

Chapter 2

Renewable Energy and CO₂: 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 CO₂ 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

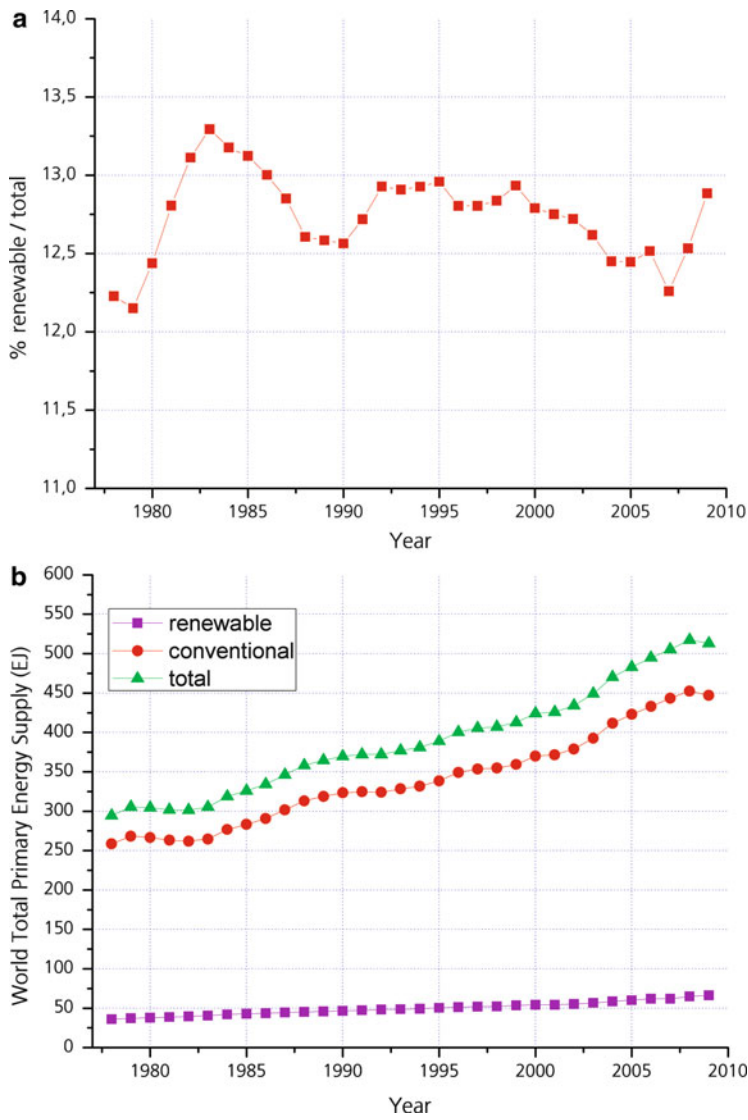


Fig. 2.1 (a) Percentage of world TPES from renewable technologies and (b) evolution of TPES from renewable and conventional energy technologies [1]

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

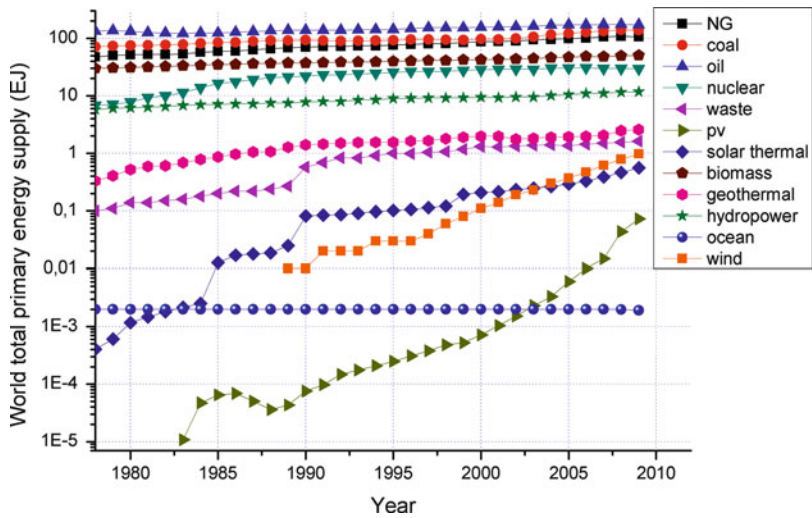


Fig. 2.2 Evolution of TPES from the different conventional and renewable energy technologies [1]

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
<i>Total Renewable</i>	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	
<i>Total Conventional</i>	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.

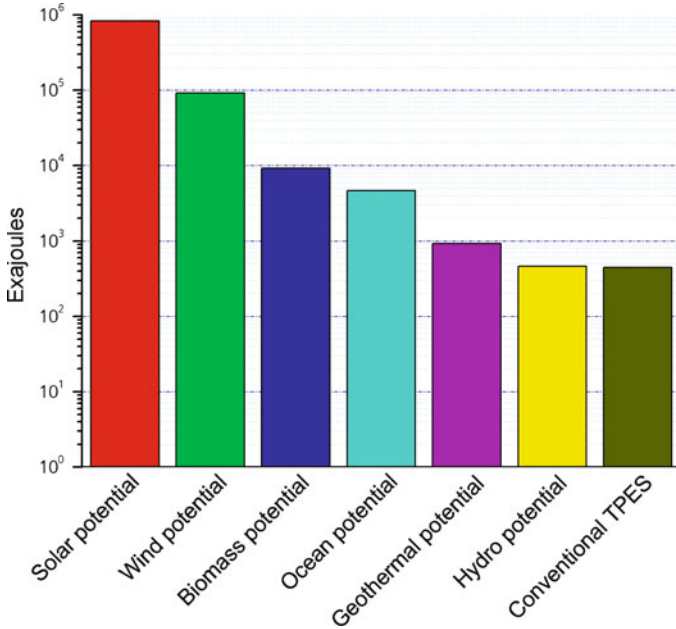


Fig. 2.3 Global technical potential for the different renewable energy resources, and compared to the world conventional annual TPES in 2009 [2]

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

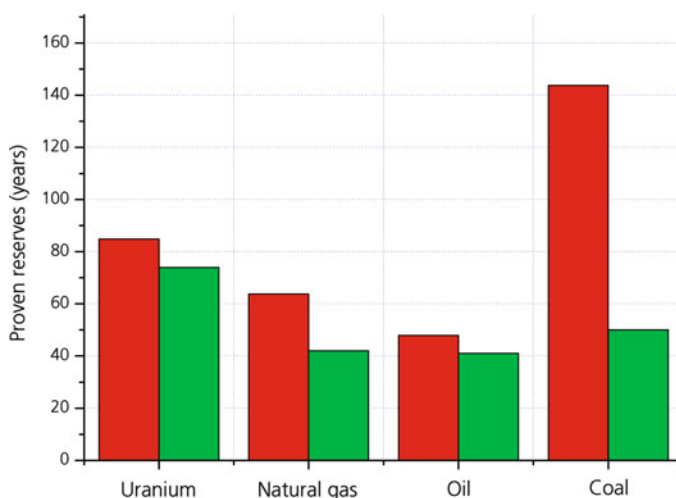


Fig. 2.4 Proven reserves of conventional energy resources in terms of years covered at 2009 TPES rates (red bars), and also adding the 2000–2009 average annual TPES growing rates (green bars)

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].

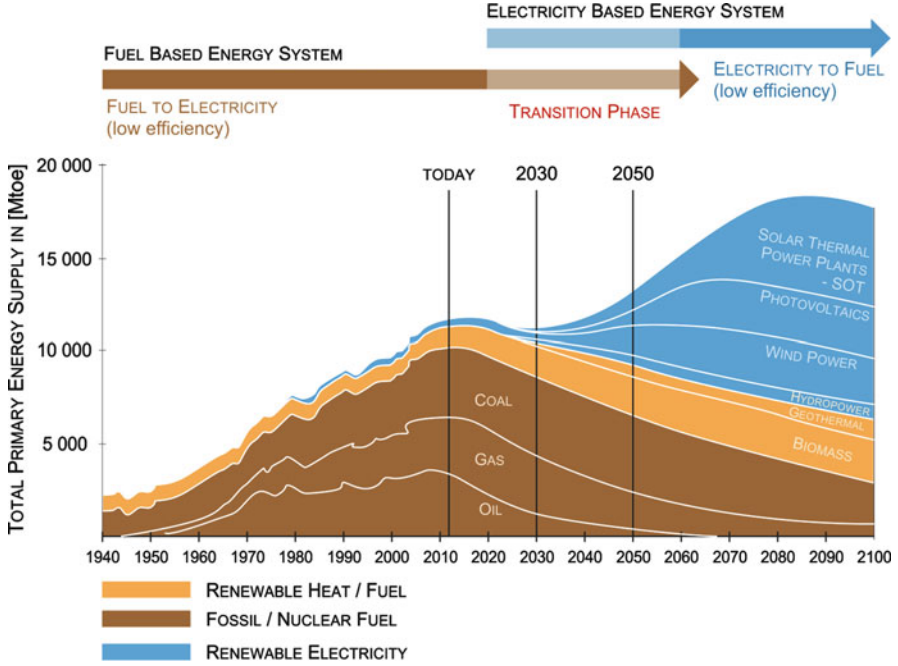


Fig. 2.5 World TPES evolution for the different energy resources and technologies, adding an example of energy mix forecast considering energy production peaks for oil, natural gas and coal proposed in the literature [8]

2.2 Evolution of CO₂ 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 CO₂ 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 CO₂ 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

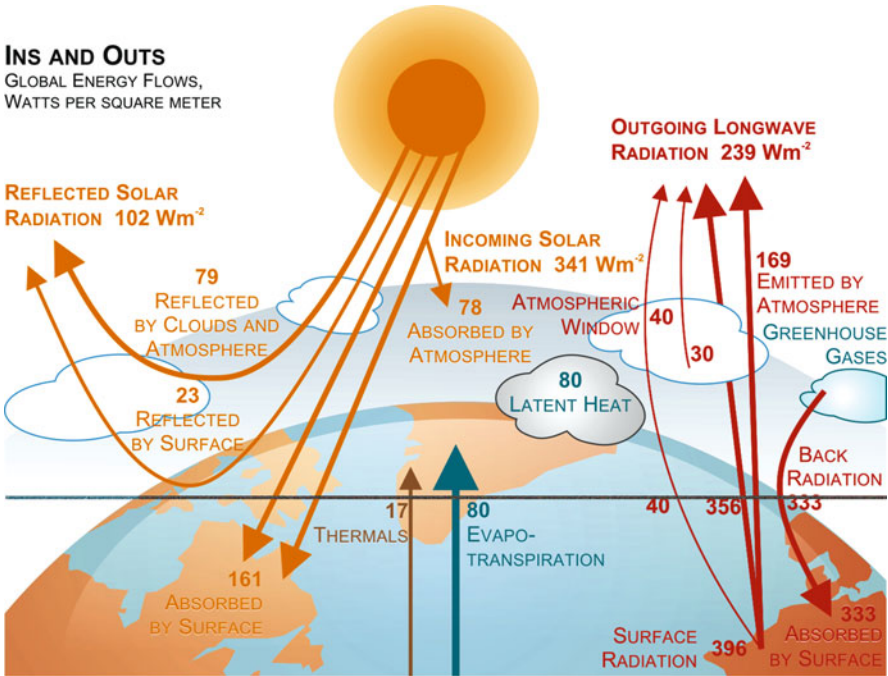


Fig. 2.6 Description of the thermodynamic balance on Earth [13]

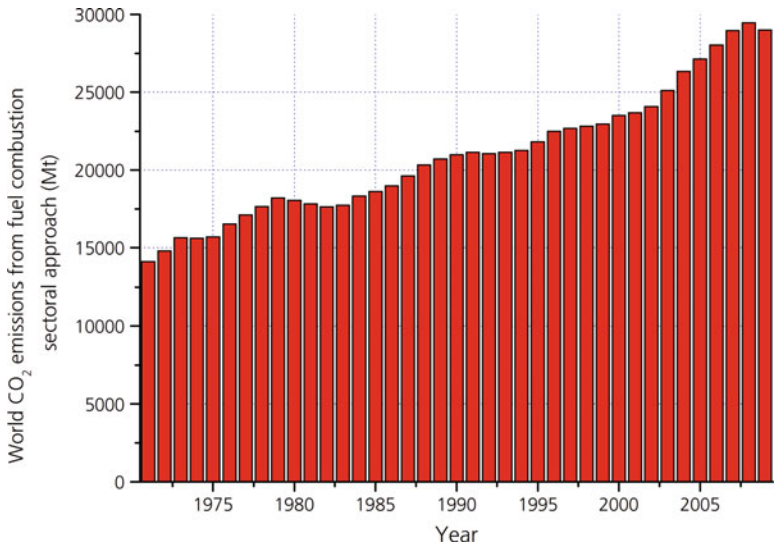


Fig. 2.7 Evolution of the world annual CO₂ emission rates in the period 1978–2009 [1]

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
<i>Total sources</i>	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
<i>Total sinks</i>	7.9 ± 0.6	8.7 ± 0.7
Global residuals	0.1 ± 1.0	0.1 ± 1.0

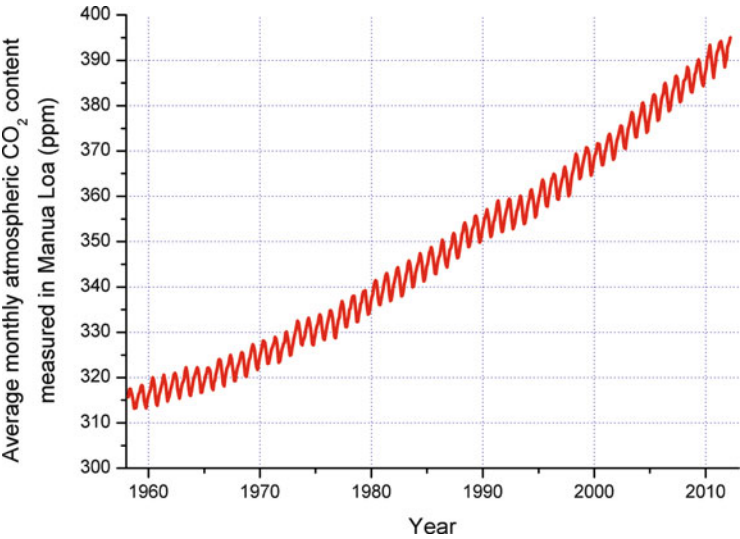


Fig. 2.8 Average monthly atmospheric CO₂ content measured at Mauna Loa Laboratory (Hawaii) [15]

in global CO₂ emissions, and established forest is decreasing its role as CO₂ sink. Consequently, the atmosphere is increasing its share in the carbon budget and, consequently, an increase in atmospheric CO₂ content is produced.

Increasing CO₂ emissions to the atmosphere is causing the average CO₂ 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 CO₂ 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].

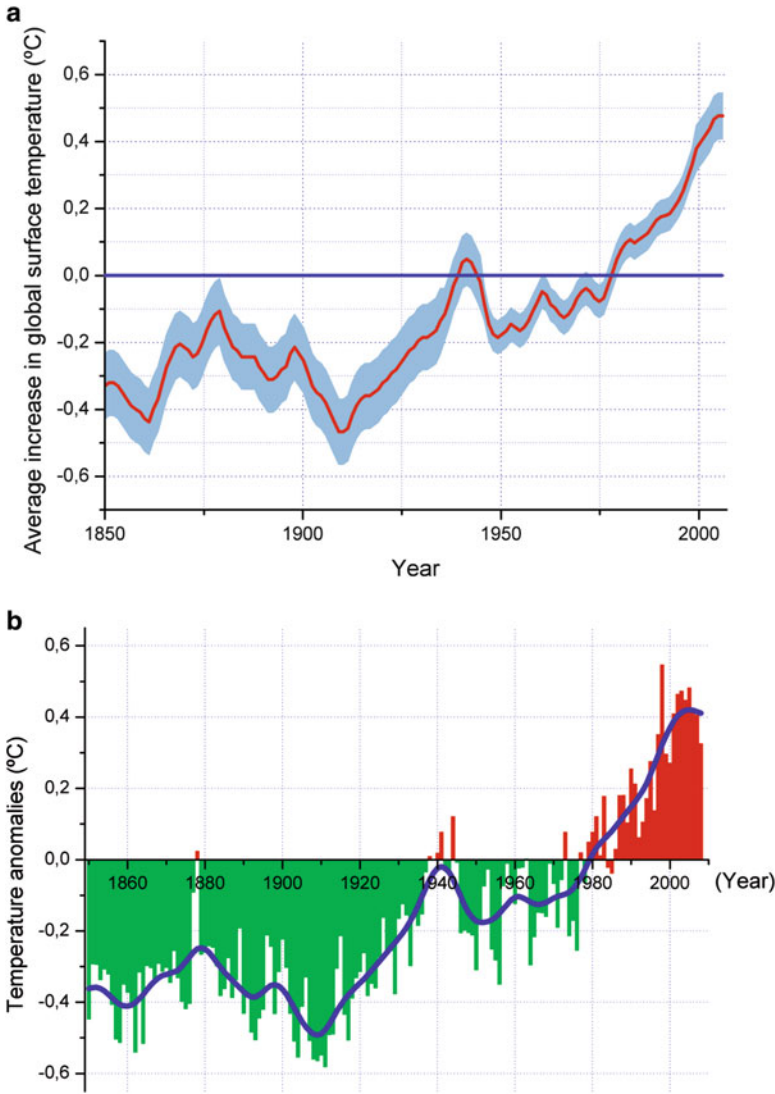


Fig. 2.9 (a) Increase in average global temperature over the period 1850–2007, considered by the International Panel on Climate Change [16]; and (b) measurement of the temperature anomalies in the period 1850–2008 according to the Met Office Hadley Centre [17]

This rise in CO₂ 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 CO₂ levels in the atmosphere are not yet stabilised [13]. Global warming is not only

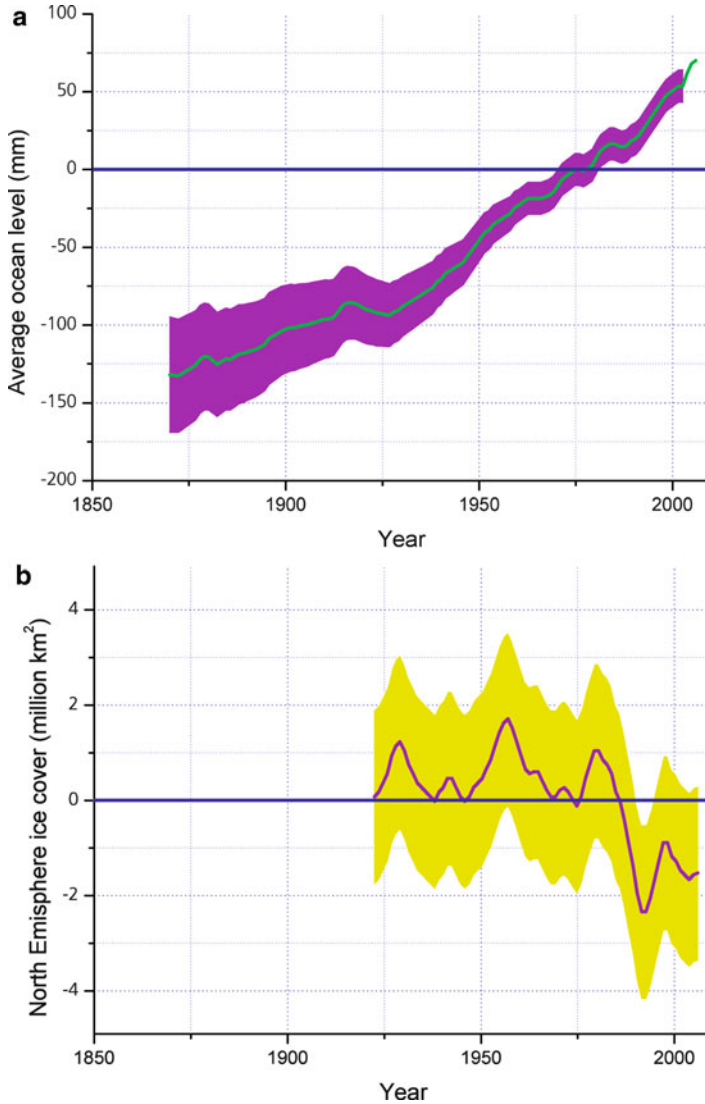


Fig. 2.10 (a) Increase in the average sea level in the period 1870–2007 and (b) changes in the extent of the Arctic ice cap in the period 1920–2007

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 CO₂ 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 CO₂ levels in which the atmospheric composition will be stabilised in the future (Fig. 2.11) [16].

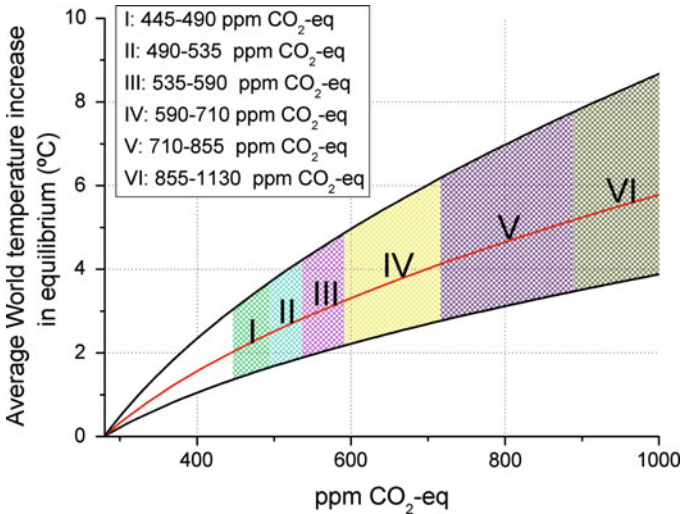


Fig. 2.11 Projected average world temperature increase in equilibrium as a function of different CO₂ concentration ranges in the atmosphere [15]

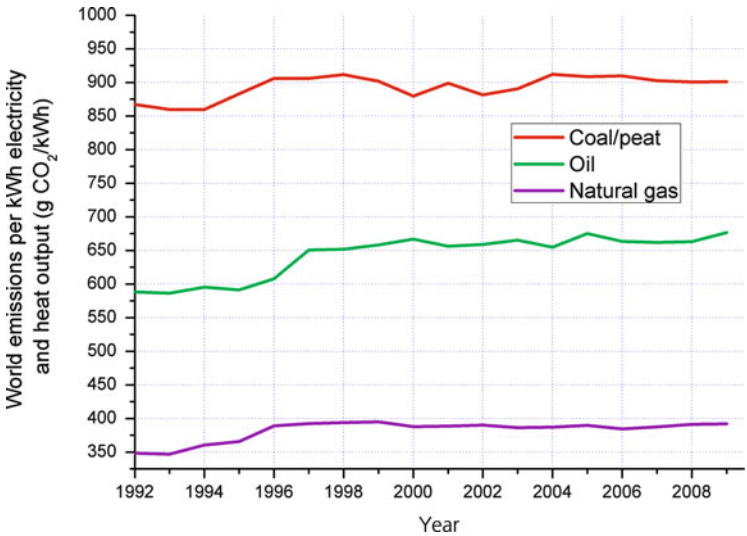


Fig. 2.12 Evolution of CO₂ emissions per kWh of electricity produced by conventional power plants fired with coal, oil or natural gas [1]

Some technological advances in the energy sector can help to reduce the CO₂ 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 CO₂ emission rates from the energy sector should



Fig. 2.13 Evolution of the daily CO₂ 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 CO₂ emitted.

To this purpose, some measures derived from the implementation of the Kyoto Protocol have been considered to encourage large industries to reduce their CO₂ 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 CO₂ emissions and even the introduction of technology to capture and storage CO₂ (cost above USD 40/t CO₂). However, it is estimated that this market has induced a CO₂ 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.

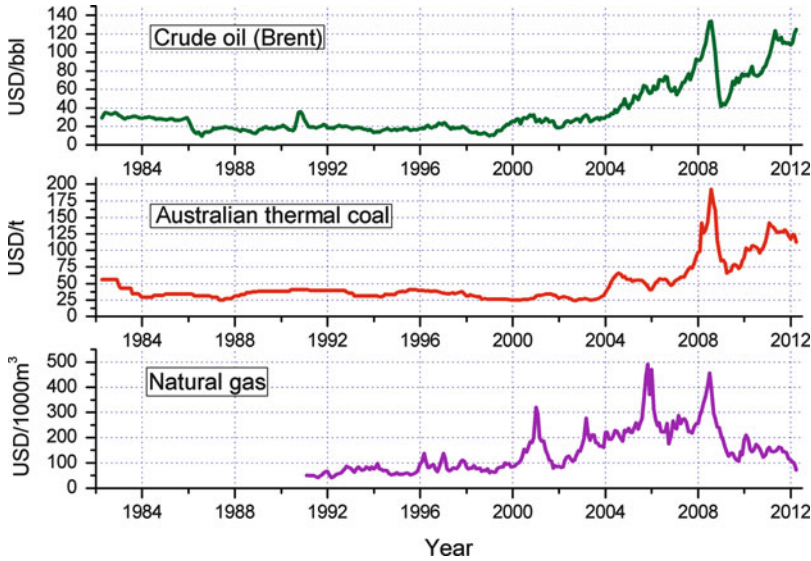


Fig. 2.14 Evolution of the oil, coal and natural gas prices in recent decades [25]

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

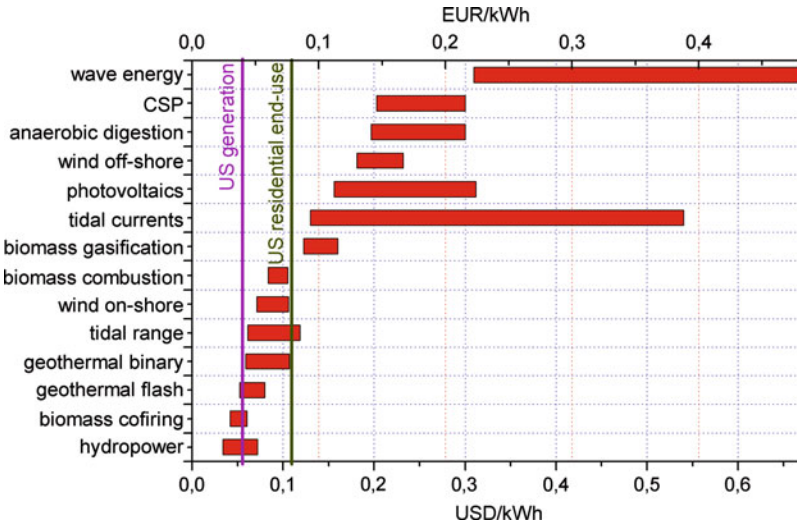


Fig. 2.15 Electricity costs in 2011 from different renewable energy resources, and compared to US average generation and residential end-use price

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}

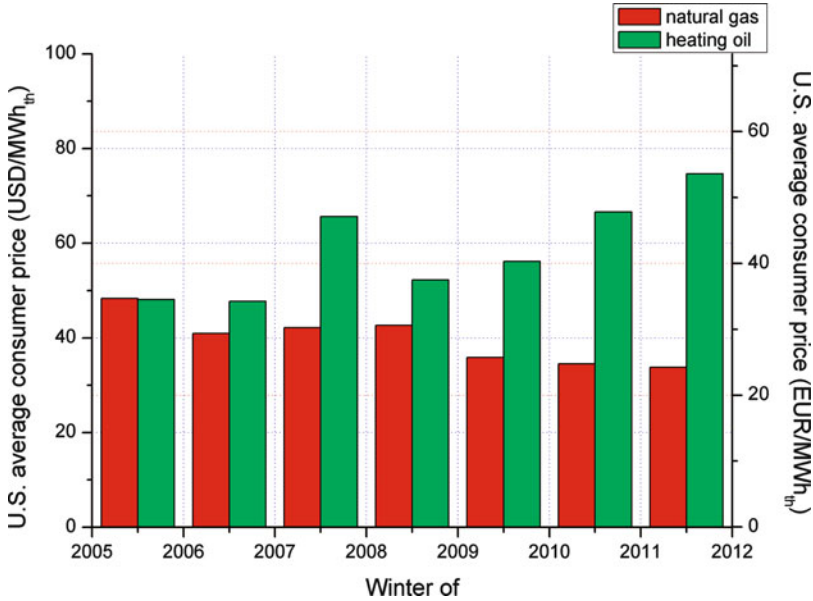


Fig. 2.16 Evolution of U.S. average consumer price for heating oil and natural gas

(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)

	Countries A	% 2009	Countries B	% 2009	OECD country	% 2010
		Hydro included		Hydro no included		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.

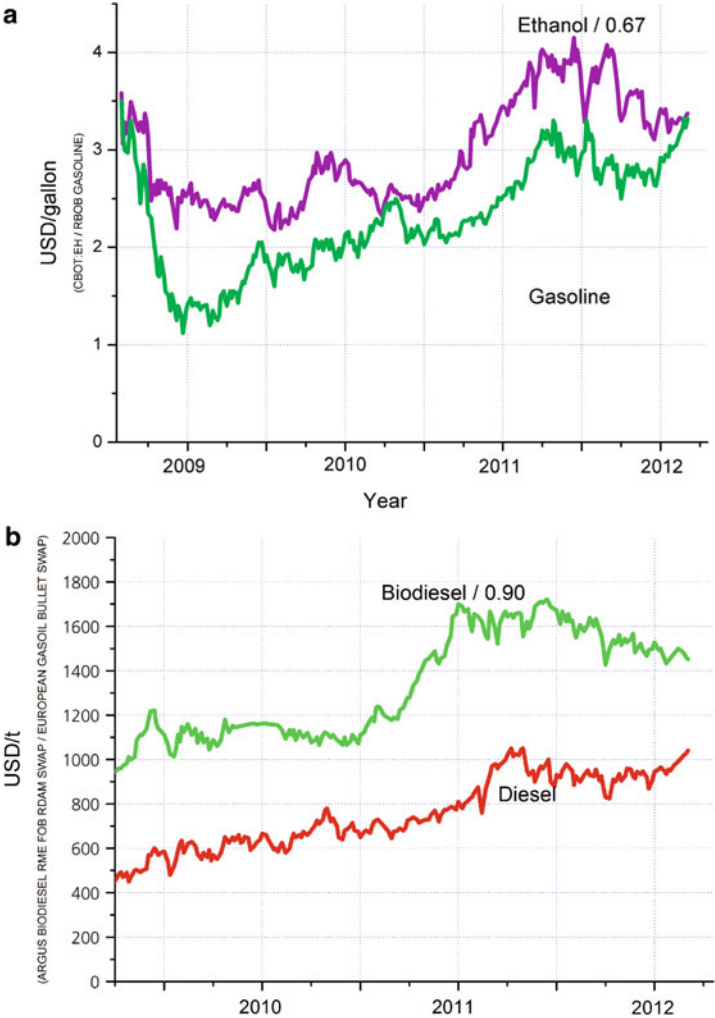


Fig. 2.17 Price evolution for different fuels in the futures market (balancing the difference in calorific values) (a) ethanol compared to gasoline and (b) biodiesel compared to diesel (source: INO)

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]:

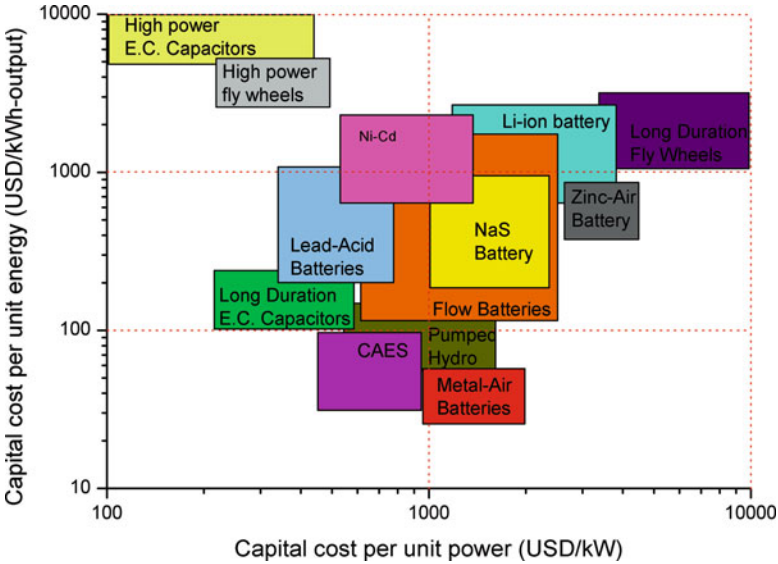


Fig. 2.18 Scheme of capital costs per unit of energy and per unit power for different storage systems [32] (CAES: compressed air energy storage, EC capacitors: electrochemical capacitors)

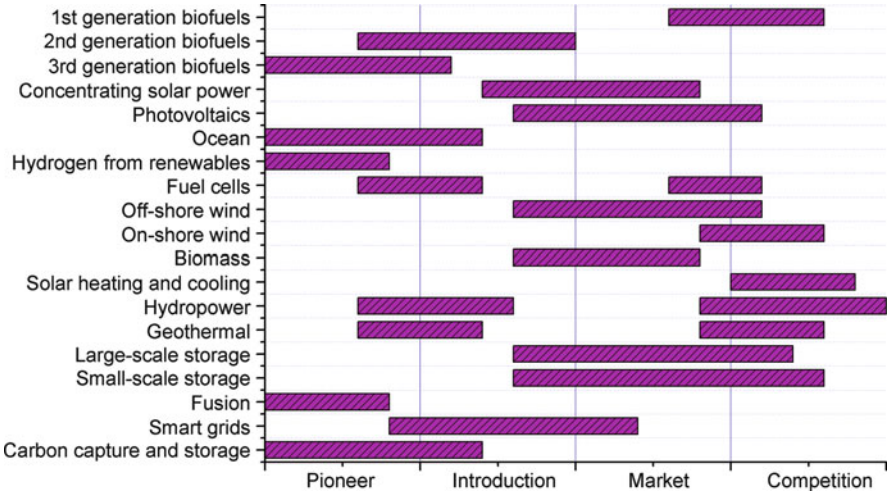


Fig. 2.19 Stage of development for each technologies discussed in this book

- 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 CO₂ 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: CO₂ 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 CO₂ emissions, at present it should be noted that the production of electricity with all renewable technologies produce CO₂ 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

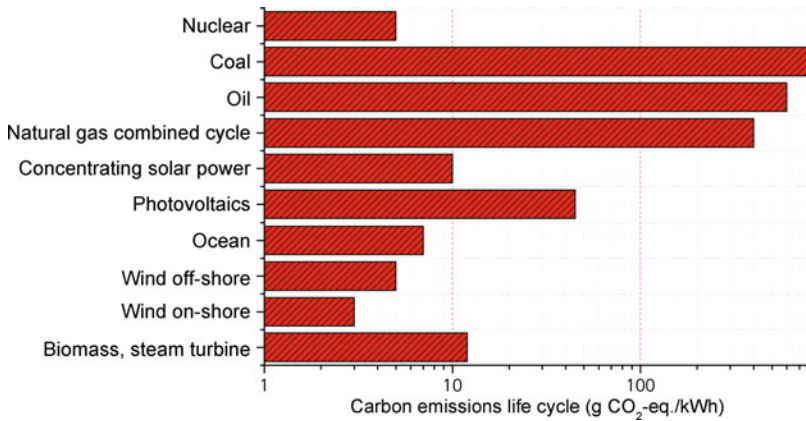


Fig. 2.20 CO₂ emissions per kWh of electricity produced from different renewable energy technologies considering the entire lifecycle of these systems [34]

(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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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

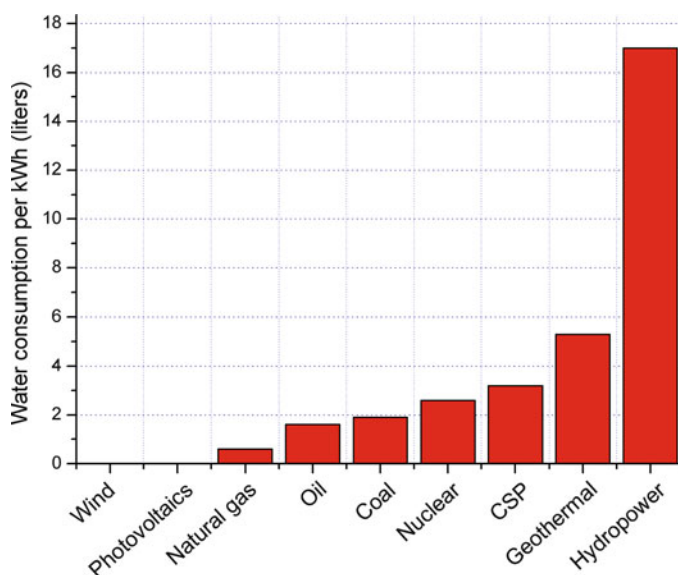


Fig. 2.21 Water consumption per kWh for different conventional and renewable energy technologies [36]

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

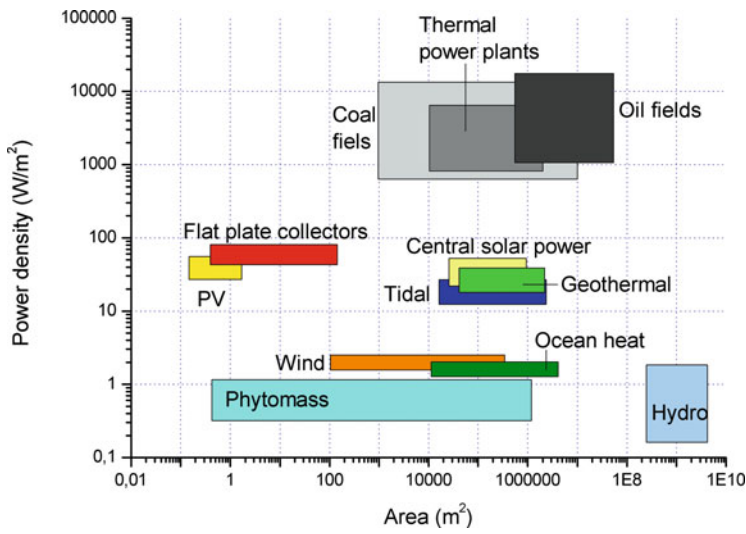


Fig. 2.22 Power density per unit area for different conventional and renewable energy resources and technologies [38]

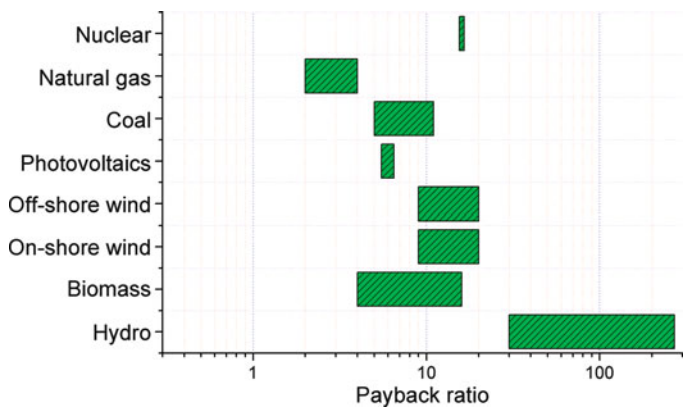


Fig. 2.23 Energy payback ratio for different conventional and renewable energy technologies [39–42]

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

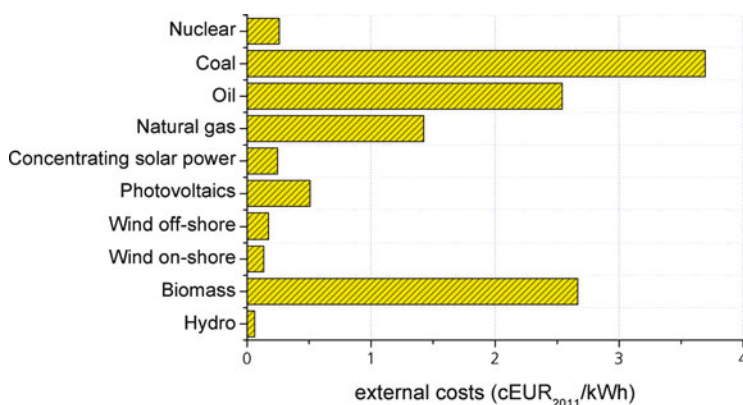


Fig. 2.24 The external costs per kWh for different renewable and conventional energy technologies [44]

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 CO₂ 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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