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FACING THE CLIMATE CHANGE, WHAT SHOULD WE DO?

Abstract: Our planet keeps warming up. In 2015, the twenty first conference of parties (COP21) rang the alarm bells. Since a million years, the concentration level of the carbon dioxide (CO_2) and other "green house gases" in the atmosphere had never reached its present level, and 196 countries recognized the human responsibility in this worrying situation by signing the Paris agreement.

In order to stabilize the climate, it appeared necessary to suppress most emissions of green house gases before 2050. Such an ambitious goal required immediate action for which all countries proposed "energy transitions" and published their commitments, their so called "INDC" s. Given this, some optimism came back.

However, in 2018, the COP24 took place in Poland and showed that saving the climate needed an ambitious policy that was far from being at reach given the attitude of various countries, especially that of the USA since the election of president Donald Trump. The planet needs to free its whole energy production from carbon. For that, all countries need to make important financial efforts, especially the developed ones. Solutions exist but they are far from being ideal especially as concerns the storage of the electricity from windmills and photoelectric panels, and since nuclear energy cannot be generalized in the whole world. In order to save the planet, more scientific and technological research is needed. More information also, in order to make the necessary transitions equitable and acceptable.

Key words: *climate, green house gases, energy transition*

1. INTRODUCTION: THE HUMAN RESPONSIBILITY

Conferences of parties (COP) are yearly conferences which gather the "parties", i. e. the countries which 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),

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COP15 in Copenhagen (2009), COP21 in Paris (2015) and COP24 in Katowice (2018). At the Rio conference, there were 178 parties. Today, nearly all countries (196) gather together at COP conferences.

COP21 was a very important step forward which looked promising. Indeed, it was probably the first time since the Universal Declaration of Human Rights in 1948 that all countries[1] agreed 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 most countries in Europe, China, Brazil, India, etc. The attitude of Russia looks still a little unclear. As for the USA, president Trump declared withdrawing the US signature in November 2016 but it is considered legally impossible before November 2020, the date of the next presidential election, so that, given the large protest it raised, the next US president may keep USA inside the Paris agreement.

COP23 took place on November 6–17, 2017 in Bonn under Fiji presidency. It was expected to "accelerate the Paris agreement" especially as concerns the funding of adaptation for developing countries, for which a goal of 100G$ per year had been defined in Paris. Surprisingly, it is not yet reached although it corresponds to a tax of much less than 1 cent per litter of gasoline.

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), the climate change is due to 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, shale gas and oil) which emit carbon dioxide (CO_2) and the emission of methane (CH_4) and that of nitrogen peroxide (N_2O) by agriculture and farming. All the countries have been asked to propose reduction plans or scenarios for the coming years. They are called "INDC" s for "Intended Nationally Determined Contributions". 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 should 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 proposed a softer constraint that was more realistic and should be more efficient, hoping of course that the USA come back to a rational attitude.

My optimism was 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 or her 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. And in-between two votes every citizen has the necessary information to do more: in the Netherlands in 2015, the association URGENDA 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. In 2018 at the COP24 conference, one realized that, in their present state, the INDCs probably lead the planet to a 3 to 4°C warming. Even more worrying is the evidence that many countries do not even follow their promised scenarios.

Future COP conferences need to evaluate the INDCs. 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, Russia and China, three of the most polluting countries. Everywhere, scientists need to describe the climate evolution and to compare risks and remedies with rational arguments. In this contribution to the "Approaching 20?? Year" International conference, we consider the origin of GHG emissions and the various solutions to be used.

2. MEASUREMENTS AND PREDICTIONS

Several research institutes measure the evolution of the climate. Their results are consistent with each other other and Picture 1 shows one of them, which was analyzed in February 2019 by James Hansen [3]. The solar irradiation warms up the equator more than the poles, producing turbulent heat exchanges in the atmosphere and in the oceans. This turbulent flow shows chaotic structures that can be seen on the map (left part of Picture 1). This map shows that, compared to the 1851–1980 mean in °C, the local temperature has increased by as much as 6°C in Siberia and in the North of Canada (pink regions) but decreased in Labrador, North Africa and the Antarctic (blue regions). The graph on the right of Picture 1 shows that when averaging the temperature on the whole planet and on running years, one finds a warming amplitude of order 0.88°C with fluctuations. One of them is due to a particular structure called "El Ninio" that is a very large mass of hot water crossing the pacific ocean from West to East. The peak temperature in 2016 corresponds to the last El Ninio which ended up in 2018 since the temperature has already started to increase again at the beginning of 2019.

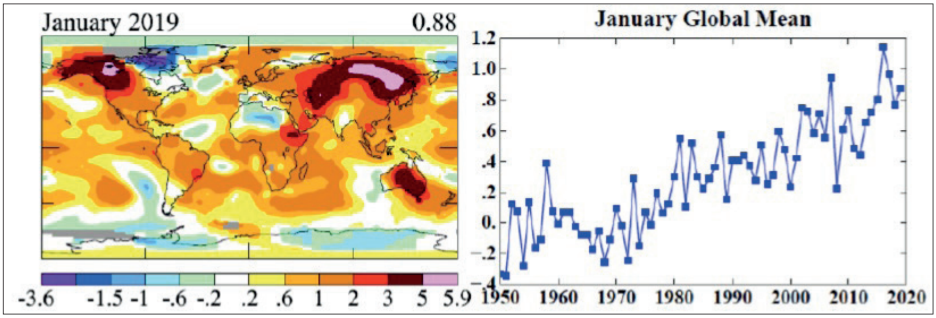

Fig. 1. The average temperature of the whole planet as measured in January 2019 [3]. The surface temperature is compared to the 1951–1980 mean in °C. In January 2019, Siberia was 6 °C above the average in the years 1951–1980. After the huge El Ninio in 2016 and then a deep Ninia, the temperature started increasing again in 2019.

Picture 2 shows that the average temperature increases more on lands that on oceans: today it is already 1.6°C more than in the pre-industrial period (1880–1920) for the land while it is 0.8°C on the oceans. It means that when countries propose to limit the global average to 1.5 or 2°C in 2100 compared to this pre-industrial period, we have nearly reached this warming level already and it will be much more inside our country lands. When mentioning a global warming of 4 degrees in 2100, one should realize that

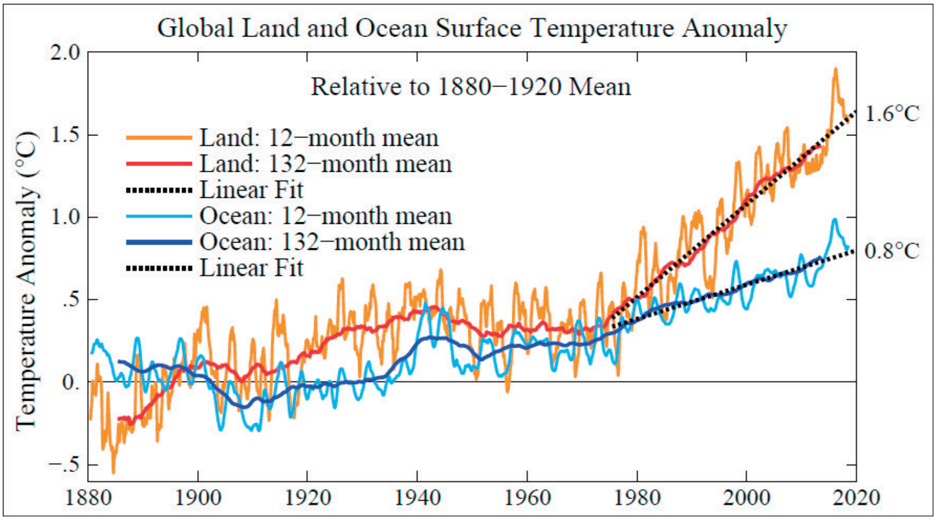

Fig. 2. The global land and the ocean temperatures since 1880 using the Goddard Institute for Space Studies global temperature data [3]. It shows that lands warm up much faster than oceans.

it probably means even more on land, especially during heat waves, which is frightening.

Picture 3 shows CO_2 emissions measurements from 1850 until 2010, extended by 4 curves in color that are the different predictions calculated by the IPCC[4]. 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 peta-grams of C per year (1 PgC/yr = 3667 $MtCO_2$/yr) if one doesn't 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 + 4.5C with respect to the pre-industrial situation in the years 1850–1900. And the temperature would keep increasing during the following centuries.

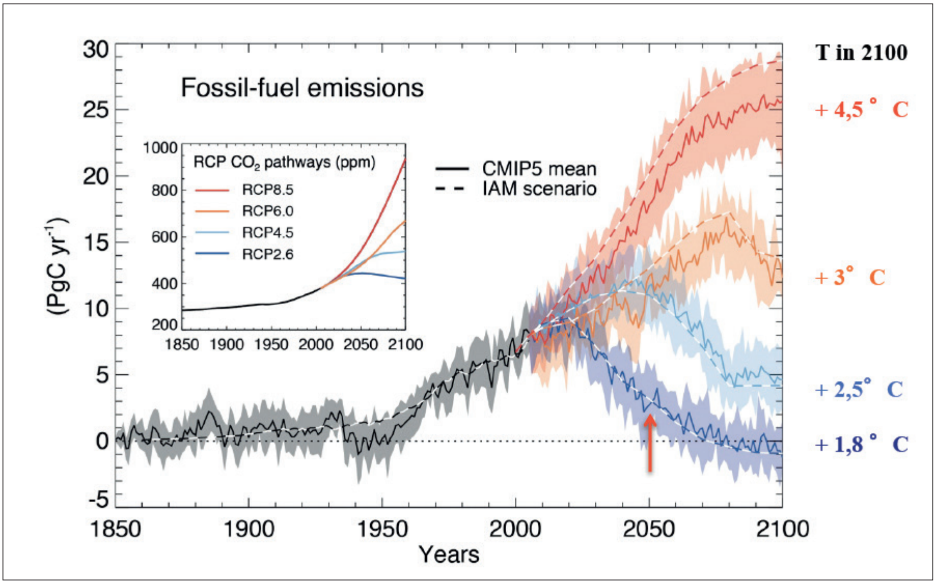

Fig. 3. The world emissions of CO_2 in petagrams of carbon per year (1PgC = 3667 $MtCO_2$) as a function of time (IPCC measurements and predictions). In black are measurements already made. In color (from red down to blue) are 4 predictions corresponding to different scenarios. Red is the "business as usual" scenario. Blue is the most optimistic scenario one can imagine. On the right, the corresponding temperatures predicted for 2100. [4]

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 tries instead of burning forests. Emissions should be immediately reduced. In 2020 they should have already started to decrease, and by 2050 they should be reduced by a factor of 3 with respect to 2014 that is a factor of 4 with respect to 1990, the reference date chosen at the Kyoto COP3 meeting. This is the only scenario allowing to stabilize the climate before the end of our century. The global temperature would reach + 1.8 °C with respect to the pre-industrial epoch 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 to 4°C in 2100. It thus appears urgent to re-examine the INDCs as soon as possible. For that, I proposed in a recent book[4] 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 1.5tCO_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 by 80 to 90%. That's the right goal, but one needs to see if the means to reach this goal 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 of fossil fuel consumption, which represents a major risk for the whole planet. As for China, they proposed some reduction but not before 2030, which would be much too late, and at present its emissions do not decrease.

3. THE HUMAN RESPONSIBILITY

The origin of the global warming has been very well demonstrated by scientific studies. First of all, our planet has never encountered such a large and fast warming since at least 800 000 years. Previous glacial and interglacial periods are consequences of the chaotic exposure of the Earth to the solar radiation which induces changes in the green house effect. They showed that a few degrees variation of the average temperature is sufficient to change the extent of glaciers and the sea level by large amounts. Since the beginning of the industrial era, it is the composition of the atmosphere which suddenly modifies the green house effect: its content in so called green house gases

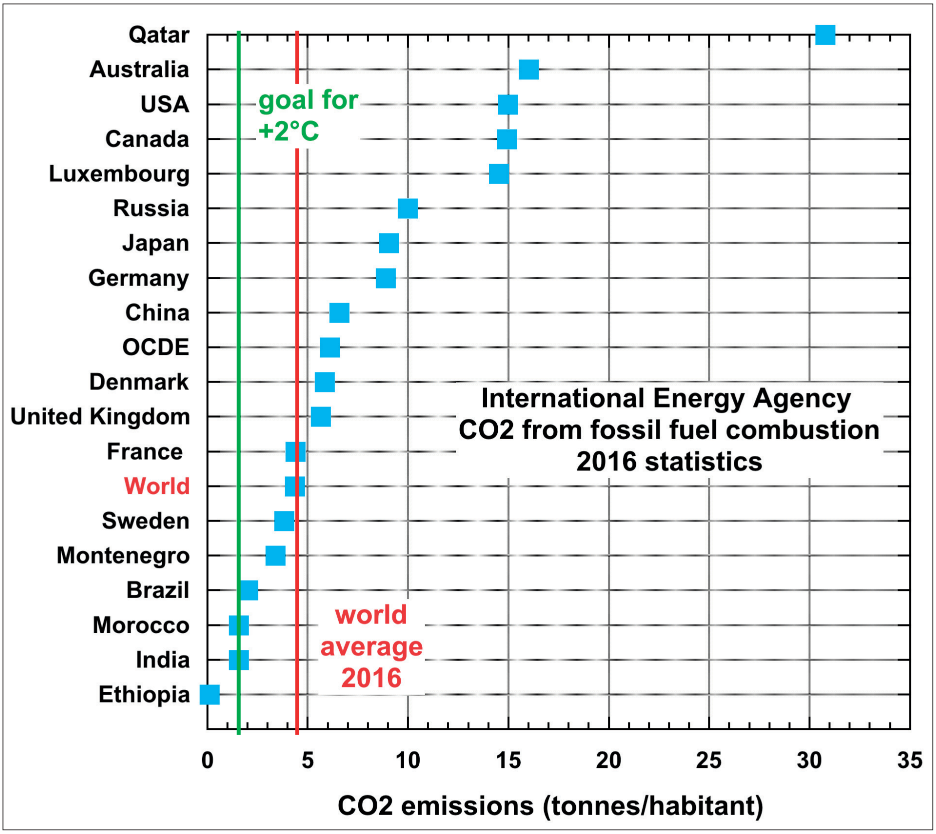

Fig. 4. The emissions in tonnes per habitant of CO_2 in various countries as published by the International Energy Agency for the year 2016 [5]. Red line ($4.35tCO_2$/hab): world average. Green line ($1.5tCO_2$/hab): necessary average to be reached in 2050 in order to stabilize the global warming below 2°C before the end of the century (5th IPCC report, 2013 [4]).

(GHGs) has doubled in one century. The most important GHG is carbon dioxide (CO_2) whose origin has been proved to be the consumption of fossil fuels by measuring its concentration in its carbon isotope C14. To CO_2 one has to add methane (CH_4) and nitrogen peroxide (N_2O) whose main origin is agriculture and farming. In summary the global warming results from human activity which should be modified. Let us now compare emissions of CO_2 in various countries.

It is obvious that Europe emits more CO_2 than France, or China than Luxembourg because their numbers of habitants are different. The climate problem being global and very difficult to solve, all countries should contribute to the necessary effort 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 habitant. As shown by picture 4, the energy policies are rather inhomogeneous.

For simplicity, picture 4 shows the emissions of CO_2 from the combustion of fossil fuels, as given by the International Energy Agency (IEA) [5], although a detailed analysis should consider the emissions of all 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. One should also consider the so called "carbon print" by taking into account what is produced in the country and what is imported from other countries. But local CO_2 emissions from fossil fuels correspond to the main part of GHG emissions and they are sufficient to draw 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 see water desalination. Qatar has recently started to install photovoltaic panels, but most of its energy comes from fossil fuels.

In the USA, Canada and Australia, the emissions are about 15 tons per habitant (15tCO_2/hab), that is nearly 4 times more than the world average (4.35tCO_2/hab, red line on picture 4). 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: California and the New-York State emit less than 10tCO_2/hab while Wyoming emits more than 100tCO_2/hab, even more than Qatar.

Luxembourg is often accused to be a tax haven. The price of oil there is 20 to 30% lower than in neighboring countries so that cars and trucks go there to fill their tanks. While countries try to impose carbon taxes, Luxembourg does not show solidarity with the rest of Europe.

The people's republic of China emits much less per habitant (6.6 tCO_2/hab in 2016) than the USA (14.9tCO_2/hab) but its total emissions (9057 tCO_2/yr) are larger than in the USA (4833 MtCO_2/yr)) because its population is much larger (1379 Mhab instead of 323) [5]. It means that the energy production and consumption are rather different in the two countries but, together, these two countries are emitting 28 + 15 = 43 % of the total world emissions (32314 MtCO_2/yr) and their respective policies is of primary importance for the future of the planet.

Germans emits more than twice as much as Swedish or French people. This is because the electricity is already carbon free in Sweden and in France thanks to nuclear and hydroelectric electricity, while coal and lignite keeps representing a large part of the energy sector in Germany. It may look surprising since Germany is well known for its renewable energies, whose electricity is carbon free. This is because windmills and photovoltaic panels are intermittent: when the wind speed goes below 15 km/h the mills stop rotating and above 90 km/h one has to stop them for precaution. Their maximum efficiency is reached with wind at 43 km/h. On average, windmills produce only 15 to 30% of their nominal power. 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 is not enough cobalt to build Li-ion batteries for the whole planet. There are 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 turbining 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, that is 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 renewables, at least not yet.

At the bottom of picture 4, Ethiopia shows negligible emissions (0.11 tCO_2/hab): 80 times less than Germany despite a similar population of 102Mhab (82Mhab in Germany). This is because Ethiopia is a developing country with very small consumption of energy, but also a large hydroelectric energy production. Eventually, picture 4 shows a green line representing the emission goal, 1.5 tCO_2/hab. According to the IPCC [4], this is the average emissions per habitant that should be reached in 2050 in order to stabilize the global warming below 2°C above the pre-industrial situation.

4. ENERGY TRANSITIONS

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

The main GHGs to be considered are CO_2, CH_4, N_2O. The first source is the transportation sector, mainly road transportation by trucks, buses and cars, which amounts to 26% of the total emissions. Then industry with 12 + 10 = 22% (manufacturing, construction, energy production), then agriculture with 16% (CH_4 due to animal farming and N_2O 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 make energy carbon-free, 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, 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 of 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 in the German one.

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

5. 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). The 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 electricity mix and 12% in France. 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 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 which amounts to 78.4% [5] and hydroelectricity (12%) and some more renewables, the French electricity is nearly totally carbon free. To produce 1kWh of electricity, France emits 79g of CO_2. Sweden is even better with 30g only. On the contrary, the emissions per kWh are 461g in Germany, 522g in the USA, 766g in China, 781g in Poland[7]. The efforts that need to be done in the latter countries are huge.

6. WIND AND SUN

The main problem with these other renewables is their intermittency. There is of course no sun at night and solar production is reduced as soon as the sun hidden. 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, their production is about 5 times less than their nominal power that is reached with ideal wind speed only. But the main problem is that their production fluctuates randomly as shown by the graph on picture 5. On the same graph, one sees also that, even if one integrates the wind power that is produced in 7

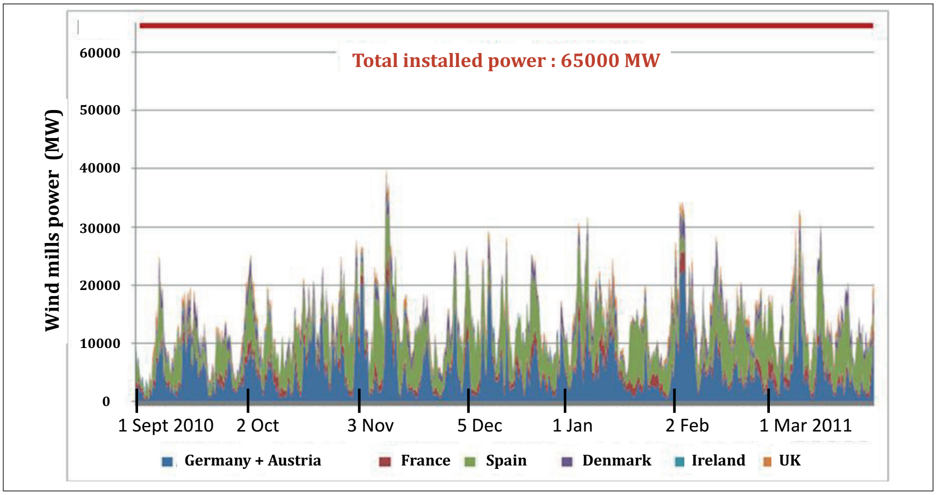

Fig. 5. The power of wind mills in 7 European countries from Sept. 2010 to Dec. 2011 [5]. Adding the total production does not wash out the intermittency. The total installed power was 65000 MW but the average power about 5 times less with fluctuations down close to zero.

European countries from Spain to Ireland and Germany, the total production keeps fluctuating by huge amounts. That is because the meteorology is rather homogeneous in the whole of Europe. As a consequence, covering Europe with a dense network of electric lines would not solve their intermittency problem.

If one knew how to store electricity in large quantities, one could accumulate electricity when the consumption is low, and consume it when the wind is too weak. But there is not enough resources to build batteries at the scale of the consumption of the whole world. The only method that is known and efficient at a large 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 renewables are 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 what Germany is presently doing.

At this stage, it becomes clear that, if Germany is forced building 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 the French association "Negawatt" propose such a non-realistic goal, it assumes that the production and consumption of electricity are drastically reduced. Even by saving some energy here and there, it is impossible to suppress the use of fossil fuel for transportation, building and industry without replacing at least part of it by some more clean electricity.

As for PV panels, their average power is only 13% of their nominal power that corresponds to their maximum instantaneous power. In 2016, French PV panels produced 8.3TWh, that is 1.6% of the total (531TWh). In Germany, their production was 36 TWh, that is 5.6% of the total (648TWh). 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 unfortunately not adapted to the climate of European countries like France (except in its south part) 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. Its 650M€ cost was supported by the German KfW, the French AFD, the World Bank, the European BEI, etc. It can also be used to desalinate ocean water. In my opinion, this type of solar stations are very well adapted to developing countries where the climate is hot and dry. They are still expensive so that 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.

7. BIOMASS

It is possible to produce methane or biofuel with the 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 tries, soya, corn and various other plants that chemistry can use to produce biogas or biofuel. However one should realize that this crop growing needs very large areas because the efficiency of photosynthesis is low. As a consequence, it competes with food production so that countries like France import their biofuel from 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 the large energy storage that is required to solve the intermittency problem of wind power or PV panels.

8. CO_2 CAPTURE AND STORAGE

Another idea is to capture the CO_2 emissions from coal power stations. 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 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. The total cost of capture + storage lies between 35 and 50$ per ton of CO_2 so that it doubles the production cost of their electricity. Given that the clean electricity has to be more expensive than dirty electricity and 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. One needs geological research on aquifer layers.

9. NUCLEAR ENERGY: SAFETY, COSTS AND WASTE

Given the difficulty of the challenges mentioned above, what about nuclear energy? Nuclear reactors emit negligible quantities of CO_2 except during their construction which is not much. They can be adapted to the consumption and to the chaotic production of intermittent renewables. We will see that its cost has increased recently but it remains competitive on the energy market, especially if one stops consuming all the fossil fuels. Facing the climate change problem, nuclear energy looks interesting but it raises three main problems: safety, wastes and cost.

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 consequences or 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 relation 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 as 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 other reactors in present 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 UK, which use weakly enriched Uranium and CO_2 gas as a cooling fluid.

At Fukushima, it 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 sea shore in order to make the use of sea water easier for the cooling system. The next two (Fukushima 5 and 6) had been constructed later on top of the nearby cliff. 51minutes after the earthquake, the six Fukushima reactors had been stopped automatically but the Tsunami destroyed the electricity supply and the connections to the sea water. This tsunami had already killed 18000 people and the civil security was trying the rescue victims of the 30m high wave 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 H2 and oxygen O2 so that, in the absence of catalyzers to recombine H2 and O2, it exploded, blowing off the roofs as everyone could see on TV screens. The accident was classified at the same maximum level as Chernobyl (level 7) although, fortunately, no death could be attributed to radioactivity. Today, the four damaged reactors are under control but 150 000 people had to leave a region of approximately 30 km radius around the reactors. Even if some of these people have already returned in this region, there remains regions where the radioactivity level is beyond the safety level.

The Fukushima accident has been frightening 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 danger of the accident so that the intervention of the security services was retarded. In the management of nuclear reactors, zero risk is an ideal that can never be really reached. It has to be continuously improved even if safety improvement decreases economic benefits.

Ordinary reactors use a few percent only of the energy that could be extracted from their fuel that is 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 life time, one 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 is presently used in some reactors but it is not sufficient. The efficient solution is to build so-called 4th generation reactors where the fast neutrons are able to burn large quantities of Pu and 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, respectively in Russia, China and India. The French one “Superphenix” was unfortunately closed in 1986 for political reasons after some technical problems but one full year of efficient production of electricity. This new generation of reactors needs more research but it 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 the natural radioactivity.

Safety improvement cannot be free. It has a cost that increased after the Fukushima accident. The construction cost of so-called “Third-generation” reactors has increased a lot compared to previous ones. For example the cost of the European EPR has reached about 10G€. 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:

80TWh in 60 years at 100€ per MWh means an income of 80 G€. Now, these investments in safety need to be compared with other costs.

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 that 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 renewables 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 financial arguments in this article. It is not the right place to do that.

10. CONCLUSION: THE ROLE OF SCIENTISTS

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 with space for lakes. As for hot and dry developing countries, it seems to me that thermal solar power stations are well adapted.

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

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