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Energy transitions after COP21 and 22

Les transitions énergétiques après les COP 21 et 22

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ABSTRACT

How far are we in the urgent fight against the climate change? This article starts with a short analysis of the results of COP21 and COP22, the two “conferences of parties” where goals have been defined. Now, to define goals is one thing, but to reach these goals is another thing. In its second part, this article analyzes the energy transition that has been voted by France in 2015, and compares it to what is planned in other countries, especially in Germany.

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RÉSUMÉ

Où en sommes nous dans notre combat urgent contre le changement climatique ? Cet article commence par une courte analyse des résultats des COP21 et 22, les deux « conférences des parties » où les objectifs à atteindre ont été définis. Maintenant, définir des objectifs est une chose, les atteindre en est une autre. Dans sa seconde partie, cet article analyse la transition énergétique qui a été votée par la France en 2015 et la compare à celles qui sont envisagées par d'autres pays, en particulier par l'Allemagne.

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1. After COP21 and COP22: summary of the situation

Conferences of parties (COP) are yearly conferences that gather the “parties”, i.e. the countries who signed the convention of the United Nations on climate change at the 1992 meeting in Rio de Janeiro. The first conference (COP1) took place in Berlin in 1995. COP3 was in Kyoto (1997), COP15 in Copenhagen (2009), COP17 in Durban (2011), COP21 in Paris (2015), and COP22 in Marrakech (2016). At the Rio conference, there were 178 parties. Today, 196 parties gather at these conferences, which means nearly all countries in the world.

COP21 was a very important step forward for the following reasons.

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First of all, it is probably the first time since the Universal Declaration of Human Rights in 1948 that all countries[1] agree on a common declaration. In September 2017, 159 of these countries, representing 86% of the CO_2 emissions in the world, had officially ratified the "Paris agreement". These included the USA before the Trump administration withdrew the US signature, most countries in Europe, China, Brazil, India, etc. Still missing today are the Czech Republic, Iraq, Kuwait, Lebanon, Qatar, Russia, Switzerland, Turkey, and a few others.

COP23 will take place on November 6–17, 2017 in Bonn under Fiji presidency. It is expected to "accelerate the Paris agreement" especially as concerns the funding of adaptation for developing countries, for which a goal of 100 G$ per year was defined in Paris, but it has not yet been reached. This goal corresponds to a tax of order 1 cent per liter of gasoline, and it should not be that difficult to reach.

A second reason for being optimistic is that all these countries have publicly declared that, as demonstrated by the Intergovernmental Panel on Climate Change (IPCC), our global climate is changing as a consequence of human activity. Consequently, the Paris agreement asks for urgent action against the emissions of Green House Gases (GHGs), whose main origins are the use of fossil fuels (coal, oil, natural gas, lignite) and the emission of methane by agriculture and farming. Even the Trump administration should admit the truth. All the countries have been asked to propose reduction plans or scenarios for the coming years. They are called "INDCs" for "Intended Nationally Determined Contributions" to the fight against climate change. To ask each nation to determine its own contribution was the only way to obtain agreement. Indeed, when the Kyoto COP3 conference proposed to force all developed countries to follow a common reduction scenario, it was unanimously rejected by the US senate, who considered that no one had any right to impose anything to the United States. The proposed constraint was by far too strong to be accepted by a large majority of nations. But the Paris agreement proposes a softer constraint, which is much more realistic and should be more efficient, hoping of course that the USA come back to a reasonable attitude.

My optimism is due to one more rule on which all nations agreed. They promised publishing their GHG emissions. By the way, in case some countries tried to hide their real emission data, it is likely that, at least for large countries, one should soon be able to measure them with satellites. As a result, every voter in every country should have the means to verify before voting that his country respects its published promises. Here is the new constraint, in giving citizens the means to control the energy policy in his/her own country. In-between two votes, every citizen has the necessary information to do more actually: in the Netherlands in 2015, the association URGENDA has suited the government for insufficient action against the climate change, and URGENDA won the case! In 2017, a similar trial started in New Zealand.

Now, it is obvious that the Paris agreement is far from being the last step one needs. Future COP conferences need to evaluate the INDCs. Are they sufficient or not? We will see below how one could assess them. And a regular survey should allow a permanent updating of the adaptation fund. Democratic principles require that nothing should be done against the will of nations. A strong effort of information is required, especially in the USA and in Russia, two of the most polluting nations. And in each country, scientists need to describe the climate situation and to compare risks and remedies with rational arguments.

As for the COP22 conference, it was obviously perturbed by the election of President Trump, whose opposition to the Paris agreement was already known. Despite the American threatening, the COP22 has made some progress towards the application of the Paris agreement. Some countries have presented plans to reach "carbon neutrality", which means a zero balance between carbon emissions and absorption in their countries. Some progress has been made in the funding of the adaptation to the unavoidable global warming. Thanks to the early ratification of the Paris Agreement by the required majority of countries, its application is now scheduled for 2018, at the COP24 meeting in Poland.

In the following section, we consider the origin of GHG emissions and the various solutions that can be used to reduce them.

2. Emissions of green house gases – reduction goals

It is obvious that Europe emits more CO_2 than France, or China than Luxembourg. The climate problem being global and very difficult to solve, all countries should contribute to the necessary fight by changing their own energy policy. In order to analyze energy policies, one needs to start by considering, not the total GHG emissions of countries, but emissions per inhabitant. As shown in Fig. 1, the energy policies are rather inhomogeneous. For simplicity, Fig. 1 shows the emissions of CO_2 released by the use of fossil fuels, as given by the International Energy Agency (IEA) [1], although a detailed analysis should consider the emissions of other GHGs like CH_4 and N_2O, which could be converted into CO_2 equivalent ($eqCO_2$). The absorption by the vegetation on land and by oceans should also be considered. But CO_2 emissions from fossil fuel correspond to the main part of GHG emissions, and they are sufficient to draw some important conclusions.

At the top of the diagram is Qatar, a small and rich country, one of the largest producers of oil and natural gas. In this country, electricity is free, produced by power plants burning local natural gas. A large part of the electricity is used for air conditioning and seawater desalination. Qatar has recently started decarbonizing its energy by installing some photovoltaic panels, but most of it is still from fossil fuels. Luxembourg is a special case – often accused to be a tax haven – where the

[1] To be precise, all except Nicaragua and Syria.

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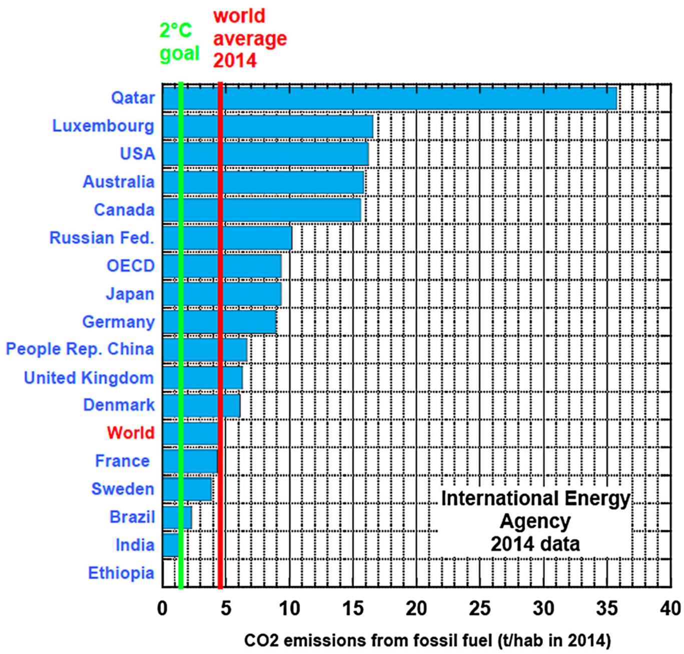

Fig. 1. CO_2 emissions from fossil fuels in tons of CO_2 per inhabitant (IEA data, 2014).

price of oil is 20 to 30% lower than in the neighboring countries, so that cars and trucks go there to fill their tanks. At a time when countries try to impose carbon taxes, Luxembourg does not show solidarity with the rest of Europe.

Then comes the USA–Canada–Australia trio, where the emissions are about 16 tons per inhabitant (16 tCO_2/hab), i.e. nearly 4 times more than the world average (4.5 tCO_2/hab, red line in Fig. 1). These three countries produce and consume very large quantities of fossil fuels, especially coal and now shale gas or shale oil in the USA and Canada. One should notice that, inside the USA, the situation is quite inhomogeneous: virtuous states like California and the New York State, emit respectively 9.3 and 8.6 tCO_2/inhabitant, while other states like Louisiana (44.5 tCO_2/inhabitant) West Virginia (52 tCO_2/inhabitant) and Wyoming (112 tCO_2/hab!) [2] are emitting even more than Qatar.

China emits much less per inhabitant than the USA (7 tCO_2/inhabitant instead of 16), but its total emissions are larger in total (9087 tCO_2/yr compared to 5176 $MtCO_2$/yr), because its population is 1364 Mhab instead of 319 Mhab in the USA (2014 data). It means that energy production and consumption are rather different in the two countries. Now the American emissions are slowly decreasing, contrary to the Chinese ones, which increase rapidly. Together, these two countries are emitting $28 + 16 = 44\%$ of the total world emissions and the evolution of their respective policies is of primary importance for the future of the whole planet.

Further down, one sees that Denmark and Germany are emitting roughly twice as much per inhabitant as Sweden and France, two comparable countries. This is because the electricity is already decarbonized in Sweden and in France thanks to nuclear and hydroelectric energy, while coal and lignite keeps representing a large part of the energy sector in Germany and in Denmark. Still, it may look surprising, since Denmark and Germany are well known for their renewable sources of energy, especially windmills, whose electricity is decarbonized, carbon free. This is because windmills and photovoltaic panels are renewable sources of energy but intermittent: when the wind speed goes below 15 km/h, the mills stop rotating, and if it goes above 90 km/h, one has to stop them as a precaution. Their maximum efficiency is reached with wind at 43 km/h. On average, windmills produce only 15 to 30% of their nominal power, and, when they stop, one has to quickly switch on other plants since one does not know how to store electricity in large quantities, except with reversible dams. There are such reversible dams called pumped-storage hydroelectric power stations such as the one built at Grand'Maison, in the French Alps. Grand'Maison is the largest of the reversible dams in France. It consumes 1275 MW in the pumping mode, and it produces 1690 MW in the turbine mode, which corresponds to about 1.7% of the total electric power in France (a little more than 100 GW). Its storage capacitance is 400 GWh, i.e. 18 days of one nuclear reactor. It is obviously very useful and it can overcome the intermittency of about 2% of wind power in the French electrical mix. But there are no other sites with similar power, because it needs two lakes with a large height difference in between. Norway and Switzerland have many such reversible installations, but Germany does not, nor Denmark, and the import from neighboring countries is not sufficient. As a result, Germany has built a large quantity of thermal power stations burning coal or lignite to cancel the intermittency of their wind and solar power stations while closing half of their nuclear plants, and it explains why the CO_2 emissions in Germany do not significantly decrease with the development of renewable energies, at least not yet. The situation in Denmark is similar, but their CO_2 emissions have decreased recently.

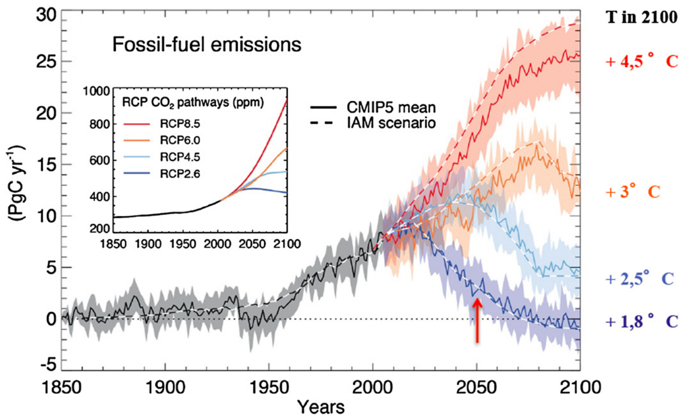

Fig. 2. The world emissions of CO_2 in petagrams of carbon per year (1PgC = 3667 $MtCO_2$) as a function of time (IPCC measurements and predictions). In black are measurements already made. In color (from red down to blue) are four predictions corresponding to different scenarios. In red is the "business-as-usual" scenario. In blue is the most optimistic scenario one can imagine.

At the bottom of the graph, Ethiopia shows negligible emissions (0.09 tCO_2/hab): 100 times less than Germany, despite a similar population of 97 million inhabitants (81 million inhabitants in Germany). This is because Ethiopia is a rather poor country with very small consumption of energy, but also because Ethiopia has a large production of hydroelectric energy.

Still on this graph, one sees a green line that shows the emission goal, 1.5 tCO_2/hab. According to the IPCC, this is the average emission per inhabitant that should be reached by 2050 if we want to stabilize the global warming below 2 °C above the pre-industrial situation.

Fig. 2 shows measurements of CO_2 emissions from 1850 until 2010, followed by four curves in color that are the different predictions calculated by the IPCC. Each color curve corresponds to a different scenario. In red on top is a curve corresponding to what is usually called "business as usual". It describes the evolution of the world CO_2 emissions in petagrams of C per year (1 PgC/yr = 3667 $MtCO_2$/yr) if one does not change energy consumption habits nor production policies. The average world temperature T is directly related to the accumulated emissions. Roughly speaking, half of the emissions is absorbed by the oceans and the vegetation, and the other half accumulates in the atmosphere. The red curve shows that, in the "business-as-usual scenario", the emissions keep increasing well after the end of this century (2100). It would correspond to a warming of +4.5 °C with respect to the pre-industrial situation in the years 1850–1900. And the temperature would keep increasing during the following centuries.

The blue curve is the most optimistic scenario, where an extremely active policy is settled to reduce the CO_2 emissions down to negative values around 2070. Negative means that one finds methods to absorb more CO_2 than what is emitted by human activity, for example by planting trees instead of burning forests. Emissions should be immediately reduced. By 2020, they should have already started to decrease, and by 2050 they should be reduced by a factor of 3 with respect to 2014, which is a factor of 4 with respect to 1990, the reference date chosen at the Kyoto COP3 meeting. This is the only scenario allowing one to stabilize the climate before the end of our century. The global temperature would reach +1.8 °C with respect to the pre-industrial time and then start decreasing slowly. But to reach zero net emissions before the end of the century already appears as an extremely difficult challenge.

Summing the INDCs proposed by the countries, one predicts a global warming reaching 3 °C. It thus appears urgent to re-examine the INDCs as soon as possible. For that, I proposed in a recent book [3] to come back to fundamental principles of human rights. If all humans have the same rights, one should tend to the same GHG emission per person in all countries, that is for example 1.5 tCO_2/yr in 2050. It would require more efforts in developed countries, but they have more technologies and more financial means to do so. In 2015, France has voted a law whose goal is to reduce the French emissions by 70% in 2050, and Germany did the same with an objective of 80 to 90%. That is the right goal, but one needs to see if the means to reach it are realistic. As for the USA, they have proposed reductions with respect to the 2005 level, where their emissions reached a maximum, and that is not sufficient. Now President Trump has proposed no reductions at all, which represents a major risk for the whole planet. As for China, they proposed a reduction, but not before 2030, which would be much too late.

3. Energy transitions

3.1. GHG sources

To establish a reduction scenario, it is not sufficient to draw a straight line on a graph between the present situation and the desired one in 2050. One has to examine whether the necessary technologies exist and whether they are efficient enough. Let us first see more precisely, considering the French case, where the CO_2 and other GHGs come from. The 2013 situation is shown on Fig. 3.

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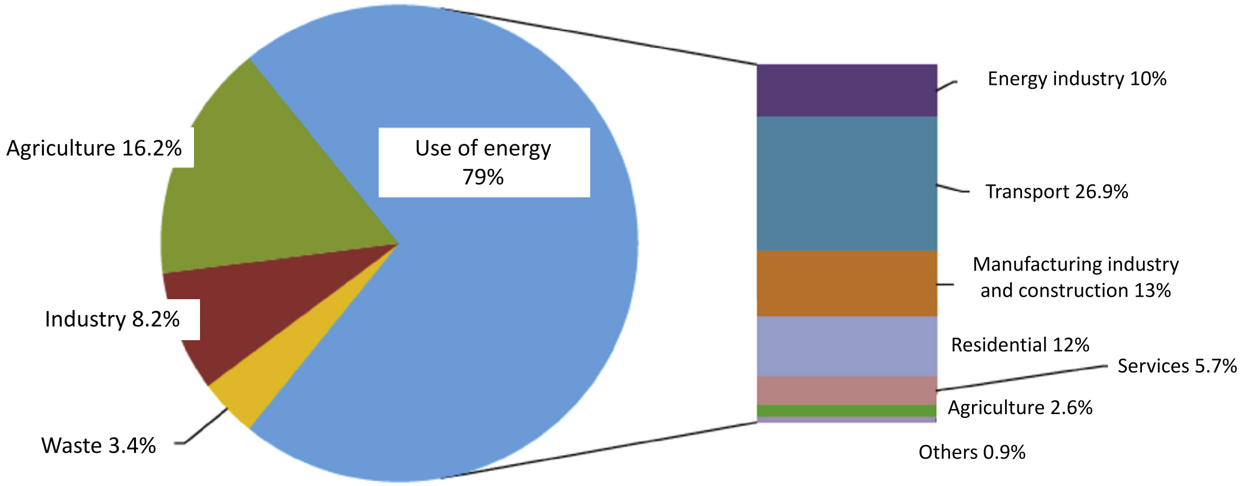

Fig. 3. The sources of French emissions of GHGs in 2013. (Data from the European Environment Agency.)

GHGs to be considered are CO_2, CH_4, N_2O and a few others of minor importance. The first source of GHGs is the transportation sector, mainly road transportation by trucks, buses, and cars, which amounts to 26% of the total. Then industry with $12 + 10 = 22\%$ (manufacturing, construction, energy production), then agriculture with 16% (CH_4 due to animal farming and N_2O due to fertilizers) +2.6% from fuel used in agricultural machinery. Then comes the residential sector (heating, hot water, air conditioning, cooking, lighting...), either private (12%) or professional (5.7%). These numbers need to be considered to evaluate the limitations of each energy transition scenario.

To decarbonate energy, the first priority is to consider all means of transportation. Replacing all usual vehicles by electric cars, trucks, buses, trains and trams requires much more clean electricity. Assuming that this is feasible in a few decades' time, as the 2017 French government presents as its new challenge, one would reduce the GHG emissions by 26% only. It would be far from sufficient. The production of concrete is known to emit large quantities of CO_2, but assuming that concrete is eliminated from construction (is it possible?), assuming also that in all industrial processes, fossil fuels are replaced by clean electricity, CO_2 capture, hydrogen produced locally by windmills before being transported and stored in large quantities (how?), one would reduce again the GHG emissions by a very maximum amount of 22%. The latter looks extremely difficult to achieve, probably unrealistic. The complete thermal insulation of all buildings would save some energy, but it would again require some more clean electricity. To reduce GHG emissions in agriculture is again an extremely difficult challenge, especially if the population keeps growing. In summary, a reduction in GHG emissions by 50% would already be a truly remarkable success requiring much more clean electricity, not less electricity, as surprisingly planned in the French law and the German one.

Given this situation, let us quickly examine what are the efficient solutions for the production of decarbonized electricity, a central challenge. And let us start with renewable energies.

3.2. Hydroelectricity

There are four main kinds of renewable energies: hydroelectricity, wind power, solar energy, and various biofuels obtained from the energetic biomass.

Hydroelectricity is perfect. No CO_2 emissions, except for the dam construction or if trees are not cut before filling the lake, as was unfortunately done in French Guyana (Petit-Saut). Electricity production by dams is even better than stable, it is quickly adaptable to the consumption or to the possible failure of other sources. Countries like Switzerland or Norway are lucky to have mountains where many hydroelectric stations have been installed. In China, hydroelectricity represents 19% of the electric mix and 12% in France [4]. In Germany, where the necessary sites are very few, it is only 3%, to be compared with 96% in Norway, 39% in Switzerland, 14% in California, and 7% in Morocco.

Some people or associations protest against dams, considering that their artificial lakes destroy the landscape or the local wildlife. This is a controversial point of view. Whatever aesthetic opinions can be, it should also be noticed that, in regions with enormous rivers like Amazonia, including French Guyana, run-of-the-river hydroelectricity looks better adapted, especially because, contrary to conventional dams, pollution is not trapped inside the lakes, it flows away.

I will consider nuclear power stations further down below, but we can see already that with nuclear power stations whose production amounts to 78.4% [4], with hydroelectricity plants (12%) and some sources of renewable energy, the

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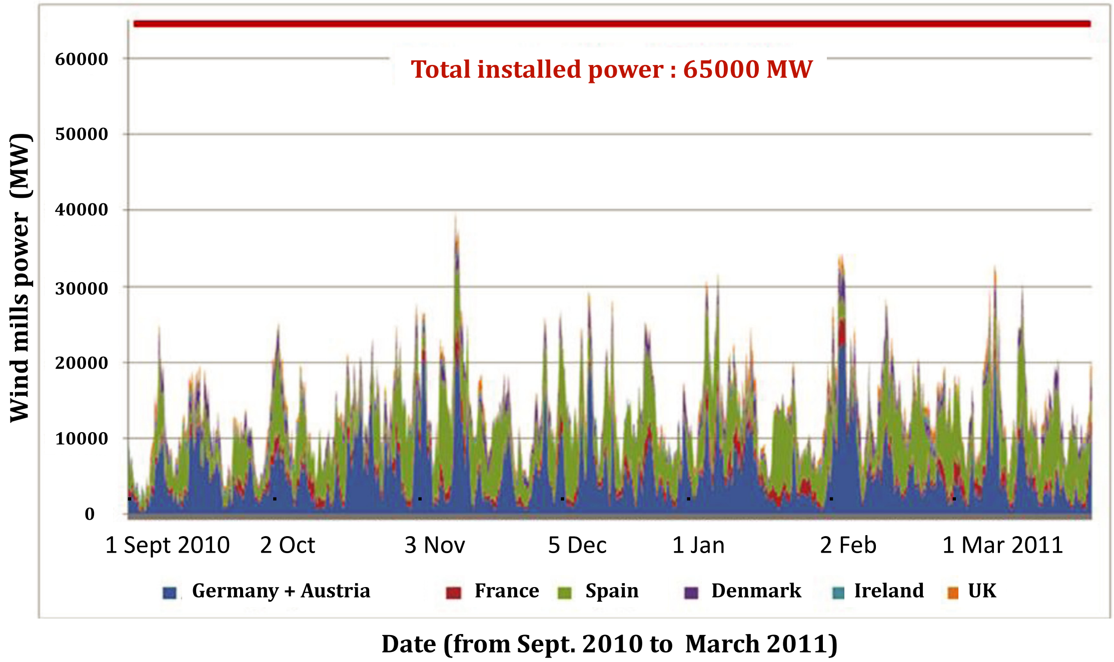

Fig. 4. The power of wind mills in seven European countries between September 2010 and December 2011 (H. Flocard et J.-P. Pervès, http://www.sauvonsleclimat.org/etudeshtml/intermittence-et-foisonnement/35-fparticles/1161-intermittence-et-foisonnement.html). By adding the production in seven different countries does not wash out the intermittency. The total installed power was 65 000 MW but the average power was about five times less, with fluctuations down close to zero.

French electricity is nearly totally decarbonized. To produce 1 kWh of electricity, France emits 79 g of CO_2. Sweden makes even better, with 30 g only. On the contrary, the emissions per kWh are 461 g in Germany, 522 g in the USA, 766 g in China, 781 g in Poland [5]. The efforts that need to be done in the latter countries are huge.

3.3. *Intermittent renewable energies: wind power and solar stations*

The main problem with these renewable energies is their intermittency. There is of course no sun at night and solar production is reduced as soon as the sun hides. The efficiency of photovoltaic stations depends on their geographical location. In France, the average power production is about 10 times less than their nominal power, which corresponds to their instantaneous power under optimal sunshine. As for windmills, they do not rotate if the wind speed is less than 15 km/h, and they need to be stopped for security if the wind is stronger than 90 km/h, as mentioned above. In the average, their production is about five times less than their nominal power, which is reached with ideal wind speed only. But the main problem is that their production fluctuates randomly, as shown by the graph in Fig. 4. On the same graph, one sees also that, even if one integrates the wind power that is produced in seven European countries from Spain to Ireland and Germany, the total production keeps fluctuating by huge amounts. This is because the meteorology is rather homogeneous in the whole of Europe. As a consequence, covering Europe with electric lines would not solve their problem of intermittency. If one knew how to store electricity, one could accumulate electricity when the consumption is less than the production, and consume it when there is not enough wind for production to be sufficient. But the only method that is known and efficient at the large scale of a national energy consumption scale, is hydroelectricity. As already mentioned above, there are pumped-storage hydroelectric power stations that are reversible, but only a few in France and none in Germany. Switzerland and Norway cannot store all the electricity that is produced by wind mills in Europe. The situation should be even more difficult if more intermittent renewable sources of energy were installed, as already planned by Germany and France. I expect the risk of a black-out at the scale of Europe to increase, except if one builds more coal power station, which is not to be recommended, but is what Germany is presently doing.

At this stage, it becomes clear that, if Germany is compelled to build more fossil fuel stations with an electric mix containing only 12% of wind power and 6% of PV solar panels (to be compared with 54% of fossil fuel), and if countries like Germany and France cannot build more hydroelectric dams because all sites are already equipped, announcing 100% renewable electricity is not realistic. When members of the French association “Negawatt” propose such a non-realistic goal, they have to assume that the production and consumption of electricity are reduced. Even by saving some energy here and there, it is impossible to suppress all uses of fossil fuel – think of the transportation, residential, and industry sectors – without replacing at least part of it by some more clean electricity [3,6].

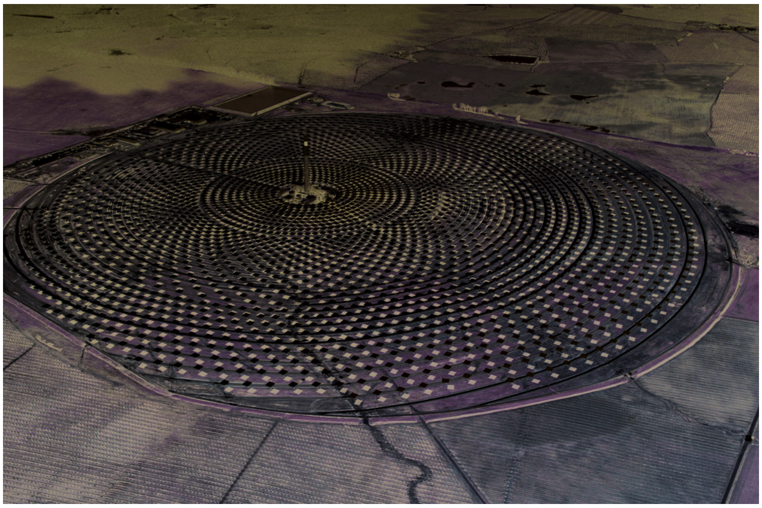

Fig. 5. The thermal solar station Noor III in Ouarzazate (Morocco). The concentration of sunlight produces up to 150 MW of electric power since 2016. Its main advantage is a storage time of 8 h. Its 650 M€ construction cost was supported by several banks and agencies in the world.

As for PV panels, their capacity factor is only 13% in France [7], meaning that their average power is only 13% of their nominal – or installed – power, which corresponds to their maximum instantaneous power. In 2016, French PV panels produced 8.3 TWh, that is 1.6% of the total (531 TWh). In Germany, their production was 36 TWh, that is 5.6% of the total (648 TWh). They suffer from the same intermittency problem as wind power. There is a different kind of solar energy that can be called thermal solar and it is much better, but it is unfortunately not adapted to the climate of European countries like France and Germany. Indeed thermal solar stations include energy storage: they are not using PV panels, but concentrating light on special fluids that are able to stay hot for several hours. For example, Noor III, the 150 MW station that was built in Morocco in 2016, keeps producing electricity for 8 hours after sunset (Fig. 5). Its cost of 650 M€ was supported by various banks or agencies like the German KfW, the French AFD, the World Bank, the European BEI, etc. It can also be used for the desalination of ocean water. In my opinion, this type of solar energy stations are very well adapted to developing countries where the climate is hot and dry. They are still expensive; thus, these countries need support to build them, but their efficiency improves rapidly, and one expects their construction cost to decrease if this technology is generalized at a large scale.

3.4. Biomass

It is possible to produce methane or biofuel with biomass. Obviously, it would be better to capture the methane produced by farming (emissions from manure) than to let it pollute the atmosphere. At a small scale, this is already done by some farmers. At a larger scale, it is possible to cultivate palm trees, soya, corn, and various other plants that chemistry can use to produce biogas or biofuel. However, one should realize that this kind of crop growing needs very large areas, because the efficiency of photosynthesis is small. As a consequence, it competes with food production so that countries like France import their biofuel from countries like Brazil or Indonesia where forests are destroyed for this purpose. Facing the challenge of saving the climate, forests absorb CO_2 and should be developed, not destroyed. In summary, the production of biofuels should be limited to the use of agricultural waste like wood shaving or straw. Contrary to what is assumed in various scenarios, biomass may help but it is not sufficient to provide us with the large energy storage that is required to solve the intermittency problem of wind power or PV panels.

3.5. CO_2 capture and storage

Another idea is to capture the CO_2 that is emitted by thermal power stations burning coal. It is possible and not so expensive. For example, the Boundary Dam station in Saskatchewan (Canada) is of medium size (110 MW) and emits about 1 Mt of CO_2 per year. It is equipped with a capture system and this CO_2 is injected with pipelines in neighboring gas wells that are empty, no longer producing natural gas. The total cost of this capture + storage lies between 35 and 50 $ per ton of CO_2, meaning that it doubles the production cost of the kilowatt hour. Given the fact that the production of clean electricity has to be more expensive than dirty electricity, given also the fact that coal is very cheap, capture and storage of CO_2 on large industrial units looks promising. The main problem would be that a generalization of this method would mean storage of $GtCO_2$ and much more sites than a few old gas wells at the end of their life. Some geological research on aquifer layers would be useful. Social acceptance is one additional problem to be studied.

3.6. Nuclear energy

Given the difficulty of the challenges mentioned above, what about nuclear energy? Nuclear reactors emit negligible quantities of CO_2. They can be adapted to the fluctuations of the consumption and to the chaotic production of the intermittent sources mentioned above. Even if, as we will see, its cost has increased recently, it remains competitive on the energy market, especially if one stops consuming all the fossil fuels. Nuclear energy looks very interesting given the present challenge raised by the climate change. But still, the use of nuclear energy for the civil purpose of electricity production raises three main problems: safety, wastes, and cost.

3.7. Safety

First of all, nuclear reactors have to be stable. The Chernobyl reactor was unstable by construction because its "void coefficient" was positive, meaning that the reaction accelerated when the cooling liquid was replaced by vapor, as happens if bubbles form in it. Chernobyl exploded as a consequence of a human error. The team in charge of the reactor control decided to disconnect the safety system in order to see what happens in case of electricity cut. There was a large gas explosion of hydrogen (not a nuclear explosion), which destroyed the building; the moderator blocks made of graphite bars took fire and sent a radioactive cloud to high altitude after the core melted. This reactor had no confinement building. According to the 2008 report by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the Chernobyl accident killed 28 people among the "liquidators" in the four months immediately following the accident. Later, 19 deaths could be identified as due to consequences of irradiation among 6000 cancer cases in the population surrounding the reactor. On a longer term, the International Atomic Energy Agency (IAEA) mentioned in its 2005 report following the Chernobyl Forum that, to the above-mentioned 47 victims, one should add some deaths among the 600 000 workers who received between 10 and 500 mSv at Chernobyl. These additional victims are difficult to count because, in the case of radiations, the dose–effect relationship is highly non-linear, and because their number is small compared to the total number of cancers in the population, but the IAEA estimated this number to about 4000. Estimations by organizations using linear laws are sometimes much higher, but not reliable. These numbers of victims are large and should never be minimized, but still, they are small compared to the victims of coal mining or to the future victims of climate change.

Eleven reactors of the same family (RBMK) are still operating. Their safety has been improved, but, in my opinion, they should be closed earlier than planned (2021 to 2034). Most of the other reactors at present in operation are stable thanks to a negative "void coefficient". They are mostly of two different types, the cooling fluid being either "boiling water" as in Fukushima or "pressurized water" as in all the French ones. The French company EDF also runs 10 reactors of AGR type in the United Kingdom, which use weakly enriched uranium and where the cooling fluid is CO_2 gas.

At Fukushima, what was visible was also a gas explosion, but of much lower amplitude than in Chernobyl, although the cores also melted. The Fukushima 1 to 4 reactors had been constructed on the seashore in order to make the use of seawater easier for the cooling system. The next two (Fukushima 5 and 6) had been constructed later on top of the nearby cliff. Fifty-one minutes after the earthquake, the 6 Fukushima reactors had been stopped automatically, but the tsunami destroyed the electricity supply and the connections to seawater. This tsunami had already killed 18 000 people and the civil security was trying to rescue victims of the enormous wave (30 m high!) which had swept the whole region. The reactors had resisted to the earthquake and Fukushima 5 and 6 did not suffer from the tsunami, but Fukushima 1 to 4 started heating up. In the absence of safety means of cooling, and without help from the civil security, the nuclear fuel melted and its reaction with the steel of their containers dissociated water into hydrogen H_2 and oxygen O_2 so that, in the absence of catalyzers to recombine the two gases, it exploded, blowing off the roofs as everyone could see on TV screens. The accident was classified at the same level as Chernobyl (maximum level 7), although, fortunately, no death could be attributed to radioactivity. Today, the four damaged reactors are under control, but 150 000 people within an approximately 30-km radius from the reactors had to leave. Even if some of these people have already returned to this region, there remains areas where the radioactivity level is beyond the safety level.

The Fukushima accident has been terrible again and it convinced several countries, like Germany, Switzerland, California etc. to close their nuclear reactors immediately. But it illustrates errors made by the TEPCO company in its management. Contrary to the French operator EDF, the private company TEPCO did not invest in safety systems like catalyzers able to recombine hydrogen, nor in safety valves with radioactivity filters able to release the pressure inside the confinement wall. TEPCO apparently minimized the seriousness of the accident, so that the intervention of the security services was delayed. In the management of nuclear reactors, zero risk is an ideal that can never be really reached. It has to be permanently improved, even if safety improvement decreases economic benefits.

3.8. Waste

Ordinary reactors use a few percent only of the energy that could be extracted from their fuel, i.e. uranium. As a result, reactors produce waste that is mainly plutonium (Pu). In front of this waste that is dangerous because highly radioactive with a long lifetime, one proposed solution is to transform waste into fuel. This is partly achieved already by including some Pu into new fuel assemblies called "MOX". The MOX fuel can be used in some present reactors, but it is not sufficient. The efficient solution is to build the so-called fourth-generation reactors where the fast neutrons are able to burn large quantities of Pu and of other actinides. Not only it would reduce the amount of waste to be buried, but it would also provide nuclear energy for thousands of years. Five fast-neutron reactors are already working, in Russia, China, and India. The French one, called "Superphenix", was unfortunately closed in 1986 for political reasons after some technical problems, but one full year of efficient production of electricity. Today, France is planning the construction of a new experimental fast-neutron reactor named ASTRID in order to study and improve the safety of this new generation of reactors, which could be the future of the whole nuclear industry.

As for the rest of waste that cannot be burned, the best to do is to bury it in very stable underground geological layers, so that its radioactivity progressively disappears in natural radioactivity.

3.9. Costs

Safety improvement cannot be free. It has a cost that has increased recently, especially after the Fukushima accident. Now, these costs or investments in safety need to be compared with other costs. The construction of the so-called "third-generation" reactors has increased a lot compared to previous ones. For example, the cost of the European EPR has reached about 10 G€. One expects this cost to decrease in the future, but it shows that improving safety is expensive. But the construction cost remains much lower than the price of its production: 80 TWh in 60 years at 100 € per MWh means an income of 80 G€.

Other opponents to nuclear energy complain about the cost (50 to 100 G€) of updating the safety level of old reactors in France, but this high amount of money is for 58 reactors in 15 years, much less than the financial support to wind power, which is increasing continuously and has already reached 7 G€ per year in France, paid by all customers on their electricity bill.

To bury waste is again expensive, but cost a total amount of 25 to 35 G€ to be paid in 140 years. Germany has already invested 300 G€ to support intermittent renewable sources of energy, and the average cost of electricity in Germany is 0.30 €/kWh, to be compared to 0.14 € in France. I do not wish to go further on an economic analysis of the cost of energy transitions in this article. It is not the right place to do that.

4. Conclusion

My main purpose in this article was to show that, facing the climate change, energy transitions are necessary in the whole world, but not all the proposed scenarios are realistic. There are limitations in energy saving, one needs more electricity to replace fossil fuels, and no energy source is ideal. By giving some numbers, I tried to guide choices between various solutions that need to be complementary and cannot be the same in all countries. Nuclear energy is well adapted to France, if it keeps being severely and rigorously controlled by independent agencies, as was done up to now by the French "Autorité de sûreté nucléaire" (ASN), but it requires a high level of technology, a particular geographic situation, and most importantly perhaps sufficient political stability. It is thus probably not possible in many countries. Hydroelectric dams are ideal but need mountains. As for hot and dry developing countries, it seems to me that thermal solar power stations are well adapted.

Whatever one may hope, I suggest to remain pragmatic, to keep searching for new methods, and to adapt continuously to the progress of technology. For example, if one invented a method of storing electricity in large quantities, the challenge facing us could change completely.

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