Georges Sapy Translation: Elisabeth Huffer

Nuclear Power reduced to 50 %: Less Security, More CO_2

Summary and Conclusions

Our predecessors, who had a strategic view of the country's future and a sense of public interest, had, in the 1970s, engaged in the construction of the nuclear power fleet we know today so as to gain energy independence from fossil fuel suppliers, this resource being nonexistent in the country. In this way, considerable savings on imports were made: where would France's commercial balance stand, very much in the red as it is, if the nation had had to import these fossil fuels to generate its electricity?

The imperative of mitigating climate warming gave an after the fact additional and powerful justification to this carbon-free, dispatchable (that adapts to demand), large-scale electricity generation, capable of meeting the needs: no other means can boast those three advantages.

This has enabled France to become the large developed country that produces the least carbon-intensive electricity on the planet. And, over the past 40 years, it has avoided the emission of more than 10 billion metric tons CO_2, that would otherwise have ensued from burning a mix of fossil fuels (1/3 coal; 1/3 oil; 1/3 gas). This corresponds to more than 30 years of current CO_2 emissions from the entire country! For the greater benefit of the climate.

And it is this remarkable industrial asset which for 40 years, has provided the country with a secure supply of low priced electricity, that the authorities are striving to reduce, arguing that "*you should not put all your eggs in the same basket*" to allegedly better guarantee the country's supply.

This is an illusion devoid of any rationality whatsoever. For a reason however obvious: replacing secure electricity production available at all times according to demand, by intermittent electricity unrelated to demand since it is contingent on the weather conditions of the moment, in no way improves the security of supply. On the contrary, it degrades it most of the time. It puts it at risk on a large scale in the cold winter spells, greatly increasing the risk of default several times each winter in France and throughout Europe, which has rushed into "all wind and photovoltaic" to produce its future electricity, without measuring all the consequences.

Moreover, the large-scale introduction of this intermittent electricity in Europe will considerably increase the flexibility required of the remaining dispatchable production means to balance supply and demand at all times. Well, only two kinds of facilities are capable of playing this role at the right scale: nuclear power and CO_2 emitting fossil-fired plants; hydropower does not have sufficient capacity; demand withdrawal or deferment, though useful, is at too small a scale; large-scale energy storage will not be available in the short term.

Less nuclear power, thus, certainly implies more recourse to fossil fuels in France or somewhere in Europe, which is inconsistent with the announced objective of carbon neutrality in 2050.

To sum up, reducing nuclear capacity represents a threefold penalty: for the country's security of supply and for the carbon neutrality objective, professed to be a national priority. This study provides the elements of the demonstration. An additional third point must be considered which, although it is beyond the scope of this study, cannot be overlooked: the economic impact of the premature decommissioning of installations in excellent working order and recognized

as safe by the Nuclear Safety Authority. They could continue to produce electricity at very competitive cost for many years to come.

This, not to mention the enormous and incomprehensible waste that such a premature decommissioning represents for the country, will undoubtedly increase the price of electricity, as a separate study published by "Save the Climate" [7] shows, and will impact the cost of living, electrical energy poverty, and the economic competitiveness of the country.

Study Outline

****

Reducing the share of nuclear power in the French electricity mix to 50 % with the planned decommissioning of 14 reactors by 2035 (including the two reactors at Fessenheim from 2020), was presented as a necessary diversification so as "*not to put all our eggs in the same basket*" and thus secure the country's electricity supply.

In reality, this will lead to the exact opposite result: perfectly "dispatchable" production means, i.e. units capable of producing according to demand, will be replaced by wind turbines and photovoltaic panels whose production is contingent on the amount of wind or sun and is unrelated to the demand...

1 - Has the Current Nuclear Power Fleet Failed to Supply the Country in its 40 Years of Existence?

First of all, note that, although the operating principles and technologies of all our reactors are the same, the "eggs" (reactors) that make up our fleet are not in a single basket but in several: they belong to different power "tiers" (900 MW, 1300 MW, 1450 MW models), they were not "laid" at the same time, nor in the same spot. This gives them a double diversification:

* In their implementation/manufacturing and operating time, significantly reducing the technical risks of common mode failure generalized to the **entire** fleet.

* In their exposure to natural risks (earthquakes, floods, extreme weather conditions, etc.) thanks to their installation on 19 different sites which gives them a diversification of location.

- **the feedback from exceptional temporary shut down situations in 40 years of operation**

This feedback from 40 years representing more than 2000 reactor x years of operation is detailed in Appendix 1 for two categories of events:

- ✓ **Generic technical temporary shut downs**

Two events fall into this category: a corrosion problem which surfaced in the 1990s and a metallurgical anomaly that required shut downs for additional inspections between late 2016 and early 2017 (see Appendix 1 § A1.1). The corrosion problem led to one reactor being shut down for roughly a year; the metallurgical anomaly led to the successive shut down of 18 reactors for about one month each. During the 2016-2017 winter, the most critical period for the grid, the cumulative simultaneous shut downs were four 900 MW reactors.

✓ **Temporary shut downs limited to a particular site**

This concerns two sites (see Appendix 1 § A1.2), one to reinforce the seismic resistance of the water supply canal passing nearby, the other to allow verifications following the TEIL earthquake of November 2019. In both cases, again, four 900 MW reactors were unavailable for about 1.5 months and 1 month respectively.

These simultaneous reactor shut downs had an **overall impact** on reactor availability that was never larger than **3.6 GW**, or **5.7%** of the total installed capacity. When compared with 40 years of operation, they represent (see Appendix 1 § A1.3) about 3.3 reactor x years lost out of more than 2000 reactor x years, i.e. less than 0.2% cumulative unavailability. This shows the very high reliability of the current nuclear fleet.

- **Could an accident on a reactor have generic consequences on production?**

As in all high-risk industries, notably aeronautics, given all safety and precautionary measures (technical, organizational, human factors, etc.) taken to avoid accidents, an accident always results from a sequence of initiating events and the failure of in-depth defense mechanisms (material, human, etc.) that make the situation evolve without its being interrupted or managed in time. In this sense, each chain of events is innately a specific case so that the probability that it will have generic consequences is very low provided two complementary conditions are met:

✓ **All safety provisions and rules have been implemented according to best practices**

This requirement includes: appropriate safety regulations and best state of the art practices for design, manufacture, operation and maintenance. It implies skilled organization, faultless operator training and strong overall safety awareness. Finally, an independent, competent and rigorous Nuclear Safety Authority (ASN) is essential to ensure that an accident is highly unlikely. All these requirements are met in the French nuclear power system.

✓ **The feedback from incidents in France and accidents around the world has been analyzed in-depth and their lessons taken into account.**

Given the complexity of the nuclear industry, feedback from incidents and accidents is undeniably the "best of teachers", far superior to the imagination of men, limited in comparison to the complexity of reality. Taking into account both national and international feedback is a major factor in reducing the risk of accidents. France has always been at the forefront in this field.

In 40 years of operation, the current French nuclear reactor fleet has undergone only one "level 3" ("serious incident") event on the International Nuclear Event Scale (INES) which has 7 severity levels. None of the other incidents exceeded "level 2" ("incident").

- **What can we infer for the future?**

It is always difficult to answer this type of question, but there are several reasons to consider that the past can reasonably inform the future, specifically:

* The previously mentioned diversity in the implementation/manufacturing, operating time and exposure to natural hazards at the different sites, greatly reduces the probability of common mode initiating events. This makes it reasonably possible to exclude consequences that would affect the entire fleet, even in the extremely unlikely event of an accident affecting one reactor and resulting in

the shut-down of the entire site concerned for a duration that would depend on the severity of the accident.

* The principle of continuous safety improvement implemented on the reactor fleet results in an in-depth renovation of the facilities to remain in line with the basic safety reference ("extensive refit" operation), along with added "post-Fukushima" safety improvements. The safety level is thus raised and comes close to the third generation reactor standard with its "0 accident + 0 leakage in case of accident" objective.

* The "teething problems" are far behind and the "aging" of the facilities is counterbalanced by the above-mentioned renovations. The parts that cannot be replaced, the containment enclosure and the reactor vessel, are rigorously and thoroughly verified every 10 years, to ensure that operation can continue safely, under the control of the Nuclear Safety Authority (ASN).

* The feedback from the many foreign reactors based on the same technology is also taken into account, in particular that from the 900 MW reactors in the United States, from which the French reactors proceed directly. The US reactors are older than the French ones and they prove to "age" well, so much so that several dozen of them have had their operating license extended to 60 years and two have just been extended to 80 years. This is an undeniable sign of trust in this technology on the part of their operators and the NRC (National Regulatory Commission, the US nuclear safety authority).

* Finally, the conditions of safety and availability are well identified: an in-depth knowledge of the facilities which continues to improve over time, increased general knowledge and technological expertise, as well as high quality monitoring and foresight on the part of the operator; all these are vital human factors: "brains" are the best guarantee of safety and availability.

On these grounds, feedback from past experience and the fact that the sites are far apart, it makes sense, then, to consider that the envelope risk of unavailability should not exceed the shut down of all the nuclear plants on a site, the largest sites representing 6 x 900 MW units (5.4 GW) or 4 x 1 300 MW units (5.2 GW). This holds regardless of the origin of the failure: generic defect, reactor accident or external site aggression. The duration of unavailability would vary from case to case. This represents an envelope unavailability of 9 % of the current installed capacity.

2 - Common Mode Systemic Risks with [Wind + Photovoltaic] Only

The uncertainties related to electricity production from fissile or fossil **energy stocks** are linked to possible failures of the facilities that transform those energies to electricity, failures that are liable to affect a limited number of such facilities. On the other hand, provided that these energy stocks are well managed, they cannot fail.

The major difference with electricity production from **flow energies**, wind or sun, apart from the fact that it is also subject to the reliability of the machines, is that it is also and above all subject to the fluctuations and/or the partial or total absence of these primary energy flows. This is much more problematic in that it can affect **all** of the installations in a region, a country, even a large part of Europe. This is obviously the case for photovoltaics which does not produce at night but also for wind in periods of weak wind, for example during certain winter polar anticyclones which can be accompanied by intense cold that greatly increases demand.

In short, the risk to the grid is proportional to the failure rate (or weakening) of these intermittent primary energy flows multiplied by their penetration level: the greater the penetration, the greater the depth of the production shortfall, a phenomenon specific to flow energies.

A crucial question arises in this context: can a guaranteed wind production be defined? There is no European consensus on this issue. In particular:

* The 4 German Transmission System Operators (TSOs), the equivalents of the French RTE (Réseau de transport d'électricité), instructed by years of operation of their very large onshore and offshore wind farms (more than 60 GW to date), consider that the guaranteed wind power does not exceed 1 % of the installed capacity, including offshore wind power (a limit of 3% is being studied at the request of the German Federal Grid Agency but that would not change the order of magnitude...);

* RTE does not explicitly use the term "guaranteed power" but assumes that, according to its own weather statistics, there is a 90 % chance that wind generation will exceed 10 % of the installed capacity. Conversely, this means that there is a 10 % chance that wind generation will be less than 10 % of the installed capacity. Now:

- a 10 % chance statistically represents 876 hours or 36 days per year, one fourth of which, i.e. 9 days, are, again statistically, during the 3 coldest winter months (December, January, February) when the demand is at its highest,

- a "less than 10 %" production corresponds to real life situations that range from 9.9 % to 0.5 %. RTE does not clarify this but things change quite a bit depending on whether one is at the high end or the low end of the interval.... In this respect, it would be more logical from a statistical point of view to choose the middle of the interval, namely 5 %, rather than the upper limit of 10 %...

In short, the production from these intermittent sources can drop to piddling levels during very cold winter nights in the event of adverse weather conditions: obviously, nonexistent photovoltaic production and wind production not exceeding a few percent. This is the case, regardless of the installed capacity: indeed, a few % of a 100 GW wind farm does not amount to more than a few GW!

It is in this sense that all [wind + photovoltaic] represents a major common mode systemic risk, resulting from the concurrence of night and a quasi-general absence of wind.

Indeed, this common mode can affect not only France, but often a large part of Western Europe: the latter extends over only two time zones so that night is largely simultaneous. Additionally, its wind patterns are strongly correlated, contradicting the widely spread adage "there is always wind somewhere", a statistical falsehood, except in few short-lived circumstances. The reality, demonstrated in several in-depth studies ([1] and [2]) is that most of the time in most Western European countries there is either a lot of wind everywhere, or little, even very little wind, the reason being that the wind patterns are mostly dominated by depressions in the Atlantic Ocean. And when the latter are not present, episodes of light winds, particularly during high pressure systems, can cover more or less of Europe.

The consequence is frightening, given that practically all European countries, under the impetus of the European Commission, are blindly embarking on the all [wind + photovoltaic]:

The common mode systemic risk of all [wind + photovoltaic] is increasing throughout Europe! This will annihilate any possibility of country to country mutual assistance via the interconnections which are meanwhile being reinforced at great expense; there is a risk that everyone will have an electricity shortage at about the same time: there will then be nothing to trade!

There are only two safeguards at the proper scale:

* Either develop large-scale storage capacity able to cover at least ten days of wind shortage (a statistically observed fact) representing a minimum of 15 to 20 TWh storage for France. A considerable amount of energy, 150 to 200 times more than France's pumped hydroelectric energy storage (PHES) capacity. Such energy storage can be achieved only by using so-called "green" [*] synthetic gas fuels, i.e. hydrogen produced by water electrolysis with carbon-free electricity and methane obtained by methanation of CO_2 with this hydrogen. But these solutions remain very

expensive and no viable economical model is available for the moment, probably for a long time to come (see below, §4).

* Or keep sufficient dispatchable production means. Now, in the perspective of carbon neutrality, there is only one means of carbon-free production at the proper scale: nuclear power.

Note: another option is often put forward: demand withdrawal/deferment. This lever should certainly not be neglected (none should be), especially in the event of strong constraints on supply and for short periods of time but its potential is limited as things stand. In 2018 ([4] and [5]), the average withdrawal volume obtained from industrial customers via RTE's "Balancing Mechanism" was 727 MW. In April 2019, RTE indicated that a special effort on this issue would allow to reach a pool of around 1 GW and that, by extending the mechanism to households, an additional 600 to 700 MW should be accessible by 2022-2023. This brings the total to less than 2 GW, or less than 2 % of the peak demand. The longer-term prospects are still to be determined.

3 - Impact on Security of Supply of Decommissioning Fourteen 900 MW Reactors

The question here is to compare the certain loss of dispatchable and guaranteed power caused by decommissioning the 14 reactors to the capacity increase of a variable power fleet [wind + photovoltaic] supplying the same annual energy as the 14 reactors, in the 10 % of critical cases during which the wind power falls to less than 10 % of its installed capacity, i.e. 36 days/year on average.

Detailed calculations are presented in Appendix 2. They show that to produce as much electricity as fourteen 900 MW reactors, approximately 56 GW [wind + photovoltaic] capacity have to be installed. The result:

Replacing fourteen 900 MW nuclear reactors, i.e. 12.6 GW, with 56 GW wind + photovoltaic reduces the power available for the grid by some ten GW (9 to 11 GW depending on the real wind residual capacity factor - less than 10 % in any case) compared to the 14 reactors and their "normal" availability (on the order of at least 90 %) for this period.

A less than 10 % wind generation is particularly critical during the ten or so days that statistically fall in the 3 coldest months of the year (December, January, February) with, in addition, very long nights resulting in a very low photovoltaic contribution.

In the event of a combination of intense cold leading to very high demand and almost no wind, losing around ten GW of power would simply be critical for the country's power supply and would have a very high probability of leading to more or less extensive power outages.

Finally, we stress that further reducing the share of nuclear power would necessarily increase the power shortfalls detailed above since even very large wind generation operating at less than 10 % of its capacity cannot under any circumstances replace nuclear generation operating at 90 % of its capacity in the winter.

4 - The Dimension of Nuclear Capacity in Europe by 2030-2035

This dimension must be considered from a twofold perspective: first, to contribute to the security of supply on the European grid, with increased interconnections between the various countries on the continent and their resulting interdependence for electricity supply and security. Second, to achieve **carbon neutrality in 2050**, a major objective shared by France and Europe. In this effort, nuclear power, the only large-scale dispatchable and carbon-free source of electricity is called upon to play an irreplaceable role on a European scale, and not only in France. There are four objectives, the first three of which relate to security of supply, the last of which concerns the climate emergency:

* Meet the French demand, in particular in the critical periods of lack of wind and sunshine as stressed above and contribute, in so far as possible, to European production.

* Provide inertia to the European electricity system, which is essential to ensure its instantaneous stability in a context of proliferating variable energy sources which do not have any, as they are connected to the grid by electronic inverters.

* But also contribute to satisfying, at the French scale and more so at the European scale, the massive, very large amplitude, flexibility needs looming at the 2030-2035 horizon and beyond to balance the cumulative variations of the demand and of the variable electricity feed-in throughout Europe.

* Last but not least, contribute to reducing the carbon content of the electricity generated, not only for France, but also for Europe, thanks to nuclear electricity exports.

Indeed, we should note that the nuclear capacity of Western European countries (other than France) which is today about **25 GW** (Germany ≈ 8.1; Spain ≈ 7.1; Belgium ≈ 6; Switzerland ≈ 3.3; the Netherlands ≈ 0.5 but has started to talk of a new reactor) is expected to have almost disappeared by 2030-2035.

Thus, the only remaining capacity on the European continental plate would be that of France and the Eastern European countries totaling some **11 GW** (Czech Republic, Slovakia, Hungary, Romania, Slovenia) which, on the contrary, have the stated intention of maintaining and developing their nuclear capacity. However, this capacity should remain stable between now and 2030, given the time it takes to make decisions and build new capacities. In total, then, continental Europe should lose **25 GW** of nuclear capacity.

Note: The nuclear capacities of the United Kingdom, Sweden and Finland (totaling ≈ 20 GW), countries which also have the stated intention to develop their nuclear capacity, are not included here because they are not part of the continental European plate to which they are connected via high-voltage direct current connections whose transfer capacity is too small to play a major role.

Let us return to the four roles to which the French nuclear power fleet will have to make a massive contribution:

- **Ensure that the French demand is satisfied during the critical periods of lack of wind and sunshine and contribute in so far as possible to European production via exports.**

The 56 GW shortfall of a [wind + photovoltaic] fleet in the event of a lack of wind on long winter nights is unlikely to be compensated by additional imports from neighboring countries, which will often experience the same shortfall with their own wind and photovoltaic fleets, given the systemic commonality emphasized in § 2.

Nuclear production will then be crucial to avoid widespread power outages, the only other solution on the right power scale being, for reasons explained further on, the massive use of fossil gas and its accompanying CO_2 emissions. Indeed, the countries without nuclear power, after having reduced their coal-fired capacities for obvious environmental reasons, will be forced to resort to that solution, as the considerable storage capacity via synthetic gas that would be needed is unlikely to be available by 2030-2035 at sustainable costs as explained further on.

France is in a position to avoid this massive recourse to fossil gas. Provided it does not weaken its nuclear capacity...

- **Provide inertia to the European electricity system to stabilize it**

The mechanical inertia of rotating machines (turbo generators) is essential to the instantaneous stability of the grid, in this case the large interconnected European plate. However, this stability will be undermined by two concomitant factors:

* The development of variable production means which do not provide inertia

* The reduction by 2030 of the nuclear capacity (25 GW, see above) as well as of the coal or brown coal-fired thermal capacity in most European countries representing up to 100 GW at the same date.

This means that about 125 GW of large highly inertial turbo-alternators will be decommissioned by 2030, bearing in mind that inertia does not concern only the national level but the entire interconnected and synchronous continental European plate. ENTSO-E estimates that 150 GW interconnected inertial means are a minimum requirement to ensure instantaneous stability on this scale.

In this context the French nuclear capacity will prove extremely valuable to provide the very large inertia of its turbo-alternators both to the French grid and, more widely, to the interconnected European grid as discussed above.

- **<u>Contribute massively to the very high flexibility needs that are on the horizon by 2030-2035 at the French and even more so at the European level.</u>**

Another aspect, emphasized for example in study [3], has to be considered: the considerable increase of the flexibility required from dispatchable production means to compensate for the net demand (demand minus variable production) variations these being much larger than those of the demand alone.
The above-mentioned study, based on 30 years' weather records in Europe as a whole clearly brings out:

* A higher frequency of large amplitude hourly power demand variations (up to 20 GW/hour) with extreme variations up to 70 GW/hour that are never observed with consumption alone. This corresponds, in France, which accounts for about 16 % of the European production, to hourly variations of 3 and 11 GW/hour respectively.

* Day to day variations up to 400 GW in 24 hours between a windy and sunny Sunday at noon and a Monday at noon with little wind and sun. At the French scale, this corresponds to about... 65 GW in 24 hours!!! Such a large variation leads to an average gradient of about 17 GW/hour for Europe as a whole (a little less than 3 GW/hour for France).

These are completely new phenomena that are the direct result of the massive insertion of variable electricity into the grids. They are also beginning to take concrete form in the countries with large variable electricity production, these early experiences confirming the results of the above-mentioned study and foreshadowing future developments, in particular:

* In Germany, a country with more than 110 GW of wind + photovoltaic in which gradients on the order of 20 GW/hour are already observed and are expected to reach 30 GW/hour or more in the very near future.

* In California where the installed photovoltaic capacity, though not very large with about 16 GW in 2017, has led to negative power gradients of 13 to 14 GW in 3 hours at sundown, that have to be compensated with dispatchable production means (gas-fired in this case). These values have since increased with the current installed capacity exceeding 20 GW and continuing to grow.

How will we cope with flexibility requirements of such amplitudes given that only dispatchable production means, massive destocking, or massive demand deferral can be up to the task?

- ✓ **large-scale dispatchable flexibility means**

Apart from nuclear and hydropower which are highly complementary (nuclear has very large flexibility ranges while hydropower has smaller but faster ranges), among the other dispatchable means, those with the lowest carbon content are gas-fired reactors (high-efficiency combined cycle gas turbines CCGT, ≈ 60 % efficiency, or combustion turbines, ≈ 40 % efficiency). These devices can burn either fossil gas (comprising 95 % methane on average) or "green" methane. Given that there is no industrial limit to building as many such machines as necessary and that they are not very expensive in terms of investment, one could think that, provided "green" gas is burned, they represent a good replacement solution, devoid of CO_2 emissions. Except that this is largely a... delusion because of two factors:

* The limited production potential of biomethane whose overall renewable resource is limited and whose other possible uses (mobility, heat production) are probably more relevant than electricity generation with its maximum efficiency of 60 %. It is unrealistic, then, to rely on this resource to meet the massive needs of the grid.

* The considerable production cost of both kinds of "green" methane compared to the cost of fossil gas, today around 20 €/MWh or less (not including the price per metric ton of CO_2 on the European emissions trading system EU-ETS):

- The cost of biomethane taken into account to evaluate public subsidy is 75 €/MWh while its real cost is currently around 95 €/MWh, i.e. almost 5 times that of fossil gas. In addition, the fact that it is produced in small decentralized units does not augur well for significant cost reductions in the future,

- The cost of synthetic methane obtained by "green" hydrogen methanation is even higher. According to RTE [6], the production cost of "green" hydrogen varies between 3 and 6.7 €/kg depending on the electricity used (off-peak, marginal renewable, nuclear), leading to a minimum of ≈ 91 €/MWh for hydrogen gas. With an estimated overall efficiency of 65 % and an estimated 20 % amortization cost for the transformation facility, the methanation process leads to synthetic methane costing at least 91/(0.65 x 0.8) ≈ 175 €/MWh, this without taking into account the extraction and purification cost of the CO_2 used. This is at least 9 times as much as fossil gas today.

Consequently: under current conditions and with a dispatchable electricity mix comprising 80 % combined cycle turbines and 20 % combustion turbines burning fossil gas, emitting 405 gCO_2/kWh on average, the price per metric ton of CO_2 on the EU-ETS market would have to reach around 185 €/t CO_2 and 385 €/t CO_2 respectively for biomethane and synthetic methane to be economically competitive. Well, the current ETS market price is in the 25 €/t CO_2 range, respectively 7 and 15 times lower than the above values...

These estimates show unambiguously that no utility company can, under present conditions, use "green" methane to produce electricity, barring rapid ruin or massive subsidies, which would then ruin the electricity consumers! In other words, "green" methane does not currently have a viable economic model for the production of electricity. Considerable advances in R&D (improved efficiency) and in industrialization (lower investment costs) would have to be made, the success and timing of which no one can prejudge.

Indeed, this observation has a major strategic consequence: the European countries will massively close down coal or lignite-fired capacity, which is essential to rapidly reduce their CO_2 emissions. However, for the reasons mentioned above, they will have to develop gas-fired capacities just as massively, these being presented by their self-serving promoters as a future carbon-free solution... with the bright prospect of switching to "green" methane... But reality will be quite different: as long as economically viable solutions for large-scale production of this "green" methane are not within reach, mainly, or exclusively, fossil gas will be used; to the detriment of the climate. Meanwhile, "green" methane will have played the role of "false nose" of its fossil counterpart for all those who want to believe in miracles...

✓ Flexibility means using the hydrogen pathway

In view of these observations, the question arises whether it would not be wiser to stick to "green" hydrogen without going on to methanation which greatly increases costs. It is technically possible to use hydrogen directly in slightly modified (mainly the combustion chamber) combined cycle gas turbines CCGT, or in simple combustion turbines, but also in fuel cells. The economic equation is then more favorable since a fuel gas cheaper than "green" methane is put to use. However, this is not a cure-all:

* Unlike "green" methane which can be stored directly in the existing gas network, a considerable economic advantage, only a small proportion of hydrogen (< 5 %, perhaps up to 20 %, subject to validation) can be stored in the gas network. Beyond that, hydrogen has to be stored at very high pressure (to reduce its considerable volume) in specific costly installations. Moreover, its handling is more risky (explosions).

* With a gas costing at least 91 €/MWh and assuming that it is burned in a combined cycle or a fuel cell, both having similar efficiencies of around 60 %, and with an estimated 25 % CAPEX charge for electricity conversion facilities, the cost of producing electricity is at least around 91/(0.6 x 0.75) ≈ 200 €/MWh. This remains very high.

- ✓ **Other flexibility means**

As for the other flexibility means mentioned above, it is unrealistic to expect them to be available by 2030-2035 for the following reasons:

* As pointed out above, large-scale storage/destocking of synthetic gas-based fuels, whether hydrogen and/or "green" methane (Power-to-gas to power) is unlikely to become economically viable before long. This would require doubling their overall efficiency and dividing the investment cost of their facilities by 2 or 3 to gain a total factor of 4 (hydrogen) to 6 (methane) on the price of these "green" gases before they can become competitive. A considerable challenge... It would also be necessary to multiply the wind and photovoltaic capacities to compensate for the enormous losses incurred in these transformations: with current efficiencies, for hydrogen 2kWh have to be produced additionally for each 1 kWh retrieved; for synthetic methane 4 kWh have to be produced additionally for each 1 kWh retrieved.

As for the very often evoked prospect of destocking electricity from car batteries as a backup to the grid, there is no guarantee that the real possibilities of such discharges will be, on the one hand, sufficient in volume and, on the other hand, compatible in time and duration with the instantaneous needs of the grid. The primary objective of car batteries, after all, is to have them sufficiently charged to ensure the next day's carbon-free journeys.

* Finally, thinking that demand withdrawal or deferment can eventually reach a sufficient scale is illusory. Except by... reversing the logic of the electricity system, i.e. moving from a situation where production adapts to demand, to a situation where demand adapts to production... This would be tantamount to asking consumers to kindly wait until production is available to consume! Absurd, of course. This did not prevent ADEME[1] from proposing such a "100 % renewable scenario" at the end of 2018-early 2019.

- ✓ **Summing up the flexibility means available by 2030-2035**

Besides nuclear and hydropower for those countries that have them, the least-bad-for-the-environment option capable of ensuring the indispensable production flexibility is fossil gas which has every chance of developing massively in Europe, "green" methane being far removed from economic competitiveness by that time. Problem: it emits CO_2...

- **Contribute to decarbonizing electricity production in Europe, not only in France**

During periods of high consumption, not necessarily extreme, which coincide with a low wind turbine capacity factor, in particular during the 876 hours per year when the capacity factor falls to less than

---

[1] ADEME - Agence de l'environnement et de la maîtrise de l'énergie - a French public agency that counsels the government on policies regarding energy, environment, and sustainable development.

10 %, especially if this happens when the photovoltaic capacity factor itself is low, or even zero (at night), dispatchable production means will necessarily be heavily solicited. Well, if nuclear capacities are reduced, these dispatchable means can only be, as discussed above, fossil gas power plants, the fossil fuel with the lowest CO_2 emissions. Their emissions would still be very significant for France alone, barring recourse to the CCS (Carbon Capture and Storage) technology which is still very far from the industrial stage and economic sustainability and is very unlikely to be so by 2030-2035.

But there is more to this: in the "merit order" of production means called upon on the grid, nuclear comes just after the "unavoidable" energy sources with zero marginal cost (wind, photovoltaic, and run-of-the-river hydro) thanks to its very low marginal production cost (< 10 €/MWh). Thus, it is, and will be all the more so in the future, called on before any other means based on fossil fuels with their higher marginal cost, which will also include an increasingly high carbon price. This holds for the European electricity markets and not only for France.

Consequently, the premature decommissioning of 12.6 GW French nuclear capacity producing 88 TWh/year of decarbonized electricity amounts to replacing a large part of this electricity in France and/or elsewhere in Europe with carbon emitting electricity, that in all likelihood will be produced from fossil gas in a European fleet that will have an imperative need of dispatchable production means for the reasons detailed above.

An energy mix comprising 80 % CCGT and 20 % combustion turbines running on fossil gas would emit 405 gCO_2/kWh on average. To replace the 14 nuclear reactors, this mix would emit more than 35 million metric tons CO_2 per year in France or in Europe, i.e. significantly more than the entire current French electricity system in the event of a complete substitution.

As a result, the premature decommissioning of 14 reactors will not help the French and European electricity systems move towards the carbon neutrality target by 2050, which implies zero CO_2 emissions for electricity production. It will have the opposite effect: a step backwards! Is this the goal?

5 - Conclusion

Europe (and France...) are pursuing two contradictory objectives:

*** Develop renewable energies massively and forcefully. Unfortunately, the only ones with a large development potential are wind and photovoltaic sources which have the effect of destabilizing the supply-demand balance on the grid,**

*** And at the same time achieve carbon neutrality by 2050... While completely (or partially as in France) depriving itself of the most efficient means of achieving this goal: nuclear power which allows large-scale carbon-free electricity production according to demand and can compensate for grid imbalances due to massive input from variable sources.**

The most likely result at the European level is that those countries that do not have nuclear power or that have withdrawn from it, since they will have to decommission their coal-fired plants for obvious environmental reasons, will have to develop gas-fired plants on a large scale to ensure their security of supply and compensate for the extremely large cumulative variations in their intermittent sources and domestic demand. Now, for the reasons detailed above, this will have to be mainly, if not only, CO_2 emitting fossil gas in the short and middle term. This will thwart the carbon neutrality objective as long as the switch to enough "green" gas is not effective, an uncertain and distant prospect today.

France has the means to do much better, i.e. to completely decarbonize its electricity production (which is already low carbon) well before 2030. This on the twofold condition that it replace its residual fossil production with renewable sources but without more, and that it retain its nuclear capacity, the only carbon-free electricity generation means that allows both:

*** To produce, according to demand, very large quantities at very high powers**

*** To ensure security of supply during critical periods of high winter demand and to compensate throughout the year for the great variability of intermittent production thanks to its flexibility resulting from two factors which reinforce each other: the maneuverability of the reactors themselves and their large number. Consequently, as many of them as possible should be kept running, with the additional advantage of enhancing availability: the impact on the electricity system of an unforeseen reactor outage is smaller if the reactor is one of many.**

Which begs the question: is France going to shoot itself in the foot by prematurely reducing its very valuable capacity just to mimic the rest of Europe? While no rational analysis justifies it? And that this option would entail risks for the security of supply?

Before destroying something that works, in the present case very reliably, one should at least make sure that there are validated alternatives that provide at least equivalent service. Well, there are none, at least in the short and middle term. And the longer term (2050) is, in spite of some illusions, fraught with major uncertainties which, in the present state of our knowledge, do not allow one to deprive the country of a major asset which has proved its worth during its 40 years of well performed duty for the greater benefit of the country... and of the climate. Regarding the latter, now a crucial issue, nuclear power has avoided the emission of over 10 billion metric tons CO_2 from France, that would have otherwise been produced by burning a mix of fossil fuels (1/3 coal, 1/3 oil, 1/3 gas). This corresponds to more than 30 years of the current CO_2 emissions from the entire country.

Finally, although this is not the main focus of this study, some major economic aspects have to be addressed, namely:

*** The extremely competitive production costs of the current nuclear fleet and the incomprehensible financial wastage for the community resulting from the premature decommissioning of installations in excellent working order and recognized as perfectly safe by the Nuclear Safety Authority,**

*** The additional costs induced by the forceful and non-optimal introduction of variable electricity into the networks, this being paid in the last resort by the consumers. This issue is the subject of a separate study by Save the Climate referenced in [7].**

Terms and References

[*] Hydrogen is called "green" in this study if it is produced by electrolysis of water using carbon-free electricity, as opposed to hydrogen obtained through steam reforming of hydrocarbons which generates large CO_2 emissions. Biomethane and synthetic methane obtained via "green" hydrogen methanation are called "green" methane because their production has absorbed CO_2 from the atmosphere (biomethane), or because it would have otherwise been released to the atmosphere by an industrial process (synthetic methane). Their combustion therefore leads to zero net emissions.

Finally "green" gas refers to both "green" hydrogen and "green" methane.

[1] **Électricité: intermittence et foisonnement des énergies renouvelables** - Hubert FLOCARD; Jean-Pierre PERVÈS; Jean-Paul HULOT - TECHNIQUES DE L'INGÉNIEUR - 10/10/2014

[2] **Wind energy in Germany and Europe - Status, potentials and challenges for baseload application: Developments in Germany since 2010** - Thomas Linnemann and Guido S. Vallana - VGB Power Tech

* Part 1 (08/2017): https://www.vgb.org/en/studie_windenergie_deutschland_europa_teil1.html

* Part 2 (11/2018): https://www.vgb.org/studie_windenergie_deutschland_europa_teil2.html

[3] **TECHNICAL AND ECONOMIC ANALYSIS OF THE EUROPEAN ELECTRICITY SYSTEM WITH 60% RES** - By Alain Burtin and Vera Silva - EDF R&D - 17 June2015

[4] **BILAN SÛRETÉ 2018** - RTE

[5] **BILAN PRÉVISIONNEL** de l'équilibre offre-demande d'électricité en France - ÉDITION 2019 - RTE

[6] **La transition vers un hydrogène bas carbone -** Atouts et enjeux pour le système électrique à l'horizon 2030-2035 - JANVIER 2020 - RTE

[7] **« 50% nucléaire »: capacités éoliennes et photovoltaïque et dépenses - Comparaison avec peu d'éolien et de photovoltaïque - Pourquoi 50% nucléaire ? Pour « sortir du nucléaire » ?** Par Henri Prévot (publication pending on the Sauvons le Climat site)

****

Appendix 1: Reactor Outages Due to Exceptional Situations in 40 Years of Operation

Two types of outage have to be considered:

* Technical outages which may be generic in nature and may affect a greater or lesser number of reactors at a given time.

* Outages limited to a particular site, due to external natural aggressions (earthquake, flooding, etc.)

A1.1 - Outages due to generic technical causes

Two important events occurred in this category:

- **Corrosion on vessel closure crossings.**

Corrosion was discovered in the early 1990s on a 900 MW reactor at the Bugey power plant, located at the penetrations on the cover of the reactor vessel. The defect was rapidly identified as being due to a wrong grade of alloy used for these penetrations. Since a new grade of this material had in the meantime been developed and successfully tested in operation on other components, the solution was then to simply replace all of the covers of the reactor vessels (34 for the 900 MW reactors and 20 for the 1 300 MW reactors) with new ones fitted with the new grade of material. This was a very extensive industrial project, but it definitively solved this "teething problem" which, moreover, turned out to be a worldwide issue for reactors of the same technology.

The impact on reactor availability was minimal, however, beyond the approximately one year shut down of the reactor on which the defect was first discovered, because the corrosion phenomenon detected was known and had **a long incubation time and slow evolution**, so that it was possible to **closely monitor** it by specific and very sensitive precursor means. And to program without taking any safety risks, the progressive replacement of the covers at the time of reactor outages for refueling, thus without any significant impact on overall availability.

The efficient handling of this incident can be attributed to in-depth knowledge that had been acquired on the corrosion of materials and on the rapid development of precursor monitoring methods so that the replacements could be spread out safely.

- **Outages required to check the bottom of some recently replaced steam generators**

Surface anomalies concerning excessive carbon content as compared to the specifications were found on the bottom of some replacement steam generators built in France and Japan. This led to an in-depth verification campaign which entailed reactor shut downs to precisely measure the excesses in situ and make sure there were no other metallurgical defects. This being done, the components were validated for safe operation, but it had consequences on reactor availability, with 18 reactors concerned.

However, as these anomalies did not present short term risks, the Nuclear Safety Authority did not require immediate shut downs but asked that inspections be carried out in the near future, within a few months. These started in autumn 2016 and ended in spring 2017, spanning a little over 6 months and allowing to limit global reactor unavailability to 3 or 4 reactors during the critical winter period, from mid-December to the end of February. **In total, then, the maximum overall unavailability incurred was 4 x 900 MW or 3.6 GW at any one time.**

The efficient handling of this incident was made possible by the fact that the anomalies observed had no possible short term impact on safety and were ultimately found not to be harmful in the long term after analysis, subject to reinforced periodic inspections.

A1.2 - Shut downs limited to a particular site

- **History**

Two such shut downs have been requested:

* The shut down of the four 900 MW reactors at the Tricastin plant to proceed with the reinforcement of the Donzères-Mondragon canal dike supplying the plant with cooling water, following the reassessment of the seismic resistance of the dike at a higher level. The reactors were stopped for about one and a half months from early October to mid-November 2017, which represented a 3.6 GW loss on the grid (about 5.7 % of the installed nuclear capacity).

Note that this reinforcement work had to be done without much delay though not with absolute urgency so that it could be programmed at a time of moderate demand without consequences on the country's supply.

* The shut down of four 900 MW reactors at the Cruas plant (one of which had already been shut down for maintenance) following the Tiel earthquake on November 11, 2019. The plant withstood the earthquake perfectly but its sensors having recorded the tremor and because its epicenter was so close, safety considerations led to in-depth inspection resulting in an unavailability of about one month. As in the Tricastin case, the loss for the grid was 3.6 GW.

- **Overall unavailability**

As the 19 reactor sites are spread over the territory, a common cause liable to bring about a **complete and simultaneous** shut down of several plants at the same time has very low probability. The largest impact can thus be reasonably set as the total shut down of one of the largest production sites, either Gravelines (six 900 MW reactors) with 5.4 GW or one of the two sites (Paluel and Cattenom) with four 1300 MW reactors or 5.2 GW.

A1.3 - Duration of the associated production losses

They are summarized in the table below and expressed in years x reactors:

Cause	duration (years x reactors)	
Corrosion on penetrations on the cover of the reactor vessel	≈ 1 (1)	**Total ≈ 3.3**
Excessive carbon content on steam generator bottoms	≈ 1.5 (2)	
Shut down for canal dike reinforcement at Tricastin	≈ 0.5 (3)	
Post earthquake in-depth inspection at Cruas	≈ 0.3 (4)	

(1): One reactor shut down for ≈ 1 year - non recurring event (growing pain)

(2): 18 reactors shut down successively for ≈ 1 month - non recurring event (lesson learned)
(3): Four reactors shut down for ≈ 1.5 months - non recurring event (one of a kind)
(4): Four reactors shut down for ≈ 1 month

Overall, these exceptional reactor shut downs amounted to about 3.3 reactors x years which, compared to over 2000, represents a less than ≈ 0.2 % unavailability rate over a 40 year period, a very small rate that proves the reliability of this fleet.

Appendix 2: Dispatchable Capacity Deficit Due to the Decommissioning of Fourteen 900 MW Reactors

The installed capacity of fourteen 900 MW nuclear reactors is: 900 x 14 = 12 600 MW or 12.6 GW.

* In terms of **annual output**, with an average availability of 80 %, they supply about 88 TWh,

* In terms of **guaranteed dispatchable capacity**, the periodical reactor outages are scheduled to ensure that maximum power is available during the 3 coldest winter months (December, January, February) which leads to an availability of between 90 % and 95 %. Here, we will assume that one of the 14 reactors is not available, which corresponds to a realistic 92.8 % availability for this period, and an available capacity of 11.7 GW.

With a renewable fleet consisting (to simplify) of equal installed capacities for onshore wind (with an average 23 % capacity factor in France) and photovoltaic (with an average 13 % capacity factor in France) the fleet's average capacity factor is (23 + 13)/2 = 18 %. Under these conditions, the overall installed capacity needed to produce 88 TWh/year is:

88 000/(8760 x 0.18) ≈ 56 GW of which **28 GW** wind and **28 GW** photovoltaic

The maximum power output from this 56 GW fleet at night (photovoltaic capacity factor naturally zero) can then be evaluated in low wind situations for several residual wind capacity factors:

Residual wind capacity factor (%)	10 %	5 %	1 %
Residual capacity of the wind + photovoltaic fleet (GW)	2.8	1.4	0.3
Power deficit relative to the 14 reactors **1 being unavailable** (GW)	**8.9**	**10.3**	**11.4**
Power deficit relative to the 14 reactors **6 being unavailable** (*) (GW)	**4.4**	**5.8**	**6.9**

(*) assuming unavailability of all reactors in the largest facility (cf. Appendix 1)

In this table, we show that replacing 12.6 GW of nuclear with 56 GW of wind + photovoltaic reduces the power available on the grid by 9 to 11 GW depending on the wind residual capacity factor (less than 10 % in any case) compared to the 14 reactors with "normal" availability at this time of year. Well, this happens 10 % of the time on average, or 36 days per year with, statistically, 9 days in the coldest months of the year (December, January, February) when nights are long and photovoltaic production, non-existent at night, is low in the day time. In case of concomitant near absence of wind and intense cold inducing very high demand, this power reduction is simply critical for the country's power supply and has a very high chance of leading to extended power outages.

NB: even supposing that of these 14 reactors, **6 are unavailable during these critical periods,** the wind power deficit would still lie between ≈ **4 and 7 GW**, still a very large amount.