

# The impasse of "100% renewable" electricity systems

## Summary and Conclusions

The introduction into electricity grids of wind and solar photovoltaic sources has two major technical impacts: on the one hand, it implies a radical change in the mode of coupling to the grids, which becomes electronic and constitutes a real technological revolution, and on the other hand, their variable and intermittent nature very strongly disrupts the essential balance at all times between the production and demand of electricity. The imbalances generated are far beyond the capabilities of the means usually used to restore balance between production and demand only and require new balancing means acting on different time scales, including much shorter ones.

These two impacts profoundly change the nature and operation of electricity systems to the point of raising two essential questions, one technical, the other economic when the share of variable and intermittent sources increases and approaches 100% of the production mix:

**1) Is such an operation physically and technically viable in terms of security of electricity supply?** This question is all the more crucial as carbon-free electricity is set to become the very dominant source of energy in 2050. However, no certain answer to this question, validated by experience in the operation of real grids, exists at the moment as no major grid is working in this way in the world. Solutions are certainly being devised to make them work, based on the addition of "technological crutches" but they are not all proven. They reduce uncertainty without eliminating it, as new issues are likely to emerge due to the resulting technological complexity which only real operating experience can dissipate. Betting on these solutions is therefore still a matter of GAMBLING. It involves strong uncertainties about operational safety and clearly increases the risk of blackouts. Is this acceptable? These issues are presented and discussed in the first part of this study. But even if we manage to make such grids work technically, their economic cost raises a second major issue, as electricity is a basic necessity.

**2) Will the electricity produced have a cost that is sustainable for the economy and society?** This is a vital question for a developed country, especially since electricity is set to become the dominant carbon-free energy of the future, replacing fossil fuels. However, from this point of view, the very large structural and functional complexity of a "100% renewable" electricity system is not in favor of economic efficiency. This is shown in the second part of this study, which compares from an economic point of view two electricity mixes supplying the same demand, one based on "100% renewable" energies with about  $\approx 93\%$  wind and photovoltaic production on average per year; the other replacing this production with nuclear power.

**The result is unambiguous: the electricity produced by a "100% renewable" mix with a very high penetration rate of wind and photovoltaic power ( $\approx 93\%$  here) is more than twice as expensive ( $\approx 2.3$  times) than that produced by a predominantly nuclear mix, the latter being calculated on the basis of the current investment cost of new nuclear power plants in France (that of the EPR2 reactors).**

This result is **consistent** with that of the 2019 NEA-OECD study [1] which concludes that when the penetration rate of wind and photovoltaic in an electricity mix reaches  $\approx 75\%$ , the cost of electricity is multiplied by about  $\approx 1.9$ .

**It should be added that the "100% renewable" mix studied cannot work without massive imports of carbon-free hydrogen, creating a problematic geostrategic dependence in a dangerous world, whereas the nuclear mix is autonomous and can on the contrary export carbon-free hydrogen.**

**3) In summary, the above results raise major strategic questions: in addition to the technical uncertainties that remain to date, which might be overcome, the economic balance of a "100% renewable" mix leads to an unsustainable cost of electricity for developed countries with significant**

energy needs, in particular for industry and the purchasing power of citizens, the consequence of which would be a decline suffered with considerable social and societal impacts. This conclusion holds in a temperate geographical and climatic context with marked seasons, cold winters with little sunshine typical of most European countries.

Is the present study theoretical? Not really: a "100% renewable" mix in 2050 is still being considered by Germany following the country's decision to phase out nuclear power. Despite the recent recognition by its leaders that this choice was a "strategic mistake", a return to nuclear power does not seem to be on the agenda. Europe has also made this choice its mantra. Even if the President of the Commission also recently acknowledged this same "strategic mistake", she continues to advocate mixes with very little (too little) nuclear power in Europe, in 2050.

Furthermore, thanks to the analysis tool used, the principle of this study can very easily be extended to any share of variable and intermittent renewables in an electricity mix. Shares of less than 100% will certainly lead to lower additional costs than in the present case, but the costs will remain a strongly increasing function of these shares, as the aforementioned NEA study has shown. In other words: the more nuclear generation there is in the mix, the cheaper the electricity is.

The above conclusions, however, cannot be extrapolated without caution to countries whose geographical, climatic and socio-economic conditions are very different, for example in the intertropical zone, which has more intense sunlight and less marked seasons.

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## **Part 1: Is "100% renewable" technically viable according to the laws of physics?**

### **The only large-scale primary energy sources available**

First, it should be remembered that there are only three types of renewable primary energies that are abundant enough to produce on a large scale the electricity necessary for large modern electricity system: hydraulic energy, which has evolved from ancient water mills to modern high-power hydraulic turbines; wind energy which has progressed from the famous windmills of Don Quixote to modern wind turbines; the sun's energy, by far the most abundant of all, mainly captured thanks to the photovoltaic effect discovered in 1839 by Edmond Becquerel, but which is only recently exploited to produce electricity on a large scale.

Several other renewable primary energy sources can also be used to produce electricity: biomass; deep geothermal energy at sufficiently high temperatures; marine energies (tides, sea currents, waves, etc.)

and a few others. But all these energies have limited production potential, their resources are essentially local (biomass, deep geothermal energy, ocean) and some are very costly to exploit (marine energy). Biomass and deep geothermal energy also have more relevant applications for producing heat directly. This is also the case for solar energy used directly for the production of hot water.

So let us go back to the three main primary renewable energy sources that can be used to produce electricity. Their intrinsic characteristics are different and their conversion into electrical energy involves different pathways. They can be classified into two subcategories:

\* Hydropower is a **stock** energy (that of high-altitude lakes) or a **flow** energy (waterway throughput) the latter being relatively stable in the short term. It is captured by conventional means, turbines that drive generators, directly coupled to the grid at 50 Hz. This makes it mostly "**dispatchable**", i.e. the power can be adjusted at will by opening the water intake valves more or less. This is an extremely valuable quality to meet a demand for electricity adapted to human needs.

\* Solar and wind energies are very low-density **flow** energies, and, more importantly, they vary in high proportions on the scale of the day and sometimes of the hour: this is obvious for the sun with the alternation of day and night and it is observed for the wind: when its speed is too small (less than 5 to 10 km/h) the wind turbines stop or rotate producing practically nothing. When it is too strong, they must be stopped for safety reasons. These energies can therefore be described as "**variable and intermittent**".

We can to a certain extent anticipate their power thanks to increasingly precise meteorological data, but on the one hand this precision has limits that remain haphazard, and on the other hand and above all we cannot modify their power, except downwards by stopping the machines. These are therefore mainly fateful energies that make the management of electricity systems much more complex. This is why they are described as "**non-dispatchable**".

There is, however, a second major difference compared to hydropower: these productions are not coupled to the grid by generators, but by electronic means (electronic power inverters) which obey physical laws that are very different from those of synchronous generators. This is a necessity for photovoltaic panels that produce direct current that must be transformed into alternating current at 50 Hz. It is a choice for modern high-power wind turbines whose rotation speed is varied according to the wind speed, in order to optimize the capture of the instantaneous power of the wind. The rotor of the wind turbine does drive a generator, but as its rotation speed varies, it delivers a variable frequency and therefore cannot be directly coupled to the grid at 50 Hz. This variable frequency alternating current must therefore be transformed into direct current, then transformed back into alternating current, at 50 Hz, as with photovoltaics.

Replacing synchronous generators with electronic devices has several major consequences on grid operation, in particular in terms of stability and control, and consequently on the security of electricity supply, as discussed below.

## Synchronous generators, the technological basis of three-phase AC power grids

Since Nikola Tesla's brilliant invention of the three-phase generator in 1891, three-phase alternating current grids have spread worldwide. Until the end of the past century, alternators (synchronous generators), whether driven by turbines (hydraulic, steam or gas) or by diesel generators, have held a monopoly on supplying power to grids: alternators are indeed capable of "**forming**" the grid **in a resilient and secure manner**, both in frequency **f** and in voltage **U**, and of maintaining these two critical parameters within the narrow limits required (to give an approximate idea, less than  $\pm 1\%$  for frequency and less than  $\pm 5\%$  for very high voltage grids to less than  $\pm 10\%$  for low voltage grids).

As a reminder, in steady state operation an alternator has **two synchronous rotating magnetic fields** linked together by very powerful electromagnetic torques that transmit power from the rotor to the stator:

\* The rotor's **inductive rotating field**, perpendicular to the rotor's axis of rotation, is created by a winding embedded in the rotor and supplied with a direct current the intensity of which can be adjusted at will.

\* The rotating field induced in **the stator**, also perpendicular to the rotor's axis of rotation, is created by the passage of the **rotor's inductive field** across the stator windings. This interaction generates two physical phenomena:

- Electromotive tensions in the stator windings, according to the Lenz-Faraday law. These electromotive tensions in turn generate **the voltage delivered to the stator of the generator which directly supplies the grid**. This voltage is adjusted by varying the intensity of the inductor current: if it is increased, the voltage increases and vice versa. This is the primary means of adjusting the voltage in power grids.

- The so-called Laplace electromagnetic forces between the rotating magnetic field of the rotor and the currents that flow in the stator windings, which **couple the rotating fields of the stator and the rotor and thus make it possible to transfer the mechanical power (brought to the rotor by the primary energy source used) to the electrical power generated in the stator**.

This very powerful coupling also gives the generators the essential ability to **operate together in a perfectly synchronous and stable way on the same grid**: they are all firmly "locked" to the grid and any frequency variation in the grid is immediately transmitted to all the generators connected, which consequently see their rotation speed vary in strict proportion to the frequency of the grid, while remaining perfectly synchronized with one another. Each imbalance between production and demand results in a variation in the frequency of the grid (upwards in the event of excess production, downwards in the event of a deficit). It is essential to restore the balance rapidly to avoid the collapse of the grid. The balancing of the overall grid power being distributed among all the coupled generators, the unit contribution of each is minimal. This regulation is essential to ensure grid stability and resilience to contingencies.

The rotors of the turbo-generators also provide the grid with their **mechanical inertia**, which has two stabilizing effects:

- Dampen rapid grid frequency changes.

- Build up a reserve of kinetic energy whose variations, during changes in the rotational speed of the generator rotors - that is, during changes of grid frequency - naturally compensate for variations in the grid's electrical energy, according to the energy conservation principle: when the frequency drops, the reduction in the rotors' kinetic energy is transferred to the grid, temporarily supporting its electrical energy and therefore its frequency.

These two stabilizing effects give the power control of the machines that drive the generators time to restore:

- Firstly, the balance between production and demand in terms of instantaneous power.

- Secondly, the nominal frequency value of 50 Hz.

This means that the grid **frequency** is regulated by the **power** of the turbines that drive the generators. This is why we speak of frequency-power balance.

Inertia thus plays an irreplaceable role: **no three-phase alternating current system can operate without sufficient inertia**. This inertia comes mainly (> 80%) from the production means based on synchronous generators and secondarily (< 20%) from rotating loads (electric motors) connected to the grid. The latter can in no way be sufficient, especially since these motors operate intermittently depending on their use, this being unpredictable as seen from the grid.

## **The technological revolution of electronically coupled production means**

This is indeed a revolution insofar as we move from the laws of electromagnetism, rational mechanics and thermodynamics, to the very different laws of software-controlled power electronics. The fundamental question is therefore to determine to what extent new grids using only electronic means that simulate synchronous machine operation are viable, first physically, second economically.

**First of all, it should be noted that no major operational grid based exclusively on power electronics is currently being operated in the world**. In addition, the inverters currently used are "**grid-following**" inverters: they imperatively need formed grids both in frequency **f** and voltage **U** to inject their power,

because they do not have the capacity to form these two parameters themselves, hence their name. To date, the large grids are still all "formed" by synchronous generators. But what will happen when these generators become too scarce in a grid to be able to "form" it robustly enough?

To answer this question, which will arise in grids with a very large share of wind and photovoltaic sources, it is planned to use so-called "**grid-forming**" inverters, capable of autonomously generating a frequency and a voltage as synchronous generators do. Their technology is known and proven and commonly used to drive variable speed synchronous motors, but this is a simple case: a single "grid-forming" inverter powers a single motor.

But what will happen when it comes to building large grids, involving the use of a very large number of "**grid-forming**" inverters working together? Will they be able to operate in a stable and safe way, like synchronous generators? The answer to this question is not yet completely certain, neither theoretically, nor even less so experimentally for large real-world operating grids. Yet, this is a major strategic issue because it conditions the physical viability of future large grids with very large shares of wind and photovoltaics, in electricity mixes that can include up to 100% renewable means, with a very small share of remaining hydropower and biomass which still drive a few synchronous generators, but whose contribution to the stabilization of the grid then becomes very insufficient.

This amounts to raising the question of the extreme case of a grid comprising only wind and photovoltaic sources coupled to the grid by a mix of "grid-forming" inverters, theoretically capable of forming the grid, and "grid-following" inverters which only provide power. Can such a grid be physically viable? Several elements of appreciation:

\* Like synchronous generators, "grid-forming" inverters certainly have the theoretical capacity to create **three-phase electric wave systems** of a given frequency  $f$  and a given voltage  $U$ . But their characteristics differ profoundly from those created in the **stators** of generators, given **the absence of coupling with a rotating magnetic field transmitting mechanical energy and inertia** (that of the rotors of the synchronous generators). This has several major consequences:

° First difference as compared to synchronous generators: **the voltage waveforms have no inertia of their own**, so that a grid comprising only inverters **has as its only inertia the rotating loads it supplies** (industrial motors in particular). But, as noted above, this inertia is very small and not constant, while no three-phase alternating current grid can operate stably without sufficient inertia. The physical reason for this statement is simple: in the event of the loss of a means of production that abruptly disrupts the balance between production and demand, the frequency of a very low-inertia grid varies almost instantaneously, in a few fractions of a second. No known means of power injection is fast enough to compensate for this loss: the fastest power injection, from a [battery + inverter] combination requires about one second. This is fast, but much longer than the time it takes for the frequency to collapse. The same goes for ultra-rapid industrial load shedding, another way to restore the balance of power very quickly. It is subject to the reaction times of the frequency measurement relays, plus the response times of the circuit-breakers, which are also too long. As a result, the grid frequency collapses very quickly and very deeply and can then exceed the permissible safety limits leading to the collapse of the grid (blackout). This phenomenon is quantified by the value of the **RoCoF** (Rate of Change of Frequency). It is proportional to the power lost and inversely proportional to the inertia of the grid. It is expressed in Hz/s. ENTSO-E has demonstrated that this parameter must remain **below 1 Hz/s** on the European grid to avoid a blackout (for example, it reached 1.6 Hz/s on the Spanish grid during the April 28, 2025, blackout).

There is, however, an effective and well-known solution to bring inertia to a grid: equip it with a large number of **synchronous condensers**, which are nothing more than synchronous generators coupled to the grid and run idle, i.e. without providing a motor torque. But they provide the same services as production synchronous generators in terms of inertia input and grid voltage adjustment. **We thus return de facto to a grid formed by synchronous machines, except that power is no longer provided by turbines but by electronic inverters.** This conclusion also applies to grids with very high shares of wind and/or photovoltaic production and very few residual synchronous generators using renewable primary energies from hydropower and/or biomass. Their inertia is not sufficient and it is imperative to add that of synchronous condensers.

° Second difference as compared to synchronous generators: the "grid-forming" inverters coupled to the grid are not firmly "locked" to the grid frequency by powerful electromagnetic forces as are synchronous generators. Yet, **there can be no difference whatsoever between the frequency they deliver and that of the grid**. This implies that the "grid-forming" inverters also operate in "grid frequency following" mode, since the frequency is not controlled directly but by adjusting the **balance between the power produced and the power consumed**. Thus, their ability to "form" the grid in terms of frequency depends on their **ability to modulate their power based on an internal frequency reference**, either local or remotely controlled, a property that "grid-following" inverters do not have. This is still not enough to guarantee with certainty upward power variations with inverters powered by variable and intermittent primary energy sources, whose upward variations are not guaranteed (for example, there may be a decrease in wind speed at the time when the inverter of a wind turbine is asked to increase its power). For this reason, it is imperative to add **battery-powered** inverters, which provide **stock** energy available at all times and thus guarantee power increases when needed, but only for a limited time (that of their discharge).

° Third difference as compared to synchronous generators: the challenge of numbers. The current French grid is "formed" mainly by less than a hundred large nuclear and hydraulic turbo-generators. In contrast, wind and solar farms liable to provide power on a close to 100 % renewable grid would require a very large number of inverters due to their lower unit capacities. This raises the issue of coordinating the power management of a large number of "grid-forming" inverters distributed over a vast territory and having different responses depending on whether they are powered by wind turbines, photovoltaic panels or batteries. Two kinds of risk should be anticipated:

- From the grid operation point of view, the risk of power oscillations between inverters that are more or less far apart due to insufficient or defective overall coordination.

- From the inverter remote control point of view, a very large complexity implying the use of complex software and AI (Artificial Intelligence), given the very short response times required.

These phenomena are extremely complex and difficult to pre-empt and only experimentation on real grids can guarantee their proper handling, with the difficulties that this poses on grids that must continue to ensure their main function i.e., supplying consumers.

° Fourth difference as compared to synchronous generators: cyber-resilience. A synchronous generator that operates at very high energy is inherently cyber-resilient. On the contrary, an inverter whose core internal functioning is digital is intrinsically cyber-vulnerable and its protection is complex, especially since it must be controlled remotely, either to regulate its power, to monitor its operation, or to update its software. In addition, their large number on large grids multiplies the possible entry points. Of course, cyber-protection countermeasures exist, but can we absolutely guarantee their effectiveness? There is room for doubt, knowing that a successful cyber-attack could have considerable consequences, going so far as to put an entire region or even one or more countries in the dark.

**In summary, apart from the crucial issue of inertia, for which there is a known, proven and functionally effective solution, namely synchronous condensers, which also have the very valuable ability to be able to regulate the voltage, another critical parameter of grid frequency stability. The use of "grid-forming" inverters raises many new and very complex issues that are still at a stage of theoretical feasibility and are therefore far from being proven on large real-life grids. Currently, this situation still amounts to a GAMBLE.**

However, a solution can be considered to overcome this situation i.e., to "duplicate" the grid comprising "grid-forming" and "grid-following" inverters that provide energy when there is wind and/or sun, with a second grid serving as the "backbone" of the electrical system, comprising on the one hand a large number of synchronous condensers providing synchronizing inertia to stabilize the frequency and the tension, and on the other hand a large number of batteries capable of providing sufficient instantaneous additional power at all times, which cannot be done by wind or solar energies. The result is a very complex solution that could perhaps work thanks to AI-based management, essential to manage this complexity in real time. A question still remains concerning the level of safety achieved compared to the current very high level obtained with synchronous generators: the more complex a system is, the more numerous its vulnerabilities and compensating for them adds even more complexity, which in turn adds other vulnerabilities... It cannot therefore

**be ruled out that the overall level of operational safety could deteriorate, leading to increased risks including that of blackouts.**

Finally, another aspect cannot be neglected: such complexity is necessarily very costly in terms of investment and also operation, ultimately resulting in an extremely high electricity price, as shown below in the second part of this study.

## Compensation for production variability and intermittency

This is the second major problem posed by wind and photovoltaic production. The result is, concretely, **under** - or **over** - production that destabilizes the grid; The demand can be made somewhat flexible, that is can **partially be adapted** to the existing production, but only within limits as compared to the considerable amplitude variations of these productions as soon as their share in the mix becomes significant (to fix ideas, starting from 10 to 15% of the total production).

- **Compensation for wind and/or photovoltaic production shortfalls**

Two complementary basic solutions exist to compensate for the variability and intermittency of these productions in the event of **production shortages**:

\* Use dispatchable back-up means based on existing primary energy **stocks** (mainly fossil gas, because of their fast response time, or hydraulic means). But with a view to decarbonizing energy, fossil gas will have to give way to hydrogen produced by water electrolysis with no CO<sub>2</sub> emissions.

\* Use **energy storage/destocking**, keeping in mind that electricity cannot be stored as such (except in very small amounts) and must be transformed into another form of energy that can be stored and then transformed back into electricity as needed. The "electricity storage" expression commonly used, is physically inappropriate; it actually refers to a chain of physical transformations such as:

Non-dispatchable electricity → **Storable/destockable energy** → Dispatchable electricity

Four main parameters characterize the "electricity storage" means: the overall **efficiency** of the physical transformation chain above; the overall **volume** of storable energy; the **duration** of storage that is physically possible or economically acceptable; and the destocking **response times** to produce electricity anew.

\* The two compensation solutions mentioned above are essential to compensate for decreases or shortfalls in wind and/or photovoltaic production on all time scales, ranging from about one **second** to guarantee the instantaneous power balance of the grid, to the **day** to compensate for the day and night intermittency of photovoltaics, and up to **one to two weeks** to compensate for a long-term lack of wind (very weak wind, a phenomenon observed in Europe every year, in seasons that can vary, the winter period of high demand being the most challenging).

Three main means of storing/destocking carbon-free energy are currently used or considered:

° Energy storage in the form of hydraulics in PHEs plants (Pumped Hydroelectric Energy Storage), a historical means that has been tried and tested for a long time, with an overall efficiency of around 70 to 75% and a significant energy storage capacity, but that is difficult to expand. Their typical storage time ranges from a few hours to a few days depending on the characteristics of the PHEs. However, they can be built only in suitable geographical locations, with sufficient differences in height and the possibility of building large capacity upper and lower reservoirs.

° Energy storage in electrochemical batteries. This is being developed at high speed with the technological advancements of batteries and their easily expandable storage capacity. Their overall efficiency is very high, in the range of 85 to 90%, and their discharge response times are very short. However, given their high investment cost, they must be charged and discharged very frequently, if possible, several times and at least once a day in order to be economically viable. Thus, these batteries address very short storage times, on the order of 1 to 4 hours for the best ones to give an idea.

° Energy storage in the form of combustible gases, the most efficient of which being hydrogen, which can store very large quantities of energy over the long term. But this type of storage suffers from a very poor overall conversion efficiency, at best 35%. In concrete terms, this means that in order to obtain 1 MWh of dispatchable electricity destocked, it is necessary to have previously consumed about 3 MWh

of non-dispatchable electricity. This storage mode, then, should be used only when the previous two are insufficient. It is also called "power to gas to power" or "P2G2P" for short.

- **Management of excess wind and/or photovoltaic production**

This is the second problem posed to electricity grids by these electricity production means, bearing in mind that the balance between production and demand is essential and must be respected in every instance: production surpluses raise the frequency above its permissible limits and are as unacceptable for grid security as production shortages that cause it to decrease.

These excesses are due to **the very large differences between the peak installed power of photovoltaic panels and wind turbines and their average annual power outputs**. Thus, with sunshine and weather conditions in France:

\* 1 kW of installed photovoltaic power produces an annual average of about 0.15 kW and between 0.8 and 0.9 kW of peak power in strong summer sunshine, at solar noon  $\pm$  3 hours, i.e. 5 to 6 times more than the average annual power. It is worse in Germany where the average annual power is only 0.1 kW while the peak power is still 0.8 to 0.9 kW during the best summer sunny hours.

\* 1 kW of installed wind power capacity produces an annual average of about 0.24 kW onshore and 0.37 kW offshore and about 0.75 kW of peak power, i.e. about 3 times more than the average annual power on land and twice more offshore.

By comparison, 1 kW of installed nuclear power produces an annual average of more than 0.9 kW if the plant operates in baseload, and between 0.7 and 0.75 kW if it has to modulate its power as is currently the case in France.

These figures show that in order to produce the same average annual power, i.e. the same annual energy, the installed power must be very large for wind power and even more so for photovoltaics. For the latter, the very large difference between its average annual power and its possible peak power (multiplication by 5 to 6 in France, see above) has the major consequence of generating very large production during the entire period of strong sunshine. These become impossible to absorb on the grid whether by the demand and/or by the storage, and they cannot generally be exported insofar as the neighboring countries are mostly very sunny at the same times. These unusable surpluses have two major negative consequences in France:

\* **They force dispatchable means, particularly nuclear power, to sharply reduce their production.** This operation of nuclear production units comes up against two limits: on the one hand, those imposed by the grid, insofar as these units are **essential in guaranteeing the frequency and voltage stability** of the electricity system, and on the other hand, their own technological limits in terms of the daily number and the amplitude of the power modulations; currently the total modulation amplitudes of nuclear means reach 20 to 25 GW within a few hours.

\* **They lower the electricity spot market prices to zero or negative.** This makes the production of dispatchable means, particularly nuclear, less profitable, as they are forced to sell their electricity at a loss since they must remain connected to the grid to guarantee its stability, as discussed above. Also, this obligation is currently not compensated financially at its fair value. This is not sustainable. At any rate, these reductions in the production of dispatchable means are no longer sufficient to ensure the production-demand balance and since 2024 it has been necessary to curtail photovoltaic production more often and increasingly deeply around meridian hours. The phenomenon can only worsen as long as demand does not increase if we continue to develop photovoltaic installations recklessly.

The same problem also applies to wind power, even if it has a slightly smaller impact, on the one hand because wind surpluses are less excessive (factor 3 compared to the annual average for onshore wind and factor 2 for offshore wind, see above) and on the other hand because wind surpluses are better distributed throughout the year, occurring mostly in winter, a period of high demand, instead of being concentrated in the period of maximum sunshine, a period of lesser demand.

To conclude on this issue, the multiplication of surplus fateful photovoltaic or wind electricity, which is unusable because it cannot be consumed, stored or exported and therefore imposes sharp load shedding, not only has major consequences on their profitability, but also calls into question the remuneration methods of wind and photovoltaic production, knowing that currently their necessary

curtailment is largely remunerated in France. Ultimately, this increases the price of electricity for consumers. With the multiplication of these productions, the financial compensation of their curtailment will no longer be sustainable and a review of the overall remuneration of these resources is mandatory. This is an operation with high financial and contractual stakes that must be anticipated as of now.

## **Part 2: Economic analysis. Is "100% renewable" sustainable for the economy of European countries?**

### **Assessment of the additional costs of "100% renewable" grids**

These additional costs mentioned in the first part of this study are mainly of three types:

\* **The cost of the additional "technological crutches"** essential to guarantee grid stability and functional security: synchronous condensers, instantaneous power balancing batteries, complexity management using AI, cybersecurity that it is much more difficult to guarantee, etc.

\* **The cost of the means aimed at compensating for the variability and intermittency** of wind and photovoltaic production, i.e. at guaranteeing at all times a quantitatively sufficient and secure supply of electricity. These are subdivided into two main categories:

° Energy storage/destocking means for different amounts and durations of storage: hourly and intra-day (batteries, PHES); infra-weekly (PHES); long-term seasonal storage, particularly from summer to winter (hydrogen). **It should be noted that energy destocking is equivalent to a dispatchable means of electricity production, but only within the limit of its available stock at the time it is requested.** This limit is obviously a strong constraint.

° Conventional dispatchable means provided that they can do power modulation. In a system close to "100% renewables", there is generally little left to do this except the hydraulics of lakes or dams, which are strongly linked to the geographical characteristics and rainfall of the country concerned. However, these resources must be quantitatively sufficient, which remains the exception (Norway in particular). **In the present study, these additional costs are mainly those of hydropower, and they are the same in the two mixes considered.**

° The additional costs of managing the electricity system following the introduction of AI and much more complex reinforced cybersecurity protections. **These additional costs are not evaluated in the rest of this analysis.**

\* **The additional grid costs**, due to the increase in the number of power lines and substations needed to connect wind and photovoltaic sources, which are by nature spatially diffuse. Whether it is a very large number of small or medium-sized onshore installations or the connection of large offshore wind farms, the costs of the grids required to connect them are very high.

### **Methodology for estimating additional costs**

The methodology is based on the following principle, data and assumptions:

\* **The principle**: it consists in **comparing two different production mixes** capable of satisfying the same consumption of around **≈ 900 TWh/year**, including grid energy losses, i.e. an average daily power of **≈ 103 GW**, able to reach a peak value of at least 150 GW, or even 190 GW in exceptional circumstances. These values roughly correspond to the estimated consumption in Germany in 2045 according to the EEG 2023 law [2] [3] and in France in 2050 (RTE's maximum estimate to date).

The two mixes compared also have the following overall characteristics (see detailed characteristics in **Appendix 1**):

° **"100% renewable" mix** taken from the above mentioned estimated German 2045 mix according to the EEG 2023 law [2], including a very small share (**≈ 7%**) of production coupled via partially dispatchable synchronous generators (hydro and biomass), the rest of the production (**≈ 93%**) coming from wind, onshore and offshore, and photovoltaics, non-dispatchable, with a total installed capacity of **630 GW**. There are also production facilities running on carbon-free hydrogen (to produce carbon-

free electricity) with a capacity of around **150 GW**, intended to meet peak demand. However, the hydrogen produced in-house by this renewable electricity mix is not sufficient and **large hydrogen imports are explicitly planned (the considerable infrastructure related to these imports is assumed to exist outside the electricity system and is therefore excluded from the present study. The question is resolved by considering the price per MWh of imported hydrogen).**

° **Comparison mix with a predominantly nuclear power supply** with exactly the same share of hydropower and biomass as the previous one ( $\approx 7\%$  in annual production), but without wind or photovoltaics. The majority of production ( $\approx 93\%$ ) is then provided by nuclear power, with an installed capacity of **130 GW**. This mix also requires a minimum use of carbon-free hydrogen to meet peak demand, but the assumption is made here that this **hydrogen is produced exclusively internally by the nuclear-based electricity system, excluding any imports for sovereignty reasons. This is a strong and structuring hypothesis that involves increasing nuclear production capacity by a few GW.**

° In both cases, hydrogen is used by means such as CCGT (Combined Cycle Gas Turbine) and OCCT (Open Cycle Combustion Turbine) whose installed capacities are adapted to each mix and operate in the energy conversion chain known as "power to gas to power" or "P2G2P".

° Finally, the assumption is made that these mixes operate in **electrical autonomy, without electricity imports or exports**. This can result in either surpluses that can be used to produce carbon-free hydrogen **exported outside the electricity system** (in the case of the predominantly nuclear mix), or deficits that are then addressed by **imports** of carbon-free hydrogen (in the case of the renewable mix).

#### \* **Energy storage/destocking efficiency data**

Energy storage/destocking systems are essential in all electricity mixes. Their necessary capacities are limited in mixes with a strong nuclear component but become very important and crucial in mixes with high shares of wind and photovoltaics in order to compensate for their very large temporal power variations. The efficiencies of these storage systems are of paramount importance because they have as a counterpart energy loss that must be **produced** additionally from wind and/or photovoltaic sources, increasing their necessary installed capacities. Three main types of storage/destocking are considered here, the characteristics of which are summarized in the following **Table 1**:

Energy storage/destocking type	Overall storage/destocking efficiency	Possible or optimal storage time	possible amount of energy stored
Electrochemical batteries	$\approx 85\%$	A few hours or < 1 day	$\approx$ Significant
PHES	$\approx 70\%$	A few hours or a few days	$\approx$ Significant
Carbon-free hydrogen	$\approx 35\%$ (1)	A few days up to months	Very significant

(1) P2G2P chain of yields: electrolysis  $\approx 60\%$ ; H2 used in a CCGT  $\approx 60\%$ ; H2 used in an OCCT  $\approx 40\%$ ; energy-weighted average with 90% CCGT and 10% OCCT  $\approx 35\%$

**NB:** the energy losses of batteries and their electronics ( $\approx 15\%$ ) and PHES ( $\approx 30\%$ ) remain moderate and therefore have little economic impact. This is not the case for hydrogen storage, which practically requires the production of  $\approx 3$  kWh of electricity to recover 1 kWh destocked. **The economic impact is therefore major in mixes with a very high share of wind and photovoltaics.**

#### \* **Unit cost data of the means of production for the two mixes**

They are summarized in the following **Table 2**:

Means used for electricity production	CAPEX (Capital Costs) in €/kW installed	OPEX (Fixed annual operating costs) in €/kW/year	OPEX (Variable annual operating costs) in €/MWh	Duration of operation (years)
Nuclear	7 750	103	9	60
Fixed offshore wind	4 010	118	0	25
Onshore wind	1 672	39	0	25
Ground-mounted photovoltaics	1 076	22	0	25
Rooftop photovoltaics	1 076	59	0	25
Batteries (1) (2)	243 €/kWh	10	0	12

Electrolyzers (2)	2 000	50	0	20
Gas Combined Cycle (CCGT)	1 242	47	(3)	20
Combustion Turbines (OCCT)	925	23	(3)	20
Hydrogen Storage (4)	0.8 €/kWh	-	-	-
Inertia Input (5)	€500 million for 1 GVA x 5 s	15	-	60

**NB:** we must add to this table the price of imported hydrogen, which is set at €5/kg, i.e. **€150/MWh of thermal energy**.

(1) For batteries, which are means of energy storage, the investment costs are based on their storage capacities expressed in kWh, and not on their power in kW as for other means of production.

(2) For electrolyzers and batteries, the costs include the costs of all ancillary equipment that enables them to operate.

(3) Value adapted in SimelSP3H according to the share of imported hydrogen.

(4) Assumed to be built **outside** the electrical system in underground salt cavities (or equivalent).

(5) Measured by the kinetic energy accumulated in the rotors, which is expressed in GVA x seconds.

#### \* **Grid cost data and assumptions associated with each mix**

This refers to expenditure to connect only the **means of production** to the grid and not to total grid expenditure, which also includes consumption connections and renovations.

##### ° **Grids associated with the "100% renewable" mix**

A "100% renewable" mix requires considerable grid extensions to connect the very many means of diffuse production, both to the transmission grid (large-scale wind or photovoltaic farms) and more so to the distribution grid (small to medium-power diffuse means) that have no common measure with the traditional grids based on a limited number of dispatchable means of large unit power exclusively connected to the transmission grid. Several sources can be cited:

- In France, RTE showed in its 2021 "Energy Futures 2050" study [5] that a "100% renewable" mix requires about **5 times more grid extensions** than a mix with 50% nuclear and 50% renewables.

- In Germany, according to the Federal Court of Auditors, investments in transmission and distribution grids will amount to **more than €460 billion between 2024 and 2040** according to provisional estimates by the Federal Network Agency. Other institutions are planning even larger amounts [2]. And as Germany will continue to equip itself with wind and photovoltaic power at a steady pace between 2040 and 2045, extrapolation to 2045 leads to an expenditure that can be expected to exceed €530 billion by that date. To this must be added the approximately €200 billion already spent to connect the very substantial wind and photovoltaic capacities commissioned before 2024, for a total of **around €730 billion in 2045**. These costs mainly concern the **connections of wind and photovoltaic means of production** to the transmission AND the distribution grids.

##### ° **Grid associated with the predominantly nuclear mix**

With this type of mix, the distribution grid **is not affected** insofar as no wind or photovoltaic means are connected to it, nor to the **transmission** grid. The latter is only concerned with **the connections of large-power nuclear means**. In addition, in a country like France, which has many existing nuclear sites already connected to the transmission grid and with space available, it is mainly a question of reinforcement of Very High Voltage and High Voltage substations and lines and a few new substations and lines to connect new sites. Based on a global unit connection cost estimate of €500 million/GW, the total cost of connections would remain well **below €65 billion**. This is in order of magnitude 10 times less than in the previous case.

#### \* **Choosing the discount rate**

In electricity mixes that involve a majority of capital-intensive means of production, which is the case for the two mixes studied, the cost per MWh produced depends very much on the discount rate chosen.

As the question is to compare two possible electricity production fleets, and since the supply of electricity is a public service, the discount rate can be the one used by the French Plan. According to the 2021 Guesnerie report, this rate is 3.21%.

In its reflection on energy futures, RTE plans now to use the average lending or borrowing interest rates in its calculations. It is considering a rate of 6% or more.

The initial calculations are made here at a rate of 4.5%. However, the simulation also makes it possible to calculate the costs with the above-mentioned values of  $\approx 3.2\%$  and 6%.

\* **The economic analysis tool used for these mixes:** we use the **SimelSP3H** simulation software which has been published. It has been developed by Henri Prévot [4]. Its being published is essential for an open unbiased discussion of the results. The software balances production and demand hour by hour based on real annual production and demand profiles over several years, in order to take into account the annual demand variability and, more importantly, that of wind and photovoltaic production which vary much more than the demand. With this software, it is possible to quantify the results of the choices made on the composition of different production mixes and to finally deduce the annual expenditure on electricity production, transmission and distribution, and ultimately the resulting average cost of electricity production, in **€/MWh**.

The simulation calculates two services provided by batteries, PHEs, demand flexibility and the flexibility of hydropower production: (i) a "common service" that these means provide together to the electricity system and which consists in storing wind and photovoltaic productions that exceed demand and putting them back on the electricity grid when these productions are insufficient; the quantities thus placed in storage and then unloaded according to needs are measured in TWh/year; and (ii) a "peak service" that reduces the need for gas production capacity, in this case carbon-free hydrogen; this service is measured in GW and is effective only for a small number of hours per year. In the following, we will call "storage" this set of means to provide these two essential services.

SimelSP3H is used here, on the one hand to replicate the "100% renewable" system, and on the other hand to build a predominantly nuclear system that satisfies the **same electricity consumption**.

Several annual hourly demand and renewable production profiles have been examined: those for the years 2012, 2013, 2016, 2019 and 2024 in France, but it is easy to introduce others as necessary. SimelSP3H also showed that 2012, which had a very harsh winter, was the most exacting and that 2019 reflects the average of recent years with significantly milder winters.

To be safe, an electricity production and storage fleet must be designed to respond to the least favorable situations - in this case, those of 2012. SimelSP3H's replica of the fleet inspired by the German projections shows that this is indeed the case, as it has a very large production capacity from carbon-free hydrogen. The same result must be true for the predominantly nuclear fleet built using SimelSP3H, which leads to its sizing in terms of **the installed capacity of production means required** on the basis of the **2012** profile.

Nevertheless, the **annual expenditures** of the two fleets thus dimensioned with their respective installed capacities are calculated on the basis of both the 2012 and the 2019 hourly profiles.

## Commented summary of the results obtained with SimelSP3H

***NB:*** the costs listed below include both the overall expenditure on **electricity production and storage** and the costs of **connecting to the grids the production means, only**; the resulting costs, expressed in **€/MWh**, are then calculated on the basis of the **final consumption, energy losses on the grid deducted**, i.e. **842 TWh/year**.

*The predominantly nuclear mix, calibrated to meet demand with no imported hydrogen even in exceptional circumstances, will generally be able to produce more hydrogen than the electricity system needs. The costs indicated below take into account the valuation of this surplus hydrogen production, up to €150/MWh (MWh thermal from gas combustion).*

- **The comparative electricity production costs of the two generation mixes as a function of the discount rate (in €/MWh).**

They are summarized in Tables 3a and 3b below for two representative hourly profiles:

\* For the **2012** profile with a high demand peak in winter:

Discount rate	2.3 %	4.5%	6 %
"100% renewable" mix	220.1	<b>261.2</b>	292.1
Predominantly nuclear mix	86.8	<b>112.3</b>	131.7
"100% renewable" extra cost / Nuclear	x 2.54	x <b>2.33</b>	x 2.22

\* For the **2019** profile with average demand, representative of recent milder winters:

Discount rate	2.3 %	4.5%	6 %
"100% renewable" mix	213.1	<b>254.2</b>	285.2
Predominantly nuclear mix	81.1	<b>106.6</b>	126.0
"100% renewable" extra cost / Nuclear	x 2.63	x <b>2.38</b>	x 2.26

Comments: These results highlight two well-known effects:

° **The major importance of the discount rate (or mean financing interest) on the cost per MWh** for the capital-intensive means of production that are concerned here. This effect is larger for nuclear power than for wind and photovoltaics due to its very large initial investment.

° The impact of the annual variability of demand on the cost of the MWh produced. However, this effect is of lesser magnitude than the previous one.

These results show that in all cases, a "100% renewable" mix produces electricity that is **more than twice as expensive as a predominantly nuclear mix**.

- **The underlying causes of the extra cost of a "100% renewable" mix**

These additional costs are analyzed based on the annual expenditure for the two mixes with the 2019 profile and a discount rate of 4.5%. They are calculated from the detailed data given in **Annex 3** and regrouped according to the main factors in Table 4 below:

Main source of the additional costs of a "100% renewable" mix	Amount of additional cost in million €/year
Wind + photovoltaic production / Nuclear production	+ 27,895 (≈ 22%)
Energy storage/destocking by PHES and batteries	+ 9,968 (≈ 8%)
Imported hydrogen, hydrogen produced by electrolysis, production from hydrogen, hydrogen storage	+ 45,455 (≈ 37%)
Biomass	+ 1,702 (≈ 1%)
Inertia to stabilize and secure the electrical system	+ 3,199 (≈ 3%)
Electricity grids	+ 36,087 (≈ 29%)
TOTAL	+ 124 306 (100 %)
<b>Extra cost per MWh consumed (in €/MWh)</b>	<b>+ 147.6</b>

Comments: If we rank the additional costs in descending order, the three largest account for ≈ 88% of the total extra cost and have the following causes:

° ≈ **37%** of the additional cost is due to the essential use of **hydrogen storage/destocking** to cope with very significant and/or long-term shortages of wind and/or sun, which PHES and batteries can in no way make up for because their capacities are insufficient in volume. **The underlying reason for the importance of this additional cost results from the very low overall efficiency (≈ 35%) of the P2G2P energy transformations process** already highlighted above:

- It is indeed necessary to produce about three MWh to recover a single one during destocking. Two MWh transformed into heat are thus lost in the process.

- And they had to be produced either with wind and/or photovoltaic surpluses, which require additional investments, or imported at a very high cost.

° ≈ **29%** of the additional cost results from **the considerable extension of the transmission and distribution grids** necessary to **connect wind and photovoltaic means of production**, as discussed above.

° ≈ **22%** of the additional cost results from wind and photovoltaic production, which **costs more than nuclear production**. This may seem counterintuitive in view of the very high initial investment cost of nuclear power. The explanation lies in the **very low average load factor of the "100% renewable" mix**

studied: given its dominant photovoltaic capacity, the **average weighted load factor of this mix** is only  $\approx 16.6\%$ , an extremely low value. As a result, **the investments made in this mix have a very low yield in TWh/year.**

By comparison, an **investment in the nuclear mix is much more productive**, with a load factor of  $\approx 78.8\%$ , i.e.  $\approx 4.7$  times larger.

- **The impact of the hourly profile on the consumption of CO2 free hydrogen using P2G2P.**

This is a significant aspect insofar as it **ranks first in additional costs** as shown above. Thus, if we compare **the hydrogen needs** expressed in thermal TWh/year (TWht/year) to produce electricity by P2G2P for the 2012 and 2019 profiles, they are very different as shown in Table 5 below:

	<b>"100% renewable" mix</b>	<b>Predominantly nuclear mix</b>
2012 hourly profile	Need for $\approx 203$ TWht/year of which: $\approx 79$ TWht produced by the electricity system <b><math>\approx 124</math> TWht imported</b>	Need for $\approx 44$ TWht/year produced by the electricity system <b>No surplus available</b>
2019 hourly profile	Need for 149 TWht/year of which: $\approx 67$ TWht produced by the electricity system <b><math>\approx 82</math> TWht imported</b>	Need for $\approx 11$ TWht/year produced by the electricity system <b><math>\approx 31</math> TWht of surplus available</b>
2019/2012 differences	Reduction in imports by $\approx 42$ TWht	Possible exports $\approx 31$ TWht (1)
Valuation (2)	Reduction of annual cost by €6,300 million	Revenue of €4,880 million

(1) Outside the electricity system, especially for industrial needs. (2) Based on €150/MWht.

Comments: the hydrogen needs of the predominantly nuclear mix only serve to compensate for variations in **demand**. Those in the "100% renewable" mix must also compensate for the variability of **wind and photovoltaic production**. The difference between the two makes it possible to estimate wind and photovoltaic variability, which is much greater than that of demand alone.

- **Hydrogen storage needs**

This issue is essential insofar as the needs for electricity production by the P2G2P process vary greatly from year to year depending on demand variations, but more so on wind and photovoltaic production variations, which have much greater amplitudes and are more rapid. This implies having hydrogen storage facilities, particularly for imported hydrogen, whose supply flow can be relatively constant, while its use is essentially random, highly variable and, above all, concentrated over particular periods of time. These storage capacity requirements, calculated by SimelSP3H, are summarized in Table 6 below for the 2012 and 2019 profiles :

	<b>"100% renewable" mix</b>	<b>Predominantly nuclear mix</b>
2012 hourly profile	Storage need: 114 TWht/year	Storage need: 42 TWht/year
2019 hourly profile	Storage need: 79 TWht/year	Storage need: 18 TWht/year

**NB:** as a precautionary measure, storage capacity needs of 130 TWht for the "100% renewable" mix and 50 TWht for the dominant nuclear mix are retained here.

Comments : The storage needs for the "100% renewable" mix must also take into account critical situations characterized by the combination of very low winds and the total absence of photovoltaic production at night, as observed in Germany. The most critical episode called *Dunkelflaute* occurred on the evening of November 6, 2024, a period during which the very large installed German wind and photovoltaic capacities produced only... 0.072 GW while demand reached 66 GW! Without the massive use of coal and gas resources and massive imports from neighboring countries, Germany would have been in the dark.

More generally, episodes of very low wind and sunshine, lasting one to two weeks, were regularly observed in Germany and more widely in Western Europe. During these episodes, neither the PHEs plants nor the batteries can be recharged and a large-scale use of P2G2P is the only solution with a "100% renewable" mix. For a consumption of about 900 TWh/year, the average electricity destocking requirement to cover such a period is around 35 TWh, requiring a hydrogen destocking of around 60 TWht. This need is covered by the storage capacities determined above, but it is extremely expensive.

- **Robustness of comparative results obtained**

This issue is legitimate and important. To answer the question, it should be noted that the cost of the "100% renewable" mix studied **does not take into account several additional costs**, either because they cannot be assessed at this stage due to a lack of existing references, or because they have been deliberately excluded. These include:

- \* The costs of real-time management of such an electricity mix, which implies the mandatory use of complex AI to manage very rapid and unpredictable variations in wind and photovoltaic production with very short time-constants. This type of AI has yet to be developed and made reliable at an undetermined cost, in the absence of industrial references.

- \* The costs of cyber-protection which are extremely complex for three reasons that combine their effects: (i) the widespread use of power electronics and associated computer software, which are intrinsically cyber-vulnerable; (ii) the very large number of these components spread over a large grid, that represent as many entry points for cyber-attacks on the electricity system; (iii) the introduction of AI to globally manage the system, which, according to all experts in the AI field, greatly complicates cybersecurity protections.

These are two major issues that condition the security of a country's electricity supply, the ultimate risks being those of more frequent blackouts, which are not a fiction (see the blackout of 28 April 2025 in Spain, which however has very different causes). Again, there are no credible operational references to date regarding the costs associated with these developments.

- \* The costs of floating offshore wind turbines, which are extremely expensive (> €6,000/kW installed). They have not been taken into account here voluntarily, insofar as the prospects for the installation of this technology are uncertain. Its introduction into the mix would significantly increase the overall cost of production.

- \* The cost of hydrogen storage. The existence of a hydrogen network with large storage capacities in underground salt cavities, or similar cavities (a condition for low-cost storage) is postulated here. As noted above and for the sake of simplification, this storage cost is assumed to be externalized. It is taken into account in the form of a simple fee. However, such hydrogen networks do not exist to date and remain hypothetical. This is another strategic uncertainty. If the electricity system were to invest in storing its hydrogen, it would probably be in high-pressure tanks, the corresponding investment cost per unit storable capacity being much higher according to various existing references. The cost of hydrogen storage would then become very high for the "100% renewable" mix studied. **This implicitly means that this mix absolutely needs an external hydrogen network with storage in underground cavities, which would also accommodate the essential imports. This is of strategic importance.**

All in all, it can therefore be said that **the costs of the "100% renewable" mix studied here are underestimated by an amount that remains to be clarified, but which reinforces the fact that the cost per MWh of this mix is more than twice as high as that of the MWh of the predominantly nuclear-based comparison mix.**

## **To summarize and survey more in depth**

A "100% renewable" electricity mix raises several major issues:

- \* First, a question of technical feasibility concerning its operational viability, reliability and safety, that are essential to supply a large, developed country. There is to date no experimental proof that this objective can be achieved on large grids in operation, yet it is with this condition that certainty can be secured in the face of such a complex system. A mix of this kind is thus currently a leap into the unknown. Is this acceptable for a system that is so vital to the functioning of a country, especially since electricity is set to constitute the majority of the carbon-free energy that will be available by 2050?

- \* Secondly, an economic question. It may be possible to make such a system work, by adding all the necessary "technological crutches". But economic analysis shows that the cost per MWh produced by such a mix is more than twice that of a mix based on nuclear power, which seems prohibitive for electricity that will be the predominant basic energy of the future, conditioning the industrial capacities of European countries and the standard of living of their residents. It is this conclusion that has in fact led to the title of this study.

Without going as far as 100% renewable energy, this study can be extended to systems comprising very high shares of variable and intermittent production. The additional cost will then be lower but will remain all the more significant, the higher the share of these energies. This is also confirmed by the aforementioned NEA study [1], which indicates that there is no share of these energies that leads to an optimum cost. **In other words: the more nuclear generation there is in the mix, the cheaper electricity is.** This is despite the fact that the very high initial investment cost of nuclear power is criticized by its opponents. Paradox? No. As shown in this study (see Table 4), the explanation is simple: nuclear power can operate autonomously without means of compensation and it is dispatchable. It has a large load factor and a long operating life (up to 80 years). It is thus possible to amortize the investment cost over a considerable amount of MWh produced; On the contrary, wind and photovoltaic power absolutely need "crutches" to operate, in particular means of storing/destocking energy, have a much lower average load factor and a much shorter operating life ( $\approx$  25 years). Their economic amortization is therefore done on a much smaller amount of MWh produced, which are thus much more expensive.

**All these factors explain up to  $\approx$  70% of the production cost difference between the two mixes.**

\* Moreover, a "100% renewable" mix imperatively needs a hydrogen transport and mass storage network in the country. It cannot operate without such a network, especially given that hydrogen imports are essential. This implies that the country concerned has previously made the necessary considerable investments.

\* Another constraint concerns the availability of rare materials and metals, as these are widely used in wind turbines and photovoltaic panels. This is a crucial geopolitical issue, which we have not dealt with here as it requires complex development in its own right. Even other less rare metals such as copper raise questions: more of it is consumed per MWh of electricity produced with these technologies than with nuclear facilities.

We will conclude with two remarks:

\* From the climate change point of view, while the two mixes studied are carbon-free **during their operation**, they are not equally decarbonized for their "grey" emissions resulting in particular from their construction. Based [6] on  $\approx$  4g/kWh for nuclear,  $\approx$  14 g/kWh for wind power and  $\approx$  44 g/kWh for photovoltaics, the "100% renewable" mix emits nearly 20 Mt/year more CO<sub>2</sub> than the predominantly nuclear mix. Although not considerable, this gap in emissions represents more than half of the carbon sink of French forests.

\* The economic conclusions of this study, drawn up in the geographical, climatic and level of development context of Europe, cannot be considered valid for different contexts. For example, for a large part of the inter-tropical zone in which sunshine conditions are both higher and more constant throughout the year, with little or no marked seasons. This greatly favors the use of photovoltaics combined with short-term storage solutions such as batteries, while avoiding the use of hydrogen storage, which is extremely expensive.

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## References

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[4] SimelSP3H software, developed by Henri Prévot, which makes it possible to balance production and consumption hour by hour, according to various annual hourly profiles observed. See further explanations on: [www.hprevot.fr/Etude-GS-HP-allem-avec-sans-nucl](http://www.hprevot.fr/Etude-GS-HP-allem-avec-sans-nucl)

[5] "Energy Futures 2050" published in October 2021 (several documents depending on the topics covered, available on the RTE website)

[6] Rounded values given in the bibliographic references (NB: with Chinese photovoltaic panels)

## Appendices

### Appendix 1: Comparative detailed characteristics of the two electricity mixes studied

(NB: these two mixes are sized in terms of **installed capacity** to meet the most severe conditions, those of the 2012 hourly profile).

<b>Assumptions for the two CO2-free generation and storage mixes</b>		
* The "100% renewable" mix <i>replicates as closely</i> as possible the German prospective; it can meet electricity demand even under unfavorable conditions (with hourly demand profiles and wind activity similar to those of 2012); with the simulation it is possible to calculate the need for hydrogen storage capacity under these adverse conditions. The "predominantly nuclear" scenario is a textbook scenario; It was built to meet the same electricity demand with minimum costs, under the same unfavorable conditions, with the same hydropower and biomass production potential, but <i>without wind or photovoltaic power or external hydrogen input</i> .		
* The use of biomethane is not retained because of its scarcity and conflicting other uses. Only carbon-free hydrogen is taken into account; This is produced from electricity from the electricity system or, only in the "100% renewable" case, imported into the electricity system.		
	<b>Installed capacity / Production potential in TWh/year</b>	
	<b>Flexibility and storage capacity in GWh</b>	
<b>Production mix</b>	<b>"100% renewable"</b>	<b>"Predominantly nuclear"</b>
	<b>≈ German prospective</b>	
<b>Non-thermal means of production</b>		
Hydropower excluding PHES	6 GW / 50 TWh/year	6 GW / 50 TWh/year
Biomass and renewable waste	9 GW / 20 TWh/year	9 GW / 20 TWh/year
Nuclear	0 GW	130 GW / 897 TWh/year**
Onshore wind (load factor: 24%)	160 GW / 336 TWh/year	0 GW
Offshore wind (load factor: 37%)	70 GW / 227 TWh/year	0 GW
Solar PV (load factor: 10%)	400 GW / 350 TWh/year	0 GW
Total wind and photovoltaic	630 GW / 913 TWh/year	0 GW
<b>Flexibilities and storage</b>		
PHESs: destocking power / Destocking capacity /efficiency	10 GW / 37 GWh / 70%*	10 GW / 37 GWh / 70%*
Hydropower flexibility, equivalent to a PHES	2 GW* / 26 GWh* / 70%*	2 GW / 26 GWh / 70%*
PHES and hydropower flexibility	12 GW / 63 GWh / 70%*	12 GW / 63 GWh / 70%*
Battery storage (1)	452 GWh / 200 GW* / 85%*	180 GWh / 85%*
<b>Thermal production means</b>		
Of which CCGT	151 GW	50 GW
Of which OCCT	63 GW 60% efficiency*	20 GW 60% efficiency*
	88 GW 40% efficiency*	30 GW 40% efficiency*
<b>P2G2P pathway: hydrogen production to produce stored hydrogen and then electricity again</b>		
Electrolyzes: capacity / efficiency	90 GW / 60%*	19.6 GW / 60%*
P2G2P pathway efficiency*	35 %*	35 %*
<b>System stability</b>		
Synchronous condensers providing inertia to ensure dynamic grid stability	70 GVA x 5 sec*	0
<b>Need for hydrogen storage capacity</b>	130 TWh thermal**	50 TWh thermal**
* These values are not specified in the German prospective.		
** Evaluated using SimelSP3H		
(1) The German outlook distinguishes between stationary batteries (178 GWh) and mobile batteries (274 GWh). The simulation takes into account all batteries only: 452 GWh		

## Appendix 2: Comparative annual production and storage of the two mixes for the 2019 hourly profile

(NB: *annual production* is calculated on the basis of the *investments* in resources mentioned in Appendix 1 and the *2019 hourly profile*, which is more representative of the average)

Electricity mix		"100% renewable"	"Predominantly Nuclear"
Final consumption, before line losses	TWhe	900.9	900.9
Consumption to maintain inertia	TWhe	9.2	0.0
<b>Direct delivery of electricity</b>			
- Hydropower and biomass	TWhe	70.0	70.0
- Wind and photovoltaic	TWhe	666.3	0.0
- Nuclear	TWhe	0.0	816.5
Storage destocking and flexibility (PHES + batteries)	TWhe	84.8	7.7
Electricity generated from P2G2P	TWhe	39.5	6,73
Imported hydrogen	TWht	82	0
Hydrogen consumption for electricity	TWht	149	11.2
Surplus hydrogen production	TWht	0	31.3
Possibility of excess electricity generation	TWhe	34	13.9

(TWhe: TWh of electricity – TWht: thermal TWh from hydrogen)

## Appendix 3: Comparative annual expenditure of the two mixes studied for the 2019 hourly profile and a discount rate of 4.5%

(NB: *annual expenditure* is calculated on the basis of the *unit costs* in Table 2, the *sizing* in Appendix 1 and the *annual production* in Appendix 2)

Electricity mix		"100% renewable"	"Predominantly Nuclear"
Production and storage/destocking	Units		
Nuclear	M€/year	0	70 282
Wind	M€/year	51 471	0
Photovoltaics	M€/year	46 706	0
Biomass*	M€/year	3 925	2 223
Production from hydrogen	M€/year	29 438	6 157
Of which: investments and fixed costs	M€/year	17 258	6157
External hydrogen inputs	M€/year	12 180	0
Electrolysis for P2G2P	M€/year	18 338	3 769
PHES + Hydro + Battery Flexibility	M€/year	16 565	6 597
Inertia supply	M€/year	3 199	0
<b>Total production</b>	M€/year	<b>169 643</b>	<b>89 028</b>
Hydrogen storage	M€/year	4 823	1 855
<b>Grids</b>	M€/year	39 612	3 525
<b>Total Expenditures</b>	M€/year	<b>214 077</b>	<b>94 408</b>
Cost per MWh put on the grid	€/MWh	237.6	104.8
Valorization of surplus hydrogen	M€/year	0	- 4 880
<b>Net Expenditures</b>	M€/year	<b>214 077</b>	<b>89 758</b>
Per MWh put on the grid (1)	€/MWh	237,6	99,58
<b>Per MWh consumed (2)</b>	€/MWh	<b>254,2</b>	<b>106,6</b>

\* To produce electricity from a certain quantity of biomass fixed a priori, the capacity of the means of production, expressed in GW, is less if the means of production works in baseload mode (in the case of the "predominantly nuclear" mix) than if it works partly in a dispatchable way as in the case of the "100% renewable" mix.

(1) Before grid energy losses

(2) After grid energy losses