Under what conditions would the electricity mix planned for France under the Energy Transition Act work?

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The energy transition plans to reduce the share of nuclear power in the electricity mix to 50%, and increase the share of wind and solar power. These intermittent energies require resources to rebalance the grid. We are using a method developed for the German energy transition (Energiewende) to work out the orders of magnitude.
With regard to the mix adopted for France, a quarter of intermittent production, 44 TWh, should be transferred between periods of surplus and shortage. This would be possible with large-scale storage - 15 TWh in volume and 45 GW in power - which unfortunately far exceeds known resources (hydroelectric dams, batteries, etc.). Without such storage, fossil fuel power stations would be used to meet demand, thereby worsening the carbon footprint. This can already be seen in the results of the past decade in Germany and Europe.

Electricity is a growing energy carrier worldwide, as it powers new uses and helps to decarbonise transport and heating in cities and megacities. Producing electricity that emits low levels of CO_2 and pollutants is therefore a major challenge. Against this backdrop, wind and solar energy sources enjoy a favourable reputation, and their installations are multiplying. The European Union is encouraging their development. In France, the Energy Transition Act, introduced in 2015, aims to give them the share of electricity gained from nuclear generation, reduced from 75% to 50%.

Our study looks at how this future electricity mix will work, with an increased share of generation from intermittent solar and wind flows. It is based on a method initiated by Friedrich Wagner to study the case of Germany [1], a country already heavily involved in wind and solar generation. Given the interest of the results obtained by this method, we decided to apply it to the French case [2].

Electricity mix with 35% wind and solar power

For France, the annual electricity mix adopted is the state targeted at the end of an energy transition which, for a target year around 2035, would see wind and solar power grow to 35% of annual production, while reducing nuclear power to 50%. In terms of annual quantities of electricity:

- domestic electricity production would remain unchanged at 548 TWh (2013 value);

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Kruonis pumped-storage power station (PSH) in Lithuania.

- nuclear power would be reduced to 50% of the total: 274 TWh (compared with 403 TWh in 2013);
- hydroelectric generation (60 TWh) and biomass and waste combustion (21 TWh) would remain unchanged;
- wind and solar power would produce the rest: 193 TWh (compared with 21 TWh in 2013), or just over 35% of the total.

To analyse how this 35% mix could cope with the intermittency of wind and solar sources, we start with the power recorded on the grid by RTE (the grid operator) and published for each half-hour of 2013. The power recorded in 2013 is transposed to the 35% mix by homotheticising the electrical power recorded each half-hour, with multiplication factors of 10 for wind power and 7.5 for solar, giving a distribution of 80% wind and 20% solar that minimises the annual transfer of intermittent electricity [1, 2]. The result for the target year on the French grid is shown in Figure 1.

This figure shows the large fluctuations in total production caused by intermittent renewable energies (IR). Fluctuations increase by a decade as

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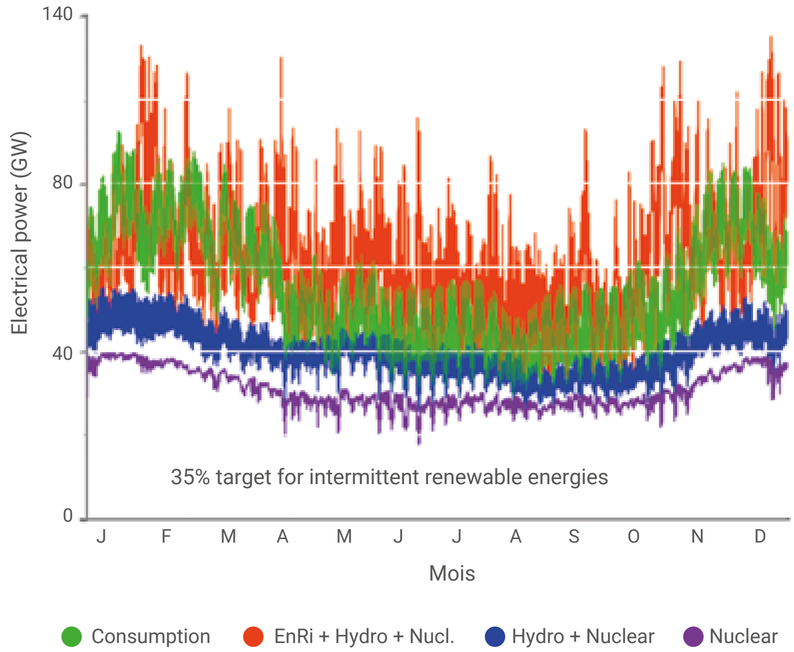

1. Values of power transiting on the French network every half-hour of a year in the 35% mix. Consumption (green curve). Generation: *nuclear* base (purple curve), to which are added hydroelectric and biomass generation (referred to as hydroelectric - blue curve), and intermittent renewable energies (EnRi, comprising wind and solar power - orange curve) .

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we move from combined nuclear and hydro generation (blue curve) to total generation including renewables (orange curve). The latter fluctuates three times more than consumption (green curve).

It is sometimes argued that the extrapolation to the 35% mix of 2013 data would exaggerate the amplitude of fluctuations. A supposed abundance would attenuate them. According to this theory, fluctuations would be neutralised with the multiplication of wind and solar sources connected to a perfect conducting European electricity grid (the copper plate). This theory is not borne out by the facts, as production levels are still correlated with the small size of the European continent. This is obvious in the case of solar energy, as Europe is no bigger than two time zones. But it's also true for wind generation, because the structures of the atmosphere extend over a thousand kilometres and, when an anticyclonic situation sets in, it covers most of the countries of Europe, depriving them of wind generation. This has been shown by several studies cited in [2], and was specified in a recent study of 18 European countries by the VGB Power Tech association [3]. We also observed it in a comparison between Germany and France [4] and very recently [5].

New needs emerging from the 35% renewable energy mix

To quantify the results of a 35% intermittent renewable energy (IRE) mix, we compare wind and solar generation with the amount that would have to be produced to match consumption, once hydropower, biomass and nuclear generation have been removed. This quantity is referred to hereafter as the "remaining load".

For the target year, the remaining load and the production of intermittent RE are equal to 193 TWh in annual values. On the other hand, for instantaneous values, at half-hourly intervals, the power required for the remaining load is not equal to the power produced by renewable energy sources, except in rare cases [2].

Two cases of inequality appear in the history of powers:

- Intermittent Renewable power greater than that of the remaining load, causing a surplus;
- Renewable energy capacity lower than the remaining load, resulting in a shortfall in production.

Therefore, dispatchable resources, whose power can be modulated at will, must be added to the production of renewable energy sources to restore balance to the grid: drawing energy from surpluses, storing it and then using it to make up for shortfalls. We refer to all these resources, the composition of which is given below, as "ideal storage".

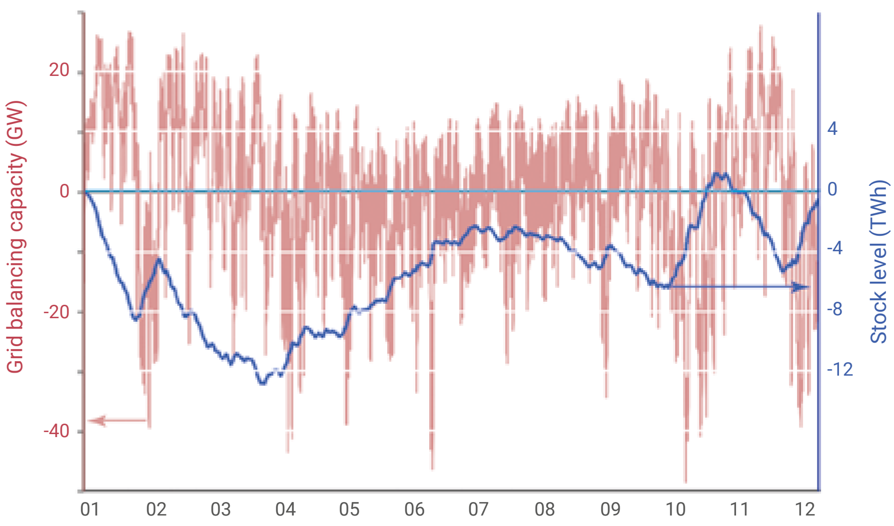
Dimensioning ideal storage

An ideal, lossless storage system alone would fulfil this balancing function. Figure 2 describes how it works over the year.

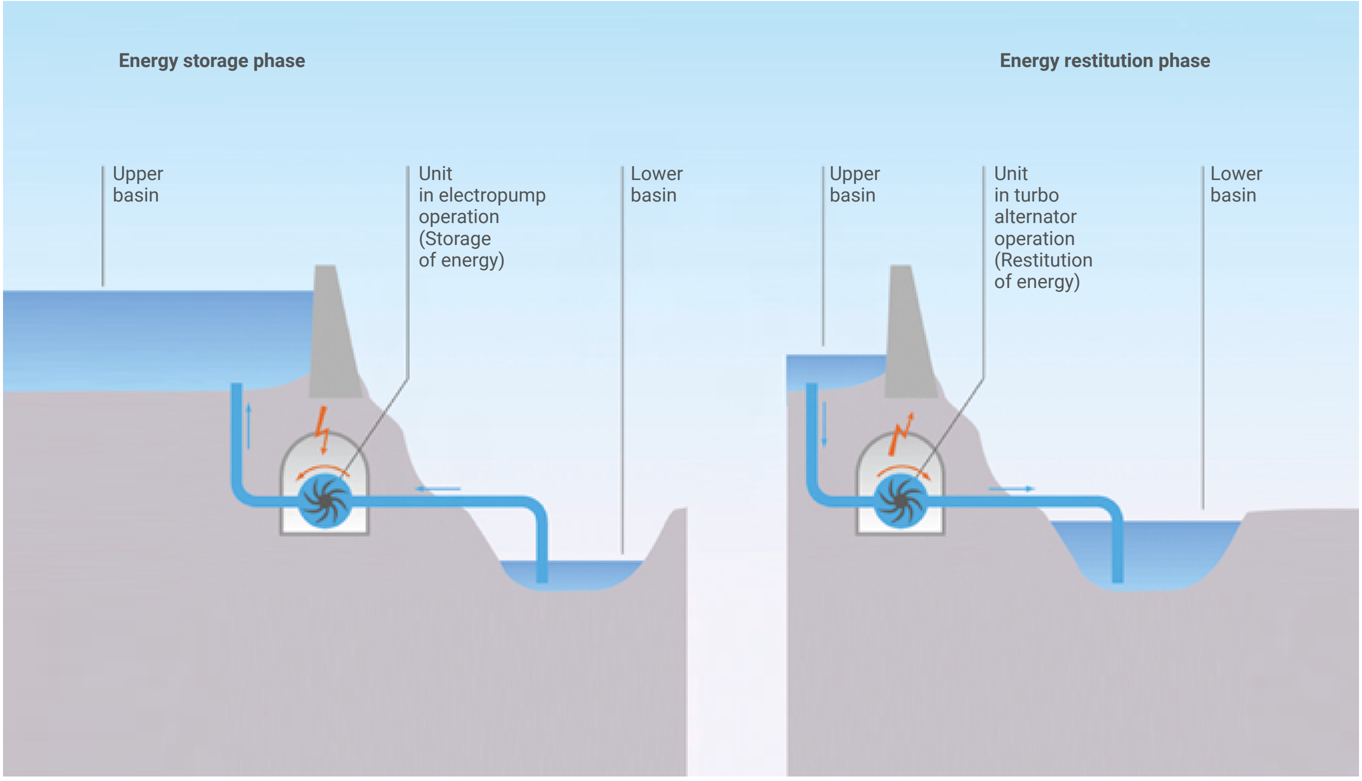
The pink curve represents the power exchanged over half an hour between storage and the grid to maintain its balance. This power is positive when, leaving the storage, it supplements production to make up for a shortfall. It is negative when the storage extracts surplus power from the grid. In the latter case, the power to be extracted can be as much as 45 GW. Switching off intermittent sources would reduce the absolute value of this power. On the other hand, the maximum positive power, 25 GW, is a production that must be reached to maintain the balance of the network. The temporal integration of positive power sequences results in an annual production of 44 TWh, which fills the gaps. This production comes from the return of the 44 TWh of energy withdrawn during surplus sequences.

Between extraction and release, energy must be stored. In order to operate continuously over the year, the storage must have a sufficient volume to contain the variable level of the energy stock over the year. The blue curve in Figure 2 shows the level of the stock and is the result of time integration of the power entering or leaving the storage. The amplitude between the maximum and minimum of the curve, 15 TWh, determines the minimum volume of storage to be available all year round.

The validity of the method used to derive the orders of magnitude is confirmed by the consistency of the results obtained with different mixes (Germany with 72% or 86% renewable energy, France with 35%), based on power histories from different years (2010, 2012, 2013). Their summary, produced with F. Wagner [4],



2. Ideal storage operation over the twelve months of the year.
Pink curve and left axis: positive (generation) or negative (withdrawal) half-hourly power (GW). Blue curve and right axis: energy level in the stock.



3. Principle of operation of pumped-storage hydroelectricity (PSH) power station. In pump-motor mode, the reversible electric hydro set consumes electricity to pump water from the lower basin to the upper basin. In turbine-generator mode, it produces electricity when transferring water from the upper basin to the lower basin.

shows that the energy to be transferred annually from periods of surplus to periods of shortage represents a quarter of the production of renewable energies. (Provided this transfer is minimised by an optimal mix of renewable energies, with 80% wind and 20% solar [1, 2]).

Practical storage solutions

In short, "ideal storage" should absorb up to 45 GW of power during surpluses and produce up to 25 GW during shortfalls. To transfer 44 TWh from surpluses to shortfalls over the course of the year, storage needs to have a volume of at least 15 TWh and dispatchable production. The various solutions that could be envisaged in the decades to come are reviewed, and their ability to meet these specifications assessed in the remainder of this article.

Relying on neighbouring countries

This storage method is currently used in Denmark and Germany. The Scandinavian countries import a large proportion of their wind-generated electricity from these two countries and, when there is no wind, they export scalable hydroelectricity to them. This system works as long as there is an abundance of dispatchable sources in neighbouring countries, but will become saturated as intermittent sources become more widespread. In fact, for the reasons mentioned above, there is a strong correlation between periods of shortage and surplus on a European scale for solar, onshore and offshore wind power, which follow the same temporal variations [3, 5].

Contribution of hydroelectricity

Pumped storage hydroelectricity (PHS) offer the largest capacity of all storage facilities, as well as one of the highest efficiencies, at 80%: the water leaving the power station is collected in a reservoir (lower basin), from where it can be lifted to the upstream dam (upper basin). It can then be pumped back to the upstream dam (upper basin) during periods of surplus electricity, to be turbined again during periods of shortage (Fig. 3). In total, France has 4.2 GW of pumped-storage hydroelectricity and a capacity of around 0.1 TWh. This capacity would have to be multiplied by 150 to reach the ideal storage capacity. A doubling of capacity would be a success, given the difficulty of finding new sites. In terms of installed capacity, the target is less remote, with PPS accounting for between a sixth and a tenth of the requirement. Today, pumped storage absorbs 7 TWh. Transferring 10 TWh from periods of surplus to periods of shortage seems possible by making full use of the flexibility of hydroelectricity, but this represents only a quarter of the requirement.

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“Transferring 10 TWh from periods of surplus to periods of shortage seems possible if full use is made of the flexibility [of the Pumped-Storage Hydroelectricity Power plants], but this only represents a quarter of the requirement”

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Storage by individuals adjusting their consumption

With the development of electric mobility, we can hope that private cars will be used as decentralised, mobile storage facilities. This requires the development of a fleet of electric vehicles whose battery capacity can be used in part to manage intermittent power, in addition to its main use - mobility - and on condition that the vehicles are connected when they are not in motion. With this and other means of adjusting consumption, we can hope to achieve a transfer of around 8 TWh [6].

Long-term storage with gas

The electricity then has to be stored for long periods, converting it into hydrogen, which is then used in fuel cells to produce electricity. The theoretical efficiency of the whole operation is 50% at best. At the cost of an additional operation, methane can be produced, which is easier to store, but the yield then falls to 30% (see the article by G. Sapy, p. 129). Industrial systems do not yet exist and will have to offer a use other than electricity storage to justify their development, which will certainly be costly.

Dispatchable resources

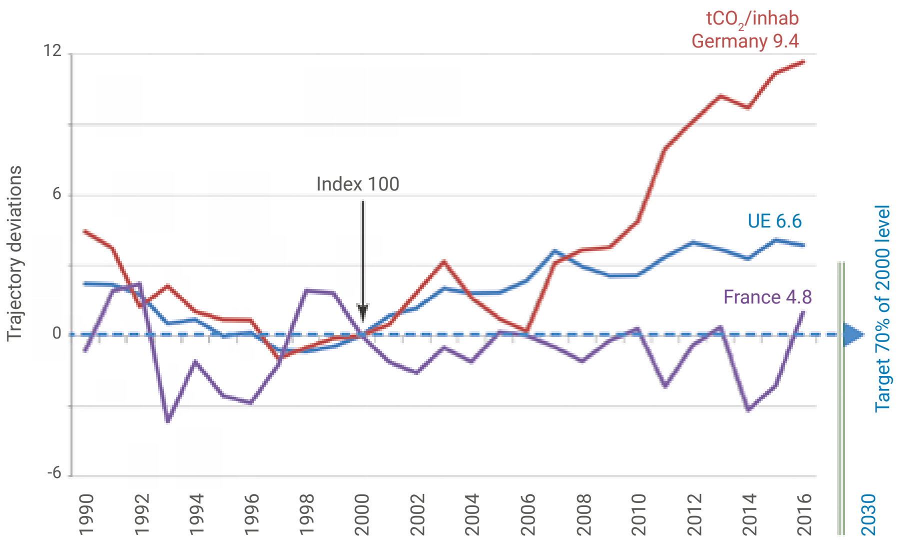
As all possible means have been mobilised to manage intermittency, more than half of the 44 TWh would still need to be produced during shortfalls. As the flexibility of hydroelectric power has already been taken into account, what remains is the flexibility of nuclear power, with part of the fleet capable of load following, as shown in Figure 1. After that, fossil-fuel power plants will have to take over.

CO_2 emissions

How can the carbon balance of this new mix be assessed? The previous results show that dispatchable means using fossil fuels remain necessary to ensure the balance of the system, all the more so as the contribution of nuclear power is reduced. The limits of a massive deployment of wind and solar power are beginning to be addressed in the public debate, especially as the European Union fails to meet its commitments to reduce CO_2 emissions.

Figure 4 shows the evolution from 1990 to 2016 of an index defined by the European Commission to monitor the carbon footprint of EU countries. CO_2 emissions from energy consumption averaged 6.6 tonnes per year per capita for a European in 2016. This compares with 4.8 tonnes for a French person and 9.4 tonnes for a German person (2016 data shown on the right of the curves), even though energy consumption is virtually the same. To check that the countries are following the same rate of reduction defined for Europe, regardless of the level, the emissions of each country in 2000 have been brought down to an index equal to 100. To achieve a target of a 40% reduction in CO_2 emissions by 2030 compared with 1990 levels (30% compared with 2000 levels), the countries' results would have to align with the horizontal axis of the graph in figure 4. (N.B.: Since this article was written, the reduction target has been set at 55% below 1990 levels by 2030).

The y-axis gives the deviation from this downward trajectory. When observed values fall below the axis in the lower half-plane, emissions are falling faster than the target rate. On the other hand, when the trajectory passes into the upper half-plane, emissions are falling insufficiently in relation to the target, which can



4. Change from 1990 to 2016 in the carbon footprint of energy consumed per capita for the European Union, Germany and France, compared with the target set for 2030. An index set at 100 in 2000 is used to compare changes in this footprint, regardless of its level. The horizontal axis points towards the target of a 40% reduction in emissions by 2030 compared with 1990 (30% compared with 2000). The ordinate shows the deviation of measured changes from this trend. (Eurostat data, European Commission) be summarised as a deterioration in the country's index. Germany's index deteriorated from 2000 onwards. The same applies to the European Union index to a lesser degree. France's index fluctuates around the axis.

However, the worsening of Germany's carbon footprint is concomitant with the massive deployment of wind and solar power and the cessation of nuclear power. A widely-held view that renewable energies (wind and solar power) would reduce man-made CO_2 emissions has been disproved by the facts. This is understandable when you consider the difficulty (mentioned above) posed by intermittency. Massively deploying wind and solar power without having put in place complementary low carbon footprint dispatchable resources means that we are dependent on fossil fuel power stations, which increase CO_2 emissions. With more hydropower than Germany and more limited development of intermittent renewable energies, France has avoided this pitfall. For the future, we must first act on the main sources of CO_2 (housing and transport) and develop dispatchable sources of electricity with a low carbon footprint.

Conclusion

Wind power and solar photovoltaics are the two renewable energy sources that can increase their share of the electricity mix in Europe, after the potential of hydroelectricity has been largely exploited. Their largely positive public image has encouraged their widespread deployment, first in Germany from 2000 onwards, and then across the European Union by mimicry. France has undertaken to reduce the use of nuclear power, which would make it possible to open up a growing share of its electricity production to these sources. Unfortunately, these decisions were taken without any studies having been carried out - or at least made public - to assess how a mix with 35% intermittent energy production dependent on random natural flows would function. The study by F. Wagner published in 2012 for Germany and ours for France, two years later, were undertaken in this context with a view to obtaining at least the main features and the orders of magnitude of the operation of this mix.

One common feature emerges: the need to transfer a quarter of intermittent production from periods of surplus to periods of shortage. A 100% renewable mix, with consumption limited to 422 TWh, would require the transfer of more than 90 TWh, more than double the mix studied here [6, 7]. Ideally, lossless storage would enable this transfer. Even with an intermittent Renewable share limited to 35%, the size of the storage would be two hundred times the potential of French Pumped-Storage Power Stations. Other means could be added but, in any case, there is a strong disproportion between the theoretical needs and the existing means. What's more, the actual systems do not have the perfect efficiency assumed for ideal reference storage. At 80%, PSH or batteries offer the best efficiency, unattainable by gas storage (hydrogen or methane), with efficiencies of around 30%.

In the absence of these resources and of nuclear power, which can provide some of the flexibility needed, the use of fossil-fuelled power stations remains unavoidable. Comparative trends in CO_2 emissions in European countries show that Germany, which is leading the way in the development of renewable energies, has been drifting away from its CO_2 emission reduction targets for over ten years, and is dragging the EU down with it. This has led to a number of warnings that the EU is not meeting its commitments. The rational development of renewable energies should be preceded by the introduction of carbon-neutral resources capable of managing intermittency. ∎

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