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Electricity Production from Renewable Energy

1.1. Decentralized or centralized production?

1.1.1. *Decentralized production*

There is no clear official definition of decentralized production. Generally, decentralized production is defined as the opposite of centralized production [CRA 08, JEN 00]. To simplify, let us say at first that decentralized units:

– are not planned in a centralized way;

– are not controlled (or dispatched) in a centralized manner;

– have a power, which does not exceed 50 to 100 MW;

– are generally connected to the distribution network and not to the transportation network.

Another characteristic of decentralized production is that it is scattered over a territory, in contrast to conventional production, which is concentrated on a limited number of well-defined sites.

The development of decentralized production over the last few years has been especially favored by the opening of the electricity markets (which has spread in Europe from the beginning of the 2000s) and the development of renewable energies, especially wind energy, driven by a real commitment to the environment on a European scale. Decentralized production is thus developing in many countries

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on the basis of cogeneration units, renewable energy systems or conventional productions, which have been installed by independent producers.

The development of this type of production can contribute to solving technical, economic and environmental problems [CRA 08, JEN 00], even if it is not the only answer to these multiple challenges.

Let us make a list of elements favoring decentralized production:

– the desire to reduce greenhouse gas emissions (mainly CO_2) encourages the development of renewable energies;

– the energy efficiency increase, which has been obtained thanks to cogeneration systems;

– the opening up of the electricity market enabling the emergence of independent producers;

– the desire to widen the range of energy supply, in order to limit the energy dependence of the European Union, which results from the use of fossil fuels;

– technological progresses contributing to the reliability and availability of 100 kW to 150 MW units;

– the greater facility to find sites able to accommodate a reduced power production;

– shorter construction periods and lower investments than for large conventional power plants;

– a production that can be carried out at the proximity of its use, thus reducing transportation costs.

Depending on the profile of the historical generation system of each country, the structure of their transport and distribution network and the organization of the electrical system, these various points can be more or less important, depending on the countries, especially within Europe.

1.1.2. *Centralized production*

The historical organization of an electricity grid is based on its centralized management at the level of the transmission grid to which the traditional production units of nuclear, thermal or hydraulic types are connected. In the case of the latter, it is a large hydraulic power plant equipped with a dam that retains a body of water in a mountain valley or along a river. These large power plants, often with a capacity of over a hundred MW, contribute to the stability of the electricity grid by, among other things, participating in ancillary services including frequency and voltage control, as explained in Chapter 6.

Certain power plants which exploit fluctuating renewable energies with huge capacity can be connected to the transmission grid. This is the case for offshore wind farms, with a capacity of several hundred MW, proliferating in the North and Baltic Seas. Due to the very intermittent upstream source, these wind turbines are barely able to contribute to ancillary services, aside from voltage control, unless they are combined with energy storage systems [ROB 15].

It should be noted that tidal power stations, similar to hydraulic power stations, can also be connected to the transmission grid, for example the La Rance Tidal Power Station in France, with a capacity of 240 MW (see Chapter 4). Certain high-power thermodynamic solar plants (see Chapter 5) could also be connected to the transmission grid, such as the 540 MW project at Ouarzazate in Morocco [CAS 20]. These plants provide some, albeit limited, energy storage capacity by storing water in a basin, or heat in a body of water or other materials with favorable properties [ROB 15].

1.2. The issue of renewable energies

1.2.1. *Observations*

The growing interest in the development of renewable energies is caused by several elements: climate change, increasing energy demand, limits of fossil fuel reserves, low global efficiency of the energy system and energy dependence, especially in the case of Western countries [CHA 04].

Climate change

The growing "greenhouse effect" leads to an increase in the global temperature at the surface of the planet. And yet, because of human activities, the concentration of greenhouse gases has soared since the pre-industrial era (1750-1800), with the concentration of carbon dioxide (CO_2) (the main greenhouse gas) increasing by more than 30%. The combined effects of all of the greenhouse gases (CO_2, methane, ozone, etc.) nowadays amounts to more than a 50% increase in CO_2 compared with this period.

Between 1860 and 2010, the mean temperature at the surface of the Earth rose by 0.6°C. Several prospective scenarios are predicting that by 2100, this temperature will increase further between 1.5 and 6°C, if energy systems and current consumption habits do not change. This significant increase would be accompanied by a sea level rise from 20 cm to 1 m. If the climate change seems non-reversible, this evolution can however be slowed down, by significantly reducing greenhouse gas emissions.

The natural CO_2 wells, such as land, trees and oceans, would only be able to absorb a little less than half of the CO_2 production resulting from human activities (produced in 2000). In order to stabilize the CO_2 concentration at its current level, we thus would have to immediately reduce the gas emissions from 50 to 70%. This drastic reduction is clearly impossible. However, it is urgent to start acting, because this is a cumulative issue. Indeed, the carbon dioxide lifespan in the atmosphere is of about one century and, therefore, the stabilization of the CO_2 concentrations to an acceptable level will take several generations.

CO_2 is produced by the combustion of all fossil fuels: oil, gas and coal. CO_2 emissions from coal are twice as high as the emissions from natural gas. Oil emissions are in-between.

At the beginning of the 21st century, the distribution by sectors of CO_2 emissions in the world was as follows: electricity production 39%, transport 23%, industry 22%, residential 10%, service sector 4% and agriculture 2%. However, this distribution varies from one country to another. For example, in France where only one tenth of the electricity is produced from fossil fuels, the transport sector is responsible for more than 40% of the CO_2 emissions into the atmosphere.

Increasing energy demand

At the beginning of the 21st century, the global energy consumption was about 10 Gtoe (toe = ton of oil equivalent; 1 toe corresponds to the energy produced by the combustion of one ton of oil). Fossil fuels represent about 8 Gtoe.

Many energy scenarios are developed each year by specialized organizations in the energy field. These scenarios plan an energy demand in 2050 of about 15 to 25 Gtoe. These prospective scenarios are based on various parameters, such as economic growth, increased by world population increase, the progressive access to electricity of the billion people still without any access to it at present, the growing needs of developing countries and the implementation of energy-saving policies in order to protect the environment. The uncertainties in relation to the evolution of these parameters explain the significant gap between extreme scenarios.

However, it seems quite reasonable to predict that by the middle of the century, the energy demand will have doubled.

Limits of the fossil fuel reserves

The R/P oil ratio (known reserves to the annual production) is about 50 years [WIK 20a]. This piece of data (which is equivalent to a period) should not be mixed up with the period during which we will still dispose of oil, nor to the one during which it will still be cheap enough. These two periods are completely unpredictable, because they depend on too many parameters. Let us note that since the 1980s, each year we consume more oil than we discover.

For natural gas, the R/P ratio is about 50 years as well. However, if we wanted to replace oil and coal with gas, in order to reduce greenhouse gas emissions, the R/P ratio would be reduced to less than about twenty years. When some countries give up nuclear energy for the benefits of gas, it could increase the consumption of resources.

Coal is the fossil fuel with the most significant reserves. Its R/P ratio is estimated at almost 200 years.

The R/P ratio of uranium is about 90 years (on the basis of "reasonably assured resources" added to "recoverable resources" for a cost between 80 and 260 $/kg of natural uranium and a conventional fission exploiting isotope 235) [WIK 20a].

The energy demand until 2050 (then predicted to be between 15 and 25 Gtoe, compared to nearly 14 Gtoe in 2018) could still be met mainly (at present) by non-renewable raw energy materials. This would have dramatic consequences for the climate in particular, and for the environment and would not really take into account the needs of future generations.

In order to limit the rise in temperature to a range from 1 to 3°C, the total emissions for centuries would have to be only a third of the current emissions, caused by the combustion of the accessible resources of gas, oil and coal. Humanity would then have to stop burning two-thirds of a relatively cheap and accessible energy source. It is thus not reasonable to bank on an early exhaustion of the resources, in order to naturally reduce greenhouse gas emissions. This is particularly true, because the relatively low price of fossil fuels (despite regular explosions) are disrupting the emergence of new technologies, which are inevitably more expensive until they become integrated into a mass production process.

Low global efficiency of the energy system

The global efficiency of our energy system is quite low: for example, in 2008, to satisfy the French requirements for the final energy (marketed) of 168 Mtoe, 262 primary Mtoe were needed to produce them, which corresponds to a 63% efficiency, all the while knowing that effectively useful energy is much lower. The energy transformation losses alone when making marketable energy are about 27%. 94 Mtoe have thus been lost in energy transformations (refining, electricity production, etc.). These losses of 94 Mtoe, associated with bad uses of the final energy (bad building insulation, low efficiency of the car heat engines, etc.) are the main item of expenditures and finally the most important cause of CO_2 emissions. For example, at the beginning of the 2000s global efficiency was about 34% and it has since evolved very slowly.

Energy dependence

About 50% of the energy consumed within the European Union comes from resources located in countries outside the EU. If nothing changes in the energy production field, and taking into account the expected consumption increase, this energy dependence will go up to 70% by 2030.

The global dependence on Middle Eastern countries (which possess 65% of the known oil reserves) should increase. The dependence is even higher for uranium (100% for France). Economic and political tensions could arise from the diminution of fossil resources, which are easily exploitable, and from their concentration in politically unstable zones. This would question the supply security of the countries in the European Union.

1.2.2. *The sustainable development context*

The concept of sustainable development was defined in 1986 as follows: “meeting the needs of the present without compromising the ability of future generations to meet their own needs”.

This concept implies the exploitation of renewable energy sources, which are the only sustainability guarantees, and the minimization of environmental impacts, associated with their conversion and the manufacturing of their converters. Fossil and fissile fuels are appearing as a finite and economically limited resource, causing emissions that affect the environment and/or contribute to climate change in the case of fossil fuels. A sustainable energy system must include renewable energy sources and/or conversion chains exploiting low emission renewable fuels, which are available at an acceptable price. Despite the fact that the implementation of new energy facilities takes several decades, an increasing number of large companies are involved in the development and marketing of these new technologies.

Sustainable development requires good management of the balance between economic development, social equity and environmental protection in all regions of the world. This concept can only become effective with real political will from an increasing number of countries.

1.2.3. *Commitments and perspectives*

The concept of sustainable development is an answer to the observations above. To implement it, several decisions and associated objectives have been progressively made on the European and international level.

Kyoto protocol and other international conferences

In 1997, the Kyoto protocol set the objective to have reduced global greenhouse gas emissions by 5.2% around 2010, in comparison to the levels in 1990. The European Union promised an 8% reduction of its emissions by 2010, and each member was allocated their own reduction quota of emissions, by taking into account the specificities of each country. More than half of the countries had to reduce their emissions (Germany, Austria, Belgium, Denmark, Italy, Luxemburg, Netherlands), some others needed to stabilize their emissions (France, Finland), while other countries were authorized to increase their emissions (Greece, Ireland, Portugal, Spain, Sweden).

To stop the increase of the carbon dioxide concentration in the atmosphere by 2050, our current emissions will have to be halved worldwide, and thus reduced to between $\frac{1}{3}$ to $\frac{1}{5}$ in developed countries. The Bali conference in December 2007 re-launched the negotiations between the States, in order to increase commitments to countries reducing CO_2 emissions.

During the 2010s, global CO_2 emissions tended to continue increasing and reached 33 GT (gigatonnes) in 2019, mainly due to the production of electricity from fossil fuels, including coal [WIK 20b]. The Paris Climate Change Conference in 2015 (COP21) set targets for reducing CO_2 emissions, in order to limit the temperature rise to less than 2°C in 2100. However, these targets appear insufficient, given the levels of greenhouse gas emissions estimated for 2030, on the basis of planned contributions at the national level, which are not compatible with least-cost scenarios allowing for a temperature rise of 2°C, but result in an emissions level of 55 GT projected for 2030, and that far greater emission reduction efforts will be required in order to reduce emissions to a 40 GT target [WIK 20c]. The Madrid Climate Change Conference in 2019 (COP25) highlighted the fact that there were more disagreements than points of convergence between participating countries on the importance of carbon reduction and strategies to help limit CO_2 emissions, doing little to encourage optimism in the short term [WIK 20d].

European Union and sustainable energy development

At the beginning of the 21st century, the European Commission made the development of renewable energies a political priority, this is described in the White paper “Energy for the future: renewable sources of energy“ and the Green paper “Towards a European strategy for the security of energy supply”.

The objective set by the Commission was to double the proportion of renewable energies in the global energy consumption, from 6% in 1997 to 12% in 2010. This doubling objective fits within a strategy of supply security and sustainable development; a particularly significant effort has to be made in the electrical field. Within the European Union, the proportion of electricity produced from renewable energy sources should reach 22.1% in 2010, compared to 14.2% in 1999. This objective was defined for the EU-15, and was significantly lowered for the EU-27, in order to reach 21%.

In 2007, the European Council promised to reduce CO_2 emissions by 20% within the European Union by 2020. The objective was that 20% of the final energy consumption should be ensured by renewable energies, with a 10% biofuel use in transport, and a 20% energy efficiency improvement.

The European Union’s target for 2030 is for at least 32% of gross final energy consumption to come from renewable sources [EUR 18].

Electricity market opening

Since the beginning of the 2000s, the electricity sector has been the scene of a deep restructuring, resulting from the European Directive CE 96-92. This directive imposes a management of the activities inherent in the transport of electricity, which is independent from the electric energy production activities. The backbone of the electrical supply remains the transport network, which is managed in each state by one or a reduced number of managers appointed by the government involved.

One of the consequences of the opening of the electricity market is the development of a decentralized production, on the basis of cogeneration units, renewable energy sources or traditional production, which is installed by independent producers.

The integration to the electrical networks of renewable energy sources, more specifically those subjected to climate vagaries, such as wind and solar power, and more generally of decentralized production, will require significant network upgrading, as well as the implementation of new equipment and new management methods. The challenge is then to maintain the reliability and quality of the power supply for private individuals and businesses, despite market liberalization and the growing use of random renewable energy sources.

Technological prospects

It is quite difficult to identify the technologies that will play a crucial role in the future for the fight against the greenhouse effect. A future energy system with low greenhouse gas emissions will probably rely on a combination of energies, of energy vectors and converters, which will take on various forms in the different regions of the world.

It is however possible to determine five trends of our energy future:

– The proportion of renewable energies is progressively increasing, but this progress will notably depend on the reduction of their costs and on the progress made in terms of massive energy storage, which could integrate important quantities of intermittent and scattered production into electrical networks [ROB 15, ROB 16, ROB 19]. However, according to the most optimistic predictions, the combination of different renewable energies could enable them to reach 30 to 50% of the market around the middle of the century (at the beginning of the 2000s, all renewable energies represented about 10% of the energy production, but nearly 20% in 2018 [WIK 20a]). However, some scenarios aim for 100% renewable energies as of 2050, due not only to a considerable increase in the efficiency of our energy system, but also thanks to a significant decrease in consumption, i.e. practicing energy sobriety [CAS 20];

– Fossil energies will still be used for several decades, all the while favoring energies with a low carbon content, such as gas. However, the capture and storage of carbon dioxide in economically bearable conditions seems to be the only technological option, which is likely to authorize the use of fossil resources, all the while limiting the CO_2 concentration in the atmosphere, while waiting for significant technological developments.

– Nuclear power does not generate CO_2, except for the CO_2 emissions during the plant construction, deconstruction, and during uranium enrichment. This type of energy will continue to be developed in some countries, such as France, by means of a well developed waste management process, the development of a new generation of safer reactors, knowing that fissile resources are also limited, and then in the long-term by the development of nuclear fusion. However, nuclear fusion is only considered on the horizon after 2050.

– The spreading of fuel cells could lead to the development of a “hydrogen economy”. The production of hydrogen does not generate CO_2 if the hydrogen is produced from renewable, nuclear or fossil energies with CO_2 sequestration. The USA did not ratify the Kyoto protocol, because they consider it to be too restrictive for their economy. In 2003 they launched an ambitious research program aiming to reduce the hydrogen production cost, while controlling greenhouse gas emissions, mastering hydrogen storage and reducing the fuel cell cost. In recent years, Europe has been developing its efforts in regards to research and development on H_2, its production and its uses.

– Finally, controlling greenhouse gas emissions will not be possible without significant progress in energy efficiency in the construction, industrial and transport sectors. The challenge is to use less energy to satisfy the same needs, all the while knowing that the potential energy savings are huge.

1.3. Renewable energy sources

In our time scale, renewable energies are those continuously provided by nature. They come from solar radiation, the core of the Earth and from the gravitational forces of the Moon and the Sun with oceans. We can distinguish several types of renewable energies: wind power, solar power, biomass, hydraulics and geothermics [MUL 03, REV].

1.3.1. *Wind energy*

The available wind resources are evaluated on a global scale at 57,000 TWh/year. The contribution of offshore wind power (at sea) is estimated to be 25,000 to 30,000 TWh/year, if we limit ourselves to sites whose depth does not exceed 50 m. The global production of electricity in 2018 was about 26,700 TWh (which corresponds to a fossil or nuclear primary consumed energy of about 66,750 TWh, related to the low efficiency of the thermo-mechanical cycles, often ranging between 30 and 40%). In theory, wind energy could satisfy the global electricity demand. However, the main disadvantage of this energy source is its instability. There is often not much or no wind during very cold or very hot periods; and yet there is an increased energy demand during these periods. This is why we could envisage an important development of wind power, all the while associating it with other renewable energy sources, which would be less random or complementary, or have thermal sources or electrical energy storage devices. There are many ideas for storing large quantities of electricity (notably pumped storage power stations), their implementation is the subject of numerous research projects aimed at increasing performance and reducing costs [ROB 15].

Europe represents 9% of the wind energy potential available in the world. In 2017, the member countries of the European Union produced 362 TWh of electricity from wind energy. The wind energy technically available in Europe, not including offshore, would be 5,000 TWh/year.

1.3.2. *Solar energy*

The projected lifespan of the sun is still five billion years, which, in our time scale, makes it an inexhaustible and thus renewable energy. The total energy received at the surface of the Earth is 720 million TWh/year, i.e. 6,000 times the current primary consumption of all human activities. But the availability of this energy depends on the day-night cycle, the latitude of where this energy is captured, the seasons and the cloud cover.

Solar thermal energy consists of producing hot water usable in construction or enabling the operation of turbines, by exploiting concentration phenomena to increase temperatures in thermal power stations with thermodynamic cycles, in order to produce electricity. This electricity generation technique is the subject of experimental power stations, whose net efficiency is around 15%. Sea surfaces are naturally heated by the sun and there is thus a gigantic energy reservoir in the tropical zone. Projects for the extraction of this "ocean thermal energy" have been carried out by implementing thermodynamic machines, which operate on the small difference found between the surface (25 to 30°C) and the depth (5°C at 1,000 m). In order for this solution to be exploitable, the temperature difference has to be higher than 20°C. However, the efficiency obtained (around 2%) is very low. It should be noted that low yields mainly translate into larger energy conversion machines, but do not have the gravity associated with the consumption of non-renewable raw materials, which are irreparably consumed and therefore lost.

Photovoltaic solar energy consists of directly producing electricity via silicon cells. When the sun shines and weather conditions are favorable, the sun supplies a peak force of 1 kW/m^2 at ground level. Photovoltaic cells were developed in the 1960s to power satellites; at that time, the cost was in the order of $1,500 per peak watt. Industrial developments have since reduced this cost to $50 per peak watt in the 1970s, and around $0.5 per peak watt today [BAR 14]. Marketed photovoltaic panels help to directly convert 10 to 15% of this power into electricity. The productivity of a photovoltaic panel varies with the level of sunshine: about 100 kWh/m^2/year in Northern Europe and twice this amount in the Southern Mediterranean region. A photovoltaic roof of 5 x 4 meters has a power of 3 kW and produces from 2 to 6 MWh/year, depending on the sunshine. If the 10,000 km^2 of roof in France were used as photovoltaic generators, the production would be 1,000 TWh/year, i.e. a little less than double the yearly final electricity consumption of France in 2017 (562 TWh).

The main "brakes" to the massive use of photovoltaic solar (and thermal) energy are the intermittence of the supplied power (which requires electricity storage for an autonomous use [ROB 19] or the use of additional energy sources) on the one hand and the economic competitiveness on the other hand. Outside the zones not connected to the network, where it is already profitable, the parity between photovoltaic production costs and electricity sale prices starts to be found in countries where electricity is the most expensive and where sunshine levels are at the highest. It should spread to all territories before 2050. This development is encouraged by the self-consumption of locally produced electrical energy [ROB 19].

1.3.3. *Hydraulics*

Hydraulics is currently the first exploited renewable source of electricity. However, the global potential could be better exploited. Global production in 2018 was 4,239 TWh/year, with an installed capacity of 1 291.8 GW. It could go up to 8,100 TWh by 2050. 14,000 TWh would technically be exploitable and the theoretical potential would be 36,000 TWh.

Large hydraulics (with a power higher than 10 MW) are exploited at almost the maximum of their potential in industrialized countries. Dams store the energy and supply it in peak energy demand. In some cases, high and low storage pools enable actual energy storage by using groups of reversible turbo-generators, which are pumping in off-peak periods. This form of storage is frequently used around the world. In France, 4,200 MW are installed for this function.

Small hydraulics (of a power lower than 10 MW) are partly made from run-of-river power plants, which depend highly on the river flow rate. The small power plants are quite interesting for decentralized production. The global production is estimated at 85 TWh. In France, while large hydraulics has almost reached saturation, the development potential of small hydraulics remains, which is estimated at 4 TWh/year, ⅓ of which comes from the improvement of the existing facilities and the remainder from new facilities.

Tidal power can be used to produce electricity. In France, the Rance Tidal Power Station (240 MW) has proved the feasibility of this electricity production technique. Other significant projects are currently studied in Canada and England; however, whether or not these studies will be put into practice remains uncertain, because of the considerable changes that would occur in local ecosystems.

Hydro turbines were developed on the same principle as wind turbines, but are completely submerged at sea, so as to harness the energy of sea currents. Since water density is 800 times greater than that of air, the blades will be that much smaller than those of wind turbines. Since they are submerged, they are very discreet and have the added benefit of a more constant source of energy than wind power.

Wave motion is an important source of energy. The average annual power on the Atlantic coast ranges between 15 and 80 kW/m of coast. However the marine environment is very restrictive and wave energy recuperators are still being researched; they are not exploitable on a large scale. However, prototypes of wave-energy power plants are in the testing stages.

Finally, osmotic energy is obtained by bringing fresh water and salt water into contact with one another at river mouth estuaries, through a semi-permeable membrane. This results in a pressure difference which makes it possible to rotate a turbine. This technology is still at the research stage; a 4 kW demonstrator exists in Norway [BAR 14].

1.3.4. *Geothermal energy*

The temperature of our planet increases considerably as we get closer to the center. In some zones of our planet we can find, at depth, water at a high temperature. High temperature geothermal energy (150 to 300°C) consists of pumping this water towards the surface, producing vapor via exchanges, then turbining this vapor as in conventional thermal power stations, so as to produce electricity.

Low temperature geothermal resources (lower than 100°C) are upgraded with heat pumps for heating requirements.

However, the potential of natural geothermal energy is limited, because there are many sites where the temperature is high (higher than 200°C), but where there is no water. This thermal resource might be exploited with the help of the so-called “hot-dry rock” technology, which is currently under development. It consists of injecting, into a well, pressurized water in in-depth zones (deeper than 3,000 m) of fractured rocks. This reheated water returns to the surface up a second well and helps to produce electricity, as in conventional thermal power stations. However, the proportion of this potential, which would technically be accessible, has not yet been specified.

1.3.5. *Biomass*

Provided a sustainable exploitation of resources, biomass is a renewable energy that supplies biofuels, which are generally solid or liquid.

Wood covers more than 10% of the primary energy demand in many countries of Asia, Africa and Latin America and in some European countries (Sweden, Finland and Austria). The use of wood in developing countries has strongly increased over the last few decades, but this resource has not always been exploited sustainably and has thus led to deforestation. Emissions coming from wood combustion in a modern industrial boiler are advantageous in comparison to fossil fuels. If the forests where wood comes from are sustainably dealt with, the CO_2 emissions from the wood energy chain are only those corresponding to the gas and oil used during plantation, crop and marketing operations. This represents about 5% of the fuel sold. We can note that a renewable energy is not necessarily a completely non-polluting energy.

The consumption of biomass in France in primary energy was 10-11 Mtoe at the beginning of the 2000s; mainly wood. Without any specific energy crop, the biomass potential could be doubled by a systematic repercussion of all organic waste: non-recyclable household and industrial waste, methanization process of the sewage sludge and agriculture waste, which generates biogas. Global biomass electricity production in 2008 amounted to 669 TWh. The French energy potential is 60 TWh/year, i.e. 15% of the final electricity consumption in France.

Biomass is frequently used in cogeneration systems that produce electricity, such as conventional power stations, all the while upgrading the heat that is usually lost in various applications: heating of the facilities, industrial needs, agriculture, etc. This technology helps to increase the efficiency of energy conversion.

Liquid biofuels are more expensive to obtain and are industrially produced from energy crops (rape, sunflower, beet, wheat, barley, corn, etc.), and are better upgraded in transport applications. They are currently mainly used in engines and are mixed in small quantities in conventional fuels, in order to improve their characteristics. Nevertheless, this type of energy use competes with the potential of these crops for food use.

1.3.6. *Contribution of the various renewable energies*

Table 1.1 presents the contribution of each renewable energy as a percentage of global energy production in 2018 [WIK 20a]:

Hydro	16%
Wind	5%
Biomass	2.5%
Solar	2%
Other	0.5%

Table 1.1. *Contribution of each renewable energy to global energy production in 2018*

In comparison, of the non-renewable sources, coal contributed 38%, gas 23%, nuclear 10% and oil 3% of global electricity generation for 2018.

The contribution of each renewable energy source in the production of renewable electricity within the European Union in 2017 is shown in Table 1.2, for a total of 975.2 TWh.

Wind	37.2%
Hydro	30.8%
Biomass	19%
Solar	12.2%
Geothermal	0.7%
Marine energy	0.1%

Table 1.2. *Contribution of each renewable energy source in the production of renewable electricity within the European Union in 2017*

The growing rates of these sectors are really high, which contributes to an improvement in the penetration rate from one year to another.

1.4. Production of electricity from renewable energies

1.4.1. *Electricity supply chains*

To carry out energy conversions to produce electricity, several supply chains can be considered, depending on the use or not of electronic power converters.

The most frequently used electricity generation cycle requires a heat source to heat the water, in order to obtain vapor under pressure. By expanding in a turbine, this vapor drives an alternator, which generates electricity. After passing through the turbine, this vapor is condensated with the help of a cold source, which is generally water (river, sea) or air in cooling towers. Figure 1.1 represents the conventional cycle of electricity generation.

When the heat generated by the vapor condensation is recovered for heating needs, we can speak about cogeneration.

The heat source is generally obtained by the combustion of fossil fuels (oil, gas, coal), or by a nuclear fission reaction in reactors designed to control the extent of this reaction.

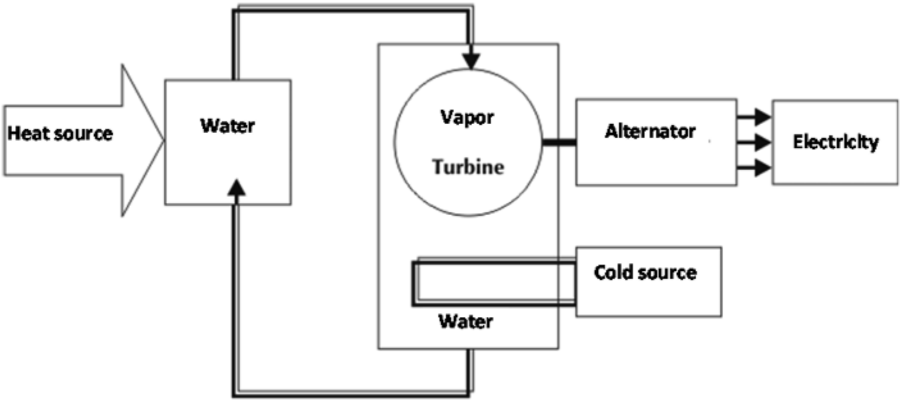


Figure 1.1. *Conventional cycle of electricity generation*

The fossil fuels or uranium used in conventional cycles can be replaced by some renewable energy sources. The heat source can then be obtained by:

– biomass combustion (wood, biogas, organic waste);

– the heat found in the depths of our planet, either by directly pumping hot water towards the surface or by exploiting the high temperature of the deep rocks by injecting them with water from the surface;

– the sun by concentrating its rays with the help of mirrors or by exploiting the water heated at the surface of the seas in tropical zones.

With some renewable energies, the electricity supply chain does not require a heat source. This is the case for wind power, hydraulics and photovoltaic solar energy.

In the case of wind power and hydraulics, the wind or water pressure drives the rotation of a turbine, which in turn drives an alternator, which produces electricity. Figure 1.2 represents this energy conversion chain.

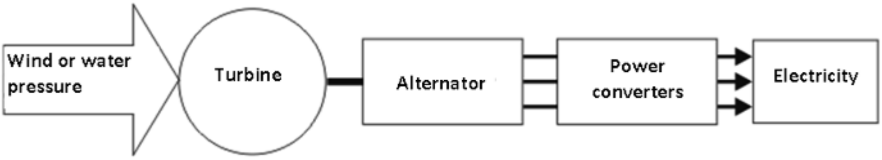


Figure 1.2. *Wind power or hydraulics electricity supply chain*

Wind pressure results from its kinetic energy. Water pressure results from its potential energy and its kinetic energy.

The electricity generated by the alternator can be directly sent along the electrical network without going through power converters, as indicated in Figure 1.2. However, in this case, in order to maintain the frequency of the voltages and the constant generated currents at 50 or 60 Hz, the alternator speed must be maintained as constant by acting on the direction of the turbine blades, or in the case of hydraulics, by winnowing upstream of the turbine.

The interesting aspect of power converters is that they enable alternators to operate at variable speed, thus increasing the energy conversion efficiency, all the while reducing the need for turbine mechanical control and for winnowing in the case of hydraulics. This variable speed operation is developing in the field of hydraulics (especially in small hydraulics), and tends to impose itself in wind powers, where this type of operation seems natural, because of the strong variations in the wind speed.

Electronic converters help us to convert power from one form to another. They can include rectifiers, inverters and choppers, or just a single inverter. The converter must be compatible with the frequency of the network and is equipped with filters, in order to satisfy power quality standards. Power electronics also ensure the protection functions of the production unit and the local network to which it is connected.

In the case of photovoltaic solar power, electricity is produced directly with the help of silicon cells using the energy from solar radiation. Power converters are generally used to ensure the optimization of energy conversion. Figure 1.3 illustrates this energy conversion chain.

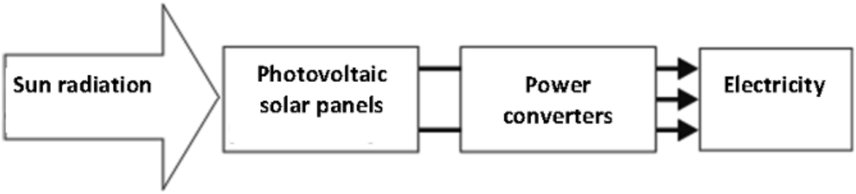


Figure 1.3. *Photovoltaic solar power chain of production generation*

Electricity can also be produced via a diesel engine or a gas turbine (derived from a jet engine) driving an alternator. The source of primary energy is generally made up of fossil fuels, but we can consider replacing them with biofuel or biogas.

1.4.2. *Efficiency factor*

The key factor for the competitiveness of energy production systems, based on renewable energies, is the cost of the kWh product. This cost is calculated from the investment cost of the generation system, its lifespan, the interest rate of the loan that may have been required and the operating costs related to maintenance and primary energy – which is free when it is the sun, wind… and not free in the case of fossil fuels, nuclear power…

In systems relying on a changeable nature (wind and solar power, run-of-river hydraulics, etc.), the system productivity fundamentally depends on natural conditions (number of hours of sunshine for example), whereas the investment cost mainly depends on the peak power. A 1 MW wind turbine will be able to supply a maximum power of 1 MW, but it will not permanently produce this power, because of the fluctuating nature of the wind speed, which is on the contrary to conventional power stations using fossil fuels or nuclear power. For this wind turbine, as well as for solar power and small hydraulics, it is the energy produced that is important.

Table 1.3 presents the efficiency factor, or energy return rate, of the electricity production chains from renewable energies, which are not based on the conventional water-vapor cycle. The efficiency factor is the ratio between the supplied energy and the production system throughout its entire lifecycle and the consumed energy, in order to build the production system.

Installation	Efficiency factor
Large hydraulics	100-200
Small hydraulics	80-100
Wind power	14-30
Photovoltaic solar energy	4-12

Table 1.3. *Efficiency factor, or energy return rate, of the systems producing electrical energy from renewable energies*

The efficiency factor strongly depends on the natural productivity of the accommodation site of the conversion system. For example, if the number of hours in the full sunshine equivalent goes from 1,000 to 2,000, the efficiency factor will double. Moreover, it is related to the lifespan of the facilities and it is often better for large facilities, thanks to generally favorable scale effects. This is notably the case for large hydraulics (lifespan of 30 to 50 years) in relation to small hydraulics (lifespan of 20 to 50 years).

The power of wind turbines has gone from a few hundred kW before 2000 to several MW after 2000, and prototypes are capable of reaching 14 MW. The lifespan of a wind turbine is 20 to 25 years.

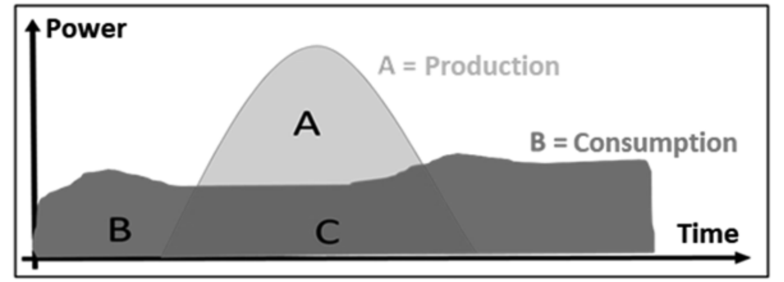
Photovoltaic systems present the lowest efficiency factor, because the manufacturing of silicon cells requires a lot of energy. In four to five years a cell reimburses the energy spent during its manufacturing. As the lifespan of a photovoltaic system is 20 to 30 years, the efficiency factor could thus be, in the best case, slightly higher than six. Let us note however a continuous improvement of this criterion, notably with the arrival of thin film technologies, with which we reach times of return on energy investment shorter than one year, i.e. efficiency factors higher than 20.

1.5. Self-production and self-consumption of energy

The development of renewable energy sources encourages local production, close to the loads needed for supply, and hence, local consumption. This is particularly true for energies whose primary source varies independently of demand, without natural storage (for example in hydraulic or fuel form) and whose production forecasts are difficult, as is the case with wind and photovoltaics. In this context, self-production and self-consumption of renewable energy are defined, on the basis of Figure 1.4, as follows [ROB 19]:

– self-production is the share of total consumption provided by local renewable energies, over a day for example, or area-C/area-B (generally calculated over one year);

– self-consumption is the share of renewable production consumed in real time, over a day for example, or area-C/area-A (generally calculated over a year).



C = Intersection between production area and consumption area

Figure 1.4. *Self-production and self-consumption over a twenty-four hour period [ROB 19]. For a color version of this figure, see www.iste.co.uk/robyns/electricity.zip*

A local energy network will only be able to operate autonomously (as an island outside of the main electricity network) if production A is, at any time, equal to or greater than consumption C, in the absence of an energy storage device.

1.6. References

[BAR 14] BARRE N., ROUBAUD M., *Les énergies renouvelables*, Editions 10/18, Usbek & Rica, 2014.

[CAS 20] CASSORET B., *Transition énergétique, Ces vérités qui dérangent*, De Boeck Supérieur, Louvain-la-Neuve, Paris, 2020.

[CHA 04] CHAMBOLLE T., MEAUX F., Rapport sur les nouvelles technologies de l'energie, Ministère délégué à la recherche et aux nouvelles technologies, Paris, 2004.

[CRA 08] CRAPPE M., *Electric Power Systems*, ISTE Ltd, London and John Wiley & Sons, New York, 2008.

[EUR 18] EUROBSERV'ER, Etat des énergies renouvelables en Europe, Edition 2018, EurObserv'ER.

[JEN 00] JENKINS N., ALLAN R., CROSSLEY P. *et al.*, *Embedded Generation*, The Institution of Electrical Engineers (IEE), London, 2000.

[MUL 03] MULTON B., "Production d'énergie électrique par sources renouvelables", *Techniques de l'Ingénieur*, Traité de Génie Electrique, D 4 005 and D 4 006, May 2003.

[REV] REVUE SYSTÈMES SOLAIRES, available at: www.energies-renouvelables.org.

[ROB 15] ROBYNS B., FRANÇOIS B., DELILLE G. *et al.*, *Energy Storage in Electric Power Grids*, ISTE Ltd, London and John Wiley & Sons, New York, 2015.

[ROB 16] ROBYNS B., SAUDEMONT C., HISSEL D. *et al.*, *Electrical Energy Storage in Transportation Systems*, ISTE Ltd, London and John Wiley & Sons, New York, 2016.

[ROB 19] ROBYNS B., DAVIGNY A., BARRY H. *et al.*, *Electrical Energy Storage for Buildings in Smart Grids*, ISTE Ltd, London and John Wiley & Sons, New York, 2019.

[WIK 20a] WIKIPEDIA, Ressources et consommation énergétiques mondiales, Wikipedia, accessed 26/03/2020.

[WIK 20b] WIKIPEDIA, Émission de dioxyde de carbone, Wikipedia, accessed 27/03/2020.

[WIK 20c] WIKIPEDIA, Accord de Paris sur le climat, Wikipedia, accessed 27/03/2020.

[WIK 20d] WIKIPEDIA, Conférence de Madrid de 2019 sur les changements climatiques, Wikipedia, accessed 27/03/2020.

[WIK 20e] WIKIPEDIA, Production d'électricité, Wikipedia, accessed 27/03/2020.