % and 4.4 % for liquid biofuels. Renewable municipal waste reached 0.59 EJ in 2009.

Only 0.7 EJ of the 50.79 EJ biomass and renewable municipal waste supplied in 2009 has been dedicated to the production of electricity and heat. Although this represents a small percentage of 1.37 %, it has been increasing continuously since 2001 (Fig. 3.2).

The distribution in terms of biomass types dedicated to the production of electricity and heat is shown in Table 3.2. The largest amount is observed for renewable municipal waste, while the percentage of primary solid biomass is minimal, and no liquid biofuels are used for this purpose. However, in absolute terms, the largest amount of biomass dedicated to the production of both electricity and heat comes from primary solid biomass.

If we consider the evolution of electricity and heat production from biomass in recent years, increasing trends are observed in most cases. More specifically, in the case of electricity production, there has been a steady increase in production dominated by solid biomass (Fig. 3.3a). For heat production, it is also solid biomass the one that leads the rankings (Fig. 3.3b).

The global technical potential of biomass is estimated in the literature that could reach 1,500 EJ/year in 2050, but if sustainability criteria are also considered, the potential would be 200–500 EJ/year (excluding aquatic biomass) [4]. Forest,

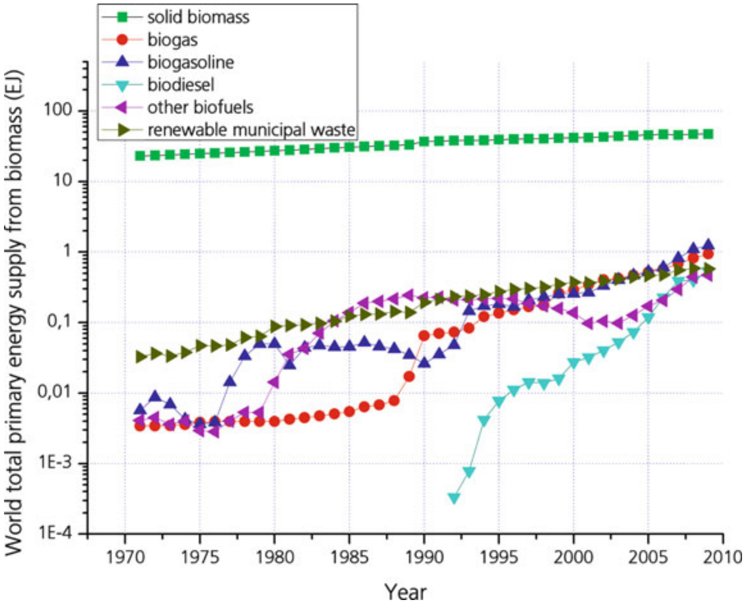


Fig. 3.1 Evolution of total primary energy supply from various types of biomass and renewable municipal waste between 1971 and 2009 [3]

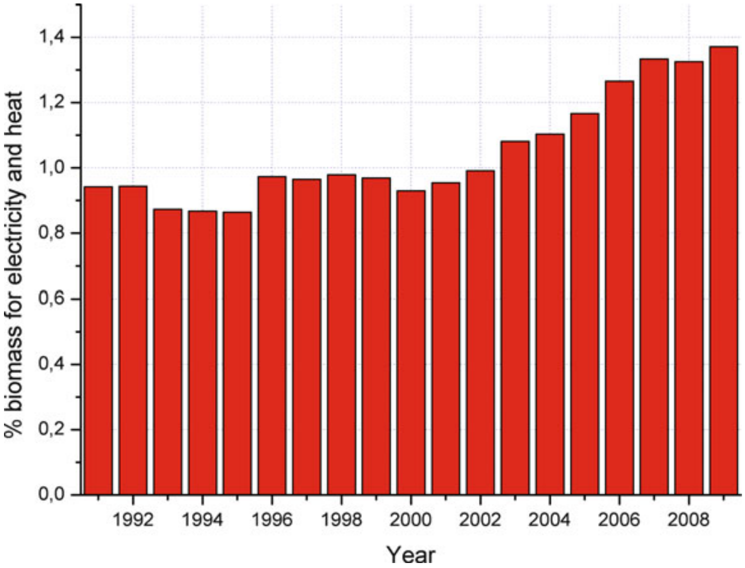


Fig. 3.2 Evolution of the percentage of biomass and renewable municipal waste supplied for the production of electricity and heat during the period 1990–2009

Table 3.2 Energy (EJ) and percentage of biomass, by type, dedicated to the supply of electricity and heat in 2009

2009	Electricity EJ—(%)	Heat EJ—(%)
Primary solid biomass	0.17—(0.37)	0.33—(0.71)
Biogas	0.04—(4.03)	0.01—(1.51)
Renewable municipal waste	0.03—(5.30)	0.10—(18.03)

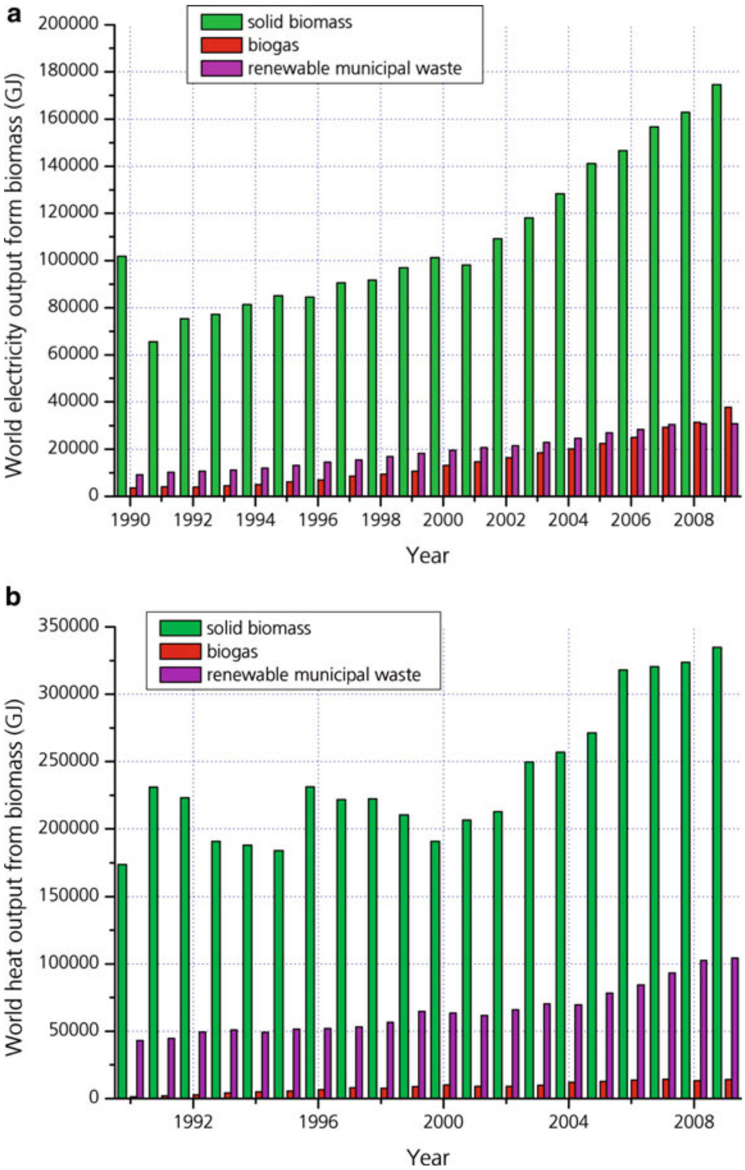


Fig. 3.3 Evolution of the gross production of (**a**) electricity and (**b**) heat from 1990 to 2009 for different types of biomass

agricultural and other waste (including municipal waste) could provide between 50 and 150 EJ/year, while the rest could be obtained from energy crops, forest surplus and increased agricultural productivity [4]. The wide variety of biomass resources at a geostrategic level can also help to improve the security in energy supply.

3.2 State of the Art

Unlike other types of technologies for exploiting renewable sources, biomass is extremely varied in its nature and, consequently, requires specific technologies in each case, both the management of the particular crops, and in the energy use, like heat, electricity, etc.

3.2.1 Energy Crops

Energy crops are receiving increasing attention for several reasons: obtaining alternative fuels to fossil fuels, reducing CO_2 emissions, reaching greater energy independence, use of fallow land, reducing water demand, etc.

Wood forest crops for energy use are obtained from modified forests having a large tree density. The harvest of forest in the short term is made cutting and gathering wood in periods of few years, in locations with favourable annual yield, like in Northern Europe where yields of up to 10 t/ha are reached [1]. The harvested timber is generally used for the production of heat and/or electricity.

To produce bioenergy from agricultural crops, the most widely used plants are sugar cane and corn, as discussed in more detail in next chapter. These plants are used for the production of liquid biofuels. Other plants such as sunflowers and soybeans are used for biodiesel production. Moreover, the yield per hectare of energy crops has grown significantly since 1960 until 2005. Thus, there has been a 70 % increase in production for sugar cane and 400 % increase for corn during this period [5].

Table 3.3 shows both the biomass yield (t/ha) and the energy equivalent produced per hectare and year for different energy crops [2]. It is assumed that the values shown are the maxima obtained in practice and that the biomass is almost dry.

For further comparisons with other energy technologies, the energy efficiency of photosynthesis is defined as the energy content (heat from glucose combustion to CO_2 and liquid H_2O at STP) of the biomass that can be harvested annually divided by the annual solar irradiance over the same area. Then, solar energy conversion efficiencies for crop plants in both temperate and tropical zones typically do not exceed 1 %; for comparison, efficiencies of 3 % are obtained for microalgae grown in bioreactors and about 5–7 % for microalgae in bubbled bioreactors. On the other hand, a theoretical limit of about 12 % can be considered for the efficiency of photosynthetic glucose production from CO_2 and water [6].

Table 3.3 Maximum performance energy harvests from dry biomass [2]

Feedstock	Yield (t/ha)	Energy (GJ/ha)
Forest wood	7	130
Tropical wood	11	200
Sorghum (3 harvest/year)	50	850
Sudan grass (6 harvest/year)	40	600
Corn	25	77
Wheat	22	
Sugar cane	30	150

3.2.2 Cultivation Techniques

The two main aspects to be considered in this section are the availability of land and its productivity. Currently, it is estimated that less than 1 % of agricultural land is dedicated to energy crops [7]. The yield of energy crops depends on many factors such as climate, soil type, available water resources and technology. Profitable performance is considered at 10–12 t of dry biomass per hectare per year, equivalent to an energy yield of 220 GJ/ha [5]. Given that the average amount of solar energy received in 1 year is about 1,000 kWh/m^2, solar energy conversion into bioenergy would reach only 0.6 % efficiency.

The cultivation techniques vary very substantially between countries in terms of cost of labour and access to automation process systems. In general, the productivity of the cultivation process increases with the level of development of the country concerned. Consequently, it is estimated that global productivity can be substantially improved as new cultivation techniques are adopted by the most underdeveloped countries.

3.2.3 Harvesting, Storage and Transportation

Obviously, energy crops, after having been grown, should be harvested, dried, cut and transported. The objective is to obtain a homogeneous product of appropriate size, high energy density and with minimal moisture.

The harvest of forest residues also arises from the cleaning and maintenance of forests and these residues are harvested using similar techniques to those used in forests devoted to energy crops. Currently, however, the larger amount of residues generated in moderate temperature regions are derived from wheat straw and corn. These residues are rarely used but burned in the field. Alternatively, these wheat straw and corn residues can be pressed up to 1 t/m^3 for easy transport [5], reaching a significant energy density of about 15 GJ/t [7].

For crops in tropical climates, most of the bioenergy is derived from sugar and rice. Precisely, the fibrous residue of sugar cane is often used for local electricity production in small power plants. Also, sugar cane residue is used more than wheat and corn to produce heat and electricity. For rice, the hulls are also very suitable for use in gasification plants.

To increase the energy densification of biomass, pellets are usually fabricated by applying pressure on biomass waste (mainly sawdust). Pellets are already subject to quality standards for a growing process of commercial activity (6–12 mm in diameter, 10–30 mm in length, moisture content below 10 %, ~650 kg/m^3 and ~17 GJ/t) [4]. For example, the new European standard for pellets (EN 14961–2:2011) provides three quality classes of pellets to be used in different heating systems [8]. The pellets are also easy to transport and handle, but these activities also require standardisation [8]. However, the pellets absorb moisture, which can lower the calorific value below 10 GJ/t with aging in contact with the atmosphere.

An additional option is to subject the biomass to torrefaction processes (200–300 °C) by which it is converted into a dry, hydrophobic and higher energy density (19–23 GJ/t) product [4], holding up 92 % of the energy of the raw material. Torrefacted biomass can also be converted into pellets, process that can lower its cost per energy unit. Moreover, torrefaction facilitates biomass transport and storage activities.

Another procedure to improve biomass energy density is through pyrolysis. In this process, the raw material is heated in the absence of oxygen, producing charcoal, bio-oils and biogas. The fraction of each product depends on the temperature and residence time of vapours in the process. The application of moderate temperatures (~500 °C) for 1 s is used to maximise the liquid fraction, in a process called fast pyrolysis. By contrast, the slow pyrolysis is commonly used for obtaining charcoal. The biogas produced is often used as energy input in the pyrolysis process itself. The bio-oils obtained have a calorific value of about 17.5 GJ/t, but the energy density per unit volume (20–30 GJ/m^3) doubles to quadruples that of the pellets and the product of torrefaction, although this is only yet about half the biodiesel energy density [4].

On the other hand, animal manure and debris from urban wastewater should also be considered, as they can be a major source of greenhouse gases. In some countries, these sources represent a significant percentage of methane emissions. This type of biomass energy is valued using anaerobic digestion to produce biogas in livestock farms.

In relation to renewable municipal waste, each household in the industrialised world produces about 1 t/year, with an energy content of about 9 GJ/t [1]. Currently, these products are being valued through combustion processes or anaerobic digestion, producing gas that can be used to generate heat or electricity. Also, the renewable municipal waste can be stored in impermeable disposal cells in which gases are produced naturally by anaerobic digestion, and later collected through a mesh of interconnected and perforated pipes to depths of about 20 m. The production of landfill gas per tonne of waste is estimated, in theory, at about 150–300 m^3, containing a high proportion of methane, and an energy of about 6 GJ/t of waste material [1].

3.2.4 Combustion

The direct combustion of biomass is the oldest technique used for energy recovery, but it is not very efficient (5–30 % efficiency in developing countries and 85–90 % in CHP systems [4]). The efficiency for electricity production ranges between 10 % for steam boilers with powers below 1 MW, and 40 % for >50 MW steam turbines combined with the latest combustion technology in fluidised beds [4].

Normally, the combustion of biomass requires a first step consisting in a simple physical treatment: sorting, crushing, compressing, air drying, etc. The low conversion efficiency for green biomass is partly due to the energy necessary to evaporate all water contained in the organic matter. Furthermore, biomass contains a high proportion of volatile materials that are emitted as vapours or tars (causing sparking during combustion) and requires additional energy, reducing the efficiency of the process. For this reason, the design of the boiler must ensure that these vapours cannot escape without burning and, consequently, oxygen must be provided. Such boilers are often used in plants of about 0.5–10 MW_{th}.

Municipal renewable raw material is very heterogeneous and polluted, thus corroding and damaging the standard infrastructure, and therefore requiring strict emission controls, as well as a robust technology to enhance energy recovery. For this reason, conversion efficiencies to produce electricity are only of about 22 % [4].

A technology improvement compared to the above process is the fluidised bed combustion (FBC), which allows a larger heat transfer during combustion, and also an enhanced temperature control (the flame temperature to ignite biofuel is lower than in conventional combustion) and reduction of gas emissions (NO_x and CO). In this technique, the fuel material is cut in small pieces and placed on a limestone bed. In this way, an enhanced mixture between biomass and air is obtained during combustion, thus increasing the performance, and allowing the use of a less homogeneous biomass. The fluidised bed may be stationary or circulating.

As mentioned above, among all plants generating electricity from biomass, only 10–40 % of the fuel energy is exploited, since the rest is evacuated as heat to the atmosphere or to the cooling circuits. For this reason, it is much more efficient a simultaneous cogeneration of heat and power, and in this case the efficiency can reach 80–90 %. In CHP plants, heat can be used to heat water for district heating or industrial processes. In industrial applications, the heat is usually transferred through steam at a temperature of 130–200 °C and pressures of 3–16 bar [5]. Obtaining heat causes the electricity production efficiency to be reduced by several percentage points [4]. In the Nordic countries, there are many CHP plants, sometimes associated with paper mills, for the simultaneous production of heat and electricity from biomass.

As an alternative to conventional combustion, organic Rankine cycles are being considered. This cycle uses an organic fluid with high molecular mass, instead of steam, to recover heat from low temperature sources. The plants work with powers of 0.5–2.0 MW, achieving efficiencies of 17 % (slightly higher than with steam boilers) and lower working temperatures. However, the net efficiency, after deducting auto-consumption, is lower.

On the other hand, in a smaller range of power capacities are the Stirling engines (10–100 kW_e), whose technology is promising for domestic cogeneration. However, Stirling engines using biomass as fuel require further tests before they are introduced in the market. Electricity conversion efficiencies in these systems are in a range of 12–20 % [4].

3.2.5 Co-firing

The co-firing of biomass and coal in coal-fired power plants for electricity production can significantly contribute to reducing CO_2 emissions as it has already been proven in many installations worldwide, mostly in Europe. Typically, the proportion of biomass burned is 5–10 %, although in some plants up to 25 % has been tested [4]. Co-firing is the most efficient and economical technology for converting biomass into heat and electricity, as it can take advantage of the existing infrastructure for coal plants, and only small investments are required to feed the biomass itself. Currently, there is fully commercial technology implemented in this area, and power plants reaching 400 MW_e capacities are being planned [4].

The co-firing processes can be performed in three different ways: (1) directly, mixed with coal, being the most widely used process; (2) indirectly, where the syngas (CO, H_2, and CH_4) resulting from the gasification of biomass is burned with coal and, consequently, contamination problems are mitigated and (3) in parallel, where biomass is burned in a separate boiler, using the generated steam to power the main steam circuit of the plant.

It is important to note the following benefits of co-firing [5]: (1) reduction of CO_2, nitrogen oxide and sulphur dioxide emissions compared to fossil fuel processes, (2) lower investment costs than using specific biomass burners, (3) larger energy efficiency than in small biomass units and (4) reduction of risks associated with biomass supply shortages.

3.2.6 Gasification

In the gasification technique, biomass is partially oxidised by means of water vapour and air (or oxygen) at high temperatures (800–1,000 °C) to form syngas (mixture of CO, CH_4 and H_2), which can also be used for secondary purposes other than energy production. The gas can be used in steam boilers, gas turbines or co-firing. The process is not very efficient, since the total energy of the gasification products is lower than that of the initial biomass. However, the fuel gas produced is more versatile and less polluting. If the gasification is carried out in air, the gaseous biofuel has a calorific value of 3–7 MJ/Nm^3, and if it is carried out in oxygen, it can reach 7–15 MJ/Nm^3 [5], although the production of oxygen requires also a considerable amount of electricity. In addition, up to 20 MJ/Nm^3 can be obtained in indirect combustion processes [4], which represents 10–45 % of the heat capacity of natural gas.

The syngas can also be cleaned of particles and condensable hydrocarbons and burned in an internal gas combustion engine, providing an electricity efficiency of 22–35 %. This efficiency is slightly higher than that achieved with the steam turbines used for biomass combustion processes [4]. This efficiency can be increased up to 40 % if the syngas is burned in gas turbines [4].

3.2.7 Anaerobic Digestion

Anaerobic digestion is the biological degradation of biomass in oxygen-free environments. The main product of this process is biogas, rich in CH_4 and CO_2. The anaerobic digestion process takes place in two phases: (1) hydrolysis and acetogenesis, which converts biodegradable material into glucose and amino acids, subsequently converted into fatty acids and (2) methanogenesis from acetic acid, also producing CO_2. The two steps can be performed in a single reactor (single-step anaerobic digestion) or in two steps (two-step anaerobic digestion). The second process is more efficient but more complex and expensive.

The biogas obtained from anaerobic digestion can be directly burned in CHP systems [4] or be upgraded to meet the standards of natural gas and injected directly into pipelines. Anaerobic digestion can operate with any type of biomass that can be digested by animals (that is, except biomass from wood). The process is particularly efficient with wet biomass, sludge from sewage treatment plants, as well as in landfill cells for municipal waste storage. If the biomass used as raw material is not contaminated, the solid digestate can be also used as fertiliser, adding value to the process.

There are two proven technologies for the use of anaerobic digestion depending on the process temperature: (1) the thermophilic digestion (50–70 °C), which offers the best performance and reduction of viruses and pathogens, is mainly used in centralised systems and (2) the mesophilic digestion (25–40 °C), which requires more technology and handling of biomass.

Considering the different feedstock and processes involved, Fig. 3.4 shows a schematic overview of the pathways followed to convert solid biomass into electricity, heat and gaseous fuels.

Also, Table 3.4 shows a summary of typical power capacities and electrical and heat efficiencies for the different technologies involved for the production of energy from biomass.

3.2.8 Stages of Development

Depending on the degree of market penetration, the different technologies exposed above that are driving the production of energy from solid biomass can be considered in different stages of development (Fig. 3.5).

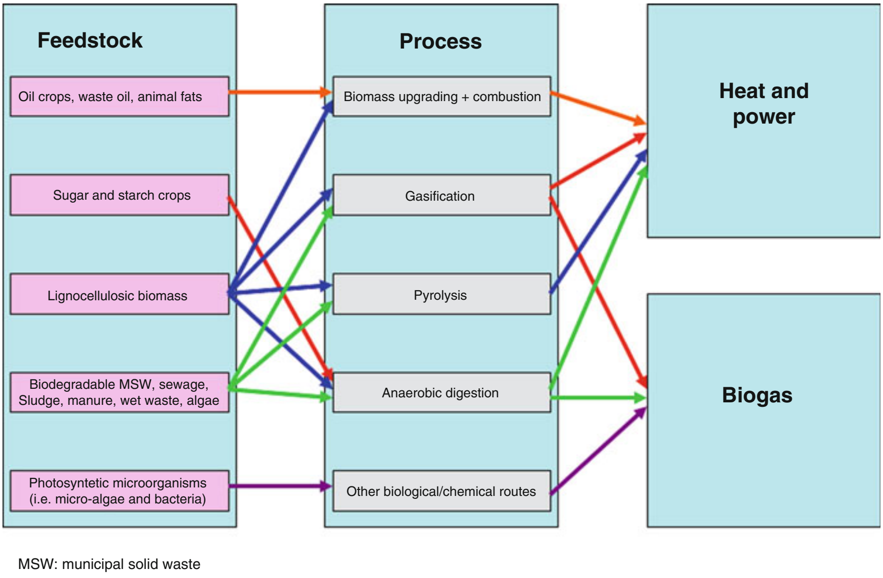


Fig. 3.4 Scheme of the different routes for the production of electricity, heat and gaseous fuels from solid biomass

Table 3.4 Typical power capacities and efficiencies for different electrical and heat technologies using biomass as fuel [5]

Conversion	Typical capacity	Net efficiency
Anaerobic digestion	<10 MW	10–15 % electrical 60–70 % heat
Landfill gas	200 kW–2 MW	10–15 % electrical
Combustion for heat	5–15 kW_{th} residential 1–5 MW_{th} industrial	10–20 % open fire 40–50 % stoves 70–90 % furnaces
Combustion for power	10–100 MW	20–40 %
Combustion for CHP	0,1–1 MW 1–50 MW	60–90 % overall 80–100 % overall
Co-firing with coal	5–100 MW existing >00 MW new plants	30–40 %
Gasification for heat	50–500 MW_{th}	80–90 %
BIGCC for power	5–10 MW demo 30–200 MW future	40–50 % plus
Gasification for CHP using gas engines	0.1–1 MW	60–80 % overall
Pyrolysis for bio-oil	10 t/h demo	60–70 %

Most of the technologies discussed in this chapter can be considered in a state of competition, although also active in the research, development and demonstration stages for reaching enhanced efficiencies and reducing costs.

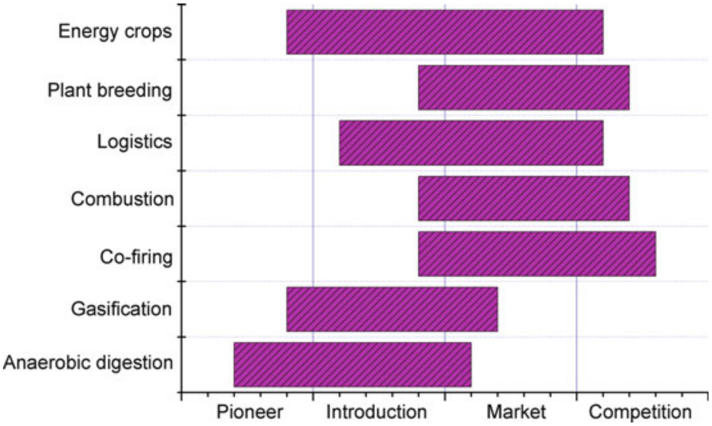


Fig. 3.5 Stage of development for each technology described in this chapter

Thus, many crop species and residues are currently being commercialised without subsidy, but further research into new crop species or genetic modification of the ones presently used is on course. In relation to cultivation techniques, the technology is in a stage of competition, but significant efforts to introduce multi-functional crops and more technology in developing countries is detected. In relation to the technology associated with harvesting, storage and transportation (logistics), it is found that they are well implemented. However, there are still opportunities for technological improvement in densification processes (pellets, torrefaction and pyrolysis) and storage, as well as in obtaining added value by implementing these processes in biorefineries.

For technologies directly related to the extraction of energy from solid biomass, co-firing processes are the most mature and competitive, but new advances are expected in indirect co-firing and co-firing in parallel. The following most mature technology is combustion, where improvements in organic Rankine cycle and Stirling engines are also expected. The gasification process can be classified as the less developed, showing BIGCC many options to improve this technology in the near term, and also by combining biomass gasification and fuel cells. In a more delayed stage, but also entering the competition phase, is anaerobic digestion, particularly in relation to the use of biogas from municipal waste landfill cells. But the anaerobic digestion to extract hydrogen from biomass is still under a very pioneering phase.

3.3 Current Costs and Future Scenarios

Unlike other types of renewable technologies with freely available resources (sun, wind, etc.), the cost of biomass typically represents between 50 and 90 % of bioenergy production (with the exception of waste). Thus, in general, the range is

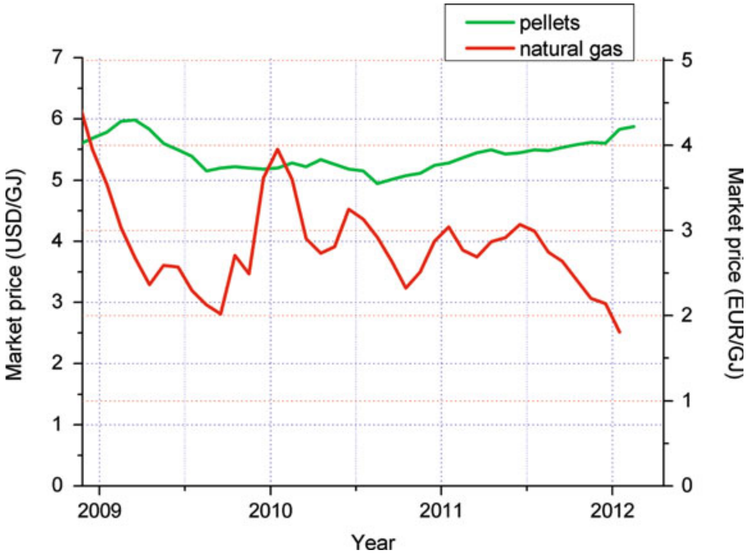


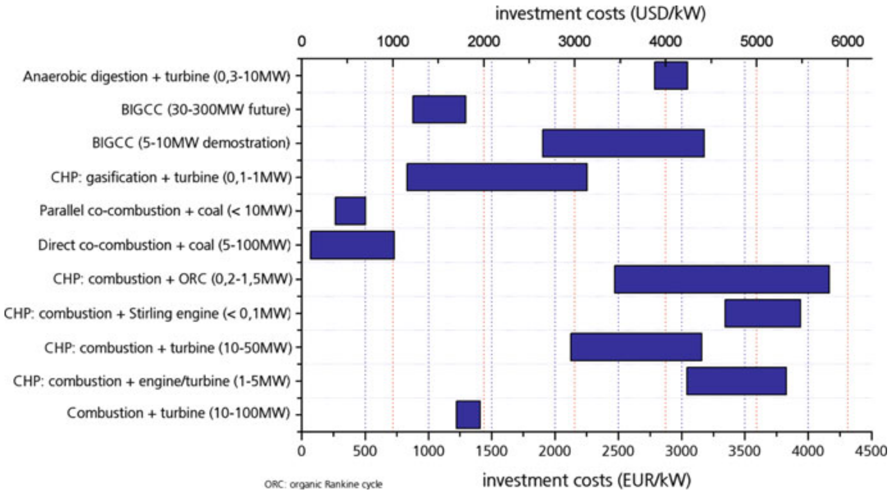
Fig. 3.6 Evolution of the market price per unit energy for pellets and natural gas (source: APX-ENDEX and CME)

usually USD 3.0–4.0/GJ (EUR 2.2–2.9/GJ) as the upper limit cost of biomass energy if strong production growth is expected. On the other hand, the use of biomass residues for other purposes, such as animal feeding, fertilisers, materials, etc., can add value and, consequently, reduce the cost of energy production, although these considerations are not quantified in this book. It should also be noted that the structure of costs largely depends upon the available infrastructure and the technology used to harvest. Moreover, the lack of transparency in some markets, especially in relation to forest resources, obstructs the resource pricing in the market [4].

Still, the forest biomass costs are well established, ranging from USD 2.3 to 6.5/GJ (EUR 1.8–4.7/GJ) for biomass delivered to an energy recovery plant [4]. These costs vary significantly depending on the country and are affected by the specific conditions of the plantation forest, distance to the energy recovery plant, techniques for collecting and processing biomass, etc.

In a detailed cost analysis of the densification processes, wood pellet costs are around USD 72–115/t (EUR 52–82/t) in Europe and USD 61–85/t (EUR 44–61/t), increasing costs a 40 % when derived from switchgrass [4]. Considering the market of the pellets in terms of price per unit energy (Fig. 3.6), except at the beginning of 2010, pellets have been more costly than natural gas for the period recorded. This scenario is expected to continue as natural gas reserves are increasing worldwide mainly due to new fracking techniques to extract it. Moreover, there is no apparent link between the price of natural gas and pellets.

Pellets costs are mainly related not only to the raw material (43 %) but also to drying (35 %), being other significant costs associated to pelletisation (7 %), personnel (6 %) and storage (3 %) [8].



ORC: organic Rankine cycle

Fig. 3.7 Investment costs for different technologies for energy production from biomass [4]

Logistics costs associated to pellets subjected to torrefaction processes are estimated that can be reduced by up to a 50 %, while biomass production costs increase around a 10 %. In relation to pyrolysis, the investment costs are around USD 2,730–6,030/kWh (EUR 1,960–4,330/$\mathrm{kW_{th}}$) for production plants with capacities of 25 MW, while production costs (excluding the cost of raw materials) are 50–100 % higher than those based on pellets or torrefaction processes [4].

The costs for the production of heat in combustion boilers using pellets as fuel are USD 11–142/GJ (EUR 8–102/GJ, with an average value of USD 37/GJ (EUR 27/GJ), which makes it competitive with fossil fuels [4]. It is expected a cost reduction of only 4–6 % in 2030 (at constant prices) as a consequence of increasing system lifetimes and efficiencies [4]. As the cost for the heating distribution network accounts for 30–55 % additional investment, high concentration customer districts and time of utilisation rates above 75 % are required to reduce this additional investment per customer.

The range of investment costs shown in Fig. 3.7 is indicative of the importance of economies of scale in energy production from biomass and the maturity of each technology (being Stirling engine, BIGCC and organic Rankine cycle the most immature). As it can be observed, the lowest costs are associated to the co-firing processes, as it capitalises thermal plants fuelled by coal. However, this process cannot be considered renewable.

The current average cost of electricity production from biomass is in the range USD 0.04–0.20/kWh (EUR 0.03–0.14/kWh). In addition, a cost reduction of only 4–6 % is expected for 2030 (at constant prices) by increasing lifetimes and efficiencies [4] as well as a reduction to USD 0.04–0.13/kWh (EUR 0.03–0.09/kWh) in 2050 [5]. Moreover, as the fuel volume demanded by the biomass power plant increases, the transport cost increases too. Consequently, a compromise between power capacity and logistics must be reached to optimise costs.

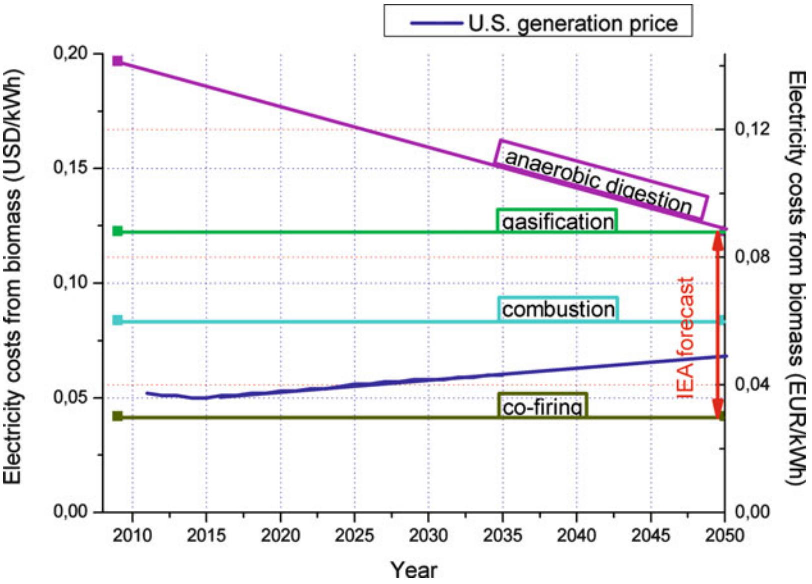


Fig. 3.8 Electricity production costs at present and those forecasted from power plants fuelled with biomass and based in different technologies. These costs are compared to the ones forecasted for US generation prices

Considering the minimal electricity cost variations from these technologies expected in the long term, we decided to assume the costs as constant (except for anaerobic digestion) to calculate the grid parities exposed below. For anaerobic digestion, we consider a linear decrease in costs because it is the most immature technology at present. This linear decrease in costs for anaerobic digestion will reach the upper range of expected costs in 2050 by the IEA [5], considering that this technology will remain more expensive over this period. Under these assumptions, the electricity production costs from biomass in 2009 and expected to 2050 are exposed in Fig. 3.8 and compared to forecasted US generation prices in constant USD and EUR per kWh.

In this sense, it is estimated that the cost of electricity production from co-firing is already below the US generation prices (Fig. 3.8). However, for the remaining technologies, no grid parity is expected in the period 2011–2050.

3.4 Energy Payback, CO_2 Emissions and External Costs

The CO_2 produced by biomass energy technologies could be considered neutral from an accounting standpoint, since the employed biomass has previously captured CO_2 from the atmosphere. However, emissions from construction and

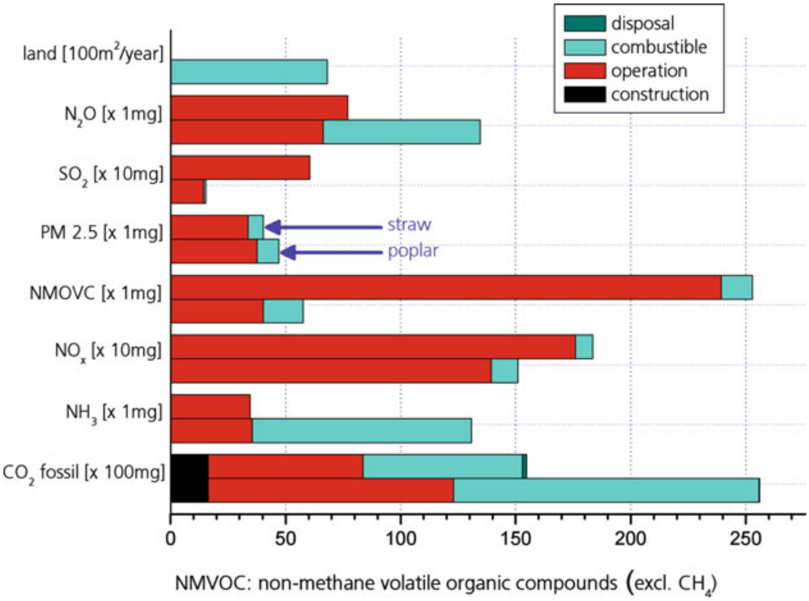


Fig. 3.9 Land emissions and land occupancy per kWh of energy produced in CHP plants [9]

decommissioning phases, as well as from biomass harvesting, treating and transporting must be also considered.

In this regard, the literature shows [9] that biomass from wood and crops burned in CHP plants (Fig. 3.9) demonstrates that CO_2 emissions are mainly originated on the biomass itself. Also, the amount of CO_2 emitted in the operation process is substantial and attributed mainly to the use of fertilisers and to transportation. In contrast, the emissions attributed to plant construction and decommissioning are under 10 % of the global emissions. Moreover, due to the production of fertilisers, large amounts of CO_2 are emitted but accompanied by ammonia and nitrogen oxide emissions.

It should be noted that this study considers that straw, as it is a residue, does neither occupy soil nor requires fertiliser for its production. In relation to transport, wood produces a larger amount of CO_2 from biomass because it has higher moisture content than the agriculture residue. In contrast, the differences in sulphur dioxide and nitrogen oxides emissions are more related to the specific composition of the biomass which, in this case, produces higher emissions than the derived from the straw. Finally, while the volume of fine particles (PM2.5) does not vary much between biomass species, production of volatile organic compounds other than methane depends on the combustion process itself.

On the other hand, although the results shown in Fig. 3.9 are for CHP technology, precise analysis will be required for the technology used since, for example, obtaining electricity from gasification emits less CO_2 than from combustion

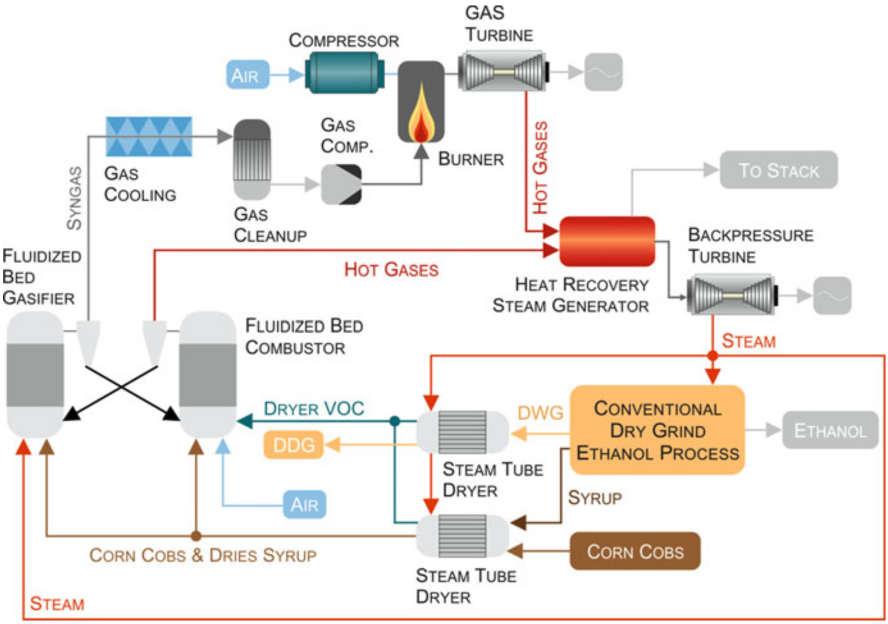


Fig. 3.10 Scheme of a BIGCC plant to produce heat and electricity from the biomass used in an ethanol production plant [15]

processes [4]. Other aspects to be considered for a detailed analysis may be related to the scale of the plant, co-products, compensating fertilisation and time at which the environmental impact occurs.

In a recent LCA study [10], different biomass plants for producing heat and/or power have been evaluated and compared with reference fossil energy systems likely to be displaced by the bioenergy system. In the cited case studies, bioenergy systems reduce GHG emissions by between 18 and 128 % compared to their counterpart fossil reference systems, but it is difficult to generalise (GHG emission reductions above 100 % mean that the involved process acts as GHG sink). Also, it is concluded that GHG mitigation is larger when biomass is used for heat and electricity applications rather than for liquid transport fuels.

Also, biomass energy production associated with the CCS technology (Chap. 17) can act as a negative CO_2 emitter, as biomass captures CO_2 from the atmosphere and is then stored. For this reason, it is expected that more rigorous studies will consider and even distinguish between different CCS technologies in the future.

Finally, the energy payback ratio using biomass as solid fuel is estimated to range between 4 and 16, while external costs are around USD 4.80 cents/kWh (EUR 3.45 cents/kWh) [11].

3.5 Future Technology Trends

3.5.1 Energy Crops

The general trend, towards the future, is on increasing biomass production for energy supply. This biomass will be mostly based on lignocellulosic crops, able to grow in poor soils and adverse climatic conditions. Lignocellulosic crops have also the advantage of requiring fewer amounts of fertilisers than food-oriented biomass.

Similarly to food crops, research on the selection of appropriate genotypes is also advancing on energy crops to enhance energy production per unit area and to minimise water requirements. The natural mission of trees and plants on Earth, after million years evolving, is their survival but not to serve as energy resources. Consequently, genetic engineering can be oriented to enhance the potential of some biomass species as energy resources. These genetic engineering activities for energy crops should be not so affected by environmental concern as for food crops. On the other hand, genetic engineering for enhancing energy potential of biomass is an alternative to the most common genetic activities, focused on achieving superior resistance to herbicides, pesticides and insects [4]. Thus, because of its interest, research in energy crops will increase because is still in the initial stages, and also due to lack of experience on crop plants genetically modified and introduced in forest, shrubs, bushes, grass, etc.

It is also necessary to study the parameters affecting the productivity of biomass, since it is susceptible to the volatility inherent to biological production (due to seasonal variations and weather conditions). Inadequate control of these parameters can produce significant variations in the quantity of production, quality and, consequently, price. Price volatility is evidently an important drawback that any renewable energy should avoid in order to compete against fossil fuels.

Finally, it is also necessary to study the effects of climate change on energy crops. In many areas where it is now adequate to cultivate specific energy crops, expected climate changes could also force a change in crop species to maintain energy production from biomass.

3.5.2 Cultivation Techniques

There is great interest to cultivate biomass in multi-functional locations. Thus, choosing optimal locations, design, management and integration of production systems, extra environmental services can be offered and thus have a higher added value to the production. Also, it is expected to recover marginal or degraded soils for energy crops. On the other hand, it is expected to improve productivity in developing countries, which may cover increases in demand for energy crops [4].

Research efforts are also on course to avoid stress in water resources or biodiversity loss associated to increasing production of energy crops. On the contrary, it is expected that these crops may help to improve conditions and fertility of degraded soils, preventing erosion, when the most suitable species for each zone are selected.

3.5.3 Harvesting, Storage and Transportation

Future trends are oriented to create standards for crops and also for new lignocellulosic energy crops to be perennial and, consequently, not generating inflationary pressures in the food industry, thus ensuring its permanent access to the market. Perennial lignocellulose would diminish biomass storage costs and degradation processes associated to stored biomass.

There is also the need to develop multi-product biorefineries, capable of increasing the added value of transforming the raw material. This strategy can reduce the power generation costs from biomass very substantially.

As it is known, biomass has a low energy density compared to fossil fuels and also high humidity (may reach 55 % in weight). Consequently, it is necessary to improve densification technologies (pellets, chipping, baling, bundling, pyrolysis and torrefaction). These densification technologies can reduce transportation costs significantly and increase production plant sizes [4], and therefore reduce infrastructure costs to produce energy from biomass per unit of energy produced. As it is known, increasing the size of the plants using biomass reduces costs but, on the other hand, increases biomass demands, also increasing transport costs (from increasingly distant places). Therefore, it is necessary to reach an optimal compromise between plant size and logistics to properly size the plant.

Storage techniques are also improving depending on the type of biomass, since the durability of the stock depends on the specific energy crop considered. In addition, low biomass humidity introduces self-ignition and self-heating risks. Consequently, it is recommended to avoid the storage and transportation of large volumes and mixing of different types of biomass.

In pellets, it is necessary to study alternative raw materials and processes to increase stability and abrasion resistance, to reduce the emission of dust in household manipulation [4] and to prevent the danger of off-gassing (primarily CO, CO_2 and CH_4) from pellets decomposition over time [8].

Regarding pyrolysis, it is especially important the stabilisation of the produced bio-oils, and to reduce their water content, corrosive nature, viscosity, as well as minimising the large number (over 300) of chemicals that compose them. In this sense, it is necessary to better understand the type of thermal reactions and the role of the catalysts for improving the processes related to bio-oils production. Also, the solid product of pyrolysis can be used in a co-firing process to provide energy to the proper pyrolysis.

Finally, for renewable municipal waste, it is necessary to improve the waste sorting processes to obtain competitive energy costs. Currently, the raw material is very heterogeneous and contaminated, requiring strict emission controls and robust technologies to obtain energy from this resource.

3.5.4 Combustion

An option that is being proposed is the conversion of CHP systems into trigeneration systems, also acting as cooling systems by applying absorption processes (Chap. 13). As the heating demand varies seasonally, the addition of cooling allows the heating demand to be more stable over the year and results in an increase of the profitability for the biomass conversion system. For electricity generation, smaller and less expensive CHP systems should be developed in order to enhance adaptability to local biomass resources.

Also, it is necessary to adapt combustion systems to specific industrial sectors, mainly in terms of temperatures reached, and the quality of the gas ejected from the combustion process. Moreover, it is necessary to improve the efficiency of organic Rankine cycles and Stirling engines. For the latter, it is estimated that the power conversion efficiency could reach up to 28 % in 150 kW engines. However, additional R&D activity is needed, as these processes are not mainly oriented to the production of power. Moreover, it is necessary to improve the reliability and costs of these processes.

Besides, new combustion boiler prototypes are demanded, offering higher efficiency, smaller size, allowing burning biomass other than wood (pruning waste, crop residues, etc.) and controlling emissions of polluting gases, especially NO_x. In this area, research modelling reactive boiling ejection of non-volatile compounds in the product stream (particularly those that enter the gas phase) should lead to better control over emissions.

For energy recovery from municipal waste, it is estimated that technological advances could increase process efficiency from 22 % to 28–30 % applying new generation power plants [4].

Other aspects that need improvement are the supply and storage of raw materials for the combustion process, as well as to avoid fluctuations in humidity and contamination by heavy metals. Humidity and biomass contamination from the combustion plant have a substantial impact on air pollution and corrosion.

3.5.5 Co-firing

At present, the proportion of biomass used in co-firing systems has reached about 10 %, but systems reaching up to 20 % are being tested. However, in this case, the resulting abundant ash should be conveniently treated, since it can be deposited on the burner and the catalyst, reducing the efficiency of the process. It is also necessary to consider how to mitigate the harm caused by the coal–biomass mix to the exhaust gas filtering systems. Also, co-firing systems that can be fed with different biomass species, specific heating temperatures and processing techniques are under research.

The electricity production efficiency usually achieved in co-firing is 20–25 % [12], but R&D activities are trying to increase it through several procedures.

One consists, for example, in improving the quality of the refractory materials of the furnace walls to increase heat insulation and, therefore, reaching higher gas temperatures. Also, the reactor design and processing of biomass is being modified to reach the most complete combustion possible. Efficiencies around 50 % have been reached by indirect co-firing processes in IGCC systems [4].

Finally, the co-firing accompanied by a previous pyrolysis of biomass could be an appropriate route for cost reduction, mainly in places where the biomass production is located at large distances from coal-fired power plants. Also, large fluidised bed supercritical boilers, with power generation efficiencies as high as 50 %, could be based on co-firing processes in the future [5].

3.5.6 Gasification

The economic viability of biomass gasification is not yet proven on a large scale, but there are currently several R&D programmes trying to advance on gas turbines powered by biomass. The most popular are the BIGCC systems. The interest in these systems surges from the fact that up to 85 % of energy from biomass is recovered in gasifiers by means of partial oxidation in oxygen or a water vapour environment. This fact, together with the use of combined cycle technology gives BIGCC a significant potential advantage over simple combustion.

A very important aspect being investigated is related to the elimination of pollutants generated by the treatment of biomass (particulate, ash, ammonia, sulphides, etc.). These pollutants cause corrosion and deposits on the turbine blades. Finally, BIGCC can be very interesting for the production of energy, both thermal and electrical, in ethanol production plants. Another option that is being tested is the use of the liquids produced in the gasification process to obtain liquid fuels and other materials, synthesised in biorefineries.

Another option consists in the synthesis of hydrogen from syngas for use in integrated fuel cells, with an estimated electric conversion efficiency of 50–55 % [4], but this technology requires further development effort (see Chap. 14). In addition, from syngas, methane-rich gas can be obtained, known as synthetic natural gas, or the syngas can be converted into a liquid fuel through a Fischer–Tropsch process (see Chap. 4).

Finally, it is necessary to study in more detail the moisture influence to the biomass gasification process and the optimisation of the cleaning processes of the reactors.

3.5.7 Anaerobic Digestion

The first objective for anaerobic digestion is to improve the biomass pretreatment to reduce fermentation times. Other objectives are (1) reducing costs, (2) increasing reliability of the technology and (3) improving the cleanliness of the biogas (especially the very corrosive H_2S). These improvements can be reached by ultrasound treatments or enzymatic reactions, currently in the R&D phase.

Other technology trends are related to the improvement of both the pretreatment processes and the selection of raw materials. The objective of this selection is to remove contaminants and to transform the digestate produced in anaerobic digestion into a nutrient for various applications. This strategy could be less expensive than cleaning the polluted digestate inside the anaerobic digestion system.

Improving biogas recovery from the anaerobic digestion of organic municipal waste is also a main research area. The technology trends are focused on reducing emissions of greenhouse gases, primarily methane, as it is much more harmful than CO_2 in causing greenhouse effects.

Finally, several research groups are very active in the direct production of hydrogen based on the anaerobic digestion of biomass in the so-called microbial fuel cells [4]. The hydrogen synthesis process has already been achieved, but demonstration plants are needed to further test this technology (see Chap. 5).

3.6 Pre-production Highlights 2009–2011

3.6.1 The World Largest Biomass Power Plant [13]

The largest power plant powered by biomass will be located in Port Talbot (Wales). With a capacity of 350 MW, it will be able to provide electricity to nearly half a million homes. The plant, designed by Preenergy Power has required an investment of EUR 650 million, and construction work is not expected to start before the end of 2011. The plant will be powered by wood chips imported from USA. The biomass plant in Wales is expected to reduce CO_2 emissions to a fifth of the emissions from a conventional coal plant. The British Environment Agency has asked the company certificates to ensure that all biomass used should come from renewable resources. Some concern about air quality and health risks are expressed by opponents.

3.6.2 New Strategies to Increase Biogas Production from Wastewater [14]

The company GENeco, a subsidiary of the British company Wessex Waters, instead of managing manure wastewater at room temperature, heats it for a few days at 40 °C and then transfers the fermented liquid to a second tank with a temperature 5 °C cooler. Then, at each stage, different bacteria can act more efficiently, thus increasing by 30 % the production of methane. In addition, there are other options emerging from different research centres such as (1) mixed pumping to accelerate the separation of methane and the movement of bacteria and (2) the use of ultrasounds for a more effective decomposition of waste. These strategies increase the methane production by about 13 %, although in the latter case the energy balance is still negative.

3.7 Innovation Highlights 2009–2011

3.7.1 BIGCC to Produce Electricity and Heat in Ethanol Plants [15]

Scientists at the University of Minnesota (USA) have experimentally demonstrated that the BIGCC technology can be used to generate heat and electricity at very low costs in ethanol production plants. These plants use corn cobs to generate syngas in a gasification process (Fig. 3.10). It has been found that an ethanol plant producing 190 million litres annually is able to continuously generate power by about 30 MW. The energy generated is used for the production of ethanol, resulting about three times cheaper than conventional ethanol produced from natural gas.

3.7.2 Electricity Production from Anaerobic Digestion in Microbial Fuel Cells [16]

Specific anaerobic bacteria can generate electricity by means of so-called microbial fuel cells following a procedure analogous to the anaerobic digestion described in Sect. 3.2.7. Scientists at the Center for Nanotechnology at the University of Cornell have developed fuel cells made by silicon microelectronics lithography and based on this technology. At the anode of the battery, the biofuels are placed (organic waste, carbohydrates, manure, etc.) and they are oxidised anaerobically by micro-organisms, producing protons and electrons. Then, the electrons are transferred to the cathode through an external circuit generating an electric current. Among the bacteria that show a higher electrochemical activity are the *Shewanella putrefaciens* and the *Aeromonas hydrophila*.

3.7.3 Using Charcoal Production to Store CO_2 and Produce Heat [17]

The use of charcoal in rural areas was discussed at the 2009 meeting of the North American Biochar Conference. In this meeting, advantages were provided about using the pyrolysis process to meta-stabilise the CO_2 fixed during the growth of different plant species as charcoal in agricultural areas. This process may introduce many advantages such as: (1) carbon capture and storage; (2) crop production improvement by buried charcoal and (3) production of heat, syngas and heavy oils that can be considered as energy resources. In addition, soils containing

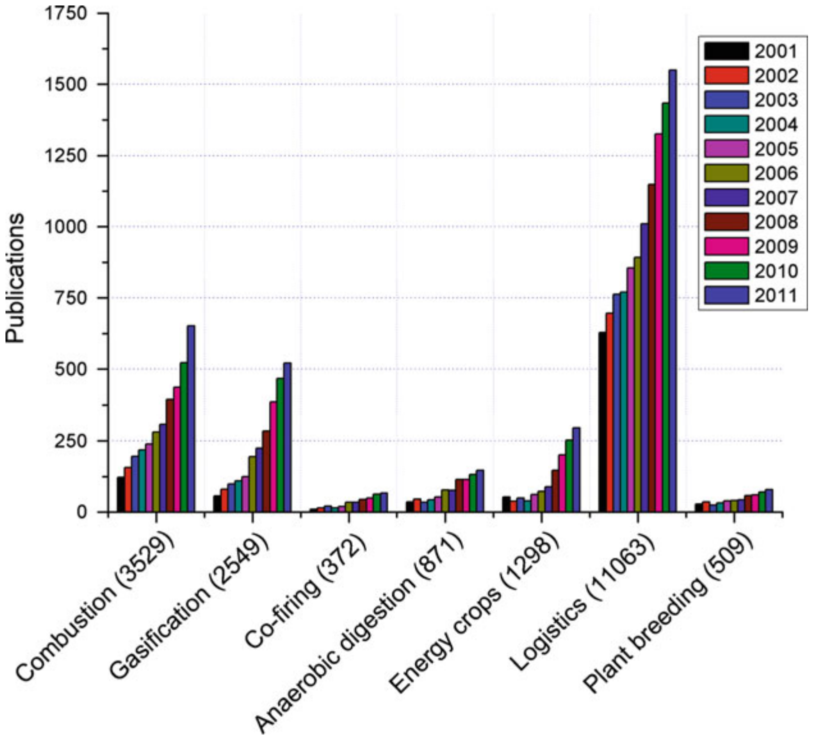


Fig. 3.11 Number of scientific publications during the period 2001–2011 for different technologies involved in energy production from biomass [18]

charcoal emit less nitrogen oxide and methane (a potent greenhouse gas) because of its catalytic properties for these gases, thus reducing their impact on climate change. It is estimated that through this process up to 20 % of CO_2 emissions could be avoided, although the calculation models still require some adjustments. However, some problems could arise if this technology induces deforestation to produce biomass to be later converted into charcoal.

3.8 Statistics of Publications and Patents

Figure 3.11 shows the number of scientific publications during the period 2001–2011 for different types of technologies involved in energy production from biomass [18].

According to Fig. 3.11, it is found that the main research activity is on logistics, i.e., related to the harvesting, storage and transportation of biomass. This can be interpreted as a consequence of the need to reduce costs and CO_2 emissions in the process related to energy production from biomass. Research areas corresponding to energy crop species are also rising in activity, but they are far below logistics.

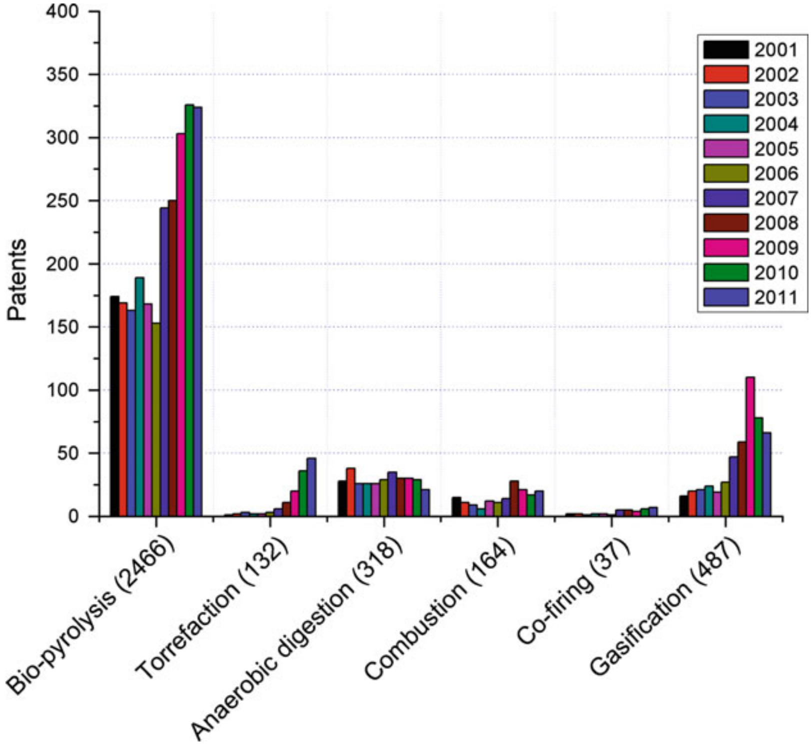


Fig. 3.12 Number of patents during the period 2001–2011 for different technologies involved in energy production from biomass [19]

Research activity related to farming techniques is also rising, but the number of publications is low compared to logistics and crops.

In relation to energy production technologies, the largest activity is detected in combustion processes, but the gasification technology is also rapidly growing. These results are attributed to the central role that BIGCC systems are expected to play in the future. Anaerobic digestion lies not only far below combustion and gasification but also with an upward trend. Finally, research activity in co-firing is the lowest and attributed to its lack of attractiveness as it combines biomass and coal combustion. Co-firing cannot be considered a clean energy technology and is not attractive for future energy models trying to mitigate the emission of GHG.

In relation to the evolution of biomass technology patents [19], our analysis has been focussed on technologies for the increase of energy density of biomass, and those to produce energy from biomass. This is because we consider that patents related to logistics, crops and farming techniques are more extensive and not only related to energy production from biomass.

From Fig. 3.12, it can be observed that the main area for patent production related to energy densification is bio-pyrolysis. In our opinion, this is due to the fact that the pyrolysis process is rich in products, as exposed above, offering large opportunities for manufacturing activities in biorefineries. Other processes, such as torrefaction and pelletisation, are very specific and oriented.

In relation to energy production from biomass, the main area for patent production is the gasification technology. We attribute this result to the expectation derived from the introduction of BIGCC systems to produce energy. This expectation also may be influencing the development of anaerobic digestion, as the second energy production technology from biomass in number of patents. On the third place is combustion, as this is a more mature technology. Finally, patent activity in co-firing is very low, and this is also attributed to its lack of attractiveness as explained above.

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Chapter 4
Biofuels

Abstract The production of liquid biofuels from biomass stocks for the substitution of crude oil products (gasoline, diesel, etc.) in the transportation sector is one of the main objectives of bioenergy research. One of the main advantages of using biofuels is that, if one considers their complete life cycle, their carbon emissions can be substantially lower than in the case of fossil fuels. In this chapter, we describe all biofuel technologies and prospects. Thus, bioethanol and biodiesel that are usually produced from agricultural crops may have reached economic viability, but they also compete against food production elevating their prices. For this reason, second-generation biofuels are currently being developed which use lignocellulosic biomass (straw, grass, forestry sawdust, etc.) and therefore do not compete for agricultural land and water. In addition, we also treat in this chapter the so-called third-generation biofuels, like those obtained from microalgae, which offer excellent prospects for the production of biodiesel due to their high concentration in lipids. Besides, microalgae do not compete for large freshwater resources and can act as CO_2 sinks during their growth. Hydrogen obtained from biomass can be considered another third-generation biofuel, but it is described in Chap. 5.

4.1 Overview

Liquid biofuels, simply called biofuels, are produced from biomass through chemical and biological processes. Liquid biofuels are mainly bioethanol and biodiesel, which are chiefly used in transportation and in the chemical industry. Due to the importance of biofuels as a real alternative to fossil fuels, mainly in the transportation sector, a full chapter is devoted to them in this book.

Following the recommendations of the IEA, biofuels can be classified in the following categories:

- First-generation biofuels: Are those that have reached a stage of commercial production. In general, they are obtained from crops grown following similar

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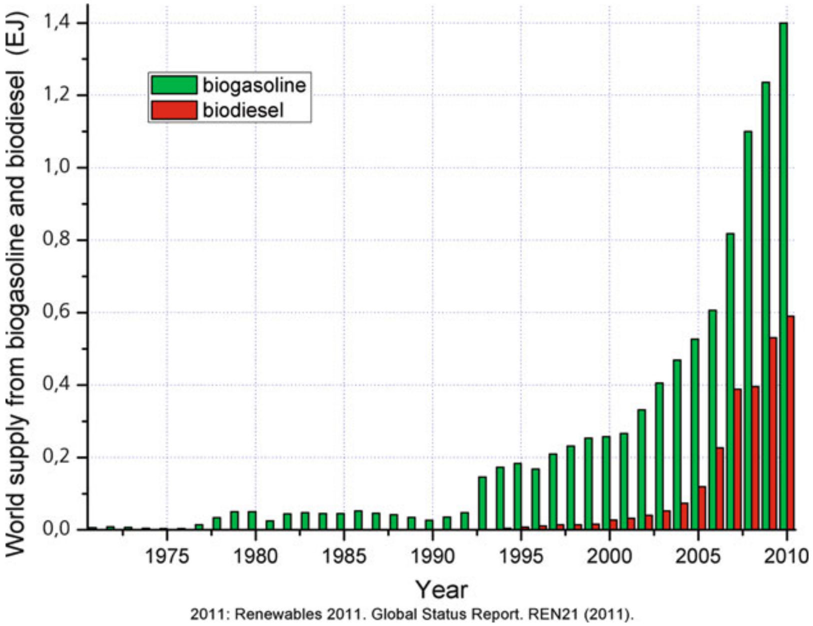

Fig. 4.1 Evolution of the production of biogasoline and biodiesel in the period 1971–2010 [1]

techniques to food crops and, consequently, compete with them for agricultural land.

- Second-generation biofuels: They do not compete for agricultural land, since they are obtained from lignocellulosic biomass such as straw, grass, stems, stalks, roots, wood, shells, etc.
- Third-generation biofuels: They mainly consist in oils from algae and hydrogen from biomass. They are still at an early stage of development and far from large-scale production. Therefore, it is not expected to reach large production in the short term.

According to the latest data available from the IEA, in 2009, biofuels supplied an energy of 1.23 EJ in the case of biogasoline and 0.53 EJ in the form of biodiesel, showing a clear upward trend since the mid-1990s (Fig. 4.1). Practically, all the energy supplied is attributable to the so-called first-generation biofuels, which in 2009 represented 0.34 % of the primary energy supplied worldwide.

The definition of biogasoline (IEA) includes bioethanol, biomethanol, bio-ETBE (ethyl tertiary butyl ether from bioethanol; the percentage by volume of bio-ETBE that is considered biofuel is 47 %) and bio-MTBE (methyl tertiary butyl ether produced from biomethanol; the percentage by volume of bio-MTBE that is considered biofuel is 36 %). The term biogasoline includes the amounts of bioethanol that are blended into gasoline but does not include the total volume of gasoline mixed.

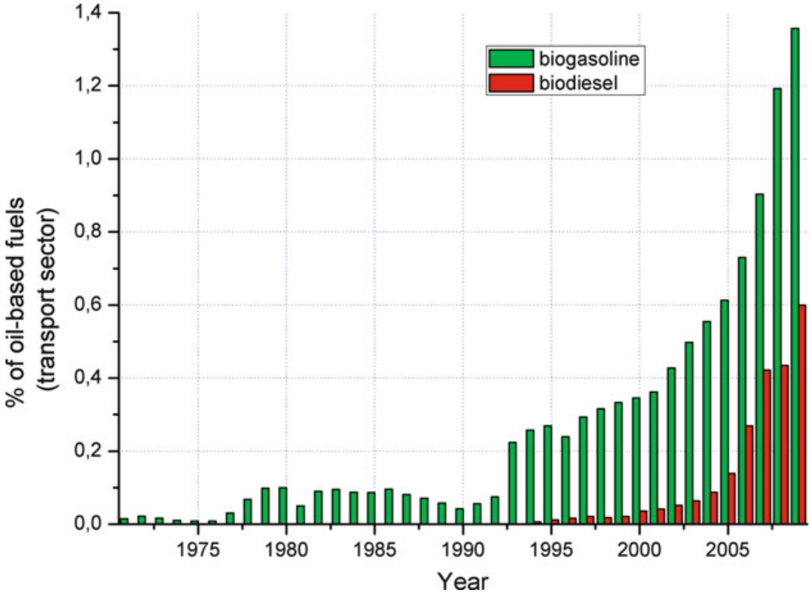

Fig. 4.2 Evolution of the percentage of biogasoline and biodiesel used in the transportation sector in relation to the total oil used for this purpose in the period 1971–2009 [1]

The definition (IEA) of biodiesel includes the biodiesel itself, dimethyl ether, Fischer Tropsch, cold pressed bio-oil (oil produced from seeds using only mechanical processes) and any liquid biofuel added, mixed or used directly as diesel fuel for transport. Biodiesel includes the amounts of biodiesel that are mixed in diesel fuel but does not include the total volume of diesel blended.

According to the same official data (2009) provided by the IEA, near 100 % of the produced biogasoline and biodiesel was consumed in the transportation sector. However, the percentage of biogasoline consumed in the transportation sector was only a 1.36 % of the total oil consumed, and the percentage of biodiesel reached a 0.60 % (Fig. 4.2). Consequently, the use of biogasoline and biodiesel for generating electricity and heat is still very small.

4.2 State of the Art

4.2.1 First-Generation Bioethanol

First-generation bioethanol (C_2H_5OH) can be produced naturally by fermentation of sugars by certain microorganisms under acidic conditions (pH between 4 and 5). The most common microorganism used is yeast (*Saccharomyces cerevisiae*). Yeast has the disadvantage of contaminating the ethanol in concentrations above 10 %.

Table 4.1 First-generation bioethanol average production yield for various biomass species [4] (lge: litres of gasoline-equivalent)

Feedstock	Region	lge/ha
Sugar cane	Brazil	4,490
Sugar cane	World average	3,630
Sugar beat	Europe	3,300
Corn	North America	1,980
Wheat	Europe	1,650

Consequently, to obtain near pure ethanol concentrations (95 %), a series of distillations and fractionations of chemical compounds are required.

Generally, bioethanol is produced from sugar cane molasses, being the conversion of saccharose into ethanol the most important chemical reaction, with an approximate 80 % efficiency [2]:

$$4C_2H_5OH \rightarrow 4CO_2 + C_{12}H_{22}O_{11}$$

The energy contents of the distillate is not very high, about 30 GJ/t [3] (the oil is 42 GJ/t). For this reason, the overall balance of ethanol production is negative, unless the use of bagasse is considered for heating during the production process. In addition, the residue of the fermentation can be washed and dried to add value to the process, commercialising it as fertiliser or feed.

The IEA [4] has estimated the production yield for first-generation bioethanol in units of litres of gasoline equivalent per hectare. The results are presented in Table 4.1 as average values of the yields for various geographic regions.

The highest yield per hectare corresponds to bioethanol obtained from sugar cane. In European mid-latitudes, ethanol can be obtained from sugar beet, but the heat needed to provide for fractional distillation is much more difficult to obtain from the residue than in the case of sugar cane.

Bioethanol can be directly used in some specific internal combustion engines (flex vehicles). Blended at required percentages with fossil fuel, the mixture obtained is called "gasohol", which can be used directly in standard internal combustion engines. For example, E10 gasohol means that the proportion of bioethanol is 10 % with respect to gasoline. The blended percentage currently is in the range 10–15 %, except in some countries, mainly Brazil, where the E85 is a commercial standard for flex vehicles.

Although the energy per unit volume of ethanol is only 67 % of that provided by gasoline, the enhanced burning properties of bioethanol, together with its low proportions in the gasohol, result in near similar litres spent per kilometre of gasohol and unleaded gasoline in standard vehicles [2].

4.2.2 First-Generation Biodiesel

First-generation biodiesel can be obtained from vegetable oils from oilseed plants, like a variety of soybean, rapeseed, sunflower, palm, etc. The energy content is

Table 4.2 Yields in the production of biodiesel from various biomass species and geographic regions [4] (lde: litres of diesel-equivalent)

Feedstock	Region	lde/ha
Rapeseed (FAME)	Europe	1,080
Soybean/oilseed rape (FAME)	USA	720
Oilseed rape (FAME)	Brazil	630
Lignocellulosic	World	3,000
Microalgae lipids	World	11,863 (lge)

about 36–40 GJ/t, 90 % of the energy contents of diesel (42 GJ/t), and above that of bioethanol [4].

Biodiesel may be burned directly in diesel engines, but its continued use may cause engine damage because of its incomplete combustion and high viscosity. To lower their viscosity, oils are submitted to hydrolysis, producing fatty acids and glycerin. Subsequently, the fatty acids are subjected to transesterification with methanol, which yields the less viscous methyl esters, with improved combustion properties in the engines.

For the production of 1 MJ of biodiesel from soybeans and methanol, 0.3 MJ of fossil fuels are currently required, mainly for the production of the methanol. Therefore, it is convenient to adapt the production process to obtain also methanol from the biomass. Thereby, carbon emissions from biodiesel production would be reduced.

Table 4.2 presents the data for biodiesel yield in units of litres diesel-equivalent per hectare, corresponding to various geographic regions and average values. For a further comparison, data of second-generation biodiesel from lignocellulosic biomass [4] and lipids from marine algae are also presented [5].

4.2.3 Lignocellulosic Bioethanol (Second Generation)

The objective of second-generation bioethanol is to extract the raw material (sugars) from cellulosic biomass instead of food-oriented agriculture, contrary to first-generation bioethanol. Thus, biomass production is more sustainable, abundant, cheap and does not directly compete with food crops. Examples of cellulosic biomass suitable for first-generation bioethanol would be stalks of many plants, herbs, wood, roots, straw, etc.

Cellulosic biomass is mainly composed of cellulose and hemicellulose molecules consisting of several tightly bound sugars and lignin, a phenyl propene compound that acts as adhesive material between the sugar chains.

The conversion of lignocellulosic biomass into bioethanol requires the following steps [6]:

1. Obtaining lignocellulosic biomass (crops/waste).
2. Pretreatment to separate the biomass into cellulose, hemicellulose and lignin.
3. Hydrolysis of cellulose and hemicellulose to produce sugars. This step may be chemical (for example, by acid hydrolysis) or biological (using an enzyme called

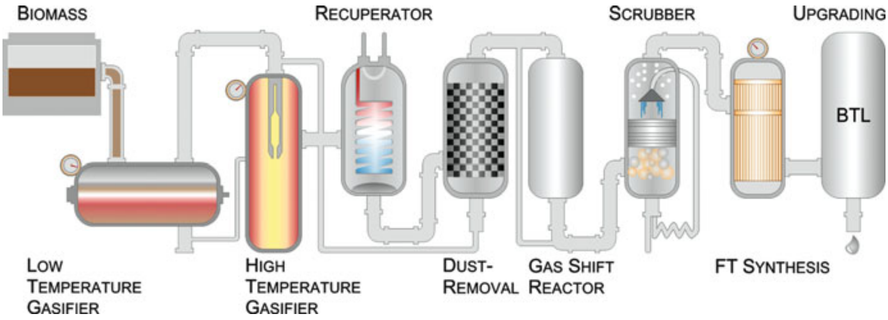

Fig. 4.3 Typical BtL process to produce second-generation biodiesel [7]

cellulase). Acid hydrolysis is a well-established technology and currently very close to commercialisation. Enzymatic hydrolysis is already very close to its mass marketing, but still research in alternative enzymes is on course, as well as on various fungi and bacteria genetically modified to ferment all biomass sugars.

4. Fermentation of sugars to produce alcohol.
5. Separation of ethanol from the co-products of fermentation.

4.2.4 *Second-Generation Biodiesel*

Second-generation biodiesel is also known as synthetic biodiesel or advanced biodiesel. It is a liquid biofuel obtained from lignocellulosic biomass through various thermochemical processes. The most widely used of these processes is known by the acronym BtL (Biomass-to-Liquids). The BtL biodiesel can be obtained from any type of biomass, especially lignocellulose with low moisture content.

A typical process to obtain BtL biodiesel is shown in Fig. 4.3 [7]. In the first stage of the process, the biomass is gasified (see Chap. 3). Then, a gas purification stage is performed in order to remove tars, particles and small amounts of pollutant gases. Thereby, a syngas with appropriate hydrogen and carbon monoxide proportions is obtained.

The main catalytic procedure for syngas conversion into liquid biofuel is the Fischer–Tropsch process. In this process, the mixture of hydrogen and carbon monoxide is carried out at high pressures and temperatures and converted into various types of liquid and gaseous hydrocarbons by the reaction:

$$(2n+1)\mathrm{H}_2 + n(\mathrm{CO}) \rightarrow \mathrm{C}_n\mathrm{H}_{(2_n+2)} + n\mathrm{H}_2\mathrm{O}$$

The most commonly used catalysts for this reaction are iron and cobalt. The gases produced in the reaction can be recycled or used for heating, while the liquids are refined to produce biodiesel suitable for use in vehicles.

The BtL biodiesel can be used directly in engines or blended (as in the case of bioethanol) with diesel obtained from fossil fuels. It is interesting to consider that for BtL biodiesel synthesis, the whole plants are used and not only seeds. Therefore, only reduced amounts of land areas are required to produce BtL compared to first-generation biodiesel. It is therefore expected that when large-scale commercialisation is achieved, both BtL production costs and GHG emissions will be substantially reduced.

4.2.5 Hydrogen from Biomass (Third Generation)

This topic is treated in the gasification and fermentation sections in Chap. 5.

4.2.6 Biodiesel from Microalgae (Third Generation)

Algae can be divided in a first approximation into two distinct groups: macroalgae and microalgae. From macroalgae, a series of products including food, vitamins, pharmaceuticals, etc., are obtained. Obviously, also biofuels could be obtained, but currently the low margins associated to biofuels compared to the traditional products obtained from macroalgae do not recommend increasing the activity related to the energy area. Microalgae can offer improved prospects, due to their high concentration of lipids, for the production of biodiesel and other biofuels.

Currently, a large number of companies and government agencies are doing research on production of biofuels from microalgae. Yield production studies of algal culture pilot plants conclude that in few decades enough biodiesel could replace much of the fossil diesel demands. An important advantage of algae cultivation is that does neither directly compete for purely agricultural land nor for large freshwater resources, because many algae species can grow in sea water, high salinity water and even wastewater [4].

Microalgae are very attractive as raw material for energy production because of their much higher growth rates than agricultural crops. This is due to several factors, including easy adaption to different water types and to the dissolved nutrients in it, CO_2 capture and access to sun radiation. Microalgae farming has been also proposed as a novel technology for carbon capture and sequestration since adding CO_2 to microalgae greatly improves the growth rate. On the other hand, microalgae lipid concentrations can reach up to 60 % and the potential yield per hectare can be up to 10–20 times higher than conventional crops [8]. In this respect, studies show typical yields for microalgae lipids reaching 11,863 l/ha-year [5]. These yield values are much higher than those projected for biofuels obtained from agriculture crops (Tables 4.1 and 4.2) due to the fact that microalgae crops can be harvested every few days.

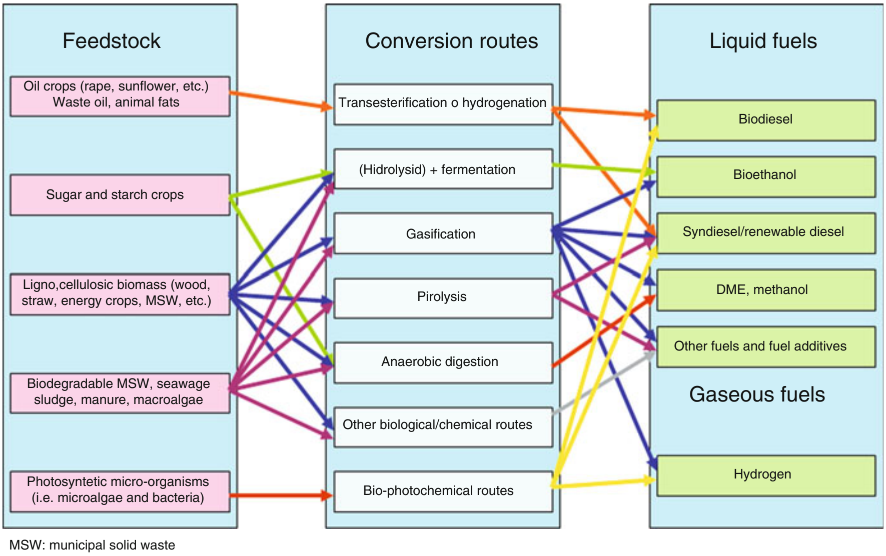

Fig. 4.4 Scheme of the different conversion routes for the production of hydrogen and liquid biofuels from biomass

Microalgae can be grown in two different systems, called open and closed. Open systems are usually ponds, which have the disadvantage that the more oily algae, which are not the quickest growing, may be invaded or contaminated by other algae species.

Alternatively, closed systems or photobioreactors provide a controlled environment for the cultivation of microalgae. In photobioreactors, the strict control of species cultivated, as well as the most suitable conditions for growth, are achieved, thus increasing substantially crop yields. However, the use of photobioreactors generally implies higher production costs. These costs may be reduced if the photobioreactors are placed near industries that emit large amounts of CO_2. Consequently, value can be added to the process from carbon sequestration, which induces a faster microalgae growth.

In addition, production of ethanol through algae photosynthesis is being tested. In this process, enzymes are introduced to directly synthesise this biofuel.

From the consideration of the above technologies, Fig. 4.4 shows a schematic overview of the feedstock, the conversion routes and the types of biofuels that can be derived through the different processes.

At this stage, it is also appropriate to provide information on the water resource footprint (WF) for the production of biofuels [9]. For this purpose, green water (rainwater) and blue water (surface water or ground irrigation) can be distinguished. The WF largely depends on the country analysed as well as the production process employed. The WF related to electricity production would be lower than that in biofuel production if the residual heat is invested in the process. Moreover, the results show that the WF values are lower for bioethanol production than for biodiesel (Fig. 4.5).

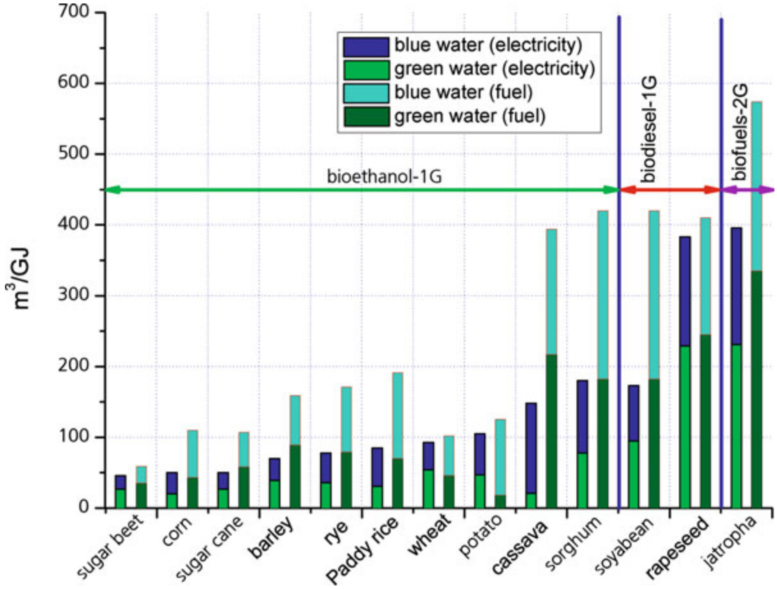

Fig. 4.5 Water footprint for various crop species for the production of electricity and biofuels

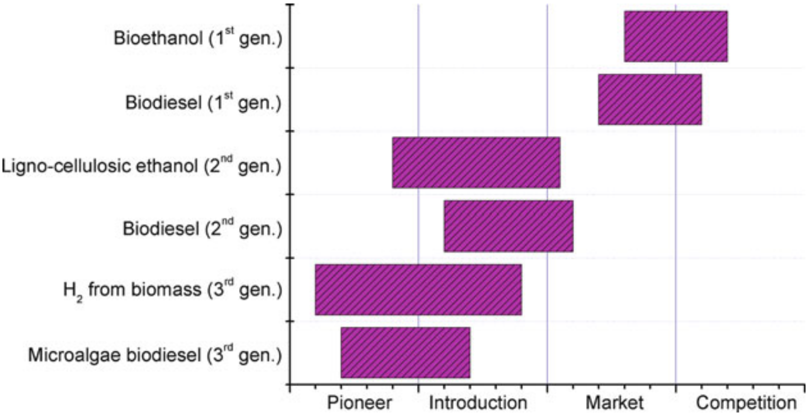

Fig. 4.6 Development stages for the different biofuel technologies exposed in this chapter

4.2.7 Stages of Development

Depending on market penetration, the different technologies that are driving biofuels into the energy sector can be classified in different stages of development (Fig. 4.6).

Thus, we can consider that first-generation biofuels are already in the competition stage. However, there are still production subsidies in many countries and, consequently, this technology can be also considered in the market stage. In addition, considering the cost evolution exposed below and adaptation of internal combustion engines to biofuels, first-generation bioethanol technology can be considered in a more advanced position than biodiesel.

For second-generation biofuels, the opposite situation must be considered, as biodiesel is in a more advanced position compared to bioethanol. Thus, the BtL Fischer–Tropsch process is known from the Second World War, although is still far from being competitive. Both, bioethanol and biodiesel obtained from lignocellulosic biomass, are entering the market stage, but still basic research is needed to design a competitive process adapted to commercial production plants.

Finally, the less market developed biofuel technologies are those related to the production of biodiesel from microalgae and the production of hydrogen from biomass. It is considered that, in the case of hydrogen more R&D activity is needed than for microalgae. However, currently, hydrogen produced from biomass is closer to the market than biodiesel from microalgae.

4.3 Current Costs and Future Scenarios

Biofuel production costs vary considerably in relation to the feedstock used, the efficiency and complexity of the production plant, the oil price, as well as the number of hours the plant operates per year. In the long term, substantial cost reductions are expected, mainly for second-generation biofuels. For first-generation biofuels, the rise and volatility in feedstock prices (Fig. 4.7) is a matter of concern, as they greatly influence the final production costs of biofuels. The instabilities in biofuel prices, typical of fossil fuels, are undesired.

In this section, we will consider production costs for the different technologies that commercialise biofuels or are close to market introduction (Fig. 4.8). However, we will focus mainly on production costs of lignocellulosic biofuels, considering that they are the main option for future biofuel production.

Thus, according to recent studies, the investment cost for a lignocellulosic biofuel plant with a production range of 50–150 Ml/year is about USD 131–262 million (EUR 94–189 million), up to ten times higher than the cost of a first-generation biodiesel production plant [12]. On the other hand, biomass feedstock price varies widely depending on the market of each country. For conventional biofuels, the main cost factor is feedstock, which accounts for 45–70 % of total production costs. For advanced biofuels, the main factor is related to capital investment costs (35–50 %), followed by feedstock (25–40 %) [13].

According to the above statements, production costs for second-generation biofuels are largely affected by the investment costs (Table 4.3) and also by feedstock costs [10]. In the long run, the investment percentage is expected to decrease (as technology matures) and, consequently, the percentage devoted to feedstock will proportionally increase.

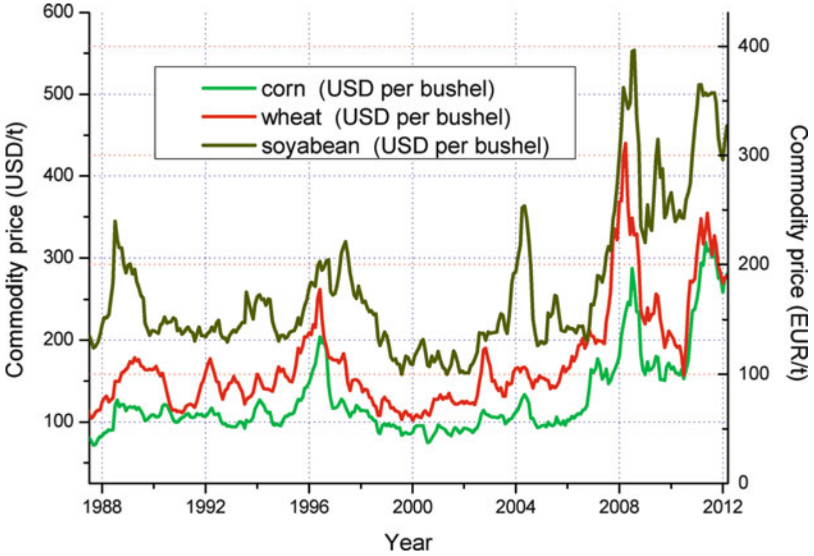

Fig. 4.7 Monthly commodity price for typical feedstock demand (corn, wheat and soyabean) for first-generation biofuel production (source: USDA Market News)

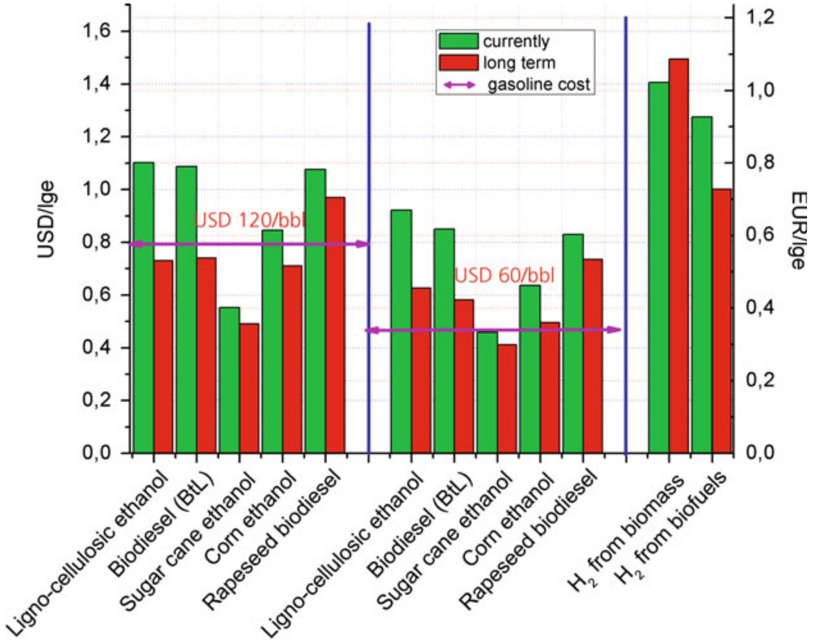

Fig. 4.8 Evolution of the production costs of biofuels and hydrogen from biomass considering different species of biomass and processes [10, 11]

Table 4.3 Production costs disclosure (%) for second-generation biofuels.

%	Lignocellulosic bioethanol	Biodiesel BtL
Capital	42	49–51
Feedstock	38–42	33–35
Other costs	16–20	14–18

On the other hand, it is not yet known when second-generation biofuels will be commercially competitive, but the IEA in its WEO 2009—450 scenario expects that it will be around 2015 [10, 13].

For third-generation biofuels, hydrogen production and distribution costs are estimated around USD 1.41/lge (EUR 1.01/lge) when obtained from gasification of biomass in centralised systems, and around USD 1.28/lge (EUR 0.92/lge) for hydrogen obtained from first-generation biofuels in decentralised plants [11].

For microalgae biofuels, no official data on costs have been found. However, initial studies [14] indicate that at present these costs are very high, considering that current technology would not be competitive with oil bbl prices even in the range of 100–200 USD [5]. Production cost estimates for the raw oil vary between USD 0.75/l (EUR 0.54/l) to more than USD 5.00/l (EUR 3.59/l), excluding costs for conversion to biofuel [15]. For this reason, different strategies are on course to reduce microalgae-based biofuel costs, mainly by adding valuable co-products (animal feed, chemicals, pigments, etc.). However, the current approximate values for these co-products may diminish strongly if the production of algae for biofuels increases substantially. The overall microalgae market was around EUR 1.34 billion (USD 1.86 billion) in 2008, implying an average price of EUR 267/kg (USD 372/kg) [16]. In contrast, palm oil (biodiesel generation) production reached 40 million tons with a market price of EUR 0.50/kg (USD 0.68/kg) [17]. However, economically feasible production of algae-derived biofuels and other new biofuels obtained by novel routes are expected for 2020–2030 [13].

Finally, it is considered appropriate to analyse the evolution of biofuel prices in the futures market and compare them with the competing fossil fuels prices. The comparison has been made after balancing their different calorific values. Thus, in different occasions, mainly when oil prices reach record highs (Fig. 4.9a), the price of ethanol and gasoline in the futures market overlap. For biodiesel (Fig. 4.9b), available data show that the price differential with gasoil remains higher than the average differential for bioethanol/gasoline and far from overlap at any time.

4.4 Energy Payback, CO_2 Emissions and External Costs

In relation to the emission of greenhouse gases as a function of the energy contents of the biofuels, Fig. 4.10 shows a summary of several studies by different authors and organisations [10] for first- and second-generation biofuels. Thus, the majority of biofuels currently produced do not involve large reductions in greenhouse gas emissions. Even in some cases, a slight increase in biofuel GHG emissions occurs

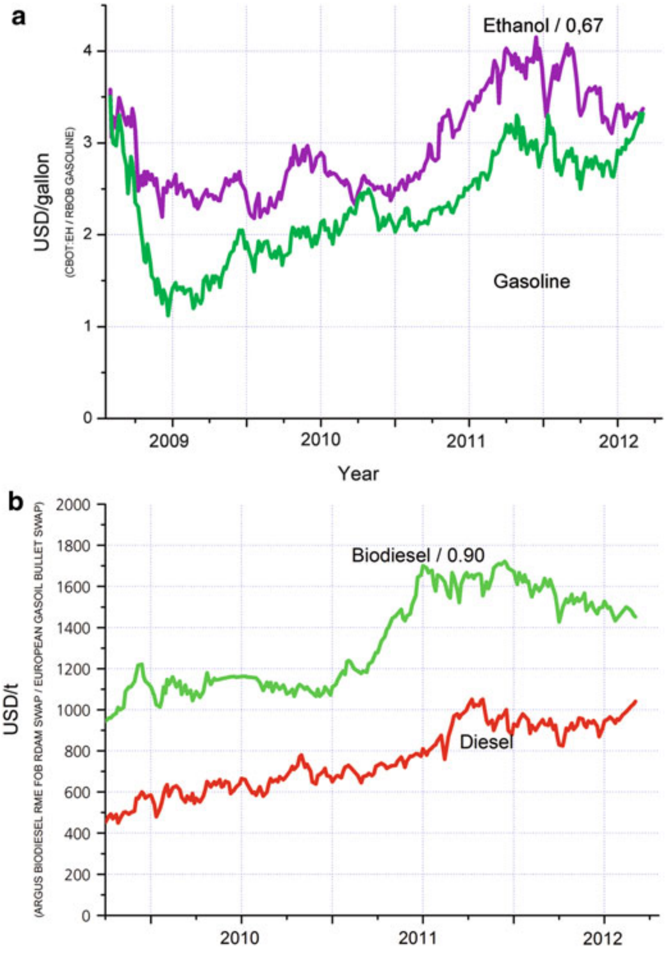

Fig. 4.9 Price evolution for different fuels in the futures market (balancing the difference in calorific values): (**a**) ethanol compared to gasoline and (**b**) biodiesel compared to diesel (source: INO)

when compared to competing fossil fuels. However, second-generation biofuels are able to avoid large GHG emissions, although these studies have been carried out in pilot plants and need to be confirmed in commercial plants. The GHG emission reductions over 100 % in Fig. 4.10 are attributed to arise from the benefits of co-products obtained during the processes of biofuel production and to also involving CCS in the process.

Moreover, for second-generation biofuels, since they exploit the entire plant residues from agriculture or forestry resources and fertilisers are not used, CO_2 emissions are largely reduced.

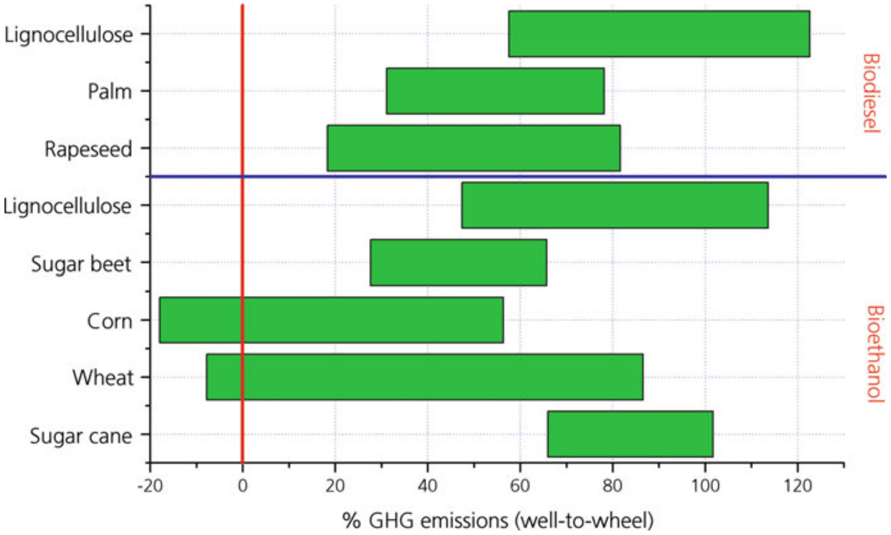

Fig. 4.10 Percentage of CO_2 well-to-wheel emissions avoided for different feedstock species for the production of bioethanol and biodiesel [10]

On the other hand, a distinction should be made between secondary lignocellulosic residues (rice husk, sugar cane bagasse, etc.), often considered as waste, and primary lignocellulosic residues (corn stalks, rice straw, leaves trees, etc.). These primary residues are often left over the soil to nourish it. Consequently, as a balance of nutrients in the soil is required, it will be necessary to consider an additional cost that should be adequately assessed.

In addition, we note that there is still no consensus on how to account for emissions of greenhouse gases, although some governments are defining official values for the different feedstock species [10]. Thus, the European Union has published its own official values in the Directive 2009/28/EC devoted to the use of energy from renewable sources. The debate is particularly intense in relation to the indirect effects due to an strong increase in the production of biofuels, especially arising from what is known as the indirect land use change (iLUC factor). This factor refers to the indirect destruction of forest to be devoted to agricultural production, as increasing agriculture land is required for feedstock production. These indirect effects are difficult to identify and evaluate [18] but obviously attenuate the impact on reducing the GHG emissions listed in Fig. 4.10. Also, the European Union has issued several communications specifying how to estimate GHG emissions for biofuels traded within its territory.

From a fundamental research analysis, studies based on partial equilibrium models indicate that the effects accounted by the iLUC factor (like in the case of corn produced in the USA) are substantial. These studies consider as more plausible the use of plant residues for the production of biofuels [16]. Other studies indicate that although the iLUC factor is important in relation to carbon emissions (doubling direct use emissions), the expected increase in fertiliser use will cause nitrous oxide emissions to be more important than carbon in terms of global warming, and therefore recommend improving the practices in the use of nitrogen fertilisers [17]. There are also more specific studies [10, 19] that, for example, consider that if "cerrado" vegetation is cleared ("cerrado" is a name for a type of vegetation that occupies large areas of Brazil) and replaced by sugar cane, it would produce CO_2 emissions equivalent to 165 t/ha, which would make sugar cane to take about 17 years to compensate the amount of CO_2 previously emitted. However, other studies [10, 20, 21] describe these approaches as based on exaggerated or not correct methodologies, which implies the need to reach an agreement on the methodology and be accepted by institutions and governments.

In relation to microalgae, no detailed studies have been found about emissions, although in a recent scientific meeting, it was estimated a reduction in CO_2 emissions reaching 25–75 % compared to oil [14].

As for energy paybacks for biofuels, very few studies have been reported. Some studies include addressing specific crops in specific geographic areas. For example, for ethanol from wheat in Sweden [22], a 1.18 payback ratio is achieved if no commercialisation of co-products is considered, and 1.28 if commercialisation of co-products is considered (for animal feeding).

No official or rigorous studies related to external costs of biofuels have been found.

4.5 Future Technology Trends

In general, the major research efforts are being dedicated to biofuels produced from lignocellulosic biomass (second-generation biofuels), as this feedstock does not compete directly for land with food agricultural crops. Simultaneously, much effort is focused on the development of third-generation biofuels due their expected large contribution in the long term.

4.5.1 First-Generation Bioethanol

This technology is relatively well established and, consequently, the research in this area is mainly aimed at improving the efficiencies of the chemical and biological processes involved. In this sense, research is primarily devoted to the design of improved enzymes to convert starch into sugars by hydrolysis. Also, bacteria are redesigned for improving fermentation processes, fractioning and distillation for water separation. Finally, plant optimisation is being considered, for example, by integrating biofuel production facilities into biorefineries [22].

4.5.2 First-Generation Biodiesel

This technology is also relatively well established. While the transesterification processes seem to prevail over hydrogenation, the latter could emerge as it produces higher quality biodiesel (improving blending with conventional diesel). However, degradation processes suffered by catalysers in the hydrogenation process should be solved. On the other hand, it is necessary to further reduce CO_2 emissions associated to this production process.

4.5.3 Second-Generation Bioethanol

Research on feedstock is focused on obtaining high-yield crops and residues with low lignin content and highly adapted to the enzymes involved in the breakdown of lignocellulosic molecules.

Research on pretreatments to separate the biomass into cellulose, hemicellulose and lignin is focused on the development of improved chemical pretreatments based on ionic liquids and biological pretreatments introducing upgraded fungi species. Also, microorganisms are being tested for simultaneously pre-processing the lignocellulosic material, breaking down the cellulose crystal structures and fermenting sugars to produce bioethanol.

Work is also in progress for the development of catalytic enzymes (cellulase) to hydrolyse cellulose and hemicellulose to produce sugars. Simultaneously, fermentation of alternative sugars, such as pentose and hexose, is in advance for the production of bioethanol. The above hydrolysis–fermentation processes are currently carried out in different stages, also involving different bioreactors. However, simultaneous fermentation and saccharose production processes are being developed to increase production and diminish costs.

All these works can be summarised in obtaining enough quantity of ethanol from the second-generation feedstock to overcome the so-called barrier of recalcitrance, currently limited to 40 % of the energy content of cellulose converted into ethanol. By contrast, the fermentation process (first generation) reaches energy conversion efficiencies of about 90 % [23].

Also, new designs for the production of lignocellulosic ethanol are being planned. They combine small biomass feedstock management to decentralise ethanol production, and larger flexibility to process different biomass species and characteristics. It is also essential to consider all aspects related to logistics in order to guarantee proper plant production [24].

Finally, new research routes are considered for the conversion of lignocellulosic biomass directly into hydrocarbons without using fermentation processes that produce alcohols [25]. Strategies are proposed in which genetically modified microorganisms act on the sugars directly generating hydrocarbons. These processes have the advantage that the production rate would be equivalent to that of fermentation, and the hydrocarbons produced would be separated spontaneously from the microorganisms. Consequently, no ethanol will poison the process, contrary to what occurs in the fermentation process to produce alcohols. Another advantage is that these hydrocarbons could reach higher blending levels in conventional internal combustion engines, thus potentially increasing market penetration [26]. However, these alternative processes are planned for the long term, as there are still many steps necessary for the hydrocarbons synthesis, which are not currently solved [27]. There are also similar strategies applying solid-phase catalysts, pyrolysis and gasification of biomass, but they are also still far from the market.

4.5.4 Second-Generation Biodiesel

Major research efforts are focused in improving the activity of catalysts in the gasification of biomass (Fischer–Tropsch process) as a first step in obtaining light biodiesel. Also, as deoxygenation (with hydrogen) and the removal of sulphur and nitrogen impurities are required in the later stages of biodiesel production, CoMo- and NiMo-based catalysts are currently being tested, as well as various zeolites that do not require the contribution of hydrogen [28].

One of the main advantages of catalytic gasification of biomass is that it allows a significant reduction in processing temperatures from 750 °C to about 600 °C or less, introducing considerable energy savings. Currently, a widely used low cost catalyst is dolomite, $CaMg(CO_2)_2$, but it has the disadvantage of being poisoned when tar residues are formed. Then, research in more resistant Ni-based catalysts is on course to solve this difficulty. Other research areas refer to catalysts that could improve the purification of gases produced by gasification, especially avoiding tar formation, as well as the development of catalysts designed to fix the H_2/CO ratio to specific biofuel requirements.

Research is also being conducted on the development of syndiesel (or renewable diesel) devoted to achieve higher blending ratios than normal biodiesel, or even being used directly in car engines. Then, syndiesel could be directly integrated into the distribution chain of diesels.

Finally, the use of bio-oils obtained by pyrolysis processes could be expected to reach the biofuels market in the near future. However, these bio-oils require reducing the acidity and water contents before they are used as biofuels for transport.

4.5.5 Hydrogen from Biomass (Third Generation)

This section refers to the hydrogen gasification and fermentation sections exposed in Chap. 5.

4.5.6 Biodiesel from Microalgae (Third Generation)

One future technology trend is to combine in the same process the biodiesel production from microalgae and wastewater treatment. However, the greatest technological challenge is to keep alive the algae populations for extended periods of time, avoiding infection by invasive species. This improvement can be achieved by microalgae cultivation in closed photobioreactors, but in this case production costs rise. Another option is to work on genetically modified microalgae to obtain more resistant species against invaders.

On the other hand, for open systems using solar radiation input, improvements in technology are needed to prevent water evaporation losses. Substantial efforts are also dedicated on achieving larger algae production and algae-derived biofuels as similar as possible to competing fossil fuels.

However, the greatest economic challenge is focused on reducing production costs. To this purpose, it has been previously commented that obtaining co-products with high added value could help to increase profitability. Another option is to link algae production locations to CO_2 emission sources, but this is difficult, for instance in the case of thermal power plants situated at large distances from the sea. Besides, research efforts must be increased to eliminate from exhaust gases, both particles and some heavy elements (e.g., mercury) before being introduced into the algal cultivation.

Finally, the technologies for extracting lipids from microalgae should be improved to maintain their functionality. Initially, spinning processes have been used, but as the concentration of biomass is generally low (<3 g/l) [29], these processes require large amounts of energy and become costly. Alternatively, flocculation processes followed by sedimentation and flotation prior to centrifugation could reduce costs. However, ideally microalgae cells should secrete lipids through thin membranes without affecting their functionality.

4.6 Pre-Production Highlights 2009–2011

4.6.1 Danish Companies Novozymes and Nanisco Announce Breakthroughs in Enzymes to Produce Ethanol from Cellulose [30]

The company Danisco presented its enzyme Acelerase DUET on 15 February 2010 and Novozymes presented its enzyme Cellic CTec2 the next day. The first of these enzymes substantially increases the breakdown of cellulose into simple sugars with only one-third of the enzyme amount required earlier (reducing costs significantly). Moreover, Acelerase DUET is more adaptable to different feedstock and pretreatments. On the other hand, the president of Novozymes announced that ethanol from agricultural residues at USD 0.54/l (EUR 0.39/l) can be reached with the new Cellic CTec 2, and further cost reductions could be expected.

4.6.2 ExxonMobil Enters the Race to Produce Biofuel from Microalgae [31]

On 17 July 2009, ExxonMobil announced that will invest USD 600 million (EUR 431 million) over the next 5–6 years to produce biofuels from microalgae. Half of the resources will be allocated to Synthetic Genomics Inc., a San Diego-based company that has achieved microalgae that directly secrete hydrocarbons. This procedure implies a big advantage over traditional methods that require collecting microalgae to extract the oil, which is then refined. The other half of the funds is transferred to the ExxonMobil R&D area to increase production volumes and improve the refining processes.

4.6.3 Genetically Modified Microbes Produce Biodiesel [32]

Scientists at the University of California, Berkeley, and the biotech company LS9, based in South San Francisco, have introduced more than a dozen modifications to the *Escherichia coli* (*E. coli*) bacteria to produce biodiesel directly from sugars or hemicellulose. Thus, the research group proposes a route to produce competitive biofuels from agriculture residues. Genetic modifications have enabled *E. coli* to produce large molecules of fatty acids, which can then be converted into biodiesel or other highly added value chemicals. To achieve this, genes from other bacteria have been inserted in the bacterium *E. coli* so that it can produce enzymes capable of breaking the molecules of the hemicellulose.

4.6.4 Hybrid Cellulosic Ethanol Plant of Abengoa Bioenergy in Kansas, USA (2010) [33]

Abengoa Bioenergy has started building the first hybrid commercial scale cellulosic ethanol and power plant in Kansas (USA) in June 2011. The plant investment cost is about USD 550 million (EUR 395 million) and is expected to produce 100 million litres (25 million gallons) of ethanol annually and 22 MW of renewable electricity from biomass. The biomass used is a mixture of agricultural waste, non-feed energy crops and wood waste and will create 65 permanent jobs. The plant is expected to start into operation in June 2013.

4.6.5 *Producing Biodiesel at Home [34]*

A growing number of consumers are starting producing biodiesel at home using cooking oil as feedstock. After heating the oil, sodium hydroxide and methanol are added. The sodium hydroxide breaks the oil molecules into fatty acids and glycerol, and the methanol reacts with the fatty acids to form esters. The sequence of processes is: drain away the glycerol, wash the remainder with water to remove impurities and surplus lye, drain the water, and then aerate what is left with an aquarium bubbler to drive off the last traces of moisture. The result is a biodiesel with an estimated cost of USD 0.44/l (EUR 0.32/l). The process is not particularly hazardous. Another option is to directly substitute the diesel by unprocessed vegetable oil after introducing some low-cost modifications in the diesel engines.

4.7 Innovation Highlights 2009–2011

4.7.1 *New Procedure to Produce Jet Fuel from Waste Biomass [35]*

Scientists at the University of Wisconsin-Madison have developed a new procedure to convert cellulose from agricultural residues into gasoline and jet fuel. The fuel is derived from products (levulinic acid and formic acid) previously discarded and coming from residues originated from the conversion of cellulose into sugars. Then, these acids are combined to form γ-valerolactone, an industrial chemical, subsequently converted into a gas called butene by applying silica and alumina catalysts. After this, the butene is easily converted into liquid hydrocarbons such as gasoline and airplane fuel. In addition, the CO_2 produced during the process can be easily captured, adding an advantage to the process since it can give rise to negative CO_2 emissions. However, cost estimates are high because of the many steps involved in this production process.

4.7.2 *Direct Conversion of CO_2 Into Biofuels [5]*

Researchers from the Department of Chemical and Molecular Engineering, at the University of California Los Angeles, have succeeded in generating a cyanobacterium by genetic modification that produces isobutanol and isobutyraldehyde from CO_2. The isobutanol compound has certain advantages over ethanol: (1) higher energy content; (2) compatibility with internal combustion engines; (3) easier purification procedure applying yeast and (4) lower corrosiveness for pipeline transportation. The productivity achieved (3,000 μg/l-h for isobutanol and

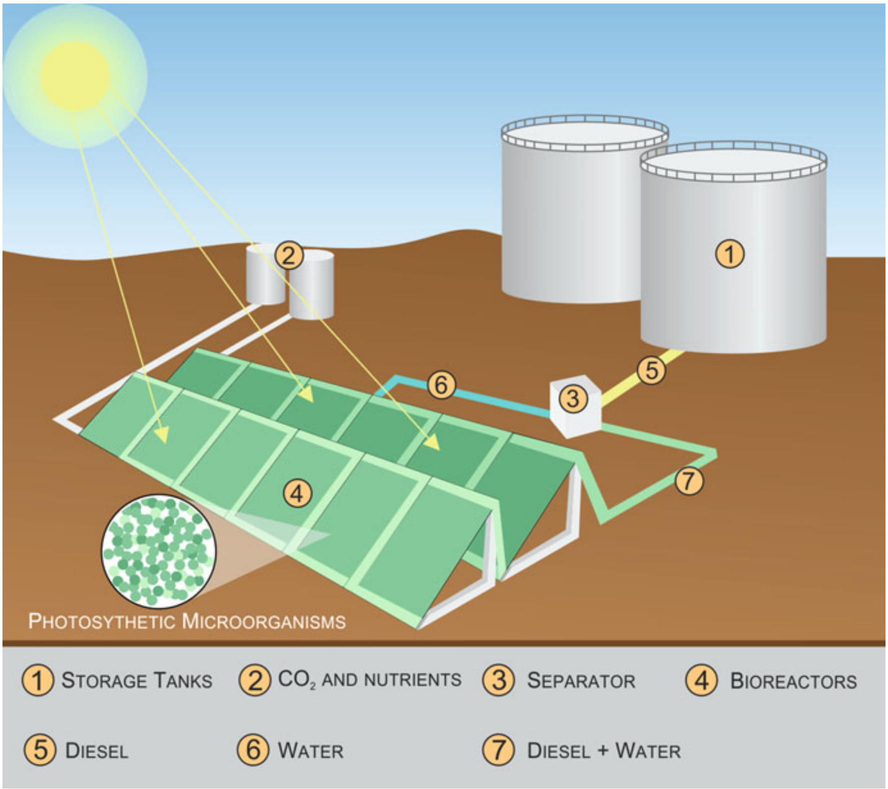

Fig. 4.11 Scheme of a biofuels production plant fed with solar energy and CO_2

6,230 μg/l-h for isobutyraldehyde) is several orders of magnitude higher than similar processes involving cyanobacteria to produce ethanol. In terms of production per hectare of land occupied, the productivity is also significantly improved compared to lignocellulosic ethanol derived from corn and even biodiesel from microalgae. However, the authors believe that these productivity values in future could relatively worsen due to productivity improvements in lignocellulosic and corn ethanols. A scheme of a biofuel production plant fed with CO_2 and sunlight is shown in Fig. 4.11. CO_2 conversion processes to other favourable energy carriers are also in progress [36].

4.7.3 Design of an Improved Process for the Use of Pyrolysis Oils [37]

Due to the fast pyrolysis of lignocellulosic biomass currently, the oils with the lowest costs are produced by this technique. In a recent paper, and using zeolite catalysts, a group of scientists from the University of Massachusetts have developed a process for increasing the hydrogen content, thus producing olefins and aromatic hydrocarbons at a rate much higher than the standard process for the simple processing of pyrolytic oils. This process may improve the commercial attractiveness of pyrolysis-derived oils as an industrial commodity.

4.7.4 Genetic Modification of E. coli *Converts Seaweed into Ethanol [38]*

As lignin makes difficult sugars extraction from lignocellulosic biomass to convert them into ethanol, a third of the sugars in seaweed takes the form of alginate, a complex polymer that industrial microbes cannot convert into ethanol. However, scientists of Bio Architecture Lab, a biotech company based in California, have developed a genetically modified *E. coli* that can break down and ferment alginate, as well as all the other major sugars present in seaweed, and convert them into ethanol. With this process, a titre of 4.7 % volume/volume, and a yield of 0.281 (weight ethanol/weight dry macroalgae) is reached (equivalent to ~80 % of the maximum theoretical yield from the sugar composition in macroalgae).

4.7.5 Discoveries on Isobutanol and on Ethanol Production in Microorganisms [39, 40]

Researchers at the U.S. DOE BioEnergy Science Center have achieved converting directly plant matter into isobutanol, which can be burned in a regular car engine with a caloric value similar to gasoline. Unlike ethanol, isobutanol can be blended at any ratio with gasoline and should eliminate the need for dedicated infrastructure in tanks or vehicles. On the other hand, researchers of the same centre have discovered the single gene that controls ethanol production capacity in a microorganism. This discovery could enhance developing biomass crops to produce higher concentrations of ethanol at lower costs. The discovery was produced in a microorganism known as “Clostridium thermocellum”. Current methods to obtain ethanol from switchgrass and agricultural waste require the addition of expensive enzymes to break down the molecules that guard energy-rich sugars. Scientists have been working to develop a more streamlined approach in which tailor-made microorganisms produce their own enzymes that unlock the plant’s sugars and ferment them into ethanol in a single step. Identifying this gene is a key step towards making the first tailor-made microorganism that yields a higher ethanol productivity.

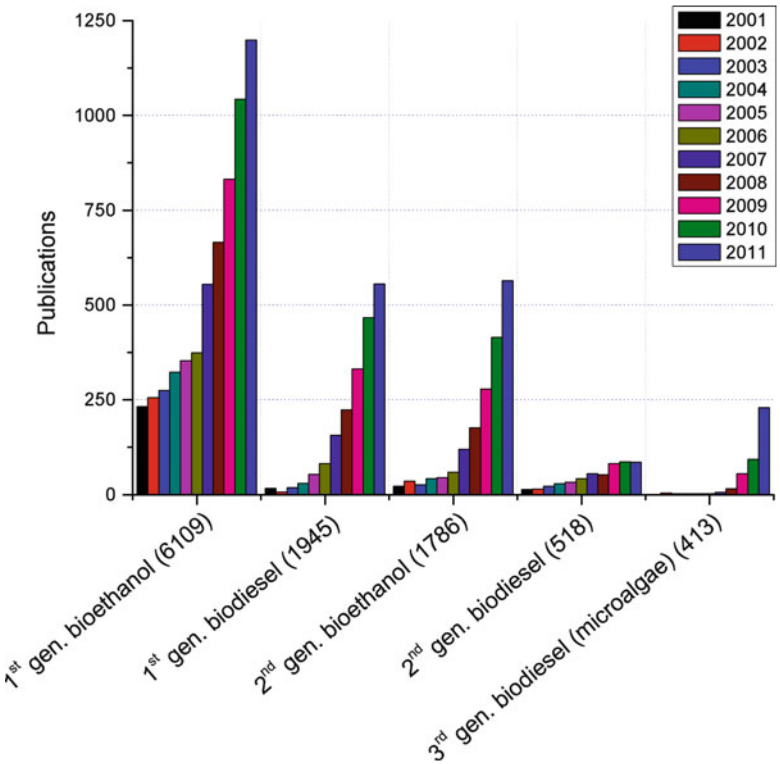

Fig. 4.12 Number of scientific publications during the period 2001–2011 for alternative biofuel production technologies [41]

4.8 Statistics of Publications and Patents

Figure 4.12 shows the number of scientific publications during the period 2001–2011 for the different alternative technologies involved in the production of biofuels that have been considered in this chapter [41].

It can be observed that the growth in the number of publications in recent years has been substantial in all technologies, but more significantly in all the matters related to bioethanol. This can be attributed to the fact that bioethanol costs are closer to fuel parity than other biofuels, and also to the existence of vehicles (flex vehicles) that can consume fuels almost completely based on ethanol.

The dominant activity is observed for first-generation bioethanol. This can be largely attributed to researchers studying different strategies to further reduce ethanol production costs and to the associated debate on the emission of greenhouse gases and iLUC.

The research activity related to first-generation biodiesel occupies the second place and is slightly higher than for second-generation bioethanol. This can be attributed to the fact that first-generation biodiesel is the main alternative to replace

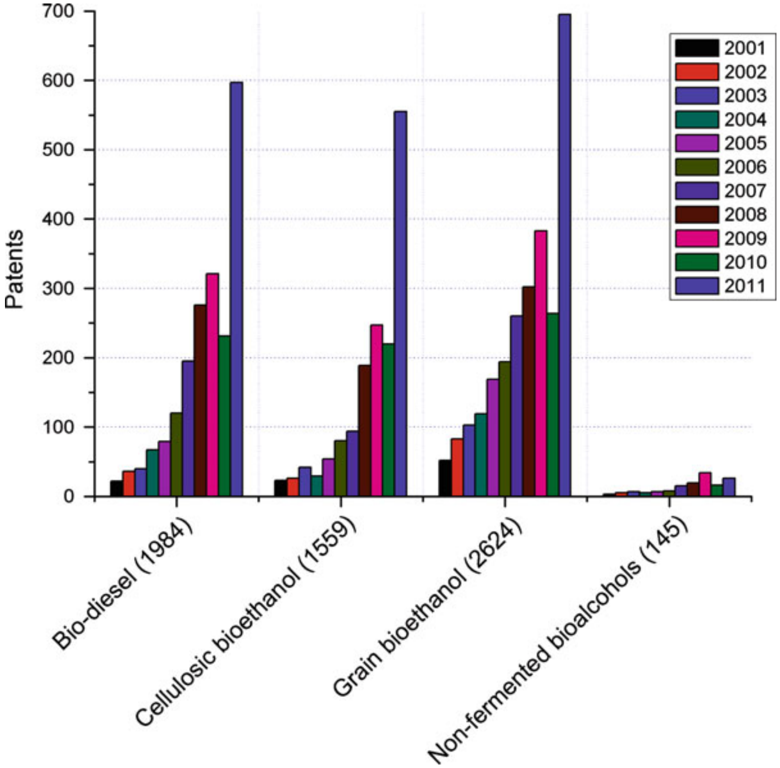

Fig. 4.13 Number of patents during the period 2001–2011 for alternative biofuel production technologies [42]

fossil diesel at present. However, the difficulties to increase the biodiesel percentage in the fuel blending limit the attractiveness of this technology.

In the third place is bioethanol obtained from lignocellulosic biomass, with a research activity similar to that detected for first-generation biodiesel. This result is attributable to the expected effect that lignocellulosic feedstock will exert avoiding much of the environmental impact and food supply concerns that first-generation biofuels suffer.

Finally, research activity in microalgae is the smallest and almost non-existent until recently, in the period analyzed. However, its growth rate over the last years has been very strong, clearly surpassing the research activity on second-generation biodiesel. Obviously, the strong growth of research in microalgae is attributed to the expectations for the future, but costs still remain the highest of all the technologies studied. On the contrary, the growth of the research activity in second-generation biodiesel is low and attributed to the lack of attractiveness for this technologies compared to the cases of bioethanol and microalgae.

In terms of patents [42], the European Patent Office uses a different classification compared to the one exposed in this chapter (Fig. 4.13). However, the information obtained from this source is very similar to that of scientific publications. Firstly, bioethanol patents dominate these statistics compared to biodiesel. On the other hand, first-generation (grain) bioethanol shows the largest activity, but second-generation (cellulosic) bioethanol is growing fast.

Finally, the number of patents related to non-fermentation paths to obtain bioalcohols is currently very low. However, it should be expected a large future growth of patents in this area if the prospects of genetic modification of microorganisms are fulfilled.

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Chapter 5
Hydrogen Production

Abstract It is well known that hydrogen can become an important carrier and storage medium of energy in the near future and a serious medium-term alternative to fossil fuels. By means of fuel cells, hydrogen can serve as a clean fuel, i.e. without the emission of pollutant gases, for the production of electricity in which it is known as the hydrogen economy. Another main advantage of hydrogen is that is the fuel, which provides the highest amount of energy per unit weight. However, the large-scale implementation of hydrogen requires significant advances in further lowering its production costs and finding efficient techniques for its storage and transportation. At present, there is also a strong interest to couple the inherent intermittent renewable energy systems with the production of hydrogen so that the hydrogen can return the energy stored by means of a fuel cell when the primary source (solar radiation, wind, etc.) is not available. In this chapter, we make a review of the most usual techniques for hydrogen production: steam methane reforming, gasification, electrolysis, renewable energies, etc., and costs. One important result from our findings is that hydrogen produced by biomass gasification can practically compete in costs with that produced from fossil fuels.

5.1 Overview

Hydrogen as an energy carrier is a serious medium-term alternative to fossil fuels. This is because the energy stored in hydrogen can easily be converted into electricity with high efficiency (60–65 % in MCFC and SOFC fuel cells [1]). This conversion is produced without emitting greenhouse gases to the atmosphere. In contrast, burning hydrogen in a combustion engine is less efficient (it is estimated that the efficiency of directly converting chemical into mechanical energy in a vehicle in a normal traffic situation does not exceed 10 %) and can cause polluting nitrogen oxides if the combustion process is carried out in atmospheric conditions.

The high interest generated by the hydrogen fuel is essentially based on its highly exothermic reaction with oxygen, which produces water with a variation in

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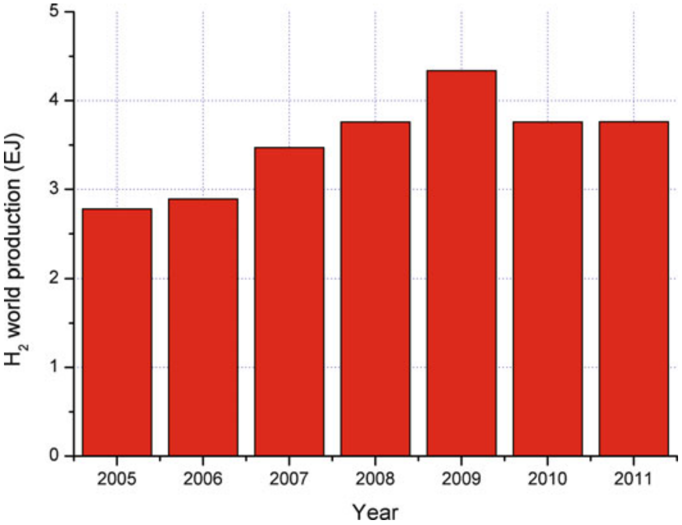

Fig. 5.1 Evolution of the annual hydrogen production in the period 2005–2011 [3]. It excludes the production of hydrogen from synthesis gas, by-product gas and stationary plants that are not owned or operated by the end-user

enthalpy of −242 kJ/mol. This value makes hydrogen the highest energy storage fuel per unit mass, with a theoretical value of 120 GJ/t [2], which is roughly three times the natural gas value.

The so-called hydrogen economy will be reached sooner or later depending largely on solving various problems related to production, storage and distribution. It is also necessary to reduce the high production costs of the current fuel cells.

Obviously, as the hydrogen fuel does not generate greenhouse gases in its use, its real interest will become more evident when it is produced with a minimum amount of such gases. Hence, the main current effort is to develop renewable energy-based techniques for this purpose.

In the case of producing hydrogen from biomass for decentralised energy production, this process could compete with the production of biofuels, with the advantage for the latter to be currently in a more advanced state of development, and having a greater access to the energy market using the existing transport infrastructure for hydrocarbon fuels. However, hydrogen production from biomass can be very attractive in relation to biofuels if the production of hydrogen is combined with carbon capture and storage in centralised facilities. Thus, the entire production and consumption process for hydrogen from biomass would be negative in terms of carbon emissions.

Although it may seem paradoxical, the current use of hydrogen as energy carrier is almost symbolic, being primarily used as chemical in the industrial sector. Thus, although the annual world production is about 3.76 EJ (Fig. 5.1) [3], it is expected to increase significantly in the coming years, mainly applied as an energy carrier and in the treatment of world increasingly heavier crude.

Regarding the use of hydrogen, from the 3.76 EJ produced today approximately 50 % is engaged in the manufacture of ammonia (which is the source of virtually all nitrogen-based synthetic fertilisers), 8 % is dedicated to the production of methanol and the rest is mainly used in the petrochemical industry [4]. The fuel industry also makes widespread use of hydrogen to remove sulphur and to convert heavy oil into gasoline, diesel, etc. Moreover, there are many other industries that use hydrogen as the semiconductor, welding, glass and power industries.

It is also important to note that over 90 % of global hydrogen production is captive production, i.e. the same industries, which need to consume large amounts of hydrogen are producing it. Consequently, only a 10 % approximately of hydrogen reaches the market [5]. This fact explains in a large extent the inherent difficulties in calculating the hydrogen market price.

5.2 State of the Art

Hydrogen is mainly produced in centralised plants, as they provide efficiencies between 5 and 10 percentage points higher than the decentralised ones [6]. However, the penetration of renewable energies for producing hydrogen will strengthen decentralised production facilities which, although involving a higher production costs, avoids the hydrogen transport and storage costs to the end-users, inherent to centralised facilities.

About 48 % of hydrogen production is currently based on steam methane reforming (SMR), 30 % from the reformed oil/gasoline at refineries and chemical industries, 18 % from coal gasification processes, 3.9 % from the electrolysis of water and 0.1 % from other sources [7].

5.2.1 Reforming

Although technologies such as partial oxidation and autothermal methane reforming (and of some biofuels) can be employed, the most used technology is the steam methane reforming (SMR), with the following reactions:

$$\mathrm{CH_4 + H_2O \rightarrow CO + 3H_2} \quad \text{enthalpy} = 206\,\mathrm{kJ/mol}(\text{endothermic})$$

$$\mathrm{CO + H_2O \rightarrow CO_2 + H_2} \quad \text{enthalpy} = -41\,\mathrm{kJ/mol}(\text{exothermic})$$

Some furnaces work at temperatures between 750 and 950 °C (although reforming can start at temperatures of 350 °C). The two reactions proceed simultaneously and can use nickel, iron oxide, etc., as catalysts, being able to obtain a gas with about 75 % hydrogen content and the rest mainly carbon oxides. Hydrogen is then obtained by passing the gas mixture through physical separation media, such as membranes (palladium, etc.) or absorbent beds as PSA (Pressure Swing Adsorption).

5.2.2 Gasification

The reaction of coal with steam produces synthesis gas (syngas) composed of a mixture of H_2, CO, CO_2, CH_4 and other compounds depending on the gasification temperature. If the temperature is increased above 1,000 °C, the proportion of H_2 and CO also increases. Then, CO can also react with water vapour producing more hydrogen (see the second reaction of the previous subsection), also called “water gas shift”.

It is observed that the reaction products are similar to the ones exposed in reforming. Consequently, again the physical methods for hydrogen separation exposed above play an important role.

In gasification processes not only the production of hydrogen from coal but also from biomass is feasible. This alternative is advanced from a technological perspective and provides attracting production costs [8], as discussed below.

5.2.3 Water Electrolysis

Water electrolysis is the decomposition of water into its constituent elements, hydrogen and oxygen, using electricity. Obviously, it would not be profitable to use this hydrogen to produce electricity through fuel cells, as the electricity obtained will be less than the initial used in the electrolysis process. But the process will be profitable if the electricity used in electrolysis is supplied by renewable sources, as it can help to decouple electricity supply and demand in non-manageable renewable energy power plants (i.e. wind and solar energy power plants).

As mentioned above, only a small percentage of hydrogen is produced by electrolysis. The process is clean and the hydrogen produced is highly pure. Generally, the conversion efficiency is only about 60–65 % because the gas bubbles produced at the electrodes makes the movement of ions difficult, but it can be raised to about 80 % if appropriate porous electrodes are used.

Currently, three types of electrolysers for the industry are used. Two of them use a solution of potassium hydroxide (KOH) due to its high conductivity and are called alkaline electrolysers (unipolar or bipolar). The third type is an electrolyser composed of solid polymer electrolyte, which represents the most promising technology today, with the advantages of avoiding the use of liquid electrolyte and the handling of corrosive solutions (contrary to the KOH-based electrolyser), but with the disadvantage of a short membrane lifetime. The water quality requirements vary depending on the type of electrolyser used, although purifiers are essential to ensure water quality.

An interesting strategy to reduce electricity consumption in the electrolysis is based on replacing a portion of the electricity supplied by heat to decompose water at elevated temperatures. Indeed, the Gibbs free energy (G) change associated with the electrochemical reaction is given in terms of changes in enthalpy (H) and entropy (S), by the equation $G = H - TS = n \cdot FV$, where F is the Faraday constant, n is the number of moles and V is the electric potential, which can be lowered as the reaction temperature is increased.

5.2.4 Thermolysis

The conditions for the decomposition of water without electricity input ($V = 0$) can be obtained from the equation on the change in Gibbs free energy, shown above. Then, the temperature will be determined by the ratio between changes in enthalpy and entropy (~ 2,700 K).

As these temperatures are very difficult to obtain in an industrial process, another option is to apply chemical processes carried out at lower temperatures. For example, the "Mark9" EURATOM (Ispra, Italy) procedure is performed at 700 °C and is based on the reaction [9]:

$$6FeCl_2 + 8H_2O \rightarrow 2Fe_3O_4 + 12HCl + 2H_2$$

5.2.5 Thermochemical Cycles

Parallel to the development of techniques for concentrating solar power (CPS) at high temperatures for the production of electricity, interest is reviving in thermochemical reactions where endothermic dissociation of compounds containing hydrogen is produced. Obviously, the most evident is water, as discussed in the thermolysis subsection.

An interesting thermochemical reaction for this technology is the reduction of zinc oxide and the reforming of methane to obtain hydrogen, according to the following reaction:

$$ZnO + CH_4 \rightarrow Zn + 2H_2 + CO$$

This reaction can be carried out in a solar reactor at about 1,200 K, atmospheric pressure and without catalysts.

Also, the thermal cycle of ammonia can be used to store solar thermal energy and to produce hydrogen. This is because the NH_3 can be exothermically dissociated into nitrogen and hydrogen in solar reactors at a temperature of about 1,100 K (see Sect. 7.2).

There are many other possible thermochemical cycles for hydrogen production on which research is intense, such as iron oxide (Fe_3O_4/FeO) and tin oxide (SnO_2/SnO).

5.2.6 Biochemical Fermentation

Biochemical fermentation to produce hydrogen is growing in importance, as hydrogen from vegetable sources can be considered near-neutral in terms of carbon emissions. This type of fermentation is based on enzymes that possess certain microorganisms, which can produce hydrogen.

Among the biochemical processes, the water biophotolysis from the so-called blue and green algae (cyanobacteria) leads the research activity, where the enzyme hydrogenase is capable of producing hydrogen. However, more research is needed to control the process and to make it profitable.

In anaerobic atmospheres, i.e., without oxygen, the basic process is the oxidation of substrates by bacteria. This process generates electrons, which, to preserve the electrical neutrality, reduce protons resulting in hydrogen. For example, glucose can be broken into either acetic acid and hydrogen, or propionic acid and hydrogen, and carbon dioxide in both cases.

5.2.7 Photocatalysis and Photoelectrolysis

A very interesting technique to produce hydrogen by a renewable route is based on the dissociation of water via sunlight acting on some semiconductors, known as photocatalysts, with a relatively wide band gap. By impinging photons with energy greater than the gap, it produces electron–hole pairs. These electron–hole pairs generate free radicals (e.g. OH^-) that can induce secondary reactions (photocatalysis) or break the water molecule (photoelectrolysis). It is important to obtain large lifetime and mobility values for these carriers and, consequently, they can generate an electric current before recombining.

In photocatalysis, the semiconductors used are generally oxides such as TiO_2 and WO_3, oxynitrides of tantalum and titanium, solid solutions of cadmium and zinc sulphides, etc. In photoelectrolysis, traditionally, processes with materials extremely rare or very expensive have been tested. Despite extensive research in this area, the efficiencies achieved are very low, partly because a large percentage of the photons of the solar spectrum has energies smaller than the semiconductor gap. As discussed below, most of this research is focused on nanostructured materials.

5.2.8 Hydrogen Storage

Another important question that should be efficiently solved in the case of hydrogen is its storage, specifically in terms of security and capacity. The latter is especially important in the car industry if road autonomy comparable to that obtained with conventional fuels is demanded. The most common storage methods are:

- Gaseous state: In stationary and transportation applications, hydrogen is usually stored in steel cylinders at pressures that typically range between 200 and 250 atm, with compression energy costs less than 10 % of the total costs. The energy stored per unit volume is equivalent to only 6 % of oil, which is about 37 GJ/m^3. Consequently, Kevlar fibre containers have been developed to store hydrogen at pressures about three times higher, although in these cases the energy demanded for compression can reach 15 % of the total cost.
- Liquid state: Although the density of stored energy is somewhat higher than in the previous case, this technique does not seem appropriate, especially in the case of cars, since to keep hydrogen liquid its temperature should remain at liquefaction, which is −253 °C. This technique requires energy for both the liquefaction process of hydrogen and the energy necessary to maintain the hydrogen to the liquefaction temperature for long periods of time. However, evaporation losses are very significant. In addition, the mixture of hydrogen with air is explosive when it reaches proportions between 4 and 75 % in volume.
- As part of solid materials: The most promising techniques for hydrogen storage are related to the search for materials in the solid state to form chemical bonds with hydrogen or to absorb it. These materials must meet several conditions, including that the concentration of H_2 stored should be high, the kinetics to release H_2 should be quick and the process must be reversible. The advantage of this technique is that it is capable of storing more energy than in liquefaction, and mainly because it is very safe, although the reversibility of the process is complex. The release of H_2 can be thermally, i.e. H_2 leaves the host material when it reaches the desorption temperature. The materials traditionally used are boron hydrides with a metal atom such as Li, Na and K. There are also certain amine salts, for example, $Mg(NH_3)_6Cl_2$ which, at about 150 °C, decomposes. In turn, the released ammonia can dissociate at high temperatures in N_2 and H_2 in fuel cells called solid oxide, which operate at very high temperatures. Finally, there is much research being developed in the field of nanomaterials dedicated to the storage of H_2.

5.2.9 Market Penetration

Depending on the degree of market penetration, the different technologies for hydrogen production can be classified in various stages of development (Fig. 5.2). Both reforming and gasification technologies can be classified in a competitive

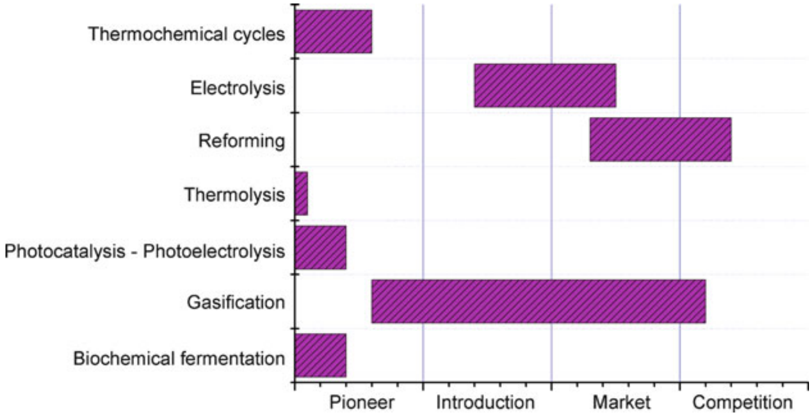

Fig. 5.2 Market penetration of each hydrogen production technology exposed in this chapter

stage due to the generation of hydrogen from natural gas and coal, respectively. In the case of gasification, the progress in the development of processes involving the use of biomass situates the market penetration also at earlier stages of technological development. Electrolysis can be considered as a highly developed technology, although it does not even reach the conventional gasification and reforming processes, more advanced in relation to their penetration in the market. The other technologies are at a very early stage in terms of market penetration.

5.3 Current Costs and Future Scenarios

There are independent assessments of hydrogen costs using water electrolysis and of distributed hydrogen from natural gas [10,13] that we can consider as a first approximation. However, current hydrogen production costs are highly influenced by the evolution of coal and natural gas prices in international markets, the latter being particularly volatile, although the price of coal is also showing increasing volatility (Fig. 5.3).

According to the evolution of these prices, linear relations can be established with the costs of hydrogen production, which also vary if the production facilities are centralised or decentralised, introducing an extra cost for transport to the consumer in the first case (Fig. 5.4) [10,12]. Consequently, an extra USD 29.2/GJ (EUR 21.0/GJ) must be added due to the liquefaction process for the hydrogen produced in centralised facilities and transportation to consumers [14]. Other factors that increase or decrease the final cost of hydrogen are [15]: (1) use of

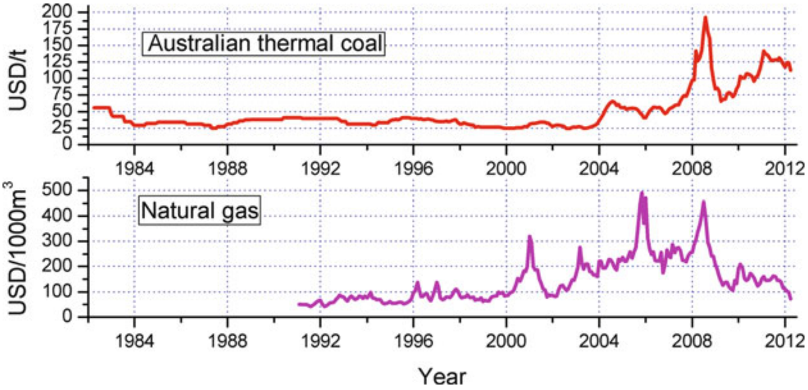

Fig. 5.3 Evolution of natural gas prices in the NYMEX futures market and of the Australian coal (source: INO and Indexmundi.com)

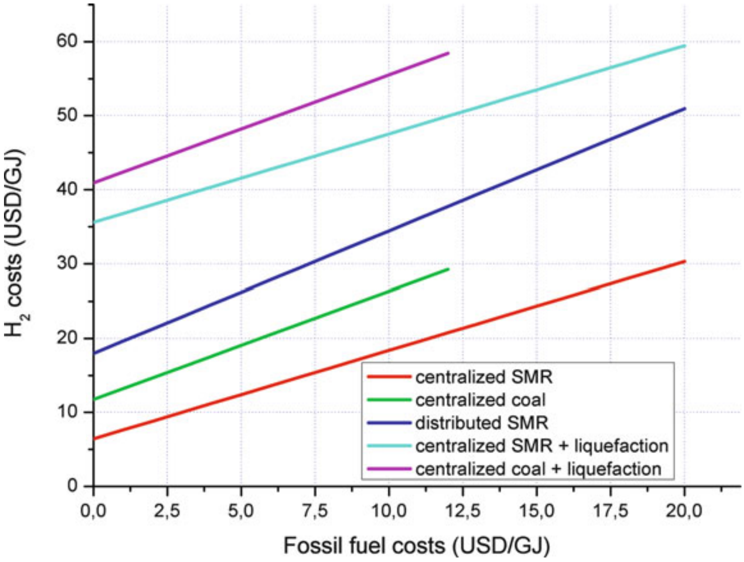

Fig. 5.4 Linear dependence of hydrogen production costs in relation to natural gas and coal prices for different configurations [10]

the oxygen produced in the process at about USD—1.5/GJ (EUR—11.1/GJ), (2) transport of the hydrogen >USD 8.3/GJ (>EUR 6.0/GJ) and (3) centralised storage of hydrogen at about USD 10.0/GJ (EUR 7.2/GJ).

According to papers published in various scientific and technological journals [16–26], the hydrogen production costs with alternative technologies to coal in centralised facilities, levelised to 2011, are represented in Fig. 5.5. In this figure, it

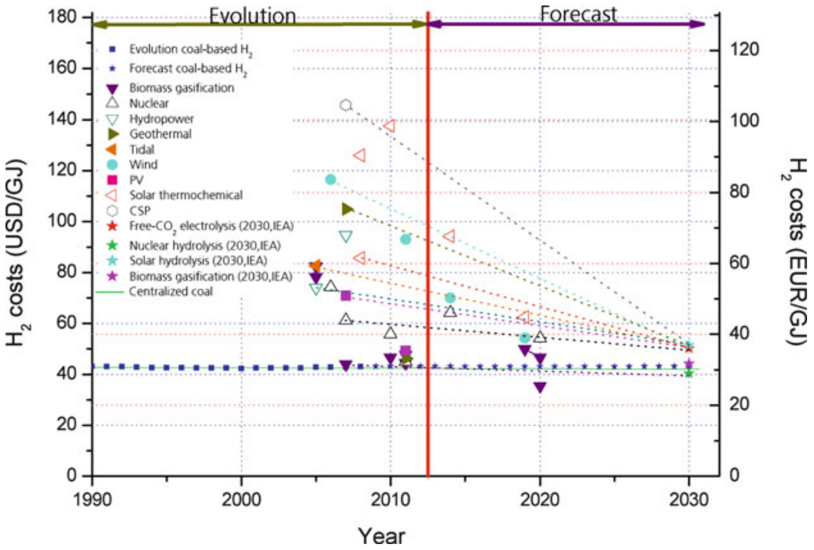

Fig. 5.5 Comparison of hydrogen production costs by coal gasification and various alternative technologies in centralised facilities (Ref. 16 updated)

is also represented the expected change in the cost of coal production by 2030 according to the EIA, as well as the IEA production costs estimates in 2030 for centralised facilities that use alternative technologies. Consequently, the renewable technology that is closer to fuel parity with coal gasification for the production of hydrogen is the gasification of biomass.

If alternative technologies for hydrogen production are compared with the production costs from SMR in centralised locations (Fig. 5.6), it is necessary to consider the expected increase in efficiency from 69 to 83 % of the SMR technology in the coming years. In this case, the renewable technology closer to fuel parity with SMR is also the biomass gasification.

Studies of hydrogen production costs from renewable sources in decentralised plants are less in number than for centralised plants, being only comparable to results from hydrogen production facilities that use decentralised SMR processes, since the production of hydrogen by coal gasification in decentralised facilities is not feasible due to economies of scale. In this case, it is found (Fig. 5.7) that the renewable technology closer to fuel parity is based on biofuels as raw material for hydrogen production. Furthermore, the cost reduction forecasts considered are those published by the EIA for 2019–2020, as the IEA has published only forecasts for centralised facilities. The estimates obtained indicate that the fuel parity between the cost of hydrogen production by decentralised SMR and renewable energies will occur in the middle of this decade.

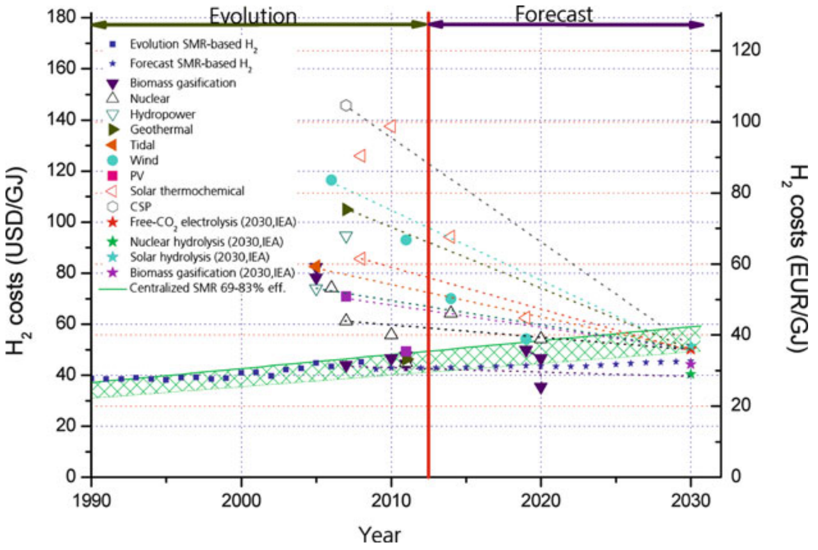

Fig. 5.6 Comparison of hydrogen production costs by steam methane reforming and various alternative technologies in centralised facilities (Ref. 16 updated)

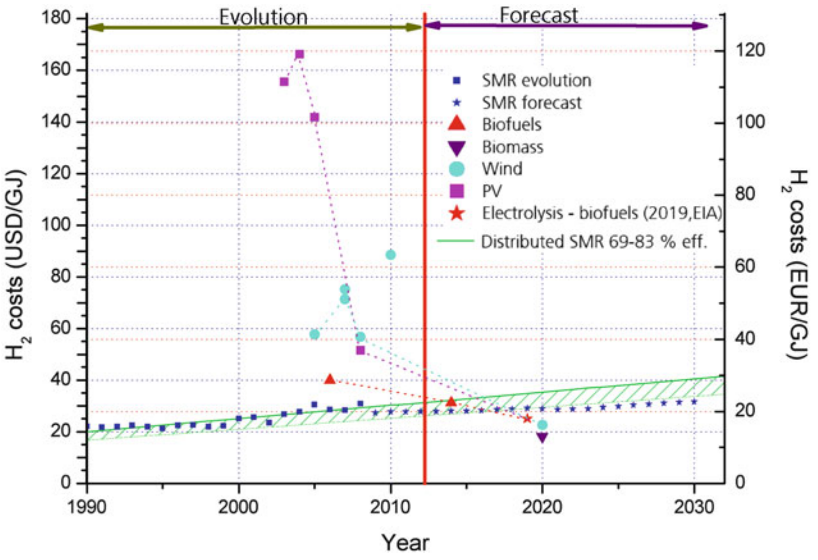

Fig. 5.7 Comparison of hydrogen costs production by steam methane reforming and various alternative technologies in decentralised facilities (Ref. 16 updated)

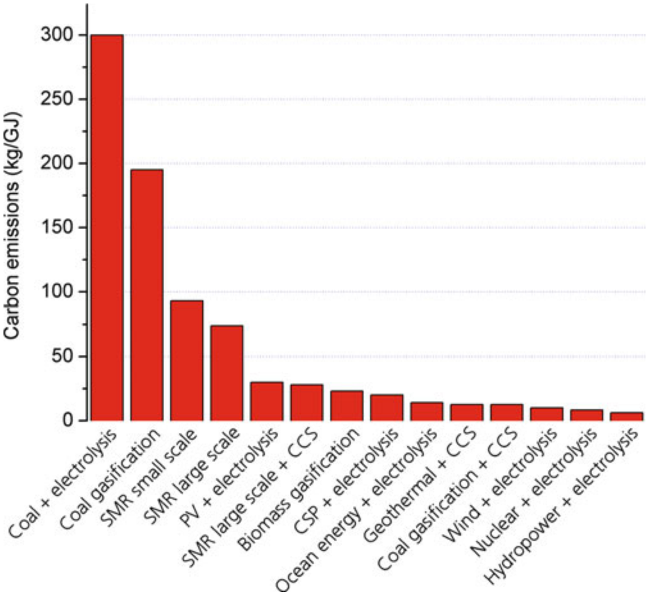

Fig. 5.8 Carbon emission rates for various hydrogen production technologies [5]

5.4 Energy Payback, Carbon Emissions and External Costs [7,8]

Carbon emissions due to hydrogen production are important because, as noted above, the technologies commonly used to synthesise it are almost entirely based on fossil fuels as raw material. Consequently, the production of hydrogen from renewable sources and near-zero carbon emissions has a great potential as the costs are lowering (Fig. 5.8) [5].

Using the data from Fig. 5.8 and applying them to the data shown in Fig. 5.7, the impact of emissions trading in the range USD 50–150/tCO_2 (EUR 108–36/tCO_2) can be observed (Fig. 5.9). Thus, it is estimated that if the carbon permits were situated at USD 50/tCO_2 (EUR 36/tCO_2), the fuel parity between production costs for decentralised hydrogen with SMR and renewable technology would occur at the beginning of this decade, while if emission rates were at USD 150/tCO_2 (EUR 108/tCO_2) the parity would have yet occurred.

It may be noted, moreover, that it is expected a reduction in CO_2 emission rates for hydrogen production from renewable energy sources, as these sources will increase their independency from carbon emissions in the future (the weight of renewable energies in the energy mix of industrialised electricity systems is increasing).

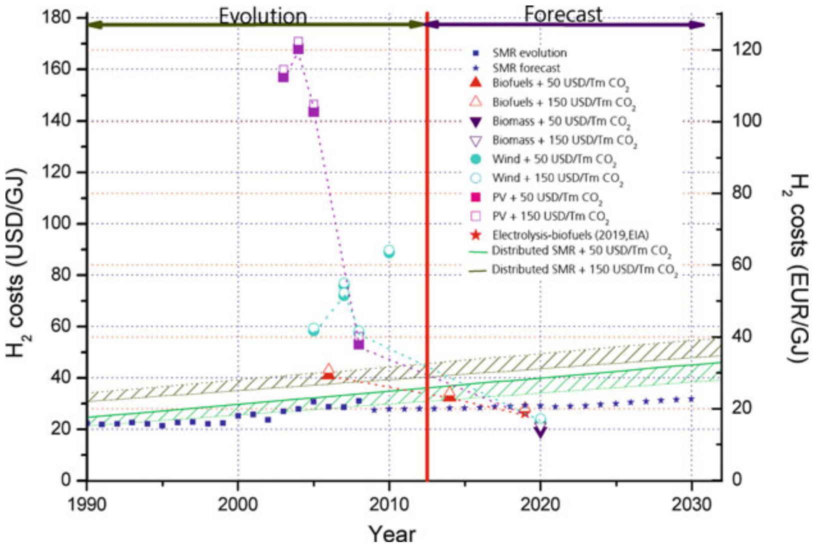

Fig. 5.9 Comparison of producing hydrogen costs by SMR and renewable technologies in decentralised facilities, introducing carbon permits at 50 and 150 USD/tCO_2 (Ref. 16 updated)

5.5 Future Technology Trends

5.5.1 Reforming

The main research efforts are on the development of advanced membrane separation and purification systems to have a more efficient reforming technology. In this sense, the EIA predicts that in 2015 the conversion efficiency will reach 83 % in these processes, compared with 69 % efficiency in 2009. Also, the methane reforming assisted by heat input from solar energy is an important future technology trend, as it can reduce the environmental and economic cost of the process.

Another future option is the use of biofuels as raw material in the reforming process, particularly in decentralised systems. Applying these processes to supply hydrogen fuel to cars, currently difficult and costly, could be very relevant in the future, mainly for light vehicles.

5.5.2 Gasification

Technological efforts in this area are on more economic gasifiers, the development of more efficient membranes for the separation of H_2, CO and CO_2, and new technologies to produce oxygen at a lower cost and taking advantage of the oxygen generated as product. There are also new concepts to integrate CO_2 separation systems and gas–water exchange through membranes, to offer higher efficiency (64–68 %). In addition, the cogeneration of hydrogen and electricity in centralised integrated gasification combined cycle plants associated with systems that capture and store CO_2 is proposed for future plants. Other tendencies consider the construction of plants to produce electricity and hydrogen, methanol and Fischer–Tropsch diesel, because they offer significant economies of scale, increasing the overall efficiency and value to the process.

Essential at this point are the efforts to make biomass gasification for hydrogen production competitive with conventional technologies and achieving economic value for the dry residues resulting from the gasification process, which would also reduce the final cost of the process.

5.5.3 Electrolysis

The most important research efforts try to increase the efficiency and stability of the electrodes in alkaline electrolysers to obtain a higher current density and at a lower applied voltage. The water molecule can be dissociated at 1.23 V under ideal heating conditions, while the current electrolysers achieve it at 1.48 V. Work is also needed for the replacement of precious metals as catalysts with others that are cheaper, as well as in solid oxide technology, currently not competitive, but a robust option in the long term.

Another important future concept in which work is needed is in the use of synthetic materials, which increase the durability and lifetime of the electrolyser, particularly if elevated temperatures are used as a partial replacement of electricity in the process. In this sense, synthetic materials for diaphragms, which offer low resistance and high pressure thresholds, are demanded. These strategies also are combined with the search of electrolysers, which work at higher pressures and temperatures to diminish the consumption of electricity for the reaction and to reuse the heat produced in the process. On the other hand, working at high pressure will be useful to save energy needed to pressurise the hydrogen for its end use.

Increasing the efficiency and reducing costs in the electrolysis process opens the possibility for the production of hydrogen using hybrid-renewable technology that combines various renewable energy sources complementarily. Systems based on renewable energy sources for this purpose are primarily wind and, in a second term, photovoltaic cells, hydroelectricity, geothermal and ocean energy. The important cost reduction in photovoltaic systems in recent years is accelerating the viability of this option to produce hydrogen.

5.5.4 Thermolysis

The main research area tests materials capable of working at such high temperatures required in these processes. Also, it is necessary to achieve water thermolysis by direct catalytic decomposition using ceramic membranes, as well as plasma-enhanced water decomposition in a chemical reactor within a CO_2 cycle. Research activity is also trying to increase the efficiency of the processes being tested to reduce the cost of the hydrogen produced, and also to avoid some very important technical problems at these high temperatures, as corrosion and heat leaks. As heat source systems, there are considerations about using solar energy and nuclear power plants. However, for this second option, new facilities designs are necessary, as the current ones cannot reach the required temperatures. In addition to nuclear energy, solar radiation is being considered as a means of heat input in thermochemical cycles, as it will be discussed below.

5.5.5 Biochemical Fermentation

This process is considered for future decentralised hydrogen production facilities. The fundamental aspects to be solved are, firstly, to speed up the production process, since it is much slower than in other types of hydrogen production plants. On the other hand, given the complexity of intermediate compounds that often are produced in biochemical fermentation process, it is necessary to limit them.

In case of photobiological production, it is expected to advance in the understanding of the natural processes involved as well as in genetic engineering to develop large bioreactors required to advance in the production process. Also, there is progress in the development of artificial photosynthesis processes, which are in a very early research stage and their final cost has not been determined yet.

5.5.6 Photocatalysis and Photoelectrolysis

In photoelectrolysis, the efforts focus on the development of nanostructured semiconductor materials to achieve much greater efficiency than currently reached. These semiconductors should have a band gap lower than 1.7 eV if they are to obtain the necessary energy from the sunlight photons.

Also, in photoelectrolysis, there is research in two-photon tandem systems and multijunction monolithic systems, where new concepts of materials science and engineering are being applied not only to increase conversion efficiencies but also to improve materials stability. Also, doping techniques for displacement of electronic bands, surface chemical modification and systems integration are being investigated. In photocatalysis, the main effort is to obtain new materials, cheaper, more durable and to offer attractive efficiencies in the hydrogen production process.

5.5.7 Thermochemical Cycles

In this area, new thermochemical cycles for the dissociation of water at high temperature using the heat from solar energy (also heat from nuclear power plants is considered) are the central research strategies, mainly for the production of metals (Zn, Sn, etc.) by reducing metal oxides or between different metal oxides (mainly ferrites). These processes have the added advantage that the metal oxides or reduced metal obtained can act as energy carrier, being transported from the places where the energy is obtained to where it is required. In the final location, it would generate hydrogen by breaking the water molecule and this hydrogen could be used for the production of electricity by fuel cells.

The main effort is on achieving thermochemical cycles at the lowest possible temperature, obtaining the largest efficiency in energy conversion, holding many consecutive cycles without degradation and achieving an optimal integration with solar technology.

5.5.8 Hydrogen Storage

In this area, the research work is primarily focused on hydrogen storage in solid matrices. Thus, solid boron-hydrides MBH_4 ($M = Li$, Na, K and B) and boranes are considered to be able to store hydrogen with a mass efficiency up to 25 %. Also, there is important research on nanostructured materials with various surface morphologies and structures acting as adsorption nuclei for hydrogen atoms. Other materials where research is improving are mixtures of metal hydrides, carbon microfibres, graphite nanofibres and materials with large surface area such as zeolites. There is also work developing storage in glass microspheres, which are filled with hydrogen in permeabilisation processes at high pressures and temperatures (300–700 bar, 300 °C) in which the gas is retained at room temperature and is recovered at 200–300 °C.

In gas storage, tanks with high-pressure steel-reinforced carbon fibre are the main concept, not only to reduce the storage volume but also to prevent the diffusion of hydrogen through the walls of the tank. In this sense, there is currently research on developing technology above 700 bar. To prevent leakage of hydrogen, there is also research activity improving the system connections. It is also being considered the study of the effects of cyclic charging, the lifetimes of the tanks and the perception of safety for the end-user.

5.6 Pre-Production Highlights 2009–2011

5.6.1 First World Fuel Cell and Hydrogen Energy Station in Orange County (USA) [27]

This is the World first trigeneration fuel cell and hydrogen energy station to provide transportation fuel to the public and electric power to an industrial facility (district wastewater treatment plant). It also produces heat. The hydrogen is obtained from the biogas produced in the wastewater treatment plant. The hydrogen produced by the system, integrated by a hydrogen purification system to recover approximately 100 kg H_2 a day, can support between 25 and 50 fuel cell electric vehicles fill-up per day. A fuel cell also produces about 250 kW of electricity supplied to the wastewater treatment plant.

5.6.2 The Commercial Vehicle That Travels More Kilometres Driven by Hydrogen [28]

According to the latest report (2011) of the U.S. Environmental Protection Agency, the commercial fuel cell vehicle that travels more kilometres is the hydrogen-powered Honda FCX Clarity, which uses a PEMFC engine and is capable of travelling 97 km/kg H_2 on road and street circuit, showing an autonomy range of 386 km.

5.6.3 Waste Treatment Plant Capable of Producing Energy with Hydrogen [29]

The plant will be located in South Korea and will use plasma gasification technology to produce hydrogen. It will be able to manage 5 t of organic waste per day and to produce electricity with a power of 50 kW from PEMFC supplied by the company Ballard. The agreement was announced on 17 March 2011.

5.7 Innovation Highlights 2009–2011

5.7.1 Thermochemical Cycles for Water Dissociation in Two Stages Using Fe_3O_4 and $NiFe_2O_4$ Particles on ZrO_2 Porous Ceramic Devices [30]

$NiFe_2O_4$ and Fe_3O_4 porous materials supported on zirconia have been used in two-stage processes for producing hydrogen by water dissociation. The first thermal reduction reaction has shown that if part of Fe is replaced by Ni atoms, the reaction is produced at temperatures of about 1,400 °C instead of 2,200 °C. The oxide, once reduced (FeO), reacts with water to produce hydrogen and oxidises again Fe_3O_4 at temperatures of about 1,000 °C. The efficiency of hydrogen production significantly increases if the ferrites are dispersedly supported on monoclinic zirconia and after this dust is settled on a porous material consisting of zirconia ceramics partially stabilised with MgO. Apart from increased efficiency in hydrogen production, other interesting aspects of this work are the details that give the authors about the reactors, the high temperature furnaces and solar simulators to perform experiments in the laboratory instead of solar concentrators.

5.7.2 Production of Hydrogen from Water by the Effect of Light on Polymeric Carbon Nitride [31]

The production of hydrogen from water using a catalyst and solar radiation is an ideal future energy source. An abundant material, polymeric carbon nitride (CN), can produce hydrogen from water when it is irradiated with light in the presence of a sacrificial donor. The advantage of the CN is to be a chemically and thermally stable material and also inexpensive to produce.

5.7.3 Production of Hydrogen from Virus [32]

The Massachusetts Institute of Technology has successfully replicated in early 2011 the first path of the photosynthesis (which splits the water molecule) using a genetically modified virus (M13) not harmful to humans, assembled to iridium oxide (one of the catalysts commonly used for the photolysis of water) and a biological pigment used to capture light. These viruses are fixed in a sol–gel system to avoid losing efficiency by a tendency to form clusters. The advantage of the system is that the virus brings appropriate distances between catalyst and pigment to act efficiently. The next step is to replace the iridium oxide catalyst by other less expensive.

5.7.4 Artificial Leaves That Produce Hydrogen [33]

At a conference of the American Chemical Society meeting in late March 2011, scientists of the Massachusetts Institute of Technology presented a silicon wafer that, exposed to the sun, is able to absorb radiation to be used to decompose water into H_2 and O_2 using catalysts. With this device, located in the right location, they have achieved a 5.5 % conversion efficiency of sunlight into hydrogen. The artificial leaves tested were designed for a low cost production system and they plan to market within 2–3 years.

5.7.5 Improvement of the Kinetics for the Water Electrolysis [34]

Improving the kinetics for the electrochemical reduction of water to molecular hydrogen in alkaline environments is crucial to reduce the high overpotentials and associated energy losses in water-alkali and chlor-alkali electrolysers. Scientists of the Argonne National Laboratory have introduced nanometer-scale $Ni(OH)_2$ clusters on a platinum electrode surface and have obtained a factor of 8 activity increase in catalysing the hydrogen evolution reaction relative to the state-of-the-art metal and metal oxide catalysts. With further engineering the surface area/volume ratios of these catalysts, these scientists expect to be close to obtaining the same efficiency as it is evolved from protons in acidic environments.

5.8 Statistics of Publications and Patents

Figure 5.10 shows the number of scientific publications during the period 2001–2011 for different hydrogen production technologies [35].

It is observed that the main activity is in the hydrogen storage area. On second position, the reforming is very prominent in publications, which can be explained not only because it is the production process most commonly used for conventional hydrogen production but also as research activity tries to apply biofuels reforming to produce hydrogen. This is a very attractive procedure in terms of costs in decentralised systems, as exposed above.

A prominent place is also occupied by the gasification technique in which, similarly to the reforming technique, it is employed to produce hydrogen not only from coal but also from biomass gasification, in quasi-profitable centralised systems. Consequently, an important research activity in this area is justified.

Electrolysis, as a basic technique to produce high purity hydrogen, has always maintained a relatively constant number of publications, although not very high. However, that number is growing in recent years, which can be attributed to the development of prototypes to produce hydrogen from renewable energy sources that supply electricity to the electrolysers.

Other processes such as semiconductor photocatalysis and photoelectrolysis also are beginning to have weight in this area in terms of scientific and technological activity, as these processes are based on renewable energy concepts. However, biochemical fermentation processes and thermochemical cycles can be considered in early stages of research. In the first case it can be attributed to the novelty of the proposed process, while for the case of thermochemical cycles the reason may lie in

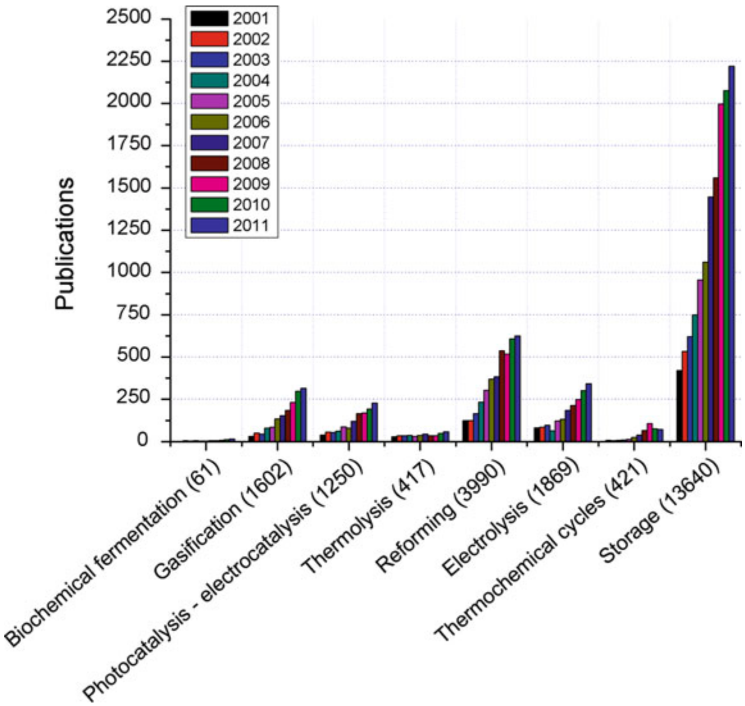

Fig. 5.10 Number of scientific publications during the period 2001–2011 for different hydrogen production technologies [35]

the high costs involved for the experimental setup, often substituted by computer simulation.

In relation to the evolution of the number of patents published in the period 2001–2011 (Fig. 5.11) [36], it is detected some correlation with the evolution in the production of scientific and technological literature. However, it is difficult to analyse in detail these correlations because the classifications defined in patents by the European Patent Office are mainly for storage alternative technologies.

Then, it is obvious that the main efforts are also on developing new technologies for hydrogen storage, mainly in deposits for gas-compressed, liquid or solid hydrogen. The storage in deposits is followed at some distance by the reversible storage using metals, rare earth metal, intermetallic compounds and metal alloys. Well below are the reversible storage technologies that use carbon as host, or those using organic compounds or solutions. Finally, with an almost negligible number of patents are situated caves used as deposits.

In connection with the hydrogen production activities, it is important the number of patents on electrolysis. Patents related to electrolysis using nuclear and renewable energy as electricity supplier are classified by the EPO separately and are also included in Fig. 5.11. Inorganic decomposition processes, i.e., splitting the water molecule by mechanisms different from electrolysis or ammonia, also occupy a

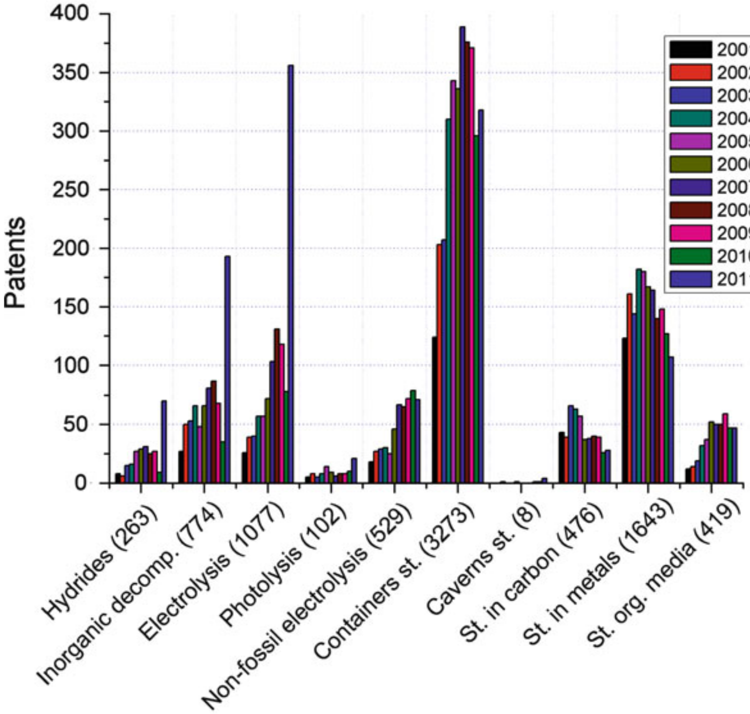

Fig. 5.11 Number of worldwide patents published during the period 2001–2011 for different hydrogen production technologies [36]

prominent place. Chemical reactions with metal hydrides, i.e. hydrolysis of boron metal hydrides, are considered as a less active technology. Lastly, photolysis is the technology with the smallest activity in terms of patents.

Finally, as it can be observed that the technological activity in the development of hydrogen patents has been rising in this period except in recent years. This recent tendency may be attributed to a side effect of the global economic crisis, but also to a lower perspective for hydrogen as fuel in the automotive sector, mainly after decisions published by the US Administration restricting public funding for research in hydrogen.

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III

Power From Renewable Sources

Chapter 6
Photovoltaics (PV)

Abstract During the last 20 years, both the photovoltaic (PV) cumulative installed power and the annual electricity production have increased at an annual rate of about 40 %, resulting in an estimated 67 GW cumulative capacity in 2011. This tremendous growth has been mainly a consequence of the continuous decrease of the cost of solar systems, 75 % in the last 3 years. Therefore, depending on the intensity of the solar resource, the PV electricity is reaching grid parity in many regions of the world. In this chapter, we make a grid parity study of PV and the efficiency of the different types of solar cells. We describe their evolution from the first-generation ones, produced from crystalline silicon, to the thin film or second-generation cells, which make use of much smaller quantities of semiconductor materials: CdTe, CIGS, amorphous-Si, etc. The evolution to the less mature third-generation solar cells, based in novel physical concepts, is also described. In summary, solar PV can be considered today as a mature technology for electricity production both at the large utility production plant level, or in domestic small-scale applications either isolated or grid connected.

6.1 Overview

Solar energy can be used to produce electricity by converting solar radiation directly into an electric current through the so-called solar cells or photovoltaic cells. The electrical power produced can either be injected directly into the grid (grid connected) or used in-situ (off-grid).

A silicon solar cell consists of a semiconductor pn junction, which is illuminated by light from the Sun. Figure 6.1a shows an scheme of a solar cell in which the n side, or emitter, directly faces the Sun. The emitter has to be quite thin, since the incident light has to reach the interface between the p-type and the n-type material, and it is known that silicon is a strong optical absorber. On the top of the emitter, an antireflection coating has to be placed to minimise losses of light by direct reflection on silicon.

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As it is well known from solid state electronics, an internal electric field arises at the area surrounding the pn interface or spatial charge region. Therefore, if the incident photons from sunlight, with energies higher than the semiconductor bandgap, reach the pn interface, they will create electron–hole pairs (see Fig. 6.1a). The electrons and holes thus created will move in opposite directions by the action of the field resulting in a current which will be the sum of the currents due to both types of carriers (recall that the holes are charged positively).

From the above concepts, it is convenient to emphasise that a solar cell under illumination behaves like an electric generator, or fem, and therefore, contrary to the case of an ohmic resistance, the output current and voltage should have different signs. The solid curved line in Fig. 6.1b represents the I–V characteristic of a typical solar cell. If the cell is in open circuit ($I = 0$), the corresponding voltage is maximum and it is called the open circuit voltage V_{oc}. On the contrary, if the terminals of the cell are shorted ($V = 0$), then the current is called the short circuit current I_{sc}, and its value is maximum.

Evidently, it is usually desired that the output power is maximum (P_{mp}), as it is the case in power generation. Therefore, the product IV should be maximum, which in terms of the diagram of Fig. 6.1b means that the operating point Q should be chosen so that the area of the rectangle subtended by Q should be maximum, i.e. $P_{\mathrm{mp}} = I_{\mathrm{mp}} \cdot V_{\mathrm{mp}}$. The proper location of the operating point is obtained by choosing the load external resistance R in such a way that the load straight line intersects the solar cell I–V characteristic at the point Q at which $P = P_{\mathrm{mp}}$.

Although the amount of energy from the sun is about 9,000 times greater than that consumed by all human activities on earth [1], the solar photovoltaic (PV) electricity can be only partially used because of, among other things, its low concentration of power, its intermittency and its costs. This leads to only 0.07 EJ produced by PV worldwide (2009) [2] compared to the 833,400 EJ of solar energy irradiance on the Earth's land surface annually (Table 2.1) [3]. However, there are considerable advantages of this technology, because electricity is "directly" produced and, therefore, there are no moving components in the photovoltaic systems, so the operation and maintenance costs are relatively low.

Each solar cell has a current density (~30 mA/cm^2) and voltage (~0.5 V) output very low, so it must be connected in series and in parallel to produce the necessary electrical power for the different applications. Modules are assembled joining several cells in series and in parallel. To produce these modules, the solar cells are encapsulated under stringent conditions to have a durability of 20 years or more under atmospheric conditions.

There are three different generations of photovoltaic cells at different stages of technological development: (1) first generation, based on crystalline silicon is a mature technology, (2) second generation, based on semiconductor thin films can be considered a quasi-mature technology and (3) third generation, based on many physical phenomena (mainly quantum effects), usually sun radiated by concentrator systems (making it necessary to use mechanical structures to track the sun path), are currently under a intense research and development activity.

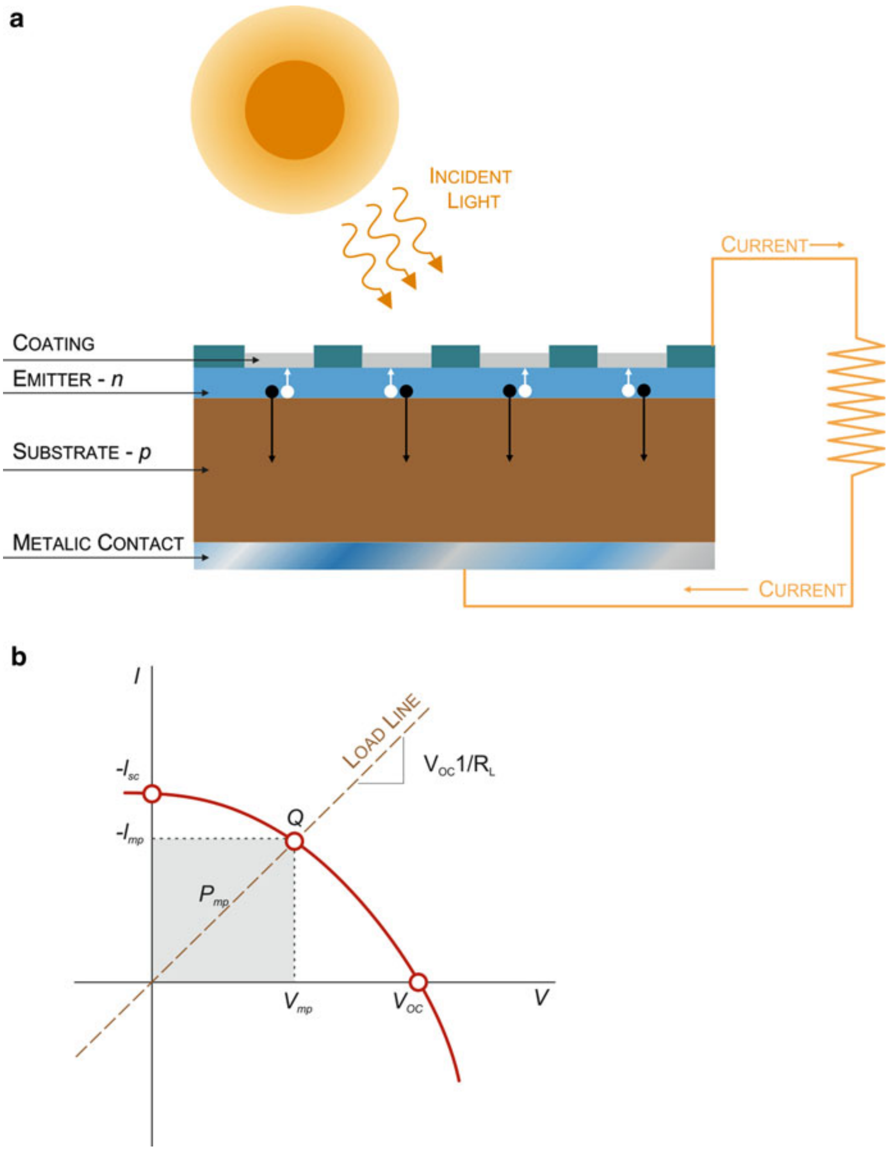

Fig. 6.1 (**a**) Scheme of a silicon solar cell; and (**b**) *I–V* characteristic of a typical solar cell

Figure 6.2 shows the evolution of the electricity produced by photovoltaic cells. As it can be observed, in the last 20 years, electricity production by PV systems has grown exponentially.

Figure 6.3 shows the cumulative PV capacity worldwide. As it can be observed, the European Photovoltaic Industry estimates that in 2011, the world has overcome

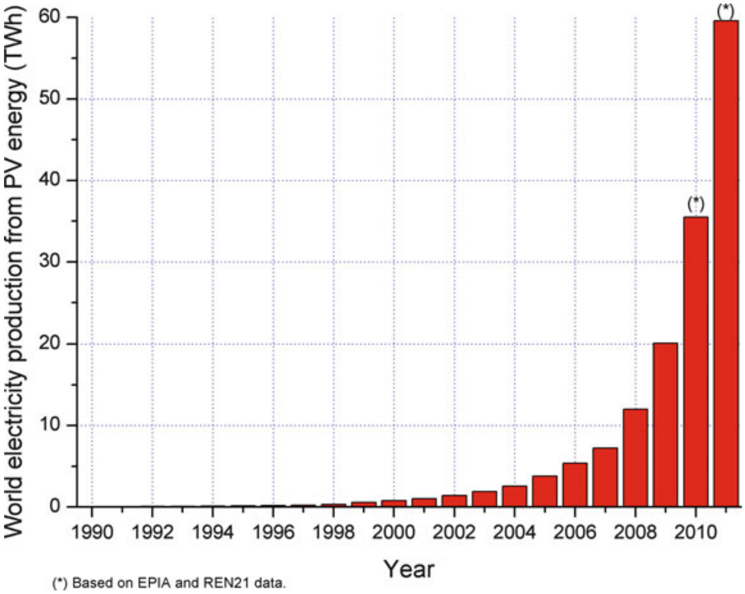

Fig. 6.2 Evolution of the annual production of electricity from PV systems in the period 1990–2011 (based on IEA, REN21 and EPIA statistics)

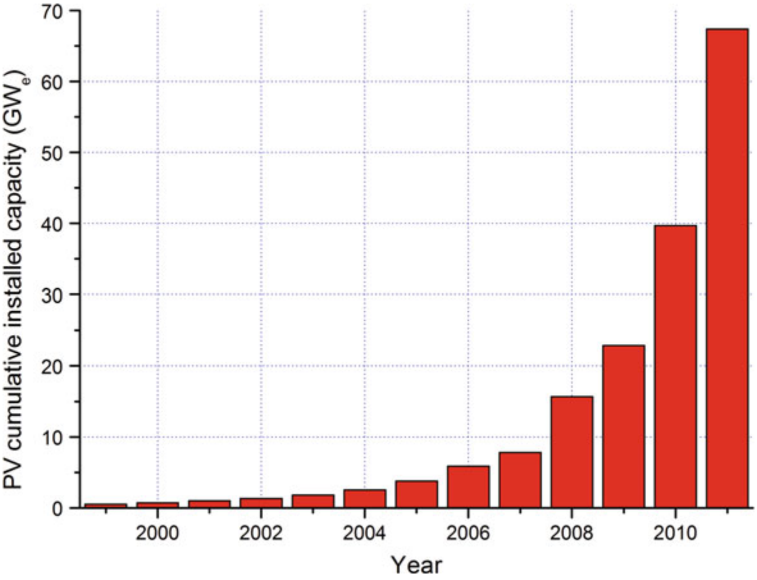

Fig. 6.3 Evolution of the annual accumulated capacity of PV electricity in the period 1999–2011 (based on EPIA statistics)

67 GW_e (electrical GW) of installed capacity, producing the largest annual increase ever recorded, despite the economic crisis.

6.2 State of the Art

To describe the state of the art for the photovoltaic technology and future trends, we make a distinction between crystalline silicon cells, thin film cells based on inorganic semiconductors, third-generation solar cells and those based on organic semiconductors and dyes.

6.2.1 Crystalline Silicon Cells

They are based on crystalline silicon either as single crystal (c-Si) or multicrystalline (mc-Si) with large grain sizes (about 1 cm side). These cells dominate the PV market and are called first-generation solar cells. The maximum efficiency of these cells converting sun radiation to electricity reached its 25 % world record, very close to its theoretical limit, in the late 1990s, in a huge technological effort that substantially raised the cost of a cell.

The mc-Si solar cells have efficiencies somewhat lower than for c-Si, reaching a 20.4 % world record. The lower efficiency compared to c-Si is offset by cheaper production costs, so they are normally preferred in the PV market, although their future will depend on the evolution of the silicon monocrystalline and multicrystalline price per kg in the international market.

One of the future savings in the cost of crystalline silicon solar cells is based on the thinning of silicon substrates. Furthermore, in order to eliminate the cutting and polishing steps in the manufacturing process, a ribbon-Si technology has been successfully developed. The most advanced ribbon-Si technique is called “Edge-defined film-fed growth” where molten silicon is solidified through a carbon die forming a tape (“ribbon”) which is introduced in a manufacturing process to produce solar cells.

6.2.2 Thin Film Cells

This technology implies a significant saving of semiconductor material. Although their efficiency is lower compared to Si-based solar cells, as discussed below, and their production costs are relatively low, these cells are less used than first-generation ones to produce electricity. There are different thin film solar cells:

6.2.2.1 Amorphous Silicon Solar Cells (a-Si:H)

They use very little material and are deposited on a substrate support after the decomposition of silane gas (SiH_4) in a plasma-enhanced chemical reactor. For this reason, the hydrogen content of the cells can reach a tenth of the thin film stoichiometry. Commercial a-Si:H modules appeared in the 1980s, but their current market penetration is still small. However, its use is expected to grow much in the coming years. The major drawback of these modules is due to the instability of the electrical output parameters of the cells, which may decrease by about 20 % after prolonged use. The efficiency record currently stands at 10.1 %.

6.2.2.2 CdTe Solar Cells

These cells can be chemically deposited in an aqueous solution, or more recently by evaporation of CdTe on a substrate. A major drawback of these cells is due to strict environmental controls for toxic elements like cadmium. Shortages in raw materials also limit production of tellurium. The maximum efficiency achieved by these cells is at 16.7 %.

6.2.2.3 CIGS Solar Cells

The first CIGS cells were produced in the early 1980s by evaporation of the constituent elements Cu, In, Ga and Se. Although CIGS cells efficiency currently reaches 19.6 %, problems arise due to the scarcity of In and its environmental impact.

6.2.3 Third-Generation Solar Cells

Such cells are based on different and, sometimes, novel optoelectronic concepts that allow or are expected to help to increase the efficiency of the cells in the future. Notable among these are the multijunction monolithic structures applied for the world efficiency record solar cells, primarily with two p–n junctions configurations (mid-1980s) and recently with three junctions configurations, reaching the current world absolute record of 43.5 % (2011).

6.2.4 Organic Solar Cells

It can be distinguished within this type of cells the ones called dye-sensitised and the proper organic cells. The development of dye-sensitised solar cells started in the early 1990s, managing to a maximum efficiency of 11.0 %. The development of organic solar cells began more intensively in 2001, reaching maximum values of efficiency still low (10.0 %). The main attraction of these cells is their low production costs, but raises important durability problems and the need to increase their efficiency to be commercially competitive.

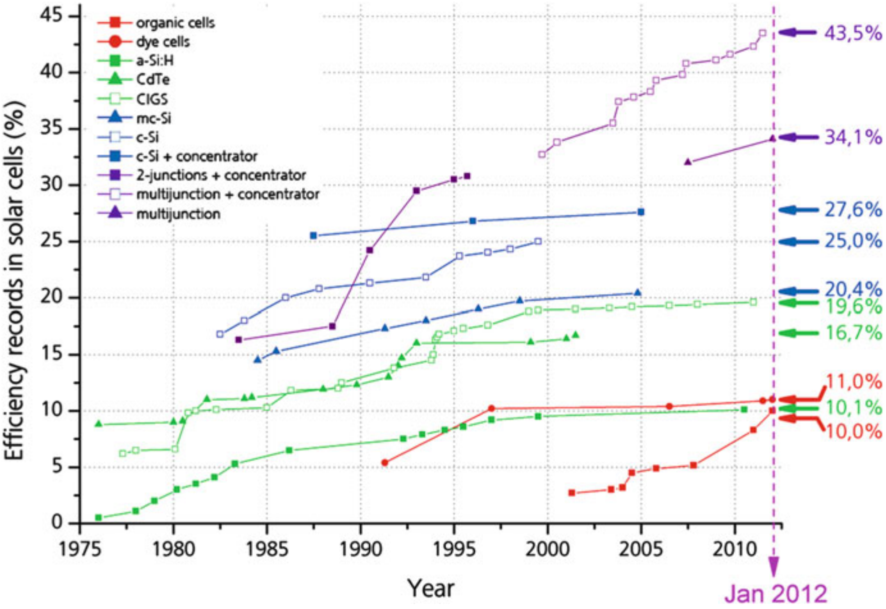

Fig. 6.4 Evolution of solar cells world record efficiencies under AM1.5 conditions (based on data from the journal *Progress in Photovoltaics*)

6.2.5 Efficiencies and Required Areas

The evolution of the solar cells efficiency produced in laboratories from 1976 to the present (January 2012) is shown in Fig. 6.4. As shown, the raise in efficiency in recent decades has been dramatic, especially in multijunction solar cells but also is being observed in organic cells. In the case of monocrystalline silicon solar cells, the efficiency is close to its theoretical limit. However, the thin-film solar cells (second generation) are still far from this limit. Finally, dye-based cells are still under development and have a low efficiency, but with great potential to be increased in the future.

The performance of most PV technologies increases with solar concentration ratios, but excessive heating can be detrimental to the efficiency and lifetime of the solar cells. Organic and amorphous silicon cells are generally too heat sensitive to be used in concentrators, but conventional monocrystalline silicon cells can operate efficiently at lower concentrations (1–100 suns) without needing active cooling mechanisms. On the other hand, GaAs and multijunction solar cells are better used in the medium-high concentration systems (100–300 suns, 300 suns and above). Mainstream concentration technologies utilised are parabolic dish collectors and Fresnel lenses.

Table 6.1 shows the approximate commercial value of the efficiencies for solar cells and modules, as well as the area of the modules per electric power generated

Table 6.1 Approximate commercial values of efficiencies and area required per kWp for solar cells and solar modules (based on EPIA data) [4]

	Thin film	Thin film	Thin film	Thin film	Thin film	Concentrated	Crystalline	Crystalline
	a-Si	CdTe	CI(G)S	a-Si/ m-Si	Dye	Multijunction III–V	c-Si	mc-Si
Cell eff.	4–8 %	10–11 %	7–12 %	7–9 %	2–4 %	30–38 %	16–22 %	14–18 %
Module eff.	4–8 %	10–11 %	7–12 %	7–9 %	2–4 %	25 %	13–19 %	11–15 %
m^2/kW_p	~15	~10	~10	~12			~7	~8

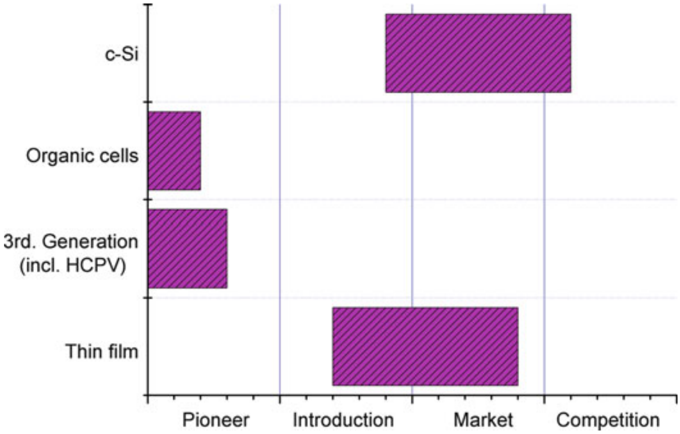

Fig. 6.5 Stage of development for each PV technology considered in this chapter

(kW_p) under standard conditions. It can be appreciated the advantage that still provides the crystalline silicon technology in terms of area requirements compared with thin film technology.

6.2.6 *Market Penetration*

Depending on the market penetration, the different solar cells technologies can be classified in different development stages (Fig. 6.5). Crystalline silicon-based technology can be considered to be in a competition stage, because although most countries offer incentives for PV installations, falling prices have been so intense since late 2008, in parallel to the increase in the price of electricity (especially in daylight hours when solar modules produce more energy) that it makes this technology currently fully competitive in daylight hours (discussed in more detail in the next section). On the other hand, we believe that the thin-film technology is still in the market stage, progressing well but still raises some uncertainties about its

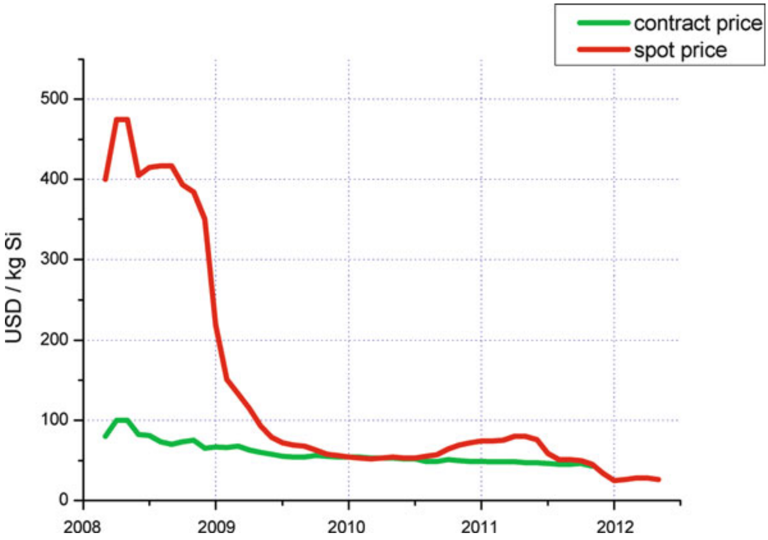

Fig. 6.6 Evolution of the silicon spot and contract price from 2008 (source: Photon Consulting)

durability and competitiveness. Finally, organic cells and third-generation solar cells can be considered still in a pioneering phase for mass production, with much research activity ahead.

6.3 Current and Future Costs Scenarios

The average total cost of a PV system in the last 3 years has been reduced by an impressive 75 % [5]. The cost of thin film PV modules in 2008 was below USD 2.25/W$_p$ (EUR 1.62/W$_p$) and c-Si USD 3.75/W$_p$ (EUR 2.69/W$_p$). In early 2011, the single crystal silicon modules (c-Si) and thin films have fallen below USD 1.0/W$_p$ (EUR 0.72/W$_p$). This is mainly not only due to the spectacular decrease in the price of silicon (Fig. 6.6) and improvements in the manufacturing technology, but also because profit margins have been reduced dramatically and overcapacity is also detected in this sector.

In future scenarios in the medium to long term, we expect fundamental changes in the PV market, both technological and economic. Thus, it is expected a gradual evolution from first-generation cells to second generation and, then, to third generation, as well as a reduction in costs associated with framing as the modules will be more integrated on building structures. Consequently, the costs of electricity generated by PV systems would fall to USD 5.0–7.0 cents/kWh (EUR 3.6–5.0 cents/kWh) in highly insolated areas (>1,600 kWh/kW$_p$/year) (Table 6.2).

These costs can be divided in the different items that compose the photovoltaic system (Table 6.3) [6], where it can be appreciated that the weight of the PV module dominates the final cost of the system.

Table 6.2 Approximate cost of photovoltaic systems (based on EPIA data [4])

USD/kW$_p$ (EUR/kW$_p$)	PV
2010	3,480–3,898 (2,500–2,800)
2030	977–1,302 (702–935)
2050	798–1,022 (573–734)

Table 6.3 Percentage of costs for the different steps involved in the production of electricity from PV systems [6]

		Costs (%)
PV module	Silicon	12.7
	Wafering	9.8
	Cell manufacturing	13.3
	Module lamination	12.7
	Framing and sorting	9.0
Power electronics	Inverter	7.3
	Connections	7.3
Emplacement	Engineering, mounting and financing	20.6
	Maintenance	7.3
	Total	100.0

The evolution of the electricity cost produced by PV systems until the first quarter 2012 and expected costs until 2040 and 2050 are exposed in Fig. 6.7. In this figure, it is exposed when it would be reached grid parity between conventional electricity prices and PV electricity costs. To forecast conventional electricity prices in future, the electricity price forecasts from the U.S. Energy Information Administration for the industrial and residential sectors are exposed (Fig. 6.7).

Thus, it is estimated that in 2016, the electricity cost produced by PV systems starts to be below the price of electricity supplied for residential buildings situated in high solar radiation areas, reaching grid parity with the price of electricity supplied to industry in 2022. In areas with moderate irradiation, this does not occur until the years 2028 and 2046, respectively (Fig. 6.7).

However, first grid parity events occur right now throughout many regions in the world, reaching an addressable market of about 75–90 % of the total global electricity market in the near future [7]. This grid parity is starting on islands and regions of good solar conditions and high electricity prices.

6.4 Energy Payback, Carbon Emissions and External Costs [8, 9]

Figure 6.8 shows the energy payback (years needed to produce the energy equivalent to the one used in the process of production and installation) for PV systems, assuming southern Europe solar irradiation (1,700 kWh/m^2/year), 30 years of average life for the cells and technologies applied in 2005–2008 (more updated technologies are not of public domain) [10]. As shown, the energy payback heavily

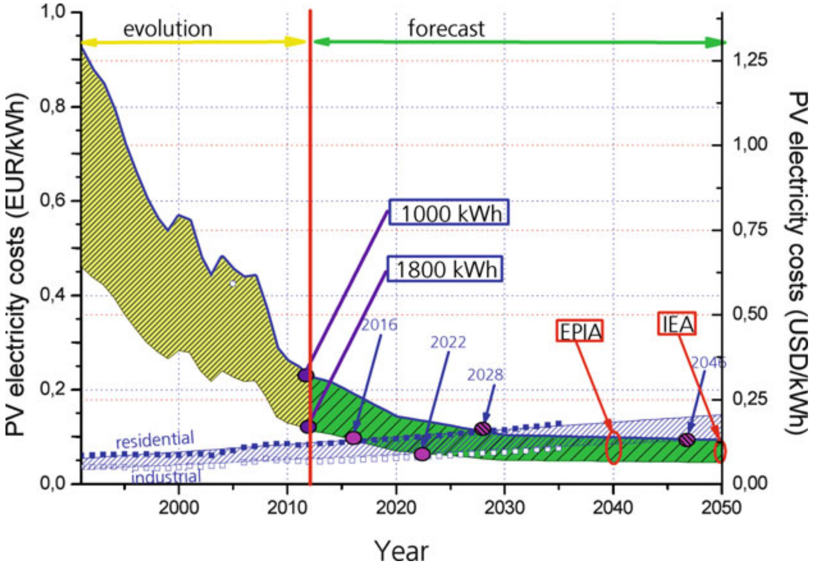

Fig. 6.7 Evolution of the cost of electricity from PV systems in terms of hours of radiation per year and estimations of grid parity compared to the electricity price predictions of the U.S. Energy Information Administration (2010–2035) for residential and industrial uses (based on market and IEA data)

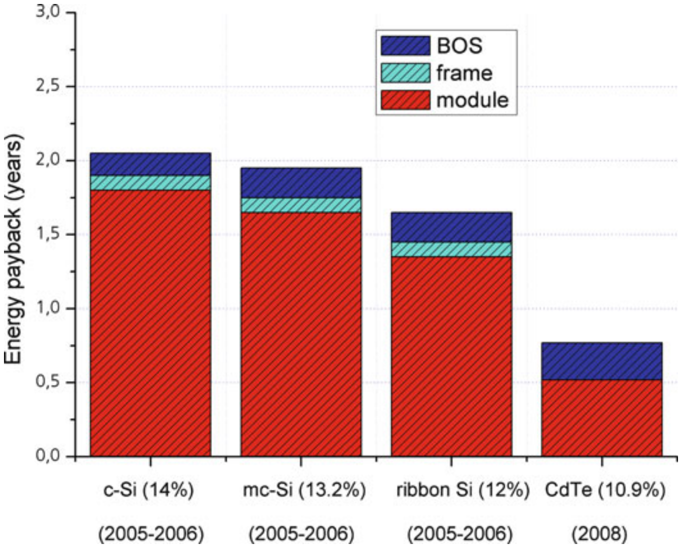

Fig. 6.8 Energy payback time of rooftop mounted PV systems estimated from the currently available LCI data for European production and installation [10]. The estimates are based on southern European irradiation of 1,700 kWh/m^2/year and performance ratio of 0.75

Table. 6.4 Percentage of the total energy required to produce a silicon-based PV module [11]

Energy	c-Si	mc-Si
Si feedstock	32.0 %	44.7 %
Ingot and wafer	47.2 %	27.6 %
Cell production	8.5 %	11.3 %
Module assessment	7.5 %	10.8 %
Frame	4.8 %	5.6 %
Total	100.0 %	100.0 %

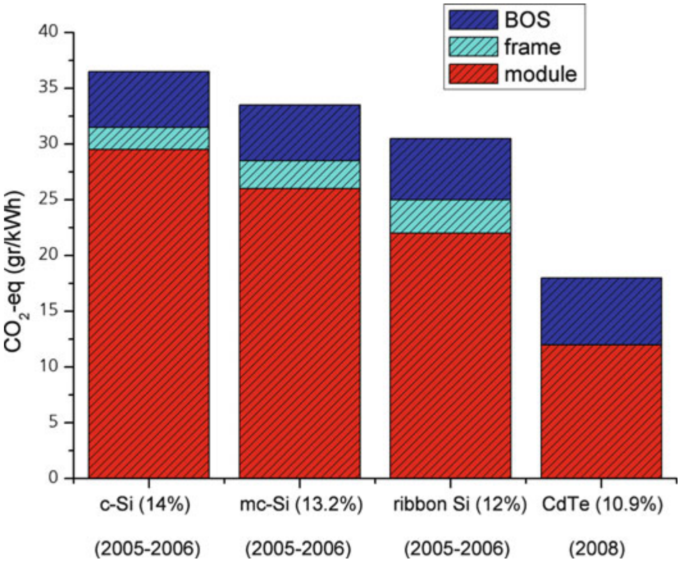

Fig. 6.9 Greenhouse gas (GHG) emissions of rooftop mounted PV systems estimated from the currently available LCI data for European production and installation. The estimates are based on southern European irradiation of 1,700 kWh/m^2/year and performance ratio of 0.75 [11]

depends on the technology used in cells manufacturing, which currently favours thin film technology. These values tend to decline with the development of larger PV production plants and, consequently, more energy efficient.

On the other hand, it is interesting to decompose the different steps in the production of Si-based PV modules in terms of energy consumption (Table 6.4) [11]. It can be appreciated that the main energy demanding steps are related to the Si feedstock, ingot and wafering.

Figure 6.9 shows the most recent and reliable calculations on the equivalent cost of carbon emissions in grams per kWh to produce electricity using PV systems and takes into account the emissions of greenhouse gases for the entire life cycle the photovoltaic cell and a corresponding insolation of 1,700 kWh/m^2/year [11]. The values shown in Fig. 6.9 for multicrystalline silicon are somewhat higher than in the case of nuclear power, but about a factor of 12–30 lower than for gas and coal, respectively.

External costs, primarily related to the environmental damage caused and the risks for health [8], calculated using the ExternE Pol Program elaborated for the European Union [9], and improved with more recent studies funded by the European Union [12], reach USD 25 cents/kWh (EUR 18 cents/kWh) for c-Si modules placed on rooftops and USD 18 cents/kWh (EUR 13 cents/kWh) for CdTe modules.

To calculate the external costs associated with PV, it has been a large debate, because until recently the costs were calculated based on very old production technologies. Then, it was not taken into account in previous calculations the huge technological progress in the last decade in relation to the production of silicon wafers (especially multicrystalline), manufacturing technologies, process automation, etc. Also, it was not taken into account the composition of the energy mix used for the production and installation of the photovoltaic infrastructure (much more environmentally friendly in Europe than in the USA and China).

6.5 Future Technology Trends

Future technological trends in PV move all in the same direction: lowering the production cost of electricity produced. This objective is planned to be achieved through the following interrelated strategies: (1) increasing the efficiency of the cells with the introduction of new concepts, (2) increasing the durability of the modules, (3) simpler production processes and (4) the use of fewer and cheaper materials. Specifically, for each technology, trends in innovation can be described as follows:

6.5.1 Crystalline Silicon Solar Cells

A significant effort is being made in improving the quality of metallurgical grade silicon (cheaper and of poorer quality than the solar grade silicon normally used), and in the development of advanced manufacturing processes for wafers, primarily a greater penetration of epitaxial deposition process, so successful in the manufacture of multijunction solar cells. Also, it is expected to intensify the effort in thinning the thickness of the cells (~30 μm) in order to save on material, but trying to maintain the efficiency values. Moreover, at the moment, 30 wafers per centimetre of ingot is a fairly standard type of wafer yield, but 50 wafers per centimetre by the end of the decade is expected. Better wafering yields and casting bigger ingots plus improved efficiency can produce important cost savings (– 60 %) in the near future [13].

6.5.2 Thin Film Solar Cells

Efforts are focused on increasing efficiency and durability and reducing the cost of the cells, which must be combined with a deep understanding of the properties of the materials that compose the cell. It is also necessary the replacement of some materials due to their high cost (mainly In and Te), and reverse the adverse effects that some materials produce in the environment (Cd). There is also work ahead on the development of new multijunction structures, using lower purity materials and, consequently, lower cost, manufacturing in large areas, and on improving contacts and transparent conductive oxides. In the case of amorphous silicon, the main effort is on controlling the hydrogen content and morphology of the thin layers during the manufacturing process, to avoid the efficiency degradation of the cells when ageing.

6.5.3 Third-Generation Solar Cells

The development of this technology will be primarily based on the application of advances that are occurring in solid-state physics, such as the use of hot electrons, multiple quantum well structures, intermediate band width nanostructures, photon up- and down-conversion, thermophotonics, impact ionisation, IR antennas, multijunction cells with up to 5 p–n junctions; multijunction silicon quantum dots embedded in silicon oxide and the use of silicon nitrides or carbides. The vast majority of these issues are far from commercial application, but offer many opportunities to further increase the efficiency of the cells.

6.5.4 Organic Solar Cells

The main efforts in the development of organic cells are on the stabilisation of the electrical parameters of the solar cells and increasing their efficiency, since both aspects are essential for commercial development and penetration on the market. Additional aspects are the possibility of colour change of these cells for value-added applications in architecture and cell manufacturing on flexible and light substrates that can be printed in any pattern. These characteristics will open organic cells to applications in new and numerous market segments.

6.5.5 Other Future Trends

Finally, it should be noted other common future trends in PV technology, as the development of procedures for recycling activities in decommissioning PV systems, especially the higher value materials, the design of low polluting production processes and installations, increase of the lifetime of the installations to a minimum of 40 years, as well as the development of new non-polluting nanocomposite polymers to seal the cells.

All these trends are coupled with a growing effort to achieve high efficiency PV cells for concentrator systems and to offset the high cost of such cells with a larger capacity for energy production. In this regard, another new concept being explored is the concentrating photovoltaics and thermal design (CPTD), where electricity and heat are simultaneously being produced in a single system.

6.6 Pre-Production Highlights (2009–2011)

6.6.1 Transport Driven by Photovoltaic Energy

On 4 July 2011, the prototype aircraft HB-SIA completed its first European tour, which is serving as a test to achieve in 2012 the first flight around the Earth powered only by solar cells. The plane, of carbon fibre, has a wingspan of 63.40 m, a length of 21.85 m, a height of 6.40 m, weighing 1,600 kg (including 400 kg of batteries with a power density of 200 W/kg), 4 electric motors of 10 hp, 10,748 cells on the wings and 880 on the horizontal stabiliser (c-Si cells 150 μm thick and 12 % efficiency), average speed of 70 km/h and maximum flying height of 8,500 m [14].

On the other hand, the world record in time of continuous flight without landing for an unmanned aircraft and powered exclusively by electricity from PV has been reached last 13 January 2011 by the Zephyr prototype, of the company QinetiQ, with a flight lasting 14 days and 21 min [15].

In ships, on 31 March 2010 was launched in the port of Kiel (Germany) the world's largest solar ship powered solely by PV, which aims to circumnavigate the world. It was successfully achieved on 4 May 2012. The ship is 31 m long and 15 m wide, with a catamaran structure that navigate at an average speed of 8 knots (15 km/h), with 38,000 solar cells with 22 % efficiency placed in a surface of 465 m^2 [16].

On 20 October 2011, the solar car built by the University Tokai of Japan won the Global Green Challenge in which vehicles powered exclusively by solar energy had to travel the 3,000 km between Darwin and Adelaide (Australia). The vehicle had an average speed exceeding 91.54 km/h during the trip (although capable of reaching 150 km/h with a single occupant), being supplied by 1.8-kW multijunction cells occupying an area of 6 m^2 (upper limit of the event) and with an efficiency of 30 % (currently used for space applications) [17].

6.6.2 PV Plants Without Feed-in Tariff Are Planning in Spain in 2012 [18]

Two German solar energy developers are planning to build giant PV plants in southern Spain that will earn a return without government subsidies. Wurth Solar intends to build a 287-MW plant in Murcia region for EUR 277 million, according to the regional authority, and Gehrlicher Solar said it plans to develop a 250-MW park in Extremadura region for about EUR 250 million. These projects, if built, would be about three times larger than any current European solar plant.

6.7 Innovation Highlights (2009–2011)

6.7.1 The New Efficiency Record for Solar Cells Reached 43.5 % [15]

The Junction Solar Company registered in January 2011 this world efficiency record using a multijunction solar cell 5.5 × 5.5 mm, illuminated by a radiation concentration of 400 suns. This record has been confirmed by the National Renewable Energy Laboratory (NREL) of USA. This success has been achieved through the Incubator program partly funded by the U.S. Department of Energy.

6.7.2 Advances in High-Efficiency GaAs Thin Films Manufacturing on Flexible Plastic Substrates [19]

The technique used is chemical vapour deposition from metal-organic molecules. Thus, it aims to exploit the excellent properties of GaAs cells, which place it as the material with greater efficiency in single junction configuration. The estimated efficiency in this new approach reaches 20.5 %, from a stack of six layers of GaAs and AlGaAs doped with Zn and Si to form a simple 1-µm thick pn junction. Subsequently, these cells were integrated on a plastic sheet (PET) of 50-µm thick to form flexible modules with a capacity to adapt to curvature radii greater than 5 mm without suffering any degradation in performance.

6.7.3 Dye-Sensitised Solar Cell Exceeds 12 % Efficiency [20]

Scientists of École Politecnique Fédérale de Laussane have introduced a specific molecular design that greatly retards the rate of interfacial back electron transfer from the conduction band of a nanocrystalline titanium oxide film to the oxidised cobalt mediator. Thus, it enables attainment of strikingly high photovoltages approaching 1 V. Because this molecular design harvests sunlight across the visible spectrum, large photocurrents are generated. Co-sensitisation of this molecular design with another organic dye further enhances the performance of the device, leading to a measured power conversion efficiency of 12.3 % under simulated air mass 1.5 global sunlight.

6.7.4 Peak External Photocurrent Quantum Efficiency Exceeding 100 % [21]

This record has been achieved by multiple exciton generation (MEG), a process that can occur in semiconductor nanocrystals, or quantum dots (QDs). In this process,

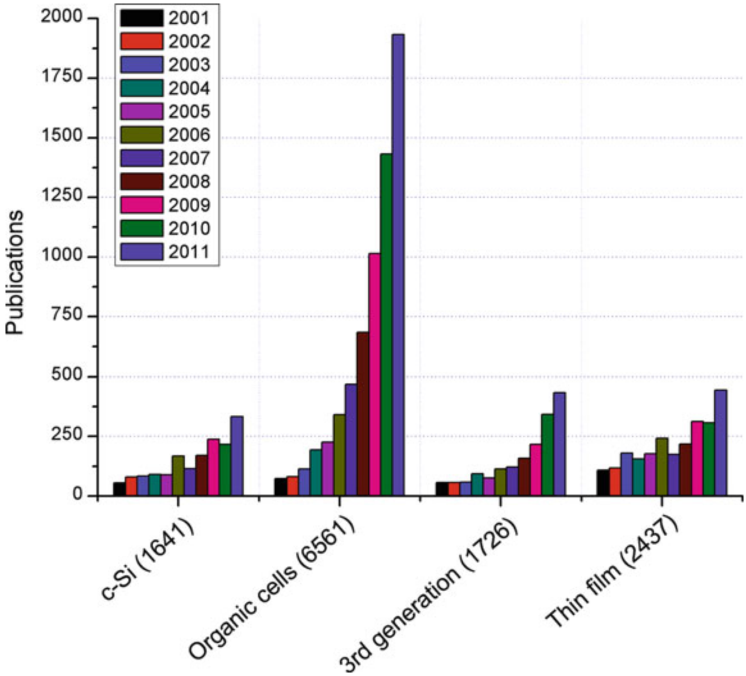

Fig. 6.10 Number of scientific publications during the period 2001–2011 for different solar cells technologies [22]

absorption of a photon bearing at least twice the bandgap energy produces two or more electron–hole pairs. The researchers report the photocurrent enhancement arising from MEG in lead selenide (PbSe) QD-based solar cells, and manifested by an external quantum efficiency (the spectrally resolved ratio of collected charge carriers to incident photons) that peaked at 114 % in the best device measured. The associated internal quantum efficiency (corrected for reflection and absorption losses) was 130 %. The results demonstrate that MEG charge carriers can be collected in suitably designed QD solar cells to enhancing the efficiency of solar light harvesting technologies.

6.8 Statistics of Publications and Patents

Figure 6.10 shows the number of scientific publications during the period 2001–2011 for different solar cells technologies [22]. It is observed that the number of publications is maintained in an almost inverse relation to the degree of development of each cell technology. This is because the scientific literature often focuses on the newest research areas in PV. Consequently, when a technology is highly developed in the market, it is more difficult to publish something original, which is the case for Si-based solar cells.

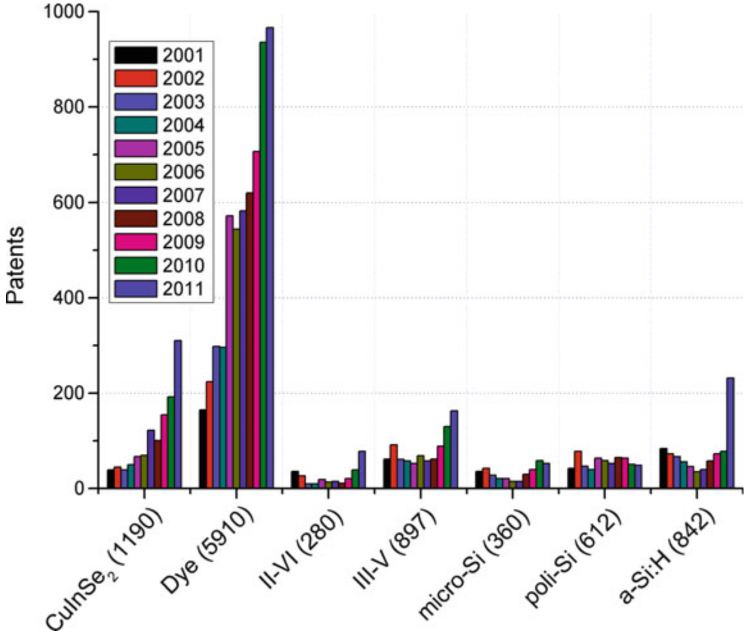

Fig. 6.11 Number of worldwide patents approved during the period 2001–2011 for different types of solar cells [23]

On the other hand, scientific production is higher in thin-film solar cells, as very often new materials are being tested to reduce the cost and the energy payback of the devices. In the case of CIGS cells, there are constantly testing different stoichiometries, as well as passivation and encapsulation methods to increase its stability and lifetime. The role of the grain boundaries of polycrystalline films in the lifetime values of carriers is also gaining interest.

Obviously, third-generation solar cells have more activity than the two previous technologies, since its operation is based on nanotechnologies and very novel physical properties, such as photon up- and down-conversion processes, multijunctions, intermediate gaps, hot electrons and impact ionisation, and in particular quantum wells. This research activity is varied and is booming in the scientific community, exemplified in terms of publications, although some production shortage is detected in the 2010 literature.

Contrary to the former, organic cells are receiving considerable attention in recent years that remains increasing. This is attributed to its low production costs and no high vacuum system required for its manufacturing. Another possible reason for high activity can be due to some overlapping with research in related devices, as organic light emitting diodes (OLEDs). Obviously, another advantage that generates research activity is that these cells can be manufactured on flexible substrates. In all these topics focuses the bulk of the literature in this area, which moved the third-generation cell technology in 2010 to a second position in terms of scientific production in the literature.

In general, there is an upward trend in scientific production, especially in organic cells, which is an unmistakable sign of the growing interest in the scientific community working on the development of PV technology and in which research is expected to produce future technological advances.

In relation to the evolution of the number of patents approved in 2001–2011 [23], it is detected some correlation with the evolution in the production of scientific and technological literature. Thus, it is clear the domain of patents related to organic cells, followed by thin film at a large distance (Fig. 6.11). In both technologies, it is detected an obvious growth, which indicates that these technologies are not yet consolidated, contrary to that observed in other technologies, where the number of approved patents is smaller and constant throughout the recent years.

Among the other technologies that show a lower number of patents than the dye and thin film solar cells, the III–V semiconductors show an important activity, which can be attributed to the growing interest in improving the efficiency records in photovoltaics, mainly in multijunction III–V semiconductor structures. There is also a recovery in the number of patents on amorphous silicon in recent years, which can be associated with and increased activity in the thin film area.

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Chapter 7
Concentrated Solar Power

Abstract After photovoltaics (PV), concentrating solar power (CSP) is at present the major technology for producing solar electricity. Generally, CSP uses concentrating high-reflective mirrors to generate high-temperature thermal energy that is fed into conventional steam or gas turbines for the production of utility-scale power. Within CSP systems, the most mature are the parabolic trough systems, which concentrate the energy from the sun by means of long cylindrical mirrors of parabolic cross section. Next in popularity are the tower systems, which use a large field of numerous flat mirrors (heliostats) to concentrate the solar direct radiation into a receiver located at the top of the tower. Also, parabolic dishes and linear Fresnel reflectors must be considered. These technologies are described in this chapter and grid parity is analysed and expected to be reached soon for locations with strong solar direct irradiation. Finally, in relation to CSP, it is important to emphasise how thermal storage as well as natural gas hybridisation can be easily added, thus practically eliminating the power intermittencies of other important renewable technologies.

7.1 Overview

Concentrated Solar Power (CSP) uses mirrors as optical elements to concentrate solar energy and converting it into thermal energy at medium (300–600 °C) and high ($\geq$600 °C) temperatures. This thermal energy, usually carried by steam or hot air, is used to move turbines and, consequently, to produce electricity. Therefore, unlike PV solar cells, which "directly" produce electricity from the sun, for CSP the sun energy is transformed into thermal energy in an intermediate step before producing electricity. When the temperatures reached are high enough ($\geq$600 °C), the CPS systems could be considered for solar fuel production, mainly hydrogen.

Generally, in CSP plants, the previously concentrated solar energy heats a fluid (heat carrier), which moves an engine or turbine according to a specific

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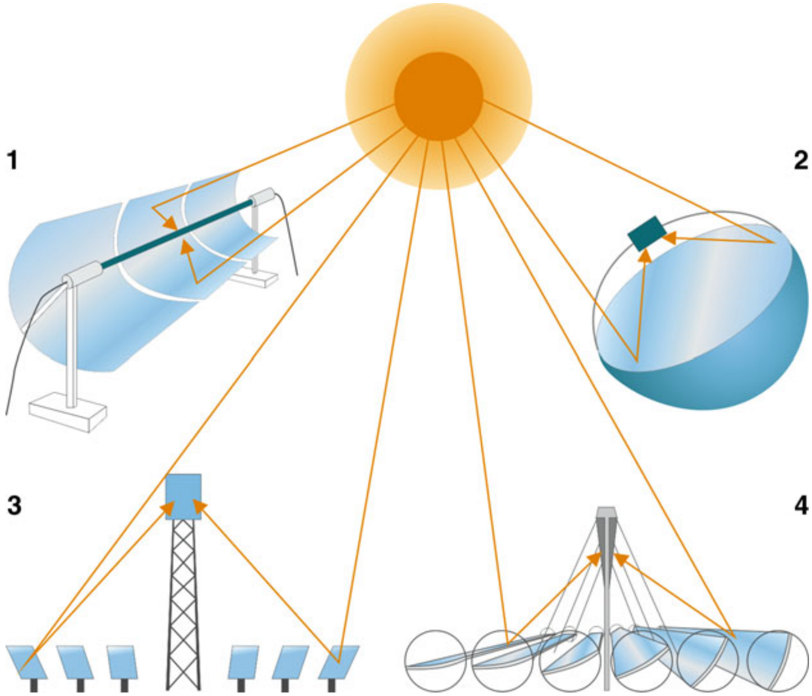

Fig. 7.1 Different CSP technologies: (1) parabolic troughs; (2) parabolic dishes; (3) tower and (4) linear Fresnel reflectors

thermodynamic cycle (Rankine, Brayton, Stirling, etc.). The different CSP technologies are classified in relation to the characteristics of the mirror system: (1) parabolic troughs; (2) parabolic dishes; (3) flat mirrors, called heliostats, focused on a receptor located in a tower and (4) linear Fresnel reflectors, where no solar tracking is needed (Fig. 7.1).

To adjust the power demand from the grid to the power output of the CSP plant and to levelised falls in electricity production due to momentary cloudy weather, increasing number of CPS plants are associated to thermal storage systems, which are much more efficient than electricity storage systems.

Figure 7.2a shows the evolution of the world electricity output from solar thermal energy, and Fig. 7.2b shows the worldwide CSP capacity in operation at present (2011) and since it was first introduced in the 1980s. As it can be observed, in 1999, a sudden fall in electricity output was recorded, attributed to a breakdown of a large CSP power plant, but no official information has been obtained in this respect. After this event, the electricity output started to increase again. This recent rise in electricity output is attributed to a simultaneous rise in CSP capacity.

The CSP capacity installed worldwide and in operation in 2011 consists mainly of parabolic troughs (1,705 MW), and to a lower extent on tower systems (56 MW), linear Fresnel reflectors (6.4 MW) and parabolic dishes (1.5 MW).

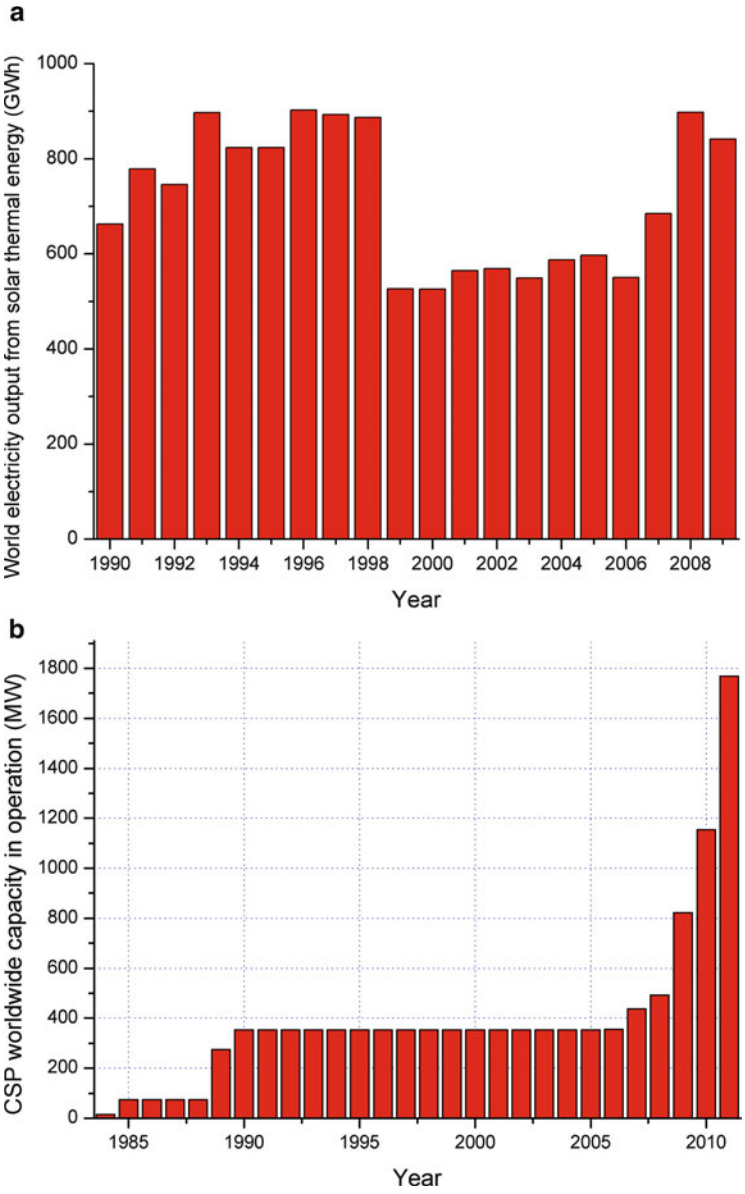

Fig. 7.2 Evolution of the (**a**) world electricity output from solar thermal energy, and (**b**) world CSP capacity in operation at present and since CSP systems were first installed (source: NREL)

The solar energy that CSP plants exploit is the direct component normal irradiance (DNI), which is the energy received on a surface tracked perpendicular to the sun's rays. This is because the diffuse component cannot be optically focused.

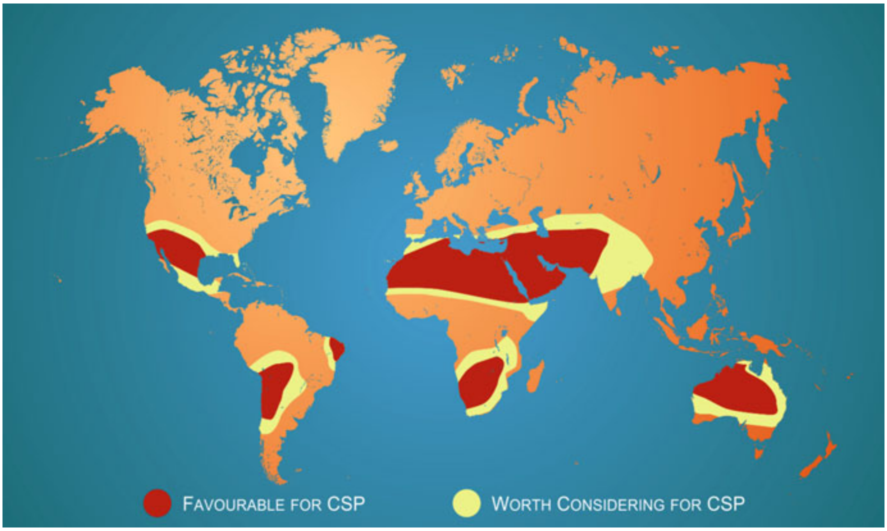

Fig. 7.3 Optimal geographical areas for installing CSP plants [2]

CSP developers typically define a bottom threshold for DNI of 1,900–2,100 kWh/m^2/year [2]. DNI measures provide only a first approximation for a CSP plant's electrical output potential. In practice, it is more important the variation in direct sunlight over the course of a day, as below a certain threshold, CSP plants have no net production, due to constant heat losses in the solar field. Optimal DNI is usually found in arid and semi-arid areas with reliably clear skies, which typically lay at latitudes from 15 to 40° North or South (Fig. 7.3). Closer to the equator, the atmosphere is usually too cloudy and wet in summer, and at higher latitudes than about 40º, values of the DNI are small, and besides the weather is usually too cloudy. DNI is also significantly larger at higher altitudes, where absorption and scattering of sunlight are much lower.

7.2 State of the Art

7.2.1 Parabolic Troughs

Parabolic troughs represent the most mature technology. The mirrors have typical concentration ratios between 50 and 200 suns and, consequently, the heating carrier temperature is not high enough to consider this technology as suitable for thermochemical solar fuel production. The mirror arrays can be more than 100 m long with a curved surface 5–6 m across. The structure can rotate on an axis parallel to the north–south direction. The movement is controlled by a computer algorithm that contains the position of the sun throughout the day. The thermal fluid (mainly, a special oil or deionised water) circulates through a tube along the cylinder axis and it is usually made of a metal, e.g. stainless steel covered by a highly absorbing

Table 7.1 Approximate values of current efficiencies and areas required for CSP technologies

	Tower	Trough	Dish	Fresnel	Storage
Peak Efficiency (%)	20–35 (concepts)	15	25–30	8–10	98[e]
Area needed (m^2/kW)	47.5[b]	23[c]	4[a]	15[f]	18 (7 h)[d]
Solar fuels	Yes	No	Yes	No	

[a] http://www.eere.energy.gov/troughnet/pdfs/solar_overview.pdf

[b] PS20 (Abengoa)

[c] Solnova I (Abengoa)

[d] Trough technology (Abengoa)

[e] "Energy storage: How solar can always meet demand". Renewable Energy World. October 2008

[f] NEEDS

optical film and insulated in an evacuated glass envelope. This tube is surrounded by a highly transparent Pyrex glass or quartz. The conversion efficiency to thermal energy can reach 60 %, while the electricity conversion efficiency can range between 8 and 35 % (Table 7.1) [1]. Troughs technology has been tested successfully in several CSP plants for many years, using a variety of transfer fluids: molten salts, mineral oils, water vapour, etc.

7.2.2 Tower Systems

In tower systems, also known as central receiver systems (CRS), the flat mirrors or heliostats focus the solar energy onto a receiver located on top of a tower. Each heliostat has a typical surface around 40–120 m^2 and a two-axis tracking system to focus all the mirrors on the receiver. The typical solar concentration in the receiver is about a thousand suns. Then, the heated fluid temperature at the receiver can be high enough to consider this technology as suitable for solar fuel production. The heated fluid can be used directly to move turbines, or/and be directed to a thermal exchanger for storing its thermal energy.

7.2.3 Parabolic Dish Concentrators ("dishes")

These collectors focus solar radiation onto a small punctual area located on the parabolic focus. The concentration ratio ranges between 3,000 and 10,000 suns and can heat the carrier fluid to temperatures above 600 °C. Then, the heating carrier temperature can be high enough to consider this technology as suitable for solar fuel production. With these high temperatures, the highest electricity conversion efficiencies of all CSP technologies can be obtained (Table 7.1). Due to its geometry, two-axis orientation tracking systems are needed to obtain maximum solar radiation parallel to the axis of the dish mirror. The dish technology is not widespread and is usually associated with relatively small plants, between 10 and 20 kW, and with Stirling heat engines (or microturbines) placed at the focal point. This design eliminates the need for a heat transfer fluid and for cooling water.

7.2.4 Linear Fresnel Systems

In this case, no tracking system is needed to concentrate the sun radiation because the Fresnel mirrors direct the sun light to the heat exchanger ideally at any incidence angle. However, the electricity conversion efficiency is the lowest of all CSP systems (Table 7.1). Then, the heating carrier temperature is not high enough to consider this technology as suitable for solar fuel production and also introduces many difficulties for efficient thermal storage. This low conversion efficiency is expected to be compensated by a significantly lower production cost than any other CSP technology and less area per kW needed than parabolic troughs and tower systems.

7.2.5 Thermal Storage

When this option is included in the CSP plant design, the size of the solar field must be increased in order to capture the extra energy required to be stored when sun light is available. A large variety of materials for thermal storage are used in different CSP plants, mainly thermophysical storage materials: (1) molten salts, which consist of a eutectic mixture of salts (typically a 60 % $NaNO_3$/40 % KNO_3, with ranging work temperatures of 260–565 °C); (2) mineral oils, which should be non-toxic or flammable and are therefore costly; (3) water/steam for direct transfer of steam to the turbine (the storage time is less than for molten salt for the same storage volume) and (4) air, as it has very low cost and easy handling. The thermophysical approaches rely on changes in a system's physical state and use sensible heat (by increasing the temperature of the storage material), latent heat (absorbed at a constant temperature, as in a phase change) or both, and thermal insulation is needed to minimise heat losses to the environment.

Thermochemical storage materials are the alternative option, where chemical reactions reversibly store energy without a need for insulation. Despite the advantages of enabling high energy density and insulation-free long-term storage, thermochemical technologies have yet to be widely used. On the other hand, thermophysical storage relies primarily on liquids and solids and offers high volumetric energy density but low gravimetric energy density. Thermochemical systems generally contain at least one gas-phase component, affording light weight but requiring large volume in the absence of mechanical compression [1].

The solar multiple is the ratio of the actual size of a CSP plant's solar field compared to the field size needed to feed the turbine at design capacity when solar irradiance is at its maximum (about 1 kW/m^2). Plants without storage have an optimal solar multiple around 1.1–1.5 (up to 2.0 for linear Fresnel reflectors), depending primarily on the amount of sunlight the plant receives and its variation throughout the day. Plants with large thermal storage capacities may have solar multiples of up to 3–5 [2].

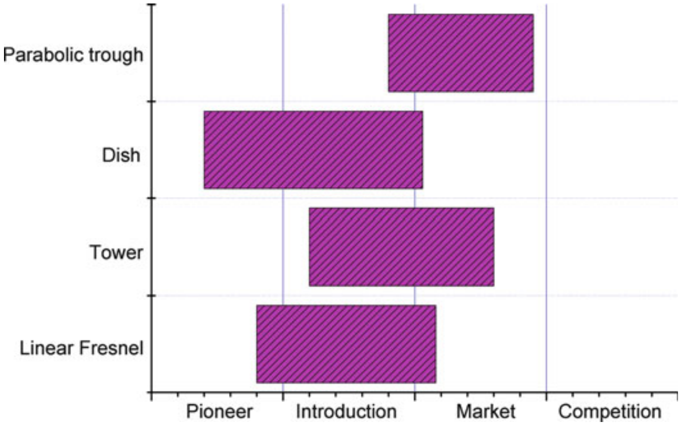

Fig. 7.4 Stages of development for each CSP technology considered in this chapter

A last aspect to be considered is the attractiveness to ensure continued electricity production, which can also require biomass or fossil fuel input (e.g. natural gas) to provide energy for the CSP plant turbines when sun radiation and storage is not available.

7.2.6 Water Consumption

CSP plants require water for cooling and condensing processes, and this resource is difficult to obtain in desert areas where the sun direct radiation is high enough to produce high power outputs. CSP water requirements are about 3,000 l/MWh for parabolic trough and linear Fresnel plants, compared to about 2,000 l/MWh for a conventional coal plant and only 800 l/MWh for combined-cycle natural gas plants. Tower CSP plants water needs are less than for trough plants but depend on the efficiency of the technology. Dishes are cooled by air [2].

Dry cooling (with air) is an alternative for all CSP technologies, but it is more costly and reduces efficiencies. Dry cooling installed on trough plants in hot desert areas reduces annual electricity production by 7 % and increases the cost of the produced electricity by about 10 %. These values are somewhat lower for solar towers than for parabolic troughs [2].

7.2.7 Stages of Development

Depending on the degree of market penetration, the various CSP technologies can be classified in different stages of development (Fig. 7.4). None of the CSP technologies can be considered in a competition stage, since in almost all countries incentives are required for CSP plants. However, all technologies are in a market phase, considering that all of them have plants over 1 MW currently in operation.

Table 7.2 Investment costs of a 50-MW trough plant associated to a 7-h thermal storage system

Concept	%
Solar field	30
Allowances	14
Storage	9
Project management	8
Balance of plant	8
Civil works	7
Project finance	6
Heat transfer fluid	5
Power block	5
Project development	3
Grid access	3
Miscellaneous	2

Then, considering the power capacity currently in operation worldwide (exposed above), parabolic troughs are ahead in terms of development, followed by the tower systems. Linear Fresnel and dish technologies are also entering in the market stage.

7.3 Current Costs and Future Scenarios [3]

Evidently, the cost of electricity produced by CSP plants depends on the direct component of solar irradiation on the geographical location where it is built and the technology selected, and on many other factors that can be included in a deeper CSP cost analysis [4].

The investment costs for large parabolic trough plants typically range from USD 4.3–8.5/W (EUR 3.1–6.1/W), depending on different parameters exposed in Table 7.2 [2]. Plants without storage systems and located in highly sun irradiated areas are on the lower range of investment costs. Investment costs for parabolic trough are expected to decrease by 20 % when CSP plants are scaled up to 200 MW.

Tower investment costs are more difficult to estimate but are generally higher than for trough systems. However, increasing efficiency from 15 to 25 %, mass production of flat mirrors and technology maturity could bring the investment costs down by 40–75 % [5]. Dish investment costs are about twice those of parabolic troughs [5].

The levelised electricity costs are about USD 0.203–0.300/kWh (EUR 0.146–0.215/kWh) for large trough plants, technology for which the figures are more readily available [5]. However, the actual cost depends mostly on the available sunlight.

We can consider the range exposed for the levelised electricity costs and expected for 2050 [5] to define the grid parity graph for the CSP technology. These costs are compared to the average generation electricity price expected in USA and the linear fit of the average generation electricity price in the Spanish wholesale market from 1999 to 2010 (Fig. 7.5). As it can be observed, for highly

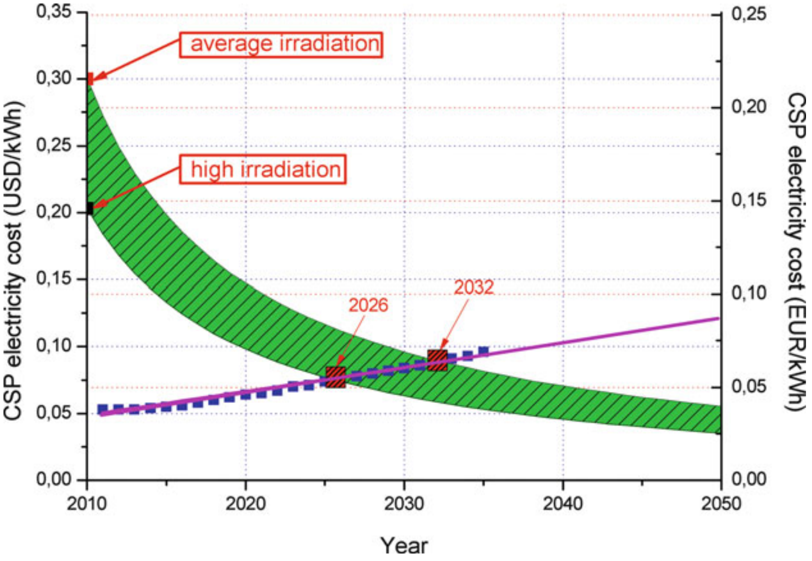

Fig. 7.5 Current CSP electricity costs and forecasts to 2050. The *solid square* represents the generation electricity costs expected in USA and the *magenta straight line* represents the linear fit of the average generation electricity price in the Spanish wholesale market

sun irradiated regions, grid parity is not expected until 2026 and 2032 for average sun irradiated regions.

For thermal storage costs, some studies [6] indicate that they introduce an extra cost for electricity production ranging at 2.6–7.5 %, depending on the technology used. Other studies [7] indicate that the technology using PCM is 2.5 % cheaper compared to the technology based in two tanks storage, while the technology using storage in concrete passive systems is 11.9 % more expensive. These cost values vary not only in terms of construction costs but also on how the plant is operated. Then, operational procedures as defocusing of the mirrors, adjusting the storage procedure based on the weather conditions at the beginning of the day, or the optimal time to discharge the storage systems are important issues to be considered to reduce storage costs.

7.4 Energy Payback, CO_2 Emissions and External Costs [8,9]

The CSP technology has acquired momentum just recently and, consequently, very little data is available about energy payback rate, CO_2 emissions and external costs. Thus, the ExternE-Pol project [8] did not analyse this technology. However, the NEEDS project [9] provides the first data about these environmental impacts. Then, the estimated external costs associated with CSP technology are USD 0.35 cents/kWh (EUR 0.25 cents/kWh).

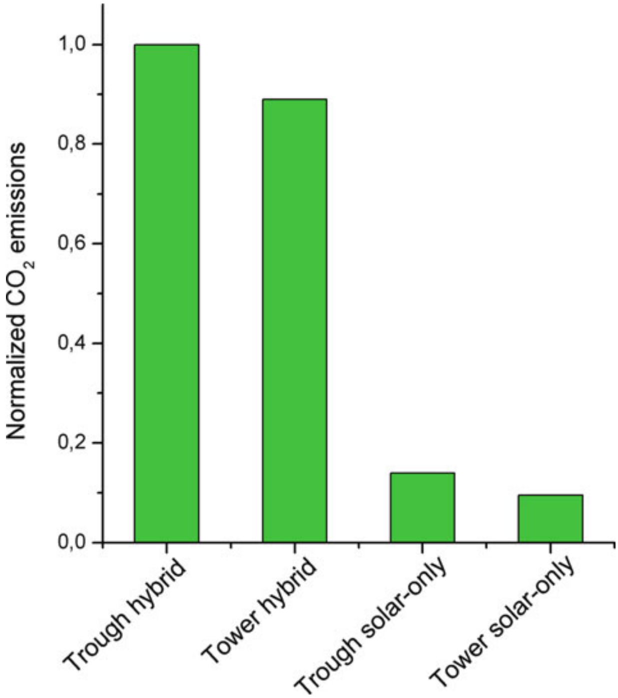

Fig. 7.6 Normalised CO_2 emissions for different CSP technologies

CO_2 emissions are about 10–15 g CO_2-eq/kWh using solar energy exclusively. There have been more detailed studies [9] showing how CO_2 emissions can be about eight times larger when hybrid CSP technology (combined with natural gas) is analysed, compared to CSP systems operating with solar energy exclusively (Fig. 7.6).

Also, these studies demonstrate that the tower technology is less polluting in terms of GHG emissions compared to the remaining technologies because it is less materials-intensive. Also, it has been considered the significant increase in N_2O emissions when CSP technology includes thermal storage in molten salts, as these salts need nitric acid for the manufacturing process.

No official data or published relevant work has been found about energy payback related to CSP technologies.

7.5 Future Technology Trends

7.5.1 Parabolic Trough

Due to the high price of mineral oil, steam is being tested as the heating transfer fluid (direct steam generation). A related problem is that superheated steam creates large mechanical stresses in the pipes for the transfer heat fluids. Consequently, to reduce these tensions, the flow patterns and steam transfer in horizontal tubes are being modelled. One recent innovation also promotes the use of ionic liquids (molten salts) for heat transfer media [10], as they are more heat-resilient than oil, and thus corrode the receiver pipes less. However, ionic liquids are very costly.

On the other hand, wider troughs, with apertures close to 7 m (versus 5–6 m currently), are under development and offer the potential for incremental cost reductions. Also, the current glass-to-metal welding of the evacuated tubes that collect the concentrated solar energy could be replaced with a mechanical seal, if it prove capable of preserving the necessary vacuum for 20 years or more.

7.5.2 Tower System

As it has been mentioned above, this technology produces high temperature heat. Working at temperatures around 800 °C, the heating transfer fluid could feed directly the gas turbines, achieving high electricity conversion efficiencies (around 50 %). Improved efficiency also means a lower cooling load, thus reducing water consumption by wet cooling in plants located in arid areas. Then, technology improvements are on course to test solar towers with supercritical steam (or carbon dioxide) cycle as those used in modern coal-fired power plants, or with air receiver (tested in Germany with the Jülich solar tower project) and gas turbine (solar-based Brayton cycles). Also, a new concept of distributed power towers (20 MW each) linked by pipelines to a single power plant is being considered for new 100–200 MW capacity CSP plants.

On the other hand, large heliostats with aperture areas of 62–120 m^2 and multiple mirror facets are expected to increase their size up to 150 m^2. With this size increase, the total number of tracking system drives would decrease, reducing tracking system costs per m^2.

7.5.3 Parabolic Dish

The main efforts for this technology is to increase the power capacity of the related CSP plants (up to 300 MW), to introduce mass-production manufacturing plants of parabolic dishes with Stirling engines and demonstrating long-term reliability.

On the other hand, there are currently two types of Stirling engines: kinematic and free piston. Both engine types are expected to evolve in order to materialise significant cost savings [11]. Multi-cylinder engines are also expected to be applied in the short term.

7.5.4 Linear Fresnel Systems

Currently, linear Fresnel technology is a hot topic, especially for small CSP plants, because of the expected low investment costs compared to the parabolic trough technology. The cost of the structures that hold the optical elements and their maintenance would be much cheaper for linear Fresnel systems than for parabolic trough systems. One of the most important efficiency improvements for Linear Fresnel systems is expected from the possibility of working with superheated steam. To achieve this, the enhancement of the receiver's absorptance, emittance and improved design, as well as more resistant receiver pipes that can withstand higher pressures (100 bars for superheated steam), is needed. Another improvement associated to this technology will be the commercialisation of Linear Fresnel power plants with added storage, but these systems have yet to be demonstrated.

7.5.5 Thermal Storage

To design future storage systems, scientists and engineers need to explore new media for thermal energy storage, mainly, ceramics, concrete and test alternative thermochemical cycles. Adding nanoparticles to increase the heat capacity of molten salts is an option. Also, lithium-based molten salts could contribute to increase the current maximum operating temperature and reduce the freezing point from 230 °C to 130 °C [11]. This would reduce freezing risk and the plant's parasitic costs, but it also could increase the investment costs.

Another possibility is to use thermocline separation between hot and cold molten salts in a single tank, mainly for small and medium-sized plants (<30 MW) [11], but leakage risks are more difficult to manage in this case.

Storage constitutes a challenging issue in CSP plants that use direct steam generation. Small amounts of saturated steam can be stored in accumulators, but this is costly and difficult to scale up. However, effective full-scale three-stage storage plants that pre-heat the water, evaporate the water and superheat the steam could be an option to overcome this requirement.

In relation to alternative thermochemical cycles, there is currently great interest in increasing the temperature of the receiver systems and, consequently, to enlarge the number of endothermic chemical reactions that can produce chemical carriers to store energy. For this purpose, research activity is on course to design and test various open and closed thermochemical cycles. Among these is the reversible NH_3 cycle decomposition into nitrogen and hydrogen. Another reversible cycle being studied is the solar reforming of methane with water or CO_2, decomposed into CO and hydrogen.

There are several other possible thermochemical cycles with the added interest that many of them lead to the production of hydrogen. These cycles mainly consist in breaking the water molecule, although the high temperatures required for the necessary endothermic reactions currently involve a technological challenge. Other cycles produce a syngas mixture of hydrogen, as the carbothermal reduction of metals, that could take place at lower temperatures. Hydrogen from CSP could be used in today's energy system by being blended in natural gas networks up to 20 % of volume [2].

Above 1,200 °C, efficient two-step cycles using reversible reduction–oxidation (redox) reactions can be used. The two steps can be separated in time and place, offering interesting possibilities for producing energy carriers. Dedicated concentrated solar fuel plants deoxidise light elements, which are easily transported to customers, where their oxidation with water produces hydrogen. Oxides are then returned to the solar plants. Aluminium, magnesium, iron and non-metallic elements such as boron are candidates as energy carriers for this purpose.

Finally, it is necessary to optimise the heating charging and discharging of the storage system. Variables as weather conditions at the beginning of the day, control of the repeatability of the storage process, or savings losses by controlled solidification processes should be optimised.

7.5.6 General Technology Trends

One of the main research efforts is on rising the process temperature above 700–800 °C in order to improve the thermodynamic efficiency and to promote alternative thermochemical cycles for energy storage. In this sense, it is expected an increased role of hydrogen as energy carrier in the coming decades and obtained from CSP-based thermochemical cycles.

Another interesting route for hydrogen production is using wide gap semiconductors as titanium or tungsten oxides. These oxides are inexpensive, stable in aqueous solutions and can be made as nanoparticles or nanowires. When sunlight irradiates these nanoconductors, it creates currents of electrons and holes that induce the water thermolysis and simultaneous hydrogen release.

It will also be important to develop new optical materials to increase the reflection of mirrors and the optical absorption of the solar absorbers. These materials must be chemically stable in harsh environments and high temperatures. Self-cleaning properties and thinner mirrors are also valuable, i.e. polymeric reflective glass to replace the current mirrors can provide longer and less costly sunlight reflectors. As the mirrors cost is an important component of CSP investment, research in new reflector materials is a key element on reducing costs.

Moreover, specific turbines adapted for CSP systems, with increasing power capacity of about 150–200 MW, achieve economies of scale that could diminish CSP investment costs. These turbines would be directly powered by the steam produced in the solar collector, and can be designed with materials capable of withstanding higher temperatures. Some of these new turbines are equipped with dry cooling systems to avoid conventional water-based cooling systems, as some CSP locations are in deserts where water is not easily available.

In relation to improving mirror maintenance, special coatings with anti-soiling and hydrophobic properties are being tested by mirror manufacturers in order to decrease mirror's cleaning requirements. Anti-soiling coatings prevent the accumulation of dirt and dust on the mirror's surface, which can reduce the number of washing cycles by 50 %. Hydrophobic coatings can reduce the amount of required water for cleaning mirrors by 30 % [11]. In parallel, further efforts are undergone to reduce the labour costs of mirror cleaning with the development of special cleaning robots. Some linear Fresnel and tower systems already use such robots.

Finally, work is in progress on prototypes to combine CSP and CHP technologies for desalination and electricity production in arid countries. These hybrid systems will increase very significantly the overall efficiency of the plant.

7.6 Pre-Production Highlights 2009–2011

7.6.1 *DESERTEC Project to Feed Europe with Electricity from Sahara Desert [12]*

Twelve companies, nine German, Swiss ABB, Algerian Cevital and the Spanish Abengoa Solar signed in Munich on 13 July 2009 the declaration of implementation of the Desertec Industrial Initiative (DII). This project intends to use the Sahara Desert to install up to 100 GW of solar power plants that supply CSP-based electricity to Europe, Africa and Middle East. The first 3 years of this project are devoted to develop the conditions necessary to implement the project. Investment costs are evaluated at EUR 400,000 million (USD 557,000 million) until 2050. The Desertec Industrial Initiative is planning to start locating a 500-MW CSP plant in Morocco, near the city of Ouarzazate, starting the construction phase in 2012 [13]. The investment cost associated to this CSP plant is estimated in about EUR 2 billion (USD 2.8 billion) and the plant will occupy 12 km^2.

7.7 Innovation Highlights 2009–2011

7.7.1 *A new Computationally Efficient Model and Biomimetic Layout for Heliostat Field Optimisation [14,15]*

Using a detailed calculation of the annual average optical efficiency accounting for cosine losses, shading and blocking, aberration and atmospheric attenuation, a new biomimetic heuristic placement has been described and evaluated. The pattern is inspired by the spirals of the phyllotaxis (sunflower) disc design and generates layouts of both higher insolation-weighted efficiency and higher ground coverage than radially staggered. This new heuristic project is shown to improve the existing PS10 system field (Seville, Spain) by 0.36 % in efficiency while simultaneously reducing the land area by 15.8 %.

7.7.2 *Thermochemical Dissociation of CO_2 and H_2O Using non-Stoichiometric Cerium [16]*

By using a solar cavity-receiver reactor, oxygen uptake and release capacity of cerium oxide and facile catalysis at elevated temperatures ($T_{\max} = 1{,}640\ °C$) has

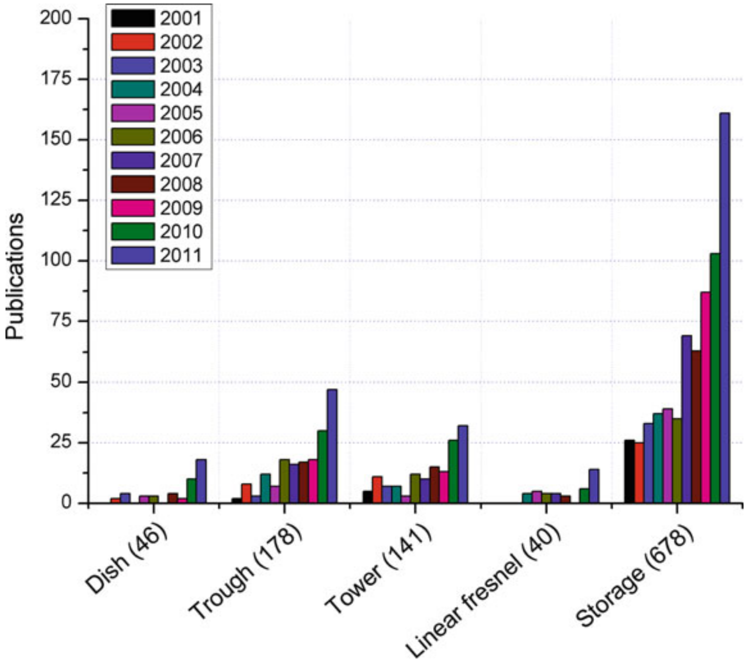

Fig. 7.7 Number of scientific publications during the period 2001–2011 for the different CSP technologies and storage systems [17]

produced the thermochemical dissociation of CO_2 and H_2O, yielding CO and H_2 as by-products. Stable and rapid generation of fuel was demonstrated over 500 cycles. Solar-to-fuel efficiencies of 0.7–0.8 % were achieved and shown to be largely limited by the system scale and design rather than by chemistry.

7.8 Statistics of Publications and Patents

Figure 7.7 shows the number of scientific publications during the period 2001–2011 for the different CSP technologies and storage systems [17].

It is observed that the number of publications for each technology is quite low (except for storage systems), relative to the activity detected in other technologies exposed in this book. This result can be interpreted in terms of the number of research groups worldwide working in CSP technology and the number of experimental facilities devoted to this research area.

However, the significant and growing activity in thermal storage can be explained by considering the attractiveness of this technology to extend solar-based power supply, define solar-based energy carriers obtained from thermochemical cycles and to solve solar irradiation intermittencies associated to weather conditions.

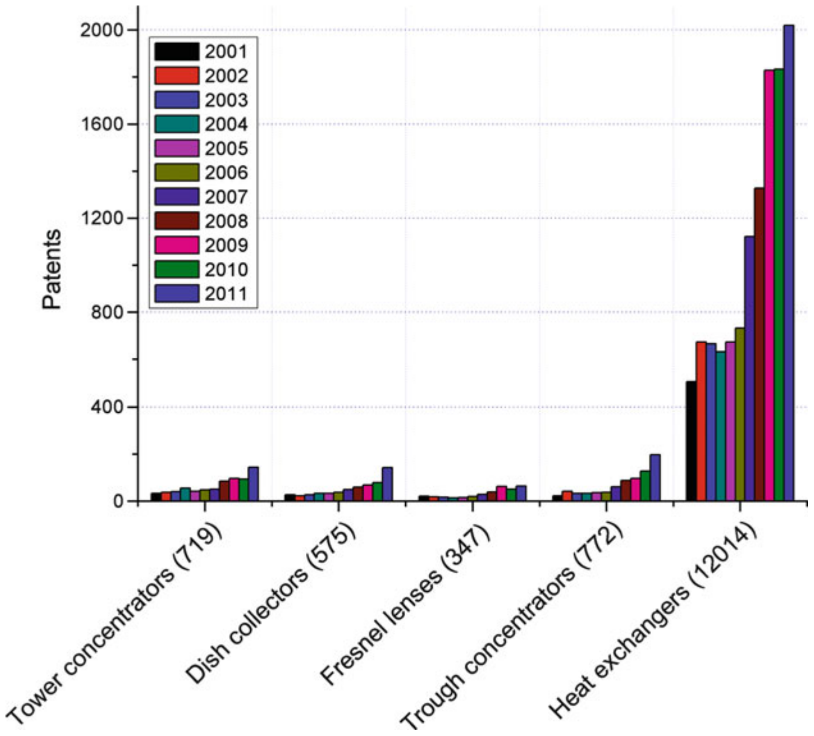

Fig. 7.8 Number of patents during the period 2001–2011 for the different CSP technologies and storage systems [18]

Within the CSP technologies, research activity in parabolic trough and towers dominates, while lower research activity is detected in dish and linear Fresnel systems. These results can be interpreted as a consequence of the high costs exposed above for dish technologies and the low efficiency associated to linear Fresnel technology. However, in general, there is an upward trend in the number of scientific publications, which is indicative of the growing interest on these technologies, mainly in matters related to thermal storage.

In terms of patents, the evolution is quite similar to that of publications (Fig. 7.8) [18]. In this respect, the number of patents devoted to storage is impressive compared to proper CSP technologies. On the other hand, the difference in number of patents between the most recognised CSP technologies (parabolic trough and tower systems) and the less mature (dish and linear Fresnel systems) is reduced compared to scientific publications. This may be attributed to the easiness to construct prototypes of dishes and linear Fresnel systems and the attractiveness that both technologies offer in terms of improving work temperature and low cost, respectively.

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Chapter 8
Wind Power

Abstract Wind energy power generation has experienced an impressive annual growth during the last decade and represents today the highest amount of the electricity produced by all renewable resources if hydroelectric power is excluded. Wind energy can be considered at present a mature technology with production costs, which reach grid parity, under favourable conditions and high capacity factors. In this chapter, we make a review of the future technology trends, as for example the construction of very large wind turbines (5–10 MW) with hub heights around 150 m, and therefore being able to access to much faster winds than those close to ground. However, the main development in wind energy technologies is related to the deployment of off-shore wind farms, since offshore wind speeds are usually higher than those on land, and especially more continuous in time. Other interesting future trends are related to the development of miniturbines to be placed in urban areas, as for example parks, and also in buildings. Finally, we would like to remark that significant efforts are being dedicated to wind resource assessment in order to increase forecasting precision.

8.1 Overview

The production of energy from wind can be seen today as an established technology that can produce electricity at costs very close to those obtained through conventional sources. This is especially true in places where there are appropriate wind speeds (8–12 m/s) for extended periods of time, or in replacing small power systems where electricity production is costly (typically small power systems).

Wind power is obtained mainly through the use of horizontal-axis wind three-bladed turbines, as they are the ones showing smaller mechanical wear and lower visual impact. The power extracted from wind is proportional to the circular area covered by the blades when they rotate, the air density and the cube of the wind speed. Consequently, it is very important to correctly evaluate the wind resource in

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every potential location because small variations in average wind speed largely influence the electricity produced over the years.

Most wind turbines are installed on-shore, but increasing efforts are on locating wind turbines off-shore, in shallow waters (<50 m depth). This is because wind speed at a given height from the sea surface is usually somewhat higher than at the same height on the ground. Also, the off-shore wind is generally more constant, predictable and with less turbulence. Moreover, the best on-shore locations in many developed countries have already been occupied. However, the technologies related to off-shore wind turbines are less mature than those installed on-shore, since the former implies greater technological challenges related to installation and O&M. This chapter is mainly devoted to wind turbines used for electricity production, as well as those associated with CAES.

The maximum rotational speed of the turbine blades is limited by the turbulence generated by the wind at their tips. To avoid it, the linear speed of the blade tip is limited to about 100 m/s (360 km/h), which corresponds to wind speeds up to about 17 m/s (60 km/h) in current large turbines [1]. If the wind speed exceeds a certain limit (80–100 km/h) then the turbine stops to avoid damage. This stop is achieved by modifying the angle of the blade with respect to the wind direction, or automatically, as wind turbulences increase at specific blade edges above a given wind speed.

Each turbine is characterised by a specific power curve as a function of the wind speed, which depends on the characteristics of the turbine. The nominal power of the turbine is its maximum in the power curve, and the average power is the power provided in terms of the average winds in the specific location.

The maximum wind turbine power available for exploitation is limited, according to Betz law, to 16/27 (approximately 60 %) of the instantaneous wind power. This limitation is due to the fact that a 100 % wind power exploitation would stop completely the wind, preventing its evacuation and, consequently, being an obstacle for new wind reaching the turbine. In addition, the mechanical power obtained from wind should be further converted into electricity. Then, in practice, the maximum conversion efficiency of wind energy into electricity is usually around 40 %.

As electricity costs from wind are evolving closer to grid parity, the annual electricity production from wind energy is growing dramatically (Fig. 8.1). Thus, among all renewable energies, the second largest growth in energy production during 2009 was wind energy (Table 2.1), reaching 0.98 EJ.

The large increase in electricity production is associated with a dramatic increase in installed power capacity worldwide. Thus, at the end of 2011, the installed wind cumulative power capacity reached 238 GW (Fig. 8.2).

With respect to off-shore wind farms, growth has been also very significant, although the cumulative capacity values are still very small. Then, at the end of 2010, only 3-GW off-shore total capacity was placed worldwide (Fig. 8.3), representing a 1.5 % of the total.

Finally, for the small-scale wind sector (turbines <100 kW), only a report has been detected related to official data for the evolution of this sector [3]. The data have been obtained from the seven countries participating in the IEA-Wind Task 27 (Australia, Japan, South Korea, Spain, Sweden, UK and USA). For this sector, the

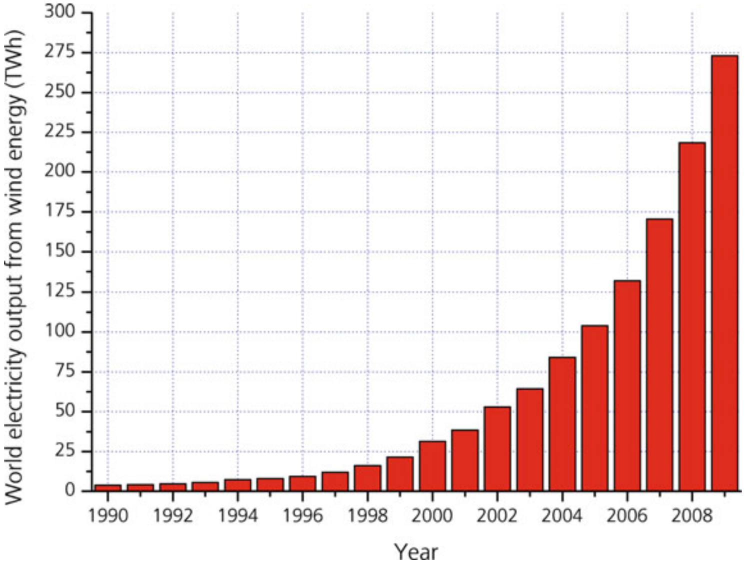


Fig. 8.1 Evolution of the annual electricity production from wind in the period 1990–2009 [2]

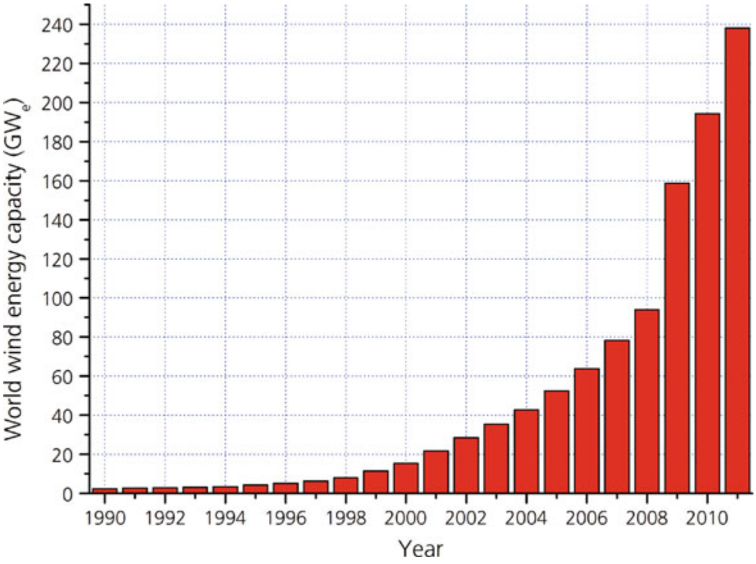


Fig. 8.2 Evolution of the annual production capacity of wind electricity in the period 1990–2011 (source: IEA and EWEA)

cumulative installed wind capacity in 2009 was 61.51 MW. Table 8.1 shows this capacity decomposed in terms of number of units, power range and connection to grid.

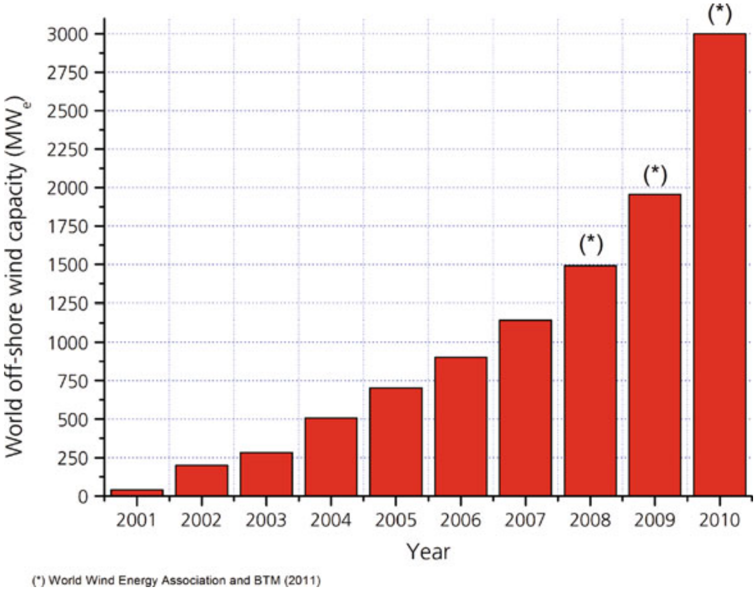


Fig. 8.3 Evolution of the annual capacity of off-shore wind electricity in the period 2001–2010 (source: WWEA and BTM)

Table 8.1 Cumulative installed small-scale wind capacity in terms of number of units, power range and connection to grid for representative IEA countries (2009)

No. of units	Grid-tie	Off-grid
Less than 1 kW	7	10,756
1–10 kW	2,010	1,938
10–65 kW	244	
65–100 kW	67	

8.2 State of the Art

8.2.1 On-Shore Turbines

As mentioned above, the standard wind turbine has three blades, horizontal axis and is connected to the grid. The maximum diameter of the circle covered by the blades has increased from 20 m in the 1980s, 50 m in the 1990s and about 130 m at present (Fig. 8.4). In the next decade, this maximum diameter is expected to grow more moderately, mainly due to increasing logistic difficulties, planning to reach 150 m in near future [4].

Generally, the power of a generator is expressed for a given wind speed, which is usually 12 m/s. Currently, the installed turbines typically have a power range between 2 and 7 MW, but it is expected to reach 10 MW in the near future [4]. The efficiency for electricity generation is measured in terms of electricity

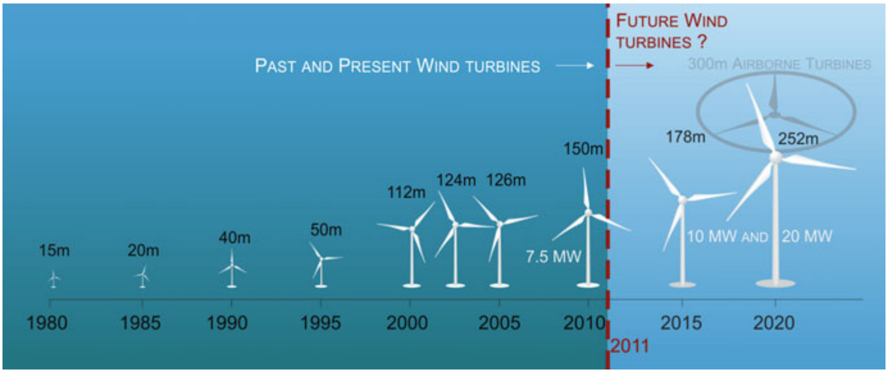


Fig. 8.4 Evolution of the diameter size for wind turbines in the period 1980–2011 and projections to 2020 [4]

produced per unit area swept by the blades (kWh/m^2), and it has been growing over 2 % annually in recent years [4].

The capacity factor (equal to unity in the case of a wind turbine continuously operating at its nominal power) is about 0.25 for current turbines. In some locations with intense and almost constant winds, the capacity factor can reach 0.4, and there are locations where the capacity factor can exceed 0.5. On the other hand, on-shore turbines can guarantee 97 % time availability for the production of energy over many years [5].

8.2.2 *Microturbines and Urban Turbines [6]*

Low power wind turbines are denominated miniturbines for power capacities below 50 kW, and microturbines for power capacities below 3 kW. These small power systems are generally isolated from the grid and are often used to generate electricity, pump water, etc. Urban wind energy can be used directly, without connection to the grid. However, the efficiency of microgenerators is much lower than the one corresponding to generators for large turbines. For example, a 5-kW miniturbine can produce 200 W/m^2, which is almost half the value obtained for a 1-MW turbine.

The system for electricity generation in microturbines is usually simpler than for large turbines, since it supplies mono-phase current instead of three-phase current. Moreover, despite using a variable speed rotor, it does not affect the frequency of the signal, since the electricity is usually stored in batteries previously to being injected in a local grid. Consequently, the concept of urban wind power is growing in relation to the introduction of small wind turbines on buildings in cities and isolated residential areas. Also, small wind turbines are being introduced in medium-sized public areas and parks. For their proper exploitation, very detailed aerodynamic models on the behaviour of wind around buildings, streets, river banks, canals, etc., have been created.

8.2.3 Wind Energy Storage Using Compressed Air (CAES) [7]

It is well known that wind power is characterised by its intermittency and, consequently, its non-manageable behaviour. Therefore, it is very important to be able to store energy from wind during time intervals of high production, and then be able to recover it when it is demanded. Also, the electricity price is high at demand peaks and low at demand valleys, and this daily price variations also incentives the incorporation of energy storage.

Among all the energy storage technologies, the second most efficient after pumped hydropower is the compressed air energy storage (CAES), where efficiencies of 45–60 % are reached. Currently, in order to store energy by CAES, air is compressed to high pressures (60–100 bar) using power-driven compressors. To regenerate electricity back, the compressed air is mixed with a small amount of natural gas and expanded in a combustion gas turbine.

Currently, there are only two major world CAES plants. One is located at Huntorf (Bremen, Germany), has a power capacity of 290 MW, a life of over 20 years of operation and can store 310,000 m^3 of air up to 66 bar pressure. The other plant is the Mc Intosh (Alabama, USA) of 110 MW, which stores the air in a former salt mine and has a storage capacity of 560,000 m^3 of air up to 74 bar pressure. However, at present, none of them uses wind power to store compressed air.

8.2.4 Off-Shore Wind Turbines

Off-shore turbine technology (Fig. 8.5) focuses on the development of large wind turbines to allow the appropriate use of foundations, since these are very expensive to build. Unlike on-shore turbines, off-shore turbines include power generators that supply power at high voltage, given the difficulties to locate transformer stations in these locations. On the other hand, the conditions of the nacelles for these turbines are enhanced, especially in dehumidification technology, which reduces maintenance costs. The power of the turbines is expected to reach 10 MW for off-shore turbines during the period 2010–2015 and 20 MW for the period 2020–2030 [8].

Off-shore wind resources present an average capacity factor of 0.375 for wind turbines compared to an average capacity factor of 0.25 for on-shore wind turbines. However, the operation availability for off-shore turbines is considered around 80–95% [5] due to the still limited maturity of the technology, compared to 97 % for on-shore turbines.

8.2.5 Off-Shore Foundations

Most off-shore wind turbines have been built in shallow waters (< 25 m depth) and relatively close to the shoreline (< 20 km). The water depth limit for off-shore foundations is established at present at about 50 m [9], as the foundation costs increase very rapidly with depth.

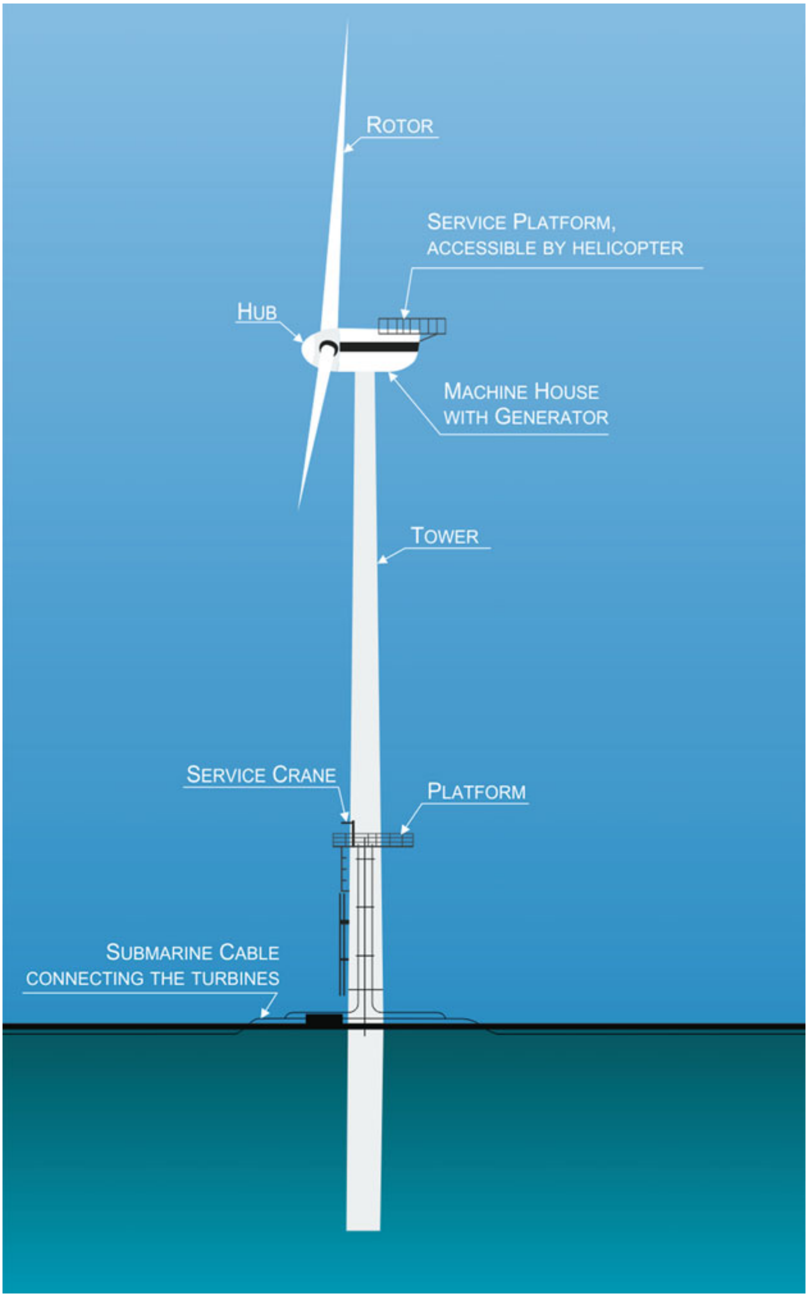


Fig. 8.5 Scheme of a typical off-shore wind turbine [5]

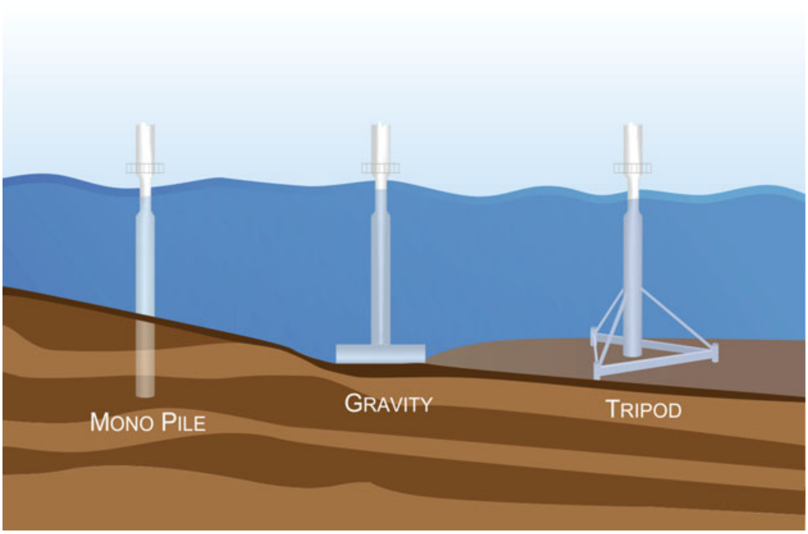


Fig. 8.6 Common foundations for off-shore wind turbines: monopile, gravity and tripod

The largest challenge for off-shore wind turbines is related to their foundations or moorings to the seabed, which are planned to be placed even deeper and in hostile weather locations. There are some specific techniques for this purpose, but currently it is an area of intense research. Figure 8.6 shows the three most common underwater foundations used at present [10]. The monopile consists of a lengthening of the tower introduced in a hole in the seabed. This technique is usually applied for shallow waters (<15 m). For larger depths, the gravity foundation is very common, which consists of a base, usually of concrete, placed on the seabed. The name for this foundation is derived from the fact that the turbine remains in the vertical position due the effect of gravity. For depths, up to about 25 m, a tripod-like foundation is also used, but it is not as common as the previous two types of foundations. The tripod can be composed of three (Fig. 8.6) or more piles.

8.2.6 Wind Resources

The correct evaluation of wind resources is of great importance, both before the wind farm is built in order to decide the best location, and once built in order to more accurately predict the amount of the electricity production of the park. This second objective is gaining in importance as non-manageable renewable energies increase their share to the grid and the grid operators require knowing in advance the amount of wind energy that should be delivered to the grid.

Commonly, the wind resource analysis is made through meteorological stations mainly equipped with anemometers, and pressure and temperature gauges, properly located to ensure a prediction that should match the future production of the wind turbine. In contrast, more sophisticated predictions combine information from satellite data, global forecasts, radar, surface observations and other variables, which, combined in a suitable computer model, allow predictions decreasing in accuracy as the temporal distance between the measurement and prediction is extended.

In the analysis for off-shore wind resources, the data are primarily based on information from satellites and global models, as a lower quantity of parameters and values are required. The models are easier because the surface roughness is minimal. Currently, also collecting data of the local marine topography is required to define the most appropriate foundations for each placement.

8.2.7 Off-Shore Logistics

Commonly, transportation and installation for off-shore wind turbines has been based on conventional engineering. However, as wind farms are installed in more remote and difficult locations, an alternative strategy is emerging based on building the off-shore turbines in docks and transport them in one piece to their locations, similarly to the case of many oil rigs.

On the other hand, currently bottlenecks are predicted for the availability of boats designed for multi-MW off-shore wind turbine installation. Also, major efforts are focused in enhanced monitoring off-shore wind turbines to predict faults and defects, reducing the O&M costs. Moreover, limitations in the ability to elevate off-shore wind turbines in their final placements are detected [8].

8.2.8 Stages of Development

Depending on the degree of market penetration, the different key technologies that are driving the wind energy development, both on-shore and off-shore, can be shown at different stages of development (Fig. 8.7).

Many of the technologies discussed can be considered in a state of competition, although in almost all countries where the wind farms are placed exist a sort of incentive for the development of wind energy. Thus, on-shore and off-shore turbines can be considered in the stage of competition, although the latter still requires further innovations to increase competitiveness. Also, off-shore foundation technology is well established, mainly from experience gained in oil rigs. However, we consider an additional activity for off-shore foundations that can be considered in pioneering-introduction stages, and it is related to floating foundations being tested for deep waters. The off-shore logistics area can be also considered in a competition stage, derived from experience in oil rig engineering, but there are still new concepts to be developed to reduce the costs of the facilities.

Less developed is the small wind turbine technology, where a large variety of prototypes are being tested and introduced in the market. However, a lack of regulation in many countries prevents a rapid expansion of this technology. Finally,

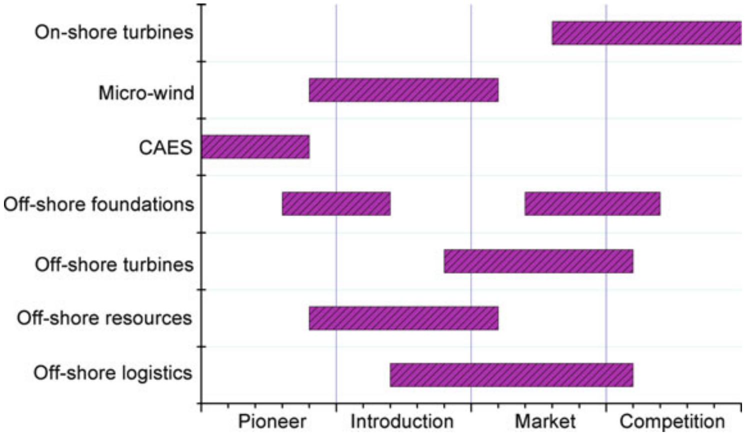


Fig. 8.7 Stage of development for the different wind energy technologies exposed in this chapter

the combination of wind energy and CAES is in the early stages of development, but it is expected a large penetration in the electrical system in future.

8.3 Current Costs and Future Scenarios

8.3.1 Turbine Costs and Total Costs

On-shore wind can now compete without special support in electricity markets endowed with steady winds and supportive regulatory frameworks (e.g., New Zealand and Brazil) [11].

The total investment costs for on-shore turbines in 2011 ranged from USD 900–1,400/kW (EUR 647–1,007/kW) depending on the manufacturer and the turbine model, with an average value of USD 1,100/kW (EUR 790/kW). It means an average costs 20 % below the peak in 2008 [12].

There are endogenous influences (labour costs, warranty provisions, turbine manufacture profitability and turbine design) and exogenous influences (raw materials prices, energy prices and foreign exchanges) that influence the wind turbine costs, but there is no a single dominant factor. Turbine upscaling is, by a significant margin, the largest single driver, as capital costs increase with size. But the advantages in terms of balance of plant costs and higher levels of energy production typically outweigh those turbine price increases with size. It is also important to consider that profit margins are falling from 2008 due to the global financial crisis and the resulting softness in turbine sales [12]. On the other hand, raw materials prices have the largest exogenous influence, accounting five materials (steel, fibreglass/resin/plastic, iron, copper and aluminium) for more than 98 % of the total. The price of steel (66–81 % of total turbine mass) has by far the largest

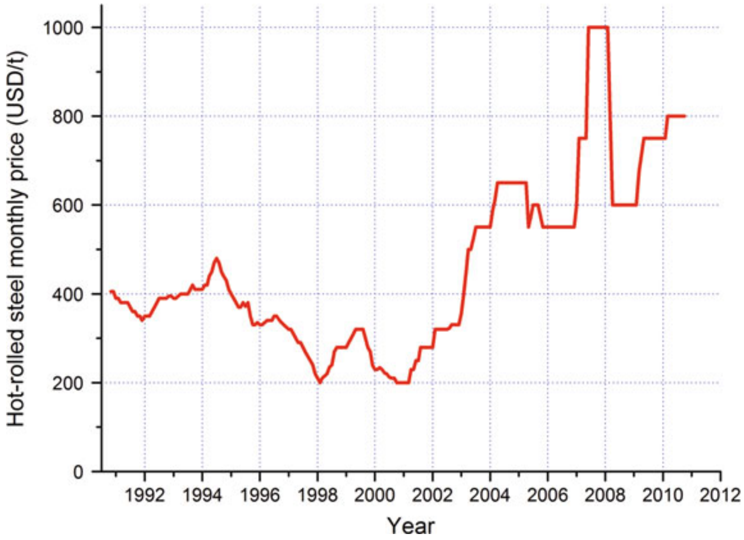


Fig. 8.8 Hot-rolled steel monthly price evolution from 1991 to 2011

Table 8.2 Typical investment costs percentages for on-shore and off-shore wind farms [17]

On-shore	% Total costs	Off-shore	% Total costs
Turbine	74–82	Turbine, including transport and erection	49
Foundations	1–6	Foundation	21
Electric installation	1–9	Internal grid between turbines	5
Grid connection	2–9	Transformer station and main cable to coast	16
Consultancy	1–3	Design, project management	6
Land	1–3	Environmental analysis	3
Financial costs	1–5	Miscellaneous	1
Road construction	1–5		

impact on turbine prices; it evolved downwards from 2008, but the price is rising again in recent years (Fig. 8.8). A breakdown of the costs for on-shore facilities shows that the turbines represent 60–70 % of total investment costs [12].

These wind turbine price declining is starting to be accounted in the new installed project costs because of the natural temporal lag between turbine purchases and writing the project of the corresponding installation. For example, wind power plant installed in 2010 often relied on turbines purchased at the peak of the market costs in 2008 [13]. However, for the electricity costs from wind energy exposed below, the estimations for each year are based on wind turbine cost data for the same year, as we consider it more useful for the reader.

It is also interesting to note the differences in costs between the facilities "on-shore" and "off-shore", the causes having been already discussed in the previous section. Typically, off-shore turbines are at least 20 % more expensive per unit of installed capacity, and prices of the foundation, at least 2.5 times higher for the same size of the turbine [14]. Considering also other factors (Table 8.2), the projected investment costs for 2011 range from USD 2,032 to 6,492/kW (EUR 1,460–4,664/kW) with a capacity-weighted average of USD 4,328/kW (EUR 3,109/kW) [15]. It is expected that water depth, distance from shoreline and project size influence the final investment cost for specific off-shore wind farms.

On the other hand, the investment cost for the world largest floating turbine of 2.3 MW and placed in Norway (described in Sect. 8.7.3) has been evaluated at about USD 30,435/kW (EUR 21,864/kW) [16]. These prices are far above the values exposed for off-shore foundations-based wind technology. Consequently, it is necessary to significantly improve this technology to gain attractiveness and penetration of the market.

8.3.2 Operation and Maintenance Costs (O&M)

For wind power plants, the O&M costs are very low compared to conventional fuel plants. Therefore, wind power plants can be considered capital intensive compared to conventional ones, for which fuel costs play a major role. Typical annual values of O&M costs for wind farms are between 2 and 4 % of the total costs of the facility, and they have remained almost constant in recent years [5]. Off-shore O&M costs are two or three times higher than those of land-based systems [15].

8.3.3 Cost of Electricity

The cost of electricity produced depends on the country analysed, because it is not always clear whether or not government incentives are included (feed-in tariffs, environmental bonds, etc). As a result, the IEA has launched a programme to study methods of calculating the cost of wind energy and has developed a series of recommendations to carry out these calculations [18].

As noted by the IEA in a recent report on the costs of electricity [19], it is also necessary to differentiate between the cost at plant level and at power system level, in the case of intermittent and non-manageable renewable energies (i.e., wind energy). Thus, the electricity cost at the power system level is more expensive, since it requires available and flexible energy reserves when wind resources cease to produce electricity. Our study considers only the electricity cost at plant level.

On the other hand, the IEA recognised in 2008 [17] that, contrary to expectations, the electricity price per kWh from wind resources has either increased from its minimum in 2004 or remained constant. In addition, since 2010 the IEA predicts that wind power costs are declining, considering a levelised cost of electricity of EUR 0.069/kWh (USD 0.097/kWh) in 2010 for the reference scenario in on-shore wind farms. This declining scenario from 2010 is not the case for off-shore wind farms, where an upward tendency is observed since data are available, and an average cost of EUR 0.161/kWh (USD 0.224/kWh) can be considered for 2010 [20].

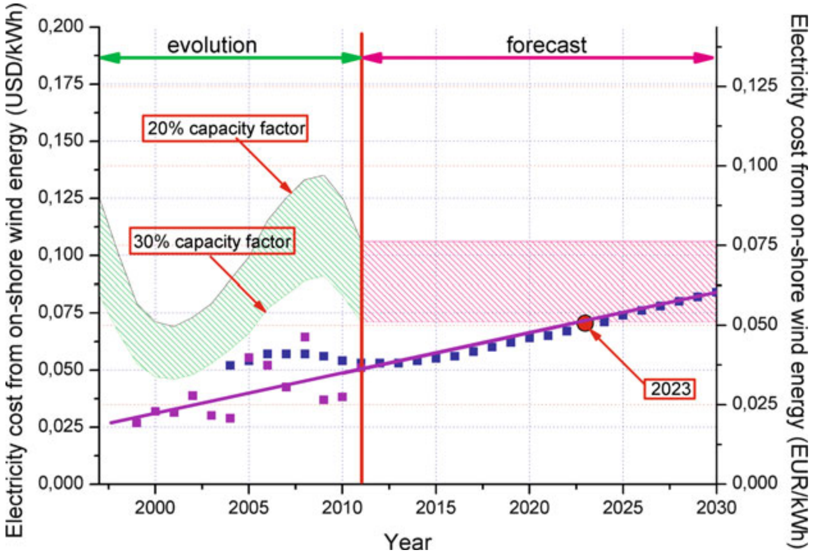


Fig. 8.9 Evolution of the electricity costs from on-shore wind power for 20–30 % capacity factor and forecast to 2030. The *blue solid square* represents the generation electricity costs expected in USA and the *magenta straight line* represents the linear fit of the annual average generation electricity price in the Spanish wholesale market in 1999–2011 (*magenta solid square*), both projected from 2011 to 2030

For our grid parity analysis exposed below, we differentiate between the cost of producing electricity on-shore and off-shore. Our input parameters are the investment costs provided by the IEA and DOE and apply a 7 % discount rate and 20 years lifetime.

For on-shore and off-shore electricity production, we use capacity factors ranging 20–30 % and 35–45 %, respectively, corresponding to locations with medium and high wind energy resources, respectively. In addition, we consider average turbine investment costs similar to those described above [12]. The O&M costs are taken as 2.5 and 6.8 % of the total costs for on-shore and off-shore wind farms, respectively. The electricity costs obtained are then compared to the generation electricity costs expected in USA and to the average generation electricity price in the Spanish wholesale market, both projected from 2011 to 2030.

Thus, the evolution of the cost of electricity produced by wind energy until 2011 and forecasted to 2030 for on-shore and off-shore technologies is exposed in Figs. 8.9 and 8.10, respectively. In Fig. 8.9, we have considered an electricity cost for on-shore wind farms constant until 2030 with respect to 2011 values, as the investment costs forecasts published by the IEA for 2030 [5, 17] are above those considered for 2011. Consequently, the grid parity for a 30 % capacity factor can be reached in 2023.

For off-shore wind energy, the electricity cost forecasted for 2030 derived from the IEA analysis [5, 17] is quite above the value considered for on-shore wind farms

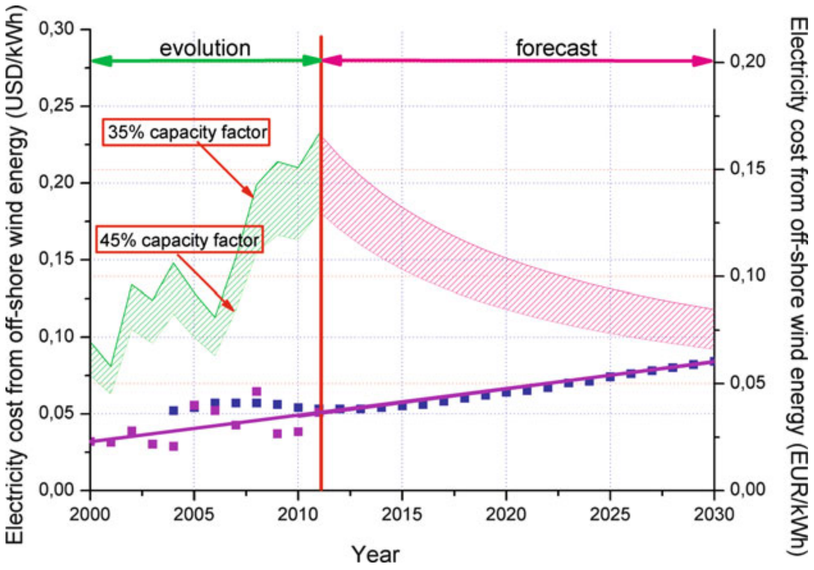


Fig. 8.10 Evolution of the electricity costs from off-shore wind power for 35–45% capacity factor and forecasted to 2030. The *blue solid square* represents the generation electricity costs expected in USA and the *magenta straight line* represents the linear fit of the annual average generation electricity price in the Spanish wholesale market in the period 1999–2011 (*magenta solid square*), both projected from 2011 to 2030

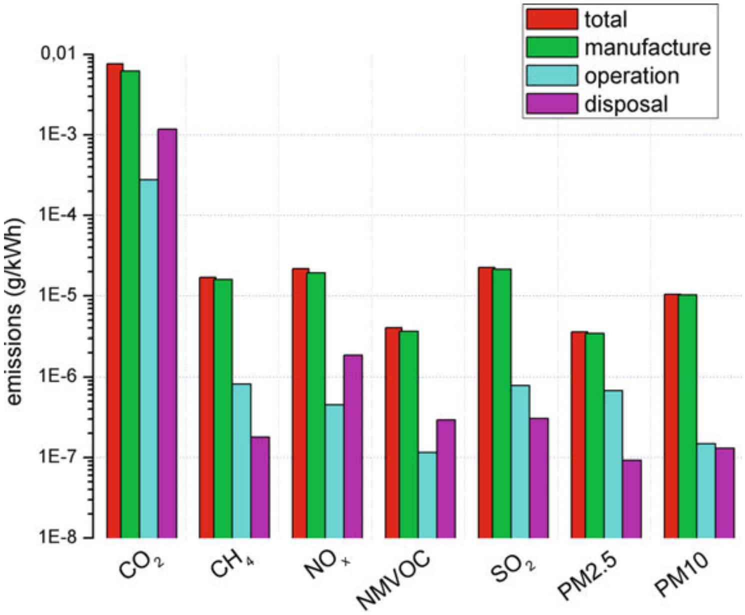
(Fig. 8.10). Consequently, grid parity is expected for off-shore wind energy that will be reached at the beginning of the 2030s decade. Also, the upward tendency in off-shore investment costs from 2006 to present should be reversed to reach earlier grid parity for this technology.

8.4 Energy Payback, CO_2 Emissions and External Costs

The energy payback ratio for both on-shore and off-shore wind technologies have been evaluated, and they are in a range of 9–20 times those necessary to cover the life cycle of the wind turbine [21]. These results place this technology in the leading group of renewable energy technologies in relation to this parameter.

Regarding CO_2 emissions, studies published within the NEEDS project [8] indicate that on-shore wind technology emits about 3 g/kWh, while off-shore wind technology reaches 5 g/kWh. This latter value is attributed to higher CO_2 emissions in the manufacturing process of off-shore facilities.

More detailed studies of greenhouse gas emissions that focus on off-shore technology (Fig. 8.11) indicate that the maximum contamination occurs in the manufacturing process and, more modestly, in decommissioning, while the pollution generated is minimal in the operation phase. The largest contributor to the environmental impact is



NMVOC: non-methane volatile organic compounds (excl. CH_4)

Fig. 8.11 Greenhouse gases and particulate emissions during the life cycle of off-shore wind technology [8]

related to the great use of steel, both in the manufacturing process and decommissioning [8]. Consequently, these manufacturing and decommissioning values could be substantially reduced if maximum penetration of renewable energy is introduced in the energy mix of leading countries producing wind mills.

Finally, the standard life cycle cost for on-shore wind energy is estimated from EUR 0.052 to 0.093/kWh (USD 0.072–0.129/kWh) [5]. For off-shore projects built between 2005 and 2008, the life cycle cost range is EUR 0.077–0.093/kWh (USD 0.108–0.129/kWh) [5]. The highest life cycle costs for off-shore technology is attributable to larger environmental impact of these installations [22].

8.5 Future Technology Trends

8.5.1 On-Shore Turbines

Since wind speed is larger as height from ground level increases and also the wind turbulence is lower, even larger turbines are expected to be installed in the future. Turbines with nominal power up to 10 MW are being designed, for which the tower height is between 150 and 178 m [9]. These turbine designs require improved materials for the blades and the tower, offering higher mechanical strength per unit mass and, simultaneously, larger flexibility. The most promising materials for this purpose are based on polymer matrix composites mixed with fibre glass and carbon. The composition ratio between these materials is important because composites must show appropriate behaviour, both in strength and stiffness testing (to avoid excessive bending of the blades), and in fatigue properties. The carbon fibres provide excellent tensile strength, while the glass ones provide strength to compression. Composite materials are formed by rolling lamination, so it is also very important to develop highly adhesive thermoplastic resins.

Fatigue tests are important because mechanical loads vary with the wind speed, turbulence and start/stop processes of the rotor system. The standard lifetime of blades must reach 20 years or more.

Another important research area is non-destructive detection of defects in blades at all manufacture stages, as well as damage from lightning, hail, etc., during operation. Increasingly precise techniques based on acoustic emission, ultrasonic pulses, optical fibre sensors, etc., are being developed. Other research areas are focused on improving aerodynamics (similar to aircraft wings), control systems and gearboxes. Finally, the introduction of LIDAR (laser imaging detection and ranging) is on course to analyse the wind resource seconds before it reaches the turbine. Then, the wind mill can modify its characteristics for adapting to different circumstances and, consequently, increase the turbine lifetime. This technology could also help to avoid birds and bats fatalities, turning off turbines and using sounds to repel them, as these techniques are probing successful in recent tests [23].

Finally, other research areas are improving cold climate solutions for wind turbines, especially anti-icing and de-icing, and estimating the effect of atmospheric icing on energy production (also useful for off-shore turbines).

8.5.2 Microturbines and Urban Turbines

Microgenerators technology is a rapidly evolving area due to their planned introduction in a number of cities, mainly in Denmark, Netherlands, Ireland, etc. The market is currently much dispersed and hundreds of manufacturers are counted around the world. Therefore, various international agencies, the IEA among them, are establishing certification mechanisms and control of basic features such as power, acoustic emission, vibration and mechanical testing. Considerable research on these properties is in course as microturbines have been removed from buildings because of the noise or vibrations that they spread to buildings.

Thus, at present, the main research areas are [6] (1) evaluation of wind resources according to the location of the microturbines (isolated high buildings, buildings producing tunnel effects and free buildings areas as parks or riverbanks); (2) estimation of noise and vibration effects on the buildings structure and (3) location of the microturbine in the building: roof, garden, mast fixed to a side wall, etc.

One of the most interesting aspects is optimising the design of the microturbine in relation to its location. In open spaces, the best performance is obtained from horizontal axis turbines. However, in urban areas where highly variable winds and turbulences are common, large vertical axis turbines show enhanced behaviour.

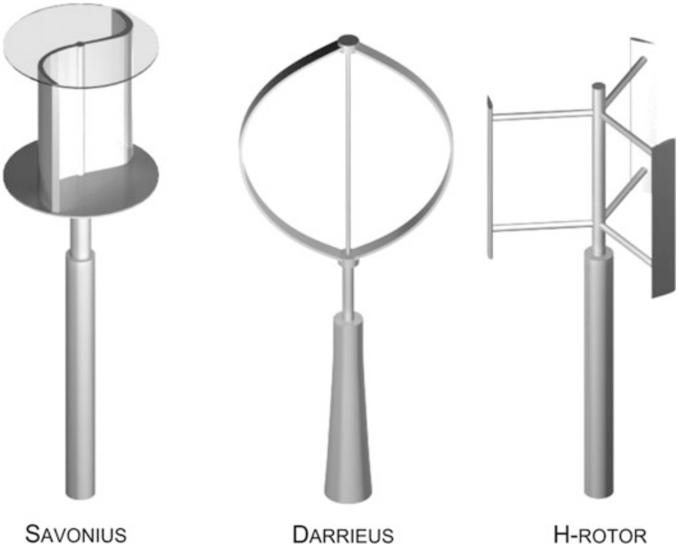


Fig. 8.12 Schemes of the most popular vertical axis turbines: Savonius, Darrieus and H-rotor [6]

Figure 8.12 shows the most popular types of vertical axis turbines: Savonius, Darrieus and H-rotor. In general, vertical axis turbine efficiency is lower than for horizontal axis. However, vertical axis turbines have advantages, such as being omnidirectional, i.e. they are able to produce energy from any wind direction without the need a mechanism of orientation. In addition, the special design of the blades in the Darrieus model makes the centrifugal forces much weaker. Consequently, the blades can be much lighter and a significant amount of material can be saved.

Finally, there are also some activities to develop airborne devices to collect energy from the wind far above the surface, where it is steadier (up to 80 % capacity factor) and stronger [24]. Jet stream, at 10,000 m height, is one of the favourite areas of study. Lightweight materials and computer guidance systems emerged make the idea feasible. Aircrafts, wings, turbine arrays and kites are the most popular prototypes being designed and tested. The power capacity associated makes these prototypes to be considered as small turbines at present, but companies involved aspire to build multi-megawatt devices to get the attention of energy utility companies.

8.5.3 Wind Energy Storage Using Compressed Air (CAES)

Although it was mentioned above that some large CAES plants are in operation, there is as yet no operational facility intended for the storage of wind energy sources. The first such facility for storage of wind energy is expected to become operational soon, but no official date has been given. The CAES plant will be built by the Municipal Association of Iowa public companies. This plant will connect a 100-MW wind farm and a 268-MW CAES unit (Fig. 8.13) [7].

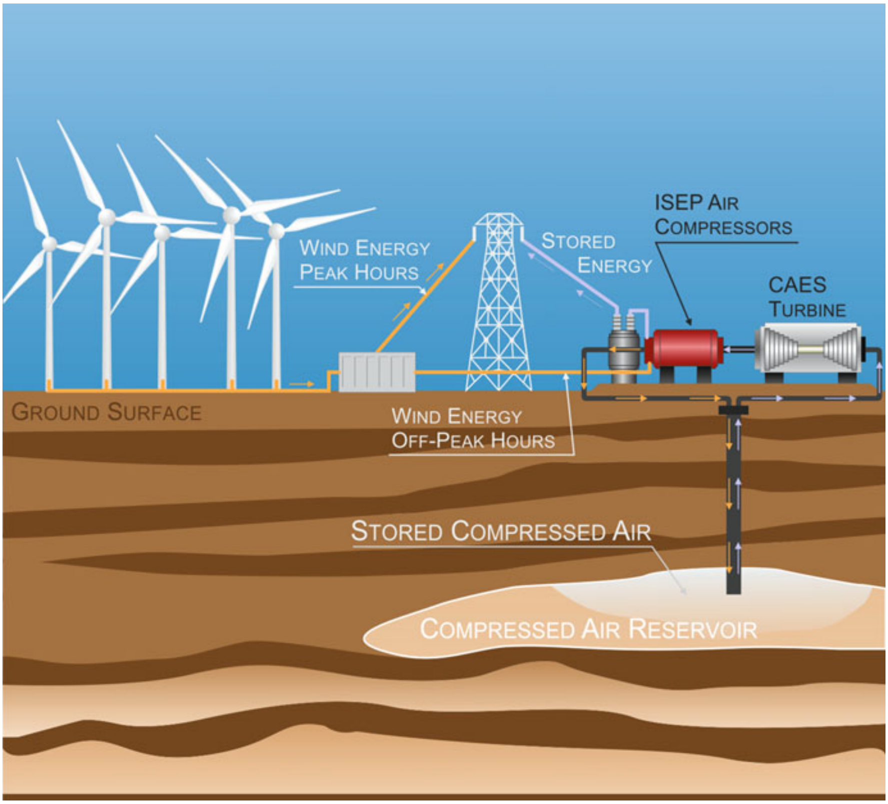


Fig. 8.13 Scheme of the wind farm in Iowa (USA), based on the CAES/wind integration

The Iowa plant will be devoted to research on natural and excavated geological cavities using techniques derived from mining. The results are expected to show better performance than the caverns of the Mc Intosh and Huntorf plants. The response of air compression equipment and power generation gas turbines to wind resource variability will be studied in terms of storage and power generation strategies. The results will provide interesting data for demonstrating the CAES/ wind integration.

Another research area is to reduce heat losses caused by compression on the storage system and, consequently, to increase the efficiency of the system. The decision on the strategy with the higher consensus will probably slow down the implementation of compression processes.

Also, research in storing compressed air in metallic spherical chambers is on course. The spheres could be placed not only in urban areas but also on the seabed close to off-shore wind farms. Consequently, these spheres can act as distributed storage systems, with many advantages over centralised ones, and avoiding the limitations imposed by the need for suitable geological locations.

Finally, compressed air is not only planned to be stored in such facilities but also heat. Heat storage can aspire to achieve efficiencies in these systems reaching 70 %.

8.5.4 *Off-Shore Turbines*

In this area, as in on-shore turbines, research in non-destructive detection of defects is important, but for off-shore turbines the need for research is larger due to the difficulties for O&M activities in off-shore plants. On the other hand, as off-shore wind turbines are placed in more corrosive environments than on-shore, a larger incentive is also on research of new materials slowing down corrosion processes, and thus allowing larger durability to the turbine.

In floating platform technology, larger and lighter turbines are demanded in order to produce more electricity per platform and to be supported without risk of collapse. Due to these and other reasons, it is expected the replacement of glass fibre by carbon fibre, as its price goes down in the manufacturing of rotor blades. Carbon fibre is a rigid, lightweight material that can help rotor blades to reach lengths of 200 m in 2050 [8].

Technological efforts are also dedicated to make compatible defence and weather radar systems with wind farms. Three different strategies can be implemented to fulfil this requirement: introducing telemetry data of these facilities to be identified in radar systems, replacing existing systems with more modern radars to avoid incompatibilities and making turbine blades “stealthy” or less visible to radar using special materials.

Long-term technology research in this area is considering a radical new approach, as vertical-axis wind turbines, new blade technology, full power transmission and control systems and a rotating, floating off-shore substructure. The objective is to develop more cost-effective MW wind turbines through singular technologies rather than advancing existing concepts that are based on on-shore technology being adapted to the sea environment. Floating off-shore wind turbines with a rating of 20 MW are considered as viable.

Finally, to reduce electricity costs from off-shore installations, strategies to combine this technology with marine energy devices incorporated in the platform and the foundation structure are gaining ground. These hybrid systems could increase the production of electricity from off-shore wind energy and extend their generation capabilities to periods without wind resource but with marine energy resources. Especially tidal currents are being considered, since the wave energy is normally coupled with the availability of the wind resource. In addition, mooring and torque effects could be exploited.

8.5.5 *Off-Shore Foundations*

Possibly the largest challenge for the development of off-shore turbines is related to foundations in waters deeper than about 25 m. For depths less than about 25 m, the main problems related to the foundation placement are practically solved. By contrast, for depths in the range 25–50 m, there are only some prototypes being tested to check the effectiveness of the foundations. Therefore, this section is limited to describe the prototypes being tested.

Thus, research is focused on jacket foundations, similar to electricity transmission towers (Fig. 8.14) [10], which have already been deployed in the Beatrice off-shore wind farm in Scotland. On the other hand, auto-installable platforms are being considered, since they are mounted on-ground and then “dropped” in the defined sea location [10]. Finally, for water depths larger than 45–50 m, studies conclude that it can be more cost-effective to install the wind turbines on floating structures.

Also, three-point anchoring systems are proposed for depths between 120 and 700 m, applying technologies similar to those used for oil rigs. Thus, the angle of the rotor blades can be also used to stabilise the movements of the whole structure. This could be done through smart software also capable to check the success of previous adjustments and, consequently, refine the staticity of the structure.

Moreover, concrete can be replaced by steel up to 30 m deep, as it is a lighter material, preventing its corrosion by means of cathodic protection [8].

Finally, off-shore foundation technology in the future will depend not only on depth values. Others factors as seabed orography, marine currents, wave characteristics and weather conditions will be also considered. In this sense, it is necessary to conduct more studies to further best correlate the type of foundation and characteristics of the location.

8.5.6 Wind Resources

It is necessary to increase the number of research units devoted to computer simulation for wind resource modelling and in situ data collection. Currently, work is also on course for the replacement of anemometers by remote monitors using SODAR technologies [5]. Research is also being conducted on computational fluid dynamics to model the wind flow; however, it is not yet sufficiently developed to prevent the use of “in-situ” anemometer measurements.

There is also research activity on off-shore wake effects, i.e. the influence on the flow of a wind turbine in another nearby, which may decrease the efficiency of a wind farm up to 10 %. This is more important for off-shore turbines because of their larger size and the uniformity of the wind direction. All these techniques can also serve to model wind patterns over irregular surfaces as shorelines.

Moreover, further research, based on meteorological data, is on course to forecast wind resources and in trying to adjust the production to the electricity demand. Predictions of wind intensity have been improving, and the information obtained should be shared with the operators of wind farms in order to predict total wind energy production in a power grid. To this end, the IEA and other agencies have recently established meetings between experts in meteorology and plant operators to improve management decisions about the production of electricity from wind and its integration into the grid.

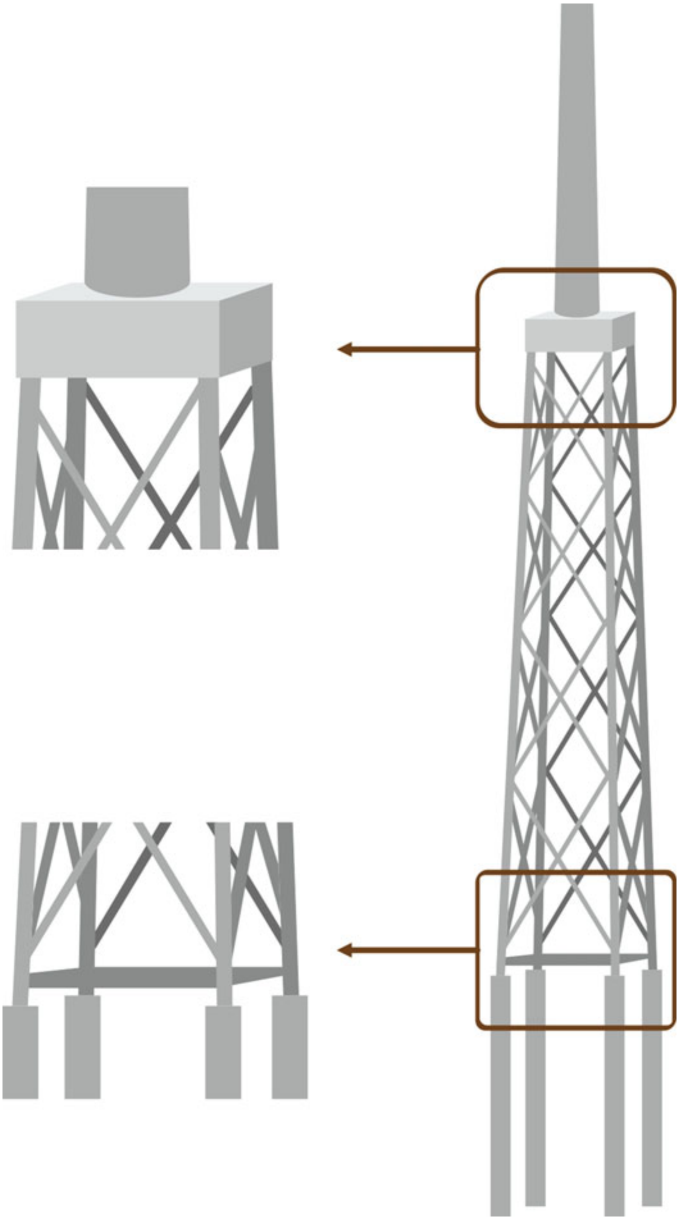


Fig. 8.14 Jacket foundation prototype for off-shore wind energy

8.5.7 Off-Shore Logistics

Specific designed boats are proposed for the placement of off-shore wind mills in difficult locations. Such boats have lengths of over 100 m and widths of over 40 m and are capable of carrying up to 4 multi-megawatts wind mills and install them on sea locations with depths of up to 40 m.

In some cases, there are also heliports on large wind turbines nacelles for maintenance activities. These heliports, combined with accurate weather forecasts, would allow maintenance activities in good weather conditions. However, as the helicopters are very limited by distance and weather conditions, the construction of staff accommodation modules off-shore, similar to oil rigs, is also planned. Then, the staff could be quickly transported to the required wind mills by helicopter or boat. In this sense, there is already extensive experience in the oil industry on evaluation of circumstances in which work is or not permitted.

Finally, there are plans to relocate some manufacturing factories in the shoreline, as many countries, especially European, plan to locate off-shore the main development of future wind turbines. This relocation of factories must be accompanied by adequate port infrastructure to facilitate the boarding process for new wind farms. Also, blades can be manufactured to be installed in pieces.

8.6 Pre-Production Highlights 2009–2011

8.6.1 Alpha Ventus Off-Shore Wind Farm Come Into Operation in the North Sea [25]

In late 2009, the first off-shore German wind farm composed by 12 turbines of 5 MW each, totalling 60 MW became installed. A feature of this wind farm is to have been built in very deep water (about 40 m), due to the demanding German environmental standards, which require off-shore wind farms far away from the coast. The plant is connected by an underwater cable to the island of Borkum, where provides electricity to 50,000 homes.

Each wind turbine is 178 m high and has a rotor diameter of 116 m. The towers are mounted on large tripods, similar to those exposed in Fig. 8.6, stacked to the seabed. The German Government plans to have a wind power capacity of 10,000 MW off-shore in 2020.

8.6.2 The world's largest wind turbine [26]

The world's largest commercial wind turbine detected in the market is the Enercon E-126. It has a rotor diameter of 127 m and a height of 137 m. Although the power of this wind turbine is qualified on-shore at 6 MW, Enercon offers in its catalogues 7.5 MW.

8.6.3 Sensors to Analyse the Wind Before Reaching the Turbine [27]

The Sustainable Energy National Laboratory Risø DTU (Denmark) has developed a system using LIDAR technology to analyse the characteristics of the wind before reaching the turbine. Wind is analysed at a distance of 100–200 m from the turbine and heights of 40, 60, 80 and 100 m. The analysed data are used to adjust the angle of the rotor blades, so damage derived from turbulences and gusts can be reduced. In this way, the energy output can be increased by about 5 %.

8.6.4 Multi-Megawatts Direct-Drive Turbines [28]

Siemens has begun selling a 3-MW turbine using a so-called direct-drive system. This turbine replaces the conventional high-speed generator with a low-speed generator that avoids the need for a gearbox. This decision can be considered a response to highly publicised gearbox failures. The new design reduces the weight of the nacelles to about 73 t (−14 % compared to its less powerful, gear-driven 2.3-MW turbines), mainly because of the use of permanent magnets in the generator rotor instead of electromagnets, and inverting the generator design.

8.7 Innovation Highlights 2009–2011

8.7.1 Nacelles Located at Ground Level [29]

The Norwegian company ChapDrive has developed a hydraulic variable speed transmission control system, which allows the wind energy captured by the rotor to be transferred to the nacelle of the turbine, which is placed on the ground at the base of the tower (Fig. 8.15). ChapDrive was funded with EUR 6 million from the Norwegian government and various organisations to develop this innovative system. Being at ground level, both generator and gearbox, it can be greatly reduced the weight of the tower and also facilitate the maintenance operations. This new system has been successfully tested in relatively low-powered turbines, but steps are being taken to introduce it for 5-MW wind turbines in 3–5 years.

8.7.2 Concrete-Steel Hybrid Towers of 100–150 m [30]

This type of towers, developed by Advanced Tower Systems are composed of two segments, the bottom one consisting of a pre-cast concrete tower built on the foundation and a conventional steel tower on it. The project started the demonstration phase at Grevenbroich (Germany) in 2009. The prototype permits a steel tower of 100 m, for example, to reach 140 m above ground level, where winds are more

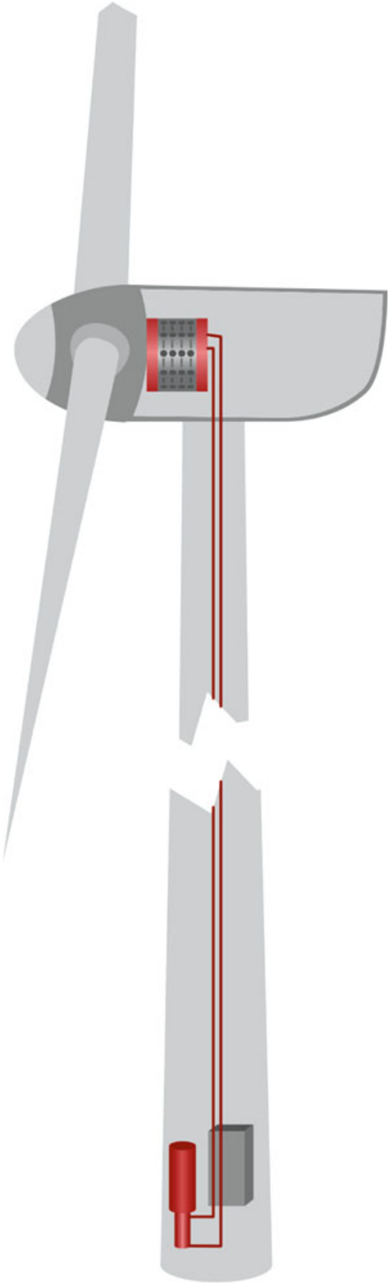


Fig. 8.15 Prototype of wind turbine with nacelle placed on the ground

intense and therefore a higher efficiency is achieved (about 18 % higher). Another advantage is related to the smaller tower diameter requirements. Thus, if a tower is built all of steel and with that height, the diameter would have to be well above the 4.3 m that is needed for the 100-m height towers tested for this hybrid system. Large tower diameters also increase the difficulties for transportation from the manufacturing company to the final location.

8.7.3 World Largest Floating Wind Turbine [31]

For off-shore wind energy, it is not economically profitable to locate wind turbines in waters with depths larger than about 40 m. For this reason, some floating turbine prototypes are being tested, which can be economically competitive for depths larger than about 25 m. In order to investigate its feasibility, the Dutch company Blue H has already mounted a small floating turbine 100 km away from the Italian coast. In addition, the company Hywind has installed a 2.3-MW floating wind turbine in the Norwegian North Sea, which started operating in September 2009. This is the world largest floating wind turbine.

8.7.4 Global Off-Shore Wind Speed Increases [32]

Recent climate change studies over a 23-year database of calibrated and validated satellite measurements discovered a global trend of increasing wind speeds over this period in oceans. At the mean and 90th percentile, wind speeds over the majority of the world's oceans have increased by at least 0.25–0.5 % per year. The increase is larger in the Southern Hemisphere. The only significant exception to this positive trend is the central north Pacific, where there are smaller localised increases or weak negative trends. At the 99th percentile, the wind speed trend becomes more positive, indicating that extreme wind speeds are increasing over the majority of the world's oceans by at least 0.75 % per year.

8.8 Statistics of Publications and Patents

Figure 8.16 shows the number of scientific publications during the period 2001–2011 for different technologies in the wind energy area [33].

Thus, we find that the largest activity is in the study of off-shore wind resources, has been mainly during the last 7 years and shows an upward tendency. This result can be attributed to the large potential that off-shore locations offer to some developed countries where best on-shore locations are mostly already occupied. As the investment costs for off-shore wind farms are huge, an accurate analysis of wind conditions constitutes a very important requirement. The second technology that shows a higher scientific activity corresponds to off-shore turbines. The explanation can be very similar to the one exposed for off-shore wind resources,

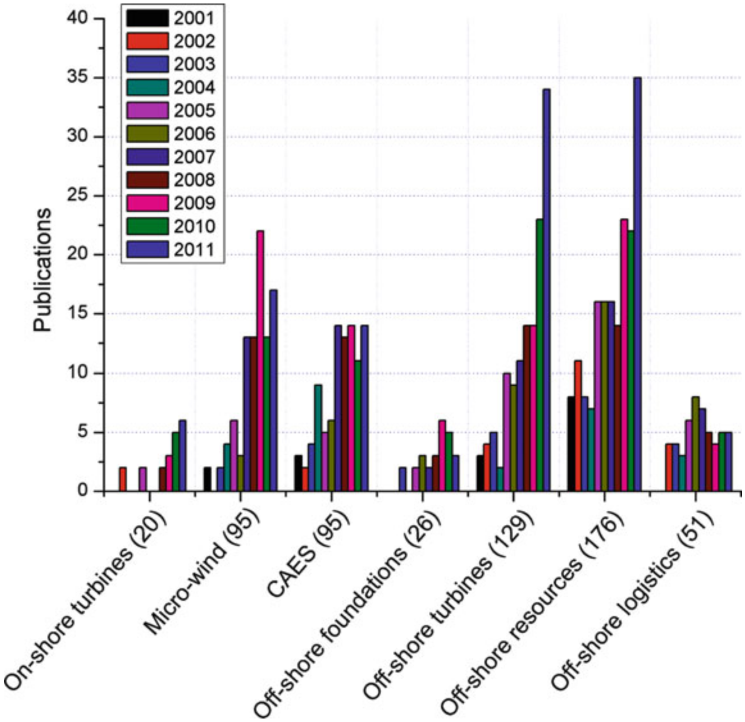


Fig. 8.16 Number of scientific publications during the period 2001–2011 for the wind energy technologies exposed in this chapter [33]

as the off-shore environment is very challenging and specific technologies are required to guarantee long lifetimes.

In third place are small wind turbines and CAES. The activity in small wind turbines can be attributed to a great potential for the penetration of distributed wind power generation in urban areas for which low solar radiation, net-metering and/or effective use of tunnel effects from high buildings can improve investment returns. In contrast, the activity is somewhat surprising in CAES as there is a shortage of projects and prototypes related to this technology. Consequently, CAES research activity can be explained considering that this technology is being used to publish many theoretical models, which help to advance the penetration of renewable energies in the energy mix. However, there is a lack of analysis of tested prototypes.

Less activity in terms of publications is shown for off-shore logistics, and with very constant values in the number of publications over the years, unlike most other technologies discussed. These results can be explained considering that off-shore logistics has no special tradition in terms of research. Moreover, logistics is being considered to address no critical issues in the implementation of off-shore wind energy.

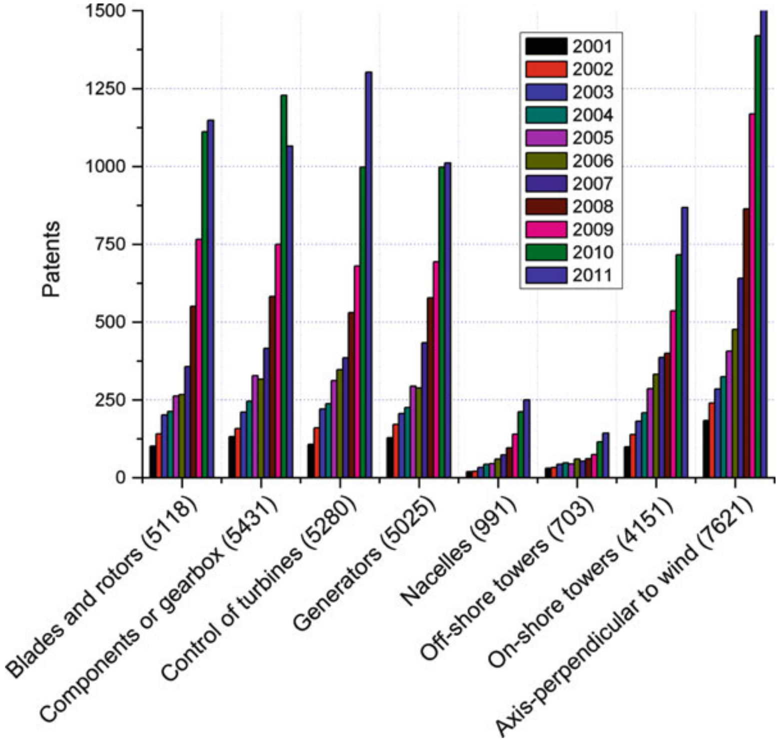


Fig. 8.17 Number of patents published during the period 2001–2011 for the wind energy technology classification defined by the European Patent Office [34]

In last place are situated publications in off-shore foundations and on-shore turbines. In the case of off-shore foundations, the small number of publications can be derived from the technology used, which is partly transferred from oil rigs. In relation to on-shore wind turbines, this technology can be considered quite mature, and therefore there is a small number of scientific publications.

In terms of patents [34], the European Patent Office uses a different classification compared to the one exposed in this chapter (Fig. 8.17). However, important information can be obtained from this source. The first conclusion is that patent activity in wind energy is immense and increasing dramatically. A second conclusion is that a very high patent activity is occurring in small wind turbines, embedded in “axis-perpendicular to wind”. This result can be explained considering the availability for small- and medium-size companies and entrepreneurs to design and execute small turbine prototypes and the potential market derived from increased fossil fuel prices and net-metering.

Finally, patents related to blades and rotors, components or gearboxes, control of turbines, generators and on-shore towers are similar in number and tendency pattern. These results may be also very much influenced by the large activity in small wind turbines. On the contrary, concepts closely related to large wind mills (nacelles and off-shore towers) are the lowest in terms of number of patents.

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Chapter 9
Hydropower

Abstract Hydropower is by large the main contributor to electricity production of all renewable resources. Hydropower is a very mature technology for the production of electricity at very competitive prices; furthermore, it can be considered for base-load generation, it responds extremely fast to energy peak demands and it can be stored by means of pumped hydro systems. However, the construction of large hydropower plants (>1 GW) often cause the displacement of large populations from their homes and significant environmental problems in river flora and fauna ecosystems. For these reasons, as we will see in this chapter, hydropower research is at present also focused on small-scale mini-power plants and run-of-river systems. We will also describe the different types of power turbines, which are most often employed depending on the height of the effective head of the reservoir, water flow and velocity, etc.

9.1 Overview

Hydropower is derived from the potential energy of water falling from a certain height, causing a rotational movement of turbines or power generators that, eventually, is transformed into electricity.

Hydropower plays a central role in renewable energy production since 83 % of world electricity generation from renewable resources is produced in hydropower plants (2009) [1]. This proportion is diminishing over the years as other renewable energy sources, such as wind, solar, etc., are gaining ground in the electricity mix. Consequently, if we calculate the contribution of hydropower to the world renewable electricity produced, its share has been lowered from 96.8 % in 1973 to 83.1 % for the most recent year of available information (2009) (Fig. 9.1) [1].

Regarding the evolution of the production of hydropower electricity, there is a considerable growth over the years (Fig. 9.2), reaching 3,329 TWh (11.71 EJ) in 2009. This growth is attributable to new facilities starting in operation recently, mainly in developing countries and to the subsequent raise in the total installed

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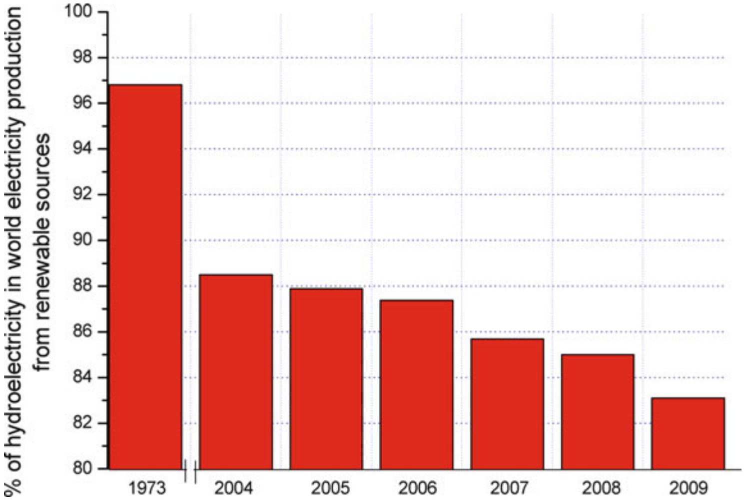


Fig. 9.1 Evolution of the percentage of hydropower in world electricity production from renewable sources in 1973 and in the period 2004–2009 [1]

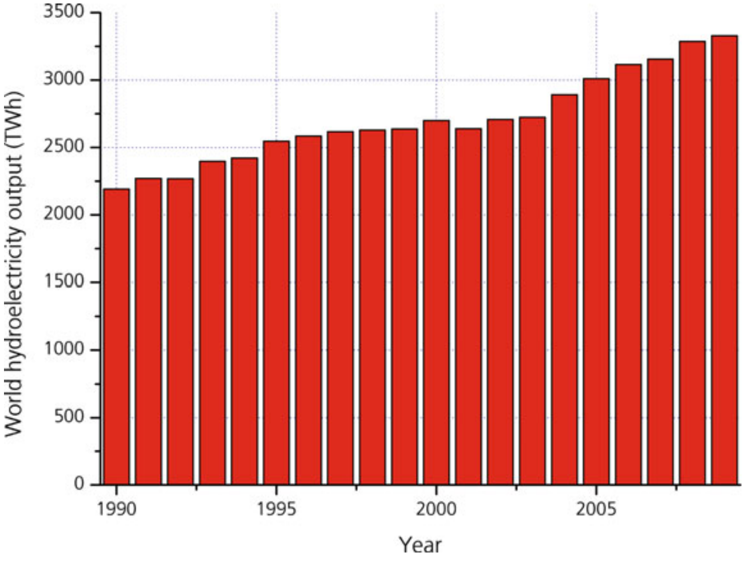


Fig. 9.2 Evolution of gross electricity production from hydropower sources between 1990 and 2009 worldwide (own elaboration from IEA statistics)

capacity in 2009 to 980 GW [2] and 1,010 GW in 2010 [3]. However, the last report of the International Hydropower Association (IHA) assures that “with respect to current installed capacity and generation of hydropower, up-to-date information is lacking and/or inconsistent, tending to be under-represented in energy reporting" [2].The International Energy Agency estimates that the technical potential of these counted facilities can be designed to achieve the 16,400 TWh/year [4].

Hydropower has a number of very significant advantages relative to other energy sources:

1. It is a well-established technology today, and it has been producing electricity at competitive prices for more than a century.
2. Hydropower produces electricity with a very flexible and quick response time (in the order of seconds), so it can cover peak-power demands and production gaps very shortly, and it is especially useful when unmanageable energy sources (mainly wind and solar) have a large capacity share in the grid.
3. Water storage in reservoirs by pumping permits an adequate management of renewable electricity excesses when they are produced from unmanageable sources. This water stored can be reconverted to electricity when it is needed.
4. The GHG emissions per kWh and energy payback show an excellent performance.

However, hydropower also has a number of drawbacks, mainly from the environmental point of view, as it is discussed below. These include flooding of high biodiversity areas, obstacle to fish passage in both directions of the rivers, decreasing of river flow to non-sustainable levels, and often, displacement of human populations. Obviously, these drawbacks largely diminish in the case of mini- and micro-hydropower plants.

An important parameter in relation to hydropower plants is the capacity factor, defined as the energy annually produced divided by the maximum it can produce. Thus, a typical capacity factor for a hydropower plant is 40%.

The estimated technical potential for hydropower is about 463 EJ/year. Most of this potential is located in Africa, Asia and Latin America, while in developed countries almost all the economic potential has been exploited. However, there are countries such as Norway, Paraguay, Brazil and the Democratic Republic of Congo, where the electricity produced by this technology can exceed 85 % of the country's demand.

Hydropower can be classified according to various criteria. As a first approach, the factor usually considered relates to power of the plants:

(a) Large hydropower systems, $P > 10$ MW.
(b) Small hydropower systems, also called mini-, 100 kW $< P <$ 10 MW.
(c) Micro-hydro systems, $P < 100$ kW.

A second criterion usually refers to the height h of the head:

(a) High head hydropower systems, $h > 100$ m.
(b) Intermediate head hydropower systems, $10\ m < h < 100$ m.
(c) Low head hydropower systems, $h < 10$ m.

Finally, hydropower systems are also classified between conventional (referring to hydropower dam and reservoir) and run-of-river systems (without reservoir or

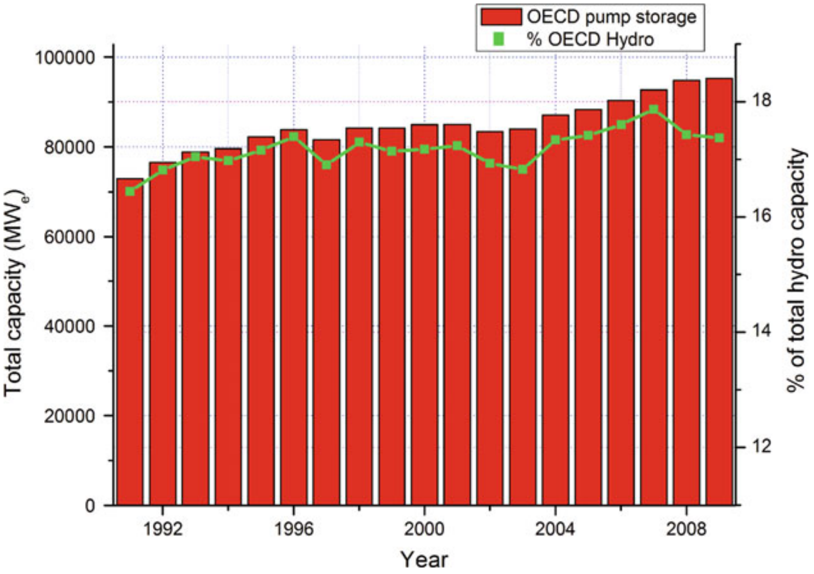


Fig. 9.3 Evolution of pump storage capacity and as percentage of hydropower capacity between 1991 and 2009 in OECD countries [1]

very small ones). Most of the run-of-river systems are also mini- and micro-hydropower systems.

Water storage in reservoirs by pumping is increasingly used to match offer and demand in a power grid, storing energy when offer is in excess and powering the grid when demand is in excess. These operations are very attractive when bulk power is not easily adjustable (nuclear power plants) or the share of unmanageable energy resources (mainly solar and wind) in the grid is too high. There are no official data of world pump storage capacity, but official data from OECD countries show an increasing capacity, reaching 95.3 GW (Fig. 9.3) and 17.4 % of the total hydropower capacity in 2009.

9.2 State of the Art

9.2.1 Turbines

Currently, there are many different types of turbines, and they are often divided into two groups (Fig. 9.4) [5]:

(a) Reaction (or pressure) turbines, driven by the hydrostatic pressure of water. The most used are the Francis, fixed pitch propeller and Kaplan turbines.
(b) Impulse (or action) turbines, driven by the kinetic energy of water. The best known among them are the Turgo, crossflow and Pelton turbines.

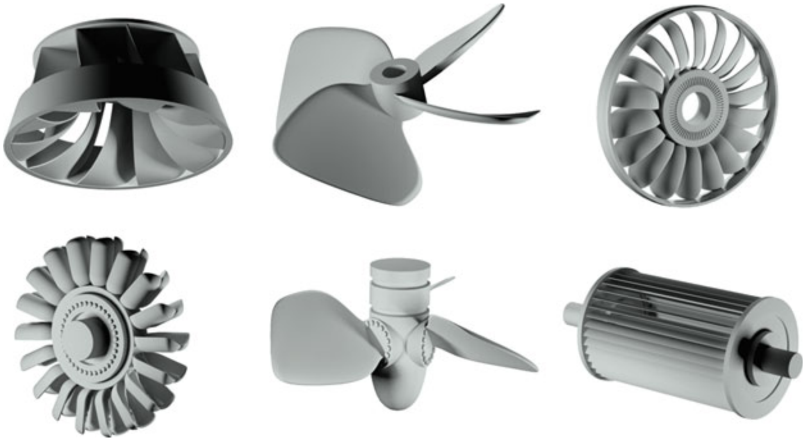


Fig. 9.4 Different types of turbines used to produce hydropower power: *top-left*: Francis; *top-centre*: Kaplan; *top-right*: Turgo; *bottom-left*: Pelton; *bottom-centre*: propeller; and *bottom-right*: crossflow

The Francis turbine is by far the most used reaction turbine for heads of 10–250 m. It is also called radial flow turbine as the water flows from the outer circumference to blades curved towards the centre. This turbine is completely submerged and its axis can be positioned both vertically and horizontally. In these turbines, the water exerts a pressure on the rotor blades and the rotational energy gained is primarily due to the pressure on the turbine.

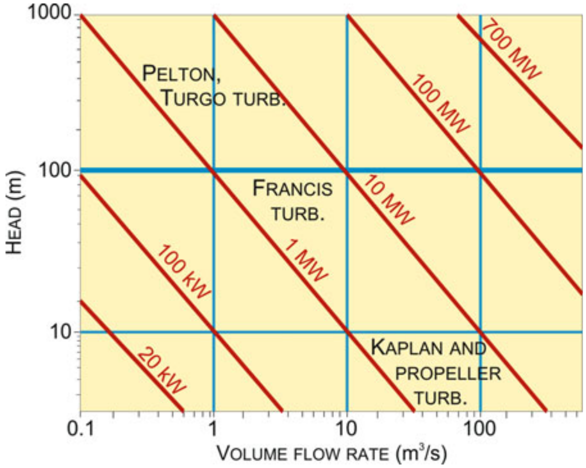
Propeller turbines operate essentially like the propeller of a boat, but in reverse. They are normally used with low and rushing heads. These are called Kaplan turbines when the angle of incidence of the blades is automatically adjusted for each flow, which allows to set the conversion efficiency to changes in electricity demand.

Among the impulse turbines, the most used is the Pelton turbine for high heads (up to 300 m). It is essentially a bladed wheel with a double ladle mounted on its edge. The high pressure water impinges on the edge that separates the two ladles. Split into two jets, the water is ejected laterally after having transferred its momentum to the wheel. Thus, the wheel can reach speeds up to 1,000 rpm. An essential difference of the Pelton impulse turbine is that while the reaction turbines described above operate entirely submerged and are affected by the pressure difference, the impulse turbines operate in air at atmospheric pressure. Figure 9.5 [5] shows a practical scheme for the correlation among different turbines for several head, flow and power ranges.

9.2.2 Large Hydropower Systems

As mentioned above, this category is related to systems with a capacity exceeding 10 MW. Currently, there exists hydropower power plants, which reach 22.5 GW (Three Gorges Dam, China), although only two more hydropower plants overcome 10 GW: Itaipu in Brazil (14 GW) and Guri in Venezuela (10.4 GW).

Fig. 9.5 Correlation between height, flow and power for different turbines



Some of these large systems are not dedicated to supply power to the grid, but to directly serve power to large industrial companies that are heavy consumers of electricity, such as those dedicated to the production of aluminium.

Hydropower systems, mainly large but increasingly also the smaller ones, are used as energy storage systems for surplus electricity by pumping water into reservoirs, being at present the less costly electricity storage systems [4]. More related information can be found in Chap. 15, dedicated to electricity storage systems.

9.2.3 Small Hydropower Systems

Hydropower systems with capacities below 10 MW show a growing activity in part because subsidies and R&D programmes, and because many places suitable for large hydropower plants are already occupied. In addition, the construction of large power plants, especially in developed countries, often faces major environmental impacts and rejection by the local population. In developing countries, there exists a different context and these small plants are attractive because they require no large investments in dams and grids.

Small hydropower systems frequently are placed in locations where a low cost hydro resource is available, in isolated areas where it is very expensive to bring the grid to the consumers or in countries where a national grid does not exist.

9.2.4 Run-of-River Systems

Mini-hydropower plants are very often run-of-river systems. They avoid the environmental damage produced by dams and stand on the river beds and without significant affection to the flow. They are very attractive for small rivers and affluent flows, especially in relatively mountainous areas.

These systems also differ from the large hydropower systems because the electricity produced is often considered for peak demand, except in countries where the contribution of hydropower to the grid is high, where they also contribute to the base production, as they generate very stable electricity during 24 h a day.

9.2.5 Systems with Reduced Environmental Footprint

The location where a hydropower plant will be installed is examined in great detail prior to construction, as the hydropower system must generate a reduced environmental impact. In the last two or three decades, there has been numerous public outcries in relation to large hydro projects, especially in developed countries. The benefits of energy production from renewable sources must not be tainted by environmental concern. For this reason, the support for mini-hydropower is also increasing, as the hydrological impacts of a run-of-river technology is usually much smaller.

In the case of reservoirs or dams, the water flow downstream cannot drastically diminish, as the effects it can produce on river fauna, changes in groundwater level, etc., are considerable. Thus, downstream of a dam always an ecological minimum flow should be maintained and therefore not all the remaining flow can be used for irrigation.

Other effects considered are the environmental impact caused by the process of constructing a large dam that can take many years. The disappearance of land with native flora and fauna, which is often replaced by lakes for fishing and leisure activities, must be evaluated. These ecological transformations must be evaluated before the beginning of the construction of dams, to avoid unwanted effects, as occurred after the construction of the Aswan Dam, where annual fertilising flooding ceased and, consequently, the soil was impoverished of nutrients.

Sometimes the environmental impact is partly diminished ensuring the fish passage in general and the periodic migrations of salmon in particular, by building scales close to the dams. Also, to prevent fish from passing through the turbines, some countries establish that the water inlet to the turbine should be protected by a mesh.

On the other hand, the water reaching the turbine contains very little sediment, leading to loss of sandbars downstream and erosion of the seabed on the river mouth, accelerated by intermittent openings of the turbines gates. Also, variations in the oxygen content of water, before and after the hydropower plant, are detected. In addition, the water leaving the turbine is usually warmer than the stored water.

In tropical countries, water reservoirs produce significant amounts of methane, a greenhouse gas far more potent than CO_2. Methane emissions from these reservoirs may become comparable to emissions from power plants producing electricity from fossil fuels, especially if the reservoirs are oversized with respect to the installed power, and if a cleaning of biomass was not considered prior to filling the reservoir [6].

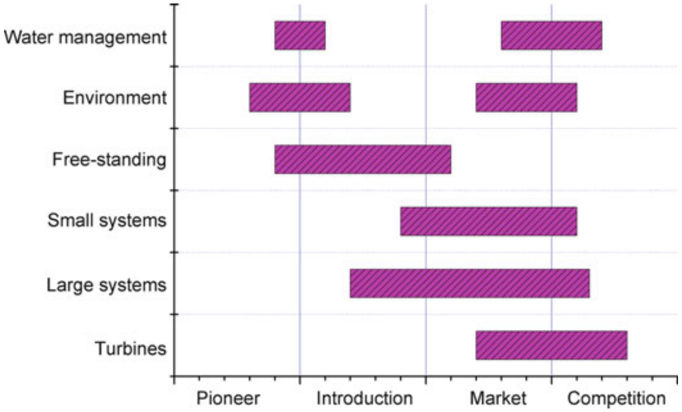


Fig. 9.6 Stages of development for each of the technologies considered in this chapter

Finally, it is also very important to consider the social impact when there is need to move people living in the affected territory. The construction of the Aswan Dam produced the displacement of nearly 100,000 inhabitants, an insignificant number compared to the Three Gorges Dam on the River Yangtze, which required the displacement of approximately 1,200,000 inhabitants.

9.2.6 Water Management Systems

As mentioned above, the priority in developed countries is, at least, the maintenance of the ecological flow of the rivers where a reservoir is placed. Sometimes, improving the efficiency of the operation in hydropower systems is associated to empty downriver to increase the system head.

On the other hand, hydropower reservoir systems are used to control the risk of flooding, ensuring a constant flow of water downriver for agricultural irrigation, and even support recreational activities.

9.2.7 Stages of Development

Depending on market penetration, we can consider, in general, that hydropower can be regarded as a mature technology, especially as it relates to turbines, large systems and many of the issues associated to water management (Fig. 9.6). However, there are some aspects where technological innovations are expected in these areas. Specifically, in water management, there is an important activity in R&D on specific topics distinguished from traditional regulatory activities of channels and enhancement of agricultural activities. The same occurs in relation to the mitigation of the environmental footprint of hydropower. These considerations lead us to divide into two segments the bars of the figure corresponding to technological development in water management and mitigation of environmental footprint.

Table 9.1 Investment costs for hydropower systems

Category	Output/unit	Storage	Power use	Investment costs in USD/kW (EUR/kW)
Small	<10 MW	Run-of-river	Base load	2,032–4,064 (1,460–2,920)
Medium	10–100 MW	Run-of-river	Base load	2,032–3,048 (1,460–2,190)
Medium	100–300 MW	Dam and reservoir	Base and peak	2,032–3,048 (1,460–2,190)
Large	>300 MW	Dam and reservoir	Base and peak	<2,032 (<1,460)

On the other hand, the development of small systems is delayed, mainly due to economies of scale, while the run-of-river hydropower technology can be considered as the most immature and in need of further improvement to reach extensive market penetration.

9.3 Current Costs and Future Scenarios

In OECD countries, the investment cost for new large hydropower systems (>300 MW) are usually less than USD 2,032/kW (EUR 1,460/kW), for small- and medium-scale hydro (<300 MW) the investment cost is USD 2,032–4,064/kW (EUR 1,460–2,920) (Table 9.1), and the production of electricity is at USD 51–102/MWh (EUR 37–73/MWh) [4].

In developing countries, the investment costs are estimated at about USD 1,050/kW (EUR 754/kW) and the production of electricity at USD 0.021–0.064/kWh (EUR 15–46/MWh) [7]. These values imply that hydropower can competitively supply base-load electricity to the grid compared to other non-renewable electricity sources. This conclusion is evident as hydropower is one traditional technology for electricity production in any electrical system that has proper water resources.

The above values are average costs, which might vary depending on site characteristics (labour, expropriations, environmental impacts, etc.). For run-of-river hydropower systems, the investment costs are estimated in the range of USD 2,000–4,000/kW (EUR 1,437–2,874/kW) [4].

On the other hand, since the hydropower resource has no cost, the investment expenditures are concentrated in the first years. Moreover, the average life of such plants is over 50 years and the lifetime of the different components of the plant is diverse. Investment plans and borrowing costs to meet the construction and operation phase of these plants must take into account this condition. Turbines have a life expectancy between 25 and 50 years, and external structures can reach a lifetime above 100 years.

Official forecasts show that the investment costs are not expected to lower as it is the case of other renewable emerging technologies (e.g., photovoltaics), since hydropower investment costs are strongly associated with the prices of raw materials, which are not expected to diminish. In relation to electricity costs, a 1–7 % downward trend is expected from 2010 to 2030, and being run-of-river and dam hydropower costs similarly both affected by the capacity of the system (Fig. 9.7) [8]. The main considerations to future costs reductions are related to

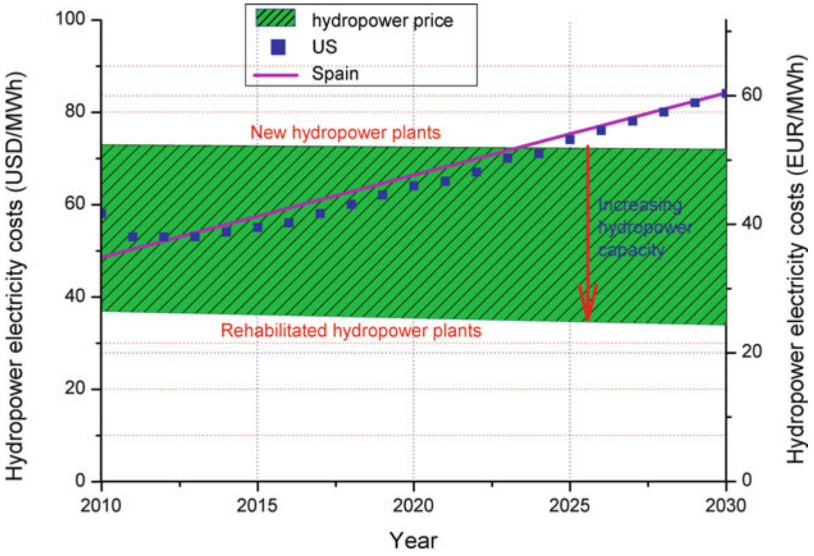


Fig. 9.7 Current hydropower electricity costs and forecasts to 2030. The *solid square* represents the generation electricity costs expected in USA and the *magenta straight line* represents the linear fit of the average generation electricity price in the Spanish wholesale market, both projected from 2011 to 2030

the increase of rehabilitation projects for old hydropower systems, use of components produced in emerging countries and reduction of profit margins.

The hydropower plants have also O&M costs, estimated at USD 5–20/MWh/year (EUR 3.6–14.4/MWh/year) for new plants of medium and large size, and approximately double for small production plants. It also should be considered the cost of distributing electricity, as the bibliography is not always explicit whether these costs are included in the electricity costs provided.

9.4 Energy Payback, CO_2 Emissions and External Costs

First, we must consider that all values presented below are averaged, since the conditions of each particular location are crucial to the final calculation. Consequently, the energy payback rate is between 30 and 270, the largest of all renewable energy sources studied. Average external costs are EUR 0.0062/kWh (USD 0.0086) and it is also the smallest external cost obtained for the different renewable energy sources [9].

Regarding CO_2 emissions, no rigorous studies have been found to provide such data. It is recognised that this technology does not emit CO_2; however, this is an underestimation since, especially in the construction phase, CO_2 emissions are very significant, as in other renewable technologies [9]. However, taking into account the long life of hydropower plants, the impact of CO_2 emissions per kWh produced is considered the smallest of all renewable technologies [9].

Also, it should be considered the emissions of CO_2 and methane from the reservoirs of the hydropower plants. Thus, there is some controversy as the low CO_2 emissions from this technology could be compensated by emissions of methane, a greenhouse gas far more potent than CO_2. In this regard, the IEA Hydropower Implementing Agreement Group under the leadership of Brazil is preparing a rigorous methodology to count the carbon balance in freshwater reservoirs, which includes life cycle analysis that even come to consider the potential impacts of floods [4].

The development of the reservoir modelling tools will be completed in 2012, and the Best Practice Guidelines to manage GHG emissions will be drafted by the end of 2012.

9.5 Future Technology Trends

Firstly, there are several general trends in hydropower technology that must be mentioned. One of them is the development of hybrid systems, especially hydrowind and hydropower-hydrogen systems that can cover both production and storage. Currently, these systems are being tested on a small scale, but the trend is to increase the market share in distributed power generation and in isolated locations.

Another general aspect to be considered is the research on the effect that climate change can have in hydropower production. These studies are especially important given that hydropower systems have lifetimes that are much extended over time and, consequently, long-term climate variations can have an important impact on the facilities currently being designed and built.

9.5.1 Turbines

In the area of turbines, new materials that demonstrate a greater resistance to wear and ablation (fibre/resin composite), and with minimal friction and self-lubricating properties, are being developed. In addition, small turbines for low heads, which are less intrusive and can exploit resources in new locations, are also being developed. Moreover, progress is observed in the development of new turbine designs by using potent fluid dynamics simulation tools.

9.5.2 Large Hydropower Systems

The main effort in this area is on improving existing facilities (especially old-fashioned ones) to achieve systems with larger power and efficiency, and low maintenance. Also, progress is ongoing for these facilities not to affect the water supply in places where it is scarce and to design dams that eliminate methane emissions from the decomposition of organic material.

Finally, major efforts are ongoing to extend the life of the hydropower plants through restoration, enhancement, and remote control facilities for process automation, as well as advanced fault diagnosis to reduce operating and maintenance costs.

9.5.3 Small Hydropower Systems

As water resources are becoming scarcer, small hydropower plants are gaining prominence. Even so, several aspects should be improved, such as the design of the plant, development of new materials, advanced control systems and power generation. The main objective is to enhance the efficiency levels and lower energy production costs as to approach those obtained for large systems. In this area also remote control technology and low maintenance systems are being developed.

9.5.4 Run-of-River Systems

As the most expensive technology exposed in this chapter, the main effort in run-of-river systems is focused on reducing costs. Consequently, the most important issues are determined by the need to increase the energy efficiency of these systems, which are characterised by being very diverse and placed in very different and variable locations. Also, there is the need to protect such systems from disturbing elements and simultaneously reduce their environment impact. Moreover, it is necessary to develop specific control systems to guarantee low power variability over time, so that run-of-river systems can supply base load to the grid.

9.5.5 Systems with Reduced Environmental Footprint

The main effort is focused on the development and application of new civil engineering design, electromechanical equipment and instrumentation effective in mitigating the ecological footprint generated by hydropower systems. Special emphasis is made in the design of systems that guarantee aquatic life, reduce methane emissions, prevent erosion of river beds and maintain the temperature and water oxygenation.

9.5.6 Water Management Systems

In a future scenario in which water is increasingly scarce, research in order to optimise the management of this resource is essential to ensure that social tensions are not generated because of its scarcity. It should also be improved the compatibility between the production of electricity and proper management of water resources.

9.6 Pre-Production Highlights 2009–2011

9.6.1 The Three Gorges Dam Starts Operating at Full Capacity [10] But Problems Arise [11]

The Three Gorges Dam (China), with a head of 185 m and a length of 2.5 km begun to operate at full capacity in 2008. The reservoir is formed by a serpentine lake 660 km long and covers 58,000 km^2. The reservoir began filling in 2003 and is expected to produce 84.7 TWh/year. The budget of the facility amounted to USD 25 billion (EUR 18 billion). However, problems arise with an additional estimated 10-year cost of USD 26.25 billion (EUR 18.9 billion), as two consequences have been proved worse than anticipated: water quality and erosion. Benefits such as power generation and flood control are out of controversy, but the local Yangtze River water, suitable for drinking by international standards in 2003, is not so at present. The problem was originated by toxic algal bloom because of slower tributary flow due to the reservoir and an excess of nutrients from land-use change. Also, increased heavy metal pollution has been detected. Sediment-light water scours riverbanks, some sections of them to collapse, and schistosomiasis (snail fever in China) are increasing the prevalence of endemic areas near lakes and wetlands of the Yangtze River basin.

9.6.2 Superconductors Applied to a Run-of-River System [12]

A new 1.7-MW high temperature superconducting generator has already been tested and it is planned to be installed at the Hirschaid run-of-river hydropower plant in Bavaria (Germany). The companies involved announced that the generator can reach an efficiency of 99 % and reduce size and weight by up to 70 % compared to conventional generators. The EU 6th Frame Work Program has funded this project with EUR 3.46 million (USD 4.82 million) and a duration of 50 months.

9.6.3 New Tunnel to Increase Power Capacity in Niagara Falls [13]

A third tunnel has been built to increase the power capacity under the city of Niagara Falls, rising the hydropower yearly output by 1.6 TWh and diverting the flow of 500 m^3/s of water. The first two tunnels were built during the 1950s. This new tunnel is deeper than the two previous ones, has 10.4 km (6.4 miles) in length and a maximum depth of 140 m. The current capacity of the hydropower plant is 2,080 MW. The project is expected to be finished in 2013.

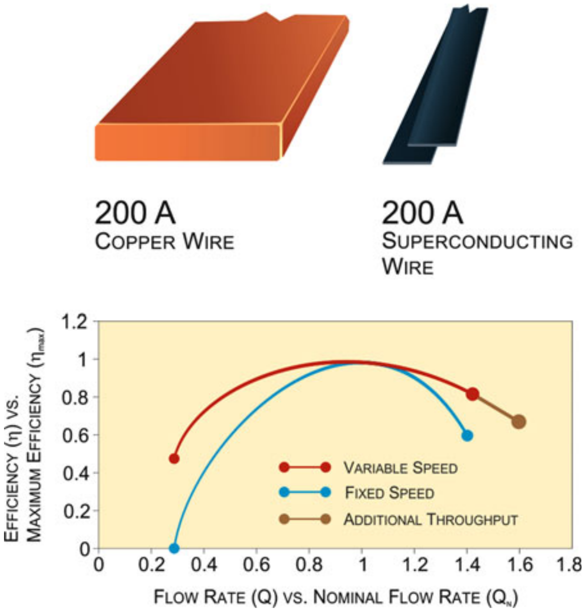


Fig. 9.8 (**a**) Image of the traditional copper section and the HTS; and (**b**) diagram generator efficiency depending on the speed of water flow [14]

9.7 Innovation Highlights 2009–2011

9.7.1 Superconducting Technology for Hydropower Generators [14]

A plant operated by E. ON Waserkraft in Germany is the first to market high temperature superconductors (HTS) in the hydropower sector, which present great advantages for mini-hydropower systems. These variable speed generators increase by 36 % the capacity of these small plants and offer a great reduction in size and weight (Fig. 9.8a), allowing the improvement of plants without the requirement of additional building. The superconducting material has been developed by ZenergyPower and the research has been funded by the EU. Tests have been performed for different flows in the river, turbine efficiency, etc. The coils of the rotor are composed by the HTS material, while copper remains in the stator. The HTS is cooled to 30 K by helium. These properties are especially beneficial for variable speed generators as shown by the increased efficiency in Fig. 9.8b.

9.7.2 Hydropower Sustainability Assessment Protocol Presented [15]

On 16 June 2011, the Hydropower Sustainability Assessment Protocol was presented in Iguaçu Falls (Brazil). As it has been mentioned above, this Protocol provides a method for assessing dams in all phases. Projects will be ranked on a

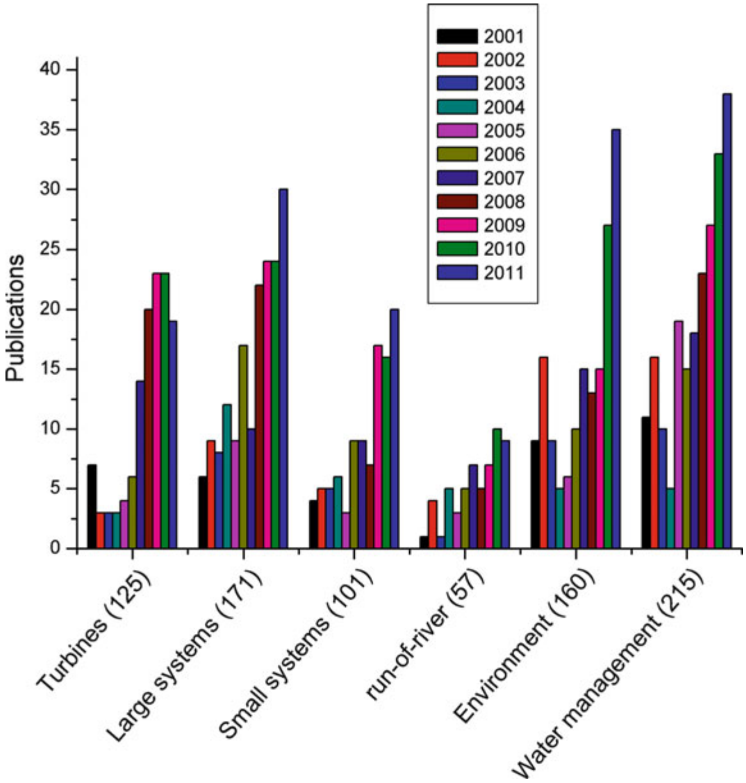


Fig. 9.9 Number of scientific publications during the period 2001–2011 for the technologies related to hydropower generation [16]

scale of one to five according to the likely effect on biodiversity, ecology, hydrology and erosion as well as on broader issues regarding regional planning, cultural heritage and effect on local inhabitants. The protocol is voluntary, and a poor rating may not prevent a project from going ahead. How the Protocol will be applied remains to be seen and it can be applied only to one dam at a time. Consequently, if there is a cascade of projects of dams in a river, a broader assessment will be needed. At least 140 major companies have signed it, but they are not required to use it or alter their projects if the assessment identifies problems. This has split environmental groups, many of which called the Protocol a dangerous public relations tool.

9.8 Statistics of Publications and Patents

Figure 9.9 shows the number of scientific publications during the period 2001–2011 for different types of technologies involved in the development of hydropower plants [16].

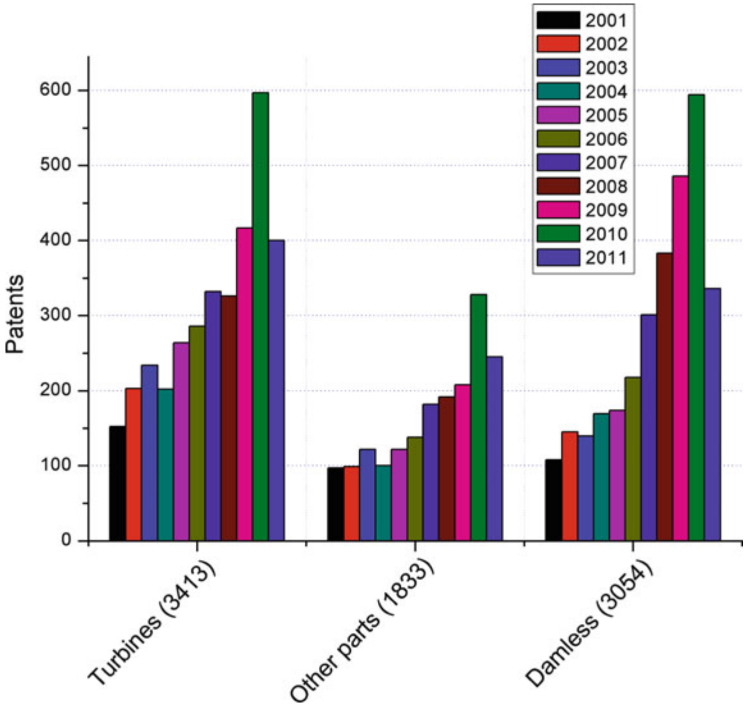


Fig. 9.10 Number of patents during the period 2001–2011 for the technologies related to hydropower generation [17]

As it can be observed, the scientific activity in this area is substantial and growing, especially in water management, since water resources are becoming scarce and strategic in the XXI century. In second place are research activities related to the analysis of the environmental impact of these infrastructures, especially controversial when it comes to large hydropower systems and affect vast populations.

In third place are the research activities related to the development of turbines, where the upward trend is attributed to the need to improve outdated facilities by increasing their efficiency. The research activity related to small hydropower systems is not so large but is continuously growing as new places need to extract energy from this water resource. Finally, the number of publications related to run-of-river systems reveals that this technology is growing, but its attractiveness should be improved by new technological developments.

In term of patents, three different categories are detected in official data [17]: turbines or waterwheels, damless hydropower and other parts. As it can be observed (Fig. 9.10), the number of patents in these areas is huge and growing, except for 2011. Also, the number of patents in turbines and damless hydropower is quite similar, being lower for the other parts category.

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Chapter 10
Geothermal Energy

Abstract Geothermal energy can be used either to generate base-load electricity with very high capacity factors and independent of seasonal conditions or to provide space heating and cooling in buildings. Globally, the annual production of geothermal electricity is somewhat smaller than solar PV production. In addition, it has already reached grid parity in locations with adequate resources. For power generation, geothermal energy can be used in conventional steam plants (flash technology) or in a closed-loop configuration (enhanced geothermal systems). Furthermore, the recently developed binary plants can produce electricity from low temperature (<100 °C) geothermal sources, which are used to boil a secondary fluid of very low boiling point (butane or pentane). A very interesting development in geothermal energy is the ground source heat pump technology. In these devices, a loop of pipes is inserted at depths about 100 m below ground, and the circulating fluid (often water) extracts thermal energy and transfers it to a heat pump.

10.1 Overview

The temperature gradient in the earth's crust is typically 30 °C/km, although there are areas where it is above 150 °C/km. When the gradient is low, the geothermal region is qualified as normal or low enthalpy region, while for high gradients of temperature it is denominated high enthalpy region. Consequently, geothermal energy is defined as the energy available as heat contained in or obtained from the crust. The main sources for geothermal energy are the heat flow from the earth's core and mantle (~40 %), and the heat flow generated by the gradual decay of radioactive isotopes in the earth's continental crust (~60 %) [1].

The geothermal energy can be used to generate electricity and provide heat. The heat is used for heating buildings and homes, aquaculture, horticulture and industrial processes. Also, it is considered as geothermal, the energy obtained from underground areas at nearly constant temperature of about 60–70 °C, and injected to heat pumps, where 3 million are installed worldwide in early 2010 [2].

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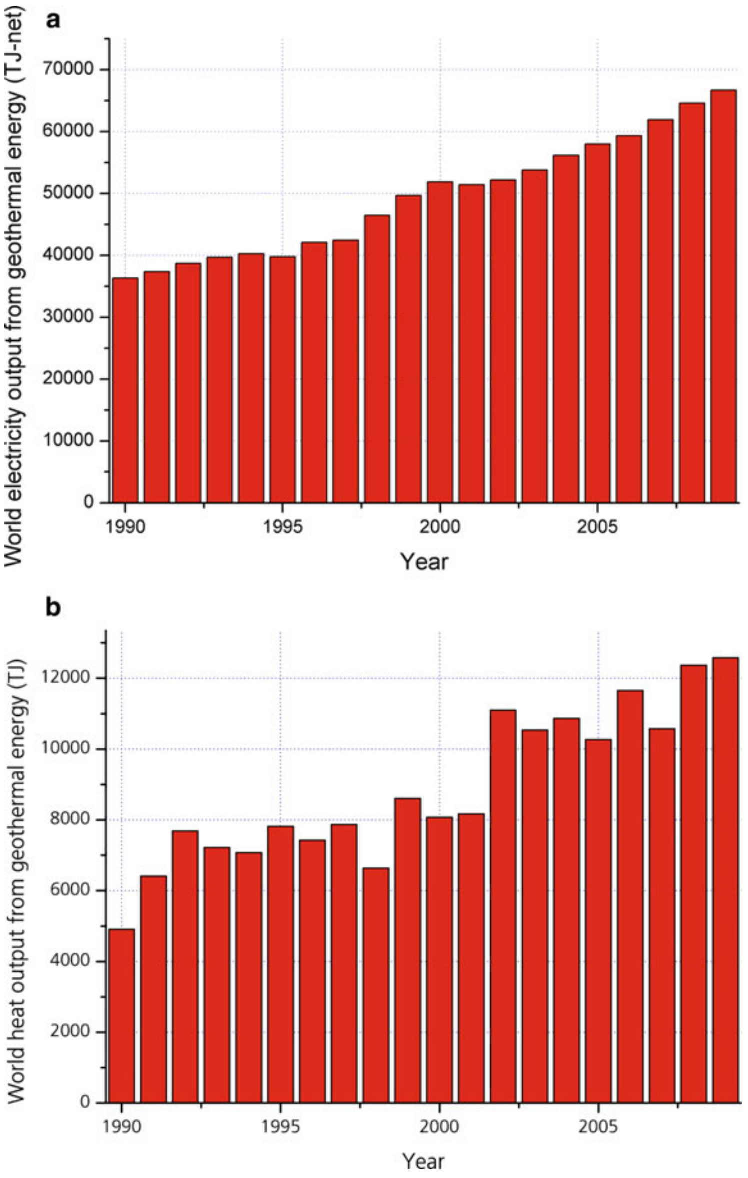

Fig. 10.1 Evolution of the annual production of geothermal energy for the production of (**a**) electricity and (**b**) heat in the period 1990–2009 [2]

The installed geothermal capacity worldwide reached 10.7 GW_e for power generation and 50.6 GW_{th} was directly used as heat in 2009 [2], producing 2.59 EJ. Figure 10.1a shows the evolution (1990–2009) of electricity production worldwide from geothermal energy (66,672 TJ-net in 2009), with a capacity factor of 71 % in 2009, loads of 84–96 % and availability of 92–99 % [2]. Figure 10.1b shows for the same period the use of geothermal energy for direct heat (12,581 TJ-net in 2009). As it can be observed, the use of geothermal energy is growing worldwide and it is mainly devoted to produce electricity. Thus, in some countries, the weight of the geothermal resource in the electricity mix is substantial (i.e. 25 % in Iceland and 22 % in El Salvador).

Geothermal energy has many positive aspects, which can be summarised as follows:

1. Ability to provide base load power.
2. Stable to seasonal variations.
3. Stable against effects of weather and climate change.
4. Integrated in centralised and decentralised production plants.
5. Availability of resources in all regions of the Earth.

Also, geothermal energy has some negative aspects, which can be summarised as follows:

1. High investment costs.
2. High risk to obtain the geothermal resource at an affordable cost.
3. Lack of knowledge about exact resource availability.
4. Environmental effects.

10.2 State of the Art

Traditionally, the geothermal energy has been extracted close to the edges of tectonic plates where high temperature geothermal resources are available near the surface (Fig. 10.2). A minimum 200–300 m distance between drillings is needed to avoid any interference between them. However, new enhanced geothermal systems are planned to exploit deeper resources, and the binary technology is also growing by extracting energy from low temperature fluids.

The thermal efficiency of geothermal electric plants is low (10–23 %), as the geothermal fluids obtained do not reach the high temperatures of steam applied to conventional power boilers. However, as the geothermal resource is almost constant over time (unlike other renewable energy sources), the capacity factor of geothermal systems to produce electricity can be large (up to 96 %). All these concepts and geothermal applications to increase comfort at home are exposed below.

10.2.1 Flash Technology

Flash is the technology most widely used. In this case, the well tank collects the high-pressure hot water and reduces this pressure in the separator, using the generated steam to drive turbines for electricity production (Fig. 10.3). The steam is condensed after crossing the turbine and re-injected. The required fluid temperature must be above 180 °C.

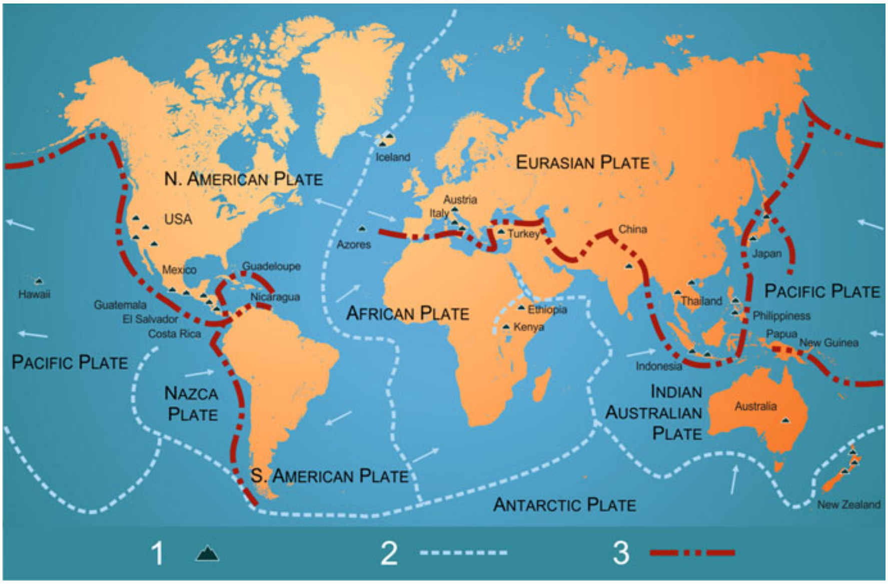

Fig. 10.2 World pattern of tectonic plates, oceanic ridges, oceanic trenches, subduction zones and geothermal fields. *Arrows* show the direction of movement of the plates towards the subduction zones. (1) Geothermal fields producing electricity; (2) mid-oceanic ridges crossed by transform faults (long transversal fractures); (3) subduction zones, where the subducting plate bends downwards and melts in the asthenosphere

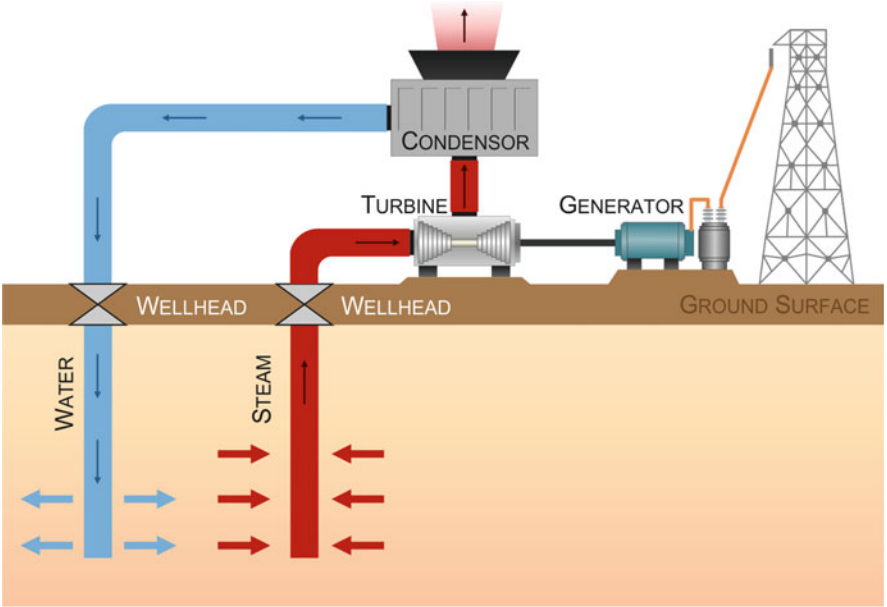

Fig. 10.3 Scheme of the flash technology for electricity production from geothermal resources

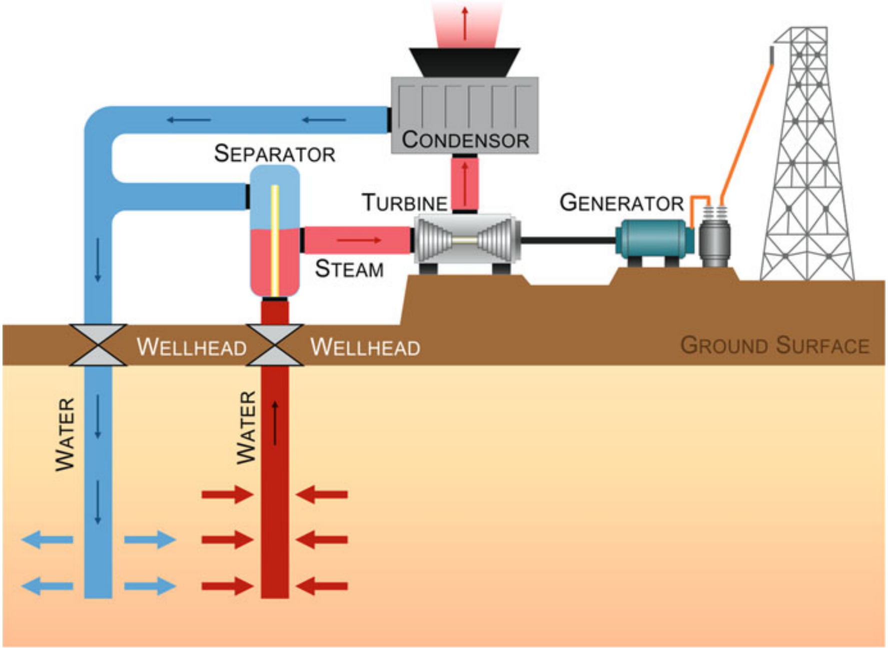

Fig. 10.4 Diagram of the EGS technology, also called hot dry rock technology

10.2.2 Enhanced Geothermal Systems

The EGS (enhanced geothermal systems) technology, formerly called hot dry rock, creates or enhances artificial geothermal reservoirs underground, circulating water (closed loop) from the surface through wells (Fig. 10.4). Thus, artificially enhancing the permeability of hot rock areas, the water is heated and extracted through other wells and sent to binary plants (explained below) to generate electricity. This system can be extended to geothermal areas that are not tectonically active. Some of these plants operate in a cascade mode, as the water used to produce power in the geothermal plant is subsequently derived for district heating before being re-injected into the geothermal reservoir.

There are several methods to solve the environmental problems caused by the small amounts of chemical pollutants (boron and arsenic) and gases (H_2S and CO_2) contained in the extracted water. Mainly, these techniques consist in that the water is re-injected into the reservoir, the gas is condensed and some chemical treatments are applied for the extraction of minerals. The costs of these processes are estimated in 1–2 % of the total costs [2]. As a drawback, these systems require large amounts of water for recirculation. Thus, a small plant of 5 MW may require about 350 m^3 of water per hour to operate, and a commercial plant would require ten times that amount [3].

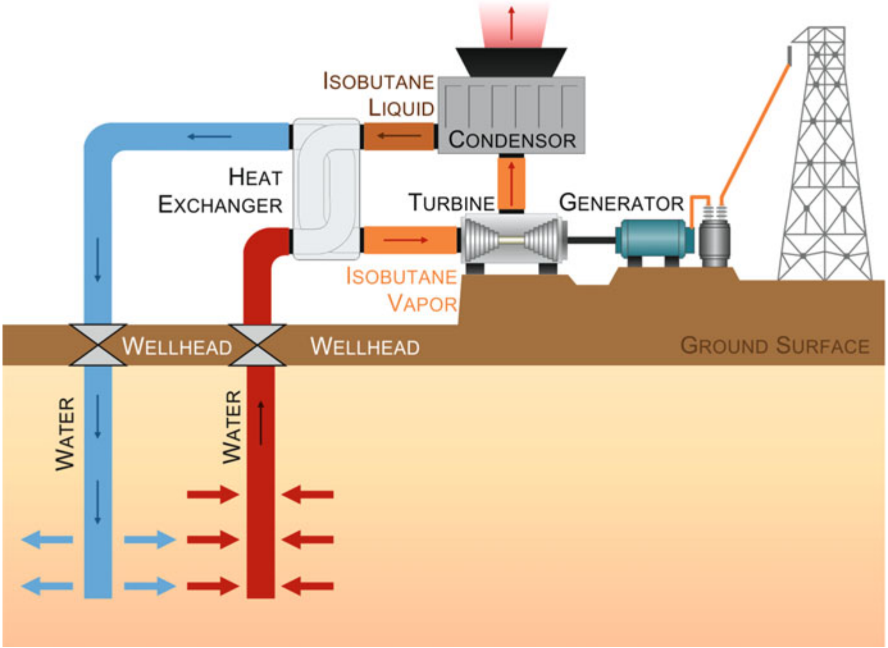

Fig. 10.5 Scheme of the binary technology for electricity production from geothermal resources

10.2.3 Low Temperature Resources Via Binary Plant Technology

This is the most recently developed technology for electricity production from geothermal resources. Binary plants typically use low temperature fluids (<180 °C) in the exchanger (having accepted fluids with temperatures of 57 °C) with secondary fluid boiling point (butane or pentane) much lower than that of water, which generates the gas that drives the turbine (Fig. 10.5). The average thermal efficiency is 10 %, reaching 0 % for fluids below 60 °C. At present, the number of binary plants is growing very fast worldwide and replacing the flash plants.

Organic Rankine cycles (mainly) and Kalina cycles are the most common in binary plants. For organic Rankine cycles, a high molecular weight organic fluid with boiling point well below the water is used. For the Kalina cycle, a working fluid consisting at least of two components (usually water and ammonia) is used, and the ratio between them varies in different parts of the system to obtain higher reversibility and, therefore, to increase the total thermodynamic efficiency of the system.

10.2.4 Geothermal Heat Pumps

This technology uses underground areas located at a constant temperature at depths below 300 m, obtaining heat through a closed water circuit. The resource is

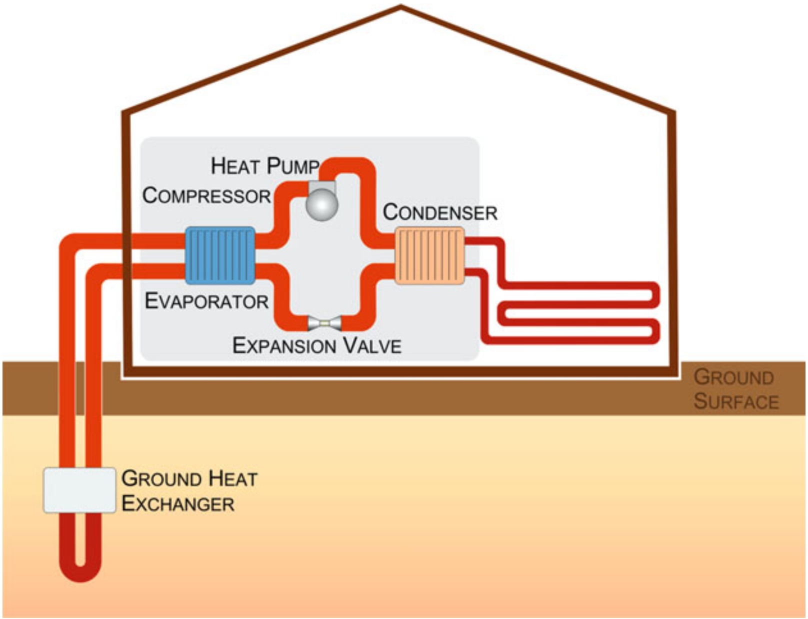

Fig. 10.6 Scheme of the of geothermal heat pump technology

considered to provide thermal stability to spaces and water heating. This technology works in two different configurations (a) vertical well heat exchangers (Fig. 10.6) and (b) horizontal subsurface loops. The former is more expensive but has improved performance and occupies less space. This technology is used for multiple applications: spas and swimming pools, snow melting, radiators, heating of water, radiant panels, air conditioning, cereal forage, breeding barn, greenhouse conditioning, vegetable drying, food processing, fisheries, metal leaching, sludge digestion, curing of concrete blocks, dry cloth, pulp and paper, etc.

10.2.5 Stages of Development

Depending on market penetration, the generation of energy from geothermal resources (Fig. 10.7) is led by the flash technology, as it is the most mature. Binary technology is less close to competition, with significant R&D activities, mainly in organic Rankine and Kalina cycle technologies. Furthermore, EGS systems (advanced systems) require still great technological efforts to be competitive. Finally, geothermal heat pump technology is mature and in a competition stage, although some degree of innovation is still expected in the future.

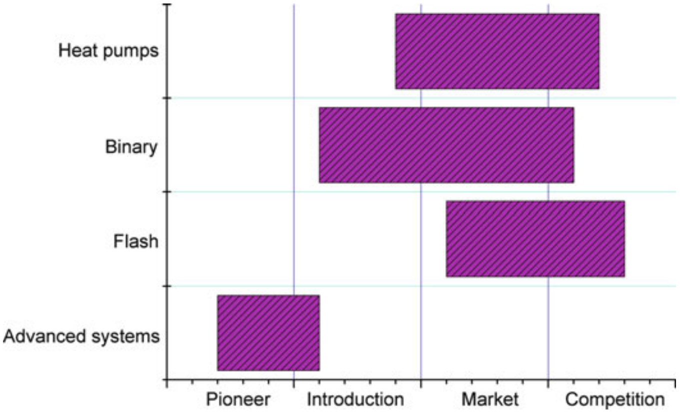

Fig. 10.7 Stages of development for each of the technologies considered in geothermal energy

10.3 Current Costs and Future Scenarios

The cost of geothermal power generation depends on the resource pressure and temperature, depth and permeability of its location, the chemical composition of the fluid, the location, drilling market characteristics, plant size and type of plant. Costs also are affected by the price of raw materials (oil, steel and concrete).

In 2008, the investment costs for flash technology ranged from USD 2,100 to 4,727/kW$_e$ (EUR 1,509 to 3,396/kW$_e$), while costs for low-temperature binary technology costs ranged from 2,530 to 6,198 USD/kW$_e$ (EUR 1,811 to 4,452/kW$_e$) [2]. The amortisation periods for such investments in Europe are between 4 and 8 years [2]. Expectations of decreasing investment costs are low over the next years (5 % by 2020 [2]). Although these studies are considering geothermal plant lifetimes of 20–30 years, usually its operational life is considerably greater, reaching in some cases more than 50 years.

The costs of electricity generation from geothermal flash technology ranges from USD 52 to 80/MWh (EUR 37 to 58/MWh) for high temperature resources, while for lower temperature binary technology costs range between USD 59 and 107/MWh (EUR 42 and 77/MWh) [4]. Consequently, geothermal energy has already reached grid parity in the electricity market (Fig. 10.8). The IEA expects electricity generation reaching USD 50–76/MWh (EUR 36–55/MWh) for geothermal flash technology and USD 54–96/MWh (EUR 39–69/MWh) for binary technology in 2030 [4].

Investment costs for geothermal district heating is USD 570–1,570/kW$_{th}$ (EUR 409–1,128/kW$_{th}$) [4]. The district heating costs oscillates from USD 45 to 85/MWh$_{th}$ (EUR 31 to 61/MWh$_{th}$) and USD 40 to 50/MWh$_{th}$ (EUR 29 to 36/MWh$_{th}$) for heating greenhouses (Table 10.1) [4]. The average fuel prices for USA consumers heating in the 2010–2011 winter was USD 34.56/MWh$_{th}$ (EUR 24.83/MWh$_{th}$) for natural gas and USD 66.63/MWh$_{th}$ (EUR 47.87/MWh$_{th}$) for

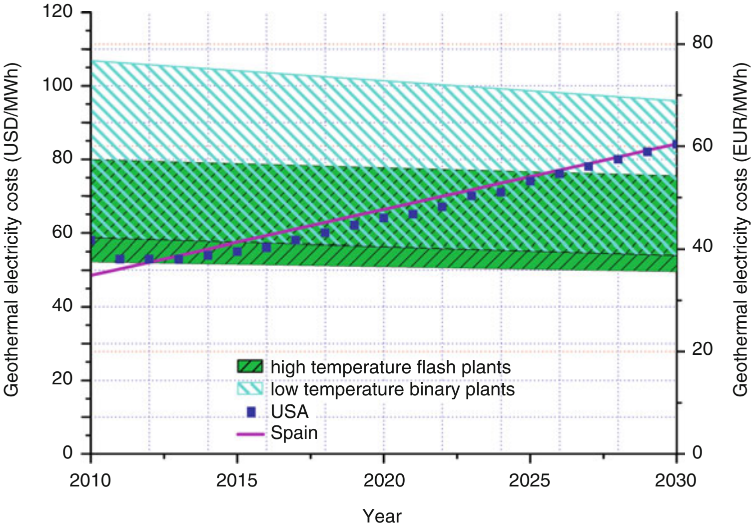

Fig. 10.8 Current geothermal electricity costs from binary and flash technologies, and forecasts to 2030. The *solid square* symbols represent the generation electricity costs expected in USA, and the *magenta straight line* represents the linear fit of the average generation electricity price in the Spanish wholesale market, both projected from 2011 to 2030

Table 10.1 Geothermal heating costs and conventional heating fuel prices for USA in winter 2010–2011

Costs	USD/MWh$_{th}$	EUR/MWh$_{th}$
Geothermal district heating	45–85	31–61
Geothermal greenhouse heating	40–50	29–36
U.S. average natural gas heating in 2010–2011 winter	34.56	24.83
U.S. average heating oil in 2010–2011 winter	66.63	47.87

heating oil [5], but the investment and O&M costs of conventional systems should be added to compare with geothermal costs. Consequently, the direct use of geothermal energy for heat supply is at present competitive with conventional energy sources.

The O&M costs range from USD 9 to 25/MWh (EUR 6 to 18/MWh) [5] and are a small percentage of total costs due to lack of fuel expenses. These costs are dependent on the power capacity, characteristics of the location, type and number of plants and the use of remote control systems. Such costs would experience significant increases if the well should be replaced.

The estimated investment cost for the energy supplied by geothermal heat pumps is highly variable depending on the country being analysed, ranging from USD 439 to 600/kW$_{th}$ (EUR 315 to 431 /kW$_{th}$) for China–India to USD 1,170 to 2,267/kW$_{th}$ (EUR 841 to 1,629/kW$_{th}$) in Europe. The estimated average heating costs for this technology are about USD 80/MWh$_{th}$ (EUR 5.8 MWh$_{th}$) [2].

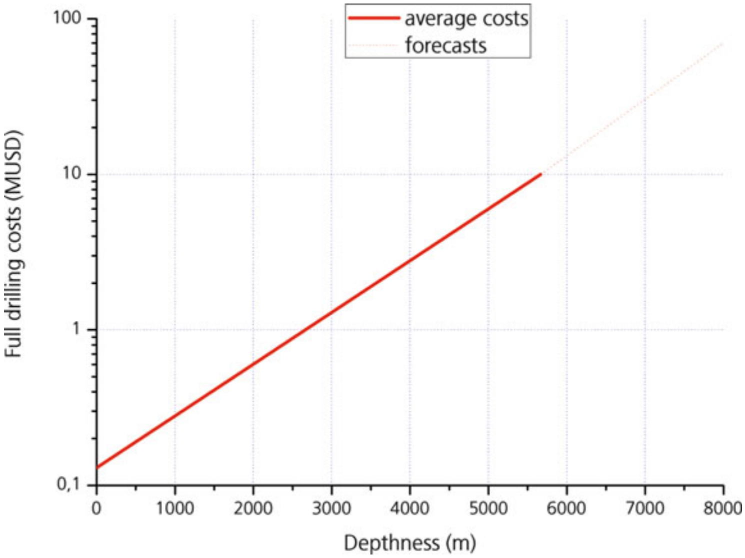

Fig. 10.9 Drilling cost for a typical geothermal plant [7]

The key parameters to reduce costs are higher temperatures and flows. Consequently, the drilling characteristics are critical to make a geothermal resource profitable. Because drilling costs increase substantially as the required drilling depth increases (Fig. 10.9), the EGS technology nearly doubles in cost per kWh of electricity the costs corresponding to more conventional systems [6]. On the other hand, geothermal drilling is more expensive (in cost per depth) than on-shore oil and gas drilling for three principal reasons: (1) special tools and techniques are required for the harsh downhole conditions; (2) large diameters are required because the produced fluid (hot water or steam) is of intrinsically low value and (3) geothermal wells, even in the same field, are more different among each other than oil and gas wells in the same field, so the learning curve from experience is less useful. Also, an indirect cost is attributed to the fact that almost all produced fluids must be re-injected, thus requiring additional wells. Added all these factors, the cost of drilling an injection well can raise to 50 % of the total project cost for a geothermal power plant [7].

10.4 Energy Payback, CO_2 Emissions and External Costs

With respect to calculations on the energy payback for geothermal technology, the most rigorous studies conducted to date in renewable energies [8, 9] have not included this technology. This fact can be attributed to huge differences between resource characteristics depending on the location and the technology employed.

On the other hand, CO_2 emissions from low-temperature geothermal resources are negligible (0–1 g/kWh [2]) and most binary systems are operating in closed loop. Consequently, their emissions are negligible. In addition, CO_2 emissions from geothermal heat pumps are reduced by at least 50 % compared to oil boilers, depending on the source considered for electricity production [2].

In relation to external costs, no official data have been found.

10.5 Future Technology Trends

There are some general trends affecting all technologies exposed, mainly efforts to reduce drilling costs and the seismicity derived, and improving estimation techniques to determine the capacity of the geothermal resource prior to drilling. Also, the technology trends are focussed in avoiding contamination of aquifers by corrosive geothermal fluids.

10.5.1 Flash Technology

There is substantial interest in pumps that can work under extreme pressure and temperature conditions. Thus, the use of supercritical fluid heat water (400–600 °C) extracted from very deep locations (4–5 km) can multiply by ten the power output of the geothermal plant, reducing costs and number of geothermal power units.

There is also important research for the recovery of deposits used in the past to extract geothermal energy. At the early times, geothermal energy plants extracted the resource from the underground without recharging it and, consequently, after years of exploitation the resource almost vanished, making it non-profitable. Currently, some depleted geothermal wells are being recovered after applying rest periods so that they are recharged naturally.

10.5.2 Enhanced Geothermal Systems

This technology consists in improving methods to construct deeper geothermal deposits, avoiding the induced seismicity associated to EGS (small seismic tremors can sometimes be felt, though on a minor scale). Moreover, new tools are being developed to obtain data from high-temperature and high-pressure wells, as these are expected to be found in deeper wells. Also, smaller test wells are being considered to reduce costs, since the investment increases exponentially with depth, as it can be observed in Fig. 10.9 [3].

Important R&D activities are also devoted to avoid the low seismicity produced in drilling at great depth, where the resource is considered to be found. Additional research activities are trying to develop tools and devices to avoid land subsidence in high-temperature plants, by monitoring and injection processes. These activities are mainly focused on the following topics: (1) preliminary screening evaluation; (2) criteria for ground vibration and noise; (3) local seismic monitoring; (4) quantifying the hazard from natural and induced seismic events; (5) characterisation of the risk of seismic events and (6) development of risk-based mitigation plans.

New techniques in drilling are also being developed, mainly drilling with casing, use of expandable tubes and better downhole feedback [7]. These technologies permit more accurate drilling on non-standard configurations and greater probabilities of success. Improving hard rock, high-temperature and high-pressure drilling technologies is needed. New improvements in compressors and heat exchangers are also expected.

On the other hand, since EGS systems require large amounts of recirculating water for the process, one goal is to apply more efficient cooling systems where water circulation in closed loop hugely reduces water demand.

Moreover, the development of deep systems (5 km) in volcanic active areas can potentially provide ten times more geothermal power since the steam conditions are more favourable (430–550 °C, 230–260 bar) [3]. However, drilling at these depths under high pressure and temperature conditions, where corrosion processes can play an important role in rising costs, can rest attractiveness to these areas [3].

Finally, other advanced geothermal technologies are being recommended for the future: (1) alternative ways to exploit hot rock resources; (2) alternative technologies to exploit hydrothermal resources such as supercritical fluids and co-produced hot water from gas and oil wells and (3) alternative technologies to exploit off-shore hydrothermal resources.

10.5.3 Low Temperature Resources Via Binary Plant Technology

Advances in this technology have succeeded in producing electricity from fluids at temperatures as low as 73 °C, considering that the lower limit is at 57 °C. However, substantial efforts are expected to increase efficiency and reduce costs applying new materials and control systems to the Rankine and Kalina cycles currently used in binary plant technology.

10.5.4 Geothermal Heat Pumps

An important task related to heat pumps is to further develop the standards and quality control systems for this technology, as demanded by the market to increase reliability. Moreover, the technology employed should protect groundwater from contamination and overexploitation. Also, it is important to avoid vertical connections between separate layers of aquifers through the wells.

10.6 Pre-Production Highlights 2009–2011

10.6.1 EGS Promoting Projects in Australia [6]

The Australian company Geodynamics has announced in September 2010 the drilling of new 90 wells to produce geothermal energy by applying the EGS technology. The wells will be located in Southern Australia and will reach depths of 4,500–5,000 m. The plants include a unit capacity of 50 MW, and the company estimates that the capacity potential of the area could reach 12.5 GW.

10.6.2 Protocol for Addressing Induced Seismicity Associated with EGS [10]

A final draft of a Protocol for addressing induced seismicity associated with EGS was presented at the GIA~IPGT Meeting in Paris, France on 3 May 2011. This document is intended to be kept up-to-date with state-of-the-art knowledge and practices, both technical and non-technical, and was prepared under the direction of the U. S. Department of Energy's Geothermal Technologies Program. The objective is to provide a flexible protocol that ensures the safety of EGS activities while allowing geothermal technology to move forward in a cost-effective manner. The document also details useful steps that geothermal project proponents can follow to deal with induced seismicity issues.

10.7 Innovation Highlights 2009–2011

10.7.1 First Steps to Use CO_2 to Improve the Extraction of Geothermal Heat [11]

The idea is that carbon dioxide stored using CCS technology can be injected thousand of metres underground, in supercritical state, also to extract heat to the surface. This idea has been supported by the U.S. Department of Energy with a grant of USD 16 million (EUR 11 million). The project has been divided into 9 subprojects led by the Lawrence Berkeley National Laboratory, along with other national laboratories, universities and companies. Also, the project tries to prevent the use of water for this purpose and, consequently, increasing the attractiveness of this technology to be applied where the water resource is scarce.

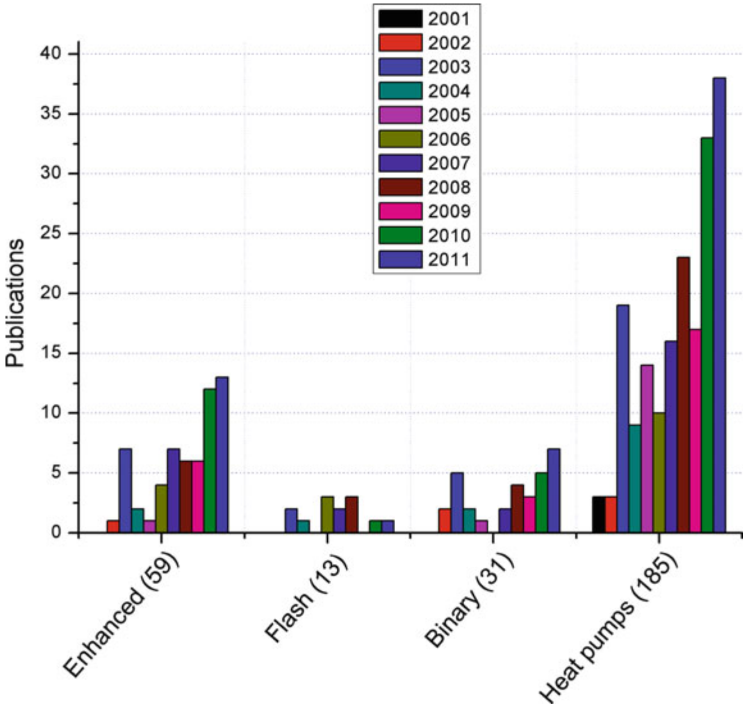

Fig. 10.10 Number of scientific publications during the period 2001–2011 for the technologies related to geothermal energy [12]

10.7.2 *Use of Spallation Systems [6]*

The American company Potter Drilling is promoting the use of a technology alternative to that used in the petroleum industry for drilling wells to extract geothermal energy. The process, called spallation, consists of superheated steam that, in contact with the rock, expands its crystalline grains creating small fractures that cause the rock to break into small particles. The spallation systems can drill faster, and using steam, the frequent replacement of the drilling heads conventionally used is largely avoided.

10.8 Statistics of Publications and Patents

Figure 10.10 shows the number of scientific publications during the period 2001–2011 for the technologies related to geothermal energy [12].

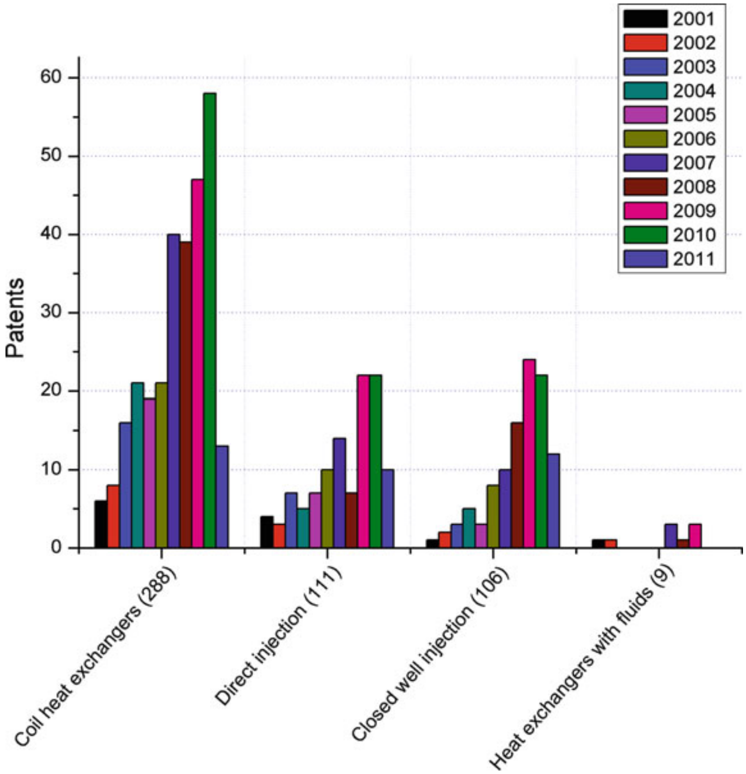

Fig. 10.11 Number of patents during the period 2001–2011 for the technologies related to geothermal energy [13]

It can be observed that the number of publications is moderate in general, but an upward trend in activity is detected in all the technologies except binary systems. Also, flash systems show the lowest activity in terms of scientific publications, which can be attributed to the maturity of this technology and the lack of attractiveness for research activities related to the other technologies exposed. Thus, among the technologies involved in energy production from geothermal resources, the one that shows the highest and upward research activity is related to EGS followed by the binary technology. It can be attributed to the vast potential that enhanced systems would offer in the coming future if this technology successfully extracts geothermal energy from deep resources.

On the other hand, geothermal heat pumps generate more research activity than the other three technologies combined. This can be attributed to the fact that the equipment for geothermal heat pumps is more affordable than for geothermal energy production plants, and also because the use of this technology is spread around the world and demands no special underground requirements.

In terms of patents, the European Patent Office [13] shows a different classification for geothermal energy to the one exposed above for publications (Fig. 10.11), where it is shown that the coil heat exchangers and compact tube assemblies dominate the patent activity, as these are essential components in any geothermal system. Secondly, it is observed a very similar evolution in terms of patents for systems injecting medium directly into the ground (e.g. EGS) and systems injecting medium in a closed well. Finally, the number of patents attributed to systems exchanging heat with fluids in pipes (e.g. for geothermal heat pumps) is very low, as the technology involved can be considered poorly adapted to produce patents.

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Chapter 11
Ocean Energy

Abstract There is a large variety of ocean energy technologies, which can be classified in various categories: tidal range and tidal currents, waves, ocean currents, thermal gradients and salinity gradients. The most mature of them, with great difference, is the one based in the rise and fall of tides (tidal range), followed by wave technologies. Of all the ocean technologies considered for the generation of electricity, it is only the tidal barrage the one that is close to grid parity, although barrage plants are faced with considerable environmental challenges. In addition, the technology is quite similar to hydropower plants, since the electricity is generated by the water released out of the barrage. In the case of tidal and marine currents, the technology is in principle not too complicated since the flow of water is used to move various types of turbines. Finally, the chapter also reviews the large variety of techniques, which can be employed to extract energy from the waves: oscillating water columns, oscillating body systems (floating or submerged), which generate electricity from their movements, overtopping converters, etc.

11.1 Overview

Ocean energy can be considered an emerging renewable energy because its worldwide capacity is at present the lowest of all renewable technologies (see Table 2.1). Also, there is not yet a consensus about the more efficient technologies to be applied to extract energy from oceanic waves and currents. Thus, in the past, large amounts of public and private funds have been dedicated without a substantial success in the short term. In this regard, it is noted that, only in 2011, about 1,000 patents were approved for devices devoted to extract energy from waves.

The energy contained in the oceans is available primarily through the exploitation of the flow of waves, ocean currents and tides, but there are also activities to extract energy from ocean thermal and salinity gradients. In addition, some studies consider the exploitation of the marine biomass as a resource to be counted within

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Table 11.1 Estimated resources for the production of electricity from the ocean energy worldwide [3]

EJ/year	Estimated global resources
Waves	288
Tidal currents	2.88
Tidal range	1.08
Salinity gradient	7.2
Thermal gradient	36

Table 11.2 Ocean Power installed and being installed and under installation worldwide (2009–2010) [1]

kW	Installed (2009)	Installed (2010)	Under installation
Wave	932	3,111	2,346
Tidal currents	2,345	3,100	2,000
Salinity gradient	5	4	–
Tidal range	260,000	260,000	254,000
Total	263,282	266,215	258,346

the ocean energy [1], although in our case it is discussed in Chaps. 3 and 4, devoted to biomass and biofuels, respectively.

Current use of ocean energy is still very low, reaching only about 0.0019 EJ/year (530 GWh) in 2009 [2], although the technical potential of ocean energy is estimated at about 926 EJ/year. Some publications even disaggregate the technical potential in relation to the different technologies involved in ocean energy (Table 11.1) [3].

Some of these technologies are taking off from very low power capacities, although with an intense activity. Others are well-established technologies but with short growth potential mainly due to technical and environmental conditions. On the other hand, updated data from the OES-IEA [4, 5] including La Rance tidal power station calculate a capacity of ocean energy facilities worldwide of 266.2 MW, mostly devoted to tidal range exploitation (Table 11.2).

Consequently, considering that La Rance tidal power station was built in 1966 and is masking the growth of new and small ocean energy installations, the annual worldwide electricity production from this resource has been almost constant in recent decades (Fig. 11.1) [2].

11.2 State of the Art

As it has been mentioned above, there are different strategies for obtaining energy from the oceans, which can be specified in the following technologies.

11.2.1 Waves

Waves, created by the wind, can travel thousands of kilometres through the oceans with minimal energy losses until they are modified by other winds. The major drawback of this kind of energy resource is its variability, although some seasonal

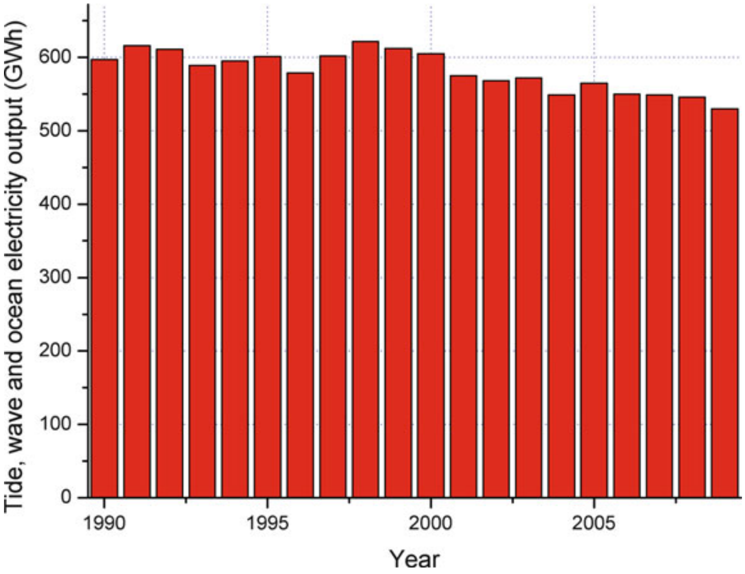

Fig. 11.1 Evolution of the electricity production from ocean energy [2]

variation patterns can be identified [6]. The wave energy level is usually defined in terms of power per unit of transversal length. Adequate locations for the exploitation of this kind of energy are those showing values between 20 and 70 kW/m. These locations are generally situated in moderate to high latitudes, with mostly constant values throughout the year in the southern hemisphere. The wave power is proportional to the period of the waves and to the square of the wave height.

Approximately, the energy flow in excess of 30 kW/m is located in a 2 % of the 800,000 km of coastline on Earth. More specifically, the best sites to generate electricity from the waves are located in Southern America, Western Australia and west of the British Isles, where the wave power can be considered about 60–70 kW/m (Fig. 11.2) [7].

Typically, devices that extract energy from waves have only one degree of freedom, although some of them can perform movements with more degrees of freedom, thus improving their efficiency in the conversion process to mechanical energy. Thus, there are six potential oscillating movements (Fig. 11.3) [8]:

The devices used to obtain energy from waves can be classified as follows according to the principle of conversion (Fig. 11.4):

11.2.1.1 Oscillating Water Column

In these devices, the wave motion of water induces a similar movement in the air column enclosed in the structure (Fig. 11.5). The electricity is obtained from a wind turbine moved by variations in surrounding air pressure. The movement of these

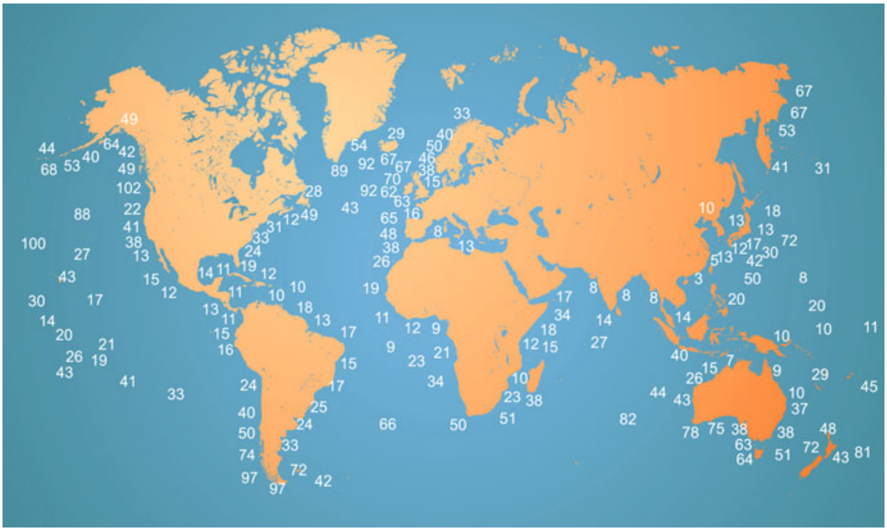

Fig. 11.2 Map of wave power per unit length (kW/m) worldwide [7]

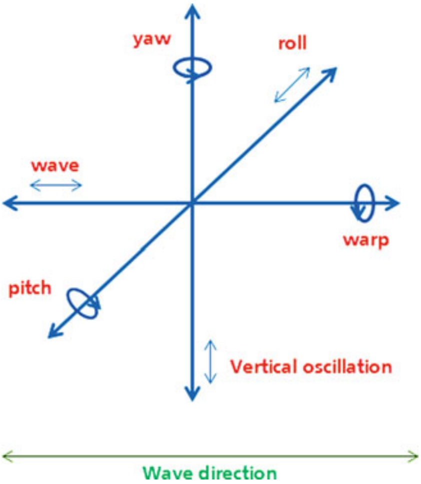

Fig. 11.3 Scheme of potential oscillating movements on a wave device

turbines is independent of the flow direction (auto-rectifying). This is due to the symmetric rotor profile, producing an identical movement in each direction.

These devices are divided between those with fixed structure (isolated or breakwaters) and floating structures. Among the isolated fixed structure, we can distinguish those installed on the shoreline and the ones anchored to the seabed. Within the first case highlights the LIMPET device, settled in Scotland in 2000 and with 500-kW nominal output, as well as another device installed at the island of

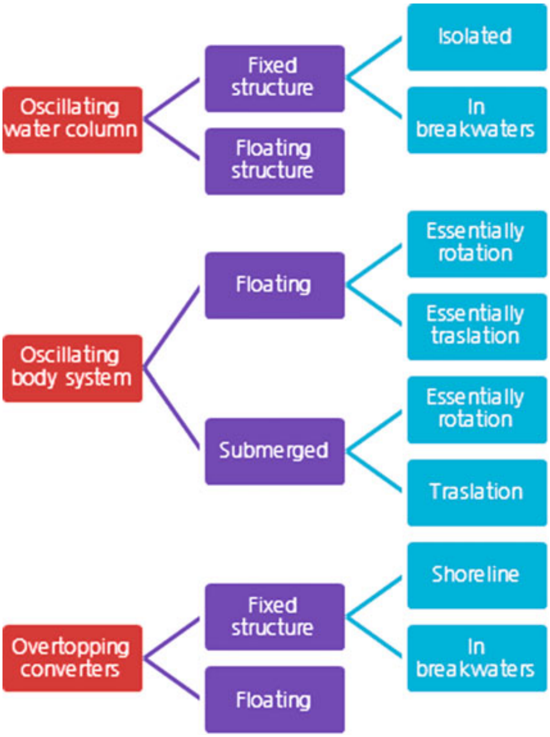

Fig. 11.4 Classification of devices to obtain energy from waves based on the principle of conversion [9]

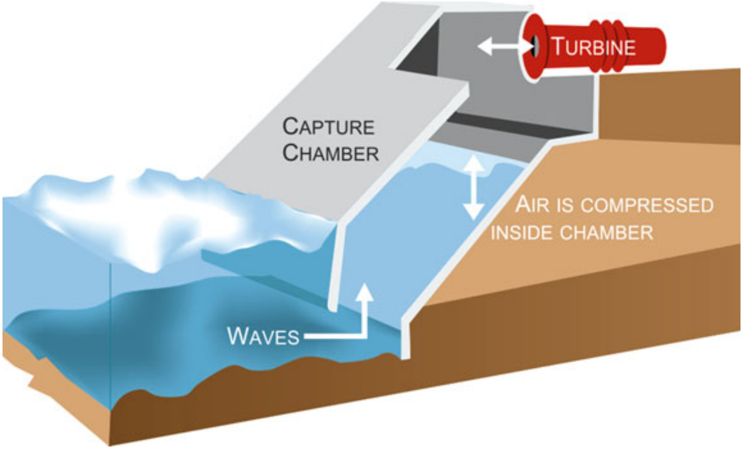

Fig. 11.5 Scheme of a shoreline oscillating water column device [10]

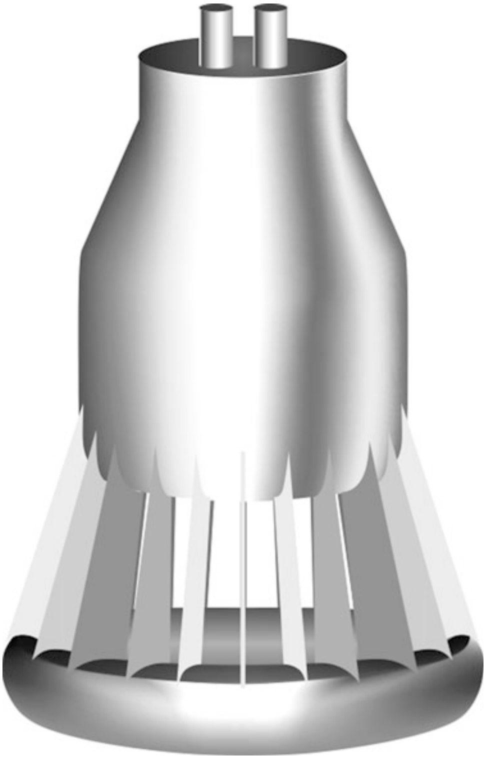

Fig. 11.6 Scheme of the Sperboy wave energy floating device

Pico (Azores). These devices are connected directly to the grid and have efficiencies around 30 %. On the other hand, the device installed at the port of Kembla (Australia) is a fixed structure, isolated and anchored to the seafloor. For devices installed on breakwaters, those located at the port of Sakata (Japan) and Mutriku (Spain) can be highlighted. Finally, in relation to the floating devices, many prototypes are currently being tested, as the Mighty Wale and Sperboy (Fig. 11.6).

11.2.1.2 Oscillating Body Systems

In this case, the electricity is obtained from hydraulic motors, hydraulic turbines or linear electric generators. Systems can be divided into floating and submerged bodies and can generate electricity from translation or rotation movements. Thus, the AquaBuoy is an example of floating system generating electricity from translational movements (Fig. 11.7a), in which buoys elevate and suck water when waves arrive. This water is driven down by a hydraulic pump when the waves move away, so that the water flow moves an oil-driven motor. Submerged systems generating

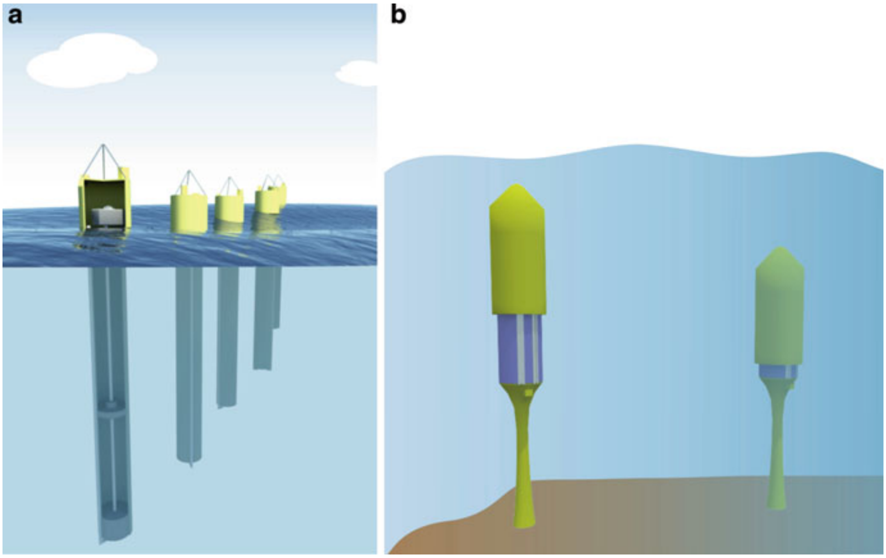

Fig. 11.7 (continued)

electricity from translational movements (Fig. 11.7b) also use to apply the same method to generate electricity.

As for the floating oscillating bodies using rotational movement to generate electricity, there are being tested multi-segment systems called attenuators, oriented parallel to the wave direction (Fig. 11.7c). The relative motion between floating bodies serves to pump high pressure oil through hydraulic motors, which move electricity generators.

Finally, for submerged oscillating bodies using rotational movement to generate electricity, surge converter devices can be mentioned (Fig. 11.7d) [11]. These devices consist of platforms anchored to the seabed oscillating back and forth, in such a way that its kinetic energy is collected by a pump with a piston that produces electricity.

11.2.1.3 Overtopping Converters

From these systems, the electricity is obtained by means of low head hydraulic turbines. They are divided among floating systems and those with fixed structure (in shoreline or breakwater). All these devices are quite similar to those used in tidal range dams, as they have reservoirs located at altitudes above the ocean but are filled with water from the waves. The water lifted by the waves, aided by the funnel effect of a channel, is stored in a reservoir. This water is then released through a pipe, which is connected to a Kaplan turbine to generate electricity. The reservoir can store energy and the electricity can be produced when it is demanded. In addition, the wave power is irrelevant as long as it is capable of adding water to

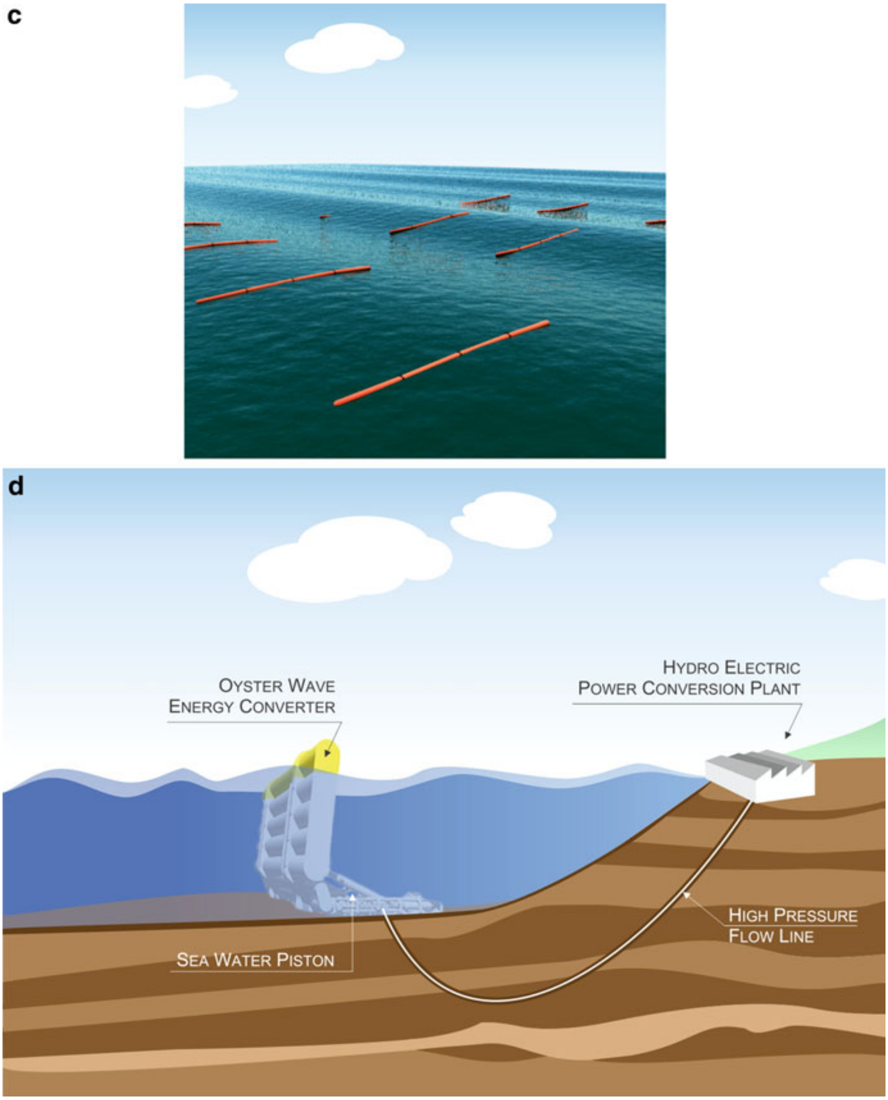

Fig. 11.7 (**a**) Floating system with translational movement, (**b**) submergible system with translational movement, (**c**) floating system with rotational movement and (**d**) submergible system with rotational movement

the reservoir. The most popular overtopping converter is the Wave Dragon, with a floating structure (Fig. 11.8).

In relation to fixed shoreline devices, the best known is the Tapchan (Fig. 11.9), having been successfully installed the first of such devices on the Norwegian island of Bergen in 1985, with an output power of 350 kW and connected to the electricity

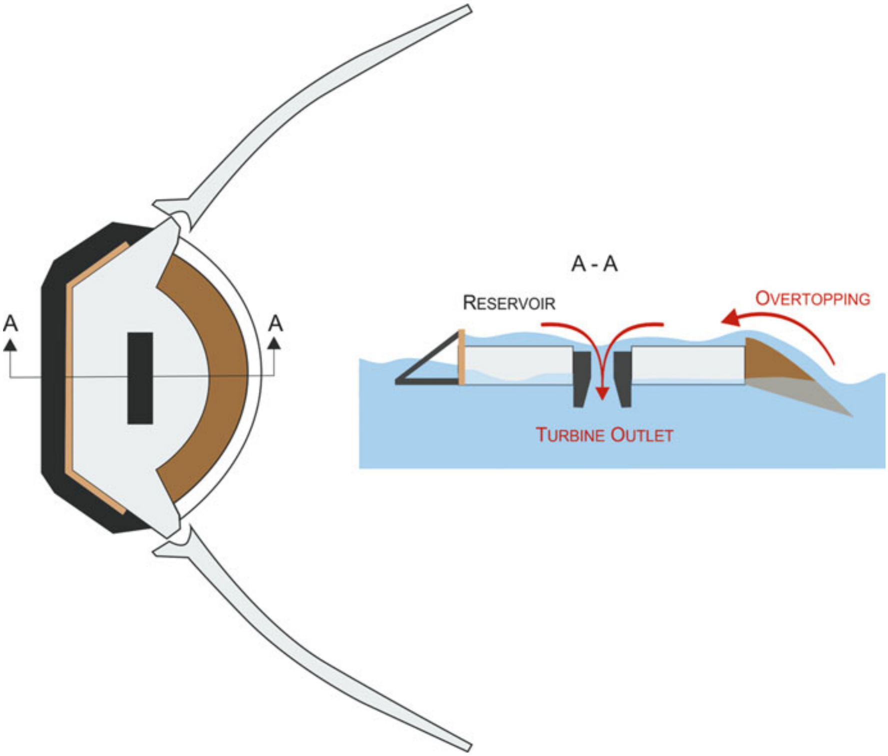

Fig. 11.8 The Wave Dragon overtopping converter floating structure diagram

grid. The locations where these overtopping converters are placed use to be near vertical cliffs that provide deep waters and, therefore, high-energy waves.

As for breakwater fixed-structure overtopping converters, the most popular is the SSG (Seawave Slot-cone Generator), composed of several tanks at different levels to collect water from waves (Fig. 11.10). The device, designed in Norway, has a special multi-stage vertical axis turbine to optimise the energy production from water stored in the different tanks.

As it has been mentioned earlier, the most common power-take-off systems installed on these devices are (1) pneumatic turbine, (2) hydraulic circuit with oil pressuriser and hydraulic motor, (3) linear electric generator (less advanced) and (4) hydraulic turbine (Kaplan or Pelton).

In terms of device location, the off-shore systems are more complex than those located near-shore or on the shoreline, mainly due to problems related to mooring, access to maintenance and the need for large seabed power transmission cables. Also, the waves have less energy near-shore, but this drawback can be compensated by wave refraction and/or diffraction in these areas. For devices placed near-shore, the shallow seabed is advantageous for installing these devices submerged on the seabed.

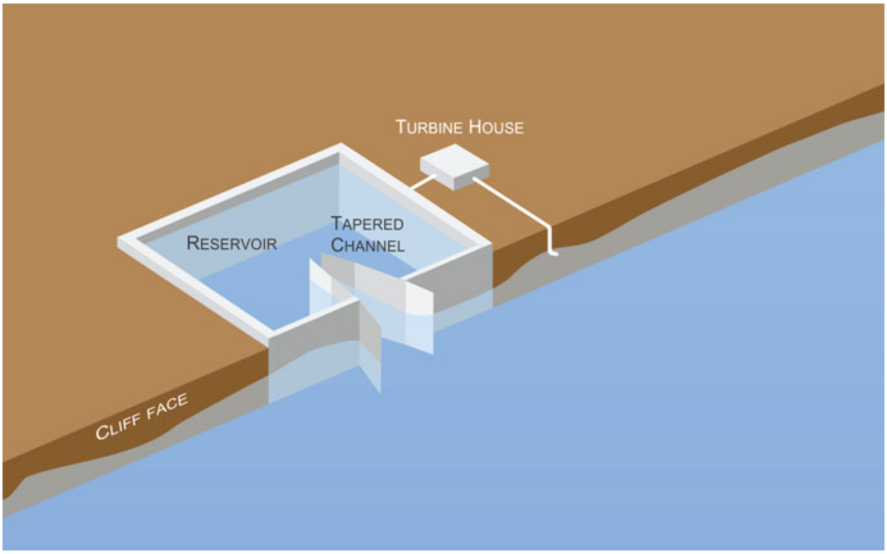

Fig. 11.9 Diagram of the Tapchan device

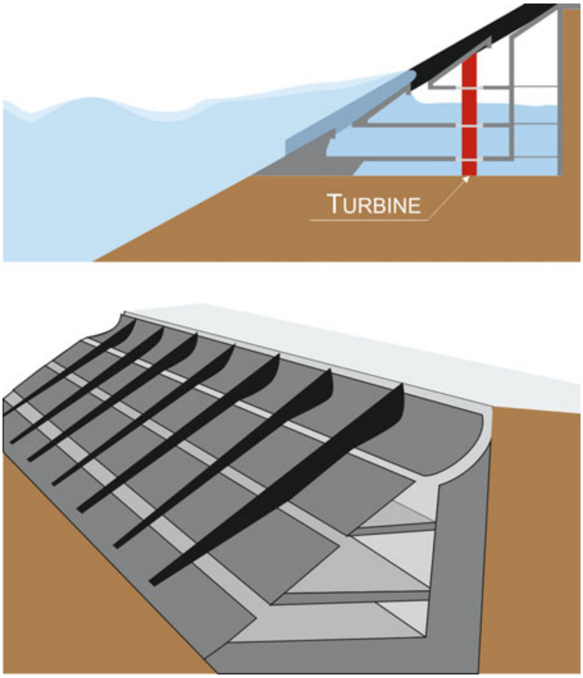

Fig. 11.10 Diagram of the breakwater fixed-structure overtopping SSG

The growth of new installations to extract energy from waves in the coming years is estimated at 10 MW/year. There are also at present several demonstration plants operating with individual powers reaching up to 0.75 MW [1].

11.2.2 Currents

Marine currents technologies are focused primarily on the use of fast flows produced by tidal induced marine currents. These flows are greatly increased by coastal topography in certain areas of the planet and reach their maximum values at half-tide periods. Generally, the power flow of the tides is greatest in shallow water, where funnel effects occur, such as straits or bays. The technology uses concepts already developed for the production of electricity from wind resources, but the fluid is about 800 times more dense than air. Then, it is estimated that if the marine current reaches an average speed of 2–2.5 m/s, the installation can be economically viable.

The technology used for the exploitation of tidal currents can be classified in any of the following:

1. Horizontal axis turbines, whose operation is very similar to those used in wind energy. Some of these turbines are covered to create flow concentration effects.
2. Vertical axis turbines, including cross-flow turbines.
3. Oscillating hydrofoils, which move up and down in a plane perpendicular to the flow of the tide. This movement creates pressure on a hydraulic fluid, which drives a hydraulic motor, and by extension, an electric generator.
4. Venturi effect devices, where the flow of water is introduced into a tube that concentrates it and produces a pressure difference, which is exploited by a second fluid to drive a turbine.

As it is discussed in more detail below (Sect. 11.6), on 12 November 2009, it was installed the first commercial turbine, 1 MW, using horizontal axis technology with some variations. The plant has been installed at the Minas Passage area in the Bay of Fundy, 3 km from the coast (Canada), in one of the world's largest tidal range areas.

A similar technology is considered for obtaining energy from the ocean currents. These currents are mainly produced by wind and solar warming affecting oceans near the equator, although variations in the density and salinity of the ocean water can have an influence. These currents are relatively constant and always flow in the same direction, in contrast to the currents produced by tides near the coast. Examples of ocean currents are the Gulf Stream, the Florida Straits Current and the California Current (Fig. 11.11) [12]. These currents tend to flow at the ocean surface, and the global potential power has been estimated at 5 TW, with power densities reaching 5 kW/m^2 [13].

The tidal currents could provide more than 10 TWh/year (about 0.4 EJ/year) in the larger estuaries, where currents can reach values up to 10 m/s [12]. The best sites are located on the west coasts of America, Britain and Australia, with energy flows that can exceed 80 kW/m^2.

The average power generated by ocean currents per unit area perpendicular to the flow is, as in the case of wind energy, proportional to the density of water and the cube

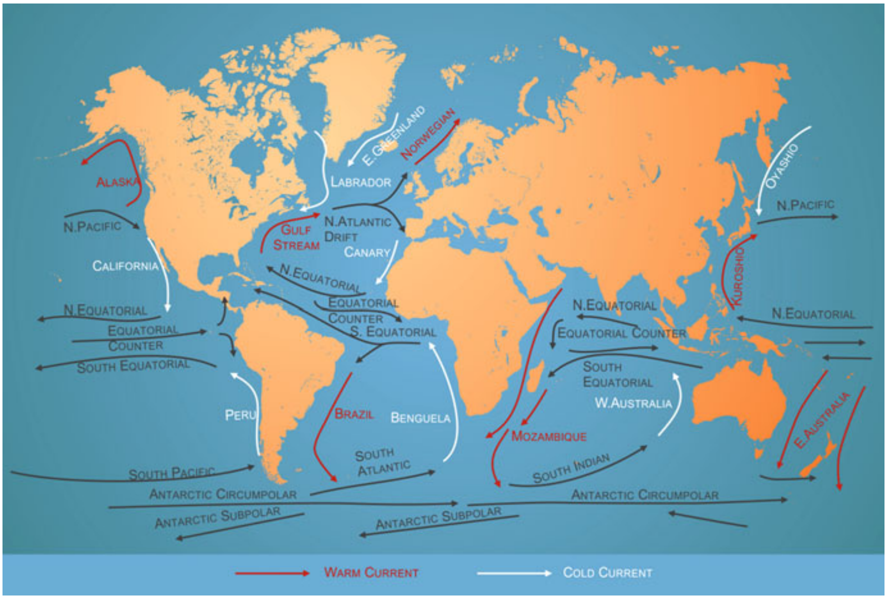

Fig. 11.11 Map showing major surface ocean currents on Earth [12]

of its speed so that, since the air density is about 800 times lower than that of water, ocean currents can carry much more energy at much lower speeds than the wind.

Although electricity generation from ocean currents is based on relatively simple physical principles, conceptually similar to those of wind generation, devices are not as developed as those for tidal currents.

11.2.3 Tidal Range

Tidal range is currently the oceanic technology in a more advanced stage of development. The most common technology to extract energy from tidal range is by installing a dam in a bay or estuary, acting very similarly to a hydropower plant. Consequently, water stored during the high tides drives a turbine as it is released at low tides. Also, turbines can be powered in the period of high tide, but it does not increase power generation significantly and, in contrast, can increase costs and operating risks.

In the case of tidal range plants, the power generated is proportional to the surface of the reservoir and the square of the range (height) of the tides. For example, a reservoir of 6 km^2 and a range of 4 m can produce an average power of approximately 10 MW.

There are very few tidal dams in operation for commercial exploitation. The best known is the plant at La Rance, in Brittany (France), built in 1956 with a capacity of

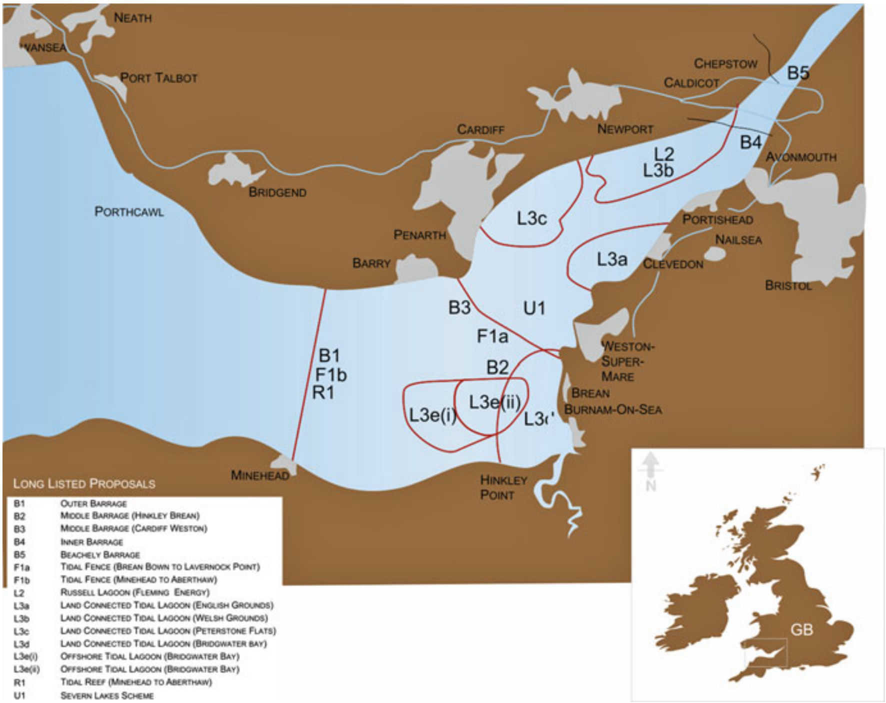

Fig. 11.12 Scheme of different tidal range systems that could obtain energy from the Severn Estuary (UK)

240 MW. Other operating plants are located in Annapolis Royal (Nova Scotia, Canada), which was launched in 1984 and consists of a single unit with a capacity of 18 MW. There is also a 400-kW plant in Kislaya Bay (Murmansk, Russia), completed in 1968, and several plants in China, including the 500 kW Jangxia Creek located in the East China Sea.

Other processes that exploit energy from the tides are called tidal reefs, lagoons and fences (Fig. 11.12). Tidal reefs use fixed flow turbines operating with a constant head difference of 2 m obtained by floating concrete blocks or moving locks. The tidal lagoons are independent structures built off-shore or in a semicircular shape connected to the shoreline, operating similarly to the dams, although there is no such system operating to date. Tidal fences are installed in shallow open waters where there are large water flows due to tidal periods, so that they can produce tidal energy in both upwards and downwards modes.

The potential of the tidal energy resource is about 800 TWh/year [14]. The most promising sites are indicated in Fig. 11.13 [15]. Some of the most favourable places are located in UK, where up to 25 % of its total electricity could be generated using this technology. Other suitable locations are situated in France, Ireland, Canada, USA, Argentina, Chile and Australia.

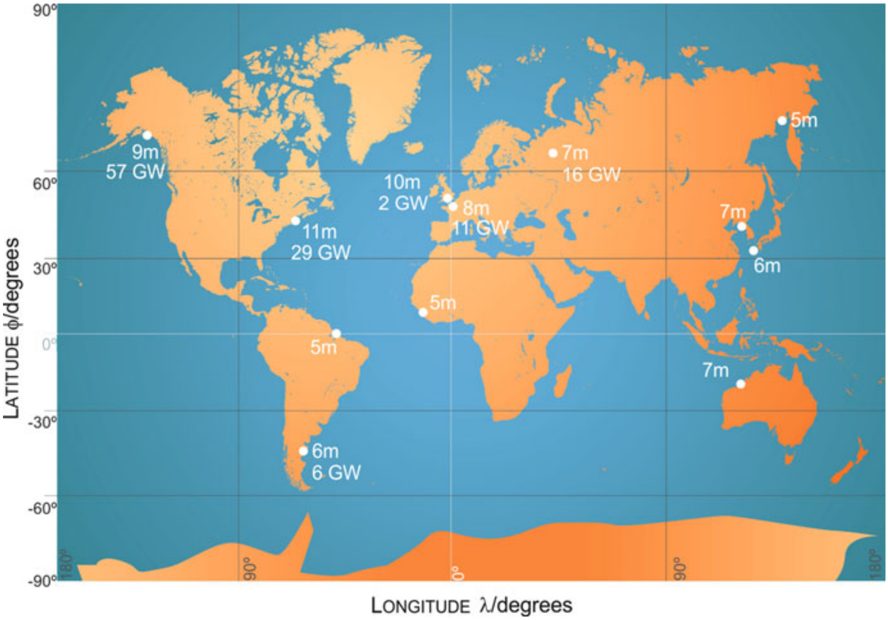

Fig. 11.13 Tidal ranges at different locations worldwide [15]

11.2.4 Salinity Gradients

This technology produces energy by increasing the entropy of mixing water with different salinity. The technology is under development, and some analyses consider that the theoretical global resources could reach 2,000 TWh/year [14]. Two strategies for converting the energy produced by the increase of entropy are on course: pressure-retarded osmosis and reverse electrodialysis.

Pressure retarded osmosis is based on the movement of a turbine by increasing pressure from the freshwater flow, which passes through a membrane, when freshwater is placed in contact with salt water. The electricity produced by this technique is very advantageous as it can be considered constant, 365 days a year. The membranes are made of polymeric compounds and the main parameter of this technology is defined in watts per square metre of polymer membrane. Thus, the first power plant using this technology achieves up to 1 W/m^2 [16], although there are membranes with densities of 3 W/m^2. Consequently, there is a substantial progress considering that in 1999 the power efficiency reached was only of 0.1 W/m^2. Globally, it is estimated that the pressure retarded osmosis technology could produce about 1,600 TWh/year [17], which implies a power of about 183 GW running at 100 % capacity.

The reverse electrodialysis uses the difference in chemical potentials between two solutions with different salinity, and separated by a membrane, to generate a voltage to produce electricity. Consequently, not the water but the sodium and chlorine ions that pass through the membrane produce the electricity. This configuration requires two types of membranes, one for each type of ion, which makes the process more complex. However, it has advantages compared to osmosis: working at lower pressures and ion transport for the creation of the current. Then, the reverse electrodialysis system does not require turbines to produce electricity.

11.2.5 Temperature Gradients

This technology uses the temperature difference between deep and shallow waters to run a heat pump. For this reason, the highest efficiencies are achieved at the lowest latitudes (tropical and equatorial regions), where shallow water temperature is high. However, the conversion efficiencies are very low due to the very small temperature differences (1–3 % efficiency, but a theoretical 6–7 % is considered). The Rankine cycle is the only one that has been considered, commonly used as the operating cycle for steam power, and a closed loop (mainly ammonia and heat exchangers) or low-pressure open-cycle water turbine. The simplicity of the open-loop system is counterbalanced by the increased demands for much larger low-pressure turbines and more complex compression systems [18], limiting the maximum power to 10 MW.

The resources for this type of technology are located in an area of over 100 million km^2 on the tropical regions of the oceans [18]. This is a technology that can deliver power with very high load capacity, so it can be part of the base load of any production system, estimating a theoretical power capacity from 3 to 10 TW [18] and an annual energy output of about 10,000 TWh [14]. Considering the temperature gradients demanded (about 20 °C), it is more appropriate to install these systems on floating structures than on the shoreline. Cold water flows are estimated from 2.5 to 3.0 m^3/s per MW of energy produced, and the required hot water flows are even larger [14]. The world largest pipeline installed to date is a 1.4 m in diameter and 2.8 km in length installed on the west coast of Hawaii in 2001 [18].

The main projects in this area are based on applying temperature gradient systems to the desalination of sea water, mainly in India. Also, there are operating plants to supply power to heat pumps for heating and cooling [1]. Plants have achieved 1,000 m^3/day desalination water, converting about 1 % of surface seawater pumped into vapour [18]. Another potential application is the use of large amounts of nutrients that can be found in deep water to be transferred to marine aquaculture.

11.2.6 Stages of Development

Figure 11.14 shows the stages of development and implementation for different ocean technologies. As it is shown, the most mature technology is the tidal range, as some plants started service in the 1960s and, therefore, are fully integrated in national power grids. Technologies devoted to obtain energy from waves and currents are close to enter into the market as commercial prototypes have been

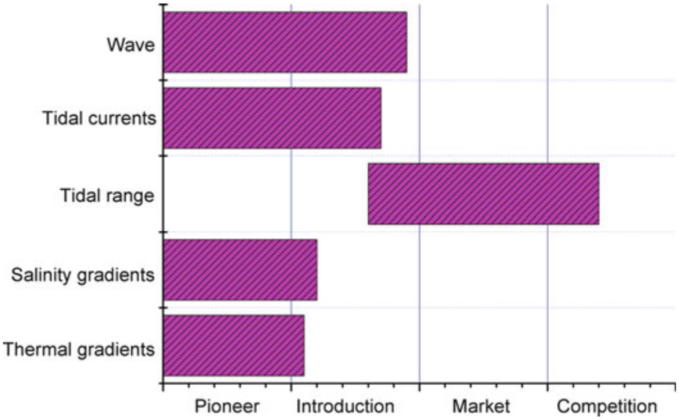

Fig. 11.14 Stage of development for the different ocean energy technologies

installed in various locations in Europe, USA and Asia. The wave energy technology can be considered in a more advanced position compared to energy from marine currents, as a larger amount of devices is being tested for the former. The salinity and temperature gradient technologies can be considered entering the introduction stage. As the first salinity gradient plan has recently come into operation and no substantial advance in temperature gradient has been detected in recent years, the former is considered in a more advanced position to reach the market.

11.3 Current Costs and Future Scenarios

In general, it is somewhat difficult to analyse the costs per kWh for electricity generated from different ocean energy technologies, since most of them are still in the demonstration and prototyping phases. In addition, the unit cost of electricity reported by the teams developing different technologies is often not very reliable [6]. In wave energy, production costs can be placed about three times higher than those associated with on-shore wind energy and, consequently, prototypes are being installed on the shores of countries offering generous bonuses to the energy produced by such sources of energy [6].

In the case of tidal range, a large 254-MW power plant has been built in Korea, with an estimated investment cost around USD 1,071/kW (EUR 770/kW) [1]. In the case of plants that take advantage of temperature gradients, estimated investment costs of USD 32,144/kW (EUR 23,092/kW) for typical power plants of 10 MW have been considered [18]. For plants that use salinity gradients based on the reverse osmosis technology delayed pressure, estimates of production costs of electricity are estimated in about USD 0.74–1.49/kWh (EUR 0.53–1.07 kWh) [17]. Temperature and salinity gradient costs are estimated that will be reduced a third or a quarter of current levels in the long term and, besides, the reliability of the installations will improve [1]. On the other hand, more than half of the ocean energy power plants budget in the shoreline or near-shore is invested in civil engineering [1].

The 2010 Energy Technology Perspectives report published by the IEA [19] states that the investment and O&M costs for 2010 for electricity generation from ocean resources is around USD 3,048–5,080/kW (EUR 2,190–3,650/kW) and USD 122/kW/year (EUR 88/kW/year), respectively, while for 2050 the costs will be reduced to USD 2,032–2,489/kW (EUR 1,460–1,788/kW) and USD 67/kW/year (EUR 48/kW/year), respectively.

In the following table (Table 11.3) [1, 5, 20], it is shown the most recent investment and electricity costs and forecasts for the main ocean energy technologies: tidal range, tidal currents and waves. It can be noted that the energy from the waves nearly triples the cost of tidal range power plants, being the later less expensive but not representative of the new technologies being developed for obtaining ocean energy [1]. Thus, it may be noted that the typical costs ranges in the production of electricity from new ocean energy technology are typically between 0.15 and 0.30 USD/kWh [1]. In addition, due to the great development that is currently occurring in wave-based devices, it is expected in about 20 years that costs parity will be reached. The costs are also relatively large in part because they depend heavily on the suitability of the chosen geographic location and distance to power grids, maintenance costs (planned and unplanned), environmental effects, etc.

The electricity production costs from ocean technology at present, as well as the one estimated for 2030 is exposed in Fig. 11.15. Since the tidal range technology is quite mature, we can consider a linear decrease in terms of future electricity costs. On the other hand, as multiple types of learning effects (by adaptation, by doing and by innovation) can influence the decrease of tidal currents and wave energy technologies in terms of costs, a substantial lowering of prices in the near future is expected.

It can be observed from Fig. 11.15 that grid parity can be reached in 2016 for tidal range technology. However, grid parity is not expected for wave energy until 2026 and tidal current technologies until late 2032.

11.4 Energy Payback, CO_2 Emissions and External Costs

There are very few studies evaluating the relation between the production of ocean energy and CO_2 emissions. Also, depending on the technology used, CO_2 emissions resulting from ocean energy production can be similar to other technologies. For example, tidal range is similar to hydropower energy, and tidal currents can be approximated to off-shore wind energy although, especially in the latter case, the materials used in both systems can differ substantially.

There are some works covering all renewable technologies and which suggest that CO_2 emissions from ocean energy is about 7 g CO_2/kWh of electricity produced [21] although, as previously noted, these values can fluctuate considerably due to the different technologies being included in ocean energy. Other recent works, consider that an amount of 300 g of CO_2 could be avoided from fossil fuel emissions for each kWh generated by ocean energy [22].

Only one work has been detected [14] studying in detail the different greenhouse gases emissions for the life cycle of ocean energy technologies. This work is

Table 11.3 Investment costs and electricity production costs for different ocean energy technologies

	Investment cost USD/kW (EUR/kW)			Electricity cost USD/kWh (EUR/kWh)		
	At present	2030	2050	At present	2030	2050
Tidal barrage	2,300–4,600 (1,652–3,305)	1,822–3,750 (1,309–2,694)	1,607–3,214 (1,155–2,330)	0.07–0.12 (0.05–0.08)	0.05–0.09 (0.04–0.06)	0.05–0.08 (0.04–0.05)
Tidal current	8,050–11,500 (5,783–8,262)	5,357–8,572 (3,849–6,158)	3,750–6,429 (2,694–4,619)	0.13–0.54 (0.09–0.39)	0.09–0.11 (0.06–0.08)	0.05–0.09 (0.04–0.06)
Wave	2,179–12,791 (1,565–9,189)	2,679–5,358 (1,924–3,848)	2,300–4,286 (1,652–3,079)	0.31–0.67 (0.22–0.48)	0.05–0.10 (0.04–0.07)	0.04–0.09 (0.03–0.06)

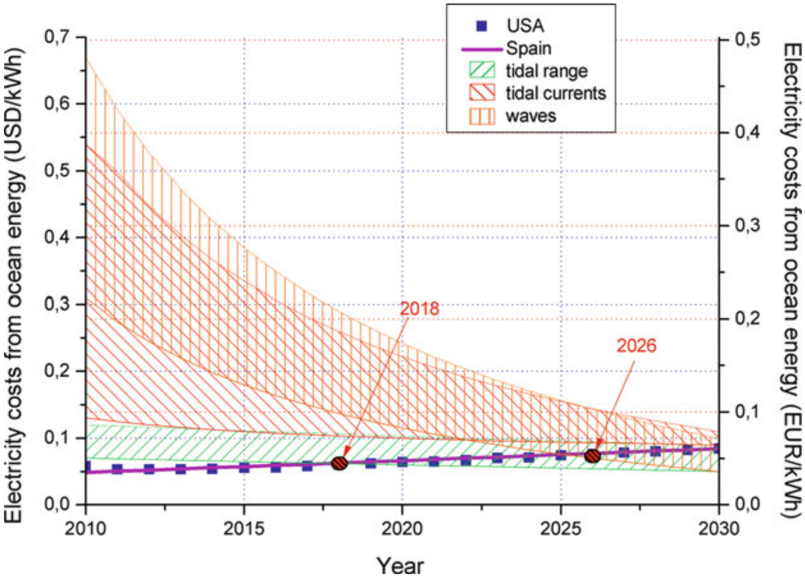

Fig. 11.15 Current electricity costs from ocean energy and forecasts to 2030. The *solid square* represents the generation electricity costs expected in USA and the *magenta straight line* represents the linear fit of the average generation electricity price in the Spanish wholesale market, both projected from 2011 to 2030

focused on the Wave Dragon system, used to extract energy from waves, although it justifies its extension to other ocean technologies. In this study (Fig. 11.16), 13.2 g CO_2/kWh is established, and considers that these emissions are mainly due to the manufacturing process (12.5 g CO_2/kWh) and, in a lesser extent, to the operation process (0.51 g CO_2/kWh). The use of steel and concrete are the main contributors to these emissions. Consequently, if a proper choice of building materials is considered, and even most of them are reused at the end of their life cycle, the emission rates can be substantially lowered.

In relation to energy payback studies, only one work has been considered [14], which exposes very attractive values for devices that are already in pre-production stage (Table 11.4). These studies also demonstrate how some of these devices have particularly long lifetimes, especially those using technologies similar to hydropower. External cost studies have not been detected.

11.5 Future Technology Trends

It is important to consider that the development of ocean energy technologies can exploit working areas related to other renewable technologies. For example, turbines to produce electricity from tidal currents have much in common with run-of-river hydropower systems, and composite materials for tidal current rotor blades can be produced in parallel with wind turbines.

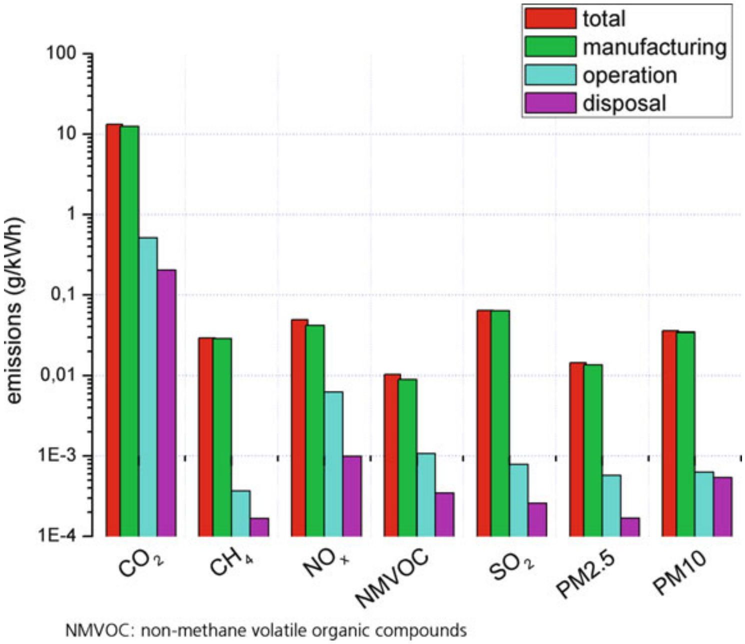

Fig. 11.16 Gases and particulate emissions during the life cycle of the Wave Dragon technology

Table 11.4 Main parameters for some leading ocean energy technologies

	Wave Dragon	Pelamis	Seagen
Technology	Wave	Wave	Tidal
Energy payback (months)	29	20	14
Weight incl. Ballasts (t)	33,000	859	465
Power (MW)	7	0.75	1.2
Lifetime (years)	50	25	20

On the other hand, it is common to all ocean energy technologies the research on specific materials that are resistant to marine corrosion. This corrosion is very intense, due to the high salinity, especially in bearings and bushings. Also, it is interesting to develop materials that prevent the growth of living organisms on their surface. Another aspect of great interest is the development of moorings that provide stability to the devices and ensure their durability in harsh environments, especially off-shore.

We also remark the efforts made in the use of synergies for a multitude of purposes: to achieve the electrification of coastal areas isolated from the grid, favour the location of aquaculture facilities, production of compressed air for the industry, integration with other renewable energies such as wind off-shore technologies, photovoltaics and desalination of seawater. To this latter respect, it should be noted the steady increase in the production of desalinated water from our seas and oceans. To improve the efficiency of these desalination processes and the use of endogenous energy sources, various ocean technologies are being tested, mainly those related to waves and temperature gradients.

Also, specifically, the following trends arise for each of the technologies discussed in this chapter:

11.5.1 Waves

Main efforts are focused on the development of electric systems to smooth power fluctuations before injection into the grid. This is especially necessary in buoys and other wave energy systems. Thus, it is important to develop improved two-way turbines that generate electricity to inflows in both directions. There are also plans to soften the power fluctuations by associated pumped storage. On the other hand, basic research on the behaviour of the wave and hydrodynamics related to wave absorption by different devices is being carried out.

For off-shore devices, future prototypes will be combined with off-shore wind technology, increasing the investment discount rate. In this sense, the use of oil rig technology is being considered to increase off-shore ocean energy capacity; although the current high demand for oil rigs to be devoted to the extraction of oil prevents rapid growth. In addition, as the wave direction and power can vary, it is very important to study the characteristics of the wave resource at each location. On the other hand, there are also efforts to ensure proper maintenance of these devices off-shore, given the difficulties of the on-site work involved. Thus, it is necessary to strengthen the sensors system to characterise the device performance and anticipate failures, avoiding unnecessary damage propagation for not taking measures in time.

In relation to near-shore technology, it shows advantages for the future because it combines a lower environmental impact than the shoreline technology, and easier logistics, maintenance and connection to the grid than off-shore technology. Thus, the main efforts for the future are the location of the emplacements with large energy potentials, mainly in shallow seas, and their compatibility with the existing and potential civil engineering infrastructure.

For shoreline wave energy technology, also specific methods for energy storage are being tested to avoid power fluctuations when connected to the grid and to couple electricity offer and demand. These storage systems are already available in terms of overtopping devices, by storing water in height, as well as oscillating water column devices, using the flywheel effect that the turbines can show (pneumatic turbine). However, flywheel effects are very small and further technological development is required, since the turbines operate in both directions.

Another very important research area is the study and reduction of the environmental impact of the devices, which currently largely limits their expansion.

11.5.2 Currents

In this area, also research is on course to avoid power fluctuations from the devices when they are connected to the grid. In tidal currents, fluctuations occur in a few hours interval in a 12-h period, but these fluctuations are much less random than those produced by extracting energy from waves. Other research activities are related to the control of the turbines and rotors speed to maximise the electrical power output.

Also in this area, prototypes are being designed to combine tidal currents technology and off-shore wind turbines, sharing the site, foundations, moorings and electrical connections. Thus, by this way, it is considered that the costs can be substantially reduced [1].

For ocean currents, the technology is less developed, and efforts are mainly devoted to determine the best locations, which are usually the most difficult to be determined in ocean energy. Consequently, this information is confidential between promoters of this technology. Among the most advanced techniques for the determination of ocean current profiles, the analysis based on the acoustic Doppler effect is surging. However, data on ocean currents are sparsely distributed on the ocean geography, so it is often necessary to interpolate or to apply numerical modelling methods based on fluid dynamics to evaluate different locations.

Finally, in this area, basic research is carried out to study the flow of the ocean currents and the effect of marine topography. There is also applied research in foundations, design of structures, turbines and installation processes [1].

11.5.3 Tidal Range

In this area, many environmental impact studies are being carried out, since the most promising geographic locations are situated in estuaries with high biodiversity. Therefore, it is necessary a previous careful study of possible locations for dams emplacement, as these infrastructures reduce the tidal range within the reservoir, and this consequence affects not only the biodiversity of estuaries but also water quality [1]. Thus, studies are being proposed to check if tidal lagoons have more or less environmental impact than dams.

On the other hand, tides can cause resonance effects when reaching estuaries, in case of coincidence of the natural frequency of estuaries matching the frequency of the tide at sea. Theoretical models are frequently used to study the resonances, but experimental models with water tanks can also be useful. These resonance effects are considerable on the coasts of Western Europe (France and England, in particular), since the 12-h tidal wave motion offers a wavelength that matches twice the width of the Atlantic Ocean (2 × 4,000 km). Resonance effects in estuaries are very complex because of the irregularities in width and depth, apart from the inherent funnel effect introduced. These effects, combined with the resonance, are being largely studied in the Severn Estuary (Fig. 11.17), where tidal range oscillation is 7–11 m, depending on the locations.

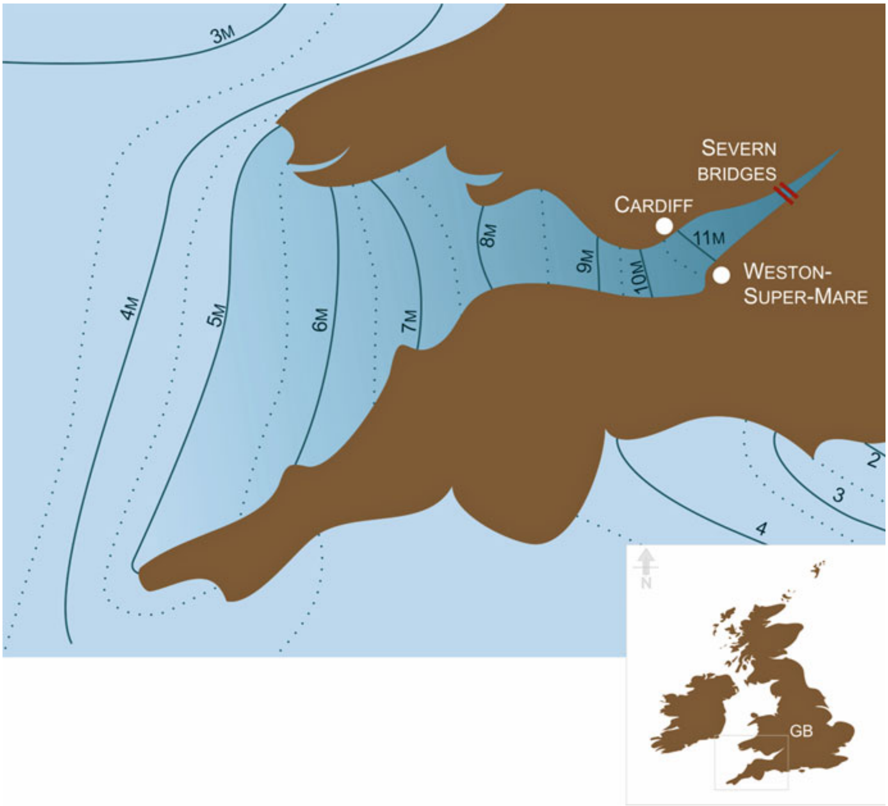

Fig. 11.17 Tidal ranges in the Severn Estuary, reinforced by the funnel effect and the resonance

11.5.4 Salinity Gradients

For installations using pressure-retarded osmosis and reverse electrodialysis as a technique for obtaining energy from salinity gradients, there are two main objectives: (1) to improve the efficiency of the system and (2) to produce energy 24 h a day for long periods.

For pressure-retarded osmosis, since the only two components of the system are the pressure exchanger and the membrane, the main efforts are focused on improving their performance and make them larger. Specifically, in relation to the membrane, achieving higher electric power per unit area is the main task, and a value up to 5 W/m^2 is expected to be reached in the coming years.

For reverse electrodialysis, technology is still needed to develop basic prototypes to be tested for long periods of time. Also, other resources different from ocean gradients are being tested, as domestic wastewater, where typical ionic conductivities are also attractive [23].

11.5.5 Temperature Gradients

The main technological challenges are limited by the engineering necessary for the proper location of the plants. The exploitation of remote ocean areas, especially in tropics using floating platforms, is a necessity that underlines significant technological challenges. A technology transfer from developed to developing countries, located where the largest temperature gradients are found in oceans, would be a necessary strategy to increase the weight of this technology in exploiting energy from oceans.

Also, niche markets can encourage a further development of this technology. As it has been mentioned, temperature gradient plants associated with seawater desalination, and with preparation or supply of nutrients from deep waters intended for aquaculture, can offer added value to this technology.

11.6 Pre-Production Highlights 2009–2011

11.6.1 Waves: Starting the Oyster Device for Harnessing Wave Energy [8]

On 20 November 2009, the 315-kW Oyster device started into operation. It is designed to produce energy from the waves at depths between 10 and 16 m. It consists of a device 12 m high and 18 m wide, which is installed in the water and close to the coastline. The oscillating motion due to waves drives pistons to pump seawater at high pressure through a pipe to an electrical generator on-shore and can generate up to 600 kW.

11.6.2 Tidal Currents: The First Commercial Device That Exploits Tidal Currents in Open Sea Comes Into Operation [24–26]

On 12 November 2009, the first commercial tidal current device (1 MW) in open sea comes into operation. The device was placed in Minas Passage area of the Bay of Fundy, 3-km off-shore Nova Scotia coast, Canada, where one of the world's largest tidal range is produced (Fig. 11.13). The turbine is 10 m high and weighs 400 t and is supported by a submarine base resting by gravity on the seabed (Fig. 11.18). The turbine is fully immersed, so that is not visible, and rotates in both directions depending on the tide currents direction, avoiding complex guidance systems. The turbine is self-lubricating, avoiding the need of oil, grease or other fluids that may damage the environment. The central part of the turbine is

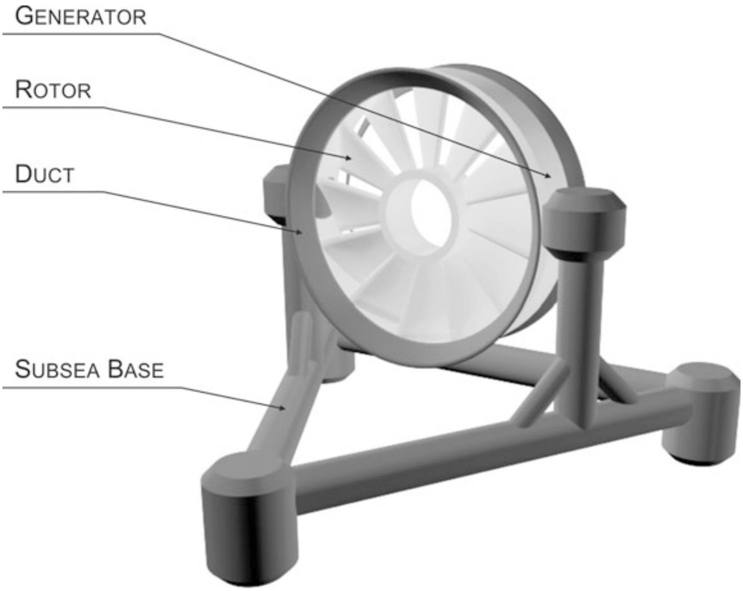

Fig. 11.18 Scheme of device installed at the Bay of Fundi

opened to facilitate the passage of marine life through it and is continuously being monitored to check that produces negligible environmental impacts. On the other hand, the first 1-MW turbine of a 10-MW tidal current array for the Sound of Islay was installed 100 ft underwater in late 2011 [25]. The investment required for this array is expected to reach USD 65 million (EUR 47 million), and the installation of the devices will be finished in 2013–2015 [26].

11.6.3 Tidal Range: Sihwa Tidal Range Plant Starts Into Operation [1, 5, 27]

Sihwa Tidal Power Plant (South Korea) was inaugurated in July 2011. The construction of this plant was initiated in December 2004. This plant includes ten turbines similar to the ones installed at La Rance, with a total capacity of 254 MW. Therefore, this tidal plant is the largest in the world. The diameter of the 25.4-MW turbine rotors is 7.5 m. The annual electricity production expected is around 552.7 GWh (24.8 % capacity factor), slightly higher than that of La Rance. Korea can become the world’s largest producer of tidal range electricity for many years, as it plans to build other plants: Ganghwa (838.2 MW), Incheon (1,440 MW) and Garorim (520 MW).

11.7 Innovation Highlights 2009–2011

11.7.1 Tidal Range: Feasibility Studies to Exploit the Range of Tides in the Severn Estuary [1, 28, 29]

The Severn Estuary is perhaps the one that has received the largest attention worldwide in terms of research projects, innovation and feasibility studies on the energy efficiency of large tidal ranges (up to 12 m). In May 2008, the UK Government launched a 2-year research project to consider many options from both the technological and economic point of view, to exploit the tidal range resource. Finally, the Energy and Climate Change Secretary of the UK Government announced in October 2010 that there was no strategic case at this time for public funding, as it would be very costly to deliver and very challenging to attract the necessary investment from the private sector alone [28]. The various plants proposed for the Severn Estuary could cover 5 % of the UK electricity demands and it will require an investment cost in excess of USD 30,000 million (EUR 21,552 million) in a construction period of 20 years.

11.7.2 Salinity Gradients: The First Power Plant Based on Osmosis Begins to Operate in Norway [16]

On 24 November 2009, the first power plant that uses fresh water from a river and seawater from the fjord to produce electricity was inaugurated. The plant, owned by the company Statkraft, consists of a system based on pressure retarded osmosis and uses polyester, polysulfone and polyamide membranes capable of producing 1 W/m^2 power. The pressure of water through the membrane from the fresh to the saline sides is equivalent to a water column of 37 m, which makes it somewhat similar to a hydropower plant. The surface of the membranes used is 2,000 m^2. The company believes that a power from 2 to 3 W/m^2 is easily achievable and hopes to commercialise the technology in 2015. It is considered that up to 10 % of Norway's electricity could be supplied from pressure retarded osmosis plants.

11.8 Publications and Patents Statistics

Regarding the publications produced in 2001–2011 in relation to ocean technology (Fig. 11.19) [30], it can be noted that the volume is high and mainly devoted to wave energy. This can be attributed to the large quantity of devices being designed worldwide, as it is exposed in term of patents below. Also, the conditions for the location of wave energy devices are the less restrictive of all ocean technologies.

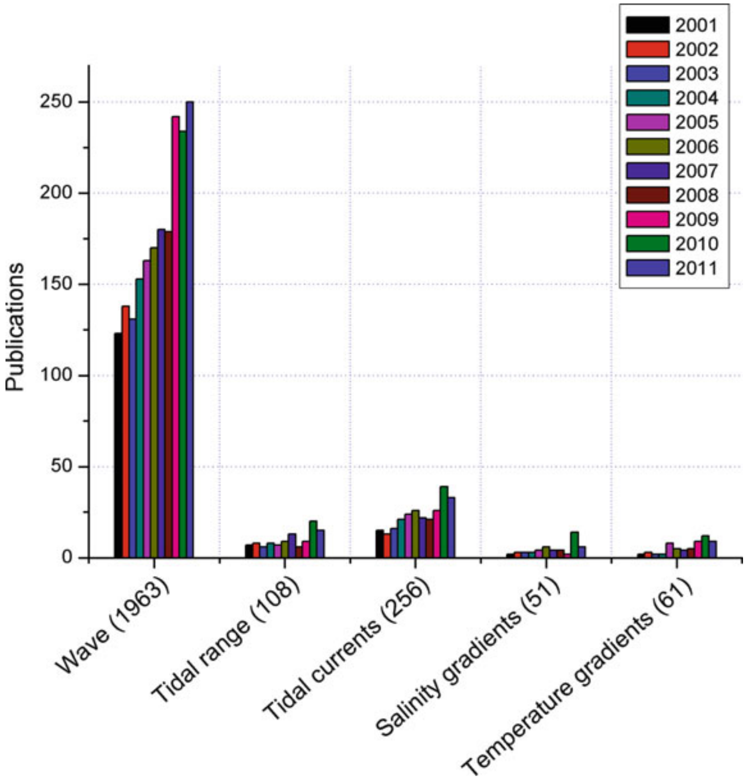

Fig. 11.19 Number of scientific publications during the period 2001–2011 for the ocean energy technologies exposed in this chapter [30]

Moreover, the research activity in wave energy is observed to grow notoriously, as prototypes are being increasingly tested in different locations around the world.

On second place is the technology to exploit energy from tidal currents. This is attributed to a lower quantity of related devices being tested and the difficulties to find optimal locations to install them. The research activity in this area is also upwards.

On third place is the tidal range, a mature technology, but where activity related to environmental impacts can explain the low number of publications detected. Finally, the research activity in thermal and salinity gradients is very moderate and constant over time, which can be attributed to the lack of attractiveness and location conditions required by these technologies in leading research countries.

In terms of patents [31], the evolution is quite similar (Fig. 11.20) to the one exposed above for the scientific literature (Fig. 11.19). However, the number of temperature gradients patents is significantly above the number of patents associated to the tidal range technology. This result can be attributed to the fact that tidal range technology is considered as a mature and closely related to

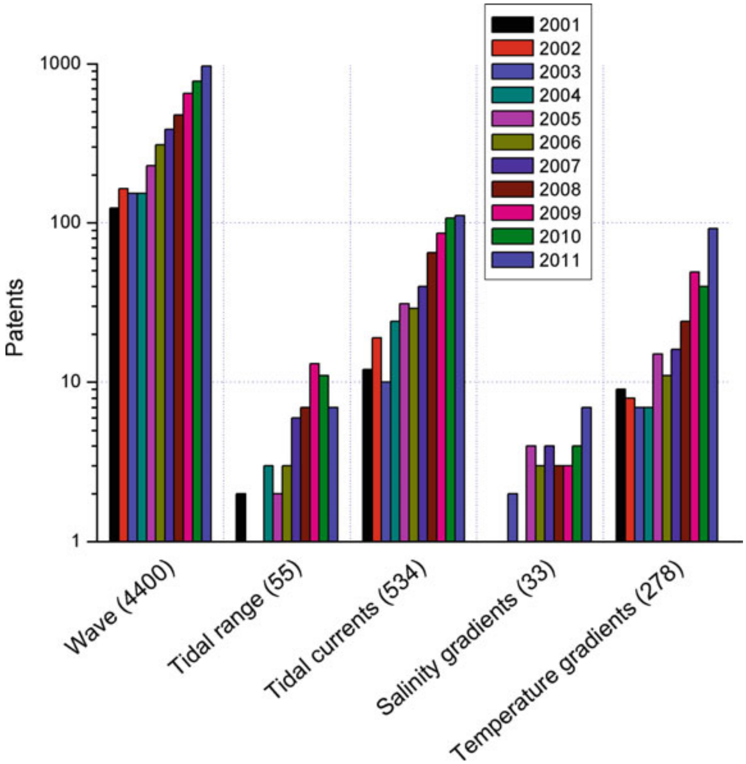

Fig. 11.20 Number of patents during the period 2001–2011 for the ocean energy technologies exposed in this chapter [31]

hydropower technology. On the contrary, temperature gradients technology is still quite immature and requires substantial technological improvements to reach the market stage.

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Chapter 12
Nuclear Fusion

Abstract Although not yet developed at the commercial stage, nuclear fusion technology is still being considered as a very promising solution for the coverage of the future global energy needs. This is mainly due to its environmental acceptability, and to the fact that, contrary to nuclear fission, its by-products cannot be used in nuclear warfare. Since research in nuclear fusion for the production of energy started about 60 years ago, the most studied reaction has been the fusion of tritium with deuterium, which produces very energetic neutrons (17.5 MeV). For this reaction to occur, the reactants have to be at extremely high temperatures (several hundred million degrees), constituting a plasma that has to be simultaneously maintained and confined. In this chapter, we study the steps that are needed for the construction of nuclear fusion reactors able to maintain these self-sustained plasmas. The most developed reactors are the magnetically confined Tokamak at the ITER (Cadarache, France) and the inertially confined system located at the Lawrence Livermore Laboratory in the USA. It is important to remark that in spite of all the research efforts devoted to nuclear fusion, it is estimated that it will still take a few decades for this technology to be available at the utility scale.

12.1 Overview

Nuclear fusion is a process in which two atomic nuclei "fuse" to form the nucleus of a single atom. The mass loss that occurs in the process (for atoms nuclei with atomic number less than Fe) is converted into energy, described by the famous equation $E = mc^2$, where c is the speed of light in vacuum. Such processes occur in environments of high mass density and temperature (stars) and it is intended to be reproduced in a controlled manner on our planet. The phenomenon is conditioned by the Lawson criterion, which states that to achieve ignition in nuclear fusion reactions, the figure of merit given by the triple product of the plasma density, confinement time and plasma temperature must result above a certain value (Fig. 12.1).

R. Guerrero-Lemus and J.M. Martínez-Duart, *Renewable Energies and CO_2*,
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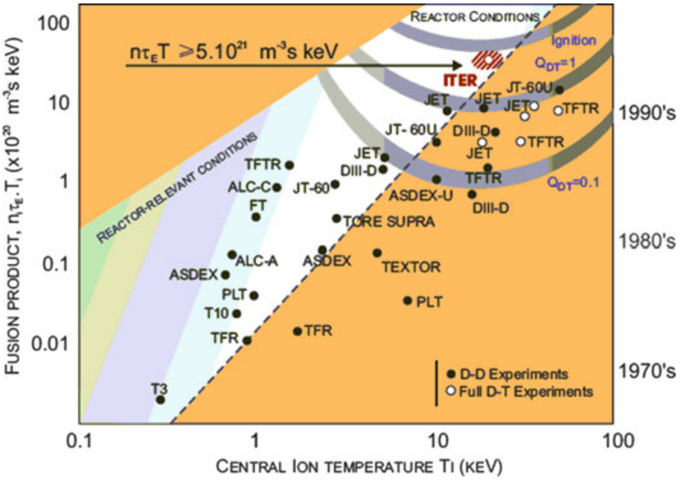

Fig. 12.1 Representation of the Lawson figure of merit versus ion temperature for different fusion reactor prototypes and two fuel types: D–D (deuterium–deuterium) and D–T (deuterium–tritium)

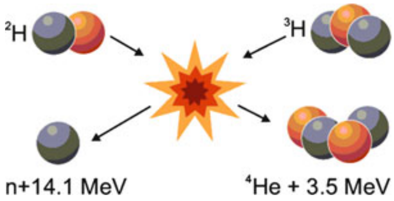

Fig. 12.2 Scheme of the nuclear fusion reaction of deuterium and tritium

The nuclear fusion reaction most studied and simple is that of helium generated from the reaction of deuterium and tritium (Fig. 12.2). Observe that very energetic neutrons are also produced. This reaction is exothermic with a released energy of 17.59 MeV, several orders of magnitude larger than those produced by chemical reactions involving only electronic bond breaking.

Deuterium is abundant in oceans and can be found in concentrations of 0.014–0.015 % of natural hydrogen compounds. However, tritium does not exist naturally in Earth, but it can be made by bombarding lithium (from seawater) with neutrons. All fusion power schemes include plans to have lithium embedded in the walls in some fashion so that some of the neutrons from fusion can breed more tritium.

For the nuclear reaction to occur, the ions have to overcome the repulsive positive forces of their atomic nuclei and, thus, it would be necessary to reach plasma temperatures of 120 million degrees Kelvin.

Other methods to achieve nuclear fusion are by confinement, considering three types:

1. Gravitational confinement: In principle ruled out due to the requirements of minimum mass (stars).

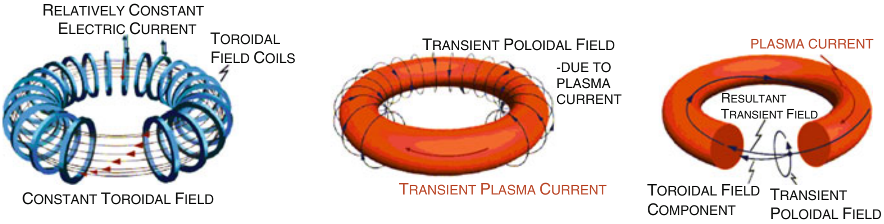

Fig. 12.3 Scheme of the tokamak

2. Magnetic confinement, using a plasma of charged particles (the most studied process today).
3. Inertial confinement: Applying a short energy pulse to a portion of a fusion fuel pellet, it can be achieved that simultaneously implodes and generates heat at very high pressure and temperature. If the fuel is dense enough and hot, the fusion reaction can be achieved.

With regard to data of energy production from nuclear fusion processes, the most notable achievement was carried out in the JET (Joint European Torus) reactor, located near Oxford, G.B. It was the first reactor using deuterium and tritium as fuel and still holds the world record for fusion power generation (1997): 16 MW for 1 s, also demonstrating an ability to continuously generate 4 MW of fusion power for 4 s. These processes were generated with an input/output power ratio of 0.64, producing a plasma heated to 300 million degrees Celsius.

12.2 State of the Art

Technological activity in nuclear fusion is mainly focused on systems based on magnetic confinement and inertial confinement, which are those we consider below.

12.2.1 Magnetic Confinement Fusion

Within this technology the device called “tokamak” is the most popular compared to other configurations tested to produce the magnetic confinement of the plasma. The tokamak is a device with toroidal structure, where the magnetic field lines must be drawn according to a torus helical shape to be able to create the plasma in equilibrium. This magnetic field is obtained from magnets and electric currents specifically disposed (Fig. 12.3).

The confinement takes place within a vacuum chamber ($10e^{-10}$ atmospheres) on which toroidal and poloidal coils are situated to generate a magnetic field of several teslas (Fig. 12.4) to produce confinement. The plasma beam acts as a secondary circuit of the transformer, while there is a central solenoid, which acts as the primary circuit. The inner surface of the vacuum chamber is coated with a

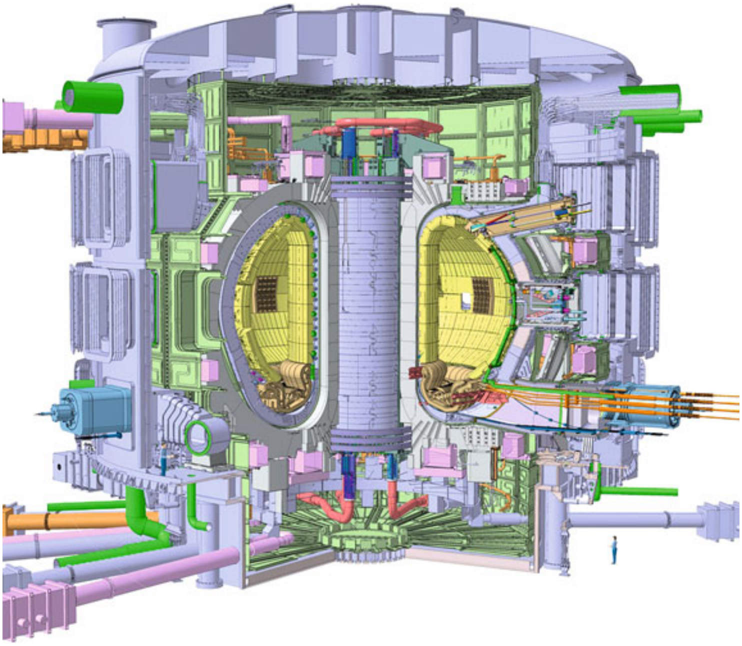

Fig. 12.4 Scheme of the tokamak designed to be the ITER fusion reactor

"breeding blanket" formed by lithium atoms, which absorb the incoming neutrons and produce tritium. The tritium can then be removed from the blanket and recycled into the plasma fuel. To remove the heat produced, the system is placed inside a cryostat to achieve the low temperatures required.

This system has been selected for JET and ITER (International Thermonuclear Experimental Reactor). ITER is the largest nuclear fusion project currently in development on our planet and aims to demonstrate that it is possible to consistently produce electrical energy from nuclear fusion. It is aimed to produce 500 MW of power with an input/output power rate >10, and a life expectancy of 20 years. An estimated 3,000 t of water and 10 t of lithium will be needed to maintain the fusion reactor at 1 GW power output per year. The ITER consortium is composed by the European Union, committing 45 % of the capital, USA, India, Japan, China, South Korea and Russia.

Other devices based on quantum confinement are the RFPs (reversed field pinches) and the stellarator. The fundamentals of the RFPs are based on the compression of an electrically conductive filament formed by plasma by magnetic fields. It uses a toroidal structure, but unlike the tokamak, as radial displacement is produced, the magnetic field reverses direction. Consequently, the plasma is compressed into short periods, allowing to lower energy demands although it becomes more unstable (Fig. 12.5).

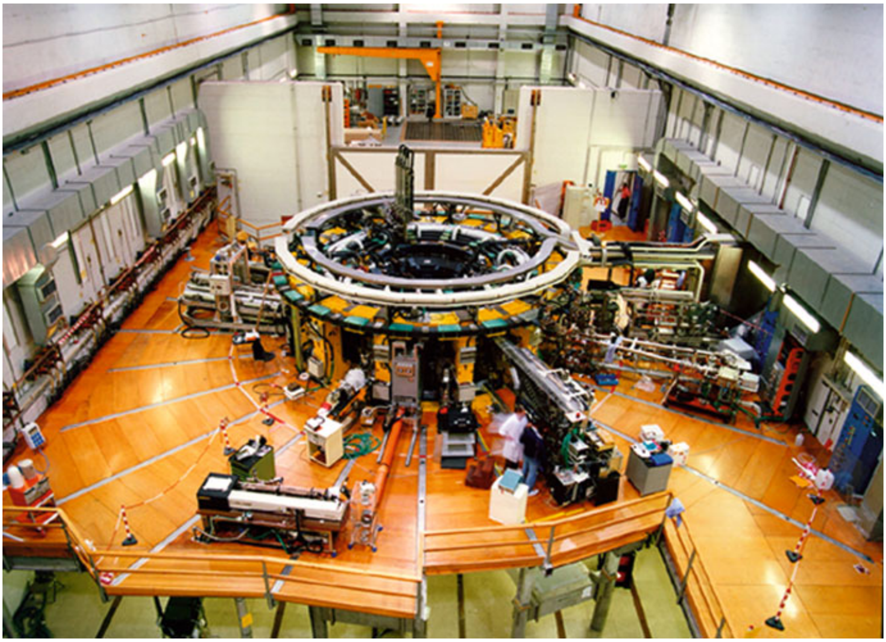

Fig. 12.5 Reversed field pinch system of Padova (Italy)

The stellarator systems are one of the first devices used to confine plasma in order to generate nuclear fusion reactions. In this case, compression of the plasma is produced with lower densities than in RFPs but for longer time periods. The reason the stellarator research activity has diminished in recent decades is because the magnetic fields used to leak plasma faster than those of a tokamak. Consequently, the challenge with stellarators is to avoid the hottest (and more appreciated) particles to escape, which is achieved through a system of variable magnetic fields and mechanical deformation. These mechanical deformations also are often replaced by helical wiring along the toroid that generates an electric field that produces an effect similar to the one produced by mechanical deformation (Fig. 12.6).

12.2.2 Inertial Confinement Fusion

In this case, the main activities are located at the National Ignition Facility (NIF), at the Lawrence Livermore National Laboratory (USA), completed in 2009 and currently in the course of testing the nuclear fusion process.

In this facility, two optical fibre lasers doped with ytterbium (called “master oscillators”) produce an infrared flash of 1,053 nm and energy in the range of nanojoules, which is divided into 48 beams that are passed through 48 preamp neodymium glass that raise the energy up to 6 joules. Then, each beam is divided into 4, so that the 192 pulses pass through phosphate glass amplifiers doped with

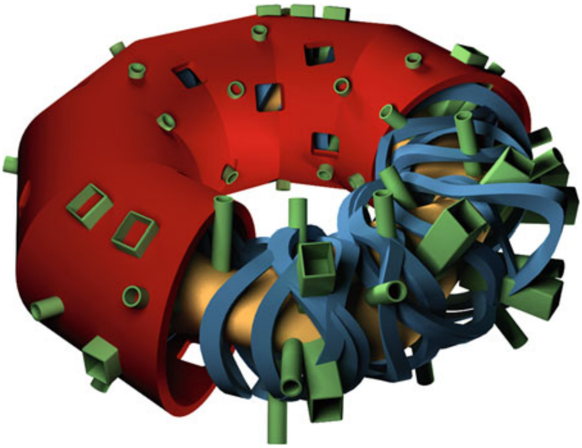

Fig. 12.6 Diagram of a stellarator

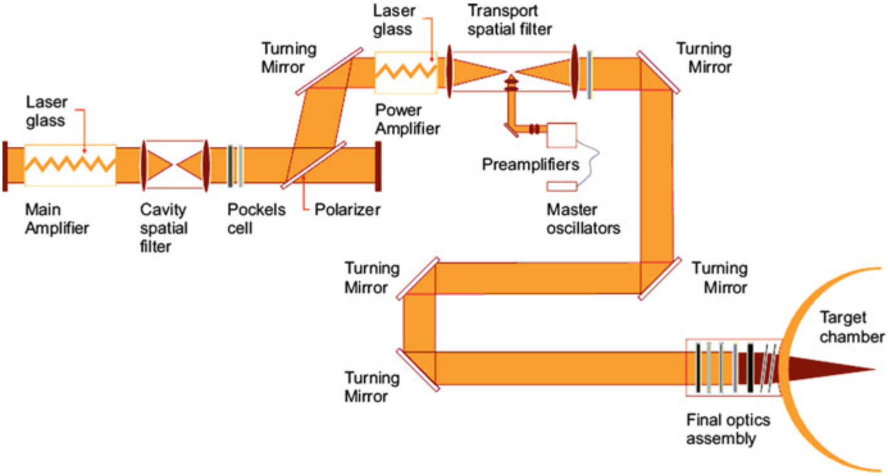

Fig. 12.7 Diagram of the inertial confinement system used at the NIF [1]

neodymium and pumped with 7680 xenon flash lamps, which store 400 MJ of electricity, and the principal beam is formed. It then uses a Pockels cell to trap the beam and direct it through the amplification system to reach an energy of 6 MJ. Subsequently, the beam is passed through a frequency converter for up-converting the IR beam to green (527 nm) and then to UV (351 nm), which is more effective for heating the target (Fig. 12.7). In this process, the energy is reduced to 1.8 MJ, and since the pulse interval is 20 ns, the power achieved before up-converting is 500 TW (larger than the entire electrical generating capacity of the USA).

The target consists of a beryllium hollow sphere of a few millimetres in diameter, containing 0.15 mg of deuterium and tritium cooled to 18 K, thus forming a thin layer of ice on the inner surface of the sphere. This sphere is placed inside a small gold cylinder called *hohlraum*. Under the ultraviolet pulse, the hohlraum is highly

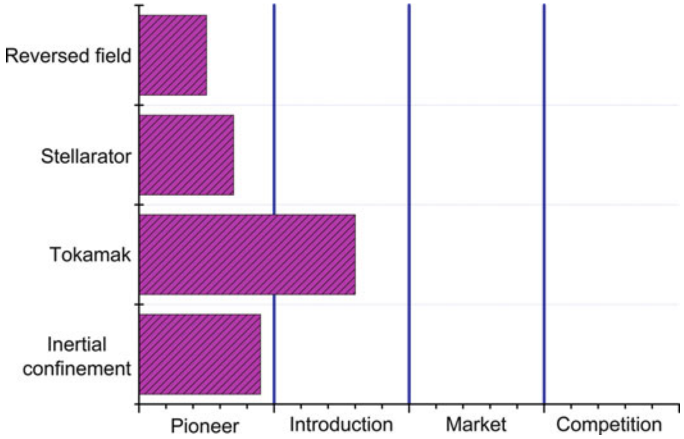

Fig. 12.8 Stages of development for each of the technologies considered in power generation from nuclear fusion

heated and emits an X-ray pulse that makes the beryllium sphere to explode, causing the ice deuterium–tritium to implode into the centre of the sphere. In this way, a material with a density 100 times larger than lead is generated, the process being accompanied by a shock wave originated by the implosion of the beryllium capsule. As a consequence, the fuel temperature will reach 100 million degrees Kelvin, so as to produce an ignition process to generate more fusion reactions.

12.2.3 Stages of Development

Depending on the level of market penetration, it is noted that the systems studied are in pioneering or introduction stages (Fig. 12.8), which prioritise the research and development in contrast to commercialisation and competition. The tokamak can be considered in an advanced position compared to the rest due to the past nuclear fusion reactions produced by magnetic confinement with torus configuration. On the other hand, the first nuclear fusion reaction produced with inertial confinement systems has not yet been reported, but it is expected to be produced soon, as it is exposed below. Interest in stellarators is recovered after some important activities being carried out at the Max Planck Institute for Plasma Physics at Garching, Germany. Finally, the expectatives related to RFPs are considered to be limited as no large research projects and activities have been detected.

12.3 Current Costs and Future Scenarios

In relation to costs, the most relevant information derives from the major projects being carried out at ITER and NIF. Thus, analysing the cost evolution of the ITER project it is found that, although the initial project budget was estimated at EUR

4.5 billion (USD 6.3 billion), the latest forecast by the European Union (announced in early May 2010) raised the amount to EUR 12.1 billion (USD 16.8 billion) [2]. This increase has been attributed to improvements in the reactor design, management costs (initially only three partners were considered) and improvements in the quality control process.

In the case of NIF, although initially the budget was estimated at USD 1 billion (EUR 0.72 billion), after 7 years of construction, the cost reached USD 3.5 billion (EUR 2.5 billion) [1]. This cost raise was attributed to some initial problems, mainly related to the capacitors associated to the pumping flash lamps and the dust deposited on the optical components.

On the other hand, initial estimates of electricity cost from inertial confinement systems have been recently exposed. Thus, the director of the NIF's laser fusion energy programme estimates that an initial 400-MW plant would produce electricity at USD 0.12/kWh (EUR 0.09/kWh), but this is not the ultimate cost performance [3].

12.4 Energy Payback, CO_2 Emissions and External Costs

No studies have been detected on these subjects, but it is clear that energy paybacks cannot be considered until the input/output power ratio exceeds one. On the other hand, given the complexity of the construction of nuclear fusion plants and the consumption of fuels and other materials during operation, CO_2 emissions and external costs should not be negligible. Also, if the reactor chambers are built from steel, it must be considered that the constant bombardment by neutrons slowly weakens it and makes it radioactive. Consequently, it has important consequences in future estimation of external costs, considering also that some researchers believe that the solution is to make the chamber a replaceable item.

12.5 Future Technology Trends

12.5.1 Magnetic Confinement Fusion

In this case, major technological efforts are focused on the construction of ITER, which should be completed in 2018. The same year (2018) plasma should be circulating inside the reactor. The main features of ITER are shown in Table 12.1. The ITER roadmap considers that during the decade 2030–2040, the first commercial nuclear reactor should be designed.

The tokamak concept also includes the development of the spherical torus. This spherical torus, with some variations, tries to improve the plasma confinement, mainly by increasing the plasma confinement stability.

Particularly, future technological trends in this field point to the need to develop new materials to ensure commercial fusion reactors developed by the ITER initiative to work properly. Specifically, research is needed to design and produce new

Table 12.1 Main features of the ITER nuclear fusion reactor (source: ITER web page)

Characteristics	ITER
Plasma current (MA)	15
Magnetic field in the axis of the toroidal structure (T)	5,3
Height (m)	26
Diameter (m)	29
Volume (m^3)	837

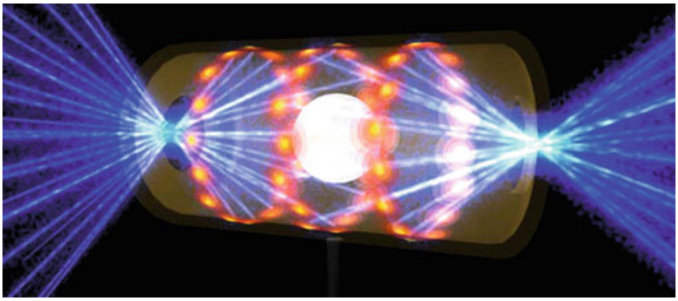

Fig. 12.9 Image recreating the capsule in which the fuel is placed and illuminated by the pulse [1]

materials to support irradiation generated during the reactor operation, especially new types of stainless steel.

Also, more experience is needed to control the liquid lithium flow within the reactor, where experience in handling corrosive liquids can be useful. In this sense, it is also critical to control the synthesis process of tritium from neutron capture from the plasma by making them collide with lithium and returning back to the plasma.

Also, research is necessary to simulate the processes during magnetic confinement. This simulation, carried out by supercomputers, should also be extended to the development of new materials.

Finally, the possibility of introducing nuclear fusion reactors (mainly ITER) in fission reactors is being considered. The nuclear fusion reactors would be employed as a neutron source to control the depletion of nuclear fission fuel, which is caused by excessive neutron absorption produced in the chain reaction [4]. This idea is not new, but progress in the development of the ITER project makes more likely these fusion–fission reactors to be operating in the long term.

12.5.2 Inertial Confinement Fusion

In this case, the initial goal is to achieve a fusion process, which produces 100 MJ of output energy per incident pulse at NIF [5]. The next step is to increase the number of pulses that can be generated from the 2 pulses per day in the current NIF, which is entirely unsuitable for a higher repetition driver in the current configuration. The goal is to reach a certain number of pulses per second, increasing the efficiency of the lasers to 20–30 % and to produce ignition capsules at a lower cost (Fig. 12.9).

Thus, the HAPL (High Average Power Laser) project is being promoted in order to be able to produce ten shots per second, design of optics to store energy for long time periods, and construct an impact camera that can absorb neutrons from the fusion process and convert them into energy, and a facility for producing ignition capsules.

It is proposed to use a krypton fluoride gas laser, improved versions of neodymium laser and the replacement of flash lamp by solid-state laser diodes. The krypton fluoride gas laser has the advantage that naturally produces UV beams and can operate for hundreds of millions of shots. Compression works better the higher the frequency of the laser beam, but the NIF crystals used to boost the frequency of the IR lasers have an efficiency penalty of 30 % [6]. However, Krypton fluoride gas lasers have low power and the single-shot ones show the highest power.

In Europe, the strategy is quite different and focuses on the process called "fast ignition fusion" in which a laser is used to compress the fuel and a high power, but very short second pulse ($10e^{15}$ W) induces the nuclear fusion reaction. This process could reduce the energy requirements for lasers.

Particularly, the fast ignition fusion tries to avoid two sources of instability: (1) laser–plasma interactions, which occur when the laser beam strikes the inner wall of the gold hohlraum generating plasma and reduces the power on the beryllium capsule and (2) hydrodynamic instabilities, which cause the capsule not to implode symmetrically. The risk of damage to the optical system should be also controlled.

On the other hand, efforts are being made to substitute the indirect drive technique (ignition capsules) by a direct drive. As the hohlraum helps to smooth out unevenness in the laser beams, it could make a target implode asymmetrically, causing the core of the fuel to break up without igniting fusion, and also the hohlraum is only 25 % efficient at converting the ultraviolet beams into X-rays [3].

Finally, some researchers use different drivers than lasers, including particle beams and intense electrical pulses. In this respect, ion beams offer some advantages, as there is no need to place optical elements close to a nuclear explosion.

12.6 Pre-Production Highlights 2009–2011

12.6.1 First Tests at NIF [6, 7]

In early January 2010, the first experiments using the 192 beams at NIF on empty fuel test targets were released, proving an efficient coupling and target symmetrical implosion. Pulses of 0.7 MJ were used, 40 % of the maximum that is estimated to provide the NIF. On the other hand, on 6 October 2010, the first integrated ignition experiment was successfully tested, in which the laser produced a beam of 192 beams on the capsule (Fig. 12.10), checking integration of the system to start the ignition campaign. However, at the end of 2011, no ignition has been reported from NIF. It is important to note that the ignition was expected to be achieved in 2010.

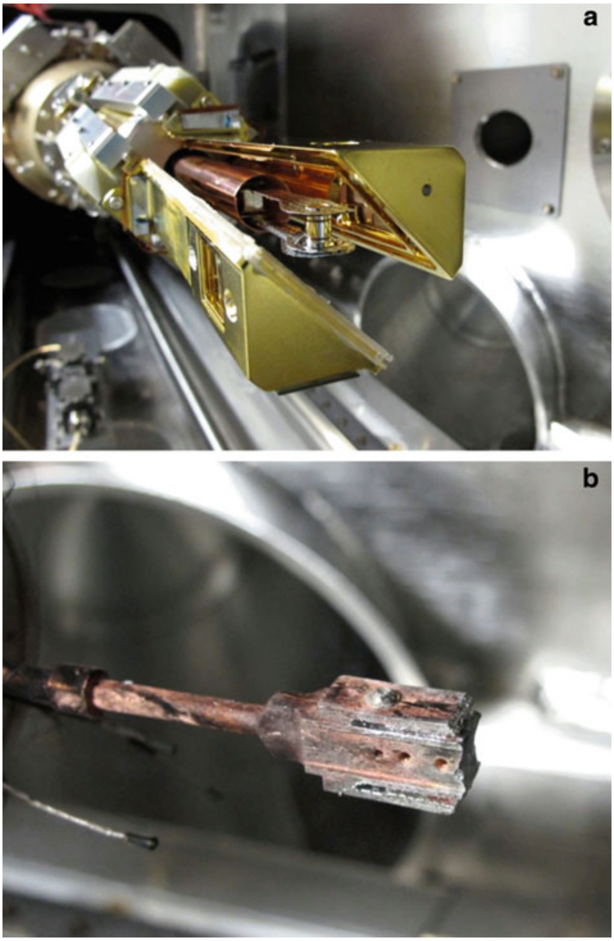

Fig. 12.10 (**a**) Image of the gold capsule before ignition process and (**b**) image of the assembly of the capsule after the laser pulse (source: NIF)

12.6.2 Uncertainty in the Financing of ITER [2, 8]

The European Commission announced in May 2010 that its contribution to the ITER project (Fig. 12.11) would have to increase from EUR 4.5 to 7.2 billion (USD 6.3 to 10.0 billion), representing a shortfall of EUR 1.4 billion (USD 1.9 billion) with respect to the proposed budget until 2013. The situation was complicated, given the current budgetary constraints in the EU and the impossibility of using credits no currently available to finance it. Finally, on 1 December 2011, EU officials agreed to take most of the needed funds from agricultural subsidies. The EU budget framework for 2014–2020 is currently under negotiation.

Fig. 12.11 Aerial image of the place where the ITER stands (Source: ITER, Cadarache, France)

12.6.3 Different Circumstances for ITER Facilities in Japan [2, 9]

On 27 April 2010 (and timely), the buildings to provide coverage of the "Broader Approach" associated with the development of ITER at Rokkasho, northern Japan were inaugurated. These facilities are designed to house research activities needed for the proper development of ITER and other future fusion reactors devoted to nuclear fusion, especially in relation to new materials and radiation resistance. For this purpose, there will be installed a particle accelerator and the most powerful supercomputer in Japan, to simulate the processes that are tested.

However, the 11 March 2011 the earthquake and tsunami that hit Japan severely damaged key facilities for testing the reactor's components. The Naka fusion Institute of the Japan Atomic Energy Agency, which is located about 100 km north-east of Tokyo, a key facility for testing and developing the magnets and heating system, was hit hard by the quake. At this moment, it is not clear if this incident will shift work away from Japan, but a new schedule and adjustments to the reactor's work plan are expected.

12.7 Innovation Highlights 2009–2011

12.7.1 Some Scientists Still Insist on Cold and Bubble Fusion [10]

Cold fusion was considered as the ability to achieve hydrogen fusion processes at room temperature (mainly through electrochemical processes) without applying very high pressures and temperatures. In 1989, Martin Fleischmann and Stanley Pons published a paper arguing that they had achieved cold fusion. Subsequently, it was shown that this achievement was false. However, although public funding for such experiments has practically disappeared and the scientific community believes that there is no theoretical explanation for the possibility that cold fusion can be achieved, usually new works appear from time to time trying to revive it. Thus, researchers at the Space and Naval Warfare Systems Command, San Diego, California, USA, have turned to risk announcing and publishing to have found traces of cold fusion [11]. Another approach through the confinement from the implosion of bubbles also finished in the courts, and his driver being condemned for scientific misconduct and removed from his teaching at Purdue University [10].

12.7.2 NIF Researchers and Ignition [12, 13]

The achievement of ignition at NIF is becoming much harder than expected. Innovation successes are pushing ahead to the goal. Firstly, the laser–plasma interactions inside the hohlraum, initially considered as source of uneven implosion, have been managed to convert the plasma into a diffraction grating to correct the shape of the implosion. On the other hand, the implosion speed is getting closer (340 km/s) to the speed considered necessary for the reaction (370 km/s) combining an especial design of the laser pulse (four short pulses to put pressure on the capsule material followed by a 300 times larger pulse to trigger the implosion) and the control of 17 key parameters of the laser and the target to be adjusted to make fusion work. However, a document known as a Baseline Change Proposal, signed by NIF Director Edward Moses on 21 December 2011, would push the gain equal to 1 milestone back by 3 months to September 2012 and delete the production of an overall energy yield of 5 MJ milestone.

12.7.3 A Team of Researchers Reignite the JET Reactor [14]

The team has restarted the world's largest fusion experiment after a new lining on JET was installed. This lining mimics the planned configuration of the ITER and is made of tiles of beryllium to better withstand the extreme conditions needed for a self-sustained fusion reaction than the carbon–fibre composite tiles used before. Carbon–fibre lining under tritium exposure formed radioactive hydrocarbons, which were not desirable from radiological, safety and economic points of view. The lining also is capable to support laser-driven fusion experiments, similar to those taking place at NIF.

12.7.4 The Last of the Five Field-Period Module of the W7-X Stellarator Assembled [15, 16]

As modern computers can handle the complex calculations required to apply adequate magnetic fields to avoid plasma leaks in stellarators, the Wendelstein 7-AS (fuel capacity of 1 m^3), built by the Max Plank Institute for Plasma Physics at

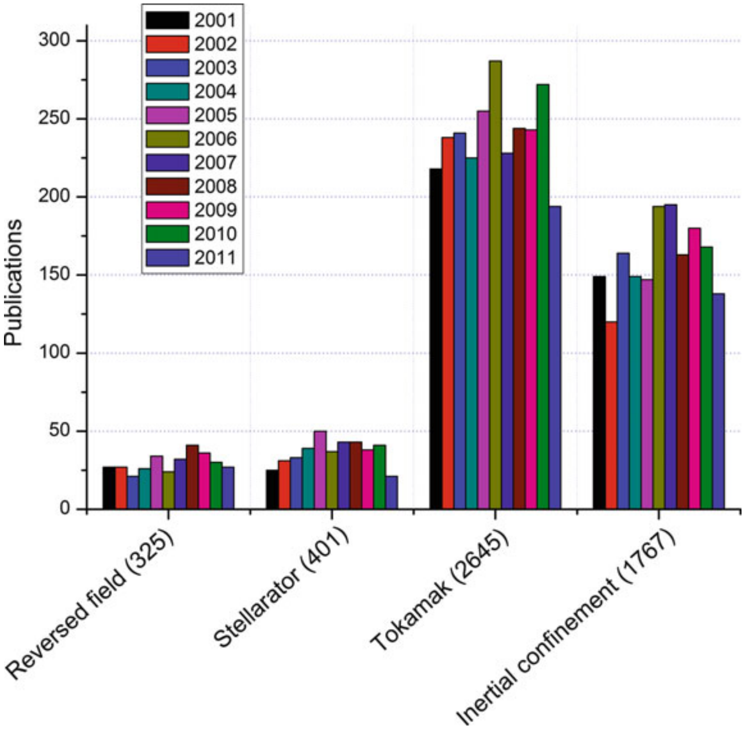

Fig. 12.12 Number of scientific publications during the period 2001–2011 for the technologies related to nuclear fusion reactions

Garching, Germany, and operated from 1988 to 2002, showed that its containment capacity did match a tokamak. As a result, the 30 m^3 fuel capacity Wendelstein 7-X (W7-X) is being built with a budget of EUR 377 million (USD 525 million) provided by the German government, the local state government, the European Union and the US Department of Energy. On 16 November 2011, the last of the five field-period module of the W7-X stellarator was assembled. The proper assembly of the device started in mid-2007, and it is expected to finish in 2014. This machine should show whether stellarators can be scaled up to a useful size and compete with other fusion reactor concepts.

12.8 Publications and Patents Analysis

Figure 12.12 shows the number of scientific publications during the period 2001–2011 for the main technologies used to produce energy from nuclear fusion reactions [17]. As it can be observed, the number of publications is dominated by the tokamak concept. This is attributable to the fact that magnetic confinement has

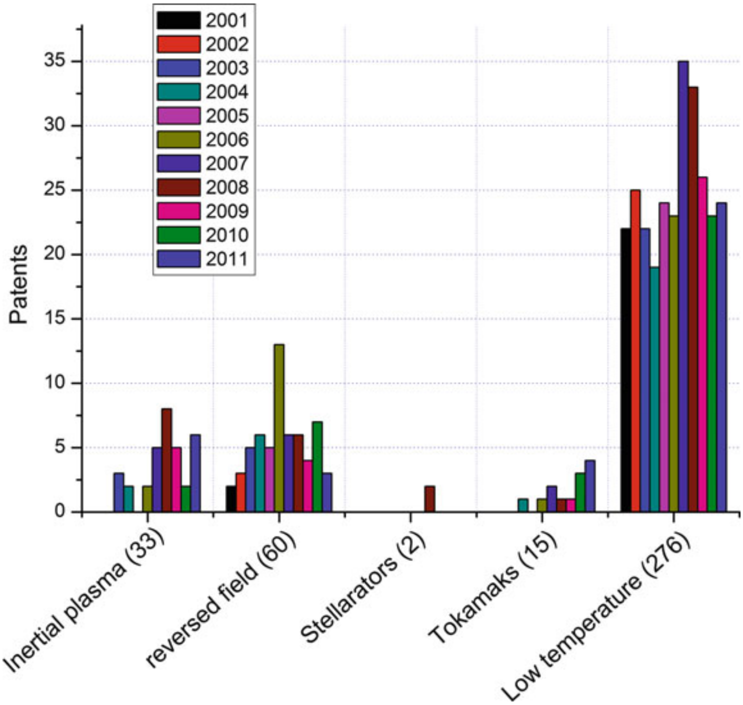

Fig. 12.13 Number of patents during the period 2001–2011 for the technologies in the fusion reactors category [18]

accomplished fusion reactions in the past and huge efforts are being made in the developing of new research facilities, mainly ITER. On second place is the inertial confinement, as a credible alternative to magnetic confinement and very close to achieve nuclear reactions at the NIF in USA. Also, inertial confinement is closely related to the development of technologies that can be used for other purposes, especially in laser technology, while the magnetic confinement is more closely related to fusion reaction processes. Publications devoted to stellarators and RFPs are moderate in number compared to tokamak and inertial confinement but show considerable research activities also in these areas.

It is also worth noting that although the volume of publications is important, it is perceived that the upward trend is weak compared to other technologies discussed in this book, which is attributed to the fact that nuclear fusion is quite stable in its science and technology activities. Also, this upward trend has been reversed somewhat in the last 2 years, which can be attributed to a side effect of the economic crisis faced by many countries. Clearly, research in nuclear fusion is closely dependent on public funds, affected by cuts that are suffering the budgets of many countries. It will be necessary to wait until 2012 data to confirm the consolidation of the downward trend.

In relation to patents (Fig. 12.13), it is impressive to check the huge amount of those related to low temperature nuclear fusion reactors, e.g., alleged cold fusion or fusion by pressure waves, compared to non-controversial nuclear fusion technologies [18]. It can be attributed to extended interest in easy-and-small systems to obtain nuclear fusion reactions and, definitely, respond to the global energy demand. On the other hand, as the procedure for patent approval has not the peer-review mechanism associated to scientific publications, it might be easier to apply for patents in this area than to publish a paper in a reputed journal.

Moreover, the production of patents related to conventional technologies exposed in this chapter shows that, in contrast to recent highlights and number of publications, the RFPs technology is the most abundant. However, a declined tendency in RFPs patents can be appreciated, unlike in inertial plasma and tokamak, where growing tendencies are observed. This effect could be associated to the huge number of research activities in ITER and NIF, where important innovations are being produced and are expected in parallel to the final goal of achieving nuclear fusion reactions.

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IV
Storage and Management

Chapter 13
Solar Heating and Cooling

Abstract Solar heating and cooling (SHC) technologies exploit solar irradiation to either produce heat or, alternatively, provide air conditioning. The basic principle behind cooling is the sorption process by which coldness is generated by the evaporation of a solvent that is later adsorbed into another medium. Solar collectors for heating can be divided into flat-plate or air collectors, evacuated tube collectors and unglazed panels. In the case of air conditioning, the dominant technologies being used today are: closed chillers, which use either liquid or solid sorption materials, and open cooling cycles. In this chapter, different analyses about technology trends and how cost can be close to conventional heating and cooling systems are exposed. Moreover, it is appreciated how solar cooling systems operate more efficiently than for heating since the peak energy demand closely coincides with the highest solar irradiation. Within the field of SHC long-term energy storage is also considered to hold the heat (warm or cold) over time.

13.1 Overview

Solar heating and cooling (SHC) technologies exploit solar radiation to directly produce heat, which is used to heat water and spaces, and can also supply heating to industrial processes and cooling in air conditioning.

The ability of these technologies to capture solar energy in the Earth's surface continues to grow worldwide, reaching at the end of 2010 the amount of 196 $\mathrm{GW_{th}}$. This quantity corresponds to an area of 280 $\mathrm{km^2}$ of installed panels (Fig. 13.1) [1]. The nominal solar thermal capacity of solar collectors surface is conventionally transformed into energy applying the conversion factor 0.7 $\mathrm{kW_{th}/m^2}$ [2]).

This capacity implies, according to the International Energy Agency [3], a world annual solar thermal energy production of 0.58 EJ in 2010 (Fig. 13.2) [4]. The amount of heat from the sun that can be captured by solar collectors ranges from 300 to 800 $\mathrm{kWh/m^2}$/year depending on the design and location [5].

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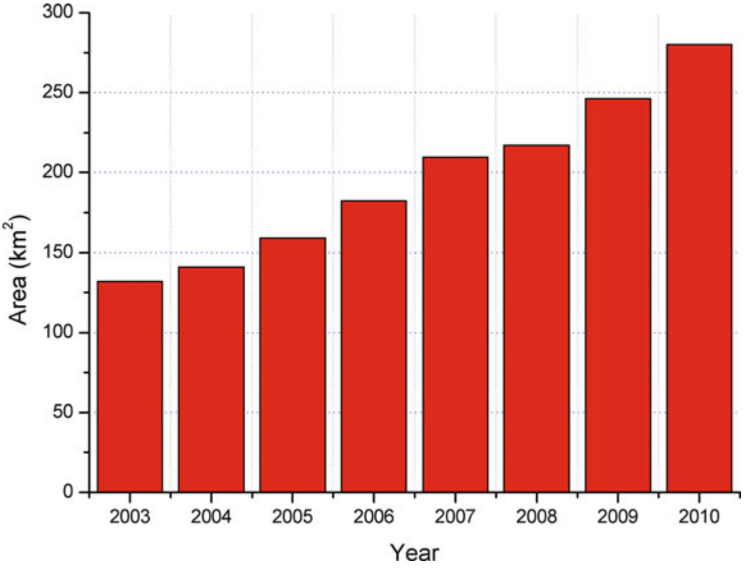

Fig. 13.1 Evolution of the global surface of solar thermal collectors from 2003 to 2010 (source: SHC-IEA)

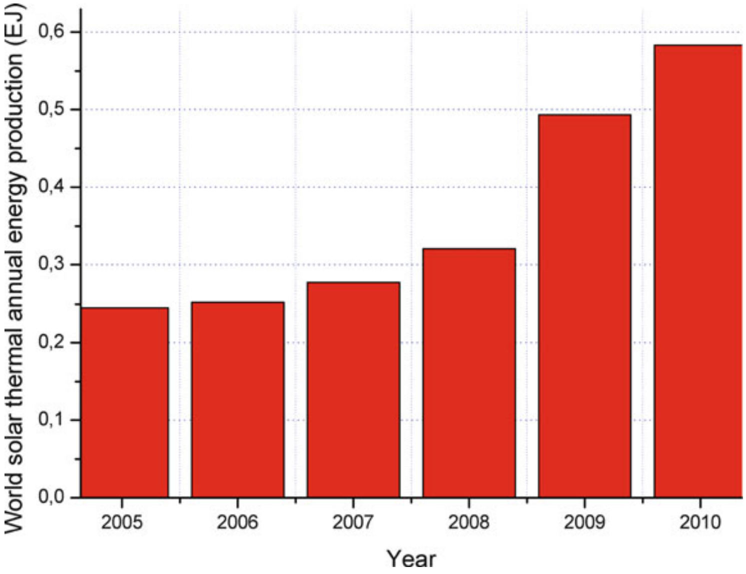

Fig. 13.2 Evolution of the global annual production of solar thermal energy (source: SHC-IEA)

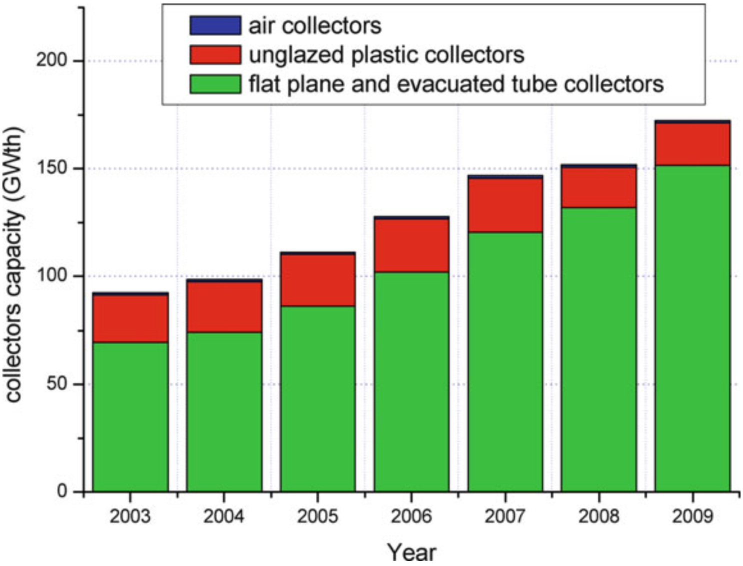

Fig. 13.3 Evolution of the global solar thermal capacity from 2003 to 2009 for different collector technologies (source: SHC-IEA)

The solar thermal collectors can be divided into flat-plate and evacuated tube collectors, unglazed plastic collectors and air collectors, being the former the main contributors to solar thermal energy production (Fig. 13.3) [1].

The SHC Program of the IEA and major solar thermal industry associations have recently agreed on a common and simple calculation method to estimate the annual solar collector energy output in kWh [6]. By calculating the amount of energy produced by solar thermal systems, worldwide solar thermal energy can now be easily compared with other (renewable) energy sources:

Unglazed collectors for pool heating:

$$Q_{\mathrm{uc}} = 0.29 H_0 A_a \tag{13.1}$$

Glazed collector in DHW (domestic hot water systems):

$$Q_{\mathrm{gc,DHW}} = 0.44 H_0 A_a \tag{13.2}$$

Glazed collector in combi-system:

$$Q_{\mathrm{gc},c} = 0.33 H_0 A_a \tag{13.3}$$

where Q_{uc} is the annual unglazed collector output [kWh], $Q_{\mathrm{gc,DHW}}$ the annual glazed collector output [kWh], $Q_{\mathrm{gc,c}}$ the annual glazed collector output in combi-systems [kWh], H_0 the annual global horizontal solar irradiation [kWh/m^2] and A_{a} the collector aperture area [m^2]

Current solar water-heating systems for single families with collector areas of 4–6 m^2 (with a 150–300 L storage tank) meet 20–70 % of the average domestic hot water needs. Solar combi-systems (space and water heating) for single families are larger, with a collector area of around 12–15 m^2 (with a 1,000–3,000 L storage tank) and can meet 20–60 % of the space heating and water heating needs [7].

For solar thermal cooling systems, only a brief study of the SHC-IEA Program [8] including systems with a cooling power above 20 kW has been found. The list counts 81 installed large-scale solar cooling systems (eventually including systems which are currently not in operation) using different technologies: 56 based on absorption chillers, 10 on adsorption chillers and 17 on DEC (desiccant evaporative cooling) systems. The overall cooling capacity of the solar thermally driven chillers was 9 MW. This overall solar cooling capacity was assisted by 23,720 m^2 of solar thermal collectors. The technology used in 53 % of the total area was flat-plate collectors, 37 % vacuum tube collectors, 7.3 % compound parabolic collectors and 2.6 % air heaters. A more recent paper estimates that close to a thousand solar air conditioning plants have been installed worldwide, covering all technologies and sizes [9].

There are also the so-called passive solar systems (thermal mass, Trombe wall, solar chimney, etc.) for their utilisation in bioclimatic architecture. However, these topics are not addressed in this book.

13.2 State of the Art

The system most widely used to collect thermal energy from the sun is the flat-plate collector, whose operating principle is based on the greenhouse effect (Fig. 13.4). The main effort is focused on achieving maximum radiation absorbed in the collector and, simultaneously, minimising the thermal energy losses. These thermal energy losses are produced:

- From convection: Reduced by a glass on the absorber, where an air–vacuum sheet is present in the space between the glass and the absorber.
- From conduction: It is necessary to use thermal insulation between the absorber and collector housing and to cover the fluid transport tubes.

Moreover, to get a maximum absorption energy in the absorber, it is necessary to use anti-reflecting coatings.

Thus, the heat absorbed by the solar collectors is transferred to a liquid carrier flowing in the primary circuit. Then, the thermal energy is transferred to sanitary water, which circulates in a secondary circuit, through a heat exchanger (Fig. 13.5). The heat exchanger is usually located inside the tank that collects the hot water of the secondary circuit until it is used. There is usually an auxiliary energy supplier to increase the water temperature of the secondary circuit when it is not high enough to be consumed. This auxiliary energy supplier usually is an electrical resistance.

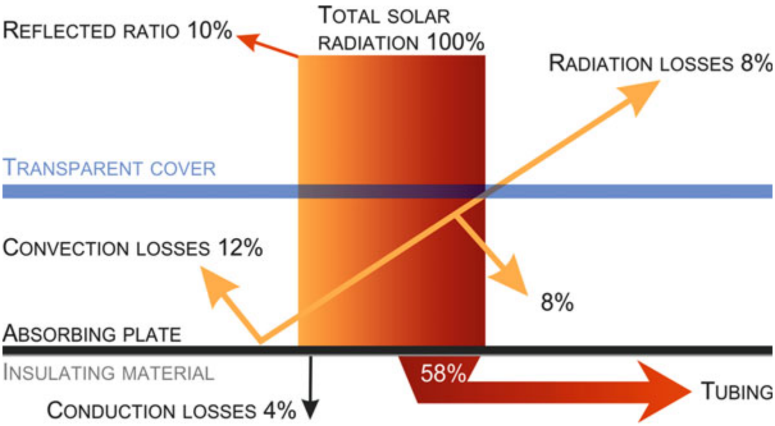

Fig. 13.4 Scheme of the energy flows on a typical flat solar collector

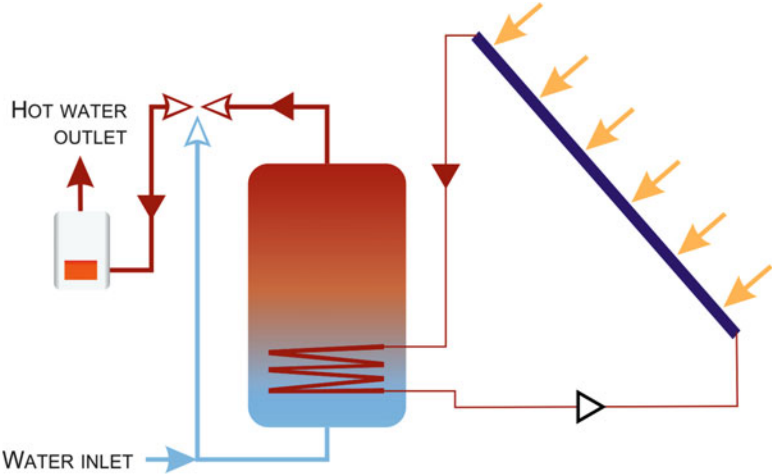

Fig. 13.5 Scheme of a basic solar thermal system

The state of the art in solar thermal energy for heating and cooling can be classified in five different topics: materials, cooling and air conditioning, long-term storage, solar thermal collectors and control systems.

13.2.1 Materials

Although the solar thermal technology for hot water production can be considered mature, it is estimated that the materials traditionally used in this technology can be replaced by new ones that offer improved performance. Thus, at present, conventional solar thermal systems use metals such as copper and aluminium, and there is a special effort to replace them by others that offer larger durability and cost reduction, with special emphasis on the use of polymers.

Other research activities aim to improve the thermal insulation and self-cleaning properties of the windows situated at the top of the collectors, raising the systems efficiency. Moreover, it is detected a progressive substitution of traditional materials by others, which offer higher resistance against corrosion processes, overheating and can offer more versatility to manufacturing non-rectangular collectors, which can improve the integration of solar collectors in some outer areas of the buildings receiving sun light.

13.2.2 Cooling and Air Conditioning

Although various technologies exist to convert solar heat into cooling there are four dominant technologies being used today:

- Closed chillers, which produce chilled water using liquid sorption materials, are the most common. The dominating material pair uses water as refrigerant and a LiBr aqueous solution as sorbent. Another pairing being used is ammonia as refrigerant and water as sorbent. LiBr–water systems also are available as single-effect machines, operating at temperatures starting at 75 °C, and as double-effect machines, with driving temperatures of 130 °C and above and, consequently, using concentrating solar collectors.
- Closed chillers using solid sorption materials and water as refrigerant. In particular, machines in the small capacity range have been developed in recent years and are entering the market in increasing numbers. Silica gel is used not only as sorbent in most cases but also as zeolite coatings applied on heat exchanger metal surfaces, which show a promising potential for the future. A completely different category of systems uses salt as sorbent material, which is completely dried during regeneration, thereby providing a kind of thermochemical storage. Thus, a mismatch between availability of driving heat (e.g., coming from solar collectors) and the operation of the cooling system (e.g., during night) can be overcome.
- Open cooling cycles using solid sorption materials, mainly using rotating wheels with a matrix impregnated with the desiccant material. Various combinations of the desiccant rotor with sensible heat exchangers and evaporative coolers (humidifiers) exist, which are adapted to different climatic conditions.
- Open cooling cycles using liquids as sorption materials, having achieved a status of early market deployment and a number of installations have been realised. Open cooling systems using a liquid desiccant have two main advantages: (1) cooling of the sorption process can be realised easier in comparison to systems with solid sorption materials and (2) the concentrated solution can be stored. This provides an attractive method of storage that allows overcoming mismatches between the availability of driving heat and the need of conditioning the ventilation air.

The solar cooling systems operate more efficiently than those for heating, since when more solar energy is available, more air conditioning is demanded. Many of these devices use solar energy to heat the process fluid. This process fluid generates cold by low pressure expansion, similarly to refrigerators.

Until recently, the smallest thermally driven chiller available on the market had a capacity of 35 kW and only one manufacturer existed. Today, at least five companies are producing small capacity systems for residential or small commercial applications starting at a rated cooling capacity of about 8 kW [10]. However, the main bottleneck for a broader application of these systems in combination with solar thermal collectors is—besides the higher initial cost in comparison to conventional technology—the lack of pre-engineered package solutions. An overview of market availability for thermally driven cooling systems based on sorption technology is exposed in Table 13.1 [9].

After many years since its introduction, the market penetration for solar thermal cooling systems remains still small. The main shortcoming from a technical perspective lies today on the system level. Many systems fail to achieve the planned energy savings because of shortcomings in proper design and energy management of systems that result in a high overall electricity consumption of auxiliary components. A particular area where faults are made is related to the heat rejection subsystem, which often has not received sufficient attention in the past. Another error often made is that many systems were far too complex and as a result created non-optimal control and big maintenance efforts. Today, systems are found on the market that work with a relatively high electricity demand and, thus, do not save much energy or—even worse—lead to a negative energy balance, that is they consume more (primary) energy compared to a conventional system [9]. But the overall energy balance is getting more in favour of solar thermal systems, if other heat needs are covered, such as heat for space heating or sanitary hot water.

13.2.3 Long-Term Storage

Thermal energy storage (TES) systems can be charged from heating or cooling environments and hold this energy over time. The usual device with zero energy consumption for hot water storage is a thermosyphon. Located above the collectors, the thermosyphon uses convection currents to storage the heated water (Fig. 13.6). These systems are cheap and can store heat for days or even 1 week or 2 at acceptable costs. But they are bulky and therefore are not an ideal solution for long-term storage.

Thermal energy storage can be categorised based on the underlying physical principles of the storage technique (Table 13.2):

The key parameters of thermal energy storage systems are their capacity, power rating (ability to discharge), efficiency (losses over time and with charge/discharge) and cost. The current values for these parameters are exposed in Table 13.3 (except for costs, described in the next section).

Table 13.1 Overview of market availability for thermally driven cooling systems based on sorption technology [9]

Type of system	Water chillers (closed thermodynamic cycles)						Direct air treatment (open thermodynamic cycles)	
Physical phase of sorption material	Liquid		Solid				Liquid	Solid
Sorption material	Water	Lithium-bromide	Zeolite		Silica gel	Lithium-chloride	Lithium-chloride	Silica gel (or zeolite), cellulose matrix with lithium-chloride
Refrigerant	Ammonia	Water	Water		Water	Water	Water	Water
Type of cycle	1-effect	1-effect		1-effect	1-effect	1-effect	Cooled sorption process	Desicant rotor
COP	0.5–0.75	0.65–0.8	1.1–1.4	0.5–0.75	0.5–0.75	0.5–0.75	0.7–1.1	0.6–0.8
Driving temperature range, °C	70–100 120–180	70–100	140–180	65–90	65–90	65–90	65–85	60–80
Solar collector	FPC, ETC. SAT	FPC, ETC.	SAT	FPC, ETC.	FPC, ETC.	FPC, ETC.	FPC, ETC., SAHC	FPC, ETC., SAHC

FPC flat-plate collector, *ETC* evacuated tube collector, *SAT* single-axis tracking solar collector, *SAHC* solar air heating collector

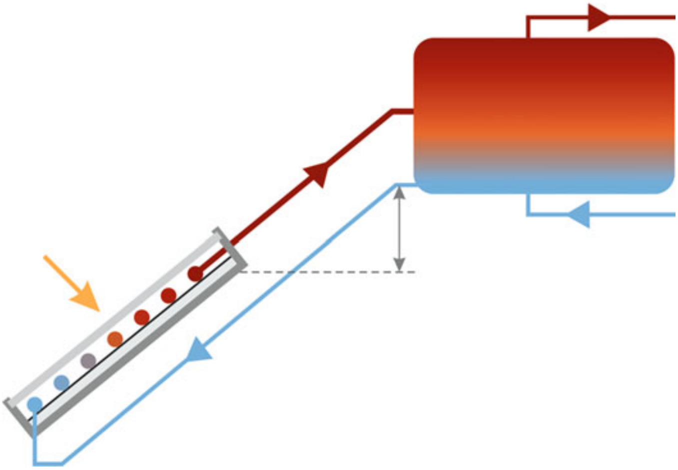

Fig. 13.6 Diagram of a solar collector with thermosyphon

Table 13.2 Low-medium temperature thermal storage categories [7]

Sensible	Latent	Thermochemical	Absorption/adsorption
(Water, ground, concrete, etc.) e.g. hot/chilled watertanks, underground thermal energy storage.	(Inorganic salts, paraffins, etc.) e.g. ice storage, PCM panel sand modules	(Chemical reactions) e.g. silica gel + water, zeolite + water	(Open/closed systems) inorganic salts + water, ammonium + water

Sensible heat storage systems (e.g., hot and chilled water) and some latent heat stores (e.g., ice storage) are mature technologies. However, developments in advanced phase change materials (PCM) and chemical reactions are creating new application possibilities described below.

13.2.4 Solar Thermal Collectors

Collectors are usually divided between the so-called flat-plate (glazed or unglazed) and vacuum tubes (with direct or indirect flow) (Fig. 13.7). The fluids most commonly used as heat carriers in the primary circuit are water, mineral and synthetic oils, water–glycol mixtures and water–glycerine mixtures. The vacuum tube systems work better in cloudy and cold environments since convection losses are reduced up to 35 %. However, they are less robust than the flat-plate collectors, especially as vacuum is lost from the tubes with ageing.

Table 13.3 Energy capacities, power, efficiency and storage time of thermal energy storage technologies [7]

TES technology	Capacity (kWh/t)	Power (kW)	Efficiency (%)	Storage time
Hot water tank	20–80	1–10,000	50–90	Day–year
Chilled water tank	10–20	1–2,000	70–90	Hour–week
ATES low temp.	5–10	500–10,000	50–90	Day–year
BTES low temp.	5–30	100–5,000	50–90	Day–year
PCM-general	50–150	1–1,000	75–90	Hour–week
Ice storage tank	100	100–1,000	80–90	Hour–week

ATES aquifer thermal energy storage, *BTES* borehole thermal energy storage

The standard configuration of the collectors is rectangular in geometry, but it is increasing the design of flat-plate collectors with different geometries to improve integration in buildings as well as the development of hybrid thermal solar—PV in order to provide both heat and electricity to buildings.

Another technology which is rising in interest is based on high-temperature solar thermal collectors. These are considered when high temperature working fluids (above 130 °C) are required and use mirrors or lenses to concentrate sunlight on the absorber. The applications requiring such high temperatures are not only, mainly, the solar cooling and air conditioning systems but also the combi-systems.

The key parameters for solar energy collectors are the output temperature and efficiency of the collected solar energy, exposed in Table 13.4:

13.2.5 Control Systems

Many applications require hot water available anytime at the consumption place (tap, shower, etc.), which involves using recirculation systems. These recirculation systems are also being applied in solar thermal installations. These systems usually demand an additional supply of power, so they add costs to the operation of the installation. Thus, programmable thermostats are being offered to optimise the cost–demand ratio. Another area where advanced control systems are being demanded is in hybrid systems, i.e. combining solar heat and biofuels (or fossil fuels) to guarantee hot water supply.

13.2.6 Stages of Development

The most developed technology among those exposed in this section is the solar collector, as a huge number of solar thermal installations are placed around the world (Fig. 13.8). The development of new materials and innovations in heat storage systems are also in the competition stage, but some additional improvements are still needed in these areas to gain in maturity. In relation to

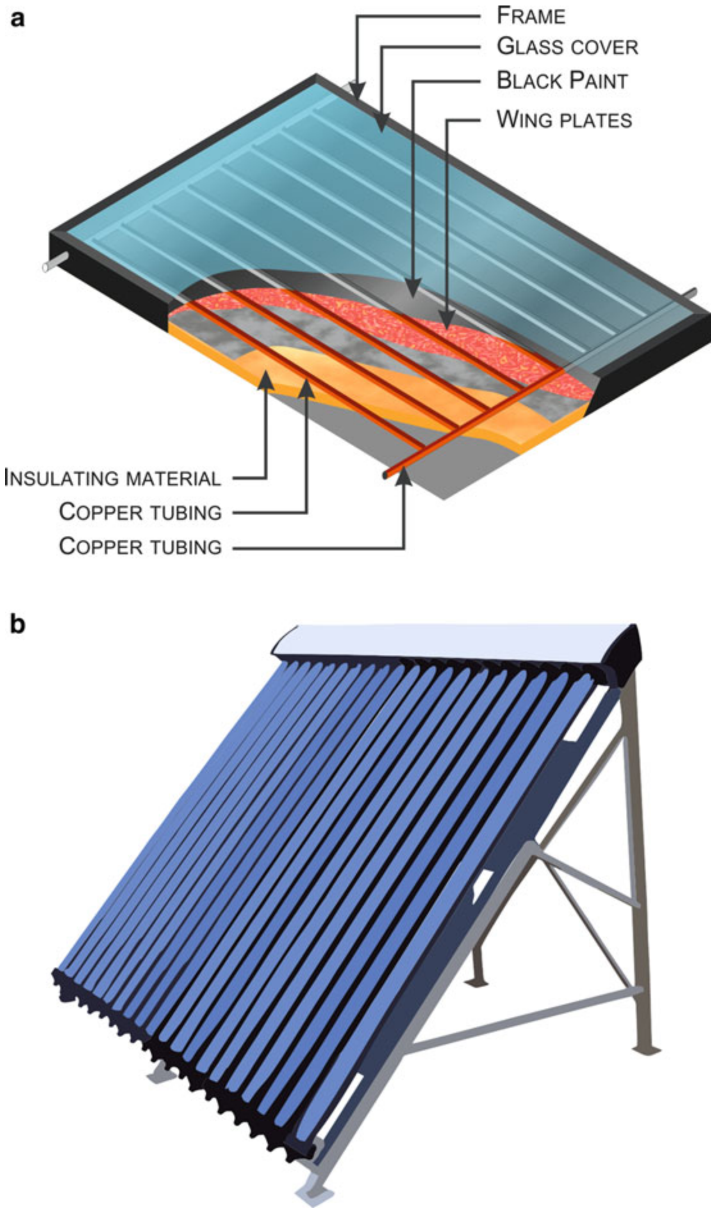

Fig. 13.7 (**a**) Scheme of flat-plate collector and (**b**) image of the vacuum tube collector

storage, different possibilities are being explored: (1) improving the aesthetic and insulating properties of conventional systems and (2) introducing new systems based on phase change materials or other thermochemical reactions, similar to those considered for CSP in Chap. 7. In addition, research in new materials itself

Table 13.4 Output temperature and efficiency of the collected solar energy

	Output temperature (°C)	Efficiency (%)
Unglazed flat-plate collector	20–40	40–50
Glazed flat-plate collector	60–110	70–75
Evacuated tube collector	90–110	75–80
High-temperature collector	>150	75–80

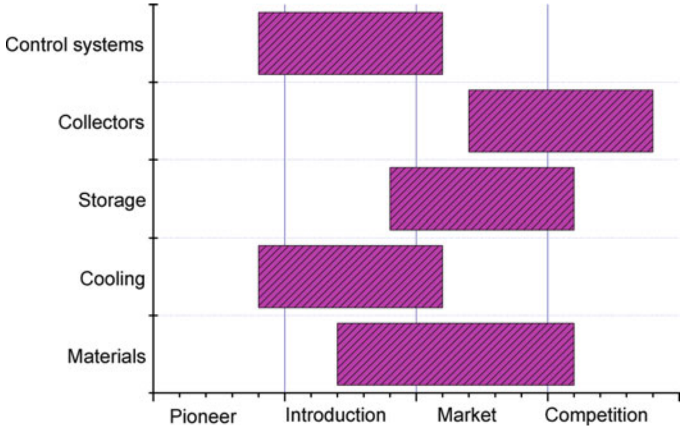

Fig. 13.8 Stages of development for each of the technologies considered in solar heating and cooling systems

still presents many opportunities for the development of these technologies in insulation, optimisation of solar radiation absorption, durability against ambient conditions, self-cleaning, etc.

Behind the above technologies in the stage of development, the cooling and air conditioning systems based on solar thermal energy can be considered, but still further improvements are needed to increase its attractiveness before being fully introduced into the market. Finally, all concepts related to control systems, both for heating and cooling, have substantial work ahead before they are introduced in the market. Consequently, all concepts related to improving the efficiency of the systems, process automation, integration into hybrid systems, etc., are still far from being fully developed.

13.3 Current Costs and Future Scenarios

Costs vary quite markedly depending on weather conditions, making necessary more or less complex installations (Table 13.5). Labour costs are also important. Thus, a thermosiphon system for heating water designed to meet the demands of a family (2.4 m^2 collector and a deposit of 150 L) has a cost of EUR 722 (USD 1,005)

Table 13.5 Investment cost for stand-alone solar thermal heating systems [12]

EUR/kW$_{th}$ (USD/kW$_{th}$)	Glazed flat-plate	Evacuated tube	High-temperature
10 kW$_{th}$	1,021 (1,421)	1,205 (1,677)	
100 kW$_{th}$	807 (1,123)	980 (1,364)	
300 kW$_{th}$	704 (980)	888 (1,236)	1,041 (1,449)
1,000 kW$_{th}$	592 (824)	766 (1,066)	919 (1,279)

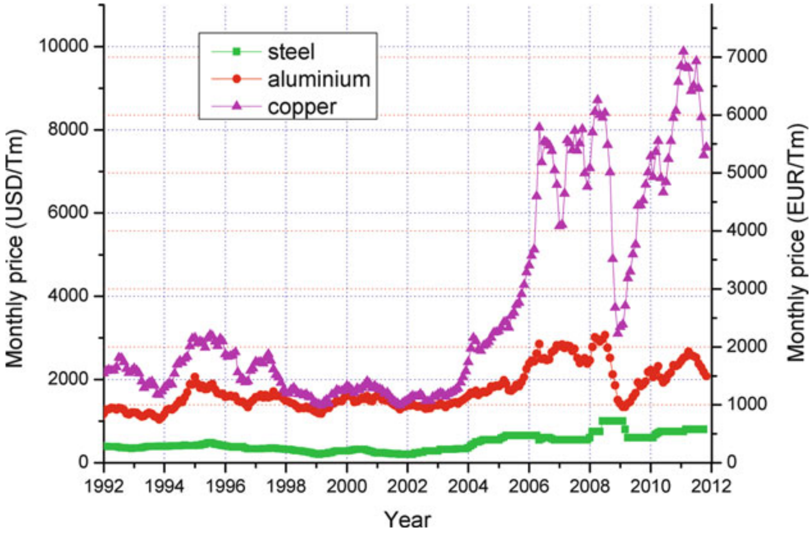

Fig. 13.9 Aluminium, steel and copper monthly price (source: indexmundi.com)

in Greece but only EUR 202 (USD 287) in China. In Central Europe, a system of 4–6 m^2 and a frost-free tank of 300 L costs about EUR 4,640 (USD 6,459) [11]. The collector has an investment weight of 30–50 % of the total cost and the accumulation system between 20 and 25 %. The cost of the regulation system is usually between 4 and 7 % of total investment. O&M costs are estimated in EUR 20–36/ kW/year (USD 28–50/kW/year).

Being the cost of the accumulation system sensitive to variation in prices of copper, aluminium and the steel (Fig. 13.9), the price percentage of the raw materials can range between 7 and 18 %. Consequently, a 100 % rise in the price of steel, copper or aluminium can increase about 10 % the investment in the installation.

Considering the average solar irradiance of Spain, stand-alone solar thermal heating energy cost EUR 85–190/MWh$_{th}$ (USD 118–264/MWh$_{th}$), usually is more expensive than heat produced from natural gas but competitive with retail electricity prices [12]. These costs mainly depend on the collector technology and system capacity (Table 13.6).

For combi-systems, the cost is between EUR 163 and 511/MWh$_{th}$ (USD 227 and 711/MWh$_{th}$) [11]. For district heating, the cost also depends on the system capacity and collector technology (Table 13.7) but is above of stand-alone systems because

Table 13.6 Cost for stand-alone solar thermal heating systems in Spain [12]

EUR_{2010}/MWh_{th} (USD/MWh_{th})	Glazed flat-plate	Evacuated tube	High-temperature
10 kW_{th}	141–179 (196–249)	159–190 (221–264)	
100 kW_{th}	113–(157–)	132– (184–)	
300 kW_{th}	97–130 (135–181)	115–142 (160–198)	133–150 (185–209)
1,000 kW_{th}	85–(118–)	102–(142–)	119–(166–)

Table 13.7 Cost for district solar thermal heating systems [12]

EUR/MWh_{th} (USD/MWh_{th})	Glazed flat-plate	Evacuated tube	High-temperature
10 kW_{th}	184 (256)	201 (280)	210 (292)
1,000 kW_{th}	173 (241)	190 (264)	202 (281)

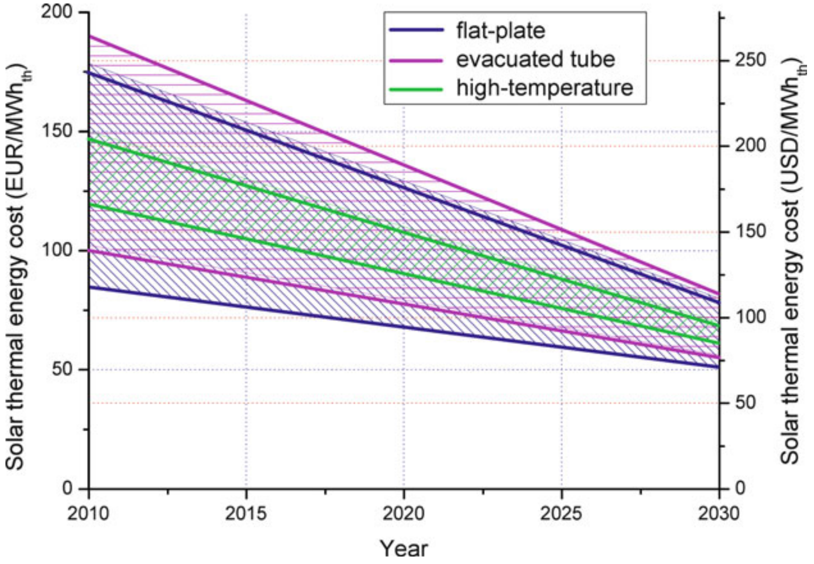

Fig. 13.10 Current solar thermal energy costs and forecasts to 2030

additional investment in the distribution network. Consequently, the investment costs (EUR 1,532–1,634/kW; USD 2,133–2,275/kW) are also above those of stand-alone systems [12].

Costs in 2030 are expected to decrease to EUR 51–82/MWh_{th} (USD 71–114/MWh_{th}) for solar water heating systems (Fig. 13.10), EUR 102–245/MWh_{th} (USD 142–341/MWh_{th}) for combi-systems and EUR 31–51/MWh_{th} (USD 43–71/MWh_{th}) for large-scale systems (>1 MWh_{th}) [11]. Experience curves for solar thermal heating systems indicate that costs are reduced by 20 % when the cumulative capacity doubles in a country.

The average fuel prices for US consumers heating in 2010–2011 winter was USD 34.56/MWh_{th} (EUR 24.83/MWh_{th}) for natural gas and USD 66.63/MWh_{th} (EUR 47.87 /MWh_{th}) for heating oil [13], but the investment and O&M costs of

Table 13.8 Current solar heating costs for 10 and 1,000 kW_{th} stand-alone systems and conventional heating fuel prices for USA in winter 2010–2011

Costs	USD/MWh_{th}	EUR/MWh_{th}
10 kW_{th} glazed flat-plate	196–249	141–179
10 kW_{th} evacuated tube	221–264	159–190
1,000 kW_{th} glazed flat-plate	118–	85–
1,000 kW_{th} evacuated tube	142–	102–
US average natural gas heating in 2010–2011 winter	34.56	24.83
US average heating oil in 2010–2011 winter	66.63	47.87

Table 13.9 Investment cost for solar thermal cooling and air conditioning systems under favourable boundary conditions [12]

EUR/MWh (USD/MWh)	Glazed flat-plate	Evacuated tube	High-temperature
10 kW	1,817 (2,529)	1,971 (2,744)	
300 kW	1,327 (1,847)	1,491 (2,075)	1,603 (2,231)

conventional systems should be added to compare with solar heating costs. Consequently, the use of high capacity solar heating energy for heat supply can be competitive with conventional energy sources (mainly heating oil) in highly sun irradiated areas (Table 13.8).

The generation of solar cooling requires a higher investment, being able to reduce costs if the facility is designed to provide cooling in summer and heating in winter, in a way that improves the balance between supply and demand.

In recent studies, investment costs of cooling systems range from EUR 2,000 to 5,000 per kW_{cold} (USD 2,784 to 6,960 per kW_{cold}) and even higher in some particular cases [9]. This large range is due to different sizes of systems, different technologies, application in different sectors and other boundary conditions. Collectors represent 20–30 % of the total investment, and the cooling system a 20–25 % [12]. Under favourable boundary conditions, investment costs are exposed in Table 13.9.

Under promising conditions, even payback times of 10 years and less can be obtained. However, commercial companies often consider a payback time of 5 years and even less in order to justify an investment. But such low values of payback time will only be achieved under very special conditions [9]. O&M costs are estimated at EUR 51–71/kW/year (USD 71–99/kW/year) [12].

Systems using electrically driven vapour compression cycles combined with photovoltaic systems may be an alternative to using solar energy for air conditioning or refrigeration. Photovoltaic modules have experienced a continuous cost reduction due to a growing market during the last two decades. In particular, when an attractive feed-in tariff for electricity produced by photovoltaic systems exists, most probably the economic outcome will be in favour of a photovoltaic-based cooling system [9].

Finally, the storage cost for the solar energy storage systems exposed in Table 13.3, are shown in Table 13.10, considering a cost reduction of 50–75 % for PCM centralised storage systems [7].

Table 13.10 Solar thermal storage costs for different technologies [7]

TES technology	USD/kWh$_{th}$ (EUR/kWh$_{th}$)
Hot water tank	0.10–0.13 (0.07–0.09)
Chilled water tank	0.10–0.13 (0.07–0.09)
PCM-general	13–65 (9–47)
Ice storage tank	6–20 (4–14)
Thermal-chemical	10–52 (7–37)

Table 13.11 Energy payback time (*E*), emission payback time (*M*) and energy return ratio (*R*) of the SHC plant analysed

	E	*M*	*R*
Palermo hot back-up	5.1	4.0	4.3
Palermo cold back-up	5.8	6.0	3.8
Zurich hot back-up	4.4	3.9	5.0
Zurich cold back-up	4.8	5.6	4.6

13.4 Energy Payback, CO_2 Emissions and External Costs

The most recent study detected on energy payback and CO_2 emissions has been published in 2011 [6]. This study analyses a SHC plant equipped with a water–ammonia absorption chiller to estimate the energy and environmental performances of the plant during its life cycle. The plant was compared to a conventional system (a vapour compression chiller used during the cold season and a gas boiler used in winter). Two different plant configurations were investigated (hot back-up and cold back-up) in two locations: Palermo (southern Italy) and Zurich (Switzerland). Energy payback time (*E*), emission payback time (*M*) and energy return ratio (*R*) were measured for each configuration and are exposed in Table 13.11.

A detailed analysis of the production phase for the different configurations showed that the main contribution to energy demand and GHG emissions was the production of solar collectors (45–50 % for energy demand and 37–50 % for GHG emissions) and absorption chillers (21–24 % for energy demand and 19–25 % for GHG emissions).

The main contributions to energy demand and GHG emissions are in the operation phase (68–74 % in Palermo and 90–91 % in Zurich, 72–73 % in Palermo and 88–90 % in Zurich, respectively), while the contribution of the end-of-life phase was negligible. The remaining energy demand and GHG emissions were mainly due to the fabrication phase. The colder the climate, the lower the payback times and the higher the energy return ratio, given the impact of the heating loads demanded to the solar systems.

13.5 Future Technology Trends

13.5.1 Materials

In order to improve durability, efficiency and reducing costs, advanced materials are being applied on all components of the solar thermal system. Low cost, anti-reflective and self-cleaning glasses are being continuously tested. Also, new materials such as polymers are being applied to improve the properties of materials commonly used (some polymers can offer thermal conductivities two orders of magnitude lower than iron and three orders of magnitude lower than aluminium), or carbon nanotubes and other components will increase durability working at high temperature. Also, to reduce costs, efforts to improve materials to extend heat input periods are being developed.

Improving the resistance to UV radiation and overheating are other properties where substantial efforts are being made. For resistance to overheating, thermotropic polymers with varying opacity as a function of temperature are being tested. Then, these polymers used in the transparent cover can regulate the temperature of the collector. As resistance materials to UV radiation, also new polymers chemically passivated for this radiation are being tested.

13.5.2 Cooling and Air Conditioning

The basic strategy for these systems is to expand the technology for applications in individual homes, thus making the market grow. Also, new types of solar collectors for medium temperature (up to 250 °C) are being tested to improve yields and therefore lowering cooling production costs to allow solar heat to be applied in air conditioning. More compact thermally driven cooling cycles (sorption chillers and desiccant systems), with higher coefficients of performance and operating at lower temperatures are being tested. This will require R&D into new sorption materials, new sorption coatings on heat exchange surfaces, new heat and mass transfer concepts and the design of new thermodynamic cycles.

Main on-going R&D on the material level is aiming to improve materials for adsorption and absorption (tailor-made adsorbents or, e.g., ionic liquids) or to extend absorption cycles. These materials and compounds have the potential to allow for more compact systems with advanced heat and mass transfer and thus will lead to lowering the cost for installation as well as broadening the application range.

Completely different solutions, such as new thermo-mechanical cycles, promising a significant increase in efficiency, are under development but have not yet left laboratory scale. Single-axis tracking solar thermal collectors to produce heat at temperatures in the range of 150–250 °C are still a rather new technology, and important cost savings may be achieved by development of advanced materials (e.g., for reflectors) and advanced production technologies [9] to achieve a significant share of the market.

Solar air conditioning is a complex technology and requires much more standardisation for the coupling of the key components and the development of robust, standardised solutions in the future. Also, a particular focus is needed on a quality procedure for designing, commissioning, monitoring, operating and maintaining solar heating and cooling systems.

13.5.3 Long-Term Storage

Long-term storage represents the greatest technological challenge in solar heating and cooling. More compact and advanced storage systems to enable a cost reduction of solar thermal energy are main goals. Thus, PCM and thermochemical processes are being explored to increase the energy density of the stored heat by about one order of magnitude [11]. Also, useful in this area are solar thermal collectors capable to work using higher temperature fluids. These high range temperature fluids can make a wider range of processes accessible, primarily chemical energy storage. PCM embedded in building materials, such as bricks, wall boards and flooring, are also being investigated.

Integrating the storage volumes underground, particularly for large-scale stores, is still a challenge for low-cost storage volumes especially in urban areas, with R&D in this area focusing on new materials and construction methods. A high number of charging and discharging cycles is critical for most TES applications, so the stability of materials in the systems is very important—not only the storage medium itself but also materials used in systems components such as containers, heat exchangers and pipes.

13.5.4 Solar Thermal Collectors

It is expected that the unglazed solar collector will be completely displaced from the market in the future. On the other hand, in this area, there are two other main tasks contemplated. Firstly, to achieve efficient collectors with non-rectangular shape, which improve integration of this technology in buildings. Moreover, as noted above, new types of medium temperature solar collectors are required to apply solar heat in industrial processes, cooling and diverse thermo-chemical cycles for storage systems. Improving the automation of manufacturing will help to reduce initial system costs and expand the economic application to a wider range of customers, particularly for retrofitting existing buildings.

13.5.5 Control Systems

In advanced control systems the increased activity is mainly driven by future technological development of progressively more complex solar thermal systems. On the one hand, the development of multifunctional facades and roofs in buildings allowing, in particular, the combi-system integration will require the use of these control systems. It is also expected the future development of improved storage systems with more complex technologies, the application of solar thermal energy to industrial and service sectors more extensively, as well as the development of solar cooling. In addition, centralised and integrated control systems will be needed to be able to benchmark and self-diagnose problems related to malfunctioning, while facilitating the integration of complementary systems (e.g., hybrid solar thermal/heat pump systems) and the upstream communicating to utilities.

13.6 Pre-Production Highlights 2009–2011

13.6.1 Thermotropic Polyamide Protection Against Overheating [14]

The Swiss company EMS-CHEMIE AG has developed a thermotropic polyamide in which the polymer core is coated on a thermoplastic material. Thus, the thermotropic layer, with a thickness of 2 mm, shows a hemispherical transmittance of 82 % at temperatures of 25 °C and 57 % at 95 °C.

13.6.2 Gasification of Biomass Energy from the Sun [15]

The company Sundrop Fuels has developed a system that synthesises fuel from biomass energy using solar thermal energy. This process doubles the performance compared to conventional gasification, since it avoids the need to burn 35–40 % of the biomass to reach the temperature (700 °C) needed to gasify biomass with steam. The developed system supplies up to 1.5 MW of thermal power. The gasifier is composed of ceramic tubes that pass through an oven, which is located on the focus of a field of heliostats. The system operates independently of the type of biomass, since it works at temperatures between 1,200 and 1,300 °C.

13.6.3 The World's Largest Solar District Heating System [1]

The world's largest solar district heating system, with a capacity of 25.4 MW_{th} (36,305 m^2; 17 MW_{th} in winter) was commissioned in April 2011 in Riyadh (Saudi Arabia) at Princess Noura Bint Abdurrahman University for Women (Project PNUW). The purpose of district heating is supplying the 8 km^2 campus for 40,000 students, faculty and staff, with over 1,000 m^3 of thermal storage capacity. In addition, this facility is integrated with approximately 75 MW_{th} conventional heating capacity, which required the design and customisation of the monitoring and control systems.

13.6.4 Database of Architecturally Appealing Solar Thermal Systems Integrated Into Buildings [16]

Experts of the 39 Task SHC-IEA program have created a database of architecturally appealing solar thermal systems integrated into buildings. The idea is that one picture says more than a thousand words, so these examples of visually appealing solar systems will encourage homeowners, builders and architects to use SHC. The Architectural Integration of Solar Thermal Energy Systems database can be found at http://www.iea-shc.org/task39/projects/default.aspx

13.6.5 Solar Thermal Energy for Enhanced Oil Recovery [17]

GlassPoint, a Californian company, has started producing steam from a solar thermal pilot plant at USD 3.58/GJ for enhanced oil recovery. This cost is cheaper than usual, as this kind of steam can be quite dirty and less warmed compared to the one used in turbines for CSP systems and also from gas (USD 5.48/GJ). As oil rigs are usually located in dusty and mucky areas, the mirrors are maintained indoor. The company has recently signed a deal with Petroleum Development Oman to produce 57 billion Btu/year of steam in a 16,000 m^2 7 MW plant.

13.7 Innovation Highlights 2009–2011

13.7.1 Solar Thermal Heat Storage in NaOH [18]

In order to obtain long-term heat stored from low temperature solar thermal production, a sodium hydroxide chemical process has been proposed (Fig. 13.11a). Solar heat produced would be used to increase the concentration of a sodium hydroxide solution (150 °C) by water evaporation (45 mbar). Then, the water is condensed using a geothermal heat pump (Fig. 13.11b). This heat would be recovered returning to the former sodium hydroxide concentration, reaching a temperature of 40 °C. The solution at this temperature is adequate for underfloor heating installations. It has been estimated that the system has an efficiency of 59 %.

13.7.2 Non-Rectangular Collector Design [14]

Conventional solar collectors are rectangular in shape, mainly due to the advantages it offers for construction processes based on the use of metals (copper and aluminium). However, the architects complain about the inability to use other collector shapes. For

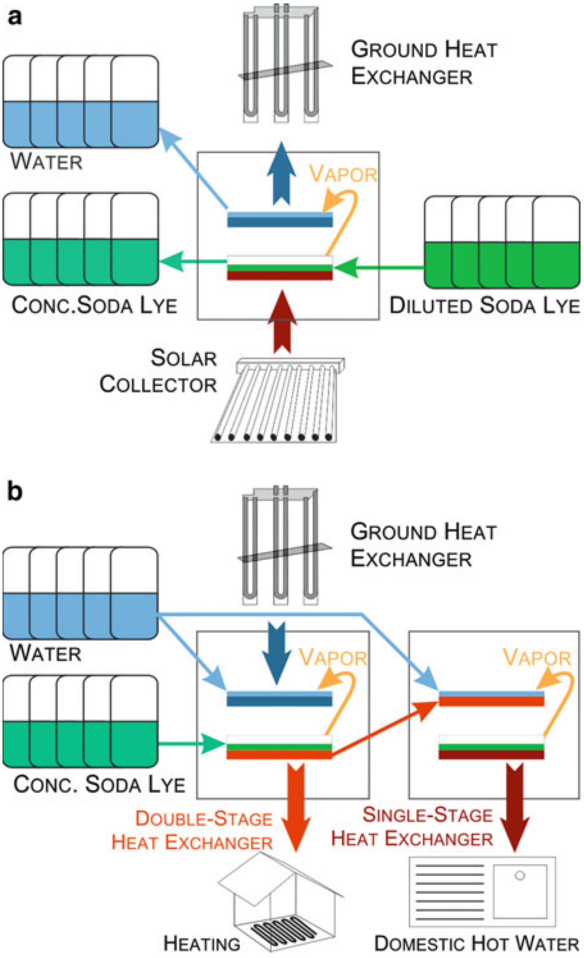

Fig. 13.11 Schematic of operation of heat storage in NaOH during (**a**) charging and (**b**) discharging

this reason, high efficiency polymeric collectors are being proposed, which may have unconventional shapes. However, the challenge for this type of unconventional shapes is to ensure uniform flow pattern across the collector. For this purpose, the company HTCO, specialised in fluid dynamics and heat transfer simulation, provides services for the design and optimisation of flow through non-rectangular collectors.

13.7.3 Thermionic-Based Solar Energy Converter [19]

The thermionic-based energy conversion process is based on two electrodes positioned close enough so that, when the cathode is heated, its electrons become excited and jump to the anode generating an electric current. Usually, this process was carried out at temperatures above 1,500 °C, but using cesium vapour larger efficiencies can be achieved by lowering the cathode temperature. A group of the University of Stanford has replaced the cesium vapour by a semiconductor (gallium nitride) and, aided by photons incident on the cathode, has achieved 25 % efficiency at a temperature of 200 °C. Such efficiency increases with temperature, so the team plans to achieve efficiencies above 50 % replacing GaN with other semiconductors (silicon) and working in the range 400–600 °C coupled to a steam turbine.

13.7.4 A New Binderless Sorption Material for Thermochemical Storage [16]

A new type of sorption storage material was developed at the University of Applied Sciences in Wildau (Germany), in collaboration with the chemical company Chemiewerke Bad Köstritz. They synthesised novel binderless molecular sieves following a new manufacturing strategy for zeolite pellets. Testing results show that the binderless molecular sieves, compared to ordinary materials, are better suited for thermochemical storage and heat transformation due to faster kinetics, higher water adsorption capacities, good hydrothermal stability and improved storage capacities.

13.8 Statistics of Publications and Patents

Figure 13.12 shows the number of scientific publications during the period 2001–2011 for different technologies associated with solar heating and cooling [20]. As it can be observed, the number of publications is comparable to other renewable energy technologies, and upward, although with occasional falls.

As it can be observed, the ranking in research activity is led by collector systems, as it is the key element of this technology. Enhanced durability and efficiency of these systems are required, as well as easier integration into buildings.

On second place is the research in new materials to solve specific problems mentioned above, such as self-cleaning properties, thermal insulation, protection against overheating and corrosion. On third place is the research activity in solar thermal storage systems, as the demand for such systems to store heat in the long term is increasing and the energy efficiency of such systems is improving. On fourth place is the research activity in control systems, although the demand for increasingly complex applications, hybrid heating systems and the optimisation of the solar resource is gaining share in the market.

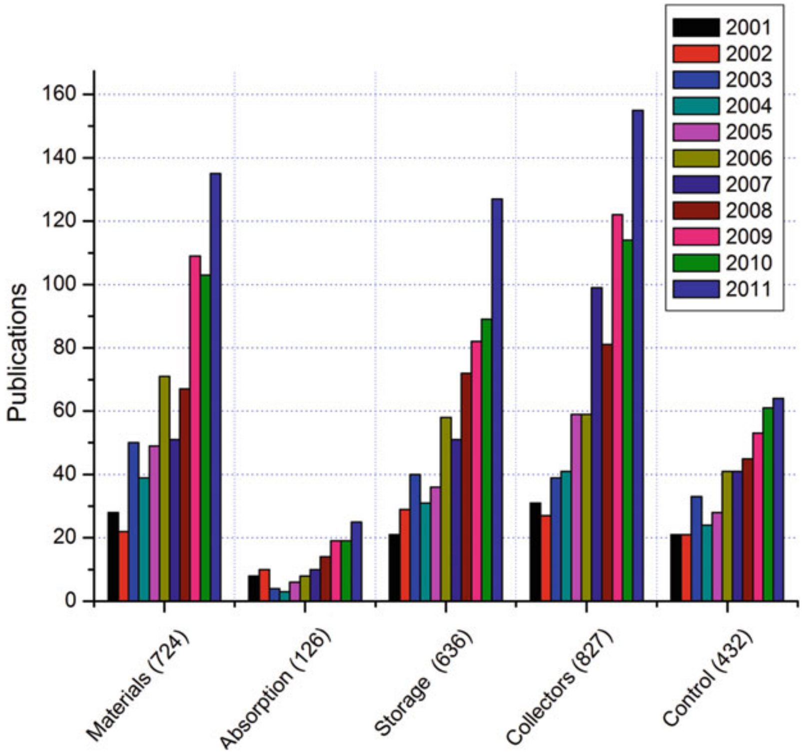

Fig. 13.12 Number of scientific publications during the period 2001–2011 for different types of technologies associated with solar heating and cooling [20]

Finally, the research activities related to cooling and air conditioning systems occupy the bottom of the ranking. As it has been mentioned above, important challenges must be solved to increase the attractiveness of this technology, mainly related to energy demand compared to alternative technologies (PV—conventional systems). Also, more engineering is needed to simplify systems and introduce them in individual houses.

Figure 13.13 shows the number of patents during the period 2001–2011 for different technologies associated with solar heating and cooling [21]. As it can be observed, the number of patents is large and upward, mainly since 2007.

The ranking in patents is led by heat exchange systems, as they are the main component of the solar heating and cooling systems. On second place are the solar mounting and tracking systems, as they are important components to assure mechanical stability for increasing the lifetime of the installation, cost reduction and integration in buildings. Also, these systems play a central role for the development of high-temperature solar collectors, as they require concentrating solar energy and, consequently, tracking the sun.

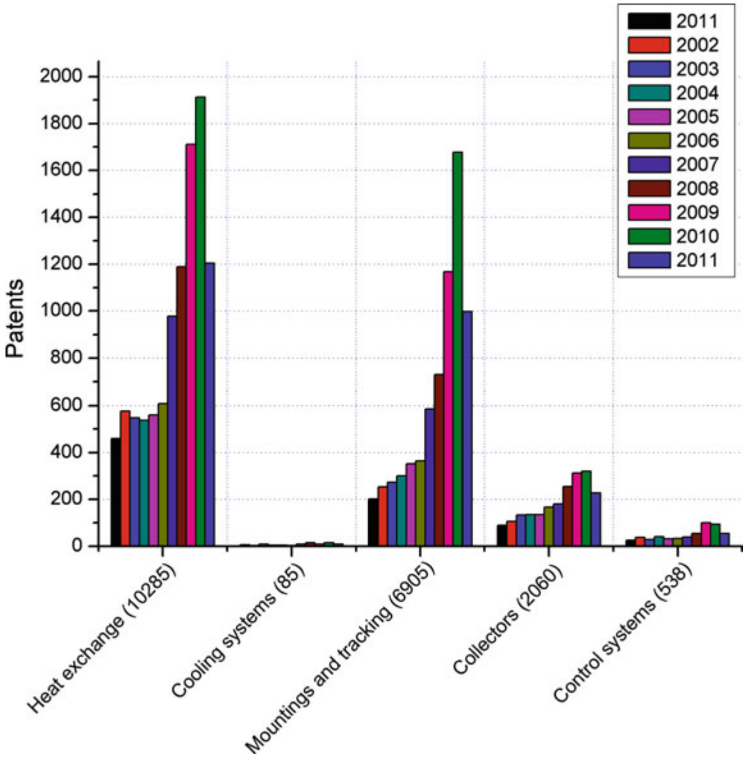

Fig. 13.13 Number of patents during the period 2001–2011 for different technologies associated with solar heating and cooling [21]

Also, the new patents related to solar collector systems have been counted, as they are in a separated classification in the database analysed but, in our opinion, there is an overlapping between these patents and those corresponding to heat exchange systems, requiring a future unification in a common category.

On the other hand, it can be observed that activity in control systems for solar heating systems is low compared to the above mentioned, but also increasing. Lastly, patent production in solar cooling and air conditioning systems is very low and constant over the years studied. It can be interpreted as another signal of the difficulties encountered by this technology in trying to increase presence in the market.

Finally, it is observed in 2011 a common decrease in the number of patents for all the technologies studied. This fact could be attributed to a collateral effect of the global financial crisis, as an important number of small companies that normally produce these patents could have important restrictions to credit to promote their technology.

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Chapter 14
Fuel Cells

Abstract The main advantages of fuel cells are their high efficiency for electricity production of about 60 %, and practically zero emissions if hydrogen is introduced as fuel, in contrast to combustion fuel engines whose efficiency is approximately of 20 % at most and are very polluting. Their principle of operation in hydrogen-based fuel cells is the reverse to the electrolysis process: hydrogen and oxygen (or air) react in the cell producing an electron DC current. In this chapter, we describe the most often employed fuel cell devices, their name being derived from the kind of electrolyte used. The market is dominated by the proton exchange membrane fuel cell (PEMFC), which is probably the best candidate for vehicles and portable applications. They are followed by the phosphoric acid fuel cells (PAFC), which have the advantage of using either hydrogen or natural gas that can be reformed in the cell itself. Other cells studied are the solid-state fuel cells (SOFC), which use a solid oxide electrolyte, the molten carbonate fuel cells (MCFC) that can use CO_2 from natural gas as fuel, etc.

14.1 Overview

Fuel cells are devices that use hydrogen (or a hydrogen-rich fuel) in an electrochemical process to produce electricity and heat. Generally, the fuel cell consists in a system of two electrodes (anode and cathode) immersed in an electrolyte, in which hydrogen is supplied to the anode and oxygen to the cathode. A catalyst ionises the hydrogen atoms into electrons and protons, taking each particle an opposite path towards the cathode. Thus, the electrons move through an external circuit (supplying an output power), while the protons move through the cell electrolyte. At the cathode, the electrons and protons react with oxygen to produce water and heat. Several fuel cells are generally connected in series and/or parallel to achieve the desired output power and voltage. This configuration is called a fuel stack. Typical fuel cell configurations and efficiencies are exposed below.

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Fuel cells can be used to power electric motors for road transport, electrical machinery, electronics and even modular facilities for heat and power. This heat and power configuration is particularly attractive as the sum of electricity and heat efficiencies place production costs closer to market prices. In addition, this mid-range power configuration is attractive for applications in uninterruptible power systems (UPS) and buildings that demand power capacity between conventional high-power CHP and small boilers for individual use.

For road transport, since electric motors have a very high efficiency in converting electrical energy into mechanical (over 90 %) [1] and fuel cells efficiencies are also considerable, hydrogen conversion efficiency in this sector almost doubles that of fossil fuels on highways and even triples in dense urban traffic conditions. However, the current cost of fuel cells is high (as discussed below), but it is expected to moderate substantially when fuel cell production volumes increase.

To analyse the production in recent years, we must make a first distinction between fuel cells for stationary, portable and transport applications [2]. In terms of MW shipped, 90.0 MW (+4.1 % compared to 2009) were shipped in 2010, and the stationary applications lead the current scenario (Fig. 14.1a) because these units have much larger power capacity compared to fuel cells devoted to portable and transport applications. However, in terms of units shipped, 229,600 units were shipped in 2010 (+39.4 % compared to 2009), where the leading role is for portable applications (Fig. 14.1b) due to a soaring demand for fuel cell toys and education kits.

14.2 State of the Art

14.2.1 Proton Exchange Membrane Fuel Cell

The most characteristic component of PEMFC is its electrolyte, which is composed by a polymeric membrane with sulphonic group CF_2. This electrolyte membrane is surpassed by protons (H^+) by means of a "hopping" mechanism (Fig. 14.2a). The base polymer is called Nafion and is manufactured by Dupont. The sensitivity of PEMFC to carbon monoxide and sulphur compounds requires the use of pure hydrogen (e.g., obtained by water electrolysis) to avoid poisoning of the platinum catalyst.

The market penetration of these fuel cells is driven by the advanced technology and the low ratio between weight and volume compared to the energy delivered. The main disadvantage is the requirement of using nanodispersed platinum electrodes as catalyst, since it is very costly. Consequently, many efforts are being made to find alternative materials to platinum that would allow to improve the competitiveness of this technology.

On the other hand, the PEMFC requires the use of non-corrosive products, like other fuel cells. It also operates at relatively low temperatures (~80 °C), allowing

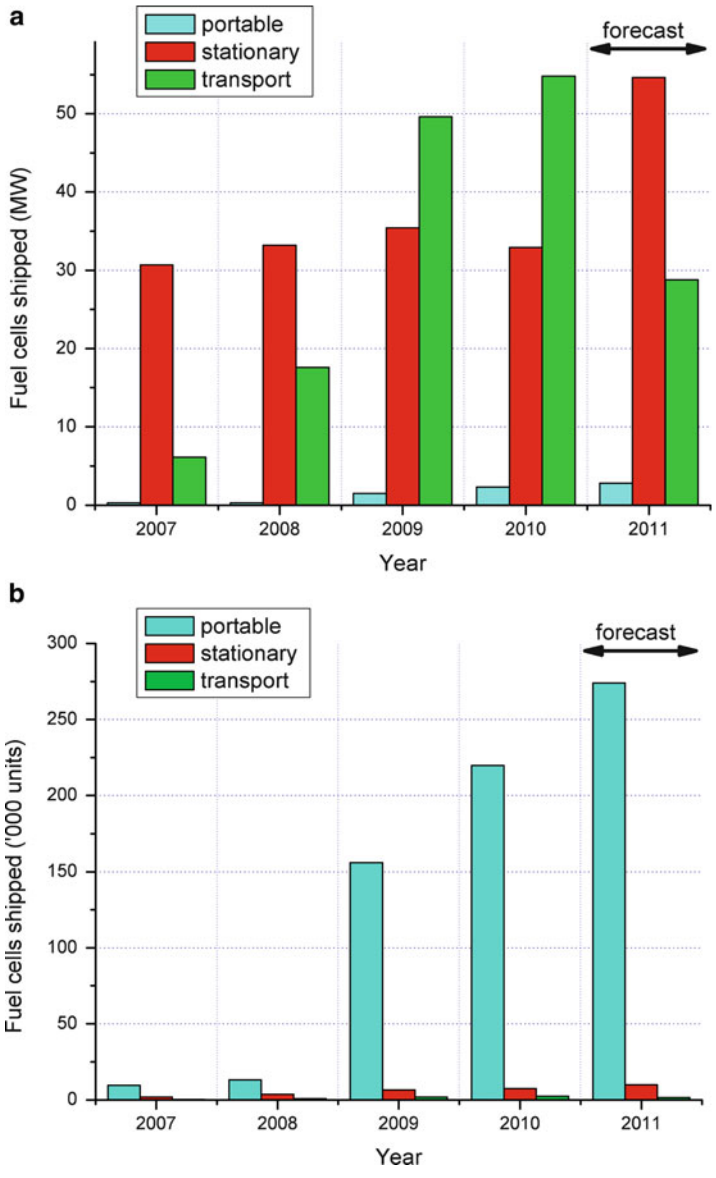

Fig. 14.1 Annual fuel cells shipments in term of (**a**) power capacity, and (**b**) in thousands of units

quick start up into operation. It also has larger durability than other fuel cells, although it requires refrigeration to avoid out of range working temperature. This refrigeration demand can be attractive for CHP applications.

Direct methanol fuel cells (DMFC) constitute a relatively recent addition to the set of fuel cell technologies (invented and developed in the 1990s). It can be

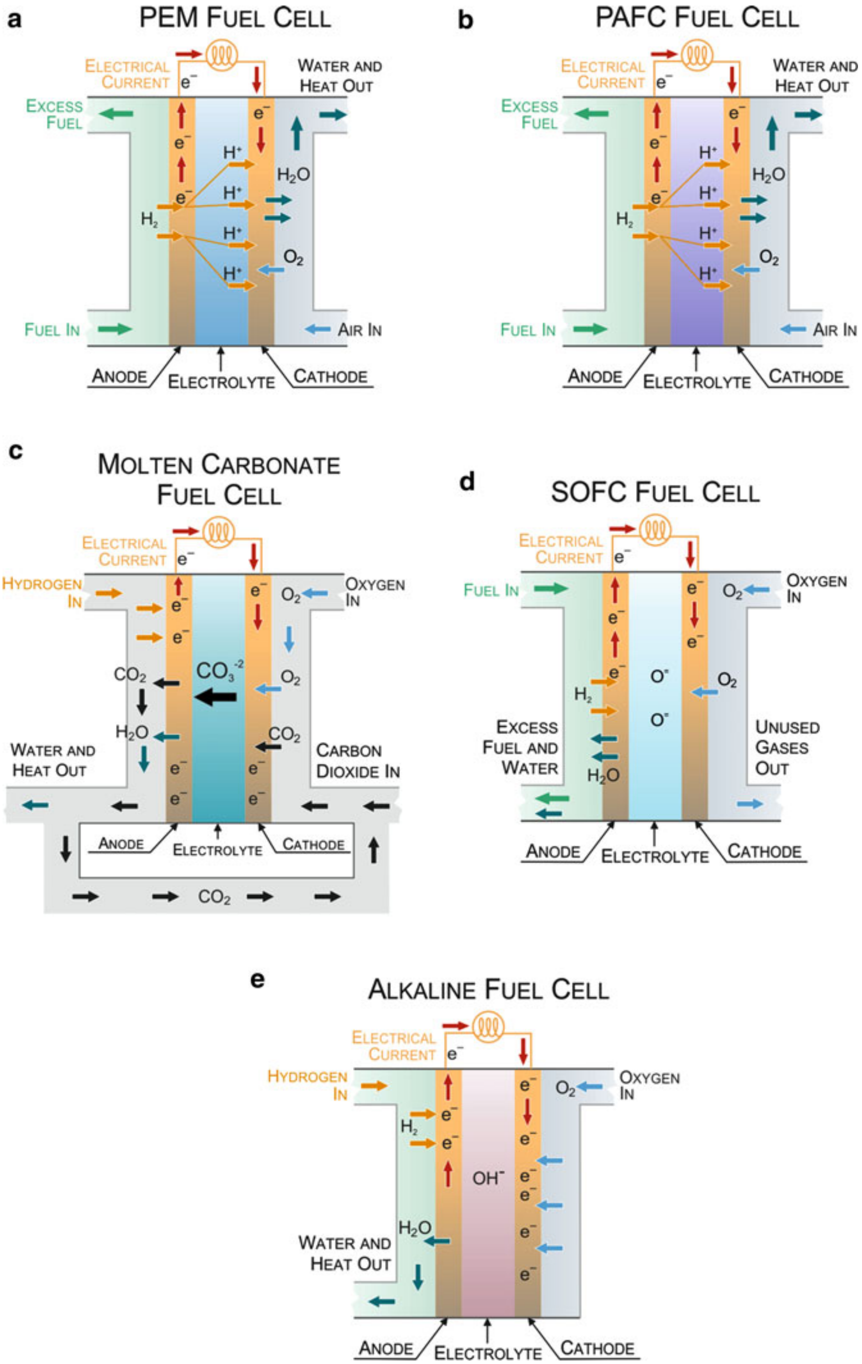

Fig. 14.2 Scheme of the different fuel cell types mentioned in this chapter: (**a**) PEMFC; (**b**) PAFC; (**c**) MCFC; (**d**) SOFC and (**e**) AFC

considered a subcategory of the PEMFC in that it uses a polymer membrane as an electrolyte. However, ruthenium is added to the platinum catalyst on the DMFC anode to draw the hydrogen from the liquid methanol, thus eliminating the need for a fuel reformer and avoiding CO poisoning of the platinum. Most fuel cells are powered by hydrogen, which can be fed to the fuel cell system directly or can be generated within it by reforming hydrogen-rich fuels, such as methanol, ethanol and hydrocarbon fuels. DMFCs, however, are powered by pure methanol, which is mixed with steam and fed directly to the fuel cell anode.

14.2.2 Phosphoric Acid Fuel Cells

These fuel cells use a hydrocarbon fuel, such as natural gas or gasoline, which is subsequently reformed, but they can also use hydrogen directly (Fig. 14.4b). They are based on a phosphoric acid electrolyte contained in a silicon carbide matrix operating near 200 °C (the boiling temperature is 250 °C). The phosphoric acid fuel cells (PAFC) use porous carbon electrodes containing platinum. These fuel cells, although were the first to be marketed, are not used in the automotive industry since they are quite expensive and very heavy. They are technologically advanced, so they are extensively used in stationary distributed power generation.

14.2.3 Molten Carbonate Fuel Cells

These fuel cells use CO_2, usually obtained from natural gas or coal (Fig. 14.2c). Consequently, they are not poisoned by carbon monoxide compounds and are very resistant to particulate matter and sulphur. They use an electrolyte composed of a molten carbonate salt, suspended in an inert ceramic matrix of lithium aluminium oxide ($LiAlO_2$). They operate at temperatures high enough (> 650 °C) to avoid the use of catalysts based on precious metals. Their main use is in mid-power plants (about some MW) and buildings, which demand both electricity and heat.

In contrast to alkaline, phosphoric acid and proton exchange membrane fuel cells, molten carbonate fuel cells (MCFC) do not require an external reformer to convert high energy density fuels into hydrogen. This is because the high temperature operation of this fuel cell directly synthesises hydrogen from hydrocarbons within the fuel cell through a process called internal reforming, which also reduces costs.

The major disadvantage of these molten carbonate fuel cells is their durability, as the high operation temperatures and the corrosive electrolyte used accelerate the breakdown of the compounds.

14.2.4 Solid Oxide Fuel Cells

These fuel cells can be powered by different fuels, including hydrogen, generally obtained by reforming, and fossil fuels like natural gas, etc. (Fig. 14.2d). The solid electrolyte consists of a non-porous ceramic membrane of zirconium oxide, ZrO_2, doped with yttrium. These cells operate at temperatures of about 800–1,000 °C, so the oxygen ions from the combustible can quickly cross the ceramic membrane. Due to the high operating temperatures, the reforming processes do not require the use of precious metals, being the type of fuel cells with higher resistance to sulphur compounds and carbon monoxide. Working at high temperatures is however disadvantageous for this type of fuel cells since, for example, they produce energy at a slow rate, and they need thermal isolation and labour protection. In addition, the power produced from this type of fuel cells is very expensive.

The solid-state fuel cells (SOFC) facilities are mainly used in relatively large CHP plants, due to their high operating temperature. These power plants reach efficiencies close to 60 %.

14.2.5 Alkaline Electrolyte Fuel Cells (AFC)

These fuel cells are one of the first technologies to be developed, mainly to produce electricity and water on-board spacecraft. Its name is attributed to the fact that the electrolyte is an alkali, usually potassium hydroxide, and can use a variety of non-precious metals as catalysts at the anode and the cathode (Fig. 14.2e). They operate at temperatures between 23 and 70 °C.

The major disadvantage of this type of fuel cells is that they are very easily poisoned by CO_2, which decreases their durability. Even a small amount of CO_2 in the atmosphere can affect the operation of the fuel cell. Consequently, it is necessary to purify both the hydrogen and oxygen, which are injected into it. This exigency makes it difficult to obtain oxygen directly from the atmosphere, as pure oxygen is demanded. In addition, the lifetimes of these fuel cells (8,000 h) are well below the target considered for stationary applications (40,000–60,000 h or 5–8 years of operation) [3].

In summary, considering that the sources of information are still in a process of standardisation of the definition parameters, the main technical specifications for each fuel cell technology are exposed below (Table 14.1).

14.2.6 Stages of Development

Fuel cells began to become commercial in a variety of applications in 2007, when they started to be sold to end-users with written warranties and service capability

Table 14.1 Main technical specifications for the fuel cell technologies exposed in this chapter

	SOFC	MCFC	PEMFC	PAFC	AFC
Main application	Stationary	Stationary	Stationary/Portable/ Transport	Stationary	Stationary/ Transport
Operation temperature (°C)	800–1,000	> 650	80–150	150–200	23–70
Combustible	H_2, hc	ng, hc	H_2	ng, H_2	H_2
Electric efficiency (%)	50–55	50–55	35–40	37–42	60
Movil lifetime (h)	–	–	2,000	–	8,000
Stationary lifetime (h)	20,000	20,000	30,000	40,000	8,000
Electrolyte	Ceramic oxide	Molten carbonates	Polymeric membrane	H_3PO_4–SiC	Alcalis
Catalyser	Perovskite	Nickel	Pt	Pt–C	Non-precious metals

ng natural gas, *hc* hydrocarbons

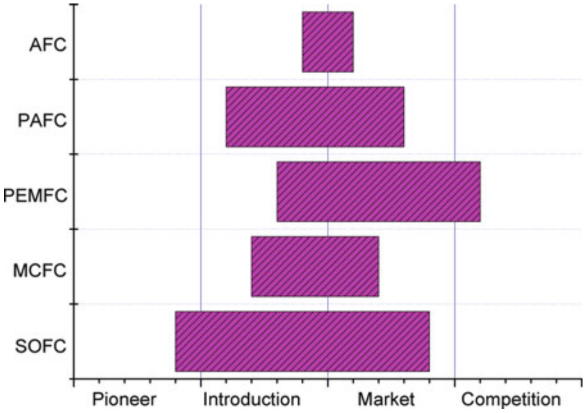

Fig. 14.3 Stages of development for each of the fuel cells technologies considered in this chapter

and met the codes and standards of the markets in which they were sold [2]. Depending on the market penetration, the various fuel cell technologies can be classified in different stages of development (Fig. 14.3). Thus, it is considered that all technologies have entered the market stage, but AFC is affected by specific constrains (H_2 purity requirements) that make them obsolete, as it can be confirmed below in Fig. 14.4. PEMFC is the more developed technology and has an absolute dominance in the market. Moreover, SOFC is well placed in the market in terms of units shipped. PAFC is behind SOFC, considering also evolution of patents and literature (exposed below), and in the last position is the MCFC technology.

It can also be depicted the recent evolution of fuel cells shipments for different technologies in terms of MW/year (Fig. 14.4) In this aspect, PEMFC dominates the market with 66.4 MW in 2010 (73.8 % of the total market). In terms of units/year also PEMFC largely dominates the market with 285,200 units, mainly for portable applications, followed by SOFC with 400 units [2].

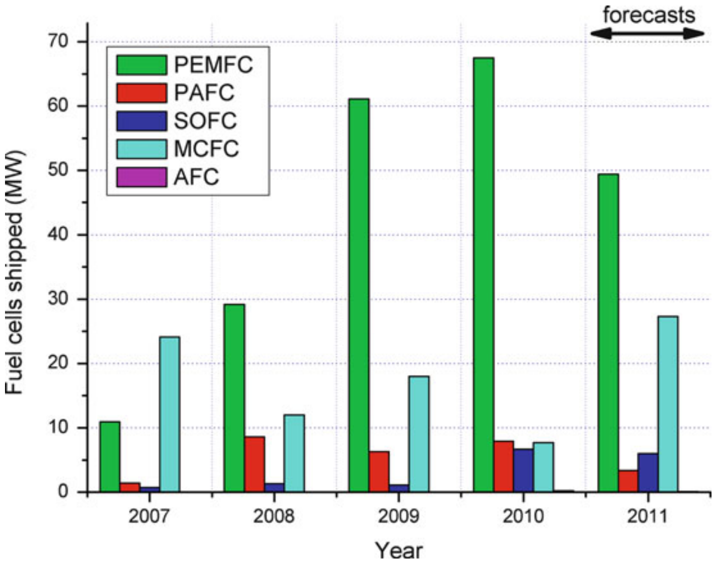

Fig. 14.4 Annual fuel cell shipment in terms of MW for the different fuel cell types mentioned in this chapter: (**a**) PEMFC; (**b**) SOFC; (**c**) MCFC; (**d**) PAFC and (**e**) AFC

14.3 Current and Future Costs Scenarios

Regarding the cost of fuel cells, we will only consider stationary plants for combined power and heat production, as costs for portable and transport fuel cells are beyond the content of this book. In this respect, there are very few reliable data, in part because medium and large capacity fuel cells are usually commissioned and, in part, because it is a technology with a very small market and, consequently, the fuel cells are usually manually fabricated, which makes costs comparison very difficult.

The cost evaluation is usually exposed in terms of capital invested per unit of installed capacity, since the cells can use different fuels and, even in the case of hydrogen, the energy carrier can be obtained from different technologies that substantially vary in cost.

Depending on size and application, updated stationary fuel cell systems are estimated to cost USD 3,048–7,112/kW (EUR 2,190–5,109/kW) [4]. The high costs are attributed to the polymeric membranes usually Nafion, the platinum electrodes involving approximately 0.2–1.4 g/kW (platinum content on PEMFC has decreased by more than 80 % between 2005 and 2010 [2]), and the bipolar plates made of graphite–polymer composites. It is expected a substantial lowering of the prices in the near future with the development of new technologies and techniques to implement large-scale production.

The cost of electricity in fuel cell based CHP systems is currently estimated at USD 0.213/kWh (EUR 0.153/kWh) considering a biogas-based facility. If the CHP

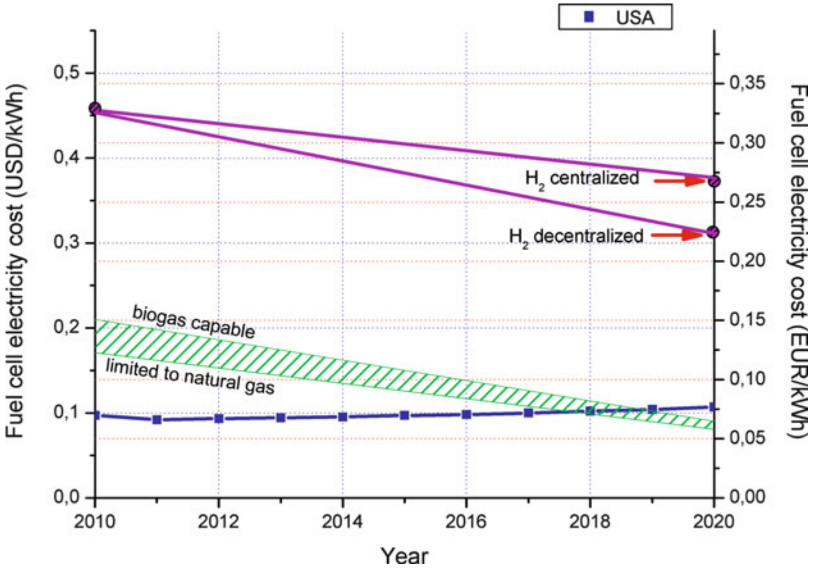

Fig. 14.5 Evolution of electricity costs for stationary fuel cell facilities with different fuels and investment costs forecasts for 2020. The solid square represents the average end-user nominal price for all sectors (residential, commercial, industrial and transportation) expected in US reference scenario projected from 2011 to 2020

plant fuel is only natural gas, the electricity cost is currently estimated at USD 0.173/kWh (EUR 0.123/kWh) [4].

The goal for grid parity in fuel cell technology is to reach USD 2,032/kW (EUR 1,460/kW) capital costs in 2020 (Fig. 14.5) [4], increasing total efficiency from current 72.7 to 78.0 %, electrical efficiency from current 39.7 to 45.1 %, current fixed O&M costs from USD 307/kW$_e$/year (EUR 220/kW$_e$/year) to USD 110/kW$_e$/year (EUR 79/kW$_e$/year) and current variable O&M costs from USD 13.9/kWh (EUR 10.0/kWh) to USD 39/kWh (USD 28/kWh) [4]. It is expected that fuel cell technology will reach USD 975/kW (EUR 701/kW) capital costs in 2040 [4]. The main reasons for this significant drop in prices are that, currently, the fuel cells are manufactured manually, so a large-scale automated production line should drop prices substantially.

Also, by considering data from Chap. 5, an estimation of production costs per kWh of electricity in centralised and decentralised systems using hydrogen as fuel derived from renewable energy sources is exposed in Fig. 14.5. We have considered the lower hydrogen production cost in centralised hydrogen production systems, which are those using biomass as raw material, resulting USD 0.456/kWh (EUR 0.328/kWh). For hydrogen production costs in decentralised hydrogen production systems, which are those using biofuels as raw material, it is calculated USD 0.462/kWh (EUR 0.332/kWh). Considering 2020 forecasts, electricity from hydrogen fuel cells is less costly if hydrogen is supplied from decentralised facilities instead of centralised ones. However, these estimations are still above the ones corresponding to natural gas or biogas supply (Fig. 14.5).

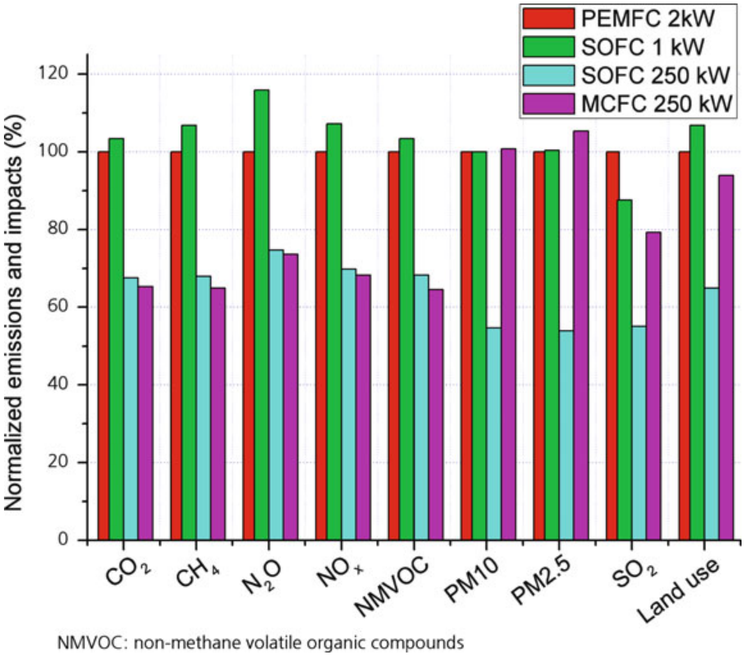

Fig. 14.6 Emissions and land use for different fuel cell technologies [7]

Thus, one can conclude that current electricity costs from stationary fuel cell systems approximately double the average end-user nominal price in US electricity. However, at the end of this decade, grid parity could be expected, primarily if natural gas is supplied to fuel cells (Fig. 14.5). On the other hand, electricity cost from hydrogen produced from renewable energy sources is far above average end-user nominal electricity price in USA. In this sense, it is more effective to directly use synthesis gas from biomass gasification or biofuels to supply the fuel cells than to convert biomass and biofuels to hydrogen and, subsequently, supply hydrogen to fuel cells (see Sects. 3.3 and 4.3).

14.4 Energy Payback, CO_2 Emissions and External Costs [5, 6]

The energy payback, CO_2 emissions and external costs in fuel cells mainly depend on the type of fuel used and, in case of hydrogen, the procedure to obtain it. Thus, it is very difficult to analyse these parameters in this case. However, there is already a life-cycle analysis of PEMFC, SOFC and MCFC technologies for stationary applications that could be useful as a reference [7].

In this analysis, it is found that small systems are those with the lower performance (Fig. 14.6). If small fuel cells are compared among themselves, PEMFC generally show better performance than the SOFC, except in SO_x emissions. This result is mainly due to the fabrication phase of the PEMFC. The differences in CO_2 and, in general, the emission of greenhouse gases, are primarily attributable to differences in electrical efficiency of these technologies.

For large systems, SOFC (250 kW) shows a lower performance compared to MCFC (250 MW) in relation to emissions of CO_2, CH_4, N_2O, NO_x and NMVOC (non-volatile organic compounds methane). However, it is expected that this behaviour will be reversed in the future, as the SOFC electrical efficiency will increase in relation to the MCFC.

On the other hand, recent studies show that assuming fuel cell CHP with 42 % high heating value (HHV) electrical efficiency and 74 % HHV overall efficiency and using EPA CHP analysis model [8], more than 35–50 % reduction in emissions over conventional CHP is reached. Reductions can be much greater (possibly more than 80 %) if biogas is used in the fuel cell [4]. In addition, fuel cells emit about 75–90 % less NO_x and about 75–80 % less particulate matter (PM) than other CHP technologies, on a life-cycle basis [9].

No contrasted information has been found about energy payback and external costs related to fuel cells technology.

14.5 Future Technology Trends

14.5.1 Proton Exchange Membrane Fuel Cell

In Proton Exchange Membrane Fuel Cell (PEMFC) technology, efforts are mainly devoted to the development of new catalysts for protons, electrons and oxygen to form water, replacing the high-cost platinum-based electrodes. For example, new platinum/ruthenium catalysts are being tested, as they show more resistance to CO poisoning. Catalysts replacement by cobalt and chromium Pt alloys is also being considered.

There is also research activity related to the development of new membrane materials to replace the nafion, operating at temperatures about 180 °C, by materials with higher resistance to poisoning and no need for refrigeration systems. Nafion has the disadvantages of being expensive and, at temperatures above 80 °C, shows a loss of proton conductivity due to dehydration. For example, there are being introduced the so-called high-temperature thermoplastics, consisting of organically modified silicates and other polymers.

A substantial amount of work is also dedicated to developing new types of bipolar plates, currently made from graphite or stainless steel coated with gold. The aim is to substitute these materials by polymers or cheaper steel alloys.

14.5.2 Phosphoric Acid Fuel Cells

PAFC are considered to be based on a mature technology and, consequently, with little chance of reducing costs. Therefore, as stated above, manufacturing companies are leaving the activities in this area to reinforce manufacturing capacity related to other fuel cell technologies with better prospects.

14.5.3 Molten Carbonate Fuel Cells (MCFC)

The technology efforts in MCFC focus primarily on the development of corrosion-resistant materials to increase the lifetimes of the fuel cells. The materials must withstand a minimum of 40,000 h at 650 °C in the presence of a molten salt in oxidising or reducing conditions. In addition, the degradation of the nickel electrodes should be solved, as Ni can penetrates the molten carbonate and causes short circuits.

There is also research activity to simplify the systems and use the process heat steam to drive turbines and, consequently, improving the electrical efficiency. Also, alternative fuel cell designs allowing the use of other fuels (liquid hydrocarbons, biofuels, gas from digesters or waste, etc.) is another research area of interest, since MCFCs have the advantage of not being affected by the amount of CO_2 carried by the fuel. In fact, already fuel cells powered by methanol and biogas are being tested.

14.5.4 Solid Oxide Fuel Cells

As for SOFCs, the research activities are mainly focused on trying to develop alternative materials to zirconium oxide membranes showing higher electrical conductivities, so that they can operate at lower temperatures (at around 500 °C), instead of the current 1,000 °C. Working at lower temperatures allows the use of less expensive materials.

These fuel cells also require further R&D on materials that can operate at high temperatures and having a large durability. It is also necessary to develop new electrodes to improve the efficiency of redox reactions and tolerance to sulphur compounds. In addition, new cathode materials and electrolytes are demanded to improve the power density per unit area of the fuel cell at lower operating temperatures. On the other hand, the heat of the process can be used to move steam turbines and, thus, improving the electrical efficiency.

14.5.5 Alkaline Electrolyte Fuel Cells

The technical problems related to the AFC short lifetimes and cost, as they demand purified hydrogen and oxygen, have drastically slowed technological development efforts in this area.

14.5.6 Other Future Aspects

There are other fuel cell technologies that could offer substantial attractiveness in the future. Of particular interest are recent activities on the manufacture of fuel micropiles (<1 W), mainly catalysed by biological enzymes. These fuel cells are considered for medical applications in environments that require power supply continuously and with difficulties for recharging. Thus, research efforts are trying to take advantage of the chemicals surrounding the fuel cells for biological refuelling.

Another R&D activity is based on the use of biogas, obtained from solid biomass or anaerobic digestion of waste, to feed fuel cells. As mentioned above, some prototypes are being tested. These systems have the advantage of producing electricity with higher efficiency than conventional production systems, especially if applied in decentralised facilities. Also, carbon emissions can be drastically reduced using biogas.

Other efforts in fuel cell technology improvements are related to the performance (e.g., power, start-up time and transient response) of fuel cell systems. These advances will require improvements in fuel cell stack and balance of plant (BOP) components. Thus, main tasks are related to the development of fuel processors to meet cost, performance, durability and output fuel quality requirements (i.e., fuel flexibility, gas clean-up for contaminants from biogas and other fuels, etc.). In addition, the optimisation of subsystems and integration concepts, including reversible or regenerative fuel cells, are also being investigated.

Finally, advanced manufacturing technologies and processes will be required to transfer fuel cells from laboratory-scale production into high-volume manufacturing, thus spurring the growth of a strong domestic supplier base.

14.6 Pre-Production Highlights 2009–2011

14.6.1 Fuel Cell Fed with Blood Sugar [10]

This fuel cell has been developed by the University of British Columbia, and, by synthesising sugar from human blood, can generate electricity. The fuel cell has a power capacity of 40 nW and is designed for medical applications that may require prolonged energy supply. This fuel cell would avoid the periodic surgery needed to replace the batteries located inside the human body.

14.6.2 World's First Fuel Cell and Hydrogen Energy Station Commissioned [11]

The world's first trigeneration fuel cell and hydrogen energy station to provide transportation fuel to the public and electric power to a district's wastewater treatment plant has been commissioned in Fountain Valley, California. The fuel station will co-produce hydrogen in addition to electricity and heat, making it a real tri-generation system. The system is integrated to a hydrogen purification system to recover approximately 100 kg of hydrogen per day. The hydrogen produced by the system is sent to a hydrogen fuelling station that will be open to the public and can support between 25 and 50 fuel cell electric vehicle fill-ups per day. The fuel cell also produces approximately 250 kW of power for use by the wastewater treatment plant. The station uses biogas from the municipal wastewater treatment plant as the fuel for the fuel cell stack.

14.7 Innovation Highlights 2009–2011

14.7.1 Advances in the Substitution or Optimisation of Pt-Based Catalysts for Fuel Cells [12, 13]

In order to reduce costs in the production of fuel cells, there have been several advances in the substitution of platinum catalysts by other materials, or by platinum compounds with a low proportion of this metal. Thus, the catalytic activity of Fe/N/C compounds has been increased by a factor 5 in relation to values reported a few years earlier. Also, the rate of electron production and the fraction of Pt atoms on the surface have been increased in platinum catalysts such as Pt_3Ni (111) and, consequently, the overall catalytic activity has augmented approximately a factor of 100 [12].

On the other hand, a new type of catalyst could lead to fuel cells that use a fifth of the platinum they use at present. The new material consists of nanoparticles with cores made of a copper–platinum alloy and an outer shell that is mostly platinum. This material is up to five times as efficient as regular platinum. Researchers have revealed the mechanism that makes this catalyst more active than regular platinum. Using X-ray scattering, they discovered that the distance between the platinum atoms on the surface of the nanoparticles exhibits certain compressive strain, which results in a shift of the electronic band structure of platinum and a weakening of the chemisorption for oxygenated species [13].

14.7.2 The Impact of Anode Microstructure on the Properties of the Solid-State Fuel Cell [14, 15]

Scientists of the National Institute of Advanced Industrial Science and Technology, in Nagoya (Japan), have shown that the efficiency of the SOFCs improves considerably when the particles forming the anode are reduced in size to form a highly porous nanostructure. Thus, the power density has been increased to more than 1 W/cm^2 at temperatures below 600 °C, using a conventional ZrO_2 electrolyte, a cermet anode based on nickel ferrite and a cathode. Simultaneously, the flow rate of hydrogen within the fuel cell has also been improved [14].

On the other hand, scientists from the start-up company SiEnergy Systems have achieved SOFC that can operate at 510 °C. The technique is based on nanoscale yttria-stabilised zirconia membranes with lateral dimensions on the scale of millimetres or centimetres. The membranes are made thermomechanically stable by depositing metallic grids on them, operating as mechanical supports. The combination of this membrane with a nanostructured dense oxide cathode produces a thin-film solid-oxide fuel cell that can achieve a power density of 155 mW/cm^2 at 510 °C. A total power output of more than 20 mW from a single fuel-cell chip is also reported.

14.7.3 High-Performance Electrocatalysts for Oxygen Reduction Derived from Polyaniline, Iron and Cobalt [16]

This work examines a family of non-precious metal catalysts that approach the performance of platinum-based catalysts at a justifiable cost for high-power fuel cell applications. The researchers use polyaniline as a precursor to a carbon–nitrogen template for high-temperature synthesis of catalysts incorporating iron and cobalt. The most active materials in the group catalyse the oxygen reduction reaction at potentials within ~60 mV of that delivered by state-of-the-art carbon-supported platinum. The new catalyst also shows remarkable performance stability for a non-precious metal system (700 h at a fuel cell voltage of 0.4 V).

14.7.4 Water and Air Produce Energy [17]

Scientists at the University of Stuttgart have developed a concentration fuel cell that produces power using only water and warm air. Water is oxidised catalytically to molecular oxygen, protons and electrons at the anode, while the reverse reaction takes place at the cathode. The water that forms at the cathode is evaporated by the air flow, maintaining the water concentration gradient between the two electrodes,

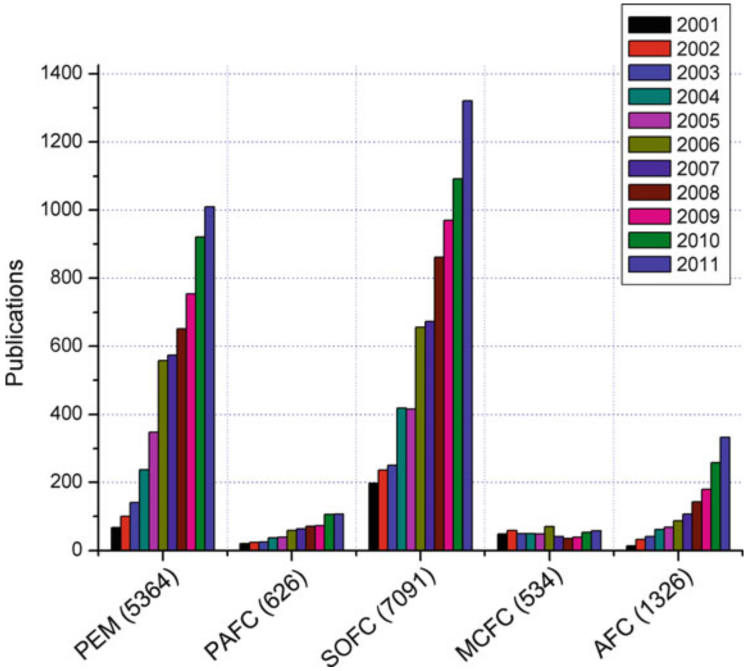

Fig. 14.7 Number of scientific publications during the period 2001–2011 for different fuel cell technologies [18]

which acts as the driving force for the reaction. The maximum power density delivered (8.7 mW/cm^2) is much smaller than that of typical fuels cells, but this system can find use in specific situations where a small energy output is needed, such as for powering small sensors or for emergency signal devices.

14.8 Statistics of Publications and Patents

Figure 14.7 shows the number of scientific publications during the period 2001–2011 for different fuel cell types [18].

From Fig. 14.7, it can be observed that SOFC and PEMFC technologies are the ones showing the largest number of publications, leading the group the solid oxide technology. This result confirms many of the considerations exposed in the preceding paragraphs regarding these technologies, especially in relation to the potential for cost reduction, increase of the power to weight ratio and applicability to biofuels and vehicles.

From Fig. 14.7, it can also be deduced that AFC is considered a mature technology, as indicated in previous sections, but demands of gas purity and low lifetimes of the devices make it not attractive for the future. However, the upward

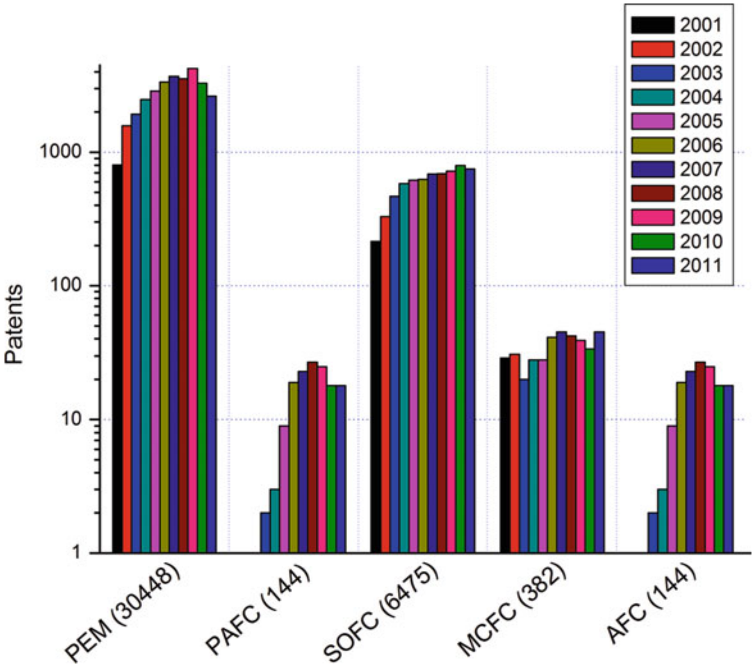

Fig. 14.8 Number of patents published during the period 2001–2011 for different fuel cell technologies [19]

tendency in the number of publications predicts that technology improvements could be expected in the near future. A lower activity and softened upward tendency is detected in PAFC, which can be attributed to the difficulties to substantially reduce the costs to make them competitive in the long run.

The number and evolution of publications in the MCFC technology indicates that it is the least attractive of all the technologies exposed, with few options to resurge in the short term. The evolution in the number of publications is almost flat, which could be interpreted as a consequence of being a discarded technology for automotive applications and due to the kind of fuel it uses.

The evolution of patents from 2001 to 2011 (Fig. 14.8) [19] shows a very similar tendency compared to the evolution of publications exposed above, where PEMFC and SOFC technologies dominate the scenario. However, in terms of patents, the PEMFC technology is largely ahead of the SOFC technology as the former is more adapted to portable applications. As we have observed above, portable applications are leading the market in terms of yearly shipments, and also in number of patents approved in 2001–2011 (stationary 169, portable 1611 and transport 414).

Finally, patents in the fuel cell technology area are also classified in relation to other aspects as components (collectors, separators, interconnectors, etc.), specific materials (electrodes, membranes, sealing or supporting material, etc.), management and control, production of reactants, treatment of residues, manufacturing processes, grouping into batteries or other fuel cell technologies (biochemical, regenerative, etc.). However, we have considered that the most effective classification to understand technology tendencies is based on the classification used in this chapter.

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Chapter 15
Electricity Storage

Abstract Electricity storage technologies emerge as a response to synchronise electricity supply and demand, thus enabling the electrical grid to be managed in a consistent manner. Electricity storage is especially needed in distribution for load-levelling and for integrating the frequently intermittent renewable resources. In the case of considerable hourly variations of the demand, the levelling of the load would substantially reduce the projected total generating capacity making it more efficient and less costly. In this chapter, we review the main electrical storage technologies. The most common storage devices are batteries, which are highly efficient. Batteries have evolved during the last decades from the lead–acid ones to the lithium ion, which are at present receiving the most attention. If high power, instead of energy management is needed, then the use of ultracapacitors is more appropriate. Evidently, if very large amounts of energy and power are needed, pumped hydro systems constitute the best choice. Other energy storage technologies reviewed in this chapter are compressed air energy storage (CAES), flywheel devices and superconducting systems.

15.1 Overview

Electricity storage technology emerges as a response to synchronise supply and demand for a commodity (electricity) that, without such storage it would have to be produced and consumed instantaneously. For non-manageable renewable resources (mainly wind and solar energy), this instantaneous exigency cannot be fulfilled. The technologies involved in electricity storage are diverse, both in terms of storage procedure and system (chemical energy, gravitational, electrical, thermal, etc.) and in terms of storage system characteristics (amount of power, energy, weight, size, efficiency, charging rate, discharging half-life, etc.).

Storage systems can, in general, be classified as large or small, and stationary or portable systems. In this chapter, mainly the stationary systems will be considered, since they are the best adapted to the renewable energy technologies discussed in this book.

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Table 15.1 Application category specifications [1]

Application category	Discharge power range	Discharge time range	Stored energy range	Representative applications
Bulk energy storage	10–1,000 MW	1–8 h	10–8,000 MWh	Load levelling spinning reserve
Distributed generation	100–2,000 kW	30 s–4 h	0.05–8 MWh	Peak shaving, transmission deferral
Power quality	0.1–2 MW	0–30 s	0.028–16.67 kWh	End-use power quality and reliability

Electricity storage systems can also be classified in relation to the application considered (Table 15.1):

1. Bulk energy storage: Used to decouple generation and power consumption. A typical application is the levelling of the demand, which involves charging the storage system when the cost of energy is low so that it can be discharged when the cost is high.
2. Distributed generation systems: They operate at intervals of seconds to minutes to ensure continuity of service when the source of energy generation is replaced.
3. Systems to improve power quality: Only operate in second and sub-second intervals to ensure the stability of the power supplied.

While some systems can operate in all functional categories, costs impose some restrictions to this versatility. Consequently, different storage systems provide different applications within the electrical systems in terms of power required and the time interval in which the storage unit can answer. Thus, systems with little storage capacity and power are used to improve power quality in the network, while higher powers are used to ensure the stability of the electrical transport system. With increased storage capacity and readiness in response are storage systems that allow larger penetration of non-manageable renewable energy sources in the grid and also the storage systems that help to control the grid frequency and voltage.

In stationary systems devoted to electricity storage, water pumping systems account for nearly 100 % of the total, because the technology is mature and there is a large amount of hydropower in the Earth. The first pumped hydropower system was built in 1892 and the world's largest plant is the 2,710-MW pumped hydropower plant at Bath County, Virginia, USA [2]. The trend in hydropower is upward in pumping capacity (see Fig. 9.3) although the difficulties in finding new locations in developed countries predicts that further projects will be located mainly in developing countries.

15.2 Current Technology

The main technologies involved in electrical energy storage are batteries (with different configurations and materials), compressed air, flywheels, superconductors, supercapacitors and pumping hydropower systems.

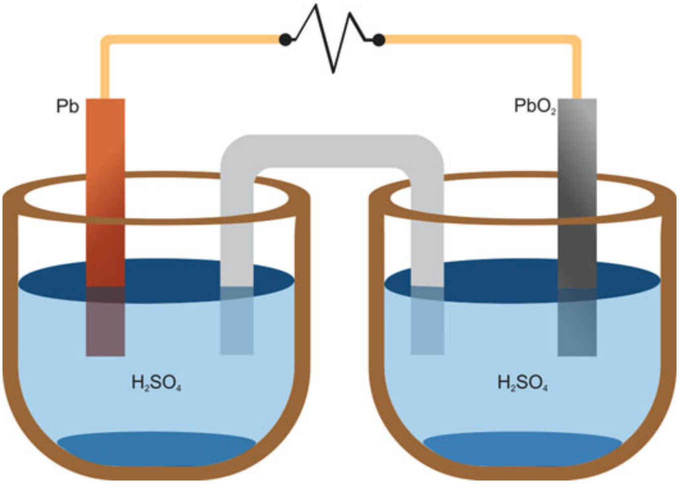

Fig. 15.1 Diagram of a lead–acid battery

15.2.1 Batteries Technology (Lead–Acid, Metal–Air, Sodium–Sulphur, Redox Flow, Li-Ion, ZnBr and NiMH)

The lead–acid batteries (Fig. 15.1) use one of the oldest technologies for batteries, have a low cost and are very popular for applications in improving power quality and in UPS. However, for energy management this technology is not widely used because its durability is low and the energy that can store is not fixed but depends on the discharge rate.

The metal–air batteries are more compact and, potentially, less expensive and environmentally friendly. Their energy density is high. However, recharging these batteries is very inefficient (50 %) and they have low durability (no more than a few hundred discharges). They are more appropriate to cover energy demands than power demands. The anodes of these batteries are ordinary metals (Al or Zn), which generate electrons when being oxidised. The cathodes are often composed of porous carbon or a metal mesh covered with a suitable catalyst. Electrolytes are usually in liquid form or as a polymer membrane saturated with KOH. Although there are metals that potentially offer larger energy densities, the Zn–air batteries are the most used [3].

The sodium–sulphur batteries consist of liquid sulphide at the positive electrode and molten sodium at the negative electrode, separated by an alumina ceramic electrolyte (Fig. 15.2). They are the most used high temperature batteries [3]. Energy density and efficiency are high but are expensive and introduce security problems. These batteries are applied to meet energy and power demands. The electrolyte allows passing only the positive sodium ions to combine with sulphur, creating a potential drop of about 2 V in the external circuit. These batteries prove to be efficient (89 %) and can be recharged, returning the sodium to its configuration as an element.

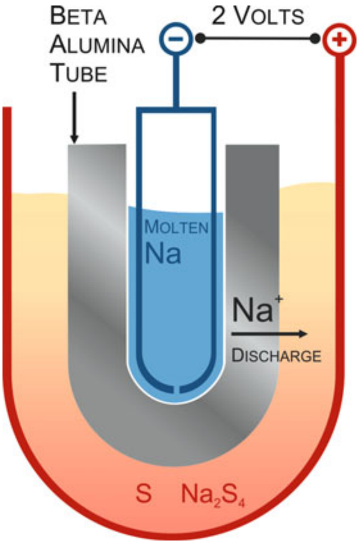

Fig. 15.2 Diagram of the sodium–sulphur battery

In addition, sodium–sulphur batteries exist in the market offering units with a power of several MW, reaching 34 MW and 245 MWh in the largest facility, applied to stabilise the energy from the wind and located in the north of Japan.

The redox–vanadium batteries are the most advanced of the so-called flow batteries (zinc bromide, bromide polysulfide and zinc–cerium) [3], and store energy using vanadium–redox pairs (V^{2+}/V^{3+} in the negative tank and V^{4+}/V^{5+} in the positive tank) in a sulphuric acid electrolyte (Fig. 15.3). These batteries are more appropriate to cover energy than power demands. During the charging and discharging processes, H^+ ions are exchanged between the two electrolyte tanks through a polymer membrane permeable to these ions. The net efficiency of these batteries reaches 85 %, but its energy density is low. The biggest advantage is that these batteries are capable of guaranteeing an almost infinite number of charges and discharges practically without losses.

The Li-ion batteries consist of a metal oxide cathode and a lithium-graphite anode. They require special circuitry for charging. These batteries can meet power and energy demands. The electrolyte consists of a lithium salt (as $LiPF_6$) dissolved in organic carbonates (Fig. 15.4). When the battery is charging, the lithium atoms in the cathode become ions and migrate into the graphite anode, where they recombine with external electrons and are deposited between the carbon layers. The reverse process occurs during the discharge. The main advantages of these batteries compared to others are (1) high energy density (300–400 kWh/m^3, 130 kWh/t), (2) high efficiency (nearly 100 %) and (3) large number of cycles within their lifetime (3,000 cycles—80 % level of discharge).

The Li-ion batteries do not experience memory effects, which is an undesirable phenomenon in which a battery's apparent discharge capacity is reduced when it is incompletely discharged and then recharged. Li-ion batteries also have a low self-

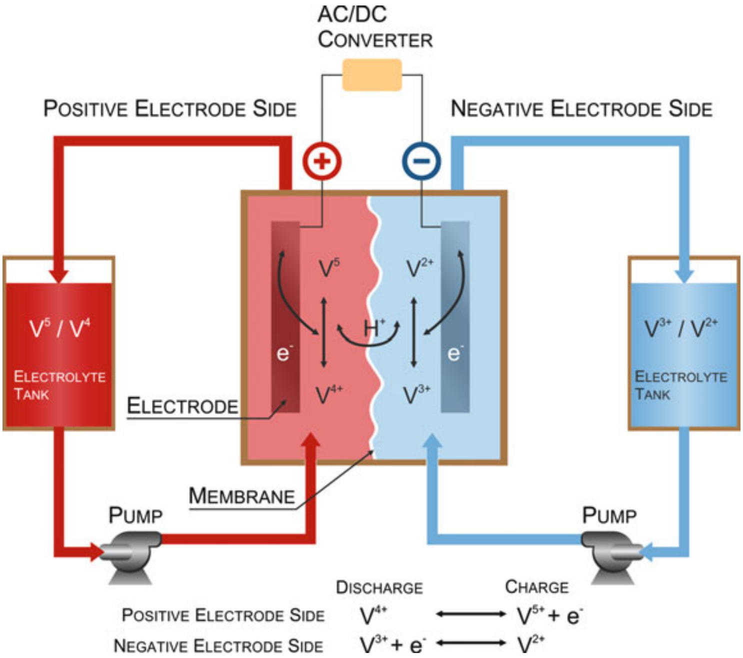

Fig. 15.3 Scheme of vanadium–redox flow battery

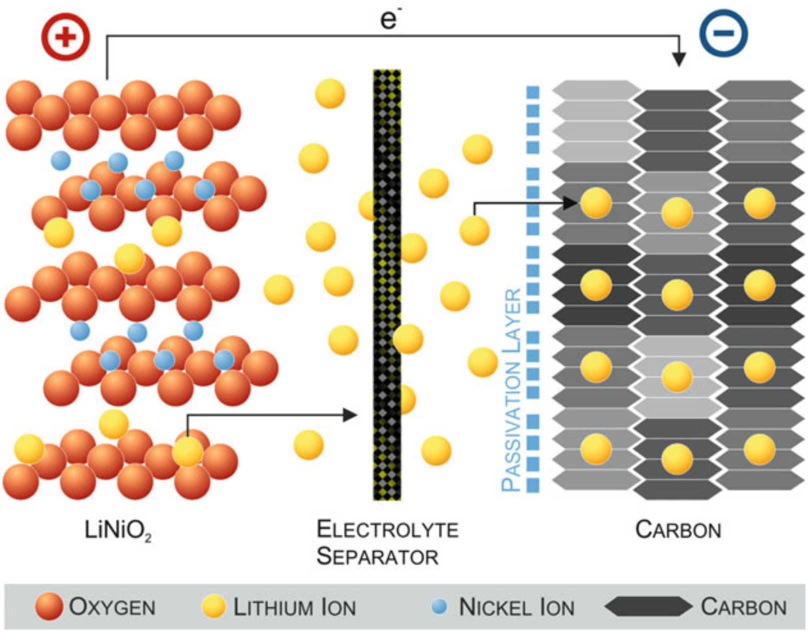

Fig. 15.4 Scheme of the lithium-ion battery

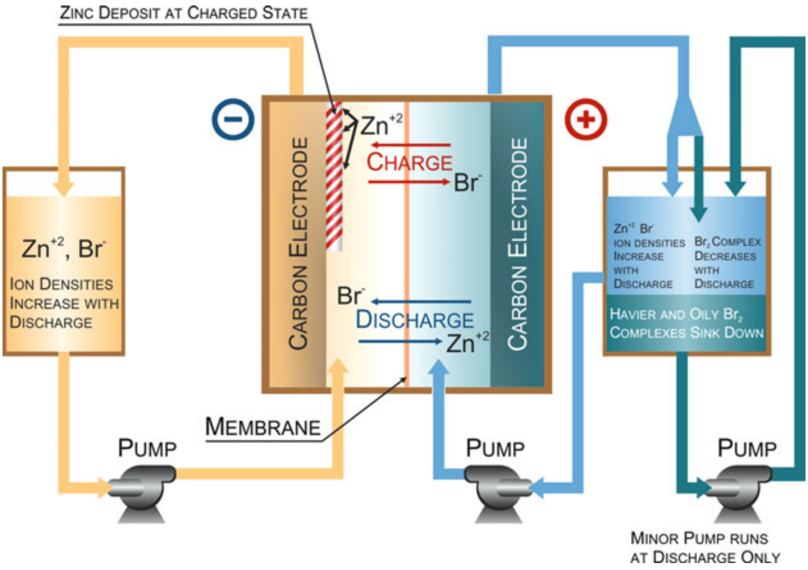

Fig. 15.5 Scheme of a ZnBr battery

discharge rate of approximately 5 % per month, compared with over 30 % per month for common nickel–metal hydride batteries and 10% per month for nickel–cadmium batteries [2].

In ZnBr batteries, two different types of electrolyte circulate in each carbon electrode, separated by a microporous polymeric membrane (Fig. 15.5). During discharge, Zn and Br provide zinc bromide and supply a voltage of 1.8 V, which increases the concentration of Zn^{2+} and Br^{-} in each tank. In the charging process, the Zn metal is deposited on a carbon electrode and the bromide is dissolved on the other side of the membrane to react with other agents (amines) to generate a dense bromine-adduct oil that sinks to the tank bottom. The net efficiency is 75 %. This technology was developed in the 1970s and is applied to installations in the range 1 MW/3 MWh and 5 kW/20 kWh.

In nickel–metal hydride batteries (called NiMH) a hydrogen compound is used as the negative electrode (replacing Cd) and nickel oxyhydroxide (NiOOH) as positive electrode, thus improving their capacity compared to the NiCd batteries. On the other hand, although the energy density per unit volume is similar to Li-ion batteries, self-discharge is higher. In the discharging process, the metal hydride ion reacts with OH^{-} generating one electron, the metal oxyhydroxide and water.

15.2.2 Compressed Air Storage

This technology is commonly called CAES (compressed air energy storage) and includes both the storage system as the gas turbine that generates electricity from the expansion of the compressed air (Fig. 15.6). It is expected to cover energy more

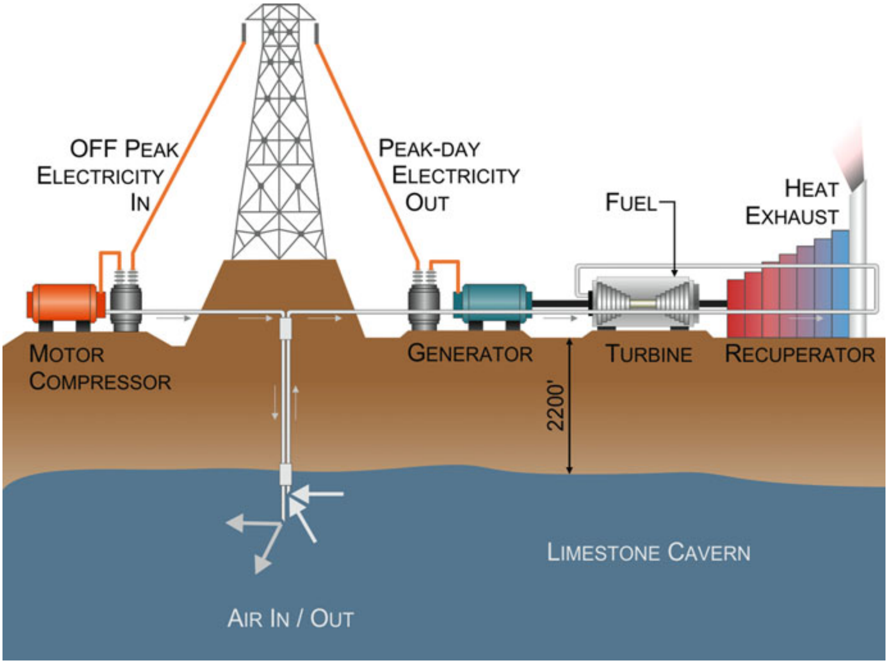

Fig. 15.6 Scheme of a storage system powered by compressed air and natural gas

than power demands. The concept is based on the ability to store compressed air (45–70 bars [2]) from excess power from the grid when the price is low and to produce electricity when prices are high.

CAES technology is expected to consume 40% less energy than conventional natural gas turbines, since in these two-thirds of natural gas is consumed to compress air for the combustion process, which is already obtained with CAES [2]. The first commercial CAES system was a 300,000 m^3 natural gas cavern and 290 MW unit built in Huntorf, Germany in 1978, reaching 42 % efficiency [4]. Only another plant exists in McIntosh, Alabama (USA).

15.2.3 Flywheels

This type of device is a rotating (30,000–40,000 rpm) high mass cylinder, suspended by magnetic levitation within a stator (Fig. 15.7). The flywheel operates in vacuum to improve efficiency and is connected to a generator to produce electricity. It is applied to cover more power than energy demands.

The main advantages of the flywheel are the few maintenance requirements, long life and inert behaviour to environmental conditions.

While high power flywheels are highly developed and applied in aerospace and UPS systems, research is carried out for applications requiring operation over

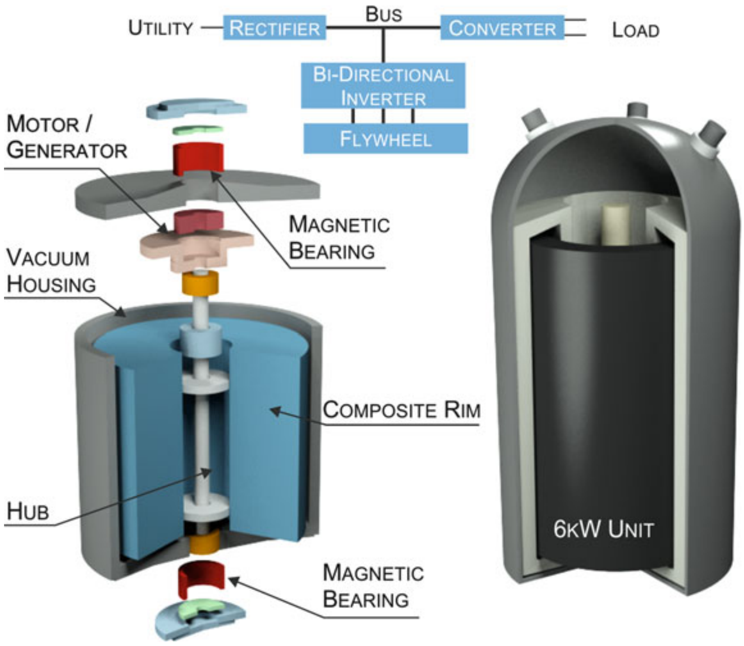

Fig. 15.7 Scheme of a flywheel

extended periods of time. In these devices, the losses in stand-by are less than 1 %, and the transition from 0 to 100 % power output is achieved in less than 5 ms.

The world's largest flywheel (in operation since 1985) consists of six disks having each a diameter of 6.6 m and a thickness of 0.4 m. One disk weights over 107 t, and during charging (6 min), the rotating speed is increased from 70 % of its limit to 100 % with a thyristor system of 19 MW. The energy discharge time is approximately 30 s, supplying up to 160 MW of power [2].

15.2.4 Storage in Superconductors

These devices are also known as superconducting magnetic energy storage systems (SMES). In these systems, the energy is stored in the magnetic field created by a flow of electric current in a superconducting coil. The coil wires must be cryogenically cooled below the critical temperature to reach the superconducting properties. Once the superconducting coil is charged, the current does not decay, so that the energy will be stored until the coil is again connected to the grid to be discharged. Only significant losses are produced in the rectifier/inverter process to pass electric current from AC to DC and vice versa. It is preferably applied to cover more power than energy demands.

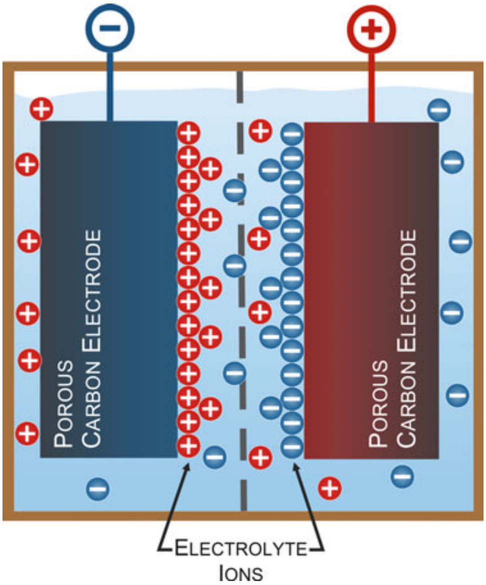

Fig. 15.8 Functional diagram of a supercapacitor

The main advantages of these systems are (1) the short time between the charging and discharging (almost instantaneous), (2) the very low energy loss in the charging and discharging process and (3) the absence of moving parts in the system main components. The largest drawback is price.

The SMES are already being implemented, primarily to provide ultra-clean electric power in industries that require it (microchips plants) or to stabilise the grid.

15.2.5 *Electrochemical Capacitors*

The electrochemical capacitors store electricity between two capacitors connected in series, each composed by an electrical double layer ion electrolyte (Fig. 15.8). They are applied to cover more power than energy demands. The distance between the capacitor plates is only of a few angstroms, and the energy density of these devices is thousands of times larger than those of conventional capacitors.

The electrodes are composed of porous carbon and the electrolyte can be organic or aqueous (the former is more expensive but more appropriate for larger energy densities). On the other hand, although the small electrochemical capacitors (conventional) are already well developed, large (supercapacitors) with energy densities above 20 kWh/m^3 are still under development.

15.2.6 Pumped Hydropower Systems

These plants are the most used type of energy storage facilities in electric power systems. The 100–400 MW and 1–2 GW class systems are the typical pumped storage power plants. They are applied to cover more energy than power demands. They are composed by two water reservoirs, vertically separated, to pump water from the lower to the upper reservoir, usually at low electricity prices, and in the opposite direction (moving a turbine) to the lower reservoir when electricity is required, usually at higher electricity prices. The efficiency of these devices is in the range 70–85 % and discharge times can range up to several days. Generally, each pumped hydropower plant consists of two to eight pump turbine units.

Underground storage can also be used in wells and other cavities, with the advantage of reducing controversies about direct impacts to human populations. Also, pumping sea water can be advantageous, avoiding the need of a lower reservoir (Yanbaru, 30 MW). Pumping sea water also can attain up to 80 % efficiency because of the short waterway length, which reduces the hydraulic losses by 93–98 % [2].

15.2.7 Stages of Development

Briefly, the above technologies can be classified according to the energy and power densities that can provide per unit mass and volume (Fig. 15.9) [5]. According to this, the lithium-ion battery offers the best performance. Consequently, these batteries are the ones preferred for energy storage in electric vehicles and ultralight aircraft.

In Table 15.2, we summarise the power characteristics, discharge time, efficiency and average lifetime of the energy storage systems described above.

As for the market penetration, we can consider the lead–acid technology the most mature for batteries (Fig. 15.10), followed by the lithium-ion technology. In the latter case, efforts to reduce costs are so important that it continues to generate much R&D activity, so that the degree of development covers all stages. In a lower stage of development, we can place the other technologies discussed above, but special mention requires NiMH batteries, which can be considered displaced from the market by the Li ion. It should also be noted that redox flow batteries are behind in the development stage, influenced by their costs (see Sect. 15.3).

Figure 15.11 shows the development stages for the energy storage technologies exposed in this chapter. It can be observed the pumping hydropower as the more mature technology. However, new demonstration systems that combine pumping hydropower and unmanageable generation from renewable sources [6] imply a second development range, which is more delayed. Batteries and flywheels are also very mature technologies. For the remaining technologies, there are already some facilities that use compressed air storage, although none of them is fed with

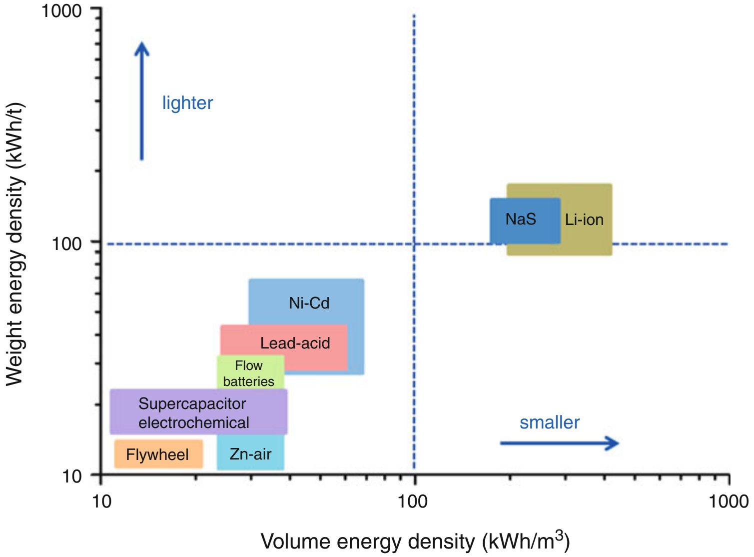

Fig. 15.9 Energy density per unit mass and volume for different energy storage technologies

Table 15.2 Power, discharge times, energy conversion efficiency and lifetime for different energy storage technologies [5]

	Power	Discharge	Efficiency (%)	Lifetime
Li-ion	5 MW	15 min–some hours	90 (DC)	15 years
Lead–acid	3–20 MW	10 s–some hours	75–80 (DC) 70–75 (AC)	4–8 years
NaS	35 MW	8 h	80–85 (DC)	15 years
Vanadium–redox	4 MW	4–8 h	75–80 (DC) 63–68 (AC)	10 years
Zn–air	20 kW–10 MW	3–4 h	40–60	Some hundred cycles
CAES (100–300 MW underground)	15–400 MW	2–24 h	76	35 years
Pump hydro	250 MW >1 GW	12 h	87	30 years
SMES	1–3 MW	1–3 s	90	>30,000 cycles
Flywheels	750–1,650 kW	15 s–15 min	93	20 years
Supercapacitors	10 MW	<30 s	90	>500,000 cycles

renewable energy. In a less stage of development are capacitors and SMES, for which some demonstration plants are already in operation, but they are still far from being introduced in the market.

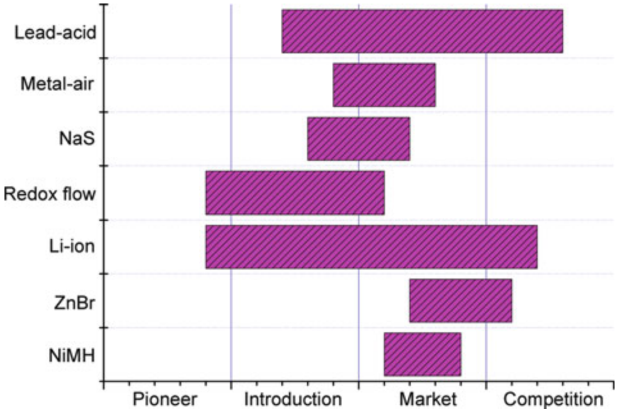

Fig. 15.10 Stages of development for each of the technologies considered for batteries in this chapter

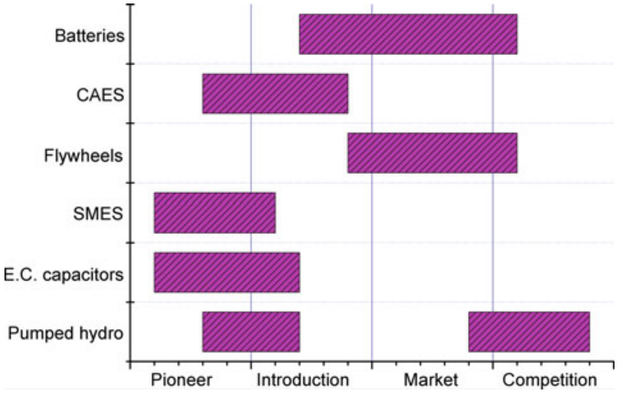

Fig. 15.11 Stages of development for each of the technologies considered in energy storage for electricity supply

15.3 Current Costs and Future Scenarios

Figure 15.12 [5] shows the storage costs depending on power and energy investment, but excluding the cost for power conversion electronics [5]. Updated storage costs with a depurated methodology are exposed in Table 15.3 [7]. These values are meant to be used for comparative purposes. The actual costs of any storage system depend on many factors and the assumptions and the means of calculating their values are still subject to continuous debate, even among experts in the field [7].

It might be concluded that the metal–air batteries are the best option to store energy, but prototypes for this type of rechargeable battery have limited lifetime and are still under development, as discussed below. On the other hand, an increase of 15 % in costs is estimated for corrosion prevention measures [2] in seawater pumped hydropower plants.

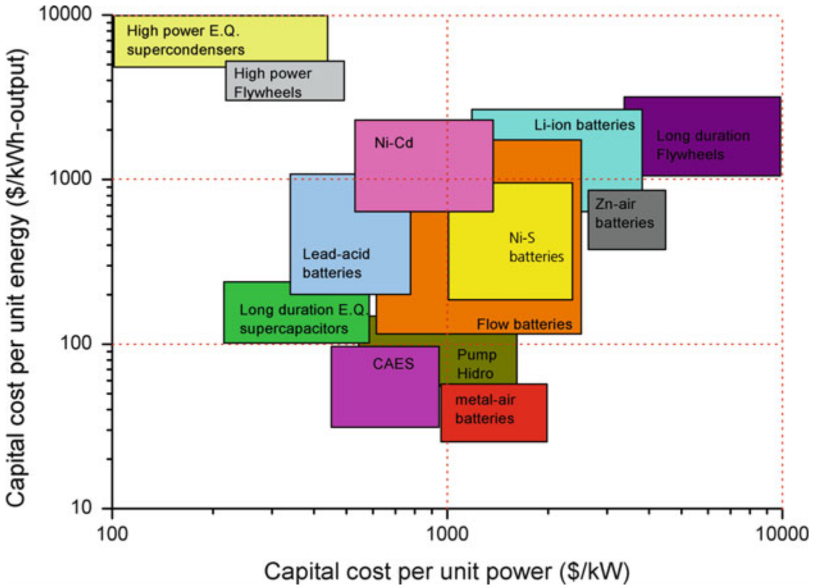

Fig. 15.12 Scheme of costs per unit of energy and power for different storage technologies [5]

Table 15.3 Costs and performance assumptions for different energy storage systems

	Power subsystem cost USD/kW (EUR/kW)	Energy storage subsystem cost USD/kWh (EUR/kWh)	Round-trip efficiency %	Cycles
Advanced lead–acid batteries (2,000 cycle life)	400(287)	330(237)	80	2,000
Sodium/sulphur Batteries	350(251)	350(237)	75	3,000
Lead–acid batteries with carbon-enhanced electrodes	400(287)	330(237)	75	20,000
Zinc/bromine batteries	400(287)	400(287)	70	3,000
Vanadium–redox batteries	400(287)	600(431)	65	5,000
Lithium-ion batteries (large)	400(287)	600(431)	85	4,000
CAES	700(503)	5(4)	N/A (70)	25,000
Pumped hydro	1,200(862)	75(54)	85	25,000
Flywheels (high speed composite)	600(431)	1,600(1,149)	95	25,000
Supercapacitors	500(359)	10,000(7,183)	95	25,000

A more appropriate cost analysis in storage systems, with frequent charging and discharging processes involved, is considering the cost per cycle. Table 15.4 [5] shows the investment cost per cycle ([capital/energy]/[cycles × efficiency]). Operating and maintenance cost, disassembly, replacement, etc. should also be added if more comprehensive studies are needed. However, this cost analysis would not be appropriate to compare storage systems used for softening power peak demands.

Table 15.4 Recharging costs for different electricity storage technologies

	Recharging costs USD cents/kWh (EUR cents/kWh)		Recharging costs USD cents/kWh (EUR cents/kWh)
Zinc–air	70–100 (50–72)	Vanadium–redox	5–80 (3.5–57)
Lead–acid	20–100 (14–72)	Long duration flywheels	3–25 (2.1–18)
Ni–Cd	18–100 (13–72)	Electrochemical supercapacitors	2–28 (1.4–20)
Li-ion	15–100 (11–72)	CAES + gas	2–5 (1.4–3.5)
NaS	9–30 (6–22)	Pump hydro	0.10–1.80 (0.07–1.29)

There are rigorous studies [1] on the annual cost of energy storage depending on the type of demand to be met. Thus, three different scenarios have been considered: (1) storage to provide base power to the grid, with an estimated maximum supply time interval of 8 h (Fig. 15.13), (2) distributed storage systems, with an estimated maximum supply of 4 h (Fig. 15.14) and (3) systems to improve the quality of power served by the grid, with an estimated maximum supply of 20 s (Fig. 15.15). The costs have been disaggregated considering financing invested capital and the purchase of fuel and electricity, as well as the replacement, operation and maintenance costs.

Thus, it is observed (Fig. 15.13) that when the storage is aimed to provide base power to the grid and there is no possibility of compressed air storage, the best option is the variable speed pump hydropower. All battery technologies are substantially more expensive. If distributed storage technology is required (in which pump hydropower systems are not available), the compressed air storage technology is the most cost effective (Fig. 15.14), and some battery technologies are also attractive.

Finally, when storage systems are only used to improve power quality, with very short power supplies to the grid, batteries are the most cost attractive (Fig. 15.15).

In relation to operation and maintenance costs, each storage technology has very characteristic values, and these costs must be considered when choosing the most appropriate technology. Thus, the flywheels have very low failure probabilities, so the operation and maintenance costs can be considered near zero, except for the bearing replacement usually every 5 years and the vacuum pump every 7 years. On the other hand, in superconducting systems, the operation and maintenance costs are considered to be about 20 % of the total annual expenses of the plant.

15.4 Payback Energy, CO_2 Emissions and External Costs

To date, there has been no rigorous study that addresses these issues for storage technologies.

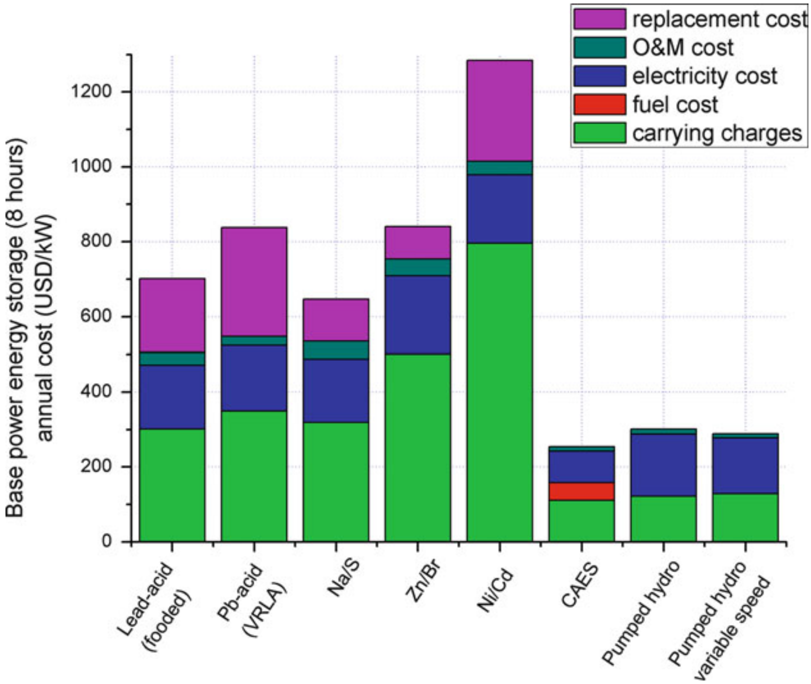

Fig. 15.13 Annual costs for various energy storage technologies to supply base power

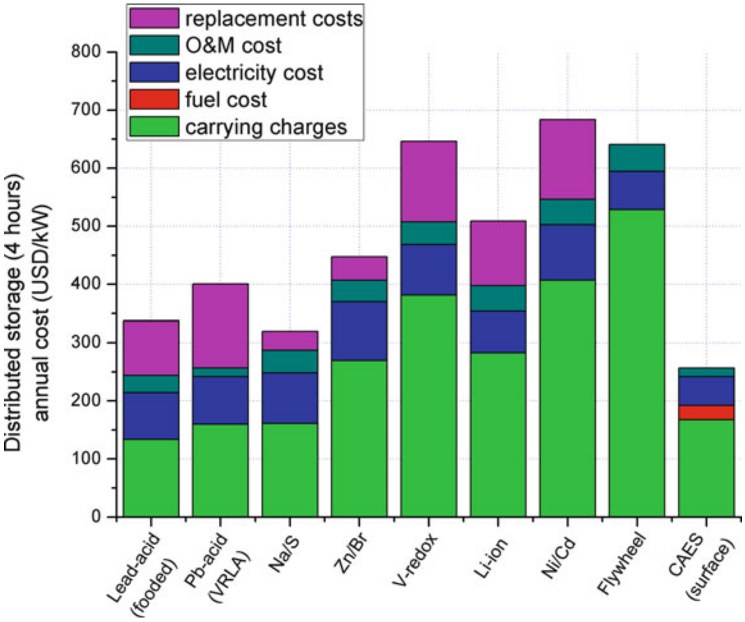

Fig. 15.14 Annual costs for various distributed energy storage technologies

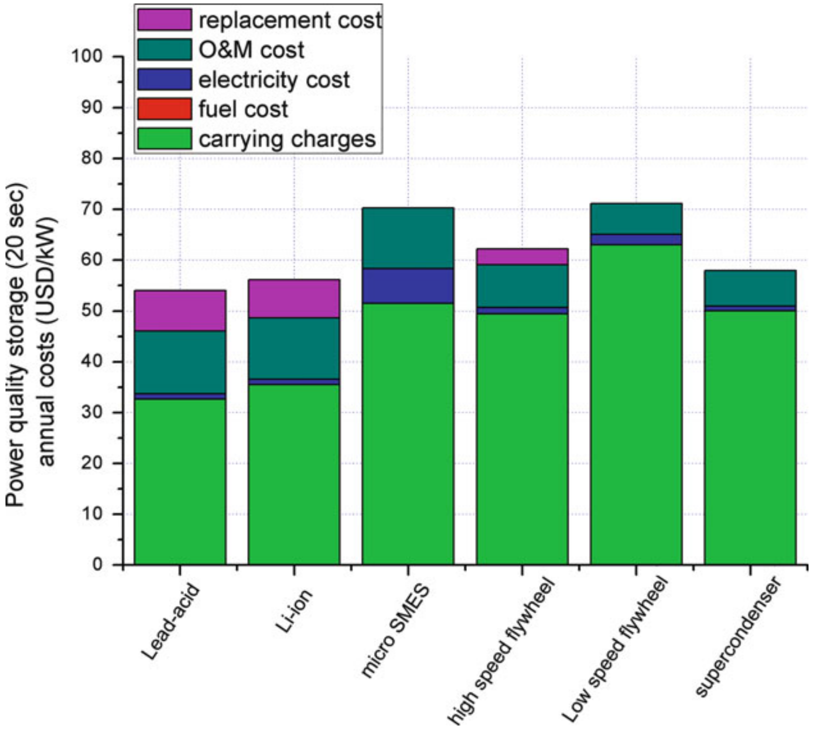

Fig. 15.15 Annual costs for various energy storage technologies to improve power quality

15.5 Future Technology Trends

In storage technology, the general trends are focused in reducing costs, and in improving energy densities per unit volume and mass, increasing the number of charging and discharging cycles, raising efficiencies and increasing the charging and discharging speed. More specifically, based on each technology, technology trends are described below.

15.5.1 Batteries

Future technology trends in batteries are mainly specific for each battery technology being considered. Thus, in metal–air batteries, the main objective is to improve the number of discharges to increase competitiveness. In lithium-ion batteries, the main trend is to incorporate nanomaterials and nanocomposites to improve the energy density. Also, the lithium-ion batteries need to ensure that there are no security problems when the lithium salt is introduced into organic solutions, as it becomes flammable, so appropriate electronics is needed to avoid high-speed charging and discharging rates. In redox flow batteries, specific requirements are focused on mitigating the noise of the pumps and reduce operation and maintenance needs that involve pumping circuits.

15.5.2 Compressed Air Storage

In compressed air energy storage, the priority is to conduct new demonstration projects that remove natural gas used in existing facilities, and to avoid CO_2 emissions, using renewable energies for the compression process. Mostly the CAES-wind combination is gaining ground for this purpose.

On the other hand, it is still under discussion the best features to deploy such systems, as well as to produce adiabatic compression processes for air to avoid losing heat generated in the process. The McIntosh plant in USA adopted this cycle, which increases efficiency to about 54 % [2]. Consequently, CAES will capture and store heat from the compression process, using it to reheat the air decompressed to improve the process efficiency.

Similar approaches with other gas turbine cycles, such as the Cheng and HAT (humid air turbine) cycles, will be applicable. The Cheng cycle consists of a gas turbine capable of being injected with a large amount of superheated steam (15–20 % of the exhaust flow) and a heat recovery steam generator (HRSG) that can generate both saturated and superheated steam with firing capability [2].

Other concepts being explored are (1) adsorption-enhanced CAES, where compressed air comes into contact with a chemical adsorbent (e.g., zeolites) that adsorbs the gas molecules into a solid layer on the surface at certain pressures only to release it again when the pressure is reduced. This greatly reduces the storage space sizes involved in traditional CAES; (2) liquid air energy storage, which provides at least ten times greater storage density than air stored as a gas and (3) transportable CAES, or T-CAES, that uses power from any source (wind, solar, electric grid, nuclear, geothermal, etc.) to drive a compressor that pressurises air to 1,200 psig in a long pipeline for later use [8].

15.5.3 Flywheels

The main effort in flywheels is to extend their operating times to a minimum of several hours without impact on costs. Also, efforts are being made on reducing noise pollution in low frequency devices.

15.5.4 Storage in Superconductors

In superconductors, there are several technology trends. More robust mechanical structures are needed to contain the effects of Lorentz forces generated in the superconductors. On the other hand, the energy storage capacity of these systems must be increased, although the space requirements are a major handicap. Thus, to achieve levels of 1 GWh storage requires a 160-km superconducting cable length. In this sense, critical current density and magnetic field values above which the superconducting properties are lost should be increased.

Furthermore, since the superconducting material is usually a ceramic, improved technology to achieve more robust materials is needed for larger applications. Systems working at higher temperatures are needed in order to reduce cooling costs without losing the superconducting properties. However, cooling costs are not so high compared to other costs (especially in large systems). Working at higher temperatures also would reduce the security risks for operators working at low temperatures.

Finally, since there is concern about electromagnetic radiation generated by the superconductor currents, further studies are needed on the health effects produced by these devices.

15.5.5 Electrochemical Capacitors

Since the main handicap electrochemical capacitors show is their poor energy storage capacity, the research trends focus on finding materials to improve this parameter. The key research efforts are on nanomaterials, because they offer higher specific surface areas than those used conventionally in capacitors [9]. Graphene is also being considered to solve this need.

15.5.6 Pumped Hydropower Systems

Similarly to the arguments exposed in the chapter dedicated to hydropower, the main effort for pumping stations are on reducing the environmental impact of dam construction and reservoirs. In this sense, there are projects for the construction of “energy islands” in the North Sea, acting as lakes in shallower areas (off-shore hydropower), which could pump water using surplus wind energy [10]. The energy island consists of a ring dike encompassing an area of approximately 10 km by 6 km. The internal lake portion of the energy island can have a depth between 32 and 40 m below the surrounding sea [8]. These plants could avoid the environmental impact that involves the construction of more hydropower plants on-shore.

There is also activity on improving hydropower plants using reversible variable speed pumps, which has already demonstrated an ability to increase the performance of these plants by a 3 % (the first adjustable-speed pumped hydro unit was installed in Japan in the 1990s [2]). Adjustable-speed pump turbines that are driven by an adjustable speed motor can be fed by variable input and, thus, enables tuning the grid frequency as well as the use of fluctuating renewable wind or solar energies to pump water to the upper reservoir. Another technological trend is to improve the response times for energy demands from the grid, to allow further penetration of renewable energy in the electrical system.

With respect to underground reservoirs, important projects are being considered. A feasibility study is currently being conducted by Riverbank Minnesota, LLC for a 1,000-MW underground storage facility in Granite Falls, Minnesota. Installation of this facility is expected to be finalised in 8–12 years [8].

Finally, in the reversible pump of a conventional pumped hydro plant, the capacity of the pump is smaller than the capacity of the water turbine [2]. Therefore, the water pumping process requires more time than the generation process. Consequently, speeding up the pumping process during periods of reduced-rate power availability is predicable.

15.6 Pre-Production Highlights 2009–2011

15.6.1 Three New World Records for the PV and Li-Ion Batteries Powered Aircraft [11]

On 7 July 2010, the prototype HB-SIA broke three world records (absolute height: 9,235 m; height gain: 8,744 m and duration: 26 h, 10 min, 19 s), which is contributing to achieve in 2012 the first flight around the Earth from an airplane powered only by photovoltaic cells. The plane, made mainly of carbon fibre, has a wingspan of 63.40 m between wings, a length of 21.85 m, a height of 6.40 m, weighing 1,600 kg (including 400 kg of lithium-polymer batteries with a power density of 200 W/kg), 4 electric motors of 10 hp per motor, 10,748 cells on the wings and 880 in the horizontal stabiliser (c-Si of 150 μm thick and 12 % eff.). The average speed of the plane is 70 km/h.

15.6.2 Batteries Also for Building Cars [12]

The STORAGE program within the European Union is trying to incorporate different battery materials to the car's body, so as to fulfil the dual function of storing energy and providing protection to users. Specifically carbon fibres made rigid by introducing them in a resin are being tested. This resin is mixed with lithium atoms, so the material acts more like a capacitor than a battery. The resin gel combines two types of crossing structures, one providing rigidity and the other to allow lithium ion conduction. Currently, only an energy density of 0.005 Wh/kg has been achieved, which is far from the 150 Wh/kg of lithium batteries, but it could be greatly improved with the introduction of carbon nanotubes.

15.6.3 Production of Planar Li-Ion Batteries with Durable Nanostructured Films [13]

This new technology is developed by Planar Energy, a company spun out of America's National Renewable Energy Laboratory in 2007. Thin-film printing methods are already used to make solar cells and display screens, but no industrial scale batteries. The bulk of the battery is a ceramic gel electrolyte. The cathode is composed by lithium manganese dioxide, and the anode combines doped tin oxides and lithium alloys. The company considers that these batteries will be more reliable than conventional lithium-ion cells, will be able to store up to three times more energy per unit weight and will last tens of thousands of recharging cycles. Planar Energy hopes to begin operations in late 2012 and applying them in portable devices.

15.6.4 Off-Shore Energy Bags [14]

The company Thin Red Line Aerospace has developed an energy bag, which will be anchored to the seabed off the coast of Scotland, as part of a renewable energy research project led by Professor Seamus Garvey of the University of Nottingham, UK. The project is being supported by E.ON. Offshore renewable energy devices such as wind turbines will fill the underwater bags with compressed air that can later contribute to supply electricity on demand. The technology is particularly suited to countries with relatively deep water near the coast, as it can be anchored at a depth of around 600 m where the pressure of the ocean takes on the role of high-performance pressure vessel. The pressure at this depth ensures high energy storage density, constant pressure and compatibility with existing high efficiency turbine technology.

15.7 Innovation Highlights 2009–2011

15.7.1 Record with Supercapacitor Energy Storage [9]

Scientists at the University of Maryland have achieved an important step in producing supercapacitors not only as devices that provide power but also energy, through the manufacture of glass and aluminium nanocondensers. These supercondensers multiply by 250 the energy storage ability compared to conventional capacitors. Consequently, they have managed to manufacture one million nanocondensadores in matrices of 125 µm width and reaching 100 µF capacitance per square centimetre.

15.7.2 New Material for Ultrafast Discharge Batteries [15]

Scientists of the Massachusetts Institute of Technology have been using $LiFePO_4$ batteries to obtain discharge speeds similar to those achieved in supercapacitors. This material shows a large mobility for lithium ions through the construction of an ion-conducting surface phase of appropriate stoichiometry. A discharge capacity equivalent to that produced in a fully charged battery in 10–20 s is achieved. Also, the batteries based on this material could be recharged very quickly, although technical requirements would largely increase costs. Another drawback is that this material results in an energy density lower than the materials used in lithium-ion batteries.

15.7.3 Concrete Storage Spheres on the Seafloor [16]

Scientists of the Massachusetts Institute of Technology have considered the possibility of constructing concrete spheres (Fig. 15.16) on the seabed close to off-shore wind farms to store excess electricity produced by these facilities and to regenerate it when it is demanded. The spheres would be approximately 31 m in diameter and be placed about 350 m deep. The surplus electricity from offshore wind farms would be used to pump out the sea water, storing air in them. When power is required, sea water would penetrate moving a turbine and generating electricity. These spheres would be able to deliver 5 MW for 4 h and could have a durability of 40 years.

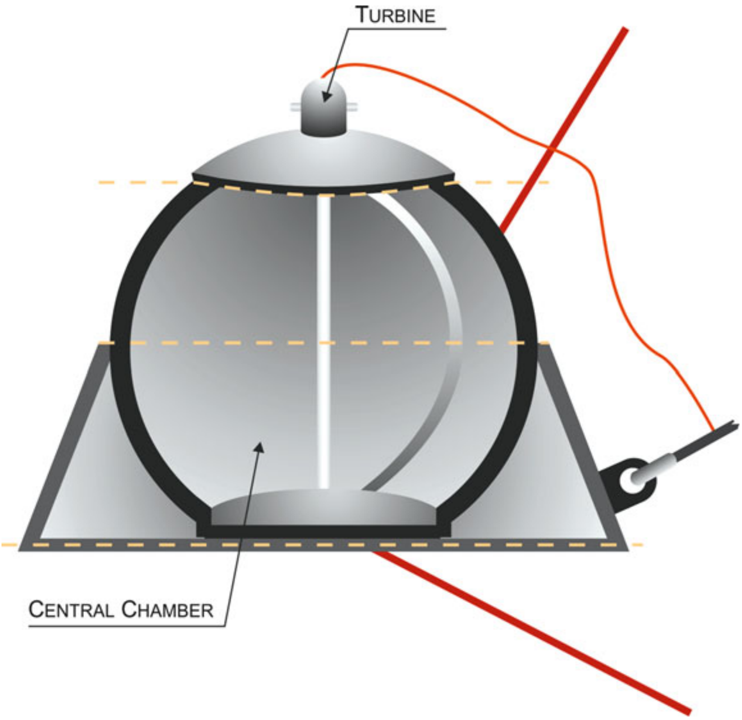

Fig. 15.16 Scheme of a sphere placed on the seabed for compressed air energy storage

15.7.4 Hopes from Aluminium to Replace Lithium as Core Raw Material in Batteries [17, 18]

As lithium supplies are limited and its price is rising dramatically in recent years, the scientific community is trying to replace it with more affordable materials, and aluminium is heading these efforts. But aluminium ions are larger than lithium ones, tend to clump together and move more slowly, so high temperature is necessary. However, a research group from Cornell University has changed the electrolyte to an ionic liquid that speeds up the ions movement, making the battery rechargeable at room temperature and with a capacity on par with lithium-ion cells. However, the ionic liquid electrolyte is too expensive for commercial use, and the anode must be improved to avoid damaging key parts of the battery.

15.7.5 Ultra-Thin Flexible Battery With the Highest Charge Capacity Reported for Thin Film Batteries [19, 20]

A research team from the company FlexEl and the University of Maryland have published this achievement. This cell demonstrates a specific charge capacity of

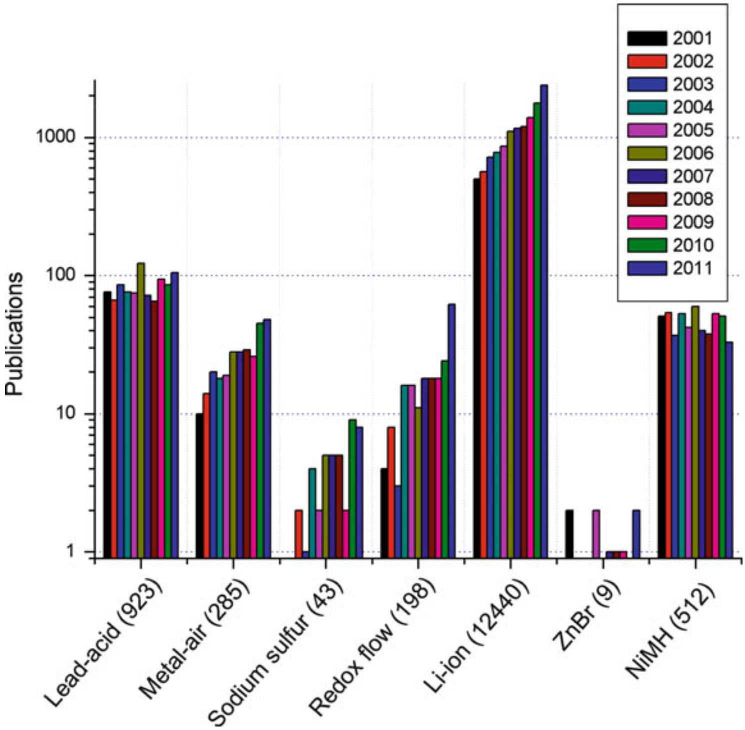

Fig. 15.17 Number of scientific publications during the period 2001–2011 for different battery technologies [24]

84.4 mAh/cm^2 of projected electrode area, which is, so far, the largest value reported for thin film cells. A cycle life of up to 400 charge–discharge cycles is also reported. The cathode is composed by $RuO_2 \cdot nH_2O$ nanoparticles and activated carbon with a supporting zinc and ammonium chloride electrolyte and a perfluorinated polymer binder. The resulting paste is spread out on a flexible and conductive current collector (a graphite film). A thin zinc sheet served as the anode and the whole assembly was packaged between sheets of flexible plastic. The authors consider that this thin galvanic cell is safe to use and non-toxic because it does not corrode in electrolyte media.

15.7.6 A New Battery That Can Be Fully Recharged in Minutes [21, 22]

A group of the University of Illinois at Urbana-Champaign has reported charge and discharge rates with minimal capacity loss by using cathodes made from a self-assembled three-dimensional bicontinuous nanoarchitecture consisting of an

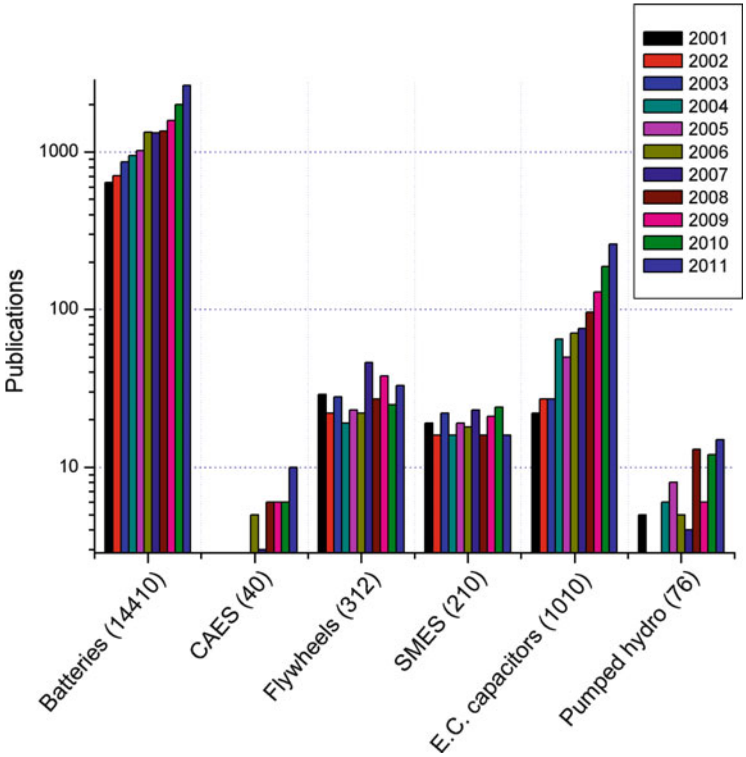

Fig. 15.18 Number of scientific publications during the period 2001–2011 for storing energy technologies [24]

electrolytically active material sandwiched between rapid ion and electron transport pathways. These rates enable the fabrication of a lithium-ion battery that can be 90 % charged in 2 min. Such rates are 10–100 times higher than those of a normal commercial battery at an estimated increase in production cost, once the process is properly industrialised, of 20–30 %.

15.7.7 Laser Scribing of High-Performance and Flexible Graphene-Based Electrochemical Capacitors [23]

Scientists at the University of California, Los Angeles, have reported a very simple and innovative process based on a standard LightScribe DVD optical drive to do the direct laser reduction of graphite oxide films to graphene. The produced films are mechanically robust, show high electrical conductivity (1,738 siemens per metre) and specific surface area (1,520 m^2/g), and can thus be used directly as EC electrodes without the need for binders or current collectors, as is the case for

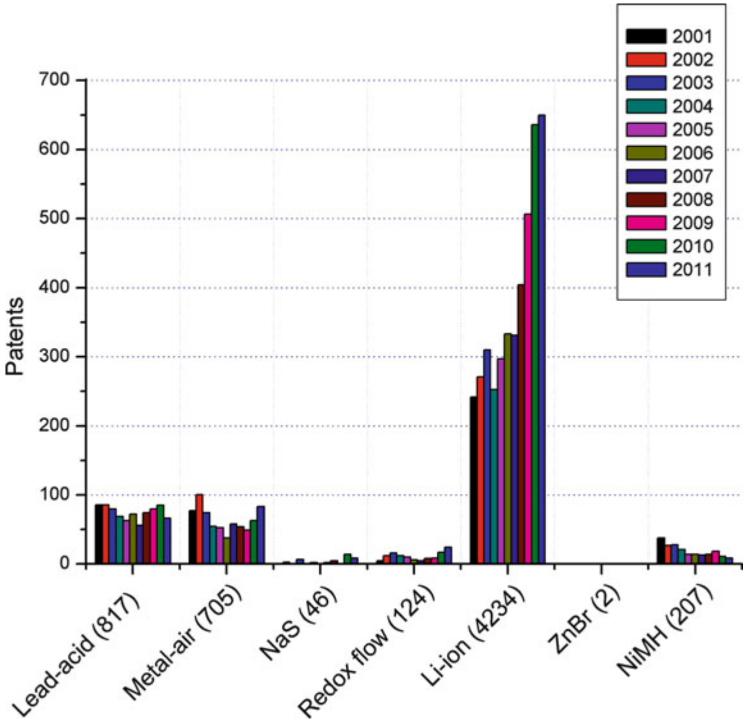

Fig. 15.19 Number of patents during the period 2001–2011 for different battery technologies [25]

conventional ECs. Devices made with these electrodes exhibit ultrahigh energy density values in different electrolytes while maintaining the high power density and excellent cycle stability of ECs. Moreover, these ECs maintain excellent electrochemical attributes under high mechanical stress and thus hold promise for high-power, flexible electronics, as required for self-powering smart dressing.

15.8 Statistics of Publications and Patents

Figure 15.17 shows the number of scientific publications during the period 2001–2011 for different types of batteries [24]. The main effort is focused on lithium batteries, with a large volume of scientific and technological production and upward. This result can be attributed to its dominance in portable energy storage systems (mainly cars, computers and phones). The remaining battery technologies are well below, some of them with increasing activity and others stabilised over the years.

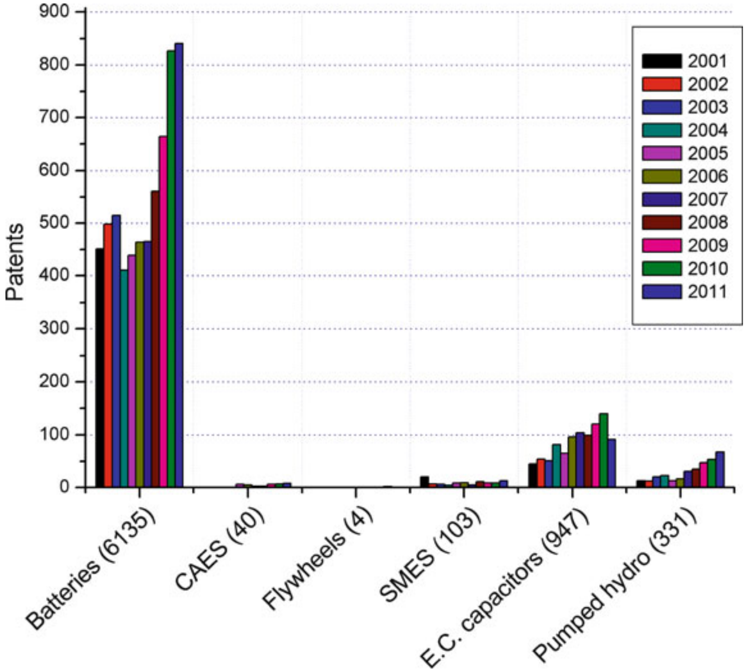

Fig. 15.20 Number of patents during the period 2001–2011 for different storage energy technologies [25]

The Pb–acid battery is in second place due to its low cost and popularity as well as to certain scientific developments in recent years. Activity related to the NiMH batteries is stable or even declining in recent years because, in spite of its good performance, they are surpassed by the Li-ion technology. It should also be noted that the technology of metal–air and redox flow batteries, though small compared to Li ion, are moderately upward. Activity in sodium–sulphur batteries is very low and almost negligible the ZnBr technology activity.

Figure 15.18 shows the number of scientific publications during the period 2001–2011 for storing energy technologies [24]. It clearly shows the overwhelming dominance of batteries, followed distantly by electrochemical capacitors, both technologies with consolidated upward trend. This is attributable to needs of energy and power storage, respectively. Consequently, batteries and electrochemical capacitors are considered the main actors in the coming years in storage technology.

Activity in other storage systems is smaller and also stabilised. This is attributable to being mature technologies in the case of the pumping hydropower, and to a lesser extent, flywheels, and technical difficulties in superconductors and CAES.

Figure 15.19 shows an evolution of battery technologies, in terms of patents [25], and the results are very similar to those exposed in Fig. 15.17 for publications, and the explanations are also analogous.

Finally, Fig. 15.20 shows an evolution of energy storage technologies, in terms of patents [25]. It can be observed that this figure is very similar to Fig. 15.18 for publications, and the discussion related is also valid to explain these patent data. Only, it should be mentioned that in terms of patents, the flywheels are very low compared to activities detected in the literature. This result requires a further discussion.

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Chapter 16
Smart Grids and Supergrids

Abstract Smart grids are necessary to take full advantage of most intermitent renewable resources such as wind and solar, since they are able to monitor and manage the delivery of power in real time. One important goal of smart grid deployment is also to reduce the peak demands, thus increasing the options for new loads such as, for example, electric vehicles. The deployment of the smart power grid will be accompanied by the development of other advanced technological areas, such as real-time monitoring of the whole power system by means of a communication meters for automatic reconfiguration of renewable resources. In addition, advanced metering enables bidirectional flow of information and, therefore, provides consumers with valuable data on electricity consumed and price. In this chapter, we also review the state of the art in supergrids, which will serve as large transmission networks between wide geographical areas. Many of the supergrids are starting to make use of high-voltage direct current (HVDC) technology, due to their very low losses specially across oceans. One interesting example of supergrid is the one projected under the Desertec program linking renewable resources from North Africa and Europe, but other supergrid projects are also in advance in other regions of the world.

16.1 Overview

Traditionally, the supply of electricity within grids has been composed by a supervisory control and data acquisition system (SCADA), which has allowed to monitor and control this process from generation to substation to detect increase/decrease generation needs or respond to system instability.

The term "smart grid" covers the next step in the supply and distribution of electricity, using information technology to make more visible and controllable the conventional grid itself and contributing with new grid elements, especially designed to manage the demand response and control small generation and storage systems (Fig. 16.1). The smart grid can be considered as an electricity network that

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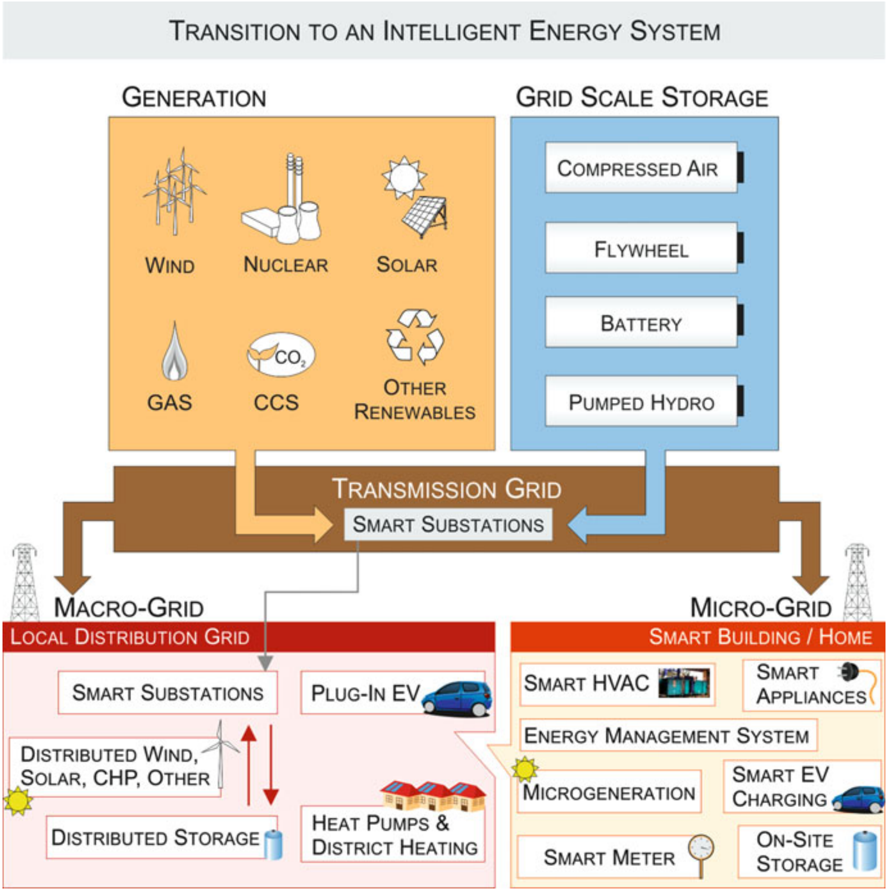

Fig. 16.1 Scheme of the elements that could compose an intelligent energy system interconnected by a smart grid

uses digital and other advanced technologies to monitor and manage the transport and distribution of electricity from all generation sources to meet the varying electricity demands of end-users.

The best control of smart grids is provided by the high-speed, two-way communications, more effective sensors and real-time coordination of all grid elements. In addition, measurement and control of grid elements can be carried out below the substation level, from controlling only the transport grid to also control the distribution grid. Thus, the smart grid will act to:

1. Guarantee the active participation of consumers.
2. Accommodate all generation and storage options.
3. Enable the development of new products, services and markets in the electricity sector.

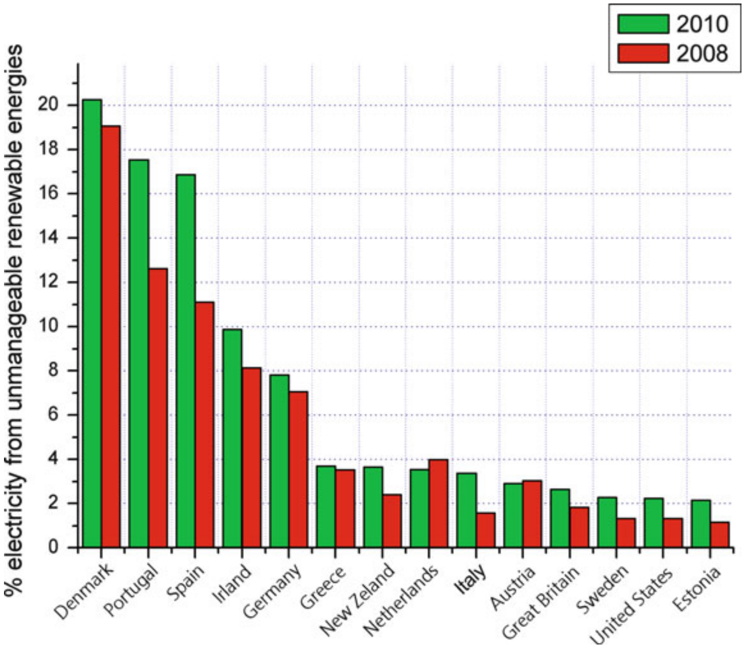

Fig. 16.2 Percentage of renewable electricity penetration from unmanageable energy sources (solar and wind energy) in the top rated 14 OECD countries in 2010

4. Optimise the operation of the grid elements.
5. Anticipate and respond to system disturbances.
6. Resist attacks and natural disasters.

In this chapter, we intend to describe the state of the art in smart grid technology mainly focused to the goal of increasing the penetration of unmanageable renewable energies (primarily solar and wind energy) in isolated power systems. This is particularly complicated because, although the penetration of renewable energies, in general, is quite high in many countries, this penetration is achieved because a significant proportion of the renewable electricity generation is manageable (mostly hydro) or because the country's electrical system is highly interconnected.

Consequently, it is interesting to establish the ranking of the 14 OECD countries with the highest penetration of solar and wind energy in their electricity system (Fig. 16.2) in 2008 and 2010 [1], since these unmanageable renewable energy sources represent the greatest technological challenge for smart grids to achieve attenuation in CO_2 emissions in the energy sector. Only OECD countries are selected because we prefer to show the most updated values (2010), and the higher unmanageable energy penetrations occur in these countries as they possess the most sophisticated smart grid technologies.

On the other hand, in this chapter also electric supergrids will be considered. These are the grids connecting substations over extremely large distances (often crossing seabeds) with technologies that reduce the losses normally attributed to such connections. The main advantage in this area is the use of high-voltage direct current (HVDC) technologies.

16.2 State of the Art

In general, smart grid technology is being introduced rapidly into the market, although in different ways depending on the analysed country. Not only the penetration of renewable sources in power systems is driving this introduction but also the serious incidents involving blackouts in Europe and North America during the first decade of this century. In contrast, the technology for supergrids is still in its infancy, unable to expose any project already in operation.

16.2.1 Smart Grid Components

The components technology is used to assess the health and quality of the grid. Thus, it is evolving towards digital technology in measurement systems and to the shortening of the intervals between these measurements. However, there is much delay in the installation of smart meters (except in a few countries), which will spur electricity demand flexibility in response to real-time electricity prices. It is also noted that the introduction of smart components is higher in the transmission than in the distribution lines.

Another emerging technology is strongly based on FACTS (flexible alternating current transmission systems), used for dynamic control of voltage, impedance and phase angle of high-voltage AC lines. We must also mention the HVDC technology, useful for coupling asynchronous systems and providing stability for achieving high energy transfer over long distances.

Important components for smart grids are the generation and storage systems for distributed power (3–10,000 kW). Thus, in the generating area can be considered primarily fuel cells, wind and photovoltaic systems (described in other chapters) and microturbines (30–400 kW) fed by natural gas (CHPs in many cases). In storage, all systems considered are those described in the chapter dedicated to energy storage.

For the transmission cable conductors in grids, currently they are mainly based on aluminium, although the trend is to replace them by composite materials that allow higher working temperatures and to double the amperage without replacing towers (Fig. 16.3). Also, the first-generation superconducting wire technology is being introduced into small segments of the transmission and distribution grid, as substations outputs for congested urban areas.

Fig. 16.3 Image of electricity transmission infrastructure

16.2.2 Smart Grid Control Systems

They are the devices and algorithms to analyse, diagnose and predict the conditions of modern grids and determine and take appropriate corrective actions to eliminate, mitigate and prevent outages and disturbances in the grid. Control of both the transport, distribution and consumer grid (Fig. 16.4) is monitored. The control systems require a large infrastructure and integrated communication capabilities to process the large amount of data that the grid provides. Currently, the telecommunication networks are very limited to completely support the data flow requirements of smart grids.

On the other hand, the power grid is evolving from a fairly simple and much closed system to a very complex and interconnected one. To maintain the privacy of the system secure from external incidents and cyber-attacks has always been a priority, but currently it becomes more difficult to guarantee the safety of the grid.

16.2.3 Smart Grid Communications

Communication systems currently used in electricity grids are too slow and too localised for the development of smart grids, mainly in distribution grids. In addition, there are too many communication standards, except in some specific

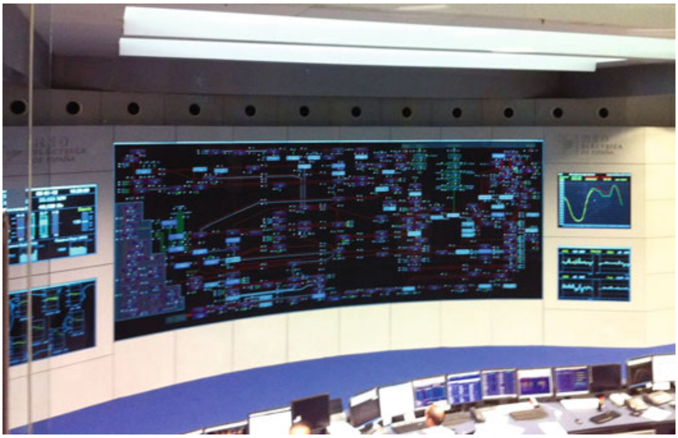

Fig. 16.4 Image of the Control Center for Renewable Energy (CECRE) of Red Eléctrica de España, SA

applications (automation of substations). The telecommunication technology for smart grids is varied, using copper cables, fibre optic cables, the electricity cable itself and wireless technology. In this regard, it is included the development of broadband power lines (BPL) for communication with the distribution grids.

16.2.4 Supergrids

The traditional choice for the transport of electricity is high-voltage alternating current (HVAC) combined with the assistance of transformers to increase or lower the tension, since it is the less costly option for connections across distances under 100 km, compared with the HVDC technology, where also DC/AC converters are needed. Thus, tensions up to 800 kV in HVAC are used in some electricity systems.

HVDC technology has been used since 1954, when the island of Gotland was connected to Sweden by a submarine cable of 96 km, 20 MW and 100 kV. There are two types of connections: (1) HVDC systems with line commuted converters (LCC), where the conversion efficiency AC/DC/AC is about 97–98 % and (2) the most recent voltage source converter (VSC), based on insulated gate bipolar transistor (IGBT) technology.

It is important to mention the low values of losses for HVDC cables, especially when they are placed on the seabed, where transmission losses are mainly attributed to capacitance effects (reactive power generation) (Table 16.1). Also, this type of cables can be placed at shorter distances to objects sensitive to electromagnetic radiation, because it avoids the problems of variable electromagnetic fields associated with HVAC lines and, therefore, facilitates the planning of new grid lines in urban areas. However, HVAC lines can transform electricity very simply, in addition to the fact that AC motors and generators are simpler and easier to maintain than DC.

Table 16.1 General characteristics of HVAC and HVDC technologies [2]

		HVAC	HVAC	HVDC	HVDC
Operation voltage	Unit (kV)	760	1.160	±600	±800
Overhead line losses	%/1.000 km	8	6	3	2,5
Sea cable losses	%/100 km	60	50	0,33	0,25
Terminal losses	%/station	0,2	0,2	0,7	0,6

16.2.5 Stages of Development

Depending on the degree of market penetration, it can be found aspects of all the technologies analysed in this chapter that can be in each of the developmental stages used to classify technologies in this section. Consequently, any classification in this section does not supply relevant information to the reader.

16.3 Current Costs and Future Scenarios

The costs of smart grids have not been discussed in detail [2], as the values will depend on available technologies and characteristics of the grid in which the smart grid components are introduced. However, average costs of transmission lines in different configurations are exposed. Thus, as it is shown in Table 16.2, the average costs of transmission lines are well defined, with variations based on market prices of raw materials, mainly aluminium and steel (the price evolution of these raw materials in international markets is exposed in previous chapters). We can observe in Table 16.2 that the costs are higher for HVDC than HVAC transmission lines. Consequently, the former is more economical for long-distance connections, while the latter is more economical for short and medium distances.

In terms of costs per unit of energy transmitted, the values depend on the country to be analysed, although it ranges from USD 5.8 to 8.4/MWh (EUR 4.2 to 6.0/MWh) [3], equivalent to a 5–10 % of total cost in electricity supplied to end-users. On the other hand, superconducting cable price has decreased about a 90 % from 1990s levels, though it remains ten times higher than that of an ordinary copper cable, at around USD 15–25 (EUR 11–18) per kA per metre, the industry's preferred unit [4].

No official studies have been detected about future costs. However, it is estimated that the costs of electricity using smart grids will be lower than conventional grids because the former can reduce peak loads and improve efficiencies, although the implementation of the new technology also involves an additional cost [2]. For example, the Telegestore project, launched in 2001 by ENEL Distribuzione S.p.A. installed 33 million smart meters (including system hardware and software architecture) and automated 100,000 distribution feeders, resulting in fewer service interruptions; furthermore, its EUR 2.1 billion (USD 2.9 billion) investment has led to actual cost savings of more than EUR 500 million (USD 696 million) per year [5].

Table 16.2 Average costs of HVAC and HVDC technologies [3]

Operation		HVAC	HVAC	HVDC	HVDC
voltage	Unit (kV)	760	1,160	±600	±800
Overhead line cost	MEUR/1,000 km (MUSD/ 1,000 km)	447–839 (623–1,167)	1,118 (1,556)	447–503 (623–700)	280–335 (389–467)
Sea cable cost	MEUR/1,000 km	3,578 (4,980)	6,596 (9,182)	2,795 (3,891)	2,012 (2,801)
Terminals cost	MEUR/station	89 (125)	89 (125)	280–391 (389–545)	280–391 (389–545)

16.4 Energy Payback, CO_2 Emissions and External Costs

To date, we have not detected any studies that address these issues for smart grids. However, it is usually argued that the use of smart grids can contribute to the decarbonisation of the electricity systems in the future. Thus, the BLUE Map scenario of the IEA considers that CO_2 emissions from electricity generation can decrease from 40 % of the total current global emissions to 21 % in 2050, representing a reduction of 20.2 Gt CO_2/year. For this reduction, smart grids would contribute with annual savings of 0.9–2.2 Gt CO_2/year [2]. This reduction in CO_2 emissions is not only attributed to a higher penetration of renewable energies but also to a lower demand in grid infrastructure (and the correlated reduction in power losses) and a more efficient use of fuels supplied to distributed power plants.

16.5 Future Technology Trends

16.5.1 Smart Grid Components

Complete replacement of electromechanical meters by solid-state meters is occurring in many countries. Especially, protective relays that reduce their contribution to generate cascading events from disruptions of the grid are being developed. This is achieved by replacing outdated electromechanical and analogic relays by digital relays that include additional features such as troubleshooting, sophisticated transformers, self-diagnostic systems, etc. Other smart components being developed are load control systems, energy analysis via the Web, systems for integration of the client's own power generation in the grid, temperature sensors to avoid overheating in conductors, phasor measurement units for electrical nodes, etc.

There is also the development of new materials (SiC, GaN, diamond, etc.) for power electronics devices to manage higher values of current and voltage, directly operating on the transmission line. In addition, power electronic devices are emerging to replace iron and copper transformers, initially in distribution grids and, subsequently, in transport grids. Work is also underway in the manufacture of improved components for HVDC systems to enable more efficient management and grid control, and lower losses in the power transmission from remote off-shore locations.

In addition, progress is being made in microelectronics for household appliances, being these sensitive to guarantee power quality when the grid is stressed. Thus, new systems are being developed capable of switching off appliances (washers, dryers, refrigerators, air conditioning, etc.) when grid voltage or frequency disruptions occur. These appliances are switched on again once the disruptions have passed. These devices already exist, but it is needed to convince manufacturers to install them in appliances (through adequate regulation) and to integrate their functionalities into grid operation.

Another future technology trend is to integrate sensors in the grid coupled with automation, measurement and control systems, to provide information and control capabilities to optimise grid operation and management of power flows within the limitations of the grid. There is also activity on the integration of micro-energy storage, which can be used as distributed generation sources to help managing peak demand and supply of reactive power to maintain standard voltage and frequency values on the grid. A step in this direction is the use of microgrids with generation and storage capacity, so they can be connected and disconnected from the grid depending on power system needs (Fig. 16.5).

For transmission cables, as noted above, the trend is the use of composite materials based on aluminium and, therefore, to offer larger performance in terms of amperage capacity and temperature. In this field, also work is intense on developing advanced power conductors, as high temperature superconductors, which can ensure that electrical systems meet changes in operation more quickly, benefiting control systems. This behaviour can be very important as renewable energy generation produced from unmanaged remote locations is increasing. Superconducting wires currently on test are called “second-generation” superconductors, because they are capable of transmitting large amounts of power at low voltage (which reduces the HVDC terminal costs) and high current. However, significant efforts are still needed for their development, especially in new materials, as brittle ceramics are incredibly tricky to spin into flexible wires, principally because their polycrystals need to be perfectly aligned in order for the electrical resistance to remain low. A decade ago, the only procedure was to sprinkle the materials into silver tubes, currently very expensive, but in the past few years, producers have devised clever manufacturing techniques, which use only a tenth as much silver as before. Some estimates consider that prices could fall 3–10 times with respect to first-generation superconductors, offering ten times lower losses. It is also considered that superconductors will be integrated into power plants generators.

Finally, we should consider the electric plug-in car as one major component of future smart grids, as it will allow more flexible management of electricity supply (particularly from renewable sources) and demand.

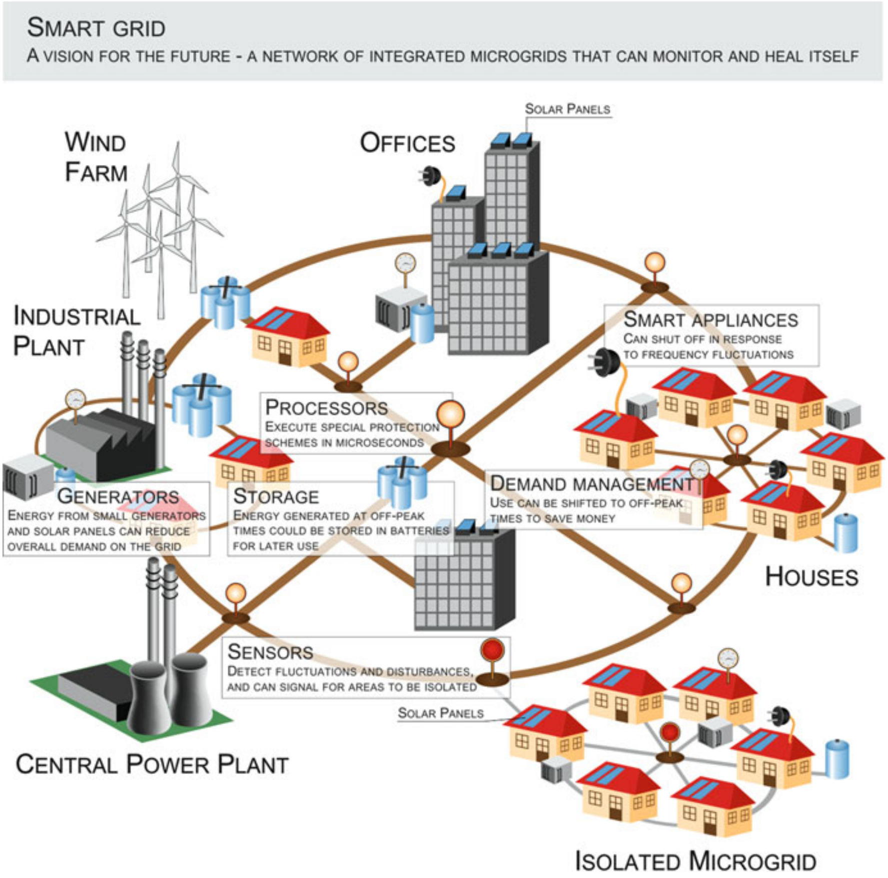

Fig. 16.5 Example of a smart grid scheme in the future

16.5.2 Smart Grid Control Systems

There are three main R&D areas on smart grid control:

1. Distributed smart agents: Semiautonomous systems that respond quickly to avoid local central control systems and human operators;
2. Analytical tools: They are the heart of the control systems and are software algorithms and powerful computers needed to process and analyse the information; and
3. Operational applications: Applications with a wider perspective than local and capable of predicting the health and capacity of the entire power system.

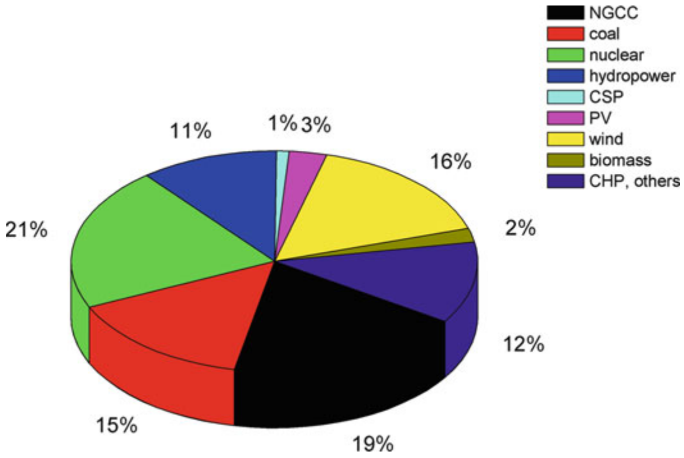

Fig. 16.6 Coverture of the Spanish electricity demand in 2011

In this area, R&D is specifically related to advanced interfaces and support decision systems for converting large amounts of data into useful information for human operators to make decisions, as well as more realistic simulation systems for human operators. In some cases, control systems must be on the consumer side, being able to make switching on and off decisions.

It should also be noted that for future human system operators more control options are needed: (1) flexible devices to transmit electric current, (2) high temperature synchronous superconductors, (3) adaptive relay systems, (4) distributed energy production, (5) management of power demand and (6) increased ability to identify areas that generate disturbances in the grid (transmission grid, distribution grid or grid on the consumer side).

To further increase the ability of human operators control, work is improving in (1) voice recognition, virtual reality and speech translation systems; (2) haptic devices; (3) holographic video; (4) geographic information systems to display spatial information; (5) colour display and animation to improve the recognition speed of the operator and the diagnosis and (6) the optimisation of data before exposing them in displays (Fig. 16.6). In addition, improvements in tool design approaches based on risk and severity probabilities for possible events (composite risk factor) are being developed to assist decision making by the system operator.

In addition, we consider that through these control systems, a higher understanding of the electricity market will be achieved and, consequently, a reduction in costs is expected.

16.5.3 Smart Grid Communications

The main trends in communications systems for smart grids are focused in achieving integrated communication, so that the grid becomes a dynamic environment that allows interactive exchange of information and power in real time. Also, through these systems, the grid can take automatically their own decisions to repair any damage or disruption.

On the other hand, it is intended that communications evolve to open systems, so they can be understood by a variety of transmitters and receivers. Also, the communication must be bidirectional, including satellite, internet and wireless communications so that both the client and the supplier can respond automatically or, after decision making, to different signals from the grid operator.

Besides, speed, redundancy and reliability are essential for the development of smart grids, as well as the development of standards that allow maximum integration of devices and power systems.

16.5.4 Supergrids

In this area, future technology trends are evolving to new types of power transmission lines. Thus, new transmission lines are expected combining lower frequency and four or six phases for HVAC lines and, in general, gas isolation transmission lines. HVAC transmission lines are also being tested at higher voltages (1,000–1,200 kV).

These new transmission lines involve large technological challenges, requiring the development of new transformers, disruptors, switches, etc., to integrate the transmission lines in the power systems.

16.6 Pre-Production Highlights 2009–2011

16.6.1 Instant Record in Wind Power, Hourly and Daily [6]

On 16 April 2012, wind generation in the Spanish power system reached its last record, 12,757 MW, providing 60.46 % of the power to the grid, 1.4 % more than the previous record on 6 November 2011. To integrate all this wind power into the grid, a percentage was exported and another percentage activated the pumping hydropower systems in the country. The small interconnection capacity of the Spanish power grid with the rest of Europe (about 3 % of the Spanish total power capacity) makes these records especially impressive.

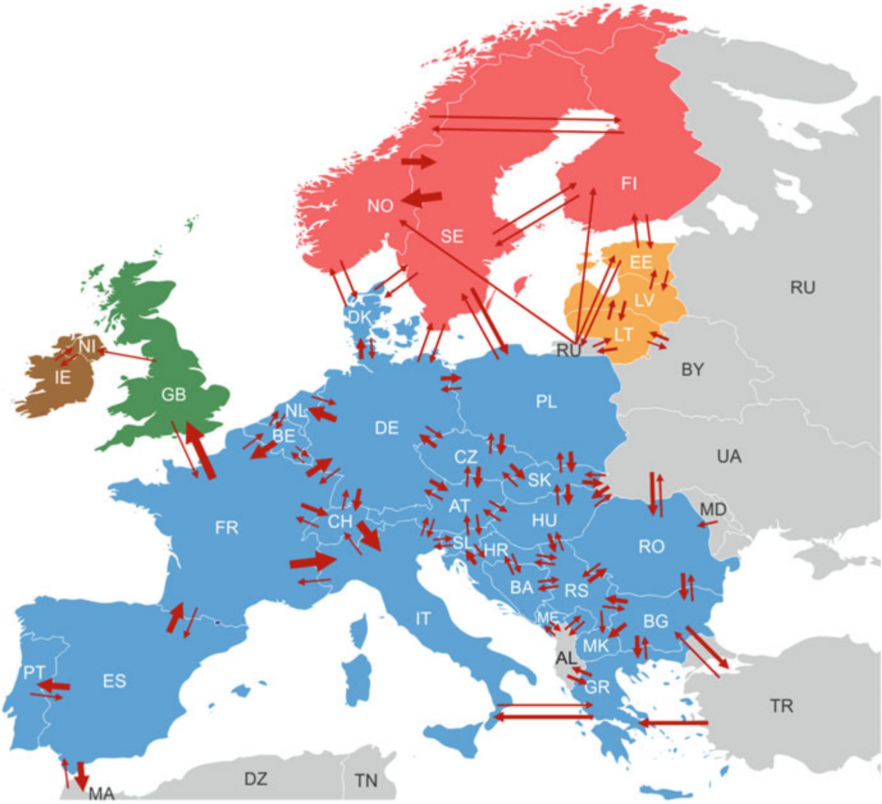

Fig. 16.7 Diagram of power sharing within the ENTSO-E and neighbouring systems in 2011

16.6.2 ENTSO-E Electrical Systems Bordering Increase Electrical Exchange in 2011 [6]

During 2011, it continued to increase power exchange between countries that form the system ENTSO-E and between this system and neighbouring systems (Fig. 16.7). Thus, a positive balance in Italy (44.2 TWh) and Hungary (5.2 TWh) reached maximum values. As a negative balance France (30.5 TWh) and Germany (16.9 TWh) reached maximum values.

16.6.3 SuperPower, Inc. Breaks Records in High-Temperature Superconducting Transmission of Power [7]

SuperPower, Inc., a developer and provider of second-generation high temperature superconducting (2-G HTS) wire, is scaling up its wire production, which incorporates Oak Ridge National Laboratory buffer technology into the wire architecture. This novel buffer technology has enabled SuperPower to increase its wire throughput while maintaining long length uniformity, establishing many world records. Among these are the world's longest 2-G wire and the world's best long length performance of 158,950 amp-meters. Just 3 years prior, a 322-m wire developed by SuperPower yielded a performance record of 70,520 amp-meters.

16.7 Innovation Highlights 2009–2011

16.7.1 Agreement Signed Between Nine European Countries to Build the First Supergrid [8]

On 7 January 2010, an agreement was signed between Germany, France, Belgium, Holland, Luxembourg, Sweden, Ireland, Denmark and Britain to build the first European HVDC supergrid in the North Sea. This agreement is driven by plans to install off-shore wind farms (100 GW) in the area, representing 10 % of the electricity consumed in Europe. The execution of this agreement will provide a substantial advance in the path for large electricity transmission grids supplied mainly with renewable energy in Europe.

16.7.2 DESERTEC Project Begins [9]

Twelve companies, nine of them German, Swiss ABB, Algeria Cevital and the Spanish Abengoa Solar signed in Munich on 13 July 2009 a declaration for implementation of the Desertec Industrial Initiative (DII), which intends to use the Sahara Desert to install up to 100 GW of solar power plants to supply mainly CPS and PV electricity to Europe, Africa and Middle East (Fig. 16.8). Companies have considered a 3-year period to develop the conditions necessary to implement the project, initially evaluated at USD 412,000 million (USD 574,000 million) until 2050. It will be necessary to connect Europe with Africa by means of a high capacity transmission line to make this project a reality. This supergrid will be based on HVDC technology. Moreover, in March 2012, the Desertec Foundation and the Japan Renewable Energy Foundation (JREF) have signed a memorandum of understanding to promote an Asian supergrid necessary for the expansion of renewable energy in Asia. Also, efforts from the Greek Government to increase incomes from electricity exports are promoting the Helios Project, offering land to Central European governments and investors to produce electricity from solar energy and transmit it to these countries to curb carbon emission targets.

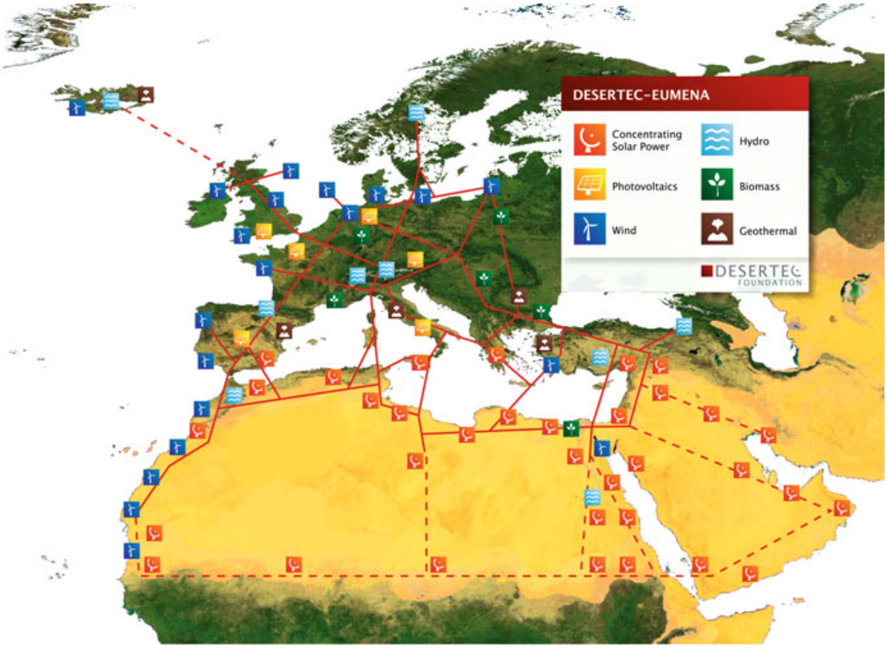

Fig. 16.8 Scheme of the Desertec supergrid expected to be installed in the near future (source: DESERTEC Foundation, http://www.desertec.org)

16.7.3 Project TWENTIES Starts [7, 8]

On 18 May 2010, the EU presented the TWENTIES project, funded with EUR 61 million (USD 85 million) in 3 years, and coordinated by REE, SA. It consists of six demonstration projects to eliminate barriers for the penetration of wind on-shore and off-shore in power systems, achieving greater integration. They use a system of 200 turbines with a total capacity of 500 MW. Pioneer methods of control voltage and frequency at different levels of the systems, demand management, sensors and control devices will avoid large-scale system instabilities for achieving the objectives. Also, a direct-current multi-node off-shore grid will be designed to study optimal coordination among off-shore wind farms and hydraulic systems to balance generation losses during extreme weather events.

16.7.4 Record Super-Thin Superconducting Cable [10]

Superconducting cabling techniques that have been currently applied have not resulted in compact, mechanically robust, high-current cables that remain flexible. A research team of the US National Institute of Standards and Technology (NIST) demonstrates that the cabling technique introduced only recently enables the

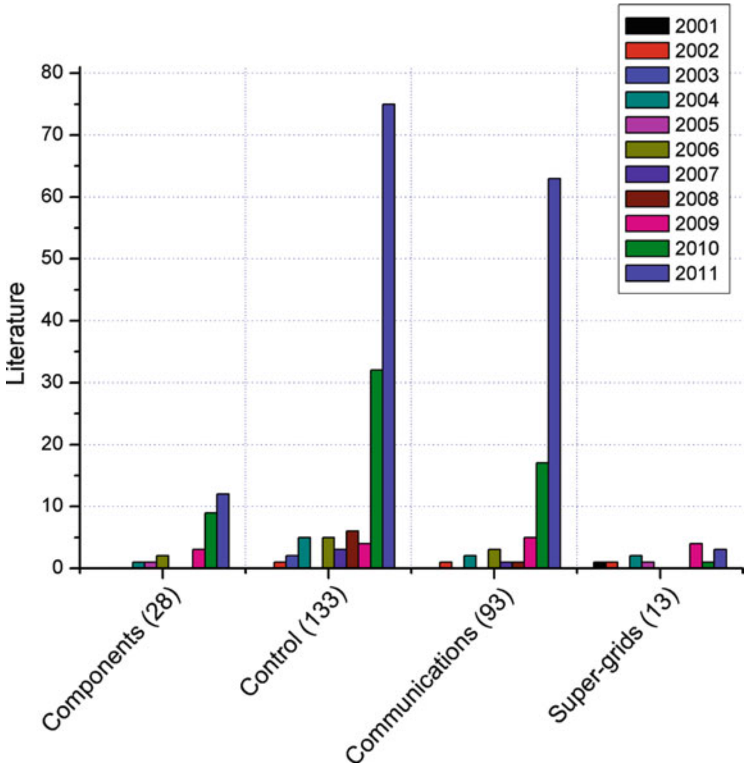

Fig. 16.9 Number of scientific publications during the period 2001–2011 for different smart grid technology areas and supergrids [11]

construction of cables from high-temperature superconducting coated conductors that meet these requirements. The cable is wound from $GdBa_2Cu_3O_7$-δ coated conductors, has an outer diameter of 7.5 mm (a tenth of usual superconducting cables) and a critical current of about 2,800 A at 76 K and self-field. The compact size and flexibility would allow superconducting power transmission lines that have been installed in the electric power grid to be reduced in diameter.

16.8 Publications and Patents Statistics

Although the number of scientific and technological contributions in the field of power grids is high (about 7,500 since the 1930s), the smart grid concept is quite recent (the first publications are dated in 1999) and much smaller in number (240) [11]. Thus, Fig. 16.9 shows the number of scientific publications during the period 2001–2011 for different smart grid technology areas and supergrids discussed in this chapter.

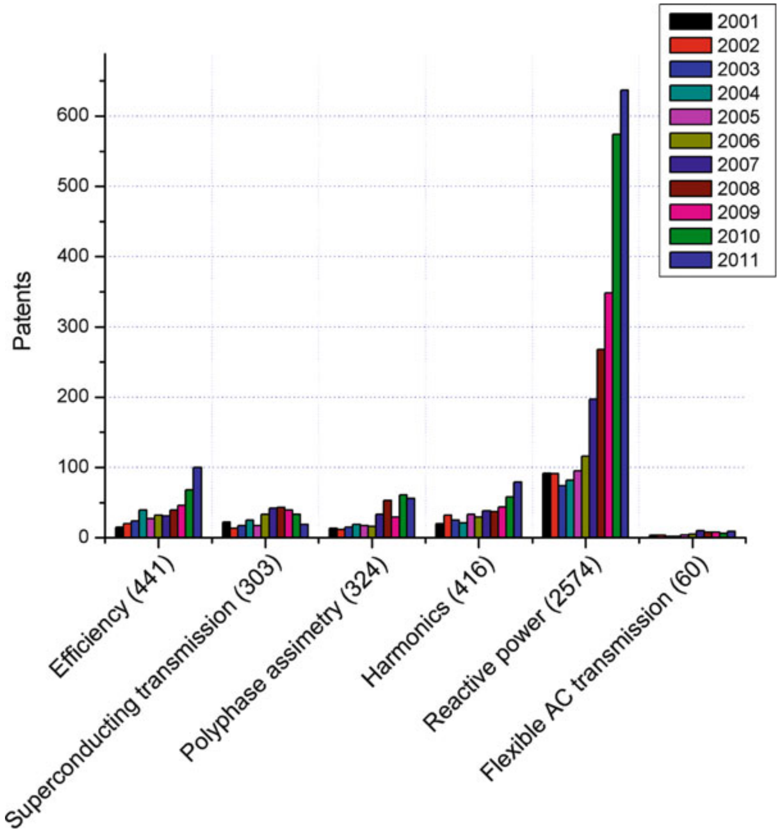

Fig. 16.10 Number of patents during the period 2001–2011 related to smart grid technology areas and supergrids [12]

In fact, Fig. 16.9 shows that the supergrids and the smart grids related concepts are very recent, beginning to generate appreciable research activity in the last 10 years. On the other hand, we observe that most efforts are focusing on research and development in control systems, compared to communication systems and components, being the development of the latter much lower. This is attributed to the fact that control is the central concept of smart grids, while the other two technologies discussed have an important but lesser role. Finally, activity in supergrids is very minuscule, but a small upward trend is detected, which is attributed to the difficulty for analysis until recently, when approved research projects and large transmission grids are taking place on ground.

In relation to patents [12], currently there is no special classification area adapted for smart grids, but instead there are classifications for technologies that offer efficient electrical power generation, transmission and distribution. In this area, we have selected the topics related to smart grids and analysed them (Fig. 16.10). Thus, a large activity in patents is detected in this area, mainly for patents related to reactive power compensation. On second place are arrangements for reducing harmonics, and methods and systems for the efficient management or operation of electric power systems (e.g. dispatch aiming to losses minimisation or emissions reduction, coordination of generating units from distributed resources or interaction with loads). Included in these patents are those related to superconducting or hyperconductive transmission lines or power lines or cables or installations thereof, and arrangements for eliminating or reducing asymmetry in polyphase networks. Finally, with a small activity compared to the rest are patents related to flexible AC transmission systems.

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Chapter 17
Carbon Capture and Storage

Abstract The main object of the carbon capture and storage (CCS) technologies is the reduction of CO_2 emissions produced in the combustion of fossil fuels such as coal, oil, or natural gas. CCS involves first the capture of the emitted CO_2, mainly from power and industrial plants, its transportation and, finally, its injection in underground reservoirs for storage. In this chapter, we describe the four main technologies for CO_2 capture: post-combustion capture, pre-combustion capture, oxy-fuelling and chemical looping. Evidently, any of these capture techniques result in a significant energy penalty to the base plant. However, it is expected that in the future CCS will contribute to reduce global CO_2 emissions. After the CO_2 is captured, it should be compressed for transportation through high-pressure pipelines or ships, and finally stored into geological formations such as depleted gas reservoirs, saline formations and deep unmineable coal seams. Depending on the capture technology, the additional costs for generating electricity from a coal plant with CCS have been evaluated.

17.1 Overview

Today, both governments and society in general, agree that it is necessary to convert the current global energy supply in a more sustainable system. To this end, several options, such as improved efficiency in energy production and consumption, conservation, increased renewable sources and, of course, the use of technologies for capturing and storing carbon dioxide (CO_2) are real options.

CO_2 is a greenhouse gas that contributes to maintain a living temperature in the Earth. However, too much CO_2 is currently generated from fossil fuel combustion (Fig. 17.1) [1], thus increasing its concentration in the atmosphere from about 280 ppm values in the pre-industrial era to above 395 ppm in 2012 (see Fig. 2.8) [2].

Thus, it is considered that the increase in CO_2 levels in our atmosphere is reducing the outward transmission of heat from the Earth's surface into space and, consequently, producing an increase in average global temperature (see Fig. 2.9b),

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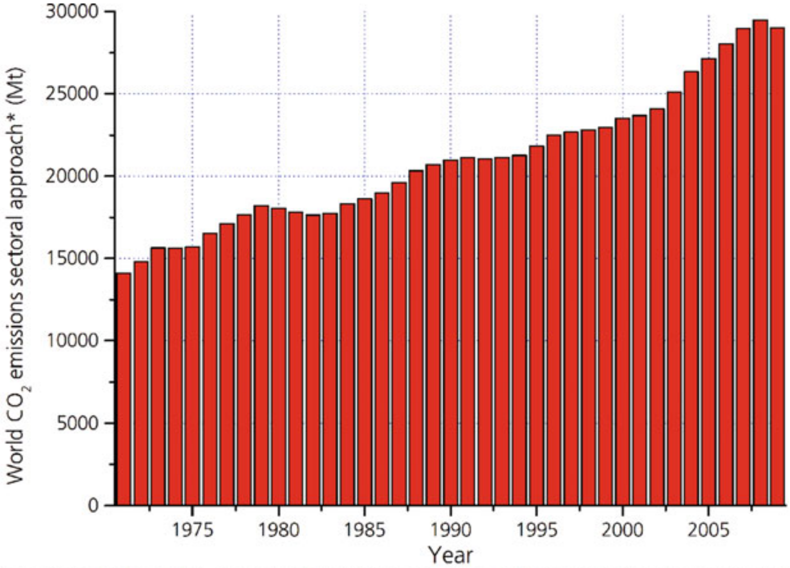
Lecture Notes in Energy 3, DOI 10.1007/978-1-4471-4385-7_17,



(*) Sectoral Approach contains total CO_2 emissions from fuel combustion as calculated using the IPCC Tier 1 Sectoral Approach and corresponds to IPCC Source/Sink Category 1 A. Emissions calculated using a Sectoral Approach include emissions only when the fuel is actually combusted.

Fig. 17.1 Evolution of annual CO_2 emissions from fuel combustion worldwide between 1971 and 2009 (source: IEA)

as well as an increase in average sea level (see Fig. 2.9a) and a decrease the land area covered by ice (see Fig. 2.10) [3].

CO_2 capture and storage (CCS) is being proposed as a key technology to achieve to halt the rise in global temperatures, mainly if applied in centralised electric power plants using fossil fuels. According to the latest IEA available statistics (for the year 2009 [4]), 40.6 % of the 20,055 TWh electricity production worldwide is obtained from coal, 21.4 % from natural gas and 5.1 % from oil, while the remaining comes from nuclear, hydro and renewables. CO_2 can be also captured and stored from other centralised emission sources, mainly the fuel transformation sector and others plants located in the industrial sector.

The capture of CO_2 from centralised sources involves several steps:

(a) Capture of CO_2 emitted from power plants, industrial plants, etc., including the transformation and compression of the emitted gases.
(b) Transportation of CO_2 gas to a sink by means of pipes, vessels, appropriate vehicles, etc.
(c) Injection of the CO_2 in underground geological formations, such as oil or gas deposits that are already empty, stored in the oceans, etc.

Since 1972, when the first large-scale integrated project (LSIP) in Val Verde (Texas, USA) started operation, eight large installations are operating on the planet, most of them dedicated to the separation of CO_2 from natural gas deposits, being

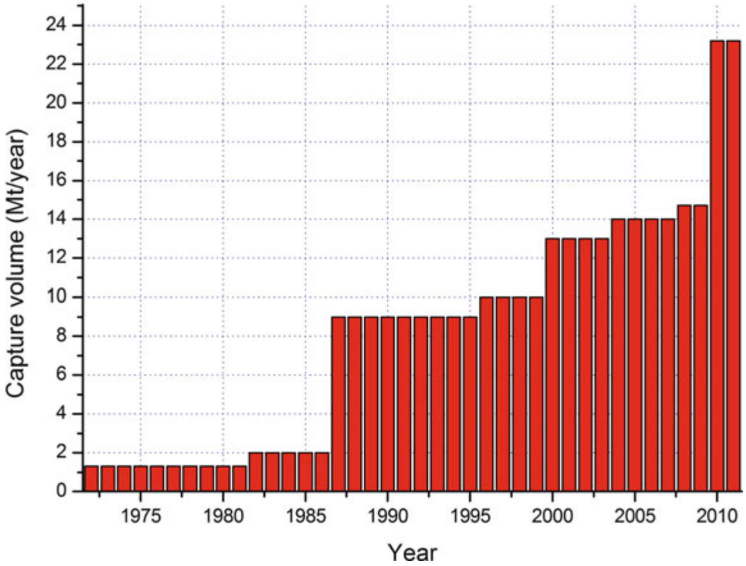


Fig. 17.2 Evolution of the world capture capacity for large CCS plants in operation (1972–2011)

then injected into geological formations at different depths (Fig. 17.2) [5]. All these plants operate with pre-combustion capture technology (exposed below).

On the other hand, there are in operation or projected 74 LSIPs around the world. The total CO_2 capture volume of all 8 projects in operation is 23.2 Mt CO_2/year (0.8 % of the annual CO_2 emissions from fuel combustion worldwide for the last data available—2011) [5].

LSIPs are defined as those projects, which involve the capture, transport and storage of CO_2 at a scale of (1) not less than 800,000 t CO_2 annually for a coal-based power plant and (2) not less than 400,000 t CO_2 annually for other emission-intensive industrial facilities (including natural gas-based power generation).

For the next years (2012–2017), the entry into operation of other 66 LSIPs is expected, with a cumulative storage capacity added of 134.2 Mt CO_2 per year, although some of the LSIPs will remain only few years in operation [6].

17.2 The State of the Art

There are four main technologies for CO_2 capture: (1) post-combustion capture, (2) pre-combustion capture, (3) oxy-fuelling and (4) chemical looping. There are also multiple pathways using different technologies, which may find more favourably particular application in certain climate conditions, locations and using specific fuels.

17.2.1 Post-Combustion Capture

Post-combustion capture of CO_2 from the exhaust gases of the combustion process, which has a CO_2 content between 2 and 25 % [7], is usually performed at low pressure. The three main post-combustion processes are:

- Absorption: The uptake of CO_2 into the bulk phase of another material, for example dissolving CO_2 molecules into a liquid solution. Once bonded, the solvent is conducted to another compartment where it is heated to release the CO_2 (almost completely pure) and, thus, the solvent becomes also regenerated.
- Adsorption: It involves the selective uptake of CO_2 onto a solid surface, which is subsequently regenerated by lowering the pressure and/or increasing the temperature to liberate the absorbed CO_2. A claimed advantage of adsorption is that the regeneration energy should be lower relative to that of the absorption solvents.
- Membranes: The separation of CO_2 from the flue gas by selectively permeating it through the membrane material. Like adsorbents, membranes are claimed to potentially offer low energy capture processes.

Within chemical solvents, amines are preferably used due to their advanced stage of development, although their oxygen content has corrosive effects. Also, the reactivity of the amine with sulphur dioxide and oxides of nitrogen dissolve it, so the amine has to be constantly replenished into the capture process or, alternatively, removing these sulphur- and nitrogen-based gases prior to the capture of CO_2.

The biggest challenge for this technology is reducing the cost of energy used in heating the solvent for the release of CO_2, since at present this process considerably reduces the efficiency of a power plant. There are currently no large CCS facilities operational in the power sector utilising post-combustion technology.

17.2.2 Pre-Combustion Capture

The oil, gas and chemical industries have been separating CO_2 from gas streams for decades at commercial scale. Also, as many of the world's natural gas fields contain CO_2, in most cases the CO_2 is removed to meet the purity requirements of the natural gas market, in an obvious pre-combustion process.

In this technology, the fuel is previously gasified producing a synthesis gas called syngas (a mixture of H_2 and CO). CO_2 removal from coal gasification syngas is a mature commercial process widely practised throughout the world. Then, the syngas is cleaned from impurities that could damage the turbines, and the CO is mixed with steam to react and produce CO_2 and H_2. In this mix, the CO_2 is separated by an absorption process and prepared for transport and storage. The remaining gas, rich in oxygen, is mixed with additional oxygen and used to power a hydrogen gas turbine, which only produces water vapour at the exhaust. This turbine cycle with hydrogen is thermally more efficient than conventional ones for electricity production [8].

Current commercially available pre-combustion CO_2 capture processes are based on the use of physical or chemical solvents. Typically, all the solvents can achieve greater than 90 % CO_2 removal, under lower pressure than current post-combustion technology.

Currently, there are a number of processes under development to demonstrate the feasibility of using pre-combustion in natural gas or coal fuelled IGCC technology (“Integrated Gasification Combined Cycle”). Great Plans Synfuels plant in North Dakota can be considered the first in the world that incorporated this technology, using gasified coal to produce syngas and synthetic natural gas, ammonium sulphate and anhydrous ammonia. The residual CO_2 from the gasification process is pumped 330 km to Weyburn, Canada, where it is injected underground to enhance oil recovery.

17.2.3 Oxy-Fuelling

In the oxy-fuelling combustion process, fuel is burned in a pure oxygen environment instead of air, thereby avoiding the need of CO_2 separation in the exhaust gases as the content is up to about 90 % of the total [5]. If permitted by regulations, the raw, dehydrated exhaust gas may be stored directly without the need for further purification. Otherwise, the exhaust gas impurities (predominantly oxygen, nitrogen and argon) may be removed.

One advantage of this technique is to facilitate the retrofitting of existing facilities, adding the ability to capture CO_2. The first electricity production plant using this technology has become operational at Schwarze Pumpe (Germany) in 2008. Oxy-fuelling combustion may be employed with solid fuels, such as coal, petroleum coke and biomass, as well as liquid and gaseous fuels.

17.2.4 Chemical Looping Combustion

This technique is still being developed to be applied in CCS, but its future looks promising, since it would consume much less energy than post-combustion technology and consequently improve the efficiency of the power plant compared to oxy-fuelling technologies. The chemical looping technique uses tiny particles of metal oxides as oxygen carriers, which make a loop between the combustion reactor and an air reactor.

Thus, by reacting with fluids in a fluidised bed reactor (combustion reactor), the metal oxide particles introduce oxygen and again become metal. The oxygen and the fuel produce a mixture of CO_2 and water vapour in the reactor, which, after water condensation, the gas released is composed of nearly pure CO_2 that can be subsequently sequestered. Thus, the combustion takes place without any contact of fuel with air and, consequently, the exhaust gas presents no nitrogen content, making easier to capture CO_2. The metal particles produced are transported to the other fluidised bed reactor where they react with air (air reactor) and re-oxidise, also releasing heat that can be used to increase the overall efficiency.

Some publications consider the chemical looping technology as an oxy-fuelling sub-technology [5].

17.2.5 Transport of CO_2

The transportation of CO_2 is based on a well-known technology. In fact, there exists nearly 6,000 km of pipelines for pumping 50 Mtpa CO_2 worldwide, mainly in USA [5]. For geological storage under the seabed, the technology is more complex, but a plant with these characteristics is already operating (Snøhvit, Norway). This facility is composed by multiple pumping lines with origin in different CO_2 emissions plants and converging to a single larger pipe on the coast, where it is pressurised and connected to the geological location in the ocean where the CO_2 is stored.

17.2.6 CO_2 Storage

Geological CO_2 storage can be produced by pumping the gas underground using several procedures, as it is shown in Fig. 17.3 [9]. One approach (process 1) is to store CO_2 in former oil or gas deposits already empty. CO_2 can also be used in the so-called enhanced oil recovery activities. In this procedure, the injected CO_2 allows the extraction of oil not directly extracted by impulsion (process 2). CO_2 can also be injected in saturated sedimentary rock deposits of salt water (process 3). These rocks consist of alternating layers of water, silt, clay, etc. The CO_2 is trapped in the pores of the sand layers, in the capillaries of the clay layers, adsorbed on carbonaceous rocks, etc. It is also planned to store CO_2 in non-extractable coal veins (process 4) or to extract natural gas from these coal veins (process 5). Finally, there is the option for storage in basalt rocks, tar sands or in cavities (process 6). It is also considered the storage of CO_2 in the subsurface of the ocean, usually at depths of 700 m or more.

In general, the technologies for CO_2 storage in deep geological formations are already highly developed, since they have been transferred from the exploration and extraction technologies for oil and natural gas. On the other hand, a storage capacity of 1,000–10,000 Gt CO_2 in salt deposits has been estimated, 600–1,200 Gt CO_2 in oil and gas fields and 3–200 Gt CO_2 in coal veins to extract methane [10]. These magnitudes can be compared with 29 Gt CO_2 (Fig. 17.1) emitted by combustion of coal, oil and gas in 2009 (latest figures available) [1].

There is also a significant effort in monitoring the stored CO_2, applying various technologies: (1) atmospheric techniques, mainly by sending an infrared laser beam, strongly absorbed by CO_2, to determine the CO_2 concentration; (2) various near subsurface techniques: geochemical analysis of the shallow depths below the surface, measurement of CO_2 concentration in places where gas is extracted and

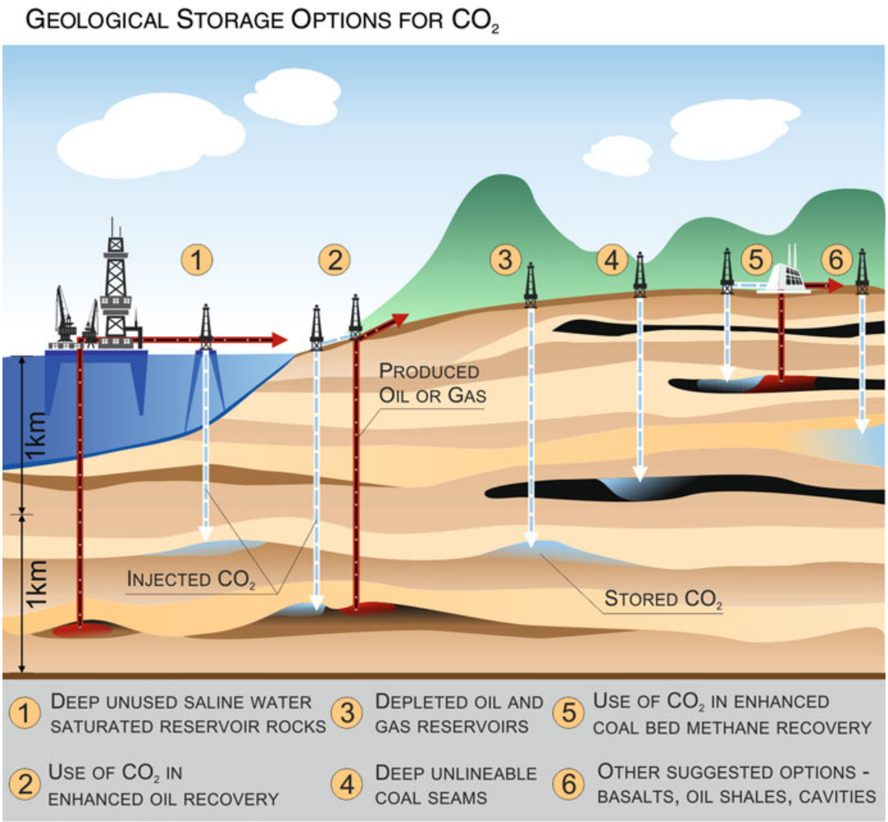


Fig. 17.3 Scheme of the different procedures for geological storage of CO_2 in the Earth [9]

introduced into a chamber to be analysed and other techniques based on the topographic measurement of the electrical conductivity of materials below the surface and (3) deep subsurface techniques, in particular geochemical, quite similar to those used in oil and natural gas fields, in which CO_2 migration can be studied using chemical tracers or measuring the variation of the signals from time-delay seismic analysis.

17.2.7 Stages of Development

Figure 17.4 shows the stage of development and implementation of the different CO_2 capture technologies exposed, since the CO_2 transport and storage technologies are considered mature and in a competitive stage.

As shown in the figure, the most developed technology is pre-combustion considering, as mentioned above, that the first LSIP in Val Verde (Texas, USA) entered into operation 1972 and several new projects followed thereafter. Next, the

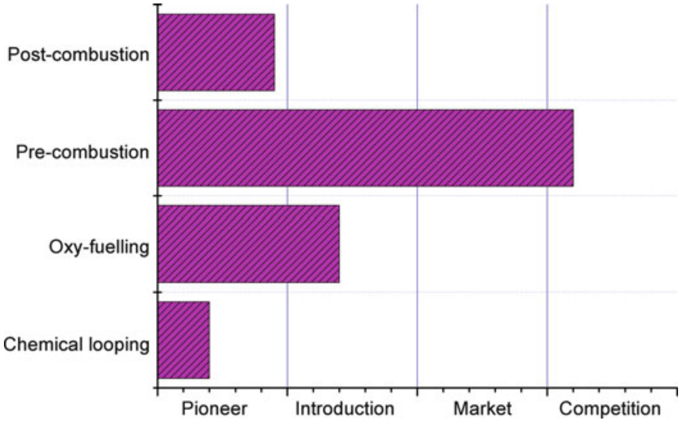


Fig. 17.4 Stages of development for each of the technologies considered for carbon capture

Table 17.1 Thermal efficiencies for various CCS integrated power plants that use coal or natural gas as fuel [8]

Fuel	Power generation technology	CCS technology	Net efficiency% (LHV)$^{(*)}$
Coal	Pulverised fuel	None	44.0
		Post-combustion	35.3
		Oxy-combustion	35.4
	IGCC, dry feed	None	43.1
		Pre-combustion	34.5
	IGCC, slurry feed	None	38.0
		Pre-combustion	31.5
Gas	Gas turbine combined cycle	None	55.6
		Post-combustion	49.6
		Oxy-combustion	44.7

[*] HHV (higher heating value) efficencies of the coal-fired plants are 0,956 times the LHV (lower heating value) efficiencies.
HHV efficiencies of the gas-fired plants are 0,904 times The LHV effiencies.

entry into operation in 2008 of the experimental plant Schwarze Pumpe in Germany, based on oxy-fuelling combustion, promoted this technology into second place in the introduction phase.

Post-combustion technology is largely recognised but must be considered in a pioneer stage because of the absence of any major facility in operation that would allow advancing its stage of technological development. Finally, we consider the chemical looping as the less developed technology, where significant research efforts are on course but on preliminary issues.

On the other hand, the IEA [8] has published a study that evaluates the thermal efficiency of various power plants based on coal and natural gas using different CCS technologies (Table 17.1). These data show efficiency losses ranging from 6.0 to 10.9 percentage points. In post-combustion technology, these efficiency losses are mainly due to the need to use some of the steam to regenerate the solvent, and the CO_2 purification and compression processes. In pre-combustion technology, the efficiency losses are attributed to the exothermic reactions losses that result from fuel conversion in the process prior to combustion. In oxy-fuelling combustion technology, the main efficiency losses are attributed to the need to feed the oxygen production unit. Finally, for chemical looping technology, studies of these characteristics have not been detected at present.

17.3 Current Costs and Future Scenarios

17.3.1 Capture and Storage Costs

The cost of the CO_2 avoided reflects the cost of reducing CO_2 emissions to the atmosphere while producing the same amount of product, such as electricity, from a reference plant that does not include CCS technology. Current studies estimate that CCS costs varies from EUR 41.6 to 67.5/t CO_2 (USD 57.9 to 94.0/t CO_2) [5], while in the larger CO_2 permits trade market (the European Union Emission Trading Scheme) the ton of CO_2 has been valued in the range EUR 6.5–16.8/t CO_2 (USD 6.1–23.4/t CO_2) (Fig. 17.5) in the 2011-2012 period exposed. Finally, we have not found chemical looping processes costs rigorously calculated in the literature.

The largest uncertainty in the cost of large-scale demonstration plants is produced in the up-front capital costs. Incorporating CCS facilities increases capital investment cost by around 30 % for an IGCC facility and by 80 % for the other coal and gas-based technologies. Total installed investment costs, including capture technology, represent around 45–50 % of the electricity costs for coal-based CCS plants. Oxy-fuelling combustion has a lower relative cost on both levelised electricity costs and avoided CO_2 costs, compared to other CCS technologies. At the same time, oxy-fuelling technologies are the least mature and have the highest level of uncertainty of the three technologies evaluated in terms of costs [5].

Specifically, CO_2 transport costs must be calculated for each individual installation, according to the transport technology used: pipelines similar to natural gas, compressed bottles in trucks, boats, etc. Costs have been evaluated for pipelines and ships [5] (Table 17.2). The investment cost for pipe transport (1-m diameter pipe) vary from USD 0.80 million/km (EUR 0.58 million/km) on-shore to USD 1.34 million/km (EUR 0.96 million/km) off-shore. These costs represent 10–15 % of the total cost of CCS [7].

In relation to the costs of geological storage cavities, they depend on many factors such as depth below ground, the location (usually the location “off-shore” is more expensive, etc.) (Table 17.2). The CO_2 storage costs are highly variable between USD 2.1 and 32.1/t CO_2 (EUR 1.5 and 23.1/t CO_2). It can typically represent between 5 and 10 % of the total cost of CCS [5]. A recent publication estimates that storage cost varies between EUR 3 and 14/t CO_2 (USD 4.2 and 19.5/t CO_2) (Table 17.3).

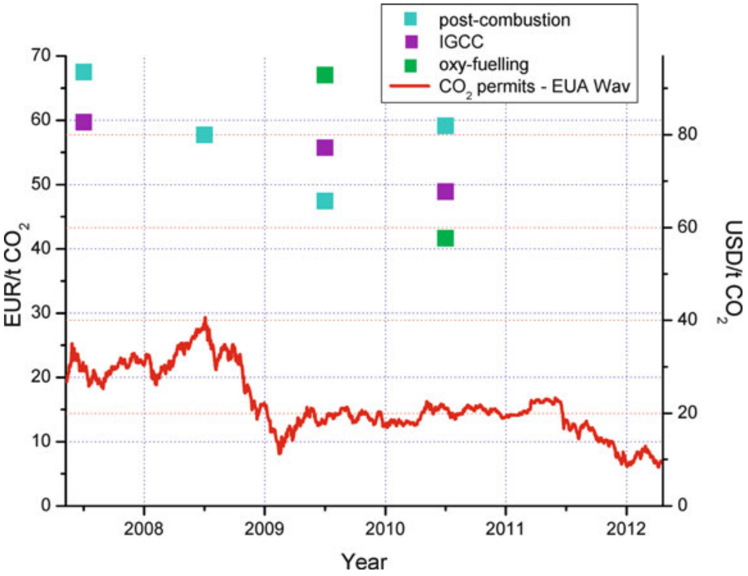


Fig. 17.5 CCS costs per ton of CO_2 for different technologies and evolution of the European Union Emission Trading Scheme for CO_2 permits

Table 17.2 Transport cost estimates for large-scale networks of 20 Mtpa CO_2 [5]

EUR/t (USD/t)	180 km	500 km	750 km	1,500 km
Onshore pipe	1.5 (2.1)	3.7 (5.2)	5.3 (7.4)	n/a
Offshore pipe	3.4 (4.7)	6.0 (8.4)	8.2 (11.4)	16.3 (22.7)
Ship (liq. incl.)	11.1 (15.5)	12.2 (17.0)	13.2 (18.4)	16.1 (22.4)

Table 17.3 Cost estimates for different CO_2 storage cavities

EUR/t CO_2 (USD/t CO_2)	On-shore	Off-shore
Depleted oil and gas fields (legacy wells)	3.0 (4.2)	6.0 (8.4)
Depleted oil and gas fields (no legacy wells)	4.0 (5.6)	10.0 (13.9)
Deep saline formation	5.0 (7.0)	14.0 (19.5)

The total CCS costs could be financially compensated and even produce an income, if it is focused to value added applications. In this sense, CCS can be beneficial from an economic point of view for enhanced oil recovery (EOR). Thus, EOR activities have an estimated cost of 38–43 USD/t CO_2 (EUR 27–31/t CO_2) and may recover a 5–23 % more oil from oil fields [7], depending on reservoir conditions and oil–CO_2 miscibility. Also, other activities can add value to CO_2 capture, such as the manufacture of chemicals, especially synthetic gases.

The CCS costs can be translated to an increase of electricity costs. Thus, the additional costs due to CCS in electricity production range from USD 0.023 to 0.085/kWh (EUR 0.017 to 0.061/kWh), which would represent an increase of the electricity bill up to USD 8.5 cents (EUR 6.1 cents) per kWh with respect to current prices.

Table 17.4 Approximate total CCS cost as well as costs added to electricity in power plants with CCS [7]

USD (EUR)	2011	2030
CCS total costs/t CO_2	57.9–94.0 (41.6–67.5)	37.5 (26.9)
Costs added/kWh	0.023–0.085 (0.017–0.061)	0.011–0.032 (0.008–0.023)

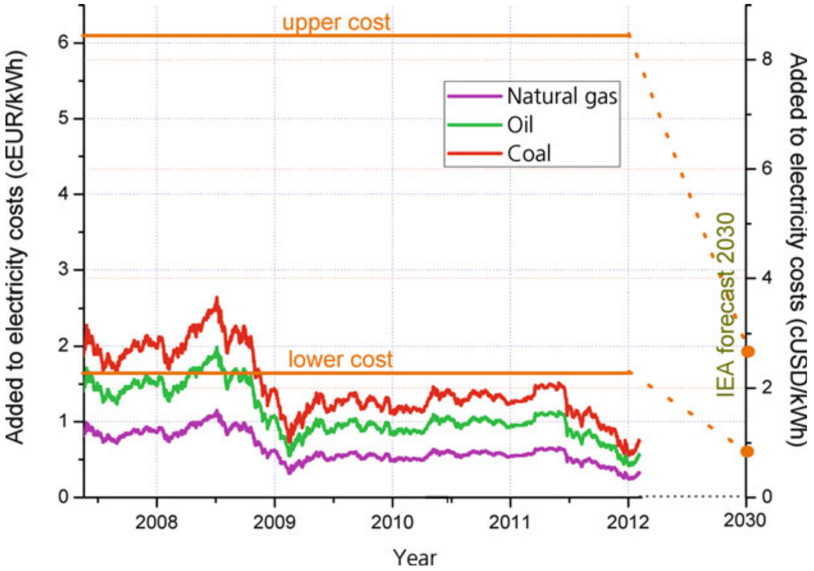


Fig. 17.6 Evolution of the additional costs to electricity production from coal, oil and natural gas, considering the variations in CO_2 emission permits in the European Union Emission Trading Scheme and compared with current estimates for future costs of CCS exposed by the IEA

Future CO_2 emission costs will depend on which technologies are more effective to capture, transport and storage of CO_2, the size of the CCS market, fuel prices, etc. The IEA estimates [7] that by 2030 a cost of USD 37.5/t CO_2 (EUR 26.9/t CO_2) for CCS technologies is expected and the additional costs of electricity varying between USD 0.011 and 0.032/kWh (EUR 0.008 and 0.023/kWh). All these data are summarised in Table 17.4.

From these results, the International Energy Agency believes that it will be necessary to introduce an incentive of USD 50/t CO_2 (EUR 36/t CO_2) to facilitate the introduction of CCS in the energy sector [7]. However, the evolution of prices for CO_2 emission permits in the European Climate Exchange market shows that the technology is still far from being attractive enough to be applied in power generation.

Thus, if we consider the latest data published by the IEA (2009) on global average CO_2 emitted per kWh in electricity production from natural gas, oil and coal power plants and they are adjusted to the daily price of the future of CO_2 emission rights [11] (Fig. 17.6), we find that, after the severe drop in the prices of those rights in the second half of 2008, prices do not cover the lowest costs

Table 17.5 Values of CO_2 emitted, captured or avoided for CCS operating in different power plants [8]

Fuel	Power generation technology	CCS capture technology	CO_2 emissions (g/kWh)	CO_2 captured (g/kWh)	CO_2 Avoided (g/kWh)		
					Same tech baseline	PF baseline	NGCC baseline
Coal	Pulverised fuel	None	743	–	–	–	–
		Post-combustion	92	832	651	651	287
		Oxy-combustion	84	831	659	659	295
	IGCC, dry feed	None	763	–	–	–	–
		Pre-combustion	142	809	621	601	237
	IGCC, slurry feed	None	833	–	–	–	–
		Pre-combustion	152	851	681	591	227
Gas	Gas turbine combined cycle	None	379	–	–	–	–
		Post-combustion	63	362	316	680	316
		Oxy-combustion	12	403	367	731	367

estimates for CCS for any conventional technology. Also, if the current market price of future CO_2 remained relatively constant, it will be even be more profitable in 2030 to purchase allowances than to incorporate the CCS technology to power plants.

17.4 CO_2 Emissions and External Costs

The IEA [8] published a study that shows the amount of CO_2 emitted, captured or avoided by power plants with different technologies for electricity production (Table 17.5). The baseline power plant produces electricity without CCS technology. The table shows three types of power plants: (1) with the same technology as used with CCS operation, (2) pulverised fuel (PF) and (3) natural gas combined cycle (NGCC).

Consequently, adding CCS increases CO_2 emissions per kWh in power plants, since the thermal efficiency for these plants decreases (except in some cases where the replaced technology is outdated and inefficient). Pre-combustion CCS technologies and post-combustion capture about 85–90 % of emitted CO_2, while oxy-fuelling plants capture rate is about 90–97 %. Also, consider that each technology captures CO_2 with diverse purity, and variations in purity affect the value of the CO_2 produced.

In relation to the emission of other gases, the same studies indicate that, when CCS technologies are applied, sulphur dioxide emissions decline, but emissions of nitrogen oxides increase except for oxy-fuelling processes [8]. It should be also indicated that post-combustion processes increase the generation of waste, especially if amines are used.

Studies of external costs that can generate the different CCS technologies have not been detected to date.

17.5 Future Technology Trends

Future technological trends are established according to the major challenges that CCS has for a principal role in mitigating CO_2 emissions. In this respect, the biggest challenge lies in scaling by a factor of ten or more CCS facilities, as well as lowering the energy demand, especially in CO_2 capture processes.

On the other hand, as the efficiency of power plants increases, the lower the cost of CO_2 capture and storage per kWh is produced. Then, new combined cycle plants, using superalloys, high temperature hydrogen turbines or more efficient CO_2 separation techniques could result in similar electricity costs to existing plants without CCS [7].

In terms of each technology described above, the technological trends are as explained below.

17.5.1 Pre-Combustion Capture

The trends in pre-combustion capture processes are mainly focused to reduce the large amount of additional power needed to capture CO_2 prior to combustion. Therefore, the main effort is focused on exploring new paths in the thermodynamic phase diagrams for the capture and subsequent release of CO_2. There is also substantial work to be produced on the development of ultra-thin membranes for CO_2 high selectivity and large flows [12]. Finally, there is a need to improve the CO-shift and CO_2-capture with new adsorption media, new catalysts and by optimising the process integration in the power plant.

17.5.2 Post-Combustion Capture

The main technological challenge in this area is to achieve an attractive adaptation of existing coal power plants for the introduction of this technology [8] by reducing the large parasitic load that CCS imposes on a power plant, mainly due to CO_2 capture and compression. Development of new project designs and novel power plant integration schemes are largely aimed. For example, using waste heat or increasing the temperature of steam in the power plant could increase the net efficiency of the system.

A major effort is needed to design more effective catalysts, stable to gas pollutant emissions and to high temperatures, and providing lower costs than current catalysts based on MEA (monoethanolamine) [12]. This effort is applied not only to the catalysts but also to novel chemicals for CO_2 dissolution and absorption, membranes, materials that react with CO_2 and fix it permanently, etc.

Finally, certain exhaust gas components form by-products, which can result in a loss of absorbent and an increase in operating costs. Pretreatment of the exhaust gas can limit the absorbent losses. On the other hand, atmospheric emissions from amine-based post-combustion processes must be fully understood and quantified to better know the environmental impact of this technology.

17.5.3 Oxy-Fuelling

This option is being considered the most promising for applications in the industrial sector, specifically in the cement industry. The oxy-fuelling technology can reduce CO_2 capture costs to less than half in relation to the post-combustion process [13]. Future efficiency improvements to the oxy-fuelling combustion process for power generation include employing advanced ultra-supercritical steam turbine cycles and gas pressurised oxy-fuel combustion, as it reduces the fan auxiliary power and improves the boiler efficiency.

Also, research activity is focused on exploring procedures to reduce excess oxygen required in the process and identify uses for the nitrogen produced [13]. The most profitable strategy for this technology will require the development of advanced materials that do not deteriorate at high temperatures in oxygen-enriched atmospheres.

17.5.4 Chemical Looping

In this technology, research is focused on applying the carbonisation processes on minerals. Consequently, the reaction product would consist on a solid material with added value such as high surface area silica, iron oxide and magnesium carbonate. These materials can provide a safe and durable CO_2 capture. Also, there is research activity to use iron oxide nanoparticles to convert syngas into high purity hydrogen, simultaneously to the CO_2 capture. This process is mainly considered for synthesis gas produced from biomass.

Finally, there is important research activity on simulation process techniques in order to study the dependence of its energy efficiency with respect to the temperature of the reaction, gas flow and particle size.

17.5.5 Transport of CO_2

For future CO_2 transport capacities to deploy CCS, the identification of potential clusters, hubs and networks is needed and should be based on a comprehensive review and matching of sources (CO_2 emitters) and sinks (CO_2 storage deposits). A clustered transport system could potentially save an important percentage of costs compared to a point-to-point system, depending on the scale of the cluster. In addition, developing such a network can significantly reduce barriers to future investment. Another important aspect being studied is finding the most adequate location of the CCS process in industrial facilities and how to be integrated [13].

Though the majority of transport networks will mainly use pipelines, for some transport corridors, ship transportation can be an alternative option in the future. Comparing the unit costs of CO_2 transport between ships and pipelines would indicate that pipelines are the most cost-effective solution when sources and sinks are located close to each other, but with increasing distance, the cost of pipelines (especially capital investment) gradually increases and can make shipping an economically more competitive solution [5]. Also, ship transportation provides flexibility in changing the capture site, the transportation route and storage site in a CCS project.

17.5.6 CO_2 Storage

Finally, the storage of CO_2 in ocean water and by mineral carbonatisation is being studied. These studies still require additional evidence to primarily ensure no environmental damage, especially when storing in oceans is used, as it could increase ocean acidification [14]. This acidification risk has already produced the exclusion of CO_2 storage in oceans as future technology by the European Union [7]. Turning the gas into solid by chemical reactions such as carbonatisation also poses some major challenges such as the large amount of reagent needed, and finding adequate locations to store the large amount of reaction product generated.

Finding alternative methods of measuring the extent of the stored CO_2 is an important area that requires further research. Reflection seismic waves have been successful as a tool for some thick layers with high porosities, but generally it has been less successful in thinner layers with lower porosities (such as In Salah, Algeria), and it is also costly. Satellite methods are attractive as they are low in terms of cost and unobtrusive but require quite specific surface conditions including limited or no vegetation cover. Also, other research areas are modelling trapping mechanisms and rock deformations, and thermodynamics analysis of complex fluids and solids.

17.6 Pre-Production Highlights 2009–2011

17.6.1 Entry Into Operation of the First CCS System Integrated in a Power Plant [15]

The 30-MW power plant was commissioned in Schwarze Pumpe in September 2008 by the company Vattenfall and is intended to serve as a test to be applied in

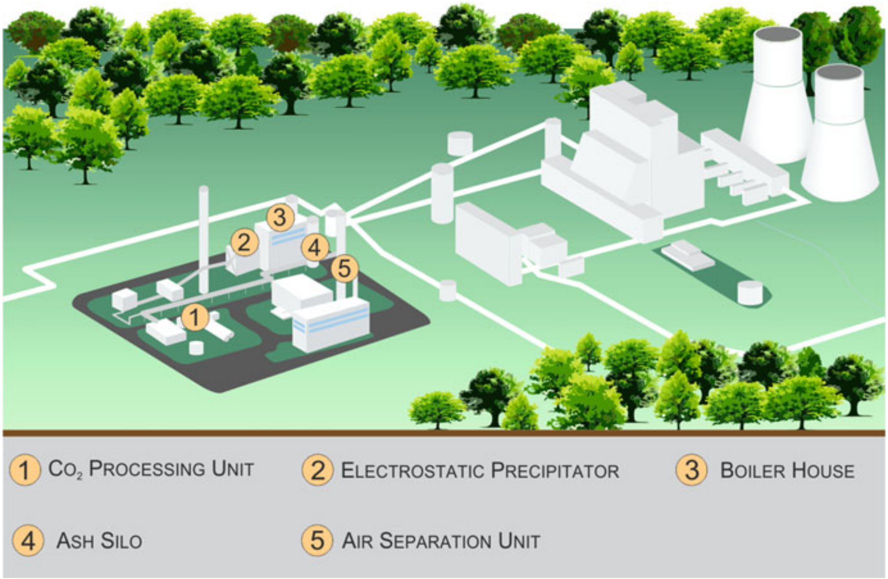


Fig. 17.7 Scheme of the first CCS integrated power plant

commercial-size power plants (250–350 MW). The plant (Fig. 17.7) will be tested for 3 years, estimating an operating period of at least 10 years. The plant uses coal as fuel, fired in an atmosphere of oxygen and recirculated CO_2 mixture that also contains water vapour. The exhaust gas is treated to remove sulphur oxides, particulates and other pollutants. Finally, the water is condensed and liquefied CO_2 is injected underground. An amount of 100,000 t CO_2 storage is estimated in 3 years [16]. Other oxy-fuelling power plants on course are Total's Lacq project in France, an oxy-natural gas 30 MW_{th} boiler in service since early 2010; CS Energy transforming a 30-MWe pulverised coal power plant to oxy-fuel combustion in Queensland, Australia (2011); and CIUDEN's oxy-coal test facility in Spain that includes a 20-MW_{th} oxy-pulverised coal (PC) boiler and a 30-MW_{th} oxy-circulating fluidised bed (CFB) boiler (2011) [5].

17.6.2 Entry Into Operation of the First China's CCS Facility [17]

In late 2009, Erdos, on the plains of Inner Mongolia, has entered into operation being the first facility in China to capture and store CO_2. It consists on a coal-to-liquid plant that burns coal and produces 3.6 Mt CO_2 per year, which is injected to recover oil with a capacity to produce 1 Mt/year of diesel and other petroleum products. The facilities are operated by the largest Chinese producer of coal, Shenhua Group, and due to its capacity, makes it the largest CCS facility worldwide.

17.6.3 Huaneng Group Opened a CCS Facility That Claims a USD 30–35/t CO_2 [18]

Huaneng Group opened a facility that captures 3 % of the CO_2 emitted by the existing 1,320-MW coal-fired Shidongkou power station using post-combustion technology. The company claims a mere cost of USD 30–35/t CO_2 (EUR 22–25/ t CO_2), including the further expense of purifying the captured gas for use in the food and beverage industry. This cost is far below the one shown in Sect. 17.3 for this technology. The company has not revealed all the technical details but considers that unspecified changes in the design of the plant and the chemistry of the solvent have increased the energy efficiency of the system by 11–14 % and reduced the cost of installation by a factor of 10 per tonne of CO_2. Critics consider that a cheap labour and fewer regulatory burdens can be the main ingredients for this cost reductions, as general costs in the Chinese coal industry tend to be about one-third of those in the USA.

17.7 Innovation Highlights 2009–2011

17.7.1 CCS Through Nanotubes [19]

Peripheral company announced that is developing gas separator membranes based on nanotubes, and the first prototypes are expected to be applied very soon to capture CO_2. These selective membranes diffuse CO_2 much more freely (at speeds 100 times larger than conventional membranes), so less energy will be needed in the processes leading to compression. Also, research continues on how to obtain even more permeable nanotube adhering to their end molecules to chemically attract CO_2 but not other gases. This behaviour has already been tried with other membranes, but the more successful results are those based on nanotubes.

17.7.2 Metal-Organic Frameworks as New Materials for the Capture of CO_2 [20]

Metal-organic frameworks are crystal lattices of organic compounds and metal atoms and have the advantage of a huge internal surface area in which the CO_2 molecules are captured, acting like crystalline sponges. The metal used in these lattices is magnesium, which produces the right environment to bind CO_2. The most interesting property of this material is that it can release 87 % of carbon dioxide at room temperature, and the remaining 13 % by heating to about 75 °C, which is well below the temperatures currently required to regenerate conventional chemical solvents.

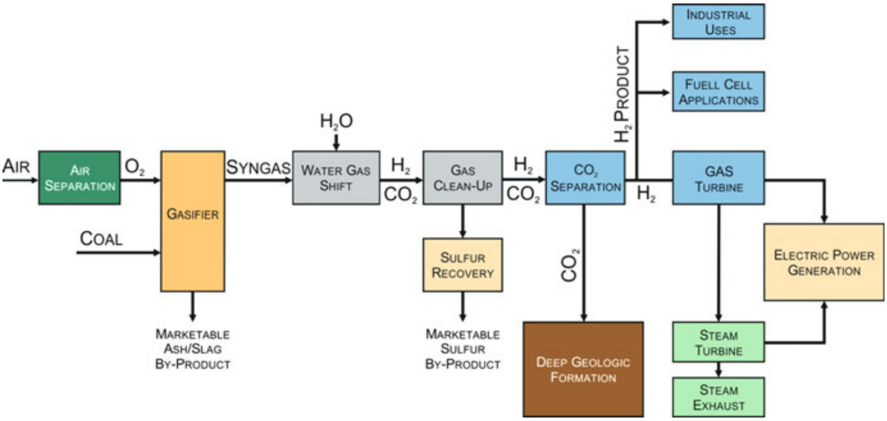


Fig. 17.8 Diagram of the FutureGen Alliance integrated IGCC plant with CCS technology

17.7.3 FutureGen Project: Final Adoption in June 2009 [21]

After many vicissitudes during the past years, the Obama Administration announced on 12 June 2009 the approval and launch of the FutureGen Project. The project, whose main partner is the U.S. DOE, is also part of an alliance of many large companies from various countries. The project aims at a single location (Mattoon, Illinois) to build a coal-fired power plant (275 MW), equipped with CCS for the virtual elimination of emissions, which are stored in a deep aquifer close to the plant (Fig. 17.8). This plant will also produce large amounts of hydrogen. The coal gasification technology to be used is the so-called IGCC with pre-combustion CCS. The project is currently in the construction phase.

17.8 Statistics of Publications and Patents

Regarding the number of publications in the period 2001–2011 for CCS (Fig. 17.9) [22], it can be noted that the volume is small in relation to other technologies exposed in this book. This can be attributed to the significant financial cost involving the development of CCS prototypes. This low volume is in contrast to the thousands of publications annually devoted to CO_2 capture and storage, but more focused on economic or environmental issues.

The research activity has been rising, mainly the last 4 years, which can be attributed, among other things, to the establishment of markets for CO_2 emission permits, with economic impact in large companies.

The major research activity lies in the post-combustion technology, which could be attributed to the existing dominant effort introducing CCS in existing coal-fired

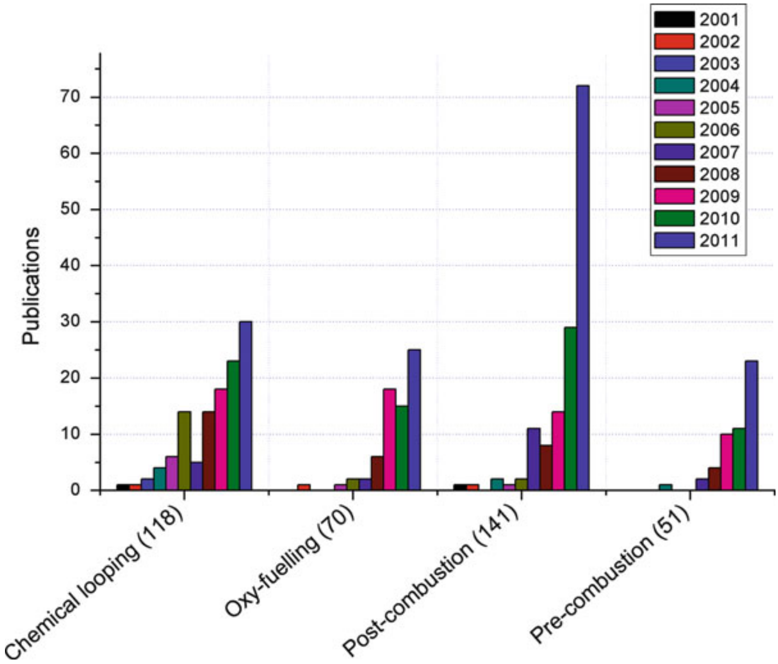


Fig. 17.9 Number of scientific publications during the period 2001–2011 for different CCS technologies [22]

power plants. This effort is mainly focused on achieving lower energy costs in this process by using new improved chemical absorbers.

The research activity in chemical looping technology also ranks high, which could be contradictory, as it is currently the less developed technology. However, this result could be explained by considering that the chemical looping technology shows many attractive aspects for its development, and also low research costs compared to other CCS technologies.

Research activity in pre-combustion and oxy-fuelling is smaller. However, rapid growth is found in the last 4 years which, if sustained, may place these technologies close to chemical looping and pre-combustion.

In relation to patents (Fig. 17.10), the classification of technologies included in the worldwide database used [23] differs from the exposed in this chapter, and it is mainly related to different capture technologies (biological, chemical, absorption, adsorption, membranes or diffusion, rectification and condensation), where the activity is dominant and growing. Adsorption, absorption and chemical separation lead the number of patents as they are the most robust technologies in pre- and post-combustion CCS, being membranes/diffusion and condensation/rectification second in volume. Biological separation is the less developed technology because of the novelty of the process, but it is also growing.

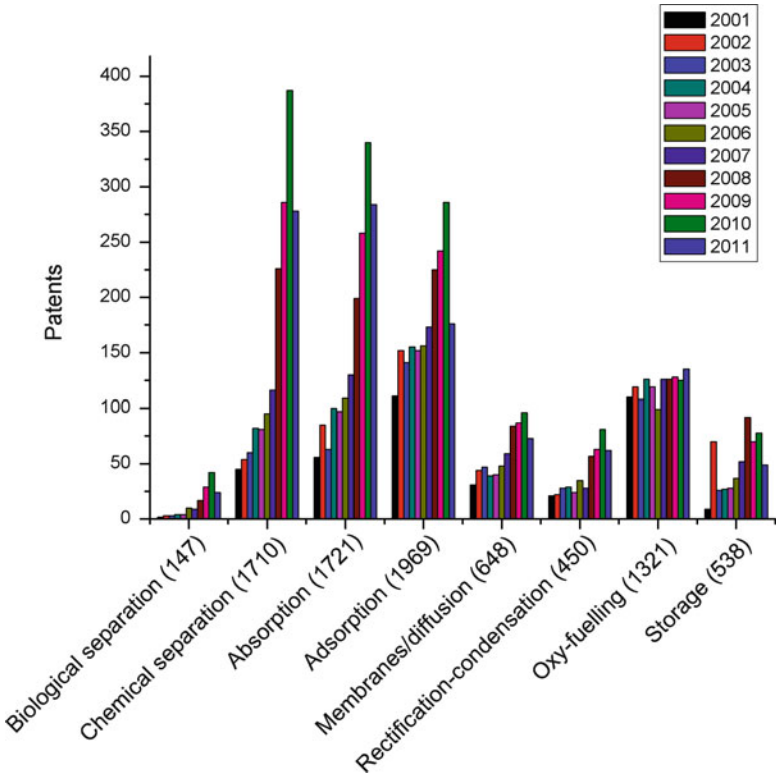


Fig. 17.10 Number of patents during the period 2001–2011 for different CCS technologies [23]

Also, a large number of patents related to oxy-fuelling are recorded, but the number annually detected is stable. This can be attributed to the fact that the patents related to oxy-fuelling have been applied in other technology areas different than CCS.

Finally, patents have been also detected and related to subterranean and submarine storage, but much lower in number than the patents devoted to capture, as the key ingredients for the success of the CCS technology must be found in this area.

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