Climate Change and Energy Perspectives: Toward a Carbon-Free Energy System

Since the beginning of our world, the development of the human societies has been driven by multiple sources of abundant and cheap energy. However, because fossil fuels exist in finite amounts under Earth's crust, their constant use has resulted in a dramatic rise of greenhouse gas concentrations, thus necessitating an energy transition. Hopefully, such a transition will be achieved by the second half of the 21st century. Here we review the present situation and current trends. The potential of energy technologies, among them renewable and nuclear sources, are presented, and proposed paths toward a carbon-free energy system are discussed.

From Holocene to Anthropocene

The present interglacial period is called "Holocene." It has prevailed for the past 10 000 years. Meanwhile, mankind conquered our planet. Humans settled in every place offering resources and mild climates. They built up their environment via land use change, housing, transportation, energy and communication networks.

Unknown spots in terrestrial land no longer exist and seas were navigated all over. Space travel is now a reality although few individuals are experiencing it: some 40 years ago, a few astronauts walked on the Moon; since 1998, the permanently staffed International Space Station is orbiting Earth.

Changes in the atmospheric composition are among the most spectacular environmental impacts of human activities. Exhibiting a continuous growth for the last 200 years, the concentrations of greenhouse gases (GHG) increased tremendously. This is mainly due to the energy system in the developed and developing countries. Indeed, 80 % of energy sources worldwide are fossil fuels: coal, oil and gas whose combustion releases GHG, mainly CO_2, that accumulate in the atmosphere. According to most climatologists, a global warming might follow.

Most primary energy is heat a large fraction of which is lost. For several reasons, this "thermal civilization" is not sustainable. Human population is expected to grow from the present 7 billions up to 9 billions in 2050. Highly populated countries, Brazil, China, India and others are developing at a high rate. Consequently, energy demand is rapidly increasing. Our industrial societies are thus facing a number of questions:

- Although known reserves cannot match future demand, are there any further fossil resources to be discovered? are fuel shortages looming?
- How, without fossil fuels, societies can fulfil an ever-increasing energy demand?
- Which technologies can be substituted to obsolete ones?
- Will mankind be able to mitigate environmental and human negative impacts of technologies, old and new?

Answers were discussed within Prospective 2100 [1]. They imply choices societies are committed to make. Energy systems are awfully intricate. Beyond internal evolutions (mainly technological), their future depends upon external elements: demography, economy, society, geopolitics… Furthermore, energy production and delivery need heavier and heavier infrastructures and running is made through complex management procedure. Therefore, energy systems carry a considerable inertia and energy transitions are slow. They need decades before being completed. Although faster transitions are conceivable, they always occurred in the past towards the negative direction: e.g. a reduced energy production following a collapse of the economy as it happened in the eastern European countries circa 1991.

After some others for different purposes, the Dutch Nobel laureate Paul Crutzen coined the word "*Anthropocene*" [2] to designate the current geological epoch that started by the end of the XVIIIth century with the inception of the industrial revolution.[1] Indeed, industrialization and economic development induced a dramatic change in the relationship between man and nature. Instead of being dominated by natural forces, we are nowadays exerting an increasing power on the biosphere and beyond. Accordingly, mankind appears as if it were in charge of the whole planetary management. Although this promethean ambition has limits, our ingenuity at developing technologies might prove effective in the control of the complex terrestrial machinery.

The trouble with greenhouse gases

Since the beginning of the industrial era, the concentration of carbon dioxide in the terrestrial atmosphere has increased by some 50%. An historical range 200-380 ppmv prevailing during the million years before present is inferred from the isotopic analysis of ice cylinders drilled out of polar caps. Concentrations up to 400 ppmv were measured in 2013 and are still rising. The same kind of behaviour holds for other greenhouse gases such as methane and nitrogen oxides. Records over a million years show a striking correlation between atmospheric temperature and greenhouse gas concentrations. In climate models, an increase of GHG concentration entails a temperature rise. A precautionary principle should apply: an energy transition towards carbon free sources is mandatory.

Reducing carbon dioxide emissions is among the goals of energy policies. The United Nations set up a dedicated body, the Framework Convention on Climate Change (UNFCCC) under the auspices of which, widely advertised international conferences (*Conferences Of Parties* i.e. *COP*) are organised. Information and recommendations to the COP are provided by the Intergovernmental Panel on Climate Change (IPCC). This institution is in charge of three working groups dealing with climate science, impacts and mitigation of climate change. Assessment reports are issued every 5 to 7 years [3].

They consist of thorough surveys of the scientific literature which encompass a review of scenarios many institutions are setting up in order to figure out the future. Emission trajectories leading to prescribed CO_2 concentrations by the end of the 21st century are derived according to various assumptions about the evolutions of societies, their energy system and the way GHG mitigation is carried on. For instance, so called RWG CO_2 emission trajectories reaching prescribed concentrations from a starting point in the 90s were determined [4]. On Figure 1, they are compared to the actual trajectory and likely trends in the near future.

[1] Not all scholars agree about the beginning of the Anthropocene.

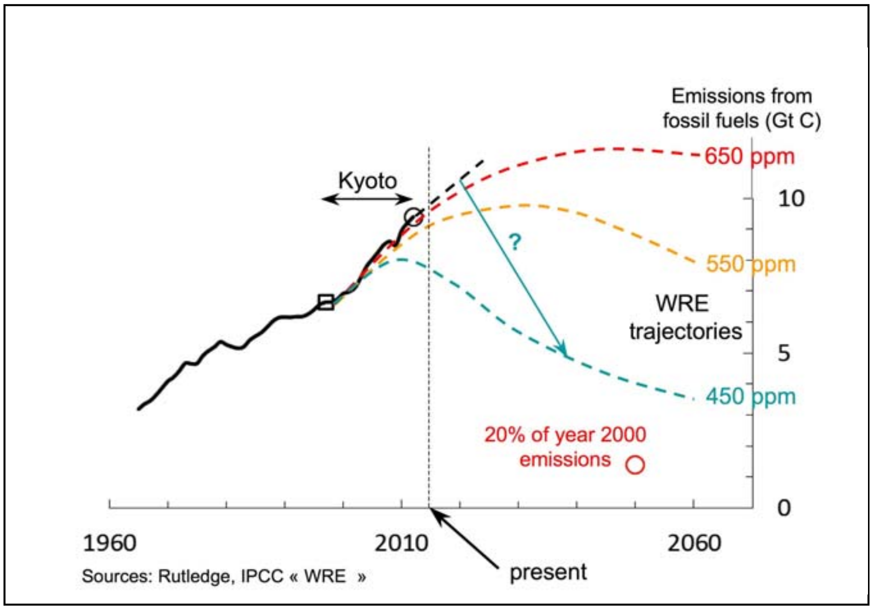

Fig. 1: CO_2 emission trajectories according to Wigley, Richels and Edmonds (WRE) [4]. Labels refer to the concentration reached asymptotically by the end of the 21st century or later. Historical records (black curve) show a rapid growth of the emissions while the Kyoto protocol was effective. No smooth trajectory can reach a 450 ppm path in the near future.

The Kyoto conference (COP-3) in 1997 adopted a protocol by which only developed countries were committed to a 5 % reduction of GHG emissions with respect to 1990 levels. Restricted to a limited number of OECD members and ignored by big emitters, the protocol did not include China and other rapidly developing countries. Eventually its effect if any turns out to be marginal (Figure 1). A general agreement is expected at the end of the COP-21 in Paris in 2015. Hopefully, action will be taken beyond speeches, reports and wishful thinking.

Given the GHG concentrations resulting from socioeconomic evolutions, climate models evaluate the induced radiative forcing i.e. the imbalance in the terrestrial heat fluxes. It ranges between 2.6 and 8.5 W/m^2, in any case a small fraction of the solar irradiance (1362 W/m^2 in the upper atmosphere), however sufficient to trigger a climate change. Predicted mean temperatures at the end of the century could be 1.5 to 6 °C higher than the 1990 value. Uncertainties grow along the process: moderate in the determination of GHG concentrations, high as far as the temperatures are concerned. The widely advertised 2 °C objective is a purely political figure from COP-15 (Copenhagen, 2009).

Supply and demand

In the decades to come, energy supply is to match an increasing demand. Planetary population is expected to grow from the present 7 billion up to 9-10 billion by 2050, mainly in developing countries. Presumably, further evolution will be much slower. However, a large uncertainty is prevailing for the second half of this century. A noteworthy feature is displayed in figure 2. Half of the human population lives in southern and southeastern Asia. Most countries there are developing[2] with China so far on a fast track. This part of the world is also the largest emitter of CO_2 and other GHG.

Whereas the growth in developed countries is to proceed at a slower pace, Brazil, China, India among others are following a high growth path implying further energy needs. Such countries aim at life standard similar to those in western nations. Now a northern American is consuming energy at an average rate 8 toe (tonnes oil equivalent) per year, a western European

[2] The notable exception is Japan whose development started in the 19th century and accelerated after World War II.

uses only 4 toe per year, figures to be compared with 0.7 toe available every year for an African. Note that according to the World Health Organisation (WHO), 1.5 toe/year is a threshold for a modern way of life. Extending American and European standards to the rest of the world looks incompatible with foreseeable fossil energy reserves that can be economically exploited. Furthermore, the environmental impact would be devastating.

Fig. 2. Half of mankind lives in the circled area extending from Pakistan to Japan and Indonesia. Countries in this part of the world are among the largest emitters of CO_2*.*

Another important factor is urbanization. By 2010, half of humans were living in towns. Urbanization is an irresistible trend. It is likely to reach 75% by 2050. Megapoles with specific energy needs will each accommodate 30 millions inhabitants or more, hence specific problems will arise.

Energy supply is a question of sources and of delivery networks. Affordable reserves are known with large uncertainties. However, there is some evidence that oil extraction worldwide is close to a peak [5]. Economy is also an important factor. Unfortunately, the cost of an energy unit from most alternative energy sources, including renewables, still exceeds the cost resulting from fossil fuels. Getting rid of GHG emissions from fossil fuels is made easier by high energy prices. Societies will be faced to an economical and political challenge: development whilst using costly energy.

Nowadays (see Figure 3), 80% of primary energy production comes from GHG emitting fossil fuels. Furthermore, most of this energy is heat which is partly converted into mechanical work or electricity with an efficiency limited by the laws of thermodynamics.

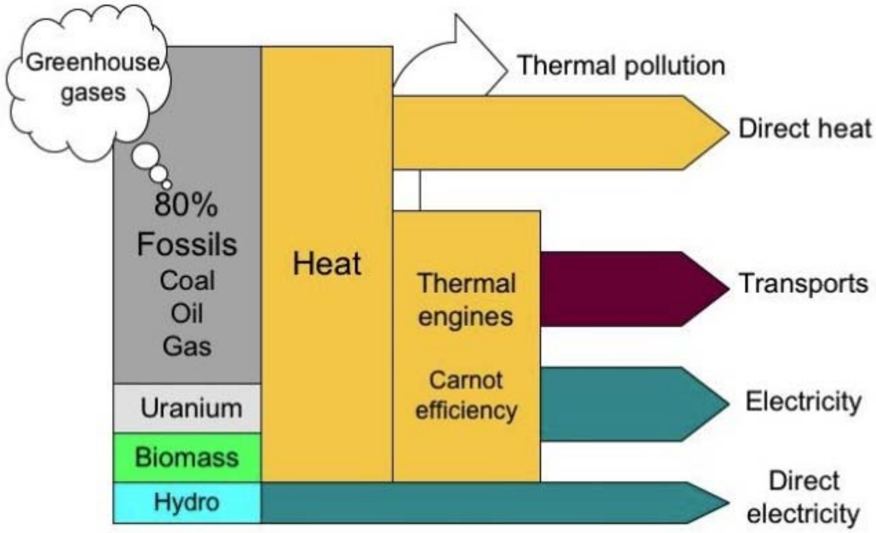

Fig. 3: Energy transformation from primary sources to end users as of 2010. Most primary energy is heat. A major part of it is wasted. Solar and wind contribute marginally to direct electricity.

Further development should be compatible with a slowly increasing energy consumption. This can be achieved provided two requirements are fulfilled. First, energy efficiency is increased dramatically. Second, carbon dioxide and other greenhouse gas (GHG) emissions are mitigated in order to avoid environmental disasters. To this end, technologies might help.

Alternatively, one way societies are not ready to follow is "*degrowth,*" i.e., giving up with economic growth and technology, restricting all sorts of consumptions and turning back to a sober life, closer to "Mother Nature" [6].

Trends and energy substitution

Energy demand is steadily increasing. Electricity demand is growing even faster. Most innovative technologies use electricity as an energy source. Similarly, so-called "new" energy sources, such as windmills and solar cells are designed for electricity production.

Implementing new technologies takes time. In the past, energy substitution, from coal to oil, for example, typically needed half a century, as shown from historical records (Figure 4). For long periods of time, a single energy source is dominant. Before the Industrial Revolution and up to 1880, it was biomass including animal and human work. Then coal prevailed for about a century. Oil took the lead in the 1970s. By the turn of the century, hydrocarbons (oil plus gas) provide 60% of the total and coal, almost steadily, 25%.

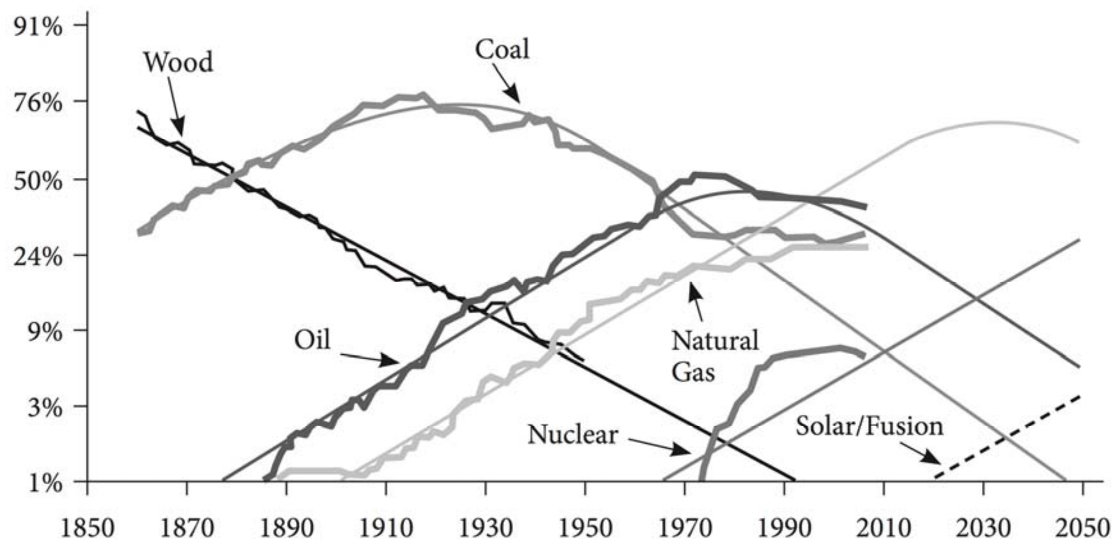

Fig. 4: Time histories of the contributions of main sources to global energy production (Th. Modis [7] after C. Marchetti [8] and BP statistical review for recent data). The ordinates are scaled according to a Fisher-Pry transform that allow modelling upwards or downwards trends with straight lines. The line labelled Solar and nuclear fusion energy correspond to C. Marchetti's personal view of the future.

The changes were not the consequences of lack of resources.[3] Energy systems evolve in two ways: improvements in existing technologies and advent of innovative ones best suited to new end uses and/or enforced environmental constraints. In the so called "energy substitutions" of the past, no real replacements occurred. The advent of new technologies induced further energy needs that new energy sources could more easily and more economically satisfy. Coal proved better than wood for steam engines. Hydrocarbons are best suited for road and air transportation. Nowadays, disregarding GHG emissions, coal turns out to be the cheapest fuel for power plants in emerging countries and in Europe as well.

Other constraints stem from the economy and politics. Oil, gas, uranium, and even biomass are unequally distributed within Earth's crust. For any fuel, including coal, the map of economically accessible reserves does not usually overlap the map of consuming human concentrations. Consequently, trading and transporting fuels and electricity are a major activity in the industrial world. In many European countries, local fossil resources are insufficient to secure energy systems.

No energy technology is completely risk and pollution free. Furthermore, modern energy systems are complex and thus vulnerable. Many kinds of threats do exist including human errors and natural disasters.

In our developed societies, citizens receive a lot of information. Rumours and irrationality propagate through all available channels: press, internet, media… They influence public opinion more efficiently than science. Combined with cultural backgrounds, they contribute to the rejection of specific technologies. Protests against nuclear energy, against oil fields in the Arctic or against shale gas extraction are commonplace. Social acceptance of technologies is a concern, policy makers ought to take into account.

Toward a great energy transition

A climate change is the major threat societies are facing. In order to limit the GHG concentrations in the atmosphere, a transition towards a sustainable energy system implies emission mitigation. Consequently, the share of fossil fuels among primary energy sources is

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[3] As the former Oil Minister of Saudi Arabia, Cheikh Ahmed Zaki Yamani, put it: "*The Stone Age did not end because of a shortage of stones."*

expected to shrink significantly unless the fossil fuelled power plants were fitted with carbon capture and storage (CCS) as strongly recommended in the latest IPCC report. Improvements in energy efficiency are expected and alternative energy sources should be developed

The CO_2 stagnation time in the atmosphere is about 100 years. Furthermore, as already noticed, energy systems carry a lot of inertia. Hence, unless a major economic crisis induces a planetary depression, the transition will be a lengthy process. Initiated during the first half of the 21st century, it will hardly be completed on A.D. 2100.

A general oversimplified scheme for the transition is given in Figure 5. It emphasizes some key issues: the future level of energy consumption, the future energy mix, and GHG mitigation.

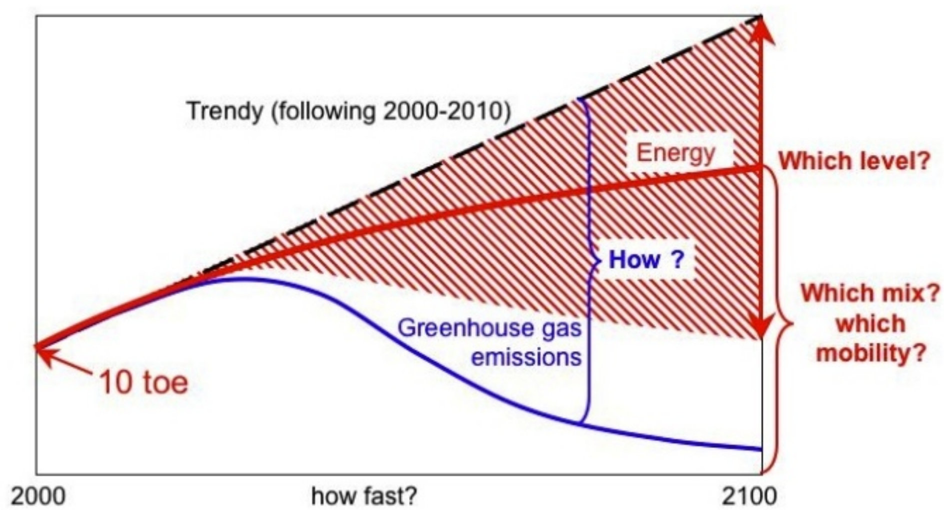

Fig. 5: Questions raised by a future energy transition. The 2000-2010 trend is not sustainable. Greenhouse gas emissions should be mitigated. How? How fast? These are the main questions future energy systems are expected to answer.

So far energy transitions stemmed from technological developments. Initiatives came bottom up from scientists, inventors and entrepreneurs. Contrary to what happened in the past, a tendency appears in which changes to come will be decided internationally or nationally in top down procedures. Note that only affluent societies can afford stringent policies of carbon mitigation. Another important point, choices made now will still influence the energy system by 2050.

Environmental activists are lobbying at the political level. They advocate an enforced policy of lower energy per capita consumption as the only way to achieve a sustainable world. Since they are considered an “unethical” energy source, nuclear power plants would be phased out although their operation is carbon free. Fossil fuels (mainly natural gas) would be marginally used. Heat would be provided by solar panels, biomass and geothermal power. Electricity would be generated by micro hydro, wind, concentrated solar power (CSP), photovoltaic and bio fuels. Hydrogen would be a favourite vector also useful for energy storage.

In every scenario, an important milestone of the transition is mid-century. Indeed the energy system at that point is partly determined by present state of the art and contemporary decisions. The sought situation by 2050 is stated in compact form by “triple 50”: 50% more people on Earth (given by demography), 50% more energy per capita (conservative) and 50% less GHG emissions with respect to 1990 (75% in developed countries).

This is indeed a considerable challenge. During the first decade of the 21st century, growth rates (excluding crises) were much larger: final energy consumption doubles in 40 years, electricity consumption doubles in only 15 years. Extrapolating such growth rate leads far beyond the objective. Obviously, some moderation of the demand has to be imposed, more so in developed countries. Provided demand is effectively reduced with respect to the trend, reasonable estimates for primary energy and end uses are given in Table 1.

Table 1: Energy production and consumption, 2010-2050.

		2010	2050
Primary energy	fuels		714 EJ (17 Gtoe)
	electricity		126 EJ (36000 TWh)
	total	500 EJ (12.5 Gtoe)	840 EJ (20 Gtoe)
End uses	electricity		340 EJ (98000 TWh)
	total	320 EJ (7 Gtoe)	520 EJ (13 Gtoe)

The main question then is: which energy mix? By 2050, energy sources are likely to be the same as in 2010, with a larger share of nuclear (provided safety is upgraded) and renewables: biomass hydro, solar and wind. Primary electricity from renewables would grow from marginal to a sizable share of the total (a 16-fold increase for solar and wind with respect to 2010 figures). Most studies agree about an electricity generation expected to be 50% renewable and 20% nuclear [9]. Renewable electricity generators include hydro which is dispatchable, wind and solar. Intermittency, partly predictable in the solar case, random at any time scale in the case of wind, is a major drawback. Managing large intermittent power on the grid is another challenge. Smart grids are required but might prove insufficient. Intermittency can be compensated in several (costly) ways: back up by gas power plants (advanced nuclear reactors can also perform some load following), energy storage. The latter includes, among others, pumped hydro and power to gas conversion whether the gas is methane or hydrogen. In 2050, fossils would still be a large part of the primary energy sources. Carbon mitigation would be far from complete. At the estimated consumption level, every available energy technology will be needed on a worldwide scale. Significant regional differences are nevertheless expected.

Advanced nuclear technology (breeders, fusion) and new renewables (marine and geothermal) could penetrate the picture after 2050 (Fig. 6). Innovative ways of energy management could appear such as the use of heat so far wasted in thermal engines and in activities needing a tremendous amount of electrical power (data centres).

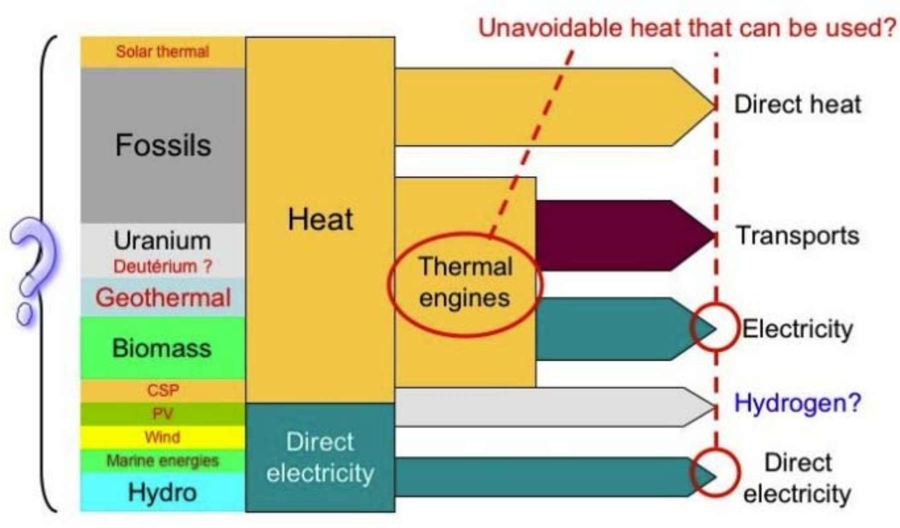

Fig 6: The energy system beyond 2050.
The main changes with respect to the 2010 situation are: a smaller share of fossil fuels (with CCS whenever possible), a bigger share of nuclear and renewables. Questionable are hydrogen as a vector, new nuclear technologies (generation 4 —fast neutron breeders, and nuclear fusion) and new renewables (marine and geothermal).

In general, most scenarios dealing with the first half of the century are conservative. They follow the present trends with only incremental deviations that hopefully anticipate major changes to come. Some changes are actually underway, e.g., shale gas in northern America. Since coal is the worst GHG emitter, substitution by gas in power plants is already contributing to CO_2 mitigation. According to the International Energy Agency (IEA), the few decades to come are likely to be a “golden age of gas”[10]. Indeed, whenever the price per barrel is over $100, many energy sources turn out to be cheaper than oil. This was the case in the U.S. for unconventional gas that could be profitably extracted and locally traded. Things look different with a barrel priced around $50. The prediction of the IEA might be defeated by the economy.

Alternative scenarios are often ideological. Proposed by environmental NGO, major switches and a fast track are postulated in the evolution of the energy system. After passing through a maximum around 2020, energy consumption by and beyond 2050 would decrease until it stays at the 2000 level. Massive energy savings would be implemented and the whole system eventually would run on renewables (Figure 7) [11]. These scenarios are popular among environmentalists. However, they look completely unrealistic. Indeed, no nation let alone international organisation, is willing to undertake such dramatic changes. Furthermore, the capacity of renewables in satisfying all energy needs, even in a downsizing perspective, is questionable.

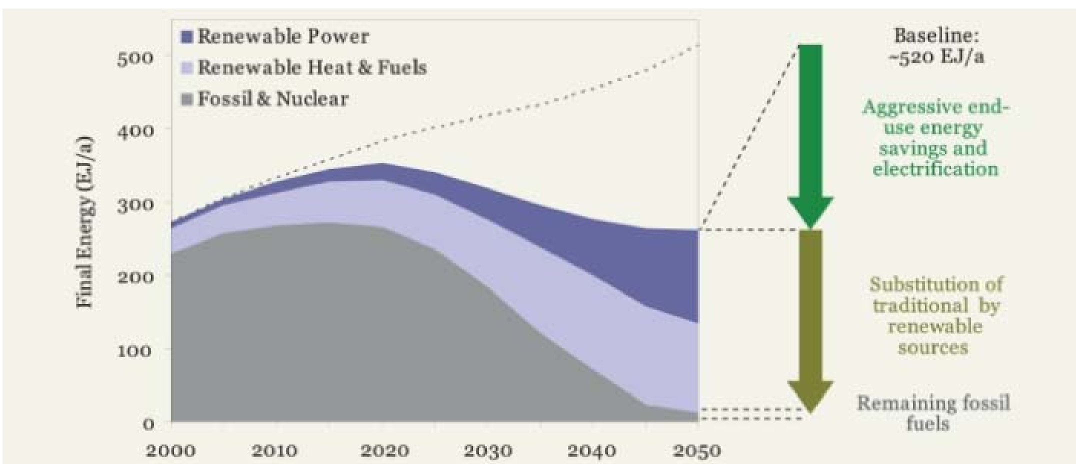

Fig. 7: A scenario for a 100% renewable energy system by 2050 (Ecofys-WWF).

For instance, nowadays, biomass accounts for 10% of the primary energy production worldwide (1 Gtoe). According to studies conducted at Prospective-2100 [12], the production could be at most doubled till 2050 (2 Gtoe) to be compared with 3.5 Gtoe (end use) expected in the Ecofys-WWF scenario. The principal limitation factor is conflicting land use: no more than 20% of cultivated land can be dedicated to energy.

Technologies for the future

In our technological societies, the future is not the mere continuation of present trends with only marginal changes. Anticipating energy choices needs considering other paths. Some appear after dedicated R&D. Imagination supplies others. The list of relevant energy technologies is long and diverse, covering a large spectrum from existing to science fictional. They are presently at different stages of development and maturity. Independent of the technological evolution, electricity production will be still growing at a high rate.

A “golden age of electricity” could follow the “golden age of gas” that IEA sees looming (Figure 8) or the more likely “golden age of coal.” Replacing toe by EJ or MWh as a reference energy unit would be a good evidence of a major shift in the energy system.

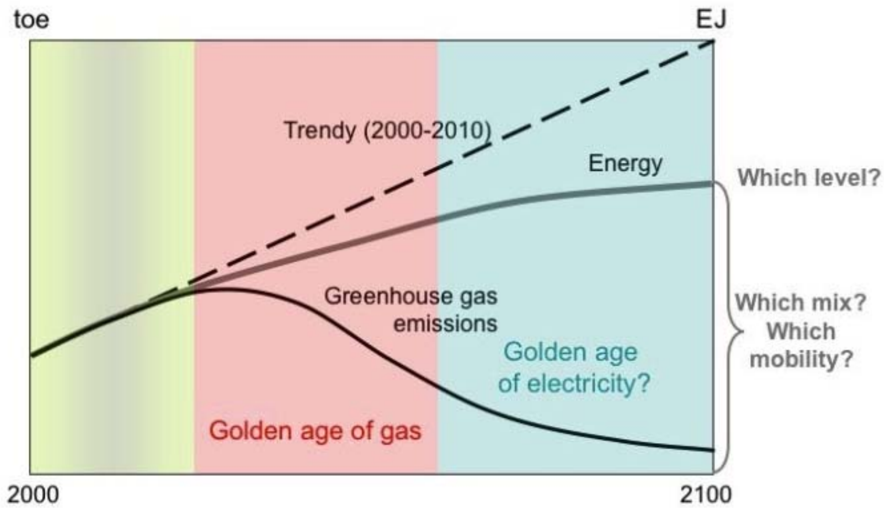

Fig. 8: Will a "golden age of electricity" follow the predicted "golden age of gas"? Hopefully, exajoules (EJ) will replace toe as a reference energy unit.

"Old" technologies will still be present in the second half the century. Gas- and coal-fired power plants will be operating. In order to match CO_2 mitigation criteria, the use of coal, the cheapest but the worst GHG emitter of all fuels, would require CCS implementation on a large scale. Then transportation to the repository sites would generate a traffic that compares to the present oil traffic. Conventional biomass, so far the main renewable energy source, is likely to stay at the same relative level: about 10% of the total energy production. Onshore windmills and second and third generation nuclear reactors can be added to the list. Depending on local culture, coexistence of old technologies as of Figure 9 will be a familiar picture.

Fig. 9: In France (Tricastin), windmills neighbour on a nuclear power plant (left), whereas in Germany (Lower Saxony), they neighbour on a biogas production plan (right).

Present commercial nuclear power plants use enriched Uranium. Fission by thermal neutrons is restricted to isotope 235, which constitutes only 0.7% of natural Uranium. Advanced nuclear reactors of the future will be breeders converting isotope 238 into fissile material, thus extending the resource by a factor of about 100. Another extension factor of at least two would be obtained by implementing the Thorium cycle. Unfortunately there is some reluctance in supporting active development programs in Generation 4 nuclear energy. Advances are appearing at a very slow pace. Furthermore, according to conventional wisdom, the more powerful a single unit, the more profitable it is. Investments are thus enormous and the return on investments takes many years. High power (> 1 GW_e) nuclear reactors are to be designed and built in order to operate for more than half a century with a high level of safety. Some attempts at downsized innovative nuclear reactors might end up in profitable devices in the second half of the century.

At this point, it should be emphasized that, unless a degrowth path is taken up, all presently running energy sources including nuclear will be necessary to match the demand at least up to 2050. There is no such thing as a silver bullet! In the foreseeable future, no single technology will provide the required electric power while complying with the severe constraints of GHG mitigation.

Beyond 2050, technologies that are nowadays invented and/or developing might become mature and penetrate the energy market at a significant level (1 Gtoe or 50 EJ). They include renewable energy sources: geothermal power, concentrated solar power, marine energies (Figures 10 and 11). Since a dry atmosphere is a mandatory requirement, CSP is to be preferably implemented in desert areas. Projects like the so far ill fated DESERTEC [13] rely on this concept. Such an energy system could unite Western Europe and Northern Africa provided a lot of technical and geopolitical problems would be solved. By the same token, a grand plan for solar energy was proposed for the U.S. [14]

Fig. 10: A prototype (2 MW) geothermal power plant running at Soultz (France).

Fig. 11: A water current turbine, aimed at harnessing marine current energy, on its barge for transport and immersion offshore Paimpol (France).

Among the future mature technologies, innovative biotechnologies, such as micro algae for bio fuels, might extend the share of biomass in the energy mix. Provided they prove efficient in terms of cost performances and safety, nuclear technologies such as fast neutrons and breeders, might contribute to a significant spreading of nuclear power plants. Since nuclear fuel reprocessing is necessary in generation 4, part of the radioactive waste could be partly eliminated in neutron irradiation stages.

Technologies of the electric current transport and delivery grid are also expected to reach maturity. High voltage direct current (HVDC) cables will allow long distance transport with minimal losses (Figure 12). Furthermore, so called “smart grids” will be in use in order to contribute to the management of the intermittent power from solar and wind energy sources.

Fig. 12: HVDC allow power transport over long distances with reduced losses. Only two cables are necessary contrary to usual AC lines (3 cables).

Besides mature ones, technologies might be developed along the second half of the century that would eventually be worth implementation on the industrial scale. Enter the category further development of biotechnologies leading to improvements of photosynthesis efficiency, controlled nuclear fusion using heavy hydrogen isotopes as a fuel, or space solar power. Space RF technologies could also be used to bypass the terrestrial grid.

Finally, the realm of utopia would encompass technologies depending on results to come from basic research. This is the case for massive electricity storage, room temperature superconductivity, artificial photo-synthesis and presumably many others, people in 2014 do not even think about.

Conclusion: Managing the Anthropocene?

Definitely, mankind is living in the Anthropocene. Unless our modern civilization comes to an abrupt end consecutive to a major crisis, there will be no return to a nature dominated Holocene. Humans have built their environment whilst multiplying. Consciously or not, they impacted ecosystems. Following the industrial revolution, the atmospheric composition has changed. This is mainly the result of an energy system in which fossil fuels were burnt without control. Something (everything?) has to change. The fate of the planet Earth as a place for life to flourish is in our hands. The sustainable future depends, in complex and intricate ways, upon natural processes and human behaviour involving technologies (the main topic of this paper), economics, sociology and politics. Managing the Anthropocene is a promethean ambition impaired by a major drawback. Indeed, we don’t have all the keys: our knowledge is far from adequate and it is difficult to predict the consequences such and such action will drive in a remote future. The best that can be done is storytelling, i.e., creating scenarios. Many institutions are involved in the task. In order to set up a scenario, assumptions are mandatory in many domains, scientific, technological, economical, social, political… Moreover, the final state should be postulated in advance.

In 2008, the IPCC issued recommendations about the development of global scenarios updating the WRE approach [15]. Four Representative Concentration Pathways (RCP) combining socio-economic developments and the climate machinery were accordingly used as guidelines for the 2014 AR-5 report [3]. The pathways lead to different levels of radiative forcing by 2200: 2.6, 4.5, 6.0 and 8.5 W/m^2 positive imbalances with respect to an assumed steady regime prevailing before the inception of the industrial era. The most desirable RCP-2.6 would result in a temperature rise below the 2°C Copenhagen statement.

The countries participating in COP-21 were asked to submit their decarbonisation objectives. Due to the unequal distribution of resources, the variety of economical models and, last but not least, cultural biases, paths differ widely from one nation to another. Altogether, the commitments look modest and far from the requirements of RCP-2.6 which might never be reached. Besides efforts aiming at GHG mitigation, human societies ought to adapt themselves to unprecedented climatic situations. Today, there is no evidence they are ready to do so.

No nation is planning for its citizens an energy sober life that would destroy or preclude its economic growth. Building up a carbon free energy system is the only way to reconcile energy and the environment both natural and manmade. In this respect, the cost of energy is of importance.

In 1998, the “end of cheap oil” was predicted by Campbell and Lahérrère [5]. A more general prediction would be the end of cheap energy. Indeed, taking for granted the necessity of an energy transition, carbon free energy sources are expected to be more expensive than 20^{th} century oil and present day coal. In any case, the future of the energy system will depend upon major advances and innovations in technology. From now on, all initiatives in the realm of energy should aim at eventually minimizing GHG emissions and other environmental impacts. Fossil plants should be progressively fitted with CCS and/or replaced by carbon free energy sources: nuclear and renewables. The choices will be driven by trade off between convenience, constraints and the economy. Public acceptance is another important issue. It might be easier in more learned and better-informed societies.

Smart grids, efficient insulation of buildings, and new mobilities are other key domains in which innovations are expected, first, to match the triple 50 challenge, and second, to complete the energy transition. It will be possible only if related technologies are fully mastered. Eventually, this will lead from an energy system dominated by fossil fuels to a golden age of electricity. A smooth transition extending over the whole 21^{st} century is most desirable. The inertia of the energy system might help.

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GLOSSARY

CCS	Carbon Capture and Storage
CSP	Concentrated Solar Power
EJ	Exa (10^{18}) Joule
GHG	GreenHouse Gas
GTOE	Giga (billion) tonnes oil equivalent
GW	Giga (billion) Watts, subscript e stand for electric
HVDC	High Voltage Direct Current
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
MW	Mega (million) Watts
NGO	Non Governmental Organisation
PPMV	parts per million in volume
R&D	Research and Development
TOE	tonne oil equivalent
UNFCCC	United Nations Framework Convention on Climate Change
TWH	Tera (1012) Watt hour
WHO	World Health Organisation
WWF	World Wildlife Fund