THE EUROPEAN ENERGY SYSTEM MOVING TO A COMPETITIVE LOW-CARBON ECONOMY

A synopsis for European policy makers and concerned citizens

2016

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PREFACE

The main object of this booklet is to provide to non-specialists the necessary information on the current energy situation and its effective management, thus helping the general public understand and participate in the decision making processes related to climate issues, environmental effects and sustainability aspects.

At present, the situation on the use of energy is quite different in the OECD countries, like the European ones (EU-28), and the non-OECD countries. While in countries like China and India, the use of energy is expected to grow intensively during the next decades, in the case of Europe, on the contrary, energy use is estimated to slowly decrease. Consequently, this report will focus mainly on the European situation. It is interesting to remark first that although the European economy represents about 22% of the world economy, Europe's emissions account for only 11%. However, it is an unfortunate fact that the influence of carbon emissions on global climate change is practically independent of the location where the emissions originate.

One of the most important national priorities of any country is to secure its energy supplies, especially in the case of Europe which imports more than half of its energy. Therefore, each of the EU-28 countries should diversify its supplies, increase its local resources (e.g., renewables), calculate its particular energy generation costs and, taking into account all these considerations, evaluate the adoption of its most convenient energy mix. What seems fairly clear is that the global increment of the share of electricity within the total energy demand will increase as our society becomes more technologically advanced (4th industrial revolution, electric vehicles, etc.). This fact will also help to reduce the so-called Energy Sector Carbon Intensity Index, or number of tonnes of CO_2 emitted per unit of energy supplied.

As a final remark, we would like to stress the role of research on advanced materials as key enabling technologies for secure energy and sustainable development. Some of the research priorities in advanced materials and nanotechnologies are related to efficient solar cells, blades for wind turbines, efficient catalysts for captured CO_2 conversion into natural gas, materials for fuel-cell electrodes, batteries with high cycling rates, etc. In addition to its role in R&D, we believe that Europe should continue to act as a leading party in the international negotiations for Climate Change like the recent UN Climate Conference (Paris 2015).

ACKNOWLEDGEMENTS

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Strasbourg, September 2016

STRUCTURE OF THE MANUSCRIPT

Section 1 starts with a short introduction to the economic and socio-political factors affecting the choice of energy supplies in a given country or region, Europe in this case. Next, **Section 2** explains the measures to be taken so that the global temperature should not increase by more than 2ºC by the end of the century as strongly recommended by the Intergovernmental Panel on Climate Change. Accordingly, greenhouse gas emissions, which are still growing, should first slow their rate of growth and then reverse this tendency and start to decrease within about one or two decades. Any delay will make much more expensive the drastic measures that will have to be taken in the future in relation to emissions abatement. In this sense, it is comforting to know that the European Union has understood this matter well and currently is the regional leader in the world in the rate of reducing emissions.

Section 3 discusses the amount of primary energy and how the ever-increasing percentage of electricity, which currently is the most important energy carrier is, expected to evolve. Next, **Section 4** deals with renewable energies, especially the intermittent ones (solar and wind) and the main role assigned to them in reducing global carbon emissions (**Section 5**).

Evidently, one of the most important aspects of energy generation and consumption is related to costs.
In **Section 6**, in order to compare costs on a systematic basis, we make use of the so-called Levelized Cost of Energy (LCOE). Comparing the magnitudes of the LCOEs, the first surprising aspect is the large spread in their values, which in the case of renewables can be attributed to the different intensities of the local resources (in the cases of wind and solar), financial interests and risks, life-span of the systems, etc. Other important factors are transport and distribution costs, which are not computed within the LCOE. Therefore, we introduce in this article the so-called System-LCOE.

The 2050 European Energy Roadmap of 2010 is also revisited since we think it will be difficult to reach some of its ambitious power targets which in some cases would imply around 90% carbon-free electricity generation. As discussed in **Sections 7-9**, a very large deployment of variable renewable energies (VRES) is a practically impossible task without the previous development of affordable energy storage (**Section 8**): large battery storage units at a competitive cost or hydrogen for long-term storage. Other advanced technologies discussed in **Section 8** that would allow substantial integration of VRES are Distributed Generation (DG) and Demand Response (DR). In addition, the deployment of Smart Grids would enable the incorporation of information and communication technologies in all aspects of power generation, distribution, and consumption.

Section 10 revises the EU energy and climate objectives (2020-2050). One problem arises from the fact that practically all targets are expressed in terms of emission reductions, but they are not identified in relation to the particular energy generating sources within the whole energy mix. Precisely, in the case of renewables, the energy components in a given mix should be specified in units of energy generated (electricity) in addition to the specification of the installed power capacities. Finally, **Section 11** exposes the main conclusions and makes a series of recommendations, for the case of Europe, related to emissions abatement, energy mix, storage, costs, research in advanced materials, implementation of smart grids, etc.

1 INTRODUCTION: EUROPE MOVING TOWARD A SECURE, SUSTAINABLE, COMPETITIVE, AND INTERCONNECTED ENERGY SUPPLY

The European Commission (EC) proposed in 2007 the Europe 2020 Initiative [EC 2010] that established objectives toward long-term policy plans in energy and climate change. The EU's strategy consisted of various ambitious objectives for the next decades on renewable energy generation, greenhouse gas emission targets, and energy efficiency for all Member States. Since climate change constitutes one of the main future menaces for humanity, the EC policies established concrete actions at European and national levels. As a consequence, in the next decades, greater investment in energy will be necessary, both to replace existing resources and to meet increasing sustainability requirements. Therefore, due to the great inertia with which alternative energy systems are implemented, decisions adopted today will condition the energy mix for the next 20 or 30 years. For this reason, we can consider that the pattern of energy production and use in 2050 is partly being established today.

The main socio-political and economic factors that affect the election of future energy systems and fuels are discussed below.

Security and diversity of supply

It is the responsibility of governments and politicians to secure their nation´s energy supply. This is especially so in the case of EU-28 countries, since more than half of their energy supplies have to be imported from countries outside Europe. As an example, about one-third of Europe's natural gas is delivered from Russia. In this sense, the utilization of indigenous stocks, like those provided by renewables, would highly enhance the security of supply and, in addition, can reduce imports significantly. Another very important aspect is that a wise energy mix should be diverse, composed of different kinds of fuels and resources, in order to minimize supply risks. Clearly, the development of renewable energies will help provide a greater variety of resources to the different European countries.

Sustainability and climate change

At present there is a broad scientific consensus that climate change and global warming have an anthropogenic origin. We can assert that in this aspect, Europe is the world´s leader in cutting carbon emissions. For instance, although the European economy represents approximately 22% of the world economy, Europe's emissions account for only 11%. In addition, the carbon content in the European electricity mix is the lowest of the great regions of the world. It is also expected that this trend will continue for the next decades according to the "European Roadmap for moving to a competitive low carbon economy in 2050" [EC 2011a, EC 2011b].

Distribution and interconnections

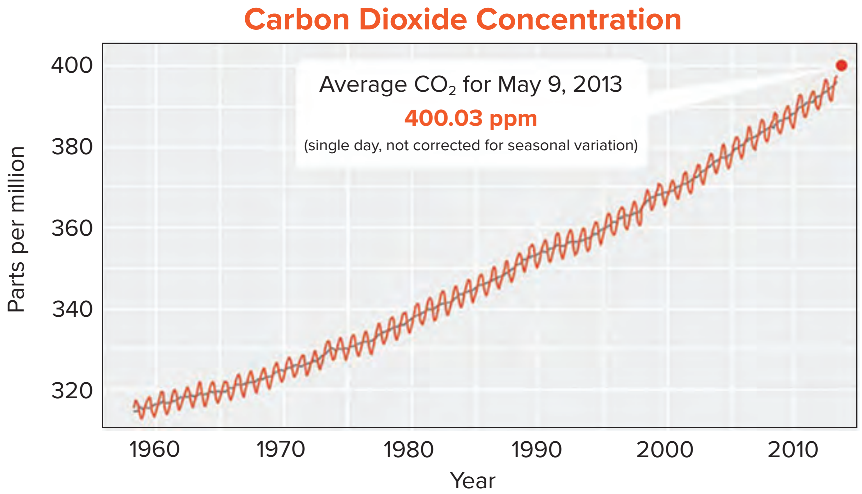
In the case of Europe, the energy distribution systems are of paramount significance since some of the most important fuels like oil and natural gas have to be imported to a great extent. On the other hand, from the point of view of electricity generation by renewables, Europe is the region of the world with the best per-capita performance. Renewable plants – due to their relatively small size, widespread distribution, and construction in locations with difficult access – pose additional difficulties to the distribution of the generated power. In addition, some European countries are too small to have completely independent distribution networks. For all these reasons, the construction of an efficient network of interconnections across the whole of Europe would greatly facilitate the distribution of energy and power across the different countries.

Competitiveness

The European Union´s growth strategy for the coming decades works on different areas to support a sustainable and competitive economy. In fact, its 2050 Energy Roadmap [EC 2011a] includes the word “competitive” in its title. The objectives of the EU on energy policy, in addition to guaranteeing security of supply, aim to be competitive throughout the economy, with a single energy market across the whole EU. The European governments have realized that most of the main challenges in the energy sector cannot be dealt with at the national level alone and, therefore, coordinated action is needed across the whole EU. The reduction of Europe’s increasing dependence on imported fossil fuels would clearly moderate risk pricing of energy supplies (mainly oil and gas). Consequently, in this booklet we will also discuss the competitiveness problems for the EU industrial and power sectors in relation to other regions of the world. In fact, higher electricity prices in Europe, as well as more stringent emissions controls, are pushing some of the more electro-intensive industries out of Europe, a phenomenon known as “carbon leakage”.

2 CLIMATE CHANGE AND CO_2 EMISSIONS: INTERNATIONAL ENERGY AGENCY SCENARIOS

In relation to climate change, probably some of the most negative recent news has been that the atmospheric CO_2 concentration has already reached the symbolic mark of 400 ppm (parts per million), as detected in May 2013 at the NOAA Earth System Research Laboratory in Hawaii [NOAA Observatory 2013]. This is the highest CO_2 concentration attained in the recent history of humanity. Furthermore, as can be checked in Figure 2.1, the slope or inclination of the concentration curve is also continuously increasing, that is, the rate of accumulation of CO_2 in the atmosphere is growing faster and faster.



Credit: NOAA/Scripps Institution of Oceanography

Figure 2.1. Evolution (1960-2014) of the carbon dioxide concentration in the atmosphere in parts per million (ppm) [NOAA Observatory 2013].

The main reason for this growth in CO_2 concentration has been the large amount of emissions sent to the atmosphere during the last decades, as a consequence of human activities mainly related to energy consumption: transportation, accommodation of buildings, industries, etc. In fact, in 2013, it amounted globally to 35.3 Gt (gigatonnes) [PBL 2014] (1 Gt equals one thousand million tonnes). What is really menacing is that if greenhouse gas emissions continue to grow at the same rate as in the last decades, the increase in temperature by the end of this century could be as much as 5-6°C according to the IPCC (Intergovernmental Panel on Climate Change) [IPCC 2013].

We can appreciate from Figure 2.2 [NOAA 2015] that, contrary to much recent discussion, the latest corrected analysis shows that global warming has continued and that there has been no slowdown in the rate of temperature increase. According also to the IPCC, in order to avoid a global warming greater than 2°C by the year 2050, it would be necessary not to surpass the mark of 450 ppm in CO_2 atmospheric concentration; however, as noted above, we have already reached the 400-ppm level [IPCC 2013].

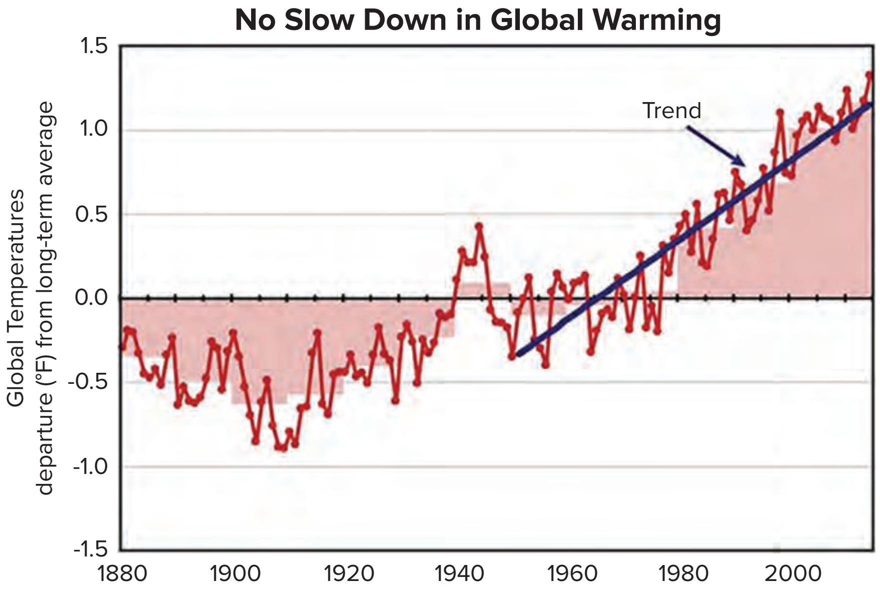


Figure 2.2. Global warming since 1880 in F degrees [NOAA 2015].

In coordination with the IPCC, the International Energy Agency (IEA) has proposed several scenarios or roadmaps, in particular, the so-called 6DS and 2DS Scenarios as shown in Figure 2.3 [IEA 2014], whose names will become clear below. The highest curve contour in this figure (6DS) shows that if we continue emitting CO_2 without taking drastic measures, the amount of emissions will increase from the present 34 Gt to about 55 Gt by 2050 due to higher energy consumption. Consequently, as the calculations made by the IPCC show, the mean temperature of the Earth could increase by up to about 6°C. However, if emissions follow the lowest contour of Figure 2.3 (marked 2DS), then the yearly emissions should not exceed about 15 Gt in the year 2050, and the increment in temperature would be limited to a manageable 2°C. At this point, we recall that the 2DS Scenario practically coincides with the previously named IEA-450 Scenario, since both assume that the CO_2 concentration will not surpass the mark of 450 ppm.

It is very significant to observe from Figure 2.3 that in order to achieve the goals of Scenario 2DS (lower line in the figure), emissions should first reduce their rate of increasing (or slope), reach a maximum, and then commence to decrease not later than within the next decade or at most two. In this way, the current yearly emissions will have to evolve from the present 34 Gt to values around 20 Gt by 2040 as shown in Figure 2.3. The time delay observed between the year when emissions start to decrease and the slowdown of the atmospheric concentration is attributed to the longevity of CO_2 molecules in the air. Although the values of CO_2 concentrations are not shown in Figure 2.3, it is supposed that in the 2DS Scenario they will stabilize around 450 ppm.

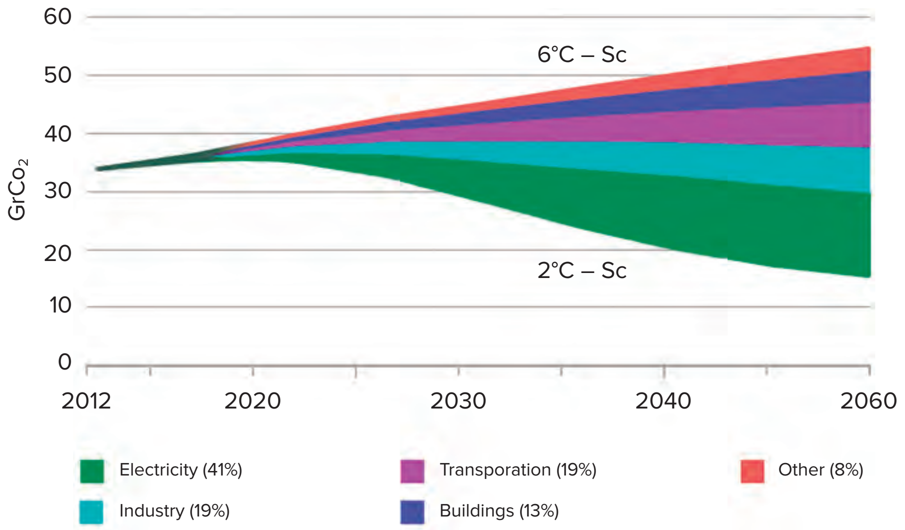


Figure 2.3. Evolution (2012-2060) of CO_2 emissions for the current situation scenario (IEA Scenario 6DS, upper curve) and for the 2DS Scenario (lower curve). Note that the width of each band within the 6DS and 2DS curves is proportional to the contributions of the different sectors to the CO_2 emissions abatement [IEA 2014].

From Figure 2.3, it is also interesting to observe that the largest amount of emissions that can be eliminated in Scenario 2DS is attributed to the electricity generation sector, with a 41% share. As we will see later in more detail, this is mainly due to the proposed substitution of many traditional power plants using fossil fuels (coal and gas) by renewable energies (such as wind and solar), discussed in Section 4.

In Appendix IV we describe the role played by CO_2 in the so-called *carbon cycle of the Earth*. This cycle describes the net balance between the CO_2 added (e.g., by combustion of fossil fuels) and subtracted from the atmosphere (e.g., CO_2 absorbed by plants in the photosynthesis process).

European Roadmap

In the case of Europe, the proposed roadmap to reduce emissions is shown in Figure 2.4 [EC 2011a]. As in the previous case of the world (Figure 2.3), the power sector will again be the one for which the reduction of emissions to 2050 is predicted to be the largest, followed by the industry sector. In this way, the percentage of emissions caused by the power generation sector will be practically null in 2050, as can be deduced from Figure 2.4. In our opinion, this drastic reduction in emissions of about 90% might be too optimistic, since it would imply an extremely ambitious plan for the implementation of renewable energies (see Sections 9 and 10) or, alternatively, the building of a large share of nuclear power plants for the production of electricity.

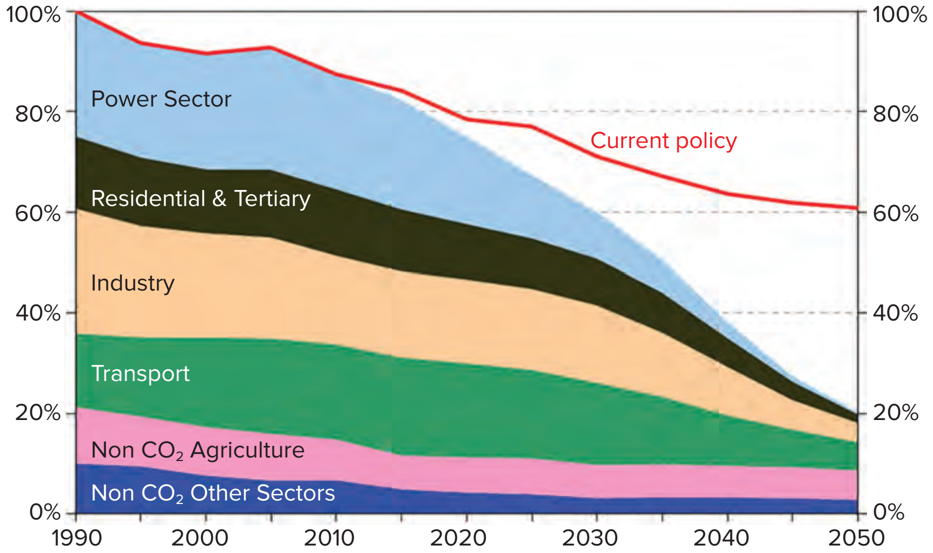


Figure 2.4. Evolution (1990-2050) of carbon emissions according to the European Energy Roadmap [EC 2011a].

According to the European 2050 Energy Roadmap [EC 2011b], by 2020 renewable energies should represent about 20% of the final energy consumption in the EU Member States. Simultaneously, energy efficiency should also increase by 20% compared to business-as-usual projections. In addition, the consumption of renewable energy in the transport sector, which is very intensive in fuel consumption, should achieve a 10% share in 2020, and the decarbonisation of transport fuels should reach 6%. EU Member States have also committed themselves to reducing greenhouse gas emissions by 20% in 2020 (relative to emissions in 1990). The good news is that in the EC report, “Renewable Energy Progress Report” [EC 2013a], it was concluded that the EU as a whole was in its trajectory toward the 2020 targets. As far as the targets for the period 2020-2050, the reader is referred to Section 5 and Section 10, where they are treated in detail.

3 GLOBAL PRIMARY ENERGY AND ELECTRIC POWER

Note: The non-specialist reader is recommended first to give a look to Appendix I for a review of the basic concepts of energy and power, the definition of the most commonly used units, and the equivalences among them. All energy and power units used in this booklet are defined in Appendix I. Next, Appendixes II and III explain how the power of renewable solar and wind systems is defined and calibrated in order to specify their nameplate capacity in Watts.

Global primary energy

Primary energy is constituted by the set of energies found in nature. Primary energy can be classified into two categories. The *non-renewable energies* are found in fossil fuels like coal, *crude* oil, and natural gas, as well as in mineral fuels like natural uranium. The *renewable energies* are mainly comprised by solar, wind, falling or flowing water, biomass, geothermal, and ocean energy (including tides and waves). Before it is used, primary energy has to be transformed and transported to the consumption sites. For instance, electricity is not a primary energy, but it is a very important energy carrier which can be generated from fossil fuel plants, thermonuclear fission reactors, and renewable sources.

Figure 3.1 shows the evolution (1990-2014) of the world consumption of primary energy according to the types of fuel [BP 2015], the total amount in 2014 being 12,928 Mtoe/year or 578.6 EJ/year. Observe that in 2014 the main fuels were still fossil: oil (32%), coal (30%), and gas (24%). The rest is completed by hydropower (7%), nuclear (4.5%), and renewables (2.5%).

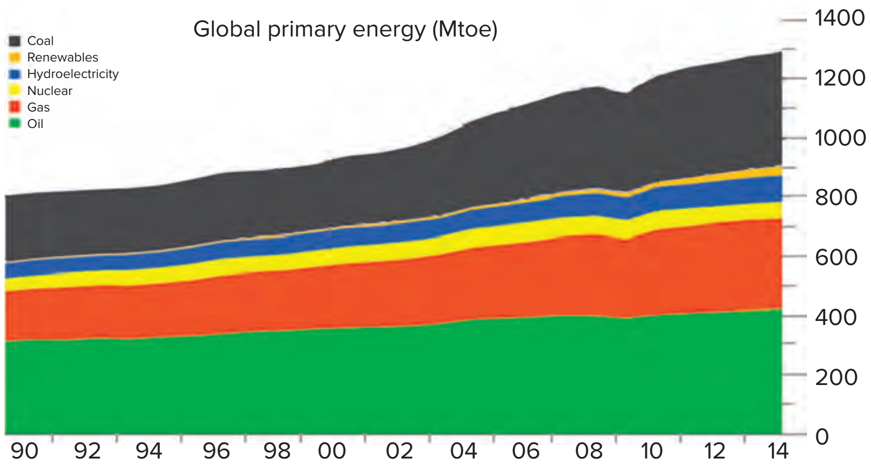


Figure 3.1 World consumption in Million tonnes oil equivalent (1989-2014) according to the type of source [BP 2015].

From the data in Figure 3.1, we would like to observe the current small percentage of carbon-free fuels, since oil is still the most important source of primary energy mainly due to its massive use in transportation. Coal and gas which follow next are primarily employed for electricity production and heating and cooling of buildings. Observe also from Figure 3.1 that the role of hydroelectricity, mainly used for power generation, has risen rather slowly during the last decades. Similarly, nuclear energy is also increasing slowly, in particular after the Fukushima accident in 2011. Finally, let us remark the large relative growth experienced by renewable energies (see also Section 4), especially since the year 2000. However, in absolute numbers, the share of renewables is still very low, thus showing that the substitution of fossil fuel plants by renewable sources constitutes an incredible challenge, especially taking into account the parallel continuous growth of the world population.

In spite of the many calls from the IPCC and other environmental organizations to reduce carbon emissions by decarbonising most of the energy system, the effects have been very modest in practice. As a consequence, as can be observed in Figure 3.2 [IEA 2014], the so-called Energy Sector Carbon Intensity Index (ESCII), or number of tonnes of CO_2 emitted per unit of energy supplied, has been maintained practically constant since the seventies (in the figure the reference 100 represents the CO_2 intensity in 2010). Notice also that from 2015 on, the ESCII line displays two branches corresponding to the IEA 6DS and 2DS Scenarios described in Section 2. The predictions indicated by these branches are partly based on the fact that a lesser increase in global temperature, together with technology improvements, will result as more renewable plants are constructed.

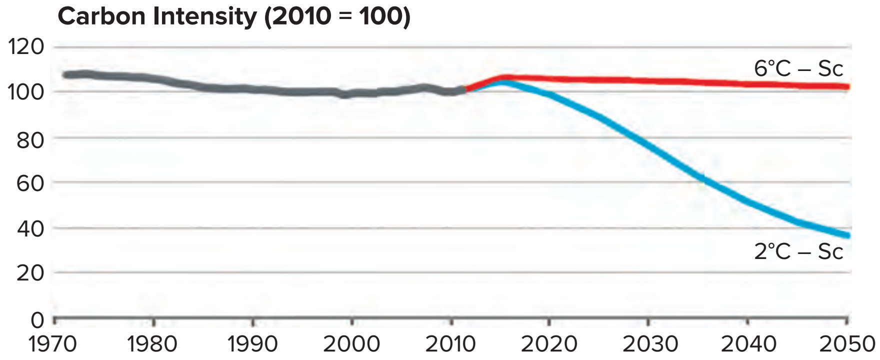


Figure 3.2. Proposed evolution of the Energy Sector Carbon Intensity Index (ESCII) according to the two IEA Scenarios, 6DS and 2DS, defined in Section 2 [IEA 2014].

Electricity as an energy carrier

First, let us recall that electricity is not a primary source of energy; rather, it is generated from the primary energy sources previously specified (Figure 3.1). However, electricity is a most important energy carrier which is still mainly generated by fossil fuels, although since about the year 2000 there has been an ever-increasing share of renewable sources (Figure 3.3).

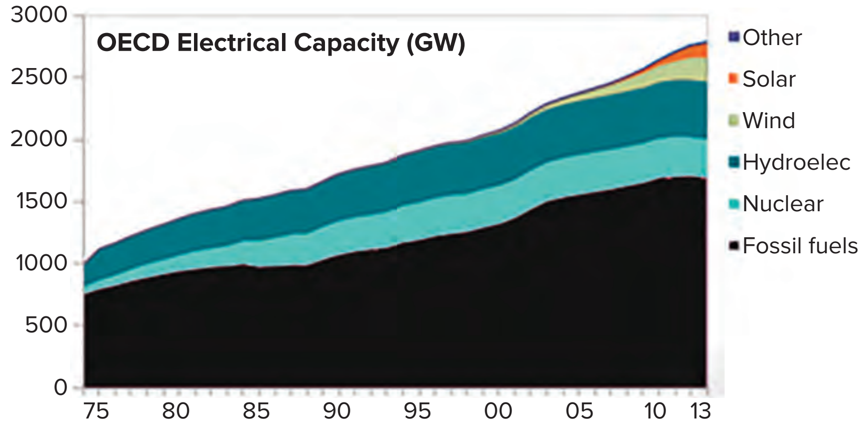


Figure 3.3. Electrical capacity (GW) by source in the OECD countries [IEA 2015a].

At present about 42% of the global primary energy is used to generate electricity, but the tendency indicates that this share will steadily increase in the future, as shown in Figure 3.4.

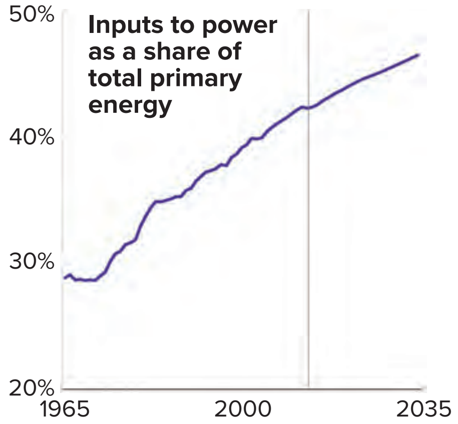


Figure 3.4. Electricity generated as a share of total primary energy [BP 2015].

However, let us remark that the main share of the growth of electricity demand is occurring in non-OECD countries (Figure 3.5 [IEA 2015b]), with China being the largest electricity producer in the world (21% of the total). This rapid growth in the amount of electricity generated is due to its versatility and widespread use in many applications: lighting, heating and cooling of buildings, industrial uses, transportation, data centres, robots, etc.

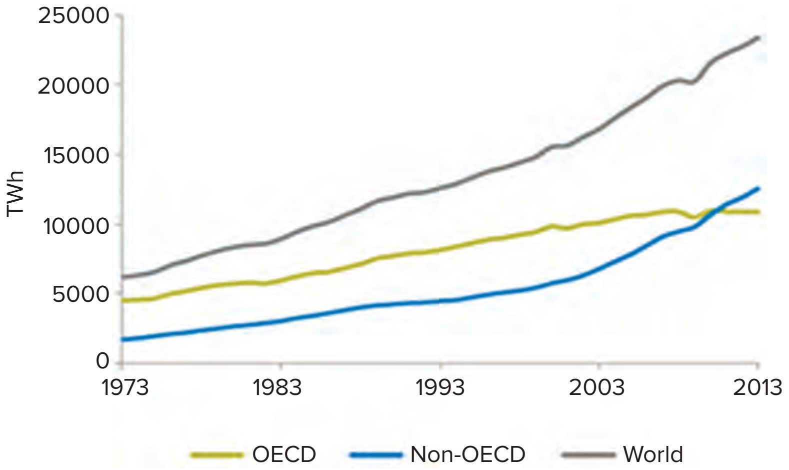


Figure 3.5. Total electricity production in the world (OECD, non-OECD) [IEA 2015b].

From the data of Figure 3.5, a world average yearly per-capita consumption can be deduced of about 3600 kWh, which is expected to increase relatively fast in the coming decades.

Therefore, the increased electrification observed in Figures 3.4 and 3.5 is a powerful force across the global energy system driving a wide transition from fossil fuels to electrification and subsequent decarbonisation. In fact, the 2DS Scenario previously described contemplates in detail the steps that are necessary to reduce the carbon intensity factor (ESCII in Figure 3.2) and simultaneously increase the energy efficiency, thus reducing carbon emissions per generated electricity unit (kWh) by 80% in 2050. To reach this target, a massive increase of renewable electricity generation is contemplated, as we will see in the next section.

4 RENEWABLE ENERGIES

Renewable energies (wind, solar, etc.) participate in the energy system mainly in the generation of electricity with a current global installed capacity of 1849 GW at the end of 2015. This amount also includes 1064 GW hydro, so that the power corresponding to modern renewables would be 785 GW as shown in Figure 4.1 [REN21 2016]. One very important fact is that at the end of 2015, more than half of the net power capacity additions to the electric sector (about 60%) corresponded to renewables. As a result, at present, 23.7% of the total electricity production is renewable with 16.6% hydro, 3.7% wind, 2.0% bio, 1.2% solar (PV), and much smaller percentages of concentrated thermal solar, geothermal, ocean, etc.

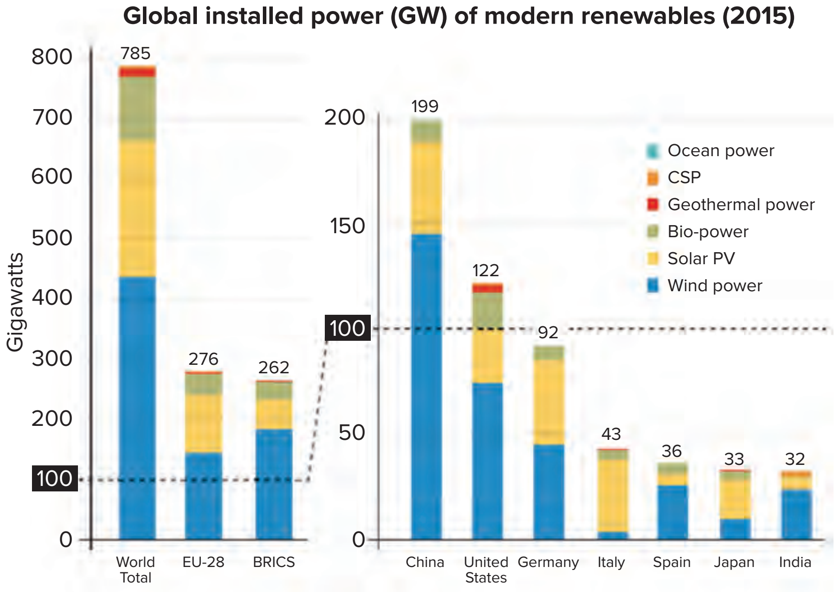


Figure 4.1. Installed power of modern renewables in the world and several countries [REN21 2016].

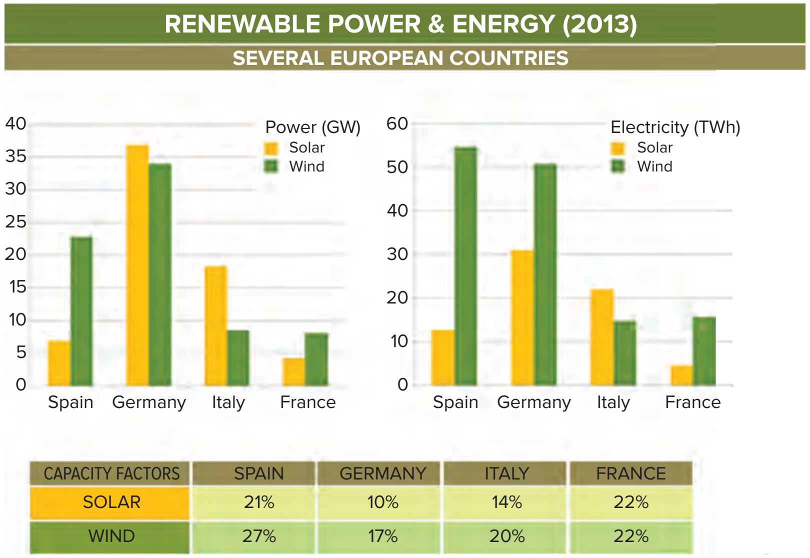
As we discuss now, it is important to notice that one has to be careful when using the installed power data from Figure 4.1 to compare the amount of energy (electricity) from the different renewables. The reason is that in the case of intermittent resources, the values of the power appearing in Figure 4.1 approximately correspond to the maximum rated power values, which most of the time are much larger than the average values. Therefore, and in order to further clarify to the non-specialist the contribution of renewables to the whole electric system, we consider it convenient to explain the concept of "capacity factor" with an example. Suppose that a solar plant of let us say 10 kW is constructed in Southern Spain. When the sun is more intense, that is, at noon in June, the plant should generate 10 kW in one hour (10 kWh). Evidently, if the sun had this intensity during all hours of the year (8760 h), the plant would produce 87,600 kWh. But we know that this is far from being the case, since: a) During one year there is sunlight during only half the hours (4380 h); b) In early morning and late afternoon, the solar radiation is much less that at noon, and therefore the same 10-kW system would produce much less electricity in one hour than the previous value of 10 kWh; c) Although close to the equator the number of daily and night hours are practically the same throughout the year, in the latitudes of the European countries the differences are large. This means, for instance, that the plant producing 10 kWh at noon in June would only produce perhaps 25% of that in the winter (as is the case in France, according to Figure 7.8 in Section 7). However, when the solar plant was purchased, it commanded a price corresponding to the 10-kW nominal (nameplate) power capacity.

The magnitude of the capacity factor (CF) of a plant in a given location reflects the facts mentioned above, as can be noticed from their values, shown in Table 4.1 for solar plants. Figure 4.2 shows this again for wind and solar renewables in some European countries. Observe, for instance, that the same solar plant would show a CF of 21% in Spain and only 10% in Germany due to the difference in solar irradiation. Another interesting fact is that in Europe the CFs corresponding to wind are on the average higher than those of solar photovoltaics (PV), especially at high latitudes. Please note that this matter is also treated in Appendixes II and III.

Country	Power, MW	Electricity, TWh	Capacity Factor (%)
Germany	38.0	34.8	10.4
Italy	19.6	23.3	14.3
Spain	6.9	13.1	21.7
France	5.3	6.0	12.9
Greece	2.4	3.9	18.6
Czech Republic	2.1	2.1	11.4

Table 4.1. Capacity Factors for PV plants in Europe.

Of course, the influence of the CF on the cost of solar and wind energies is very significant, as we will see in Section 6 on energy economics. This is expected, since the CF is evidently linked to the most important characteristics of the resources, especially solar irradiance, wind velocity, etc. Also very important is their temporal dependence and lack of uniformity throughout the year.


RENEWABLE POWER & ENERGY (2013)

SEVERAL EUROPEAN COUNTRIES

CAPACITY FACTORS	SPAIN	GERMANY	ITALY	FRANCE
SOLAR	21%	10%	14%	22%
WIND	27%	17%	20%	22%

Figure 4.2. Renewable power, energy, and capacity factors in several European countries.

We would like also to remark the tremendous growth of the main renewable resources for power generation during the last decade, as shown in Figure 4.3 [Martinez-Duart, J. et al. 2015]. Thus, at the end of 2014 [Jäger-Waldau, A. 2014] the cumulative installed power reached 375 GW and 180 GW for wind and solar, respectively.

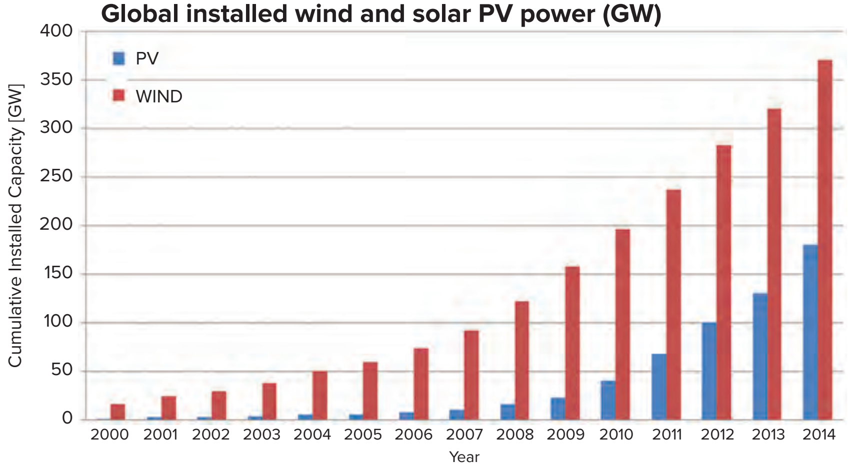


Figure 4.3. Evolution (2000-2014) of the global installed capacity for wind power and solar PV [Jäger-Waldau, A. 2014, REN21 2015, Martinez-Duart, J. et al. 2015].

As we will see in Sections 7 and 8, the higher the share of renewable electricity in the power system, the more demanding will be its integration into the distribution grid, especially in the case of very high penetrations (more than about 40%). This is, for instance, the case of Denmark, which has 40% wind in its electricity mix. In these cases, policy makers are advising utilities to expand and update their grid infrastructures and even build additional lines to access sites with high renewable resources [REN21 2015]. Observe also in Figure 4.1 above how renewable power plants are distributed in the world: Europe-28 with 276 GW is the region with the highest per-capita renewable resources for power generation.

Looking into the future, we have already noticed from Figure 3.4 the current marked tendency to increase the share of electricity generation from the total primary energy sources. This together with the necessity of energy decarbonisation by a drastic decrease of fossil fuels in the power sector, as contemplated by all scenarios, results in a probable electricity generation mix by 2050 composed mainly of renewables such as solar, wind, and hydro, each with percentages in the 16-20% range. This mix will probably be completed by some nuclear energy, perhaps about 14-16%, and also some fossil fuels like gas in combined-cycle plants, especially for backup systems (see Sections 7 and 8).

5 CARBON EMISSIONS

We have seen in Section 2 the tremendous amount of CO_2 emitted from the Earth to the atmosphere and its influence on climate change. Among all major countries in the world, the role that the main emitters (United States and China) will play in limiting CO_2 emissions will be crucial. At present the most contaminating country in the world is China, with an amount of emissions in 2013 almost double those of the United States which is second. However, if one looks at CO_2 emissions per capita in 2013, the United States (21 tonnes/cap), Australia (18 tonnes/cap), and Canada (17 tonnes/cap) are more than double those of China (7.4 tonnes/cap) [PBL 2014]. On the positive side, we would like to remark that the emissions per unit of GDP, or carbon intensity, are diminishing at a fairly high rate in most places. In the case of China, for instance, in recent years the rate of emissions growth (slope of the curve in Figure 5.1) has been decreasing, and it is planned that in the near future, this trend will continue at a higher pace and reach a maximum slowdown around 2030.

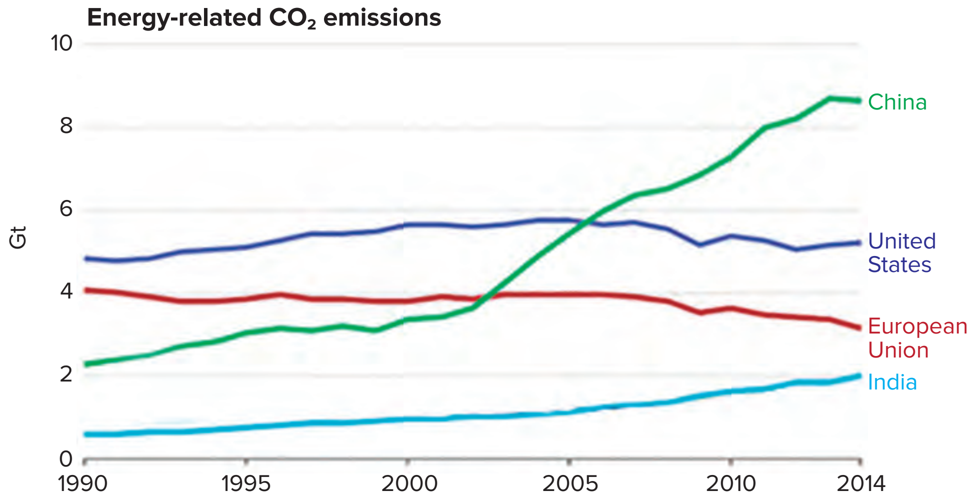


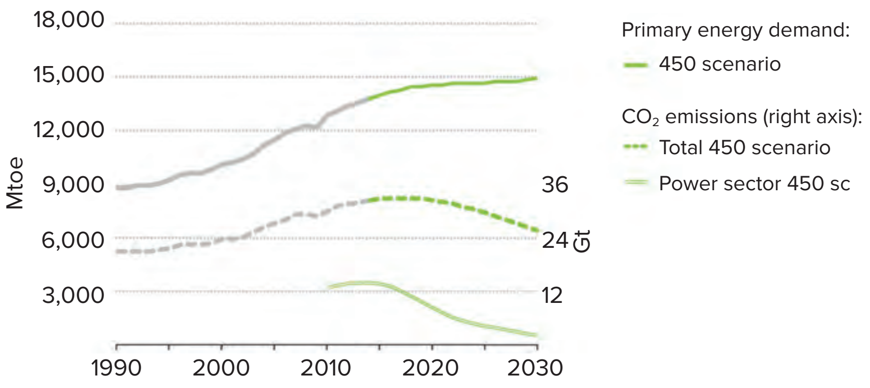
Figure 5.1. Energy-related CO_2 emissions by countries and selected regions [IEA 2015b].

In Figure 5.1, the growth of emissions over the last two and a half decades is shown for several regions of the world [IEA 2015b]. The increase of emissions corresponding to China, and to a lesser extent to India, is extraordinary. On the other hand, it is interesting to observe the almost continuous decrease of emissions in Europe, due in part to its stringent environmental legislation.

Figure 5.2 shows in the upper curve (referring to the left vertical axis) the estimations to 2030 of primary energy demand [IEA 2015b]. Evidently, up to 2014, the curve coincides with the one shown earlier in Figure 3.1, as it should. From 2015 on, we can observe the evolution corresponding to the IEA-450 Scenario (Section 2). In addition to estimating primary energy demand, the middle curve of Figure 5.2 shows the predictions for CO_2 emissions. As can be appreciated, they are very similar to the 2DS curve shown in Figure 2.3, as expected based on the similarities of the 450-ppm and 2DS Scenarios already pointed out. What is really meaningful is that in less than a decade, CO_2 emissions will have to peak to a maximum and then start to decrease to a value of about 24 Gt by 2030 (right vertical axis in the figure).

As we have previously described in the context of Figures 2.3 and 2.4 in Section 2, it is the electricity generation sector – the one among all of them – that is expected to achieve the largest reduction in emissions, both in absolute and relative terms. This can be appreciated from the evolution of emissions in the lowest curve of Figure 5.2. However, we should not forget that the afore-mentioned emissions reductions are based on the recommendations of the IPCC and the IEA (Scenario 450), which are more stringent than the targets that the countries attending the UN Paris 2015 Climate Meeting will presumably approve.

The great difficulties found in reaching an agreement for the reduction of emissions on a global scale in the United Nations meetings on Climate Change are based on the following facts: 1) Although emissions are local, they have global effects, and therefore the investments made by a given country to limit emissions profit equally all others; in addition, the benefits of cutting emissions are felt many years later, perhaps several decades. 2) Sudden cuts in emissions normally have negative impacts on the



Note: Mtoe = million tonnes of oil equivalent; Gt = gigatones

Figure 5.2. Estimations to 2030 of primary energy, total CO_2 emissions, and emissions due to the power sector, according to the IEA-450 Scenario defined in Section 2.

economy, and therefore unilateral cuts of emissions in one country put their industries at an economic disadvantage in relation to the others. 3) A significant decrease of emissions in the short run in Europe is somewhat questionable since in other regions, China for example, emissions will meanwhile keep increasing at a much higher rate. 4) Due to the very long residence time of CO_2 molecules in the atmosphere, even if we stop emitting today, the improvement in CO_2 concentration will only be felt several decades later.

European situation

Let us now review the European situation on future emission targets. From the point of view of climate change, the main goal of the European Union is to limit future global warming below 2°C in comparison with pre-industrial temperature levels. To reach this objective, the EU committed itself to reduce greenhouse gas emissions (GHG) by 2020 by 20% in relation to the 1990 level (see Figure 5.3 [Eurostat 2015]), according to the Directive “Energy 2020” [EC 2010]. The total amount of *emissions* in 2012 in the European Union was 4683 million tonnes CO_2 equivalent. The four largest emitters, representing more than 50% of total emissions, were Germany (20%), UK (13%), France (11%), and Italy (10%). In October 2014, the European Council approved the Climate and Energy Policy Framework for 2030 [EC 2014a] with a GHG target reduction of 40%, as also shown in Figure 5.3. From this graph, it can be concluded that Europe is on the right track, partly due to the development of renewables and the recent economic crisis, which diminished final energy consumption. In addition, as previously pointed out, the decrease in Europe of energy-intensive industrial activity in favour of other regions in Asia or America has also helped emissions abatement.

In the long run, a reduction of around 80-90% is contemplated, as specified in the EU document “Roadmap for moving to a competitive low carbon economy in 2050” [EC 2011a, EC 2013a]. This Roadmap proposes by 2050 the target of cutting carbon emissions by about 80% (Figure 2.4), following partial reductions of 40% and 60% in 2030 and 2040, respectively. The Roadmap also indicates the main sectors in which emissions should be avoided: power generation, transport, and conditioning of buildings. Finally, the Roadmap estimates the costs of the transition to a competitive low-carbon economy, which would amount to about 270 billion €, or 1.5% of the EU’s GDP, over the next four decades. On the positive side, it has been estimated that more than one million jobs would be created by 2020, in a great part financed by revenues from CO_2 emission taxes.

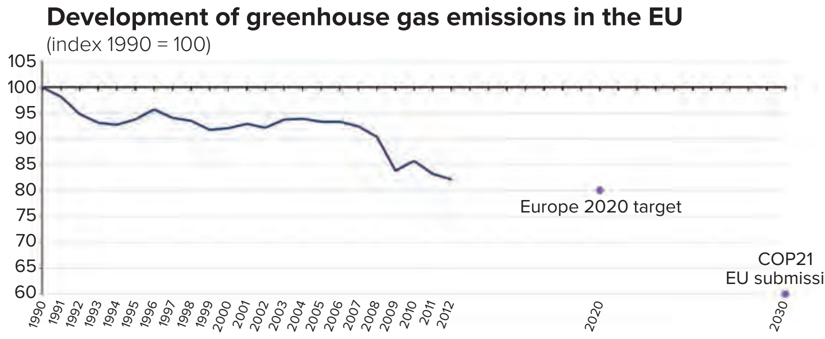


Figure 5.3. Evolution of greenhouse gas emissions in the EU since 1990 and the emission reduction targets for 2020 and 2030 [Eurostat 2015].

6 ENERGY ECONOMICS: THE COSTS OF ENERGY AND ELECTRICITY

The concept of LCOE

The so-called Levelized Cost of Energy (LCOE) is the most appropriate economic parameter for comparing the cost of energy produced by different technologies. The LCOE is defined as the price to sell the produced energy so that the project is economically viable and the investors obtain a fair return. The LCOE depends also on the maturity of the technology of the project and its associated risks. To better explain how the LCOE is calculated, let us refer to solar photovoltaic energy as an example. Evidently, the LCOE should be **proportional** to the *cost of the solar plant*, *C*, as well as to the *operation and maintenance costs*, *O&M*. In addition, it is also proportional to the *discount rate*, *d*, which is a very important parameter that takes into account several economic variables, such as the interest applied to the capital, the inflation rate, the risk of the project, etc., and in the case of mature PV projects amounts to about 8%, as recommended by the IEA.

On the other hand, the LCOE is **inversely proportional**, as expected, to the intensity of the solar resource. This is completely logical since solar electricity will have lower costs in places with higher solar irradiation. Thus, in sunny Southern Spain, the cost of producing a kWh of solar electricity should be in principle about half the cost in Germany (see the discussion on capacity factors in Section 4). However, as we will see below, this is not always the case because other factors influence the LCOE (as will be shown in Figure 8.5).

A very interesting fact that can be observed in most renewable energy technologies is that as the years advance and more plants are constructed, the cost of the systems, C(t), is found to diminish. This is due to the so-called "learning by doing" and to the "economies of scale". In effect, in the case of PV modules, it can be observed in Figure 6.1 that for instance when the cumulative capacity (MW) increased by a factor of 100,000 in the period 1976-2013, the cost of the modules decreased by a tremendous factor of close to 100; that is, at present their cost is about 1% in comparison with 40 years ago [Martinez-Duart, J. and J. Hernandez-Moro 2013]. As a consequence, currently the cost of a solar module is less than one US dollar per Watt-peak. This represents a learning rate of about 20%, which means a decrease in costs close to 20% every time the cumulative installed capacity doubles. At this moment we should remark, however, that the decrease in PV system cost overall is less than that, because the modules represent only about one-half of the costs, with the other half corresponding to the balance of system (inverters, cabling, mounting structures, etc.).

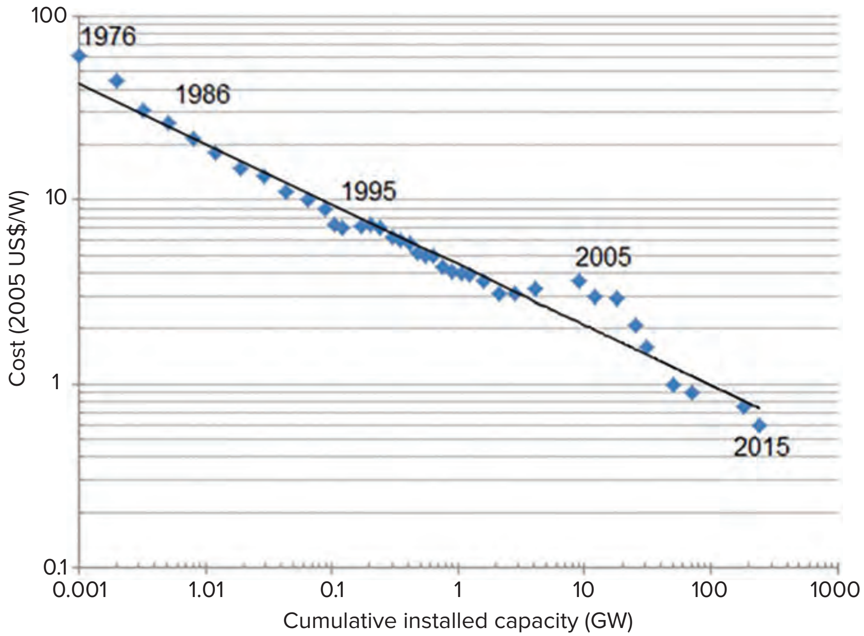


Figure 6.1. Learning curve for PV modules (1976-2014) [Martinez-Duart, J. and J. Hernandez-Moro 2013]

There is at present a consensus that this trend of lower prices in the LCOEs of renewable energies will continue in the future, although it is possible that the rate of diminution will slow down progressively, at least in the case of solar PV. Due to this diminution in costs, it is expected that a point will be reached when the LCOE of renewables will approach or equal the cost of electricity provided by utilities. This is already the case for wind in some locations, which explains its widespread use, apart from simultaneously reducing emissions. In other cases, like in various islands, some electricity must be imported, and thus the cost of renewable power can currently be competitive. When this happens, it is said that "grid parity" has been reached. As a consequence, regions with good solar resources, or areas like some islands (for instance, the Canary Islands) where electricity has to be imported, can reach grid parity very soon, if they have not done so already.

Figure 6.2 shows the recently published LCOEs [IEA 2015c] of solar and wind energies for three different values of the discount rate. The first thing that might surprise the non-specialist is the wide margin of values for a given technology between the highest and lowest LCOE costs, and also the different values of the discount rate already explained. Precisely we have chosen the LCOEs provided by the IEA because they show in each case the median values in each range, and besides give the costs for three different values of the discount rate (3%, 7%, and 10%). The value assigned to the discount rate can change the costs in some cases by almost 100%, especially renewable energies. This is due to the fact that solar and wind plants are capital-intensive, i.e., what is really expensive is the cost of the plant (paid initially) for power generation, while there are no corresponding fuel costs .

Other factors that have a large influence on the LCOE are the intensity of the resource (solar irradiance corresponding to the geographical location in the case of solar), the systems' years of operational life, some country-specific parameters like interest rates, taxes, and local regulations, labour costs, interconnection to the grid, risk of the country, or even the discount rate, since some calculations use unrealistic values. Another important parameter which is not always specified is related to the size of the plants and their use. For this reason in Figure 6.2 the solar PV plants are divided into three groups: residential, commercial, and utility-scale. Finally, we would like to remark that the above LCOEs do not take into account the transport and distribution of electricity, which typically might represent 50-60% of the total cost (see Section 8).

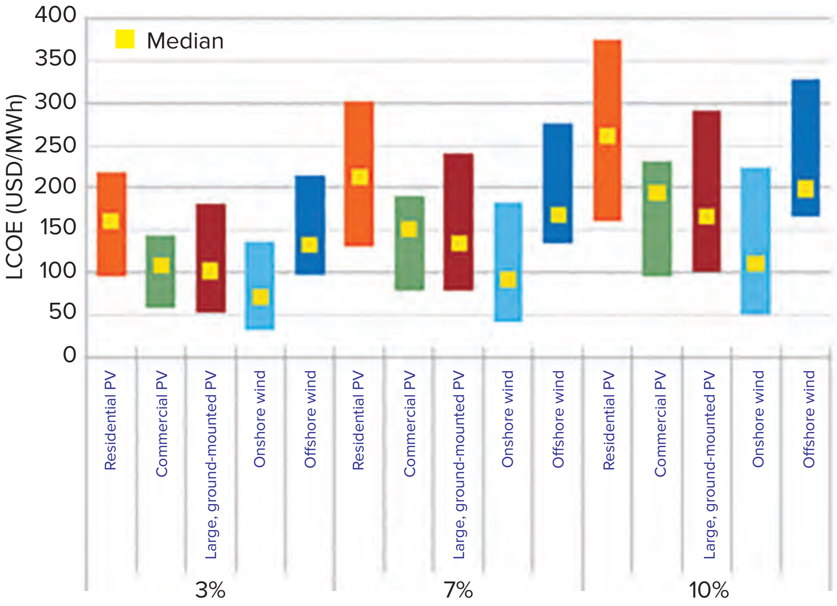


Figure 6.2. LCOE costs for wind and solar PV for different values of the discount rate [IEA 2015c].

In the European Union, stringent emission targets have a great impact on its energy mix and consequently on power costs and economic competitiveness. Wholesale energy prices have increased in the EU during the past years, and the EU Energy Roadmap 2050 (Section 2) suggests that this trend will continue in the future [EC 2013b]. Divergence of prices in the EU in comparison to other major industrial economies in the world such as the United States and China are expected to continue increasing. In 2012 according to the IEA, the industry gas prices in Europe were more than double those of the United States, and between 2005 and 2012 real electricity prices for industry in Europe increased on average by 38% while in the US they remained practically constant [IEA 2013]. As a consequence, nowadays there is a great concern in many European countries about the lack of competitiveness in the industrial sector because of these increases in energy costs. For this reason, some European firms are finding abroad better conditions for their production. For example, some German chemical industries are shifting a large share of their investments to the United States and China.

7 INTEGRATION OF RENEWABLE SOURCES INTO THE GRID

The electricity generated in the different plants of a country is transported to the consumption sites through an electrical transmission system, which is commonly called “the grid”. One important characteristic of the distribution of power is that in general the electricity produced should at every instant match the demand, since electricity cannot be stored yet economically in large quantities or over long periods of time. As the percentage of electricity from variable renewable energies, VRES (wind and solar), gets above some 30% of the mix, the problems of integrating this variable electricity supply into the distribution grid rise significantly [Agora Energiewende 2013]. In fact, the characteristic intermittency of renewable sources necessarily demands some combination of efficient and flexible backup plants, large energy storage systems, smart grids, etc., and, consequently, the costs of electricity could be notably increased [Denholm, P. 2012].

Efficient management of electricity necessitates several types of generation units, as shown in Figure 7.1 for the demand of a typical working day in Spain. *Baseload plants*, like nuclear or coal, are usually designed to operate at full output and therefore have high capacity factors (Section 4), thus providing electricity at low cost. *Intermediate plants* are usually operated to meet the daily high demand periods and consist mainly of combined-cycle natural gas systems. *Peaking plants*, so named because they are operated during peak demand periods, are usually based on gas-fired combustion turbines. Since evidently solar and wind resources have no fuel costs, the renewable plants are given priority in the distribution process, thus displacing other plants which consume costly fuels. Because of this priority, the integration of VRES into the grid at high percentages influences the use of all other components of the electricity mix. In addition, VRES systems will have to be provided with *backup plants* in case the renewable resources do not provide enough power, a situation that can happen if simultaneously the solar and wind supplies shrink to small values [NREL 2015].

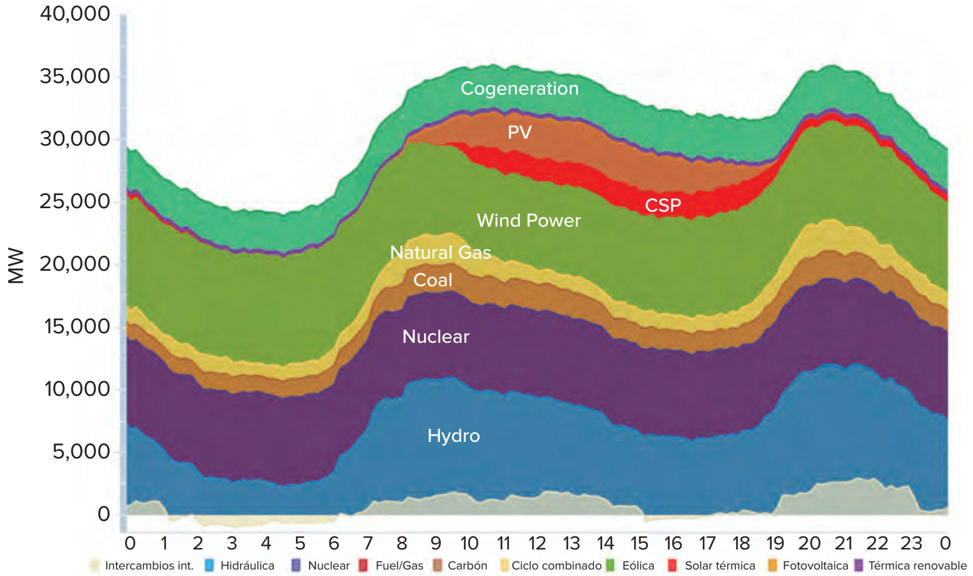


Figure 7.1 Typical daily generation of electricity in Spain from different sources [REE 2013].

Figure 7.2 [REE 2013] shows the variation in demand for a 7-day period of a typical week of summer in Spain starting at 0:00 hours of Monday. Observe in the figure the notorious drop in electricity consumption during the night and also during the days on the weekends. We have chosen in Figure 7.2 a summer week so that we can better appreciate the solar contribution. Observe also that the maxima in electricity from solar energy (PV and thermoelectric) are relatively coincident in time with the maximum daily demand. In addition, in the case of concentrating solar power (CSP) electricity, there is also production during the first hours of the night, since part of the solar energy can be stored in salt tanks as thermal energy.

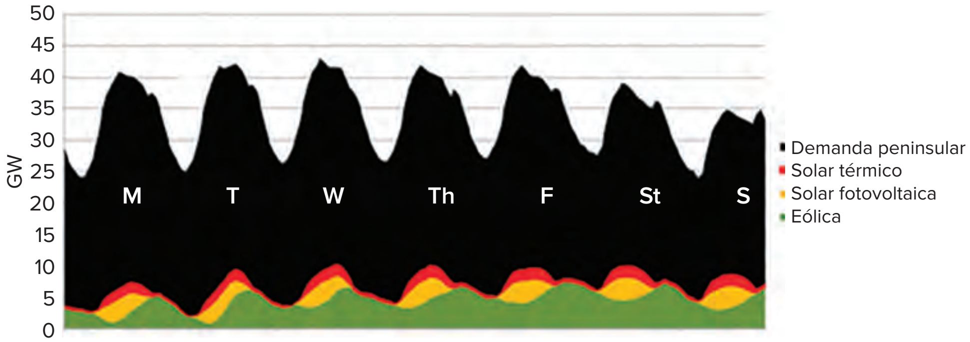


Figure 7.2. Representation of the demand, wind and solar (PV and CSP), in Spain for a typical summer week [REE 2013].

The graph shown in Figure 7.3 [REE 2013] corresponds to the values of the load taken every hour during the whole year of 2013 in Spain and therefore consists of 8760 points which evidently cannot be resolved individually. In this figure every apparent peak corresponds approximately to each of the 52 weeks of the year. The structure of the curve in Figure 7.3 arises as a consequence of the lower demand during the two weekend days. At the horizontal time scale of the whole year, the minima at the two extremes of the graph (end and beginning of the year) correspond to the Christmas vacation period, and the one at the end of March to Easter vacation. From Figures 7.2 and 7.3, it can be appreciated that in periods of high demand, the power required can reach values around 40 GW, which is more than double the minimum in demand (less than 20 GW). Due to these differences in power demand, the cost of electricity would in general be increased, since the generating systems have to be acquired according to their maximum rating, independently of whether they are operating or idle.

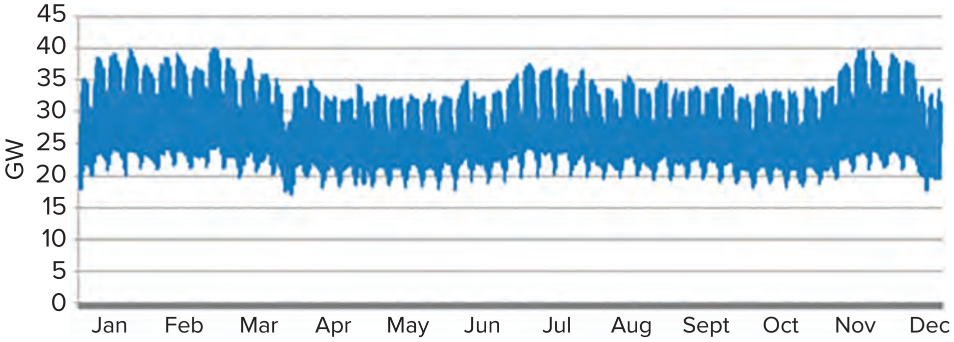
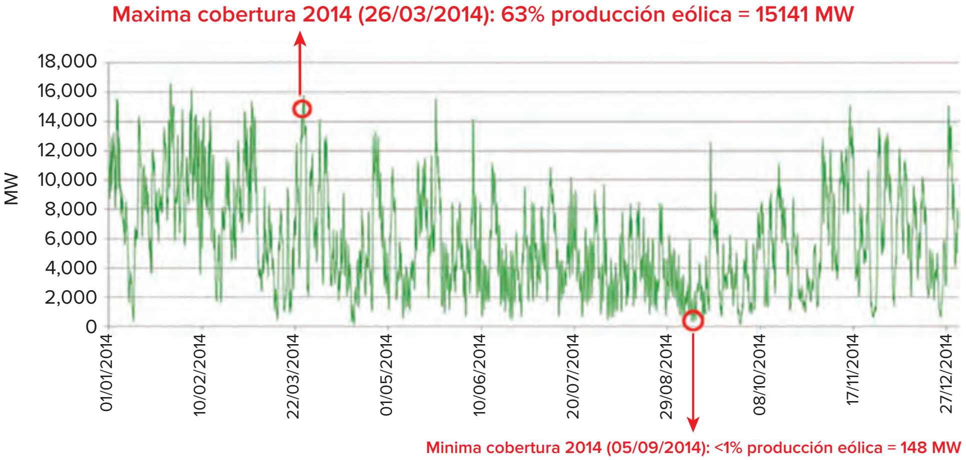


Figure 7.3. Demand curve in GW during the whole year of 2013 in Spain. Observe that every peak in the upper or lower contours corresponds to one week [REE 2013].

One of the main issues in relation to the high integration of large quantities of wind electricity into the grid is associated with the huge variability of the resource in short intervals of time. As it can be appreciated in Figure 7.4 [Seco 2015], in which is represented the wind generation in Spain during the year 2014, there are intervals of time in which the wind electricity can represent 63% of the demand, while there are others in which the contribution is practically null (less than 1%). However, what introduces greater stress into the whole electricity generation and distribution system is the large ramping rates, on the order of 100 MW/min, in situations when periods of intense winds are suddenly followed by calms.



Maxima cobertura 2014 (26/03/2014): 63% producción eólica = 15141 MW

Minima cobertura 2014 (05/09/2014): <1% producción eólica = 148 MW

Figure 7.4. Wind electricity generation in Spain during the year 2014 [Seco 2015].

When the capacity of installed wind power is relatively large and the wind velocity is high, it is sometimes necessary either to curtail the turbines or export electricity, since the grids and distribution systems might not be prepared to handle these surpluses. This is for instance the case in Germany and some of its surrounding countries (Czech Republic, Poland) whose transmission grids could be damaged. Something similar occurs in France with respect to some surrounding countries, but in this case with the electricity being produced by nuclear plants. As another possibility of dealing with these situations, they could be partially solved by the implementation of massive grid extensions or by promoting demand-response consumption (Section 8.2). Finally, another solution can be based on storage as we will also see in the next section.

In the European continent, Germany is the top country in wind electricity generation, with yearly production of 55 TWh, followed by Spain with 51 TWh and France with 17.7 TWh. Figure 7.5 [RTE 2015] shows the monthly wind generation in France, in which can be observed large differences, up to a factor of 2 to 3, between production in the winter months compared to the summer ones. These differences are reflected in the values of the monthly capacity factors in France, which are represented by the green line in Figure 7.5.

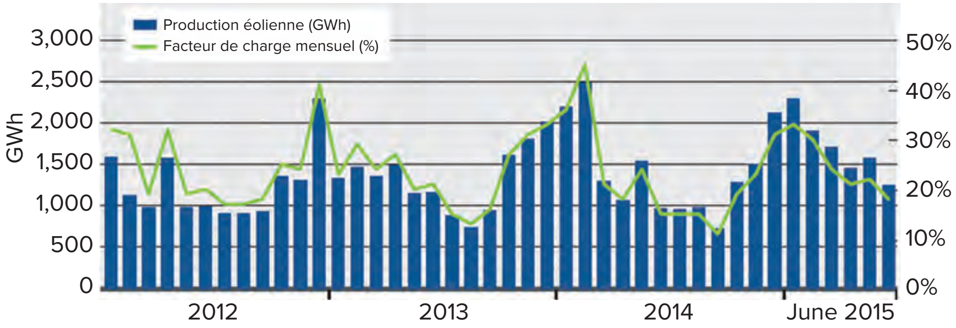


Figure 7.5 Monthly wind electricity production in France between January 2012 and June 2015 (blue columns) and monthly capacity factors (green curve) [RTE 2015].

Evidently, the intermittency and unpredictability of solar PV generation is caused by the variability of the solar resource. Figure 7.6 shows the solar insolation at noon depending on the month of the year and the latitude, and Figure 7.7 represents a map of the yearly insolation in Europe. It is interesting to observe that for median European latitudes like Bordeaux or Milan, the insolation in June is quite high and not too far from the values corresponding to the Sahara desert. However, the insolation in December at noon is almost a factor of 3 smaller. As a consequence, the yearly capacity factors are quite low for solar PV, not only because half of the year's hours are at night, but also because in winter the insolation is very low. Nevertheless, what is even worse is that when a solar PV system with a given power rating is purchased, we have to pay a price according to its nameplate power (see Appendix II) of, for instance, 1 kW, but this power will only be provided around June and perhaps for one or two hours near noon; evidently, at any other time the power provided will be smaller. Similarly, for the case of higher latitudes like that of Stockholm, the situation would be even worse, as explained also in Appendix II.

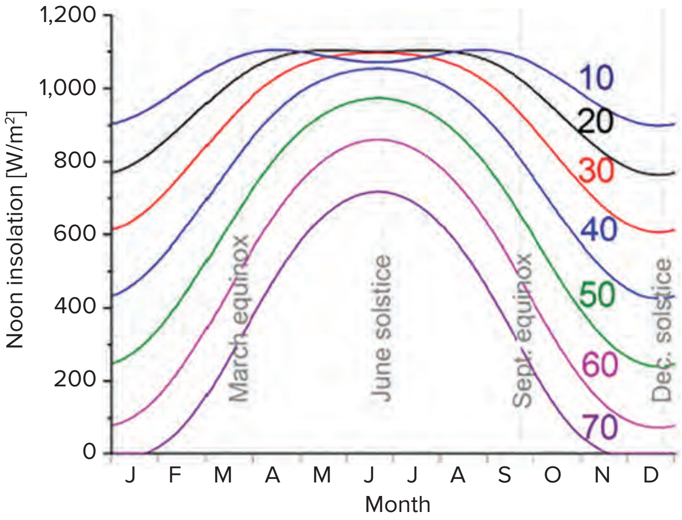


Figure 7.6. Noon solar insolation (W/m^2) as a function of the month of the year and for latitudes from 10° to 70° in the northern hemisphere.

Analogously to the case of wind, we show in Figure 7.8 [RTE 2015] the monthly generation of PV electricity in France for the past few years in GWh units (left vertical axis), as well as the monthly capacity factors which are more than 20% in some summer months and less than 5% in some winter ones. One interesting fact to observe by comparing the graphs in Figures 7.5 and 7.8 is that the monthly oscillations of wind- and solar-generated power are out of phase for about half the year and, consequently, the sum of the contributions of the two main VRES resources would have a smaller seasonal relative variation than each individual contribution.

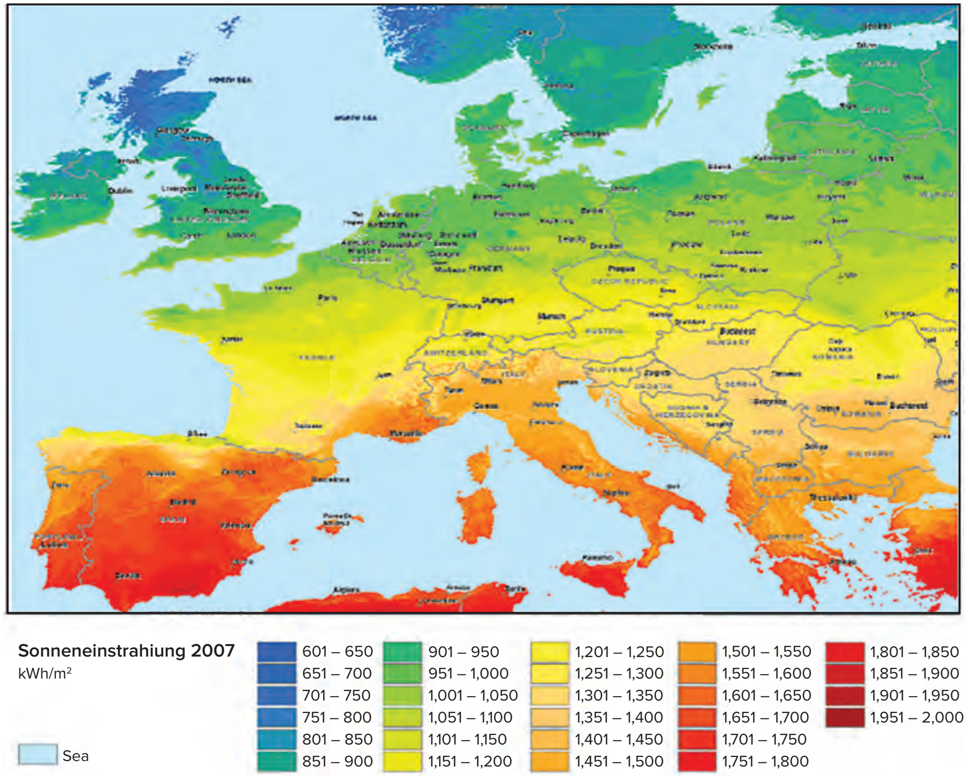


Figure 7.7. European map of the yearly solar insolation.

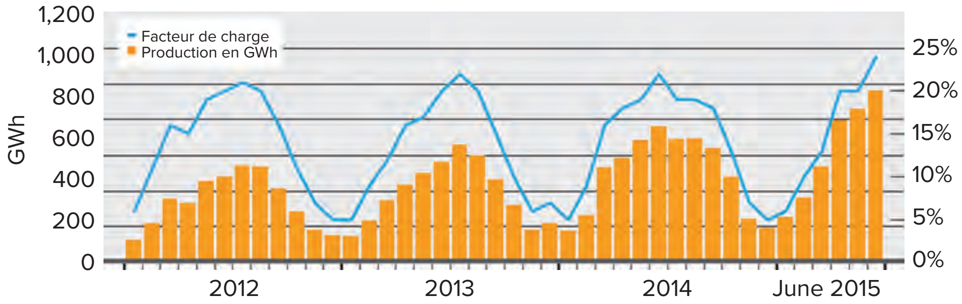


Figure 7.8. Monthly solar PV electricity generation in France from January 2012 to June 2015 (yellow columns) in GWh and monthly capacity factors (blue curve, scale at the vertical right axis) [RTE 2015].

From the above discussion, it can be concluded that correct management of the whole power distribution system is quite complex because of the following factors: a) Large daily (day-night), weekly (labour days and weekends), and seasonal (summer-winter) variations in the values of the resources. b) The fact that there does not exist yet an economically viable technology for storing electricity (see Section 8.1), and therefore the generation of electricity has to be constantly adjusted to the demand for it, in some cases at high ramping rates. c) The main renewable resources, wind and solar, are intermittent and quite unpredictable; therefore, when they are fed into the grid, the other resources have to be flexible and adapt their production of electricity.

8 ENERGY STORAGE, SMART GRIDS, AND SYSTEM-LCOE FOR RENEWABLES GRID INTEGRATION

We will describe in this section the problems that arise when high shares of variable renewable energies (VRES) are integrated into the electricity distribution grid.

8.1 Storage

For efficient integration of high percentages of VRES (mainly solar or wind) into the electric distribution grid, it would be necessary to implement efficient and affordable energy storing facilities. In this case, the surplus electricity, provided for instance by the sun in the central hours of the day, could be stored for later use. However, this is not yet possible since the storing capabilities provided by batteries are still too expensive for large-scale implementation [Agora Energiewende 2013]. Therefore, backup fossil fuel plants are needed to provide security of supply in the grid distribution system. But additional backup plants increase electricity costs and also emit some CO_2 that could interfere in achieving future emissions targets (Figure 5.3).

One of the main reasons for interest in energy storage systems is for applications related to the integration of renewables, especially in the following cases: a) seasonal storage that would allow the large amount of solar electricity generated in summer to be stored until winter; b) weekly and daily storage, similar to case a, but for shorter time intervals; c) storage of electricity that could be used later in high demand periods when prices peak; d) use in cases of system contingencies, such as when power output is rapidly lost; e) utilization in off-grid small PV or wind systems in isolated geographical areas, replacing oil or diesel fuels normally used at present; and f) self-consumption by on-site generation.

Currently, one of the most efficient techniques for storing electricity is hydro-pumping (Figure 8.1 [IEA 2014]). There is in the world about 141 GW capacity of hydro-pumping, which represents only a small portion compared to the total generation capacity (5250 GW). Of all electricity storage techniques, hydro-pumped storage (HPS) represents 99.3%, leaving electrochemical and other types of storage with only a very small share. Because of its efficiency during long periods of time, HPS has been traditionally used in very large electricity storage facilities, especially in mountainous countries with high reliefs. One special application of HPS is in relation to nuclear plants which, due to their normally constant output, cannot be ramped up quickly enough following periods of low demand; however, they can be used to pump water overnight when electricity is less expensive and sell it in the diurnal periods. In general, the use of hydro-pumping as a storage technique is somewhat limited unless the dams are fed by rivers with high volumes of flow.

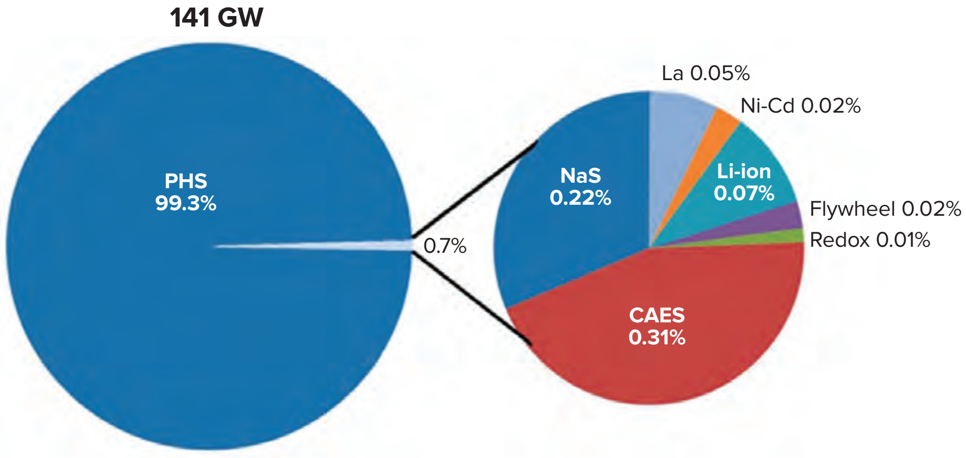


Figure 8.1. World electricity capacity storage in 2012 [IEA 2014].

At present there are great efforts towards the development of large-scale, economical battery storage facilities for power distribution systems. The advantage of batteries is a consequence of their modularity, controllability, and responsiveness [Martínez-Duart, J. et al. 2015]. The distribution grids should be able to accept the highest VRES peaks by storing their electricity and using backup generators only when the demand exceeds the supply. Therefore, the use of electricity storage units should be very convenient in these situations since they introduce flexibility into the system. (The flexibility is related to the ability of the system to efficiently handle the various patterns of electricity generation and demand.) Currently, the most employed and developed batteries for electricity storage are the lead-acid and lithium (Li)-ion types. Lead-acid batteries can be considered a mature technology today, although they present some environmental problems. During the last decades, Li-ion batteries have been the most investigated and are approaching electricity storage densities up to about 500 Wh/kg or more. As an example, the research group of N. Mizuno (U. Tokyo), in collaboration with Nippon Shokubai Co, Ltd., [Hamada 2014, Okuoka 2014] has reported densities of more than 2000 Wh/kg by adding cobalt to the crystal structure of lithium oxide.

Currently there are hopes that batteries will improve in the next decade such that they will permit big developments, for instance in the electric vehicle industry and in the high integration of VRES into the distribution grid. Figure 8.2 shows the evolution during the last two decades for Li-ion batteries, in terms of energy density and costs, which have improved by a factor of ten and six, respectively. However, the price of batteries will still need to go down by some 60-70% to be economically profitable.

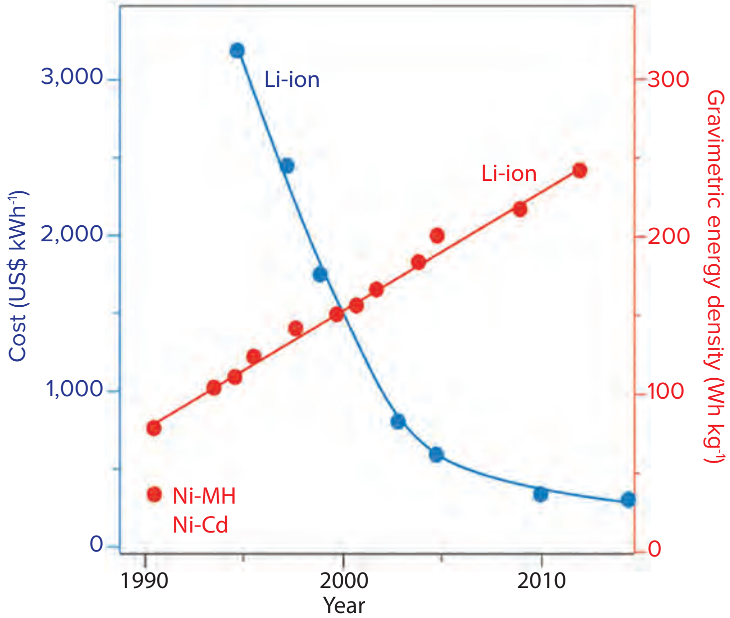


Figure 8.2 Evolution of the energy density and cost for Li-ion batteries during the last two decades. [After Crabtree 2015 with Ni-based point added.]

Small units of battery storage combined with roof-top PV arrays are considered for home self-consumption of electricity, especially in Germany since it is the country with the highest solar PV installed capacity (Figure 4.1). However, studies carried out in Germany have shown that these systems are still too expensive. In effect, Figure 8.3 [Agora Energiewende 2013] shows the cost of a typical PV home unit of 4 kW and a battery of 6 kWh and its expected evolution till 2033. At present the approximate cost of the system (11,000€) is not low enough to be competitive in Germany in comparison to power supplied by utilities. However, it is expected that it will be competitive in less than two decades, especially if some breakthrough occurs in battery fabrication costs. Of course, if similar calculations are carried out for countries like Spain, with PV capacity factors about twice those of Germany (see Figure 4.2), the results would be more optimistic.

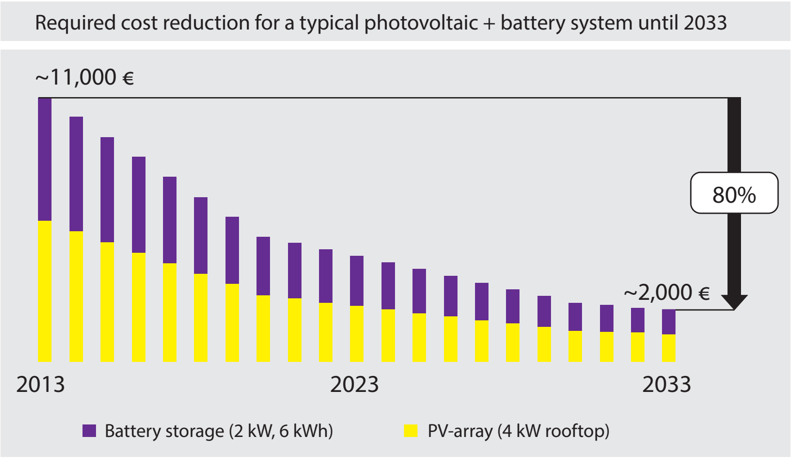


Figure 8.3. Estimated cost evolution until 2033 of a typical solar PV home array (4 kW) plus battery storage (2 kW, 6kWh) [Agora Energiewende 2013].

An interesting and relatively new concept is that of *Distributed Storage* (DS), particularly in combination with smart grids. In fact, DS is a very useful tool for adding capabilities to electric grids, especially when dealing with variable and intermittent renewable energies. In this way, VRES renewables (wind and solar) can be used in larger amounts since the storage systems can buffer the changes introduced by the different power resources and thus optimize their management. The technologies contemplated in DS are mainly based on batteries, along with some on flywheels. However, due to the economic costs and relatively short life of some batteries (5 to 10 years), DS is largely still in a pilot project phase. In the case that electric vehicles become widely deployed in the near future, their batteries could be used also as distributed storage units.

8.2. Smart grids and flexible systems

As we have seen in previous sections, the introduction of VRES renewables, particularly solar and wind, for CO_2 emissions abatement implies the integration of high levels of intermittent power into the electricity distribution grids. In fact, as recommended by the "UN Program of Sustainable Energy for All", one of the main objectives to slow down climate change is to double the share of renewable energies in the global energy mix by 2030 [UN 2012]. This will require the implementation of highly flexible power generation systems as well as smart grid technologies.

Most of the present distribution grids provide some smart functionality to balance supply and demand. However, in the near future the wide deployment of smart grids will incorporate information and communications technologies in all aspects of power generation, distribution, and consumption. Following the definition of the International Energy Agency [IEA 2015d], a smart grid is an electric network system that monitors and manages the power generators and lines of transport to meet the varying electricity demands of the end users. Furthermore, smart grids are able to coordinate the requirements of all generators, end users, and electricity market stakeholders in such a way as to optimize asset utilization and simultaneously minimize both costs and environmental impacts [Guerrero-Lemus, R. and J.M. Martinez-Duart 2013].

Figure 8.4 [IEA 2015d] represents at its left the scheme of a present smart grid system and at the right the scheme of how the smart grid is expected to evolve over the coming years in which all units will be connected by digital communications. Observe also that this smart grid system contemplates units for electricity storage, charging of electrical vehicles, etc.

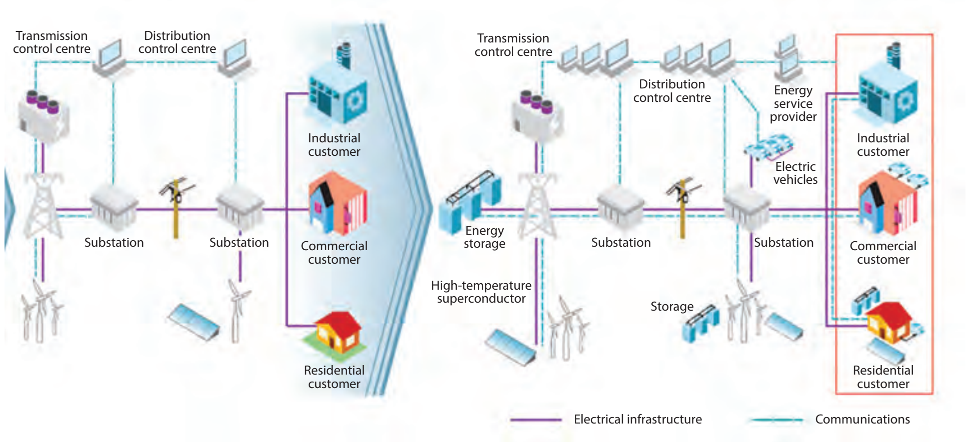


Figure 8.4. Scheme of a smart grid system (left) and its evolution to a more advanced system (right) incorporating storage, charging of electric vehicles, and increased digital communications [IEA 2015d].

Smart grids are essential to the transformation of electric distribution networks into flexible systems that favour the transition to the 2DS Scenario [IEA 2014] by permitting the high integration of variable renewables into the grid. The term "flexibility" of operation of a system has been introduced recently and measures its ability to respond to a change in demand or supply.

Next, we describe below some cases of how smart grids can help solve some of the challenges that VRES pose to grid distribution systems.

Smart grids and VRES intermittency and variability:

In the case of traditional fossil and hydroelectric plants, their output can be controlled with relative ease, thus allowing operators to match electrical supply and demand. On the contrary, renewable solar and wind generation depend on continually variable resources; for instance, strong winds can be followed by periods of calm. In situations like this, other generation plants like gas-fuelled combined-cycle, can be put into operation without delay. Smart grids can help by first detecting the changes in VRES output and then giving adequate orders to backup plants to start operating [IRENA 2013].

Smart meters for smart grids:

Smart meters are electronic devices that continuously register and provide real-time information on customers' electricity consumption and communicate this information to utilities for monitoring and billing purposes. The established communication should be of the "two-way" type between the consumer's meter and the utility, allowing companies to introduce different prices for electricity consumption depending on the time of the day, season, etc. Evidently, this helps consumers to better manage their available budget for energy expenses, although it does not provide additional electricity if needed.

Demand Response (DR) and Distributed Generation (DG):

Due to the large differences in electricity demand between day and night (Figures 7.1 and 7.2) and the consequent variations in costs, the main purpose of DR is the transfer of some activities that consume large amounts of electricity (for instance water heaters and washing machines) from the peak to the valley hours. Of course, the same could apply in the case of working days during the week versus weekend days (see Figure 7.2). Evidently, the objective of reducing demand in the peak hours can be realized more effectively by introducing smart communications into the grids. Here are some examples of DR techniques: a) Direct load control, where utilities remotely turn off some devices (for example, water heaters), with permission from their customers. b) "Demand limiting" to maintain the overall energy consumption below a budgetary limit fixed by the customer. c) Similarly, Distributed Generation enables consumers to produce power by off-grid generation elements (roof-top solar systems, wind mini-turbines, etc.), as well as consume energy individually (houses, electric cars, etc.), by the control of smart grids.

8.3. System-LCOE

It is frequently accepted that when the LCOE of some VRES like wind or solar PV drops below that of conventional plants, the corresponding renewables become economically competitive. However, this conclusion is finding increasing criticism, especially in the case of high-penetration renewables [Ueckerdet, F. 2013]. In effect, the output of VRES depends mainly on climatic and meteorological conditions, and not only on the characteristics of the generating power plants, contrary to the case of the dispatchable conventional plants. As a consequence, the new concept of System-LCOE has been introduced that takes into account both the generation costs and the integration costs. Evidently, these latter costs cannot be directly calculated from the specific parameters that only characterize power generating plants.

In the case of VRES, the concept of "integration costs" comprehends all additional costs not related to generation and includes 1) the corresponding share of the transport electric grid, 2) the costs of balancing and storage systems, 3) the costs of reserve and backup plants, and 4) the impact on the rest of the system´s conventional plants. Among grid integration costs, the following costs shown below in Figure 8.5 have to be considered [Ueckerdet, F. 2013].

Profile costs: These are a consequence of the variability of VRES, which causes difficulties in matching the power demand and also results from the additional backup conventional plants that are needed when the wind or solar resources drop markedly. In some cases, the opposite may occur; that is, generation can exceed demand, producing surplus power which is lost.

Balancing costs: In case errors occur in the prediction of day-ahead meteorological forecasts, the dispatchable conventional plants may not be ready to respond to the intra-day demand, and therefore special peaking plants will have to start operating within very short intervals of time.

Grid costs: Often investments in transmission grids are needed, especially to handle situations of very high windy days that generate very large current densities across the transmission lines, which can damage the grids.

Time integration costs: In the process of building the first new VRES plants at specific sites, additional costs will be incurred for the adaptation of the conventional plants until the whole system is again adjusted. Usually this cost depends on the length of the whole period of adaptation and is higher for the first new VRES plants constructed.

Although economic models have not yet been developed to fully account for integration costs, we describe next some estimations made recently [Ueckerdet, F. 2013]. Let us assume in Figure 8.5 a generation LCOE cost of 60 €/MWh for the case of wind in Germany, represented by the dotted horizontal line. To this value, it should be added the following costs discussed above: profile costs, balancing costs, grid costs, and time integration costs. As can be appreciated from Figure 8.5, the addition of all these costs constitutes the recent concept of System-LCOE.

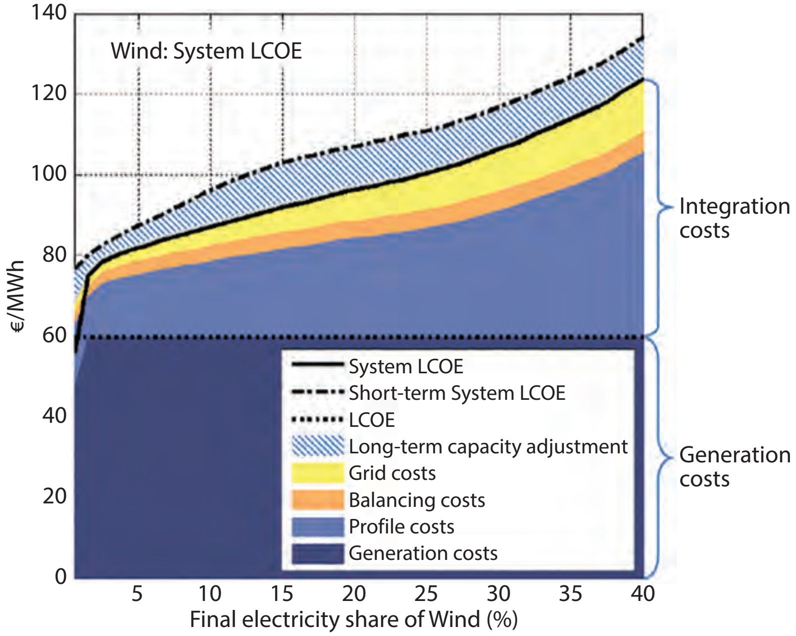


Figure 8.5. Example of system-LCOE for wind as a function of integration share [Ueckerdet, F. 2013].

From the results of Figure 8.5, it can be deduced that the integration costs markedly increase with the percentage of penetration, so that for shares above some 30%, the integration costs exceed the generation costs. Therefore, integration costs can become an economic obstacle for the deployment of new VRES at high shares (>25%), unless high prices for CO_2 emissions are implemented. In addition, the use of advanced meteorological forecast models and the integration of power systems at the European scale are recommended, since in this way the large peaks caused by wind and PV generation would be highly shielded.

9 INTEGRATION OF HIGH SHARES OF VARIABLE RENEWABLE ENERGIES (VRES) IN EUROPE

Based on the European plans to implement a high share of renewables for the reduction of CO_2 emissions as expressed in the 2050 European Energy Roadmap [EC 2011a], we analyse in this section some of the main issues that can arise in the high integration of VRES. In the case of Europe, the Roadmap proposes that the power sector will be the one with the largest reduction of emissions from now to 2050, next being followed by the industry sector (see Figure 2.4). In this way, the percentage of emissions caused by the power generation sector will be in 2050 only around 10% of its current value.

Figure 9.1 [EDF 2015] shows for Europe the amount of renewable electricity generation for the period 2011-2014, as well as the share of the VRES sources in 2014, in which 23% and 8% correspond to wind and solar, respectively. It is also appreciated that at present the main contribution to renewables comes from hydropower.

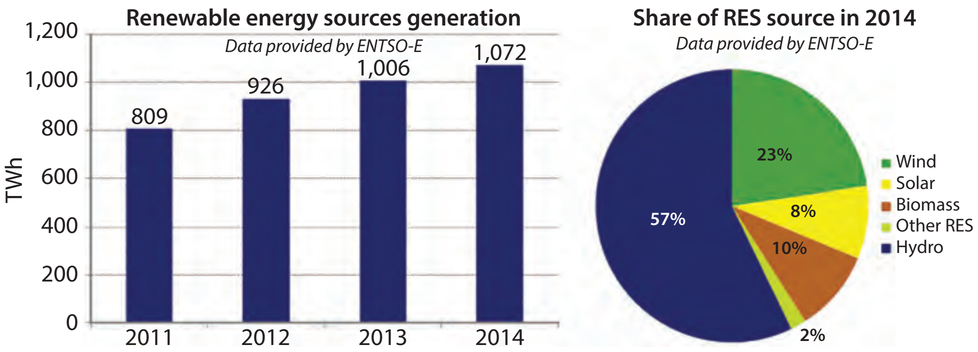


Figure 9.1. Renewable electricity generation (TWh) in Europe (2011-2014) and its share in 2014 [EDF 2015].

It is also known that the European plans for expanding the use of VRES are based mainly on the deployment of wind and solar PV, which together could represent around 28% (wind 22%, PV 6%) of the total electricity mix by 2030 and 35% (wind 26%, PV 9%) in 2050 (Figure 9.2), according to the “EU Energy Trends to 2050-Reference Scenario 2013” [EU 2014]. If these percentages are only expressed in terms of the renewable part of the electric mix, wind would represent 50% and solar 17%. The rest of the mix mainly comprises hydroelectricity and biomass, as well as the conventional thermal sources: nuclear, natural gas, and coal, as deduced from Figure 9.2.

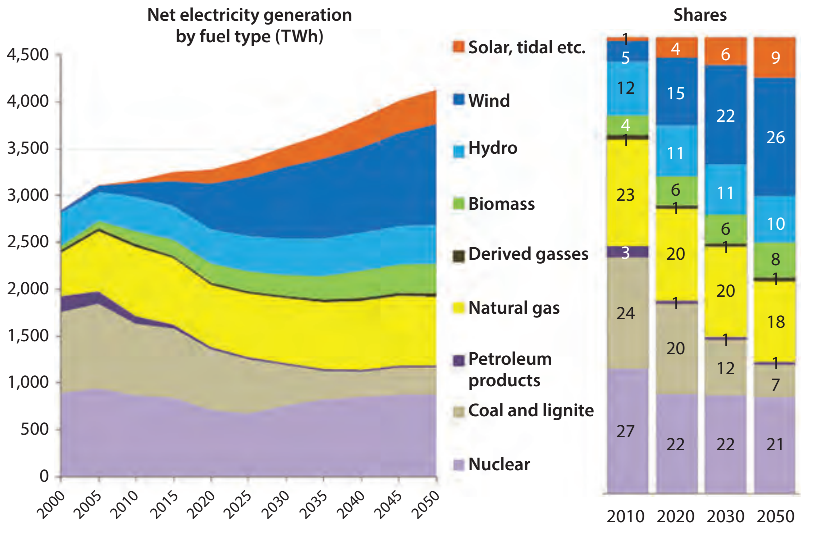


Figure 9.2. Electricity generation (TWh) in Europe by fuel type and projections to 2020, 2030, and 2050 according to the “EU Energy Trends” [EU 2014].

Considering the major regions of the world, Europe is at this moment the one planning for the next decades the greatest implementation of variable renewables in the electricity mix. The problem with integrating high shares of VRES is mainly due to their high variability and intermittency (Section 7) and, therefore, they are considered non-dispatchable, that is, their output is not in general controllable. It has only been recently that energy policy makers have started to consider the additional costs that a high share of VRES would imply [Wagner, F. 2014, EDF 2015, Ueckerdet, F. 2013]. As a consequence, let us consider some of the main questions that are at present being considered, mainly by energy planners in Europe and the US:

1. A high share of VRES requires in parallel the adoption of conventional peaking plants with very fast ramping rates. In effect, due to the steep wind-induced ramps (Figure 7.4), other plants will have to be connected or disconnected when wind is ramping down or up, respectively. In Europe, total electricity generation is expected to grow rather slowly for the next 35 years (Figure 9.2) in comparison with wind and solar PV and, therefore, many of the conventional plants will have to be used as peaking plants and backup plants.

2. The low capacity factors typical of VRES plants (20-30% wind and 10-20% solar PV, Section 4), which are much lower than those of the conventional plants to be displaced, will imply VRES plants with much higher nameplate power capacities (see Appendixes II and III). Therefore, these substitutions will imply high power cost increases.

3. For the estimation of the CO_2 avoided by new VRES plants, it is not enough to subtract the values of the emissions of the previous existing conventional plants since, as we have seen, the addition of VRES plants always needs accompanying backup gas or coal plants.

4. With a large share of VRES, the load/generation (demand/supply) balancing (Section 8.3) will be highly affected by weather conditions, and therefore the use of advanced meteorological forecast models is highly recommended.

5. Cross-border exchanges by means of interconnections among European countries should minimize surplus generation and curtailment, as is already the case with the Nordic Grid [Nordic 2014]. But it is also true that political problems can be caused by environmental disagreements, as was the case between France and Spain, provoked by the deployment of high-voltage lines at the border.

6. In the calculations of electricity costs from a specific resource, the recently introduced concept of System-LCOE (accounting also for integration costs incurred by transmission grids, balancing, storage, etc.) should be used [Ueckerdet, F. 2013].

10 EU´S ENERGY AND CLIMATE OBJECTIVES (PRESENT TO 2050)

Let us now analyse whether or not Europe is on its way to comply with the energy and climate objectives established at the beginning in Section 1.

10.1 Climate warming and emissions

As we have seen previously in detail in Section 5 (Figure 5.3) and Section 2 (Figure 2.4), Europe has clearly specified its emission targets through 2050. In our opinion, the targets to 2020 and 2030 can be reached without great difficulties (see also below), since they are based on viable objectives in the development of renewables and energy efficiency. In effect, the Directive known as 20-20-20 sets a share of 20% of *renewable energies* in the gross final energy consumption by 2020 for the EU as a whole. During the 10-year period since 2004, in which the share at the beginning represented 8%, the percentage of renewables has grown steadily to 15% in 2013. Figure 10.1 represents for every country of the EU the current percentage of renewables; the bars above each column represent the targets for 2020 [Eurostat 2015, EC 2013b]. Observe that in 2013, some countries like France and the United Kingdom were still far from their objectives, while others like Sweden and Romania have already accomplished them. In conclusion, it seems that the EU is on the right track for achieving the 2020 targets.

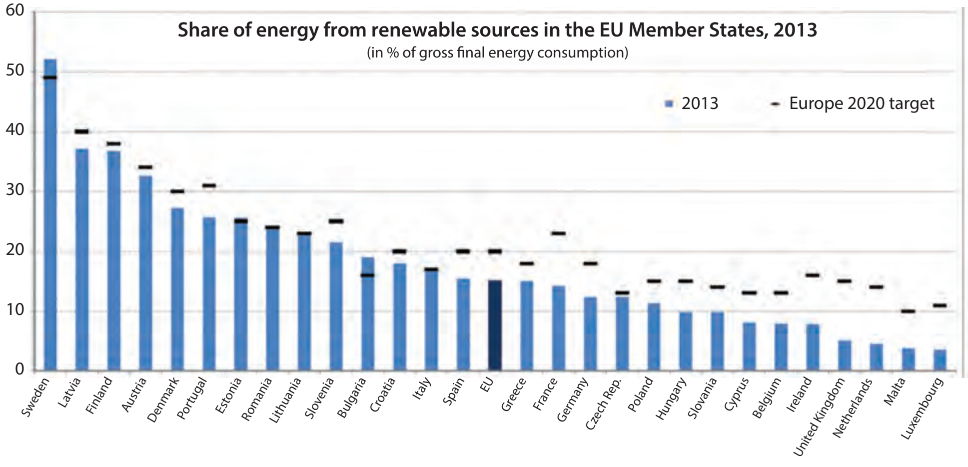


Figure 10.1. Share of renewables as a percentage of the final energy consumption for the EU countries in 2013. The bars above each column represent the 2020 targets set by the EU for each country [Eurostat 2015, EC 2013b].

From Figure 10.2 it can be observed that the evolution of primary energy consumption in the EU is continuously decreasing, from a value of 1720 million tonnes in 2006 to a target of about 1500 million tonnes in 2020 [Eurostat 2015]. Hopefully the proposed decrease will be mainly attributed to an increase in energy efficiency.

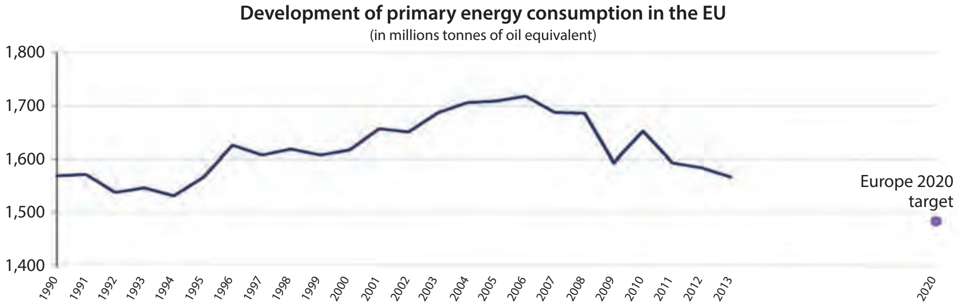


Figure 10.2. Evolution of primary energy consumption in the EU since 1990 and the 2020 target [Eurostat 2015].

However, the great cuts in emissions for 2040 expressed in Section 5, and especially the one for 2050, which is an 80% cut (Figure 2.4), we think will be difficult to reach since, as discussed in Section 9, the reduction is mainly based on the large-scale implementation of intermittent renewables such as solar and wind.

10.2 Security of supply

The security of energy supply in the European countries is still considered an individual issue because of the specificity of the energy mix of each nation. We should not forget that the EU imports more than 80% and 60% of its oil and gas needs, respectively. In the case of these fuels, there are many countries in the EU dependent on imports from Russia, the Middle East, and Algeria, which could become problematical. Some of the plans to increase the security of stocks consist of the establishment of new electricity distribution lines between Member States, as well as improving gas interconnections and LNG imports independent of gas pipelines. Also, the addition of renewables to the energy mix increases the degree of security of supply as well as diminishing energy consumption by improving energy efficiency.

10.3 Competitiveness

The main goal in competitiveness consists of the completion of the European single internal energy market and the promotion of R&D activities on new and *innovative energy technologies*. As specified in the 2050 Roadmap [EC 2011a], reaching a competitive low-carbon European economy will imply, among other things, the creation of a fully integrated and interconnected market for electricity and gas, to be achieved with common large infrastructures such as international interconnects. For this purpose, two new programs have been launched. The first is *Horizon 2020*, which is the main program for the promotion of research and innovation and includes the "Energy Challenge: Secure, Clean and Efficient Energy ", whose initial focus will be on low-carbon technologies, energy efficiency, and smart cities. The second program is the *SET-Plan*, whose goal is the development of competitive low-carbon technologies by joint planning and cooperation of research centres, industries, and policy makers.

10.4 Distribution, smart grids, storage, and international interconnects

One of the main features needed to make the EU energy system competitive is focused on the "flexibility in the EU power system" (see also Section 8.2), designed to deal with VRES. In this line, the EU has recently launched an Energy Package to create a single internal market for electricity and gas [EC 2009a]. In addition, there is strong support for Demand Response techniques (Section 8.2), cross-border power exchanges, and electricity storage [EC 2009b]. In the last case, it is currently planned to design an EU legal framework to enable the deployment of storage at all levels [EC 2013b].

A rather urgent infrastructure that needs to be updated is related to the grid system, which is out of date and fragmented and, due to the stringent requirements posed by VRES, could in the near future often become overloaded or unbalanced. In this sense, the EU has started actions to develop an integrated European energy network (Directive EU 347/2013). This plan also foresees that the current interconnection level, now at 8%, be increased to 15% by 2030. The plan provides details related to reinforcing transmission lines, building grids for the integration of wind plants, etc. [See EC 2014b].

11 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

11.1. Energy mix and security of supply

In the EU-28 countries, more than half (53%) of the energy needed has to be imported from abroad. Recently, after some temporary disruptions of natural gas supplies from Russia, the EU began undertaking a series of measures to secure its energy needs, among them: diversification of suppliers (especially of gas), increasing indigenous renewables, the building of an integrated EU energy market, and R&D in storage. The security of supply can also be enforced by the construction of an efficient interconnected grid across the different European countries for the distribution of electricity. For instance, solar electricity could be mostly generated in the Southern countries and distributed to the Northern ones. Evidently, taking into account all the above factors, and also the energy generation costs, every country should design its most convenient energy mix. One important aspect to take into account is that although primary energy consumption in Europe is forecasted to slowly decrease in the future, the demand for electricity (4th industrial revolution, electric cars, etc.) is, on the contrary, expected to increase considerably. This is one of the reasons why we believe that in addition to renewables, a fair percentage of CO_2-free nuclear electricity should be considered within the targets marked by the 2050 European Energy Roadmap, at least in the cases of countries with a large nuclear tradition (France, Sweden, etc.)

11.2. CO_2 emissions

Currently, Europe has an ambitious program for the reduction of CO_2 emissions that in 2050 are planned to represent merely 20% of its 1990 emissions as an average of all sectors. But this reduction implies that the power (electricity) generation sector will have practically zero emissions as a consequence of the large-scale implementation of renewables for the generation of almost all the electricity. However, in our opinion this target would be almost impossible to reach in only three and a half decades without resorting to nuclear electricity, which is free from emissions and the cheapest source of electricity. Otherwise, further increases in the price of electricity will be unavoidable, making many European products non-competitive internationally, with all the negative economic consequences. Besides, if this great effort in the reduction of emissions is carried out only in Europe, the results would be practically worthless at the global scale due to the high diffusivity of CO_2 molecules throughout the world´s atmosphere. Therefore, in our opinion, what Europe should do is reinforce its position as a leading participant in international negotiations like the UN Climate Conferences (Paris 2015) and simultaneously be competitive in the implementation of renewable technologies and systems. It should also be considered that some European countries will not be able to move to an almost fossil-free economy unless some nuclear share is considered (currently more than 60 new reactors are planned worldwide).

11.3. The costs of energy

The change from fossil to renewable resources proposed in the European 2050 Energy Roadmap will imply a tremendous amount of financial investment. One problem for their calculations is that, as we have seen in detail in this document, the *Levelized Costs of Energy* (*LCOE*) can easily vary by factors close to 100%, due mainly to the intensity of the local resources (solar irradiation, wind speed), the value of the financial discount rate, the lifetime of the systems, etc. But in addition one should also consider the *System-LCOE costs*, which comprise in the case of electricity the *grid and distribution costs, the "intermittency costs" due to the variability of solar and wind resources, etc*. These costs markedly increase for the case of high-penetration renewables (more than 50%), the main reason being the need for flexible backup systems to cover the displaced baseload power generation from traditional plants. It is then evident that Europe should carefully define an energy mix to become economically competitive. It is also important to keep in mind when calculating electricity costs that, in the case of some renewables like solar energy, the power capacity of the systems is given in *peak wattage*, W_p, i.e., the electricity delivered at noon time in summer, not in effective or average energy produced. Therefore, the solar electricity average in the case of Europe would correspond to only 10-20% of the equivalent amount of peak power (W_p) working continuously. Finally, we would like to remark that European energy costs, as a result of political decisions, will have a crucial effect on our worldwide economic competitiveness. Already today, some large chemical companies are investing preferably in the US for its lower energy prices.

11.4. Integration of high shares of variable renewables (VRES)

The European 2050 Energy Roadmap contemplates integrating a high share of variable and intermittent renewables (about 90% in the *High-Ren Scenario*) into the distribution grid. For this to be possible, it would be necessary to substantially transform our present power generation and distribution infrastructures by introducing advanced technologies such as: i) Distributed Generation to produce power off-grid (e.g., self-consumption); ii) Demand Response to transfer high electricity consumption loads from peak to valley hours; iii) smart meters to give information to the consumer of the hours with less demand and lower prices; iv) development of efficient and inexpensive energy storage units; v) the implementation of backup generators for the periods of sudden dropouts of wind or solar resources; and vi) greater generation flexibility in conventional power plants, as demanded by the large variations of VRES, to cover the sudden power down-falls when the wind calms or the skies become cloudy. In our opinion, some of these objectives cannot be reached yet because of the lack of large-scale storage techniques.

11.5. Energy storage

The European 2050 Energy Roadmap is partly based on an extensive implementation of variable renewable energies, especially wind and solar, which are highly intermittent and unpredictable. Therefore, in order to generate dispatchable electricity, it would be necessary to implement efficient and affordable energy storage facilities. As a consequence, strong support of R&D to develop Li-ion batteries with high power/weight ratios is highly recommended, since they are essential for the development of electric cars (in 2030, the electric car market should reach a share of about 10% of new cars). However, Li-ion batteries are not able yet to store the amount of electricity needed for cars at a competitive cost. Seasonal or inter-annual storage would also be necessary to keep solar energy from summer to winter. However, for very long-term storage, it is more recommendable than batteries to use the recently proposed “Gas-to-Power” technologies. In this case, the CO_2 emitted from the combustion of fossil fuels is first captured and later treated as a “new raw material”, which can be transformed into synthetic natural gas by means of hydrogen and the assistance of special catalysts. The resulting gas can then be stockpiled in the city gas pipes and later be used for energy applications or for the manufacture of organic products.

11.6. Distributed Generation and smart grids

The implementation of a high share of renewables will probably lead to the use of *Distributed Generation* technologies, thus enabling the power generation units (roof-top solar panels, wind mini-turbines, etc.) to be closer to the sites where the energy will be consumed. For this reason, in addition to the cost of electricity generation, one should take into account the costs of the deployment of new transmission and distribution grids. In this context, the wide utilization of smart grids would enable the incorporation of information and communications technologies in all aspects of power generation, distribution, and consumption. In addition, the use of DG, smart grids, and smart meters would allow the management of linked mini-power generators, storage units, and distribution lines. However, these problems are now far from being solved.

11.7. Re-examination of the 2050 European Energy Roadmap

Although the European Union Energy Roadmap is quite specific on the emission targets for the period 2020-2050, it is hard to believe that the almost null emissions attributed by 2050 to the power sector in this document can be achieved. In effect, the so-called *High Renewable Energy Sources* contemplates a share of renewables in electricity consumption of an incredible 97%. Therefore, we propose that the existing Roadmap be re-examined, specifying clearly the new renewable sources as well as the expected yearly amount of generated electricity in energy units (W-hour), all of it for the period until 2050. At present, most of the time, the renewable electricity is expressed only in terms of the power capacity (W) of the systems that will be implemented. However, the renewable electricity produced depends in a great part on the geographical location and weather. In addition, for the case of solar, the installed power is specified in terms of peak watts (W_p), which corresponds to the maximum power delivered by the system (with the sun at its zenith in summer). However, it is known that for Europe the average solar electricity is equivalent to only 10-20% of the electricity delivered by a system working constantly at W_p. Therefore, all the electricity supplies should be characterized also by the actual energy expected to be generated at the plant´s site.

11.8. R&D in advanced materials for energy

Currently one of the major priorities in research in the EU is in low-carbon technologies for sustainable energies in order to meet the 2050 targets on emissions and climate change. It is widely admitted that to reach these targets it is necessary to dedicate a great effort in R&D in advanced materials for energy applications, and it is recognized that Europe is in an excellent position to do this, due to the high level of its scientific research in the field of materials. Some of the research priorities in advanced materials will be in applications for efficient solar cells, blades for wind turbines, fuel cells, efficient batteries with high cycling rates, LED materials for lighting, catalysts for CO_2 conversion into synthetic natural gas, etc. In this sense Europe appears to be at present on the right track through the announcement of several research calls under the H2020 Program. This should be in addition to the very ambitious national programs carried out in some European countries, for instance on advanced materials for CO_2 recycling, similar to those run in China and Japan.

APPENDIX I: ENERGY AND POWER UNITS

The terms energy and power are closely interrelated, and both have to be used in dealing with energy policies. We are frequently familiar with the various forms of **energy** used in many aspects of our lives such as transportation, conditioning of buildings, and generation of electricity. The time rate at which energy is used is known as **power**, which is equal to energy divided by time.

When we refer to systems or machines delivering energy, they are usually described in terms of power, for instance a car of 120 horsepower (120 HP = 120 x 746 Watts) or a light bulb of 100 W. Evidently, since energy is equal to power multiplied by time, it is very common to express energy in units, for instance, 1 kWh, which is the energy provided by a system when it supplies 1 kW of electric power during a 1-hour period.

In physics, the basic units of energy and power are the Joule and the Watt, respectively, but since these units are too small for everyday applications, the following multiples are often used:

Prefixes most often used:

10^3 or Kilo (k) = 1,000

10^6 or Mega (M) = 1,000,000

10^9 or Giga (G) = 1,000,000,000

10^{12} or Tera (T) = 1,000,000,000,000

10^{15} or Peta (P) = 1,000,000,000,000,000

10^{18} or Exa (E) = 1,000,000,000,000,000,000

Examples of power in Watts:

- A horse or a bull can usually develop around 1 HP and a person perhaps about 15% of this, or some 120 W.
- 1 kW, a typical air-conditioning unit; 5 kW, typical power supplied to an apartment by utilities.
- 1 MW, typical wind turbine.
- 1 GW, typical nuclear reactor.
- 550 GW, capacity of wind plus solar plants in the whole world.
- 1 TW, about the total installed electricity power capacity in the European Union.

Examples of energy consumption:

- World energy consumption in 1 year: approximately 540 EJ
- Electric car: 12 kWh in 100 km.

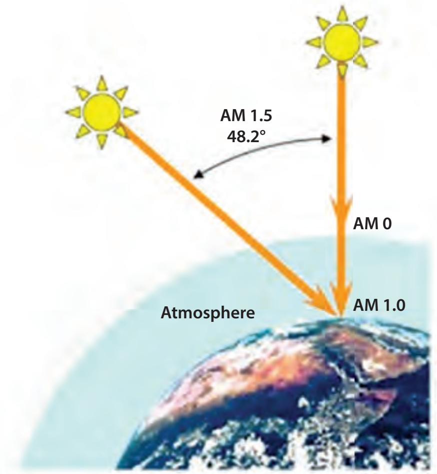
Let us next indicate some conversion factors:

- 1 kWh = 3.6 MJ
- 1 tonne coal equivalent = 29.3 GJ
- 1 tonne oil equivalent (toe) = 42.6 GJ. (Observe the units in Figure 3.1, which are toe.)

Example of average power needed by each person in the world: The average energy corresponding to each person is obtained by dividing (see above) the world energy consumption of 540 EJ by approximately 7,000 million inhabitants, yielding about 77 GJ per person per year. Let us next divide this amount by the numbers of seconds in a year, resulting finally that it is as if every person (on average) would constantly demand a power of 2.5 kW.

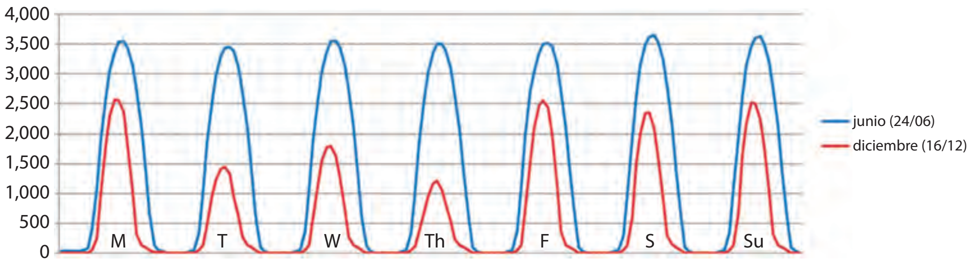
APPENDIX II: HOW TO CALIBRATE THE POWER PERFORMANCE OF SOLAR PV CELLS

The technical conditions for the calibration of the power of solar cells and modules are as follows: a) The temperature of the cell should be 25°C. b) The incident radiation on the cell should be 1000 W/m^2. c) The incident radiation should have a spectral distribution known as AM1.5. The "Air Mass (AM)" is related to how far the sunlight travels through the atmosphere. As indicated in the figure below, AMO describes the sun´s solar radiation before crossing the atmosphere, AM1 when the radiation reaches the Earth´s surface perpendicular to it, and AM1.5 when the angle is 48°, since the length of atmosphere crossed is proportional to the inverse of the cosine, and 1/cos48° = 1.5.



Air Mass (AM) test conditions: AM0 corresponds to the solar radiation in free space, AM1 reaching the earth´s surface perpendicularly, and AM1.5 at an angle of about 48°.

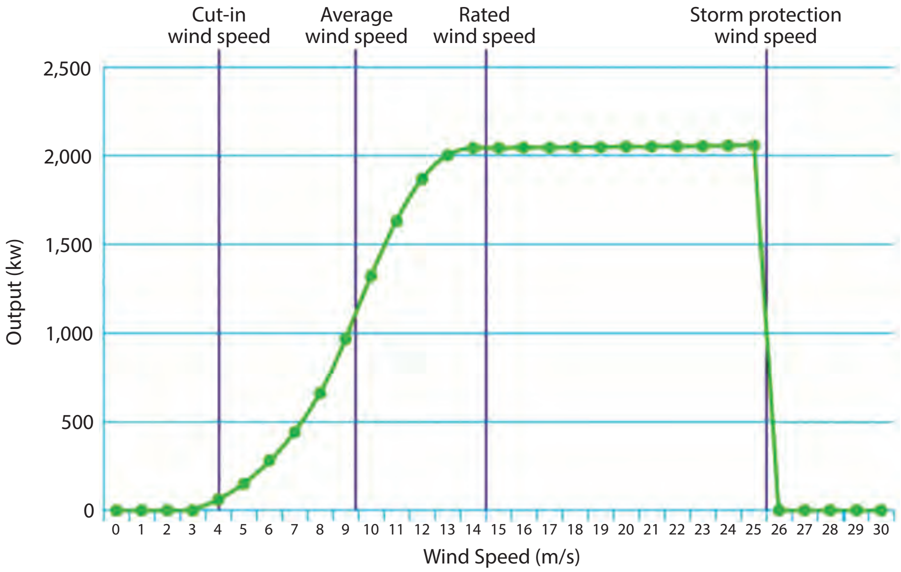
Although the radiation from the sun is about 1365 W/m^2 in AMO conditions, in the case of AM1.5 it is very close to 1000 W/m^2. (Evidently, the cells and modules are calibrated in the laboratory by using solar simulators provided with spectral power lamps with a distribution similar to the sun´s radiation in conditions AM1.5.) The power rating of a solar cell is therefore specified in units of peak watts (W_p) by measuring the power output supplied when it receives 1000 W/m^2 from a spectral distribution equivalent to AM1.5 conditions. We calculated in Section 4 (Table 4.1 and Figure 4.2) the values of the capacity factors of solar PV for several European countries and observed that they were quite low. Evidently the main reason is that due to the latitudes of these countries, the radiation from the sun has to travel through lengths of the atmosphere much longer than its thickness. In addition, the amount of electricity generated in winter is quite small, as can be observed in the figure below for the case of Spain. The area underneath the two curves gives the generated electricity yielding 234 GWh and 89 GWh for typical summer and winter weeks, respectively.



Power (MW) generated by PV solar plants in Spain for the week of June 24-30, 2013, compared to the week of December 16-22, 2013 [REE 2013].

APPENDIX III: HOW TO CALIBRATE THE POWER PERFORMANCE OF WIND TURBINES

The power rating of a wind turbine is based on the so-called wind-speed power curves like the one shown in the figure below. When the wind reaches speeds of about 4 m/s, or the *cut-in speed*, the turbine starts working and generates power, which increases approximately as the cube of the wind speed. However, there is a limit in wind speeds (about 15 m/s in the figure) that the turbine is not allowed to surpass, in order to protect its mechanical parts (blades) as well as the electronic components that control the rotors. Since the turbine cannot rotate the blades faster, this wind speed corresponds to the so-called *rated power wind speed*, at which turbines are rated in power. For higher wind speeds than the rated one (15 m/s), the turbine produces a constant output power (see figure) equal to the rated one until a limit known as *shut-down speed* (25 m/s) is reached. For wind speeds higher than 25 m/s, the turbines are shut down to avoid damaging the electrical and mechanical components, and the power output drops to zero.

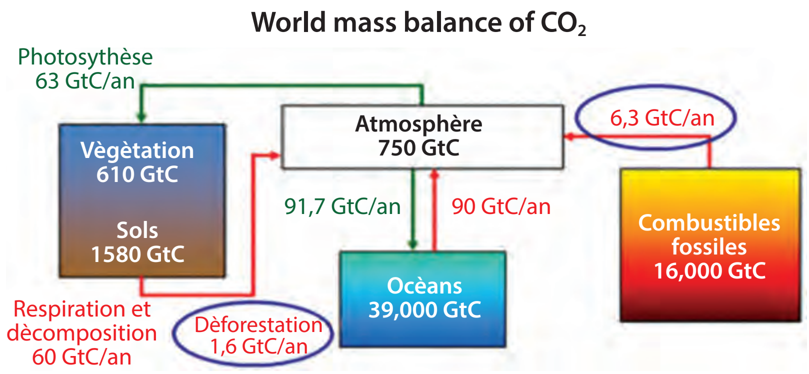


Typical power vs wind-speed curve for a turbine with a rated power of about 2 MW.

As we have explained, the power rating of the turbine wind-speed curve is that shown in the figure (vertical axis) and is about 2 MW. However, the energy produced per year would be much less than 2 MW x 8760h = 17520 MWh, since the turbine only generates 2 MW during a small percentage of hours in the year. During many hours, the turbines will be working around the average wind speed, and in some periods with very weak winds they are idle. In Europe, a generation of about 25% (capacity factor) of the above calculation would be considered normal (see Figures 4.2 and 7.5).

APPENDIX IV: CO_2 AND THE EARTH'S CARBON CYCLE

Let us now look at the Earth´s balance of CO_2, considered within the more general, relatively well-known carbon cycle. During photosynthesis the action of the sun´s radiation on the chlorophyll of plants produces the growth of vegetal biomass by the reaction of water with CO_2. Although plants also produce CO_2 by respiration and decomposition, the equilibrium among both processes has been broken in the last decades as a consequence of deforestation and land-use. As a result, the equivalent to an additional emission to the atmosphere of about 1.6 Gt/yr is produced, as indicated in the figure below. Notice from the figure that in each box we have also indicated the estimated carbon reserves corresponding to vegetation and soils at the Earth´s surface and combustible fossil fuels under the surface of the Earth and bottom of the oceans.



World mass balance of CO_2 (the units correspond to Gt of carbon atoms).

Most importantly, the combustion of fossil fuels like coal, oil, and natural gas produces a significant additional yearly amount of CO_2 equivalent, between 6 and 7 Gt/yr. As a consequence, the Earth's carbon cycle is being altered by human activities. Therefore, the concentration of the CO_2 in the atmosphere is increasing because emissions surpass by over 8 Gt/yr the Earth´s natural sinks, and the corresponding rise has an anthropogenic origin. Observe that the amounts corresponding to the above magnitudes of CO_2 might seem quite different from those reported previously in the context of Figure 2.3, the reason being that now, since we are dealing with the carbon cycle, the units are referred to amount of carbon atoms without considering the weight of the oxygen atoms in the CO_2 molecules.

Finally, there is another process, corresponding to the interchange of CO_2 between the atmosphere and the oceans, which yields a net ocean uptake favouring the diminution of the atmospheric CO_2 concentration. However, it is rather unknown how this process will evolve in the distant future, since it takes a much longer time for the deep layers of the oceans to absorb CO_2, once the more superficial layers become saturated.

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