

How much can wind reduce the French CO₂ emissions? (I)

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Abstract

This report analyses the information recently made available by the French electricity transport network RTE (Réseau de Transport d'Électricité). It consists in a detailed data set which gives the time evolution of the power either consumed by the country or generated with the diverse production modes exploited by utilities within France. For the first time the French public is also provided some analytical information on a major renewable energy: wind. Our analysis shows that the French wind-turbine-fleet efficiency over last fall-winter semester is 24.3%. The wind production displays the strong fluctuations expected for this intermittent non-controllable energy. It is observed that the time and energy distributions of the power delivered by the French wind turbines are not related to the increased electricity needs which occurred during a semester where a few cold waves hit the country. As a consequence, the controllable productions which already ensure the balance of consumption versus production had also to carry the extra load associated with the handling of wind fluctuations. In a second part of this report, based on the actual data provided by RTE, the report determines the maximal reduction of the CO₂ emissions which can be expected from the completion of the national wind energy program endorsed by the government. We conclude that in the absence of a significant strengthening of the electric network and an increase of the national energy storage capacity, the wind energy policy decided by the French government will only yield limited results on the reduction of both the GHG emissions and the country reliance on fossil fuel burning plants.

A) Context

During the years 2007-2009, the French government organized a general round of discussions and negotiations which was referred to as the “Grenelle de l'Environnement”. In this text, following now established French usage, it will be shortened as a noun “the Grenelle” or as a qualifier as in “a Grenelle recommendation”. The proclaimed goal of the Grenelle was to find a national consensus on an optimal policy both friendly to environment and beneficial to France's economy. The first part of the Grenelle consisted in a long process of consultations and meetings within ad-hoc committees. It involved representatives of the concerned ministries, delegates of all the economic sectors, the trade unions, a selection of NGOs, and some distinguished personalities with specific competences¹. Following comprehensive analyses and discussions, reports were produced. Finally, the government announced a long list of measures² on all sorts of questions relating to building insulation, transportation, management of the economy and energy production or consumption. Within the energy package, an optimal magnitude for the deployment of various types of renewable energies over a period extending to 2020 was prescribed. For the wind energy, following the recommendations of the Grenelle, the construction of a fleet of onshore wind turbines up to 19 GW (installed power) was decided along with 6 GW of offshore wind turbines. This official planning defines the framework of the present analysis.

At the beginning of 2011, the installed wind power within continental France totaled about 5.4 GW³. After a slow start, its growth has been steady over the last few years. The present rate exceeds 1

¹ Interestingly, it was not judged useful to include official representations of the scientific world such as, for instance, the science or the technology academies, the major research institutions (CNRS, CEA, ...) or the main French science or economy universities.

² Over a hundred.

³ Values may differ by a few hundred MW depending on the possible source (ERDF: the national electricity distributor to which most wind turbines are connected, ADEME: the French agency for energy savings, MEEDM: the

GW per year. The wind fleet is certainly already large enough to allow a fair estimate of wind productivity in France and to provide a solid basis for an analysis of what can be expected in the future when more wind turbines are erected. In addition, although it is not clear why a very significant fraction of the turbines is presently set up in regions which data show not to be very windy⁴, one can at least say that a representative geographical sampling is already available. On the other hand, 5.4 GW is still far from the goal set by the Grenelle for the year 2020. Almost 20 GW are still missing. Thus, before final decisions of construction are taken, there is still some time left to assess with improved accuracy the benefits as well as the constraints to be expected from the full scale wind turbine deployment announced in the Grenelle⁵.

The economic value of wind energy is still very much disputed⁶. German experience has established the negative impact on the electric network stability of this intermittent production⁷. Wind cannot improve much France's energy independence. It does not permit a significant reduction of the investment in conventional power plants. Indeed a solid backup remains essential to compensate the small production for instance during cold anticyclone periods. We will discuss these points below⁸. The contribution to the French job market is not large since no wind turbines erected on French soil has (and presumably will be) built in France. Generally the turbines are also tele-operated by their constructors⁹.

Therefore the protection of the environment via CO₂ emission reductions appears as the most solid motivation for erecting five times more wind turbines in France. This work determines the maximal reduction of GHG emissions of the electricity production-consumption phase which is made possible by an extra wind electric production. In particular we do not consider the CO₂ emissions entailed either by the construction of the turbines, the necessary strengthening of the electricity network or the construction of new energy storage capacity. Finally, we do not calculate the price of the avoided ton of CO₂ as the wind fleet increases in size. This would involve knowing the cost of various technical or financial components (wind turbines, power lines, hydraulic storage capacity, coal and gas prices, discount rates, etc.). Such an effort is beyond the range of this work. We nevertheless believe that some results presented here can be a useful input for a cost calculation.

Ministry of Environment, or SER: the French renewable energies lobby). In this document, for the installed wind power and its evolution, we rely on information published on the ADEME website (<http://www.suivi-eolien.com/>) which also specifies in which region the turbines are erected.

⁴ To convince oneself of this fact, it suffices to compare the map of wind potential over France, given for instance on the ADEME website with that of the wind-power regional distribution regularly updated by the Ministry of Environment. For instance at the end of March 2011, the installed powers in the not so windy Champagne-Ardenne and Lorraine regions were 800 MW and 530 MW respectively, while it was only 420 MW in the Languedoc Roussillon region which has one of the largest wind potential.

⁵ It was not possible at the time of the Grenelle discussions, since ADEME had interrupted the publication of wind data since mars 2006. RTE data has only been available since 2010 July 1st. Thus the Grenelle discussion on wind energy took place in the absence of any publicly available information.

⁶ Recently the Commission de Régulation de l'Énergie estimated the cost to the consumer of the MWh produced by onshore wind turbines at 86€. For a mature industry such as wind there are little hopes of cost reductions. Presently, the wind MWh cost is thus about twice larger than that of conventional power plants (fossil or nuclear powered). This ratio is between 4 and 5 (definite values for France will be available in the first half of 2012) for offshore turbines.

⁷ In Germany, network managers are allowed to disconnect wind turbines when they estimate that large inputs of wind electricity endanger the stability of the network. On the other hand, the producers of wind energy have obtained to be paid for the electricity they don't produce.

⁸ Appendix B of the "Sauvons Le Climat" document "Le vent souffle où [et quand] il veut" (It can be downloaded from the website : <http://www.sauvonsleclimat.org>) gives additional illustrations based on Danish and German wind data during the cold waves of Dec2007 and Jan2010.

⁹ The wind turbines of the French firms AREVA and Alstom are built in Germany and in Spain.

This work is concerned with continental France¹⁰. It relies on the detailed information on energy production and consumption which the French Electricity Network RTE (Réseau de Transport d'Electricité) has recently started publishing on its web site¹¹ (with a time resolution of a quarter hour). Here, we do not analyze the rich content of the data provided by RTE. We refer the interested reader to the "Sauvons le Climat" (SLC) publication: "Le vent souffle où [et quand] il veut" (see footnote 8).

The present work covers the six months from September 2010 to February 2011. For the sake of concision in the rest of this document we reserve the usage of the word *semester* (in lowercase italic) to this particular period.

In percent of France's electric consumption, Table 1 gives the energy delivered to the network by various means of production. As is well known, the fraction of electricity which France produces from fossil fuel powered plants is less than 10%. We analyze in what measure the planned deployment of wind turbines may help to further decrease it.

Oil	Coal	Gas	Nuclear	Wind	Hydraulic ¹²	« Autres »	Import-Export	Consumption	Production
0.39	3.82	3.36	80.15	1.99	8.59	7.03	-5.33	100	105,33

Table 1. Percentage of French electric consumption over the *semester* Sept2010-Febr2011 delivered by various production modes. The column "Import-Export" corresponds to cross-border exchanges. The negative sign indicates a dominance of export. We explain below what the column labeled "Autres" (Others) corresponds to. Transport losses over the network, not shown here, should in principle be added to the production column.

As announced by its title, this work also attempts a projection of what could be expected from the realization of the Grenelle planning. We consider 20 hypothetical France(s). Each has the same population living under the same weather conditions and with the same economy. Thus each has the same electricity needs (consumption) as had the real France during the *semester*. These twenty countries will only differ from the real one in that each has a some additional installed wind power: 1, 2, ... or 20 more GW.

The fatal character of wind insures that, in a first approximation, the delivered energy in each of these twenty Frances is at any time larger by a constant factor¹³ than that measured by RTE. There is some uncertainty on how this factor will grow in relation to the additional installed wind power. Indeed, it could be that the overall efficiency decreases as the wind fleet gets bigger (as it has been observed in Germany). This stems from the necessity to implant turbines in less and less favorable places. On the other hand, out of the 20 GW which are still missing, the French government has decided that 6 GW will correspond to offshore wind turbines which are advertised to be much more efficient. However, the unreliability of earlier predictions of wind efficiency by promoters of this energy justifies some caution. In the face of these unknowns, we have adopted the simplest solution, i.e. a straightforward proportionality of delivered energy to the installed power. In Section D, most results will be plotted as a

¹⁰ It excludes Corsica, the French Caribbean islands, the Réunion island and New Caledonia.

¹¹ <http://www.rte-france.com/fr/developpement-durable/maitriser-sa-consommation-electrique/eco2mix-consommation-production-et-contenu-co2-de-l-electricite-francaise#mixEnergetique>

¹² Here "Hydraulic" only refers to mountain dams. RTE includes the production of dams on rivers in the "Autres" section.

¹³ Admittedly, the same proportionality factor at any time may not be strictly valid, depending on the geographical implantation of the additional wind turbines within France. On the other hand, the comparison of wind data, from France, Germany, and Denmark indicates that the geographical averaging of wind production often given as an argument supporting wind energy deployment in France (by ADEME for instance) or elsewhere, is not convincingly demonstrated. Only the publication of regional wind data, or even better, of a selection of wind parks data over several months would clarify the situation. At the qualitative level of the present work, we estimate that we can neglect this effect.

function of additional installed power ranging from 1 to 20 (GW). Should experience show a decreasing (resp. increasing) efficiency of the future turbines a global or local horizontal stretching (resp. compression) of the figure would yield the correct curves.

We assume that the present French regulation, which gives the highest priority to the injection of renewable electricity such as produced by wind into the network, is still enforced in the twenty hypothetical France(s). Since, according to our hypotheses, consumption is the same as was measured by RTE, other means of production, coal, gas, oil, hydraulic and nuclear, will have to decrease their production to make way for the additional wind production.

We have seen (Table 1) that RTE data also contains information on the time evolution of the cross-border electricity exchange. However, since it almost always corresponds to export and certainly always does when the wind blows, we didn't consider it as an option to compensate extra wind energy production¹⁴.

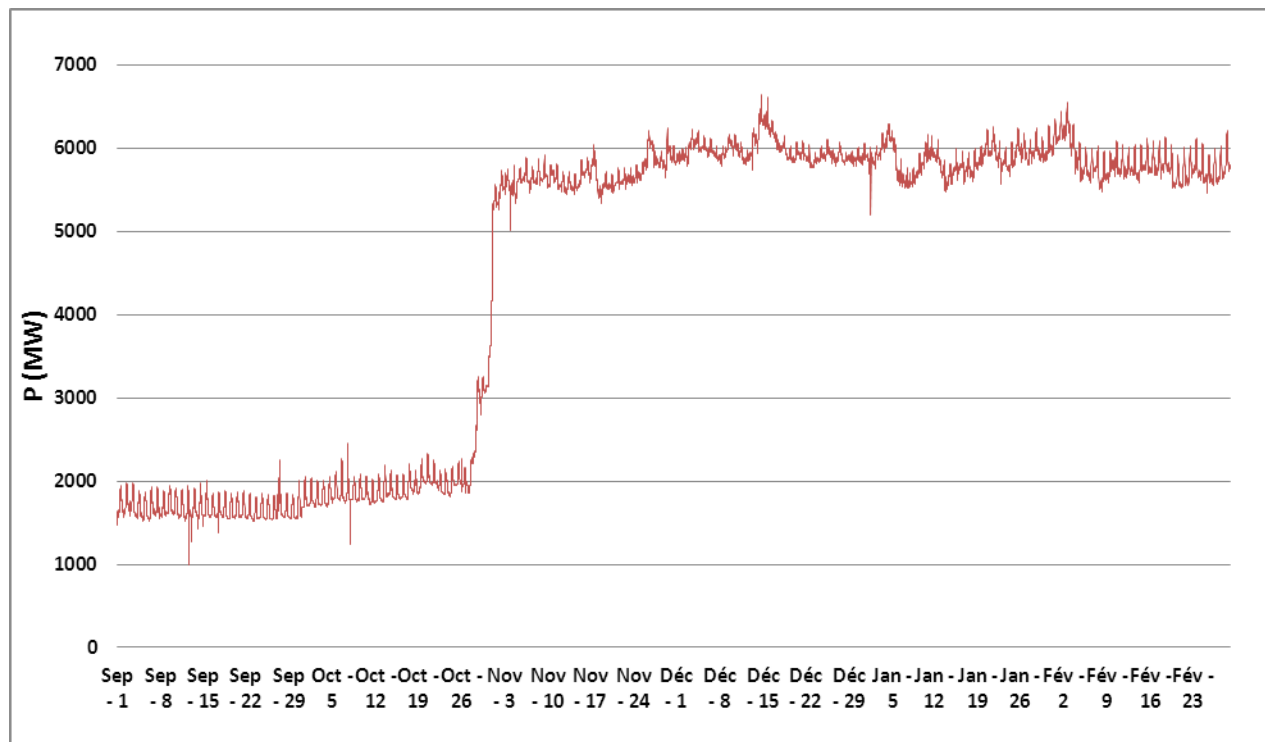


Fig.1 Time evolution of the power associated the “Autres” production (see text) over the semester.

The data set also provides figures for a production that RTE labels “Autres” (Others). “Autres” appears to sum up various productions such as from dams on rivers (Rhône and Rhine), the Rance tide plant, small hydraulic, biogas, biofuel, waste, photovoltaic solar and also cogeneration turbines¹⁵. For two different reasons, these energies can be considered to have the same fatal character as the wind energy. This is obvious for all but the last since Nature (or Society in the case of waste) dictates how much is produced for a given installed power. For the cogeneration gas turbines, the reason is different. Their electric production, although it generates CO₂ emissions, is subsidized from the 1st of November to

¹⁴ As experienced by Denmark, exporting electricity when there is too much wind has not a good economic value. In addition, it would not help reducing French CO₂ emissions. We also do not consider that countries which refuse nuclear power for themselves would accept importing nuclear produced electricity to reduce their CO₂ emissions.

¹⁵ On January 1st 2011, the national electricity distributor ERDF reported the following installed powers: small hydraulic 1.3 GW, biogas and biofuel 196 MW, waste 442 MW, solar 808 MW.

the 31st of March. As a result, the time evolution of the “Autres” production shown in Fig.1 is fully disconnected from either the consumption of French society or the financial constraints of the electricity market. On the first of November, one witnesses a sudden jump of the production. From then on, night and day, the production remains at the same value and is only affected by slow evolutions such as, for instance, the increasing efficiency of river dams as one enters a rainy season. Thus, we assumed that Nature and the French government (which decrees when a production should be subsidized) had decided that the “Autres” production had a fatal character and could not be used to accommodate fluctuations of the wind production.

As explained in Sect. C.2, our calculation, assumes that any power adjustments imposed by wind energy falls on the shoulders of the coal, gas, oil and nuclear plants. Hydroelectricity from dams is also called upon. Finally, we investigate how much can be expected from the pumped-up hydraulic energy storage capacity.

Before getting into the prospective analysis announced in the title, we review some data on the French wind production as it has been measured by RTE over the *semester*. This is a period in which, on the average, wind energy is more productive than during the other half of the year.

B) The wind production in continental France over the *semester* Sep2010-Feb2011

A study of the contributions of the controllable modes of production (coal, gas, oil, hydraulic nuclear)¹⁶ show that they adjust the power they deliver in time to satisfy the electricity consumption needs of the country. Of course, the introduction of their production into the network also depends on the “cost merit order” principle which each producer manages by taking into account the estimated needs of its customers, the characteristics of its own specific fleet of power plants and the value of the electric MWh on the open market¹⁷.

Over the *semester*, according to ADEME (see footnote 3), the installed wind power within continental France has grown from 5 GW to almost 5.5 GW. Uncertainties of the order of a few hundreds MW exist on these values. For this analysis, we have chosen to neglect this evolution and to assume an average value of 5.24 GW for the installed wind power. This choice puts the wind production of the last two months in a more favorable light as compared to that of the first two. Figure 2 displays the evolution of the wind power connected to the network during the *semester*.

The curve displays the irregular fluctuating pattern well known for this electricity production mode. Needless to say, these fluctuations are not correlated with the evolution of the French consumption. The average power 1.27 GW corresponds to a 24.3% load factor. The time smoothing which, according to ADEME, should result from geographical averaging of the French wind production (thanks to some expected de-correlation of wind over the three French sea fronts) is not detectable. Wind production can be very weak over long periods all over France (September, second half of November).

¹⁶ See reference given in footnote 8.

¹⁷ The « merit order » principle applies neither to wind energy nor to « Autres » which both benefit from a priority of injection into the network.

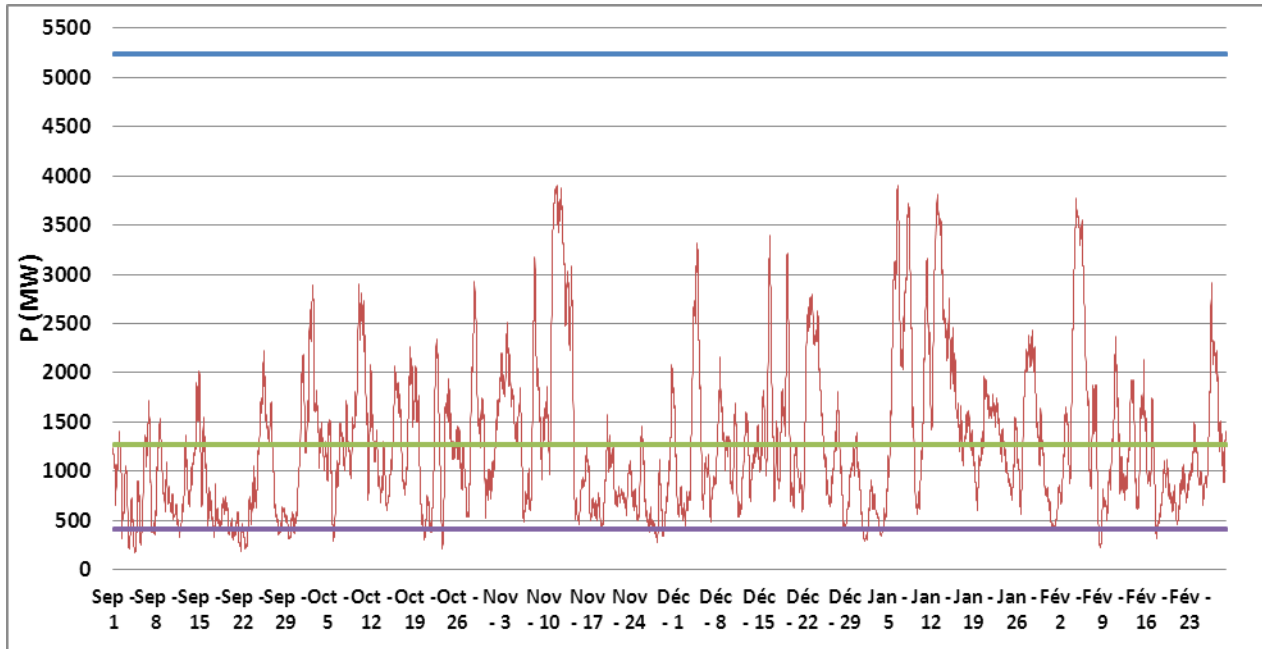


Fig.2 Time evolution of wind power production in continental France over the *semester*. The blue horizontal line at the top indicates the averaged-over-the-*semester* installed power (5.24GW, see text). The green line indicates the average power delivered to the network (1.27 GW). The purple line gives the power which is warranted at the 95% level (407 MW, see text).

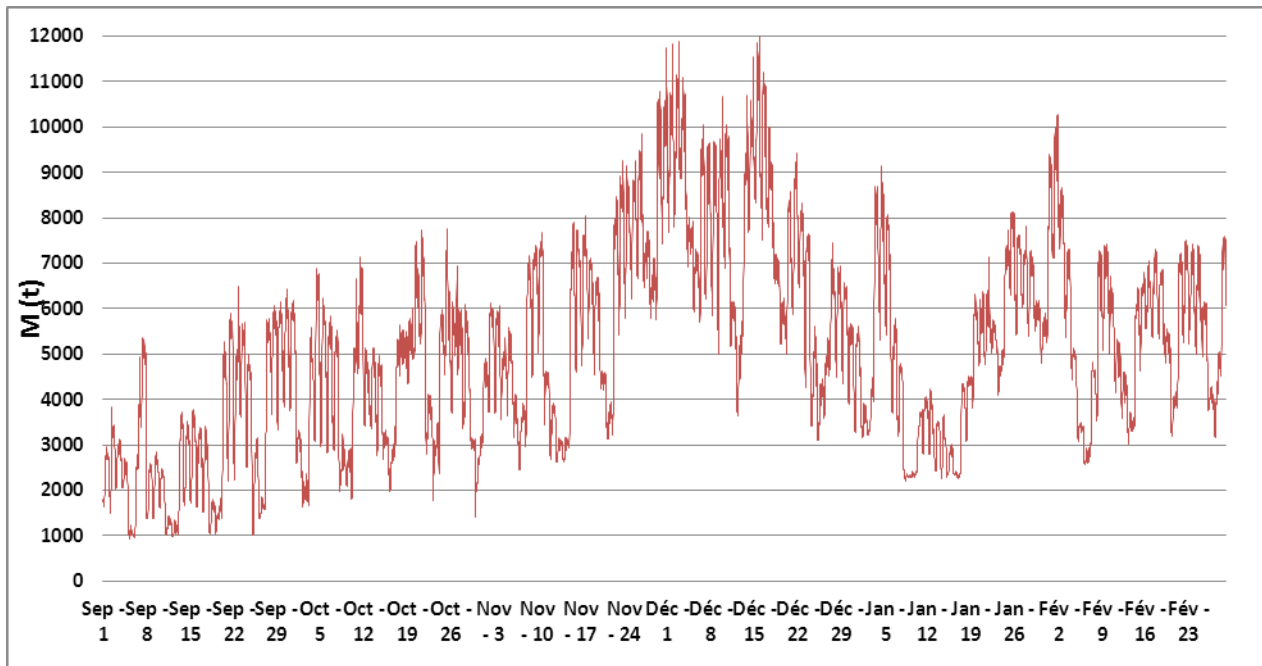


Fig. 3 Time evolution over the *semester* of the CO₂ emissions (in tons) associated with French electricity production as given by RTE. Although plotted for every 1/4h the values correspond to what would be generated over a full hour with the distribution of production means.

The “warranted” power (purple line in Fig. 2) indicates which power could be delivered at a 95% certainty level¹⁸. Its value 407 MW, about 8% of the installed wind power, provides a first indication of the amount of controllable power which could be pulled back thanks to the construction of the present 5.25 GW wind fleet. The results given in Section D confirm this order of magnitude.

Before returning in more detail to the wind production, in Figure 3, we present the time evolution of the CO₂ emissions (in tons) associated with French electricity production. It displays typical daily and weekly patterns. On the average, the CO₂ production has been the largest during the cold and almost windless period which covered the second half of November and the first half of December. The relatively smaller electricity consumption during the Xmas-New year season is also visible.

One observes some signs of anti-correlation between the CO₂-emissions and the wind power curves. During the cold period, the wind production was small. The four peaks of wind production (1 in November, 2 in January, 1 in February) correspond to minima of CO₂ emissions. As a matter of fact, the coal and gas plants were almost turned off during these periods. The CO₂ emissions were mostly generated by the cogeneration turbines in the “Autres” production. Since these emissions are, in some sense, protected by subsidies, the wind energy can’t help reduce them.

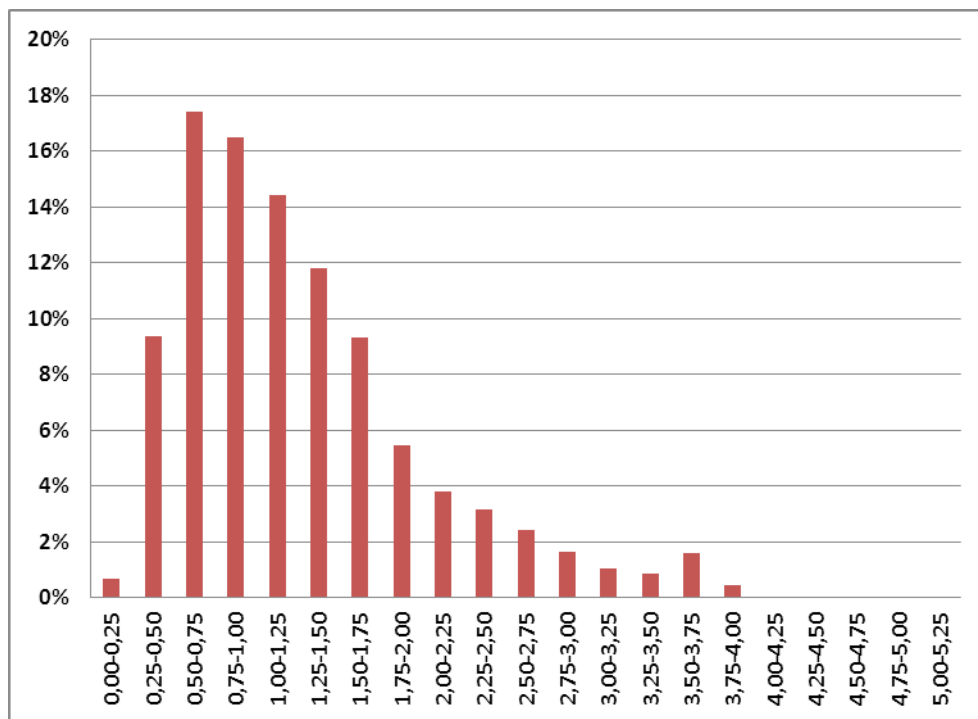


Fig.4 Distribution of the number of 1/4h (in % of the total number: 17376) versus the power delivered by the continental France wind fleet (energy width interval 250 MW). The average installed wind power is 5.24 GW.

The contribution of wind can also be analyzed in terms of the number of 1/4h during which the delivered power belongs to a given energy interval. Fig.4 shows this distribution. In agreement with the average wind power over the *semester* (1.27 GW) the distribution peaks between 0.50 and 1.25 GW. Only during a small percentage of the time has the power been larger than half the installed power. The probability of a power smaller than 1/10th of the installed power (525 MW) is larger than that of a power

¹⁸ The statutory obligation of RTE is an average default of electricity furniture to consumers not exceeding three hours per year, a value much lower than 5%.

above 50%. Over the *semester*, the load factor of the wind fleet has only exceeded 70% (i.e. 3.7 GW) for a few days (November, January and February)¹⁹.

Fig. 5 analyzes that period of November which was particularly favorable to the wind energy. It roughly extended over a half week from Thursday 11 to Sunday 14. As shown by the left graph, the wind power often exceeded 3 GW. On the other hand, for two reasons, the national request for electric power was very low during these few days. First, the Atlantic depression which generated the high winds also brought with it relatively mild temperatures. Second, on Thursday, the long weekend associated with the 11th November celebrations had begun. Not much power was needed to cover France's electricity consumption. The output of the coal, gas and oil power plants was very small. As explained in Sect.A (see Fig.1), "Autres" didn't modify its production. Thus the task of simultaneously balancing the evolution of the consumption and the untimely surplus of wind electricity fell exclusively on hydraulic dams and nuclear power plants. At that time only about 50 GW of nuclear power were available²⁰. As a consequence, nuclear power could only be adjusted downward as is visible in the graph on the right. One sees that EDF was able to lower and boost up the production of its plants by more than 8 GW (1/6th of the available power) over only few hours. This illustrates that, despite the often made statement that nuclear energy can only work as a base-load energy²¹, it has enough flexibility to participate to the regulation of the network (so-called operation in the "gray rod mode").

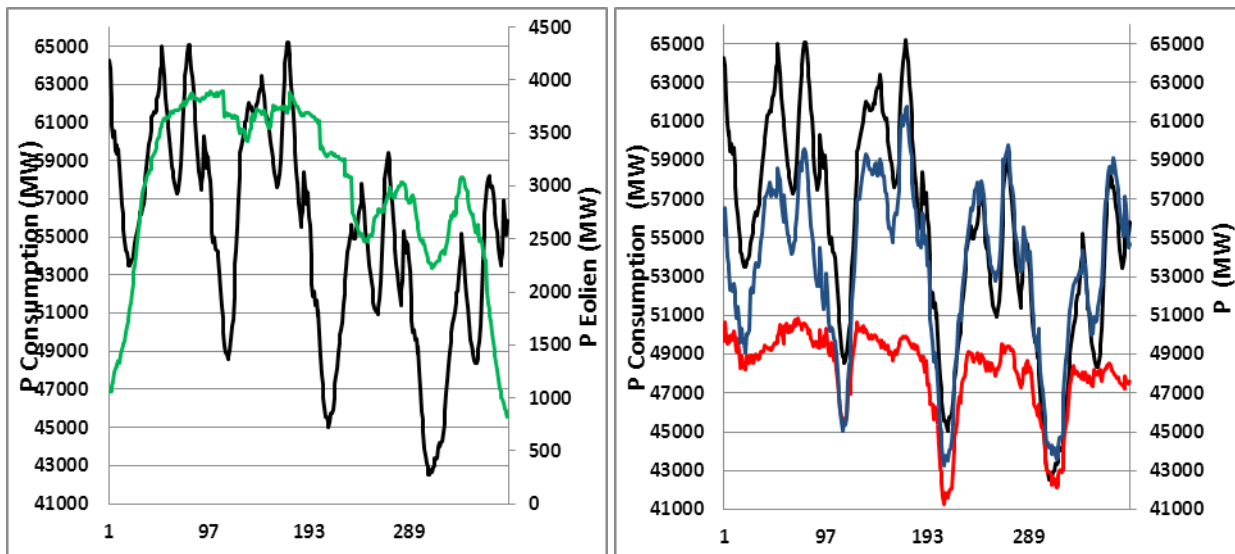


Fig.5 time evolution of the country electricity consumption (black curves and left scales on both graphs) over the four day period from November Thursday 11 to Sunday 14. The left graph shows also the evolution of wind production (green curve, scale on right side). The red curve in the graph on the right gives the nuclear production. The blue curve is the sum of nuclear and hydraulic (dam) powers. Time abscissa is given by the number of 1/4h with a numbering starting on November 11th 00:00. Consecutive labels correspond to 1day (96 1/4h).

¹⁹ Such events are so extraordinary that they often generate communiqués from the renewable energies lobby (SER).

²⁰ This might be a consequence of the maintenance and refueling planning of the fleet nuclear power plants. It has to be decided a long time in advance. It is only at the beginning of January 2011 that EDF announced that all its power plants (~60 GW) were operational.

²¹ Of course, operating a nuclear power plant for base-load production has optimal economic value since yearly load factors of 95% are accessible.

The Figure 6 shows the gradients²² of wind power (unit MW/h). One sees that they often exceed 200 MW/h. Sometimes they are as high as 400 MW/h²³. By the year 2020, when the wind fleet power reaches 25 GW (factor five bigger) it will be necessary to keep the equivalent of a 2 GW plant with a rapid kinematics in a permanent state of readiness in order to compensate erratic wind fluctuations. Over the *semester*, RTE data shows that maximal gradients of the French consumption never exceed 8 GW/h. Therefore, when the ambitions of the Grenelle are reached, the difficulty of stabilizing the electricity network will have increased in absolute value by more than 25%.

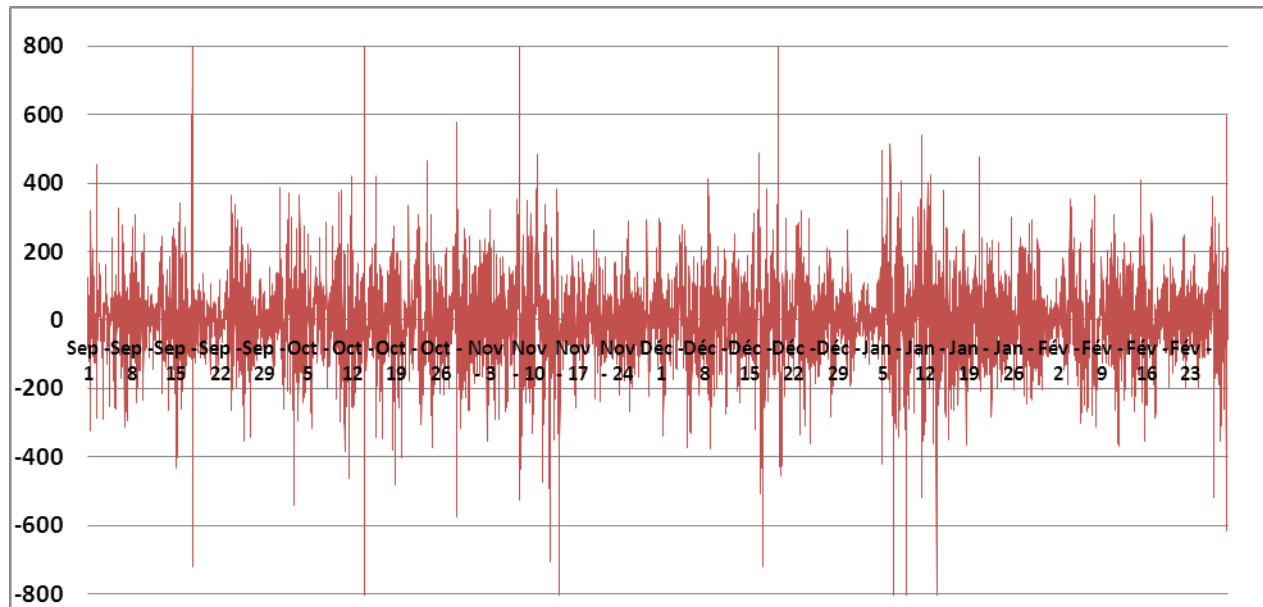


Fig.6 Time evolution of the wind power gradients (see text and footnote 22) in unit MW/h over the *semester*.

Figure 7 shows the wind power as a function of the electric consumption power. Over the semester this power varied from 35 GW (September) to almost 95 GW during the cold period in the first half of December. By splitting this interval into bins of 2.5-GW width we can estimate whether a given production adjusts to the electricity needs of the nation²⁴. In Fig.7 the height of each bar gives the averaged wind power over all 1/4h falling into a given interval of consumption power.

It can be seen that the average power in each bin fluctuates about the average (1.27GW) over the entire range of consumption powers (first bar: “average”). This illustrates the “indifference” of wind energy with respect to the electricity needs of the French society needs. Wind delivers about the same power whether the request for electric power is small or big. In that respect, it behaves very differently from all other production modes listed in Table 1 whose productions are correlated to French consumption.

²² The power gradient (unit MW/h) for a given quarter hour measures the speed of variation of the power at this time. It is a crucial parameter for the network stability. Here, for each point, it is calculated as twice the difference of power delivered during the 1/4h before and after.

²³ Although some points in Figure 6 correspond to gradient values up to 800MW/h, we chose not to consider them. Indeed, it is not obvious that the quality of the data published by RTE warrants dwelling too much on their significance. We do not consider gradient values when they only rely on a set of three consecutive values of wind power.

²⁴ This value, 2.5 GW, is such that the number of 1/4h falling in each bin is large enough (over several hundreds) to justify statistical treatments such as averaging.

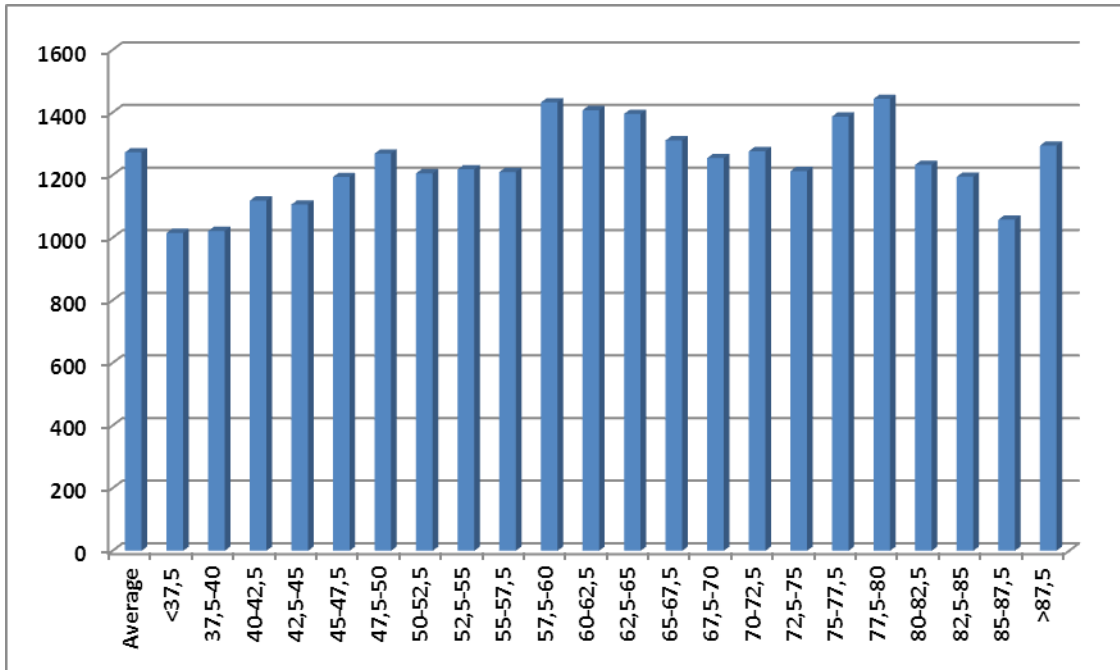


Fig.7. Wind power (MW) delivered to the network versus consumed electric power (interval width 2.5 GW). The first bar gives power delivered to the network averaged over the entire range of consumption power from 35 GW to 95 GW.

With Figure 8, we conclude this section by a comparison of the correlation of wind and nuclear powers with the French consumption power (2688 points, one for each 1/4h) over the month of February 2011. In the left graph (wind), aside from an interesting Jackson-Pollock-dripping pattern, the trend, if anything, is mostly one of anti-correlation (down-going trend). By contrast, in graph B (nuclear), the positive correlation is obvious. On the right side of graph B, one also observes a saturation (the points accumulate on vertical lines). This is an indication that the availability of several more GW of nuclear power could have been useful and would have avoided calling fossil-fuel burning power plants.

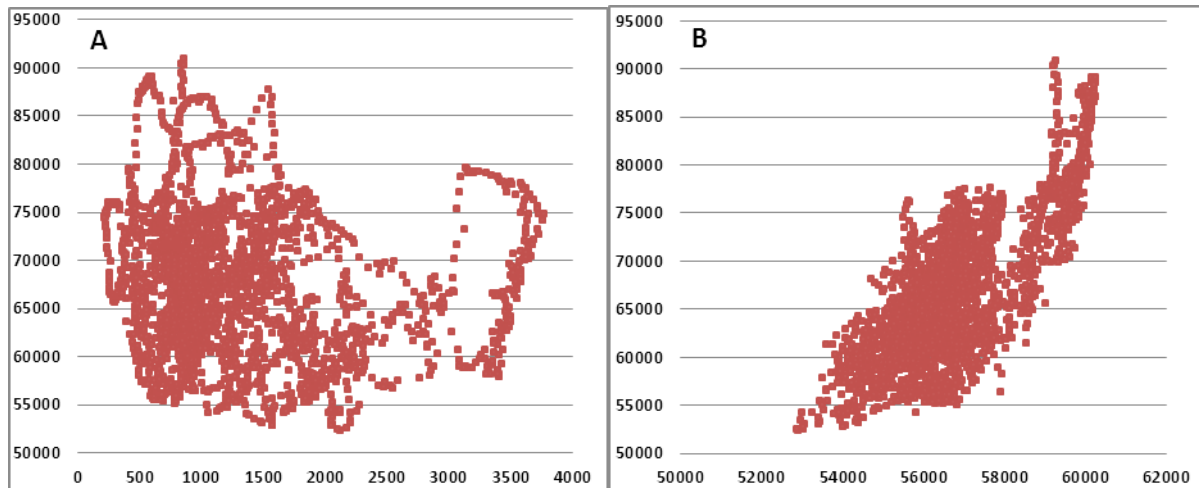


Fig.8 Correlation of consumption electric power (vertical axes) over the month of February 2011 with the wind power (graph A, horizontal axis) and the nuclear power (graph B, horizontal axis). Horizontal of graph B is compressed by a factor 2.5 relative to graph A. Powers are in MW.

Following this brief review of what happened in the France of 2010-11, we elaborate on this knowledge to estimate how the realization of the Grenelle goal for wind energy can help the country in

its fight against CO₂ emissions. The next section describes our method of calculation and the hypotheses it is built upon.

C An algorithm to estimate maximal CO₂-emission reduction by wind energy

C.1 Principle

According to the goal stated in Sect.A, the following algorithm investigates how, in the 20 hypothetical France(s), the extra wind energy provided by the additional 1, 2, ... 20 GW of new wind turbines can be used to **maximally** reduce the CO₂ emissions which RTE has measured over the *semester*. We recall that we assume that the power delivered by any installed GW of turbine is the same fraction, 1/(5.24) of the wind power measured by RTE.

C.2 Implementation

Our calculation proceeds in three stages. Section C.4 discusses the hypotheses on the network, the electric production means and the energy storage systems, it relies on.

Stage I. This first stage includes the following succession of steps. It is qualified “**instant**” in the rest of the document

- One first assumes that any amount of wind power can be made to instantaneously cancel the same amount of power generated by coal fired plants.
- Should there be enough wind power to annihilate the complete coal fired plant production, we turn to gas plants and proceed in the same way.
- After the gas plants, we treat in the same manner the oil powered turbines (in France, they produce very little electricity, mostly at times of peak power consumption, when wind energy production is small).
- It sometimes happens that there is more wind power available than is needed to stop all fossil-fuel-burning plants. We then choose to use the extra wind power to decrease the production of the hydroelectric dams, keeping water in their reservoir. Stage II uses this saved hydraulic energy to decrease the output of coal, gas and oil plants at later times.
- When the magnitude of wind power allows a complete stop of the flow of water into the dam turbines, in order to balance the production versus the consumption, three options are open.

Option 1: Some nuclear power is turned off or equivalently the additional energy sold at its market value. Presumably, it will be at a small price²⁵, given the fact that wind overproduction often tends to affect simultaneously all European countries within intervals of at most few hours²⁶.

Option 2: The wind turbines are turned off so as to not disrupt the safe operation of the network (see footnote 7).

Option 3: It will be investigated in the Stage III of the algorithm. We assume that water storage reservoirs (pump upward and turbine downward) can be called to help. In the rest of this document, this type of reservoirs is referred to by its French acronym STEP

²⁵ In some instances, negative prices have even been observed on the electricity markets.

²⁶ This is illustrated by a comparison of French and German wind productions when the cold anticyclone hit and then left Europe over the month of January 2010. The data are shown in Fig B.3 of the Appendix B of the SLC document “Le vent souffle où [et quand] il veut”. See footnote 8.

(Station de Transfert d'Énergie par Pompage)²⁷. Again the stored energy is used to reduce coal, gas or oil power at later times.

Stage II. We call it “delayed-hydro”

When, thanks to wind, some water has been preserved in the reservoirs of the mountain dams, we use it to decrease as much as possible the electricity production from coal, gas and finally oil which remains after the instant reduction described in Stage I has been effected. This is performed as soon as possible, until all the energy saved in the reservoirs thanks to former large wind electricity production has been used. An accounting of how much energy (implicitly) goes in and (explicitly) goes out of the hydraulic reservoir is kept. The calculation introduces no constraint on how much wind energy can be saved in this way or on the maximal hydroelectric power when it is later used to reduce electricity generation by fossil plants. For France, in first order²⁸, this is a plausible assumption since, in all the calculations performed within the Grenelle framework, we find that that the energy saved through this “delayed-hydro” scheme never exceeds 1.4 TWh. Moreover, the combined power of all fossil burning power plants compares well with the power that French dams can deliver.

Stage III. We call it “delayed-STEP”

We consider now what was called “Option 3” in the last step of Stage I. Instead of turning off the wind turbines or slowing down the nuclear plants, we assume that we can ask STEPs to save part or all the wind energy which, after Stages I and II, remains once all fossil and hydroelectric production has been cancelled. In Stage II, the saving of energy didn't involve a physical flow of water but rather prevented it by keeping the water inside the dam reservoirs. In contrast, with a STEP, the saving of energy involves pumping of some water up from a lower to a higher elevated reservoir. It leads us to introduce three constraints into the calculation. First, there is a limit on the power for either the up or down-going flows²⁹. Here, we take 5 GW as it approximately corresponds to the combined power of the six French STEPs presently in operation. Another parameter is the total energy capacity of the STEPs. In France, in most cases, it is determined by the volume of the lower reservoir. Although no figure is published, based on the power and operation times of the STEPs, the total energy storage capacity of the French STEPs can be estimated to be smaller than 120 GWh³⁰. This is the value we use to obtain the results presented in Section D. As we will see, this is a rather small value. It corresponds to less than two hours of fall or winter French consumption while windy periods up to a two or three days can happen. During a high wind spell, for the wind turbine fleet announced by the Grenelle, there is more wind electric energy remaining (red zones in Fig.10 or B.1) than can be stored in the available French STEPS³¹. Once the STEPs storage capacity is exhausted, the extra electric energy must either be cancelled (turning off wind turbines) or compensated (reducing nuclear power, attempting to export the electricity). The

²⁷ We have not studied other advertised ways of storing energy such as batteries or hydrogen. The present technical performances of the former do not appear to be adequately sized for the amounts of energy involved for a country such as France. It does not seem that the latter can be available before several decades. The technical and economic competitiveness of both, as compared to STEPs, is far from ascertained.

²⁸ For a discussion, see Sect. C.4 items 5) and 6).

²⁹ The pumping stage of a STEP (consuming electric energy) may function at a different power than the production stage (giving back part of the saved energy to the network as hydroelectricity). Differences may correspond to several hundred MW. Our calculation neglects this feature.

³⁰ No value for the French STEPs energy capacity is available in the literature. On the other hand, summing the products of the powers (GW) of the French STEPS by their operating time (hours) leads to a value slightly exceeding 100 GWh.

³¹ Our calculation shows that, for a full efficiency in the saving of wind electricity, the STEPS must have a total power of 13 GW and a storage capacity of the order of 0.5 TWh (4 times the present French capacity). Apart from the difficulty of finding socially acceptable sites, the corresponding cost investment would be rather high.

last STEP parameter is the global efficiency of a STEP cycle. In the present work, we have assumed the same efficacy for pumps and turbines. We have worked with the value $0.723 = (0.85)^2$.

C.3 Illustration

In order to show the functioning of the three stages of this algorithm, we consider a month of November 2010 and a hypothetical France in which instead of 5.24 GW, there are 25.24 GW of installed wind turbines. Because of its simple wind pattern, the month of November 2010 demonstrates well how Stages II and III of the calculation work. Indeed, during the first half of the month, the temperatures were mild and the wind blew strongly over France. The second part was cold and the wind became weak. Two months with different wind patterns, December 2010 and January 2011, are discussed in Appendices A and B.

To make the impact of the STEP on CO₂-emission reductions more visible we assume here (while not in Section D) that the STEP energy capacity is 240 GWh; i.e. more than twice the present French situation.

The figure 9 shows the load factor of the French wind turbines last November: the ratio of delivered wind power over the total installed power. The wind pattern described above is discernable. In particular, for almost two days just before the middle of the month, the efficiency exceeded 70%.

The next figure, (Fig. 10), illustrates the Stage I “instant” part of the calculation. We have plotted, superimposed on each other, the coal, gas, fuel, hydraulic and nuclear powers which can be saved with 20 GW more of wind turbines. The powers have been normalized to 20 GW (i.e. 20 GW=100%), so that, by construction, the upper envelope of the set of curves is identical to the curve in Fig. 9. According to the logic of Stage I, coal production has been fully eliminated when the black zone (coal) is topped by a gold color zone (gas). When it is not, as in the second half of the month, it is an indication that some coal production is still not compensated by the wind production. The reasoning can be pursued. When the gold color zone is topped by a blue zone, there is neither coal, gas nor oil production left to shutdown³². Finally, nuclear power (red) is reduced only when coal, gas, fuel and hydraulic production are cancelled. For a wind fleet sized according to the Grenelle recommendation, this is the case in periods of strong wind. One notes that, often when the wind production stops, the coal power jumps up (Nov 15 and Nov 22).

We now proceed to Stage II and use the energy saved in the reservoirs of the dams in the first half of the month (blue zone) to reduce the electricity production from burning fossil fuels in the second half of the month. The impact of Stage II is illustrated in Fig.11. We use the same color coding as in Fig. 10 for the “instant” power reductions of Stage I. The gray, pale yellow and pink zones show the additional reductions of coal, gas and oil power which, in the second half of the month, are made possible by the release of the energy saved by the diminution or the stopping of hydroelectric production (blue zone) during the first fifteen days.

When black or dark gray zones are topped by a gold or pale yellow zone, we know that all coal plants have been stopped. It is the case for the first 26 days of the month. On the other hand, on the 27th, the “delayed-hydro” reduction of CO₂ emissions abruptly stops indicating that all the hydraulic energy preserved in the dams has been used.

³² In November 2010, electricity production from oil burning has been very small, often zero

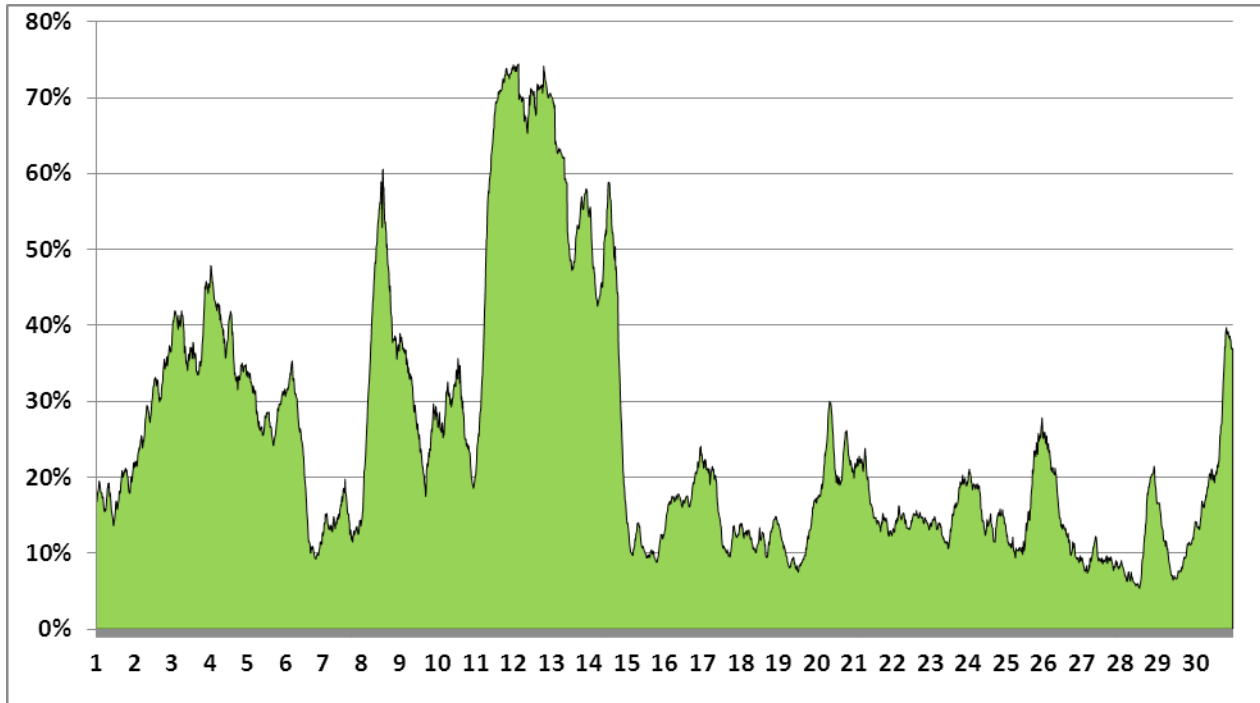


Fig. 9 Efficiency of the French wind turbine fleet over November 2010. Abscissae indicate the day in the month.

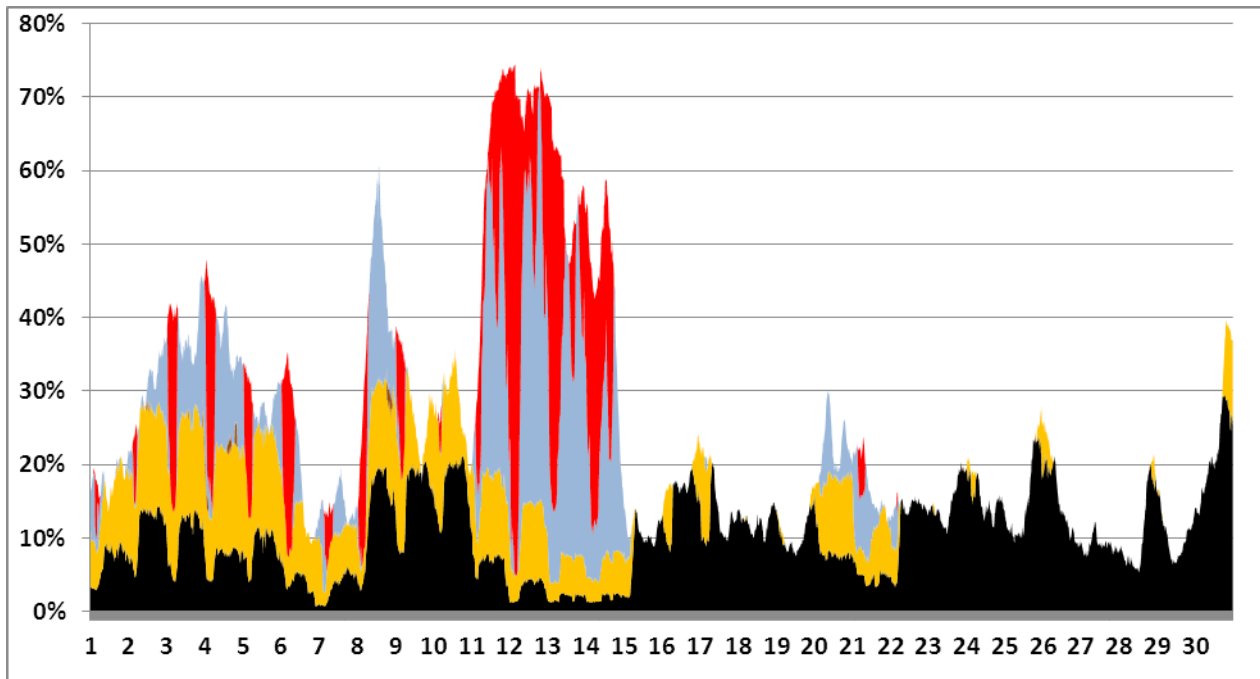


Fig. 10. November 2010. Instant use of extra wind energy. Fraction of the installed wind power (here 20 GW) available for avoiding coal (black), gas (gold), fuel (brown), hydraulic (blue) and nuclear (red) powers. Abscissae indicate the day in the month.

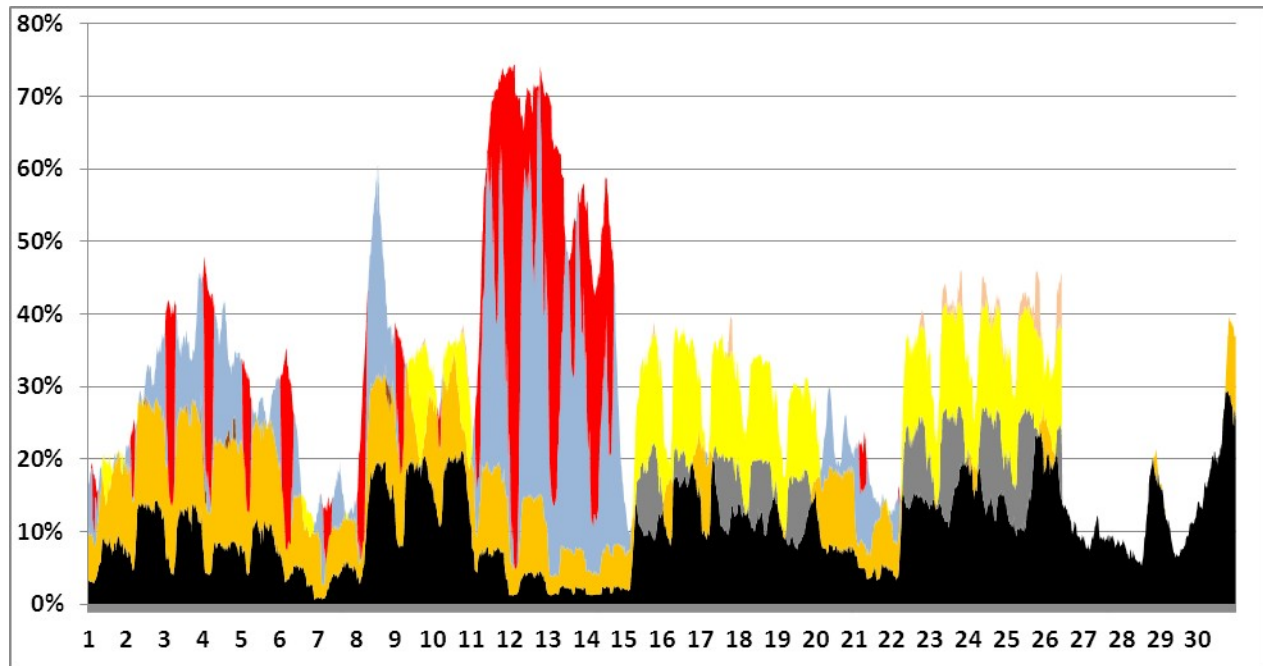


Fig. 11. November 2010. Delayed used of preserved hydraulic energy. Fraction of the installed wind power (here 20 GW) available for avoiding other powers : instant reductions, identical to those of Fig.10, for coal (black), gas (gold), fuel (brown), hydraulic (blue) and nuclear (red) powers ; additional delayed reductions achieved by “delayed hydro” Stage I for coal (gray), gas (pale yellow) and fuel (pink) powers. Abscissae indicate the day in the month.

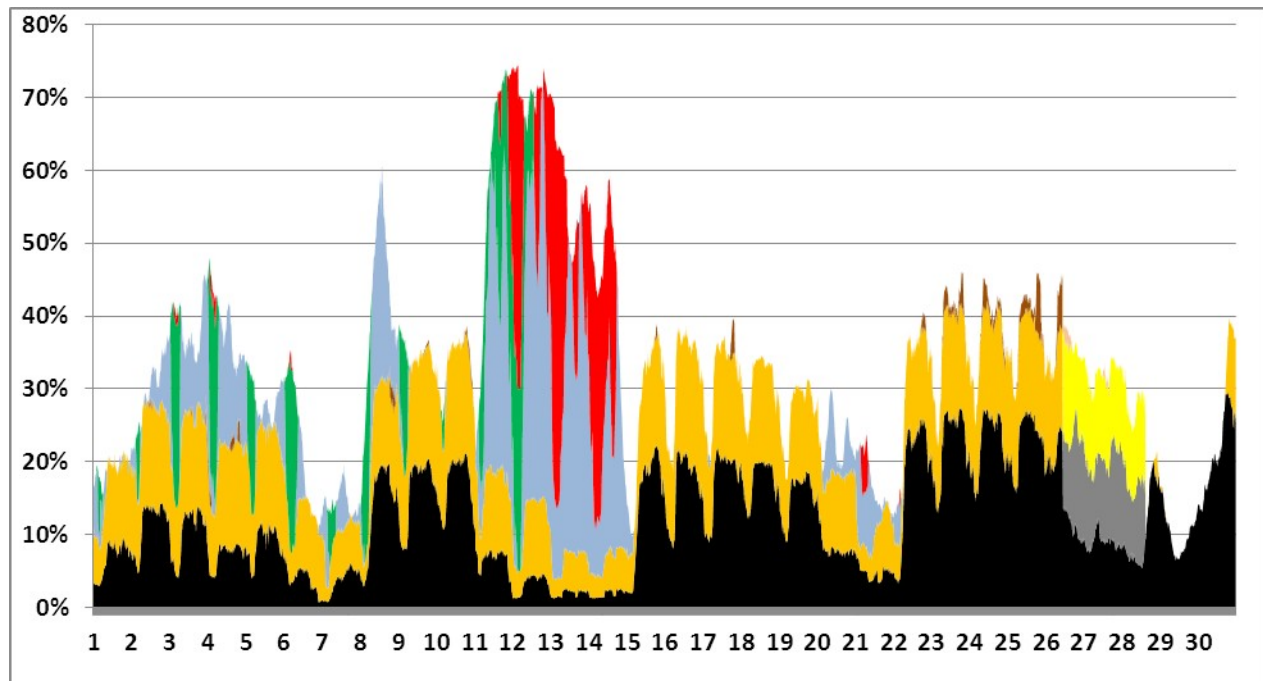


Fig. 12. November 2010. Delayed used of energy stored in STEPs. Fraction of the installed wind power (here 20 GW) available for avoiding other powers. The black, gold, brown, blue and red zones correspond respectively to respectively the (black + gray), (gold + pale yellow), (brown + pink) zones in Fig.11. The green zone shows which power can be saved by the STEPs. This time, the gray, pale yellow and pink zones show the additional coal, gas and fuel power reductions that can be achieved by “delayed STEP” Stage III. Abscissae indicate the day in the month.

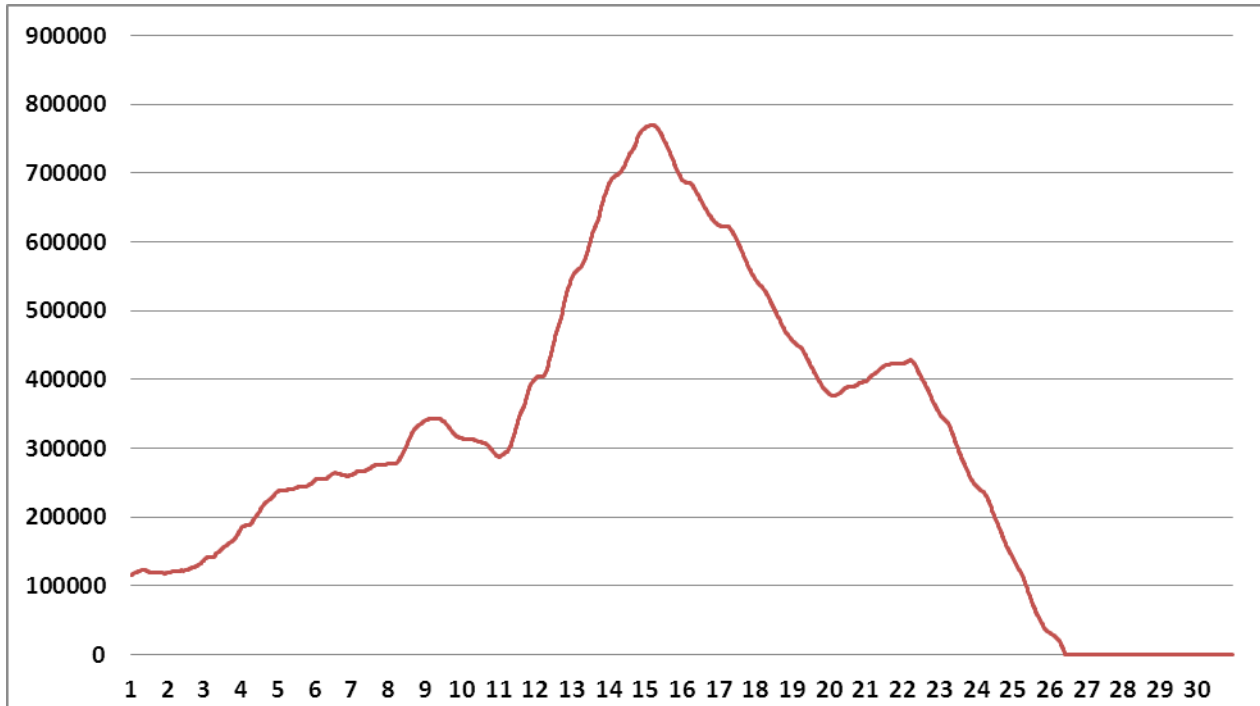


Fig.13. November 2010. Time evolution over November of the hydraulic energy (MWh) originating from the surplus production (after Stage I) of 20 GW additional wind power which is preserved in dams and later spent to replace the production of fossil fuel burning plants. Abscissae indicate the day in the month.

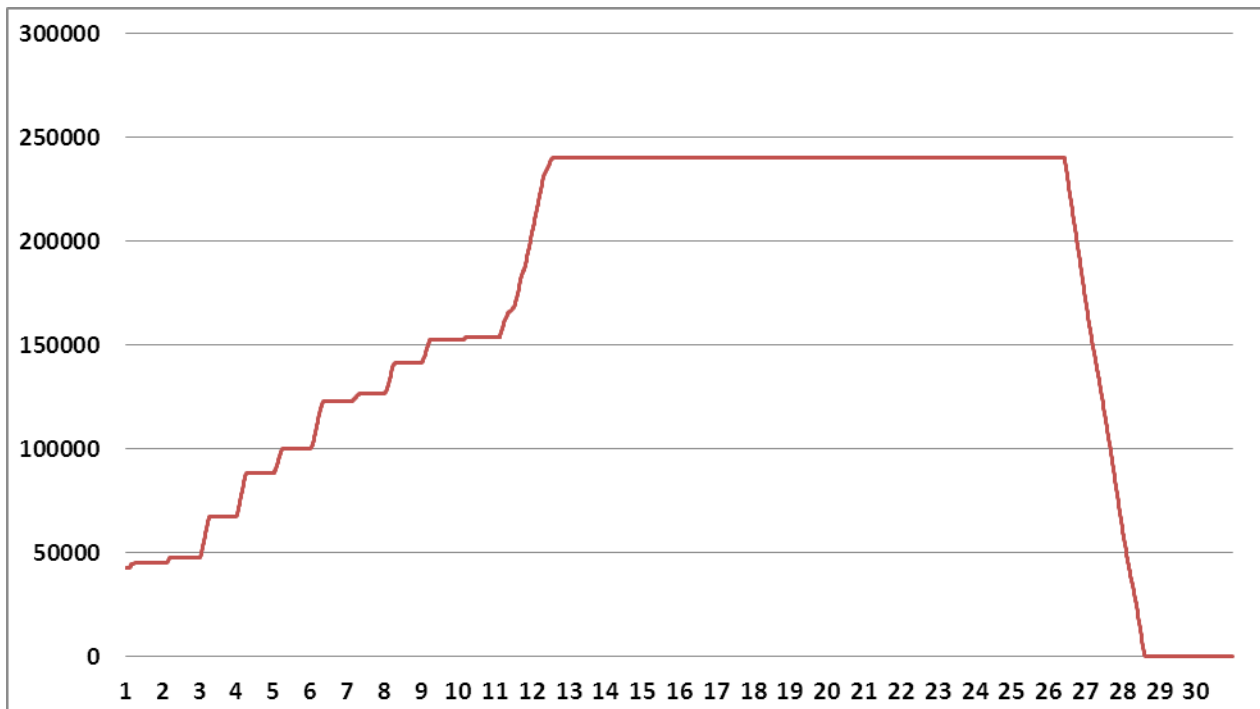


Fig.14. November 2010. Time evolution over November of the hydraulic energy (MWh) stored in STEPs of total capacity 240 GWh originating from the surplus production (after Stage I and II) of 20 GW additional wind power and later spent to replace the production of fossil fuel burning plants.

The effect of the “delayed-STEP” Stage III is illustrated in Fig. 12. The green zone indicates which fraction of the wind energy can be pumped into STEP storage. We observe the effect of the two limiting parameters of the STEP. First, when the vertical extension of the red zone in Figs. 10 exceeds 25% (day 12 for instance) corresponding to a value larger than the STEP maximal power, only the fraction up to 5 GW can be transferred to the STEP. Second, Fig.11 shows that water is moved into the upper reservoir only during the first eleven days. At this point the full capacity of the STEP (240 GWh) is reached and no more energy can be stored. From then on, the red zone in Fig. 12 remains the same as in Fig. 10. No opportunity to empty the STEPs arises before day 27. Then, in less than two days the STEP exhausts its 240 GWh energy content at replacing coal and gas power plants. Appendix A shows that the December cold weather and wind pattern did not provide an opportunity to refill the STEP before the beginning of the Xmas season³³.

We conclude this section with Figs. 13 and 14. They display the time evolution of the energies which are either kept in the dam reservoirs or stored in the STEPs. Fig.13 just as Fig. 11 shows that hydraulic energy is saved over the first half of the month and spent in the second half until day 26 when it is exhausted. At its maximum it almost reaches 800 GWh. Fig.14 gives the evolution of the energy stored in the STEP. Over the first eleven days, it increases until the 240 GWh upper limit is reached. The energy content keeps a constant value till day 26. Then the STEPs replace the dams which have exhausted their saved wind energy. After two days, no more energy is left in the STEPs.

C.4 Assumptions

The hypotheses which underlie the design of the algorithm allow us to obtain an **upper bound** of the results that, in its fight against GHG emissions, the country can expect by enforcing the wind energy policy defined by the Grenelle. Indeed the assumptions on the general organization of the electric system are systematically favorable to wind energy. They are also those that the wind lobby and some NGOs generally take for granted in their argumentation to support a massive deployment of wind power. As we will now argue, they often contradict basic technical facts. Still given the influence of this lobby and the NGOs on the definition of national and international policies, it is worthwhile to follow their logic to its natural end. Only this time, it is applied to real rather than dreamed up data.

Let us list and comment the most important of these hypotheses.

- 1) The network is supposed to be adequately reinforced by the construction of power lines and necessary control systems. It is flexible enough to allow a smooth transfer of electricity in such a way that electricity produced by a wind turbine near Perpignan can be used to decrease the power of a coal plant based in Dunkirk. The same applies for gas, oil, nuclear plants and hydroelectric dams wherever they are. The network can handle any gradient of power imposed by wind energy.
- 2) The manager of the network is able to handle the wind electricity production, wherever it happens and use it to optimally adjust the power delivered by the other plants or dams irrespective of where they are. This is a rather demanding hypothesis. It involves a perfect coordination of the French distributor ERDF which collects most of the renewable energy production, with RTE the operator of the network to which the main power plants are connected³⁴.

³³ By interchanging Stage III and Stage II, i.e. by giving a higher priority to STEP usage over discharging the water preserved in the dam reservoirs, the small red zone at Nov 21, could have been used for STEP storage. However given the small size of the French STEPs (about twice smaller than the value taken in this example) as well as the qualitative character of this study, we think that our main conclusions remains valid.

³⁴ This added complexity is a consequence of the reorganization which France had to implement in order to follow EU directives on the liberalization of the electricity markets.

- 3) Transfers of energy required by the wind industry are performed without any loss. Implementing a 5-6% dissipation in the three stages of the calculation would have been more realistic since this is the value usually mentioned for the energy loss in electricity transport and distribution. To get an approximate idea of the consequences, an appropriate scaling of the horizontal axis of the figures in the “D Results” section is enough. For instance a 5% energy loss means that 20 GW of additional turbines only achieve the performances which the present calculation finds for 19 GW. Any additional GW of installed wind power would thus lose 5% of efficiency in the fight against CO₂ emissions.
- 4) All controllable power plants are able to adjust their production in time, as requested by the wind-power time evolution, whatever its power gradient, whether it could be anticipated or not³⁵. With the exception of dams and possibly oil powered turbines, this is obviously a strong assumption. It would thus be interesting to perform another calculation in which limits are set on the lowest power level of the plants (can a coal-burning plant full stop for several hours and instantly restart to any desired power?) and on the maximum acceptable power gradients.
- 5) The storage capacity above the dams is large enough to keep water for an energy amount of at least 1.4 TWh. The hydroelectric power is larger than 15 GW. These two values do not appear incompatible with the French situation in late summer, fall and early winter when the water level in the reservoirs has already somewhat decreased. On the other hand, there is a limit on how much water a dam can safely hold in its reservoir. In springtime, the melting mountain snow naturally fills the reservoirs. When this happens, the still unused fraction of the water which wind energy has helped save during the winter season will have to be released, whether it can compensate the production of the CO₂ emitting power plants or not.
- 6) In Stages II and III when the energy saved in the dams or via the STEPs is released to cancel the production of fossil burning plants, we assume an independence of this process from the hydraulic production. It cannot be always so since the same turbines are often involved in the three processes. When, at a given time, the dams are used to stabilize the network by regulating the peaks and dips of the French electric consumption, they cannot simultaneously work to help wind energy demonstrate that it can be useful to decrease the production of coal, gas and oil plants. Obviously, the priority of the former mission is higher than that of the latter. It would be a simple matter of programming to introduce into the calculation an upper limit on the power delivered by the dams and to ensure that any power used to compensate CO₂ emitting production is smaller than the difference between this upper bound and the hydraulic power at the same time. This would naturally lead to smaller GHG-emission reductions. On the other hand, we would also run into the same problems that we skirt around thanks to assumption 4) but, this time made more difficult. Indeed, the coal and gas plants would be asked not only to adjust their production to the wind power gradients but to the much larger hydraulic ones. Thus, any improvement of the algorithm requires that assumptions 4), 5) and 6) be handled together. This involves an effort beyond the scope of the present work.
- 7) The electricity producers owning the fossil-fuel powered plants accept to stop their production for the sake of proving the efficiency of wind at reducing CO₂ emissions.

³⁵ Predictions of wind power are unreliable. For instance, in January 2010, the error of prediction for the 10 GW wind turbine fleet connected to the German network EON-Transpower was sometimes as high as 2 GW. This is shown in Fig. B.1 in the appendix B of the SLC report “Le vent souffle où [et quand] il veut”. See footnote 8.

This they do, irrespective of their obligation of electricity furniture to their own customers. Thus, the coal and gas plants although they remain essential during some specific periods are poorly used over the year. Should the producers not graciously accept smaller returns on the investments for the construction of these plants in order to allow maximal reward to investments in wind turbines, it'd be the task of the Commission de Régulation de l'Énergie (CRE) to work out a compensating scheme and to calculate how much of it should be charged to the customers.

- 8) As we will see, wind power makes a far from optimal usage of the STEPs as compared to what could be achieved with a controllable energy. Nevertheless, we assume that STEPS are as much as possible maintained in a state such that they can accept any extra wind electricity coming their way. No other use, no economical reason³⁶, can divert their usage from the sole service of wind energy. In addition, we assume a perfect sharing of either the pumping or discharge tasks between the six French STEPS. This sharing is done in proportion to their power. It is also assumed that the energy storage capacity of each STEP is exactly proportional to its power. Such a proportionality is optimal for energy saving (on the other hand, this condition is far from being satisfied by the present set of French STEPS).

Having described our method of calculation (Section C.2) and discussed its hypotheses (Section C.4) we now present the results obtained when a 5 GW-120 GWh set of STEPs is permanently kept available to the wind energy.

D) Results

RTE data shows that, over the *semester*, coal, gas and oil plant productions have been small in periods of strong wind (see for instance figure 10 or Appendix B). This indicates that some elimination of the power from fossil-burning plants is already implemented³⁷. We do not know what the corresponding CO₂-emissions reduction savings amount to. Here, we only consider how much more can be expected from a bigger wind turbine fleet. Our GHG emission saving counter is set at zero at the present installed wind power (5.24 GW). It is nevertheless clear that during the short periods favorable to wind energy, no significant gains on CO₂ emissions can be expected in the future³⁸.

The three graphs in Fig.15 show which fraction of coal, gas and oil electric energy, produced in France during the *semester*, can be saved in the 20 hypothetical France introduced in Section A. Reduction efforts are first applied to coal plants because of the high CO₂ content of the coal produced MWh³⁹. Gas is ranked second on the priority list. Only after, comes oil⁴⁰. The left graph shows that for the

³⁶ Given the high cost of such installations, this is a rather unlikely hypothesis.

³⁷ The coal and gas power reduction does not happen immediately when the wind electric production rises (see Figs. 10 and A.1) but only after one or two days. The reason may be technical (the windy period could not be predicted) or it may be economics. Indeed, the excess of delivered wind energy leads to a drop in electricity prices on the spot market. For a coal or gas plant owner, it becomes advantageous to buy electricity on the market rather than to produce it. It is worthwhile to note that the wind energy producers do not suffer from the low prices of the electricity they generate. They sell the MWh at the same high price which is guaranteed by the decree.

³⁸ Unless the government stops subsidizing the cogeneration turbines contributing to the "Autres" production.

³⁹ In its evaluations, such as those leading to data plotted in Fig. 3, RTE uses the following values: coal 0.96 t/MWh, gas 0.30 t/MWh, Oil 0.8 t/MWh. See Sect.E for comments on the value RTE attributes to gas.

⁴⁰ Although oil has a higher CO₂ content than gas, this choice was made for two reasons. First oil weighs very little in the electricity production of continental France (see Table 1 and 2). Second, it is used mostly to handle extreme peaks of consumption when generally wind energy production is small for a long time. Then none of the actions performed in Stages I, II and III can affect it. Permuting the order of gas and fuel in the reduction scheme would certainly lead to an upward move of the brown curve. On the other hand, it would slightly lower the gold curve. In addition, it would only marginally change the main output of this calculation: the CO₂-emission reduction results

coal emissions, for 5 GW more of installed wind power, the Stage I reduction is 40%. It is 63% for 10 GW and 85% for 20 GW. The corresponding figures for gas produced electricity are 8%, 22% and 53%. Preserving water in the dam reservoirs and using it later moves both curves upward. For coal the figures becomes 40%, 66% and 93% while for gas, now that most coal production has been stopped, the figures are significantly higher: 11%, 33% and 82%.

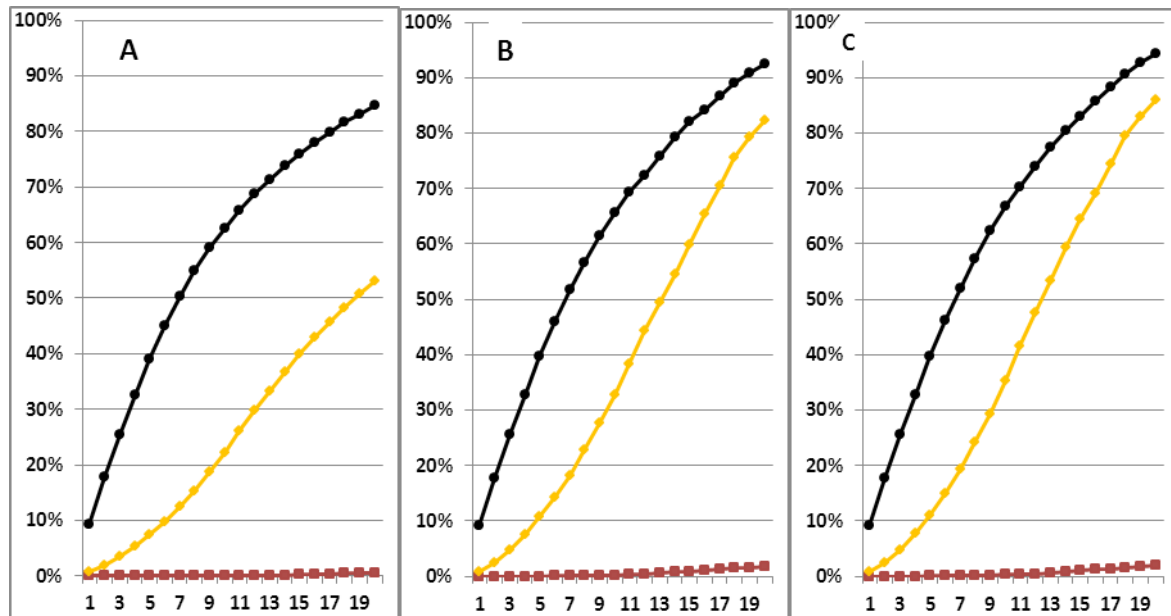


Fig. 15. Percentage of the electricity associated with CO₂ emissions, produced over the *semester*, which can be replaced by the production of additional wind power. The horizontal axis gives the quantity of additional installed wind power in GW. The black, gold and brown curves correspond to coal, gas and oil respectively.

Introducing the STEPs (graph C) with their present characteristics (5 GW-120 GWh) only leads to marginal improvements of the order 2-3%. To evaluate how effectively the STEPS have been used, we compare the energy they have delivered during the *semester* to the maximal energy they could have released had they been used repeatedly⁴¹. We find an efficiency of 6.5%⁴².

Expectedly, each additional GW of wind energy yields an improvement. Since we assume that wind energy production is proportional to installed power, it cannot be otherwise⁴³. However, as evidenced by the decreasing slopes of the curves in the three graphs of Fig. 15, each added GW of wind turbines has a diminishing efficacy. In addition, most of the coal production is eliminated at Stage I of the calculation. The removal of the gas plants is less effective in terms of CO₂ emission reductions. Fig. 16 gives the amount of CO₂-emissions which is avoided by each new GW of installed wind energy over the *semester*. The three curves correspond to the three stages of the calculation.

shown in Fig.16.

⁴¹ This value results from the multiplication of the energy storage capacity, 120 GWh, by the maximal number of times it could have been operated. With a 5 GW power for the STEPs, a full cycle of pumping and release of the water takes two days. Thus, over half a year, the STEPs can be operated at most 91 times (365/(2x2)) with a total energy yield of 10.9 TWh.

⁴² The exchange of Stages II and III, as discussed in footnote 33, would increase this value.

⁴³ The German wind production over the years 2008, 2009 and 2010 displays a different behavior. The installed wind turbine power has steadily grown while the output of wind electricity has stagnated or has decreased.

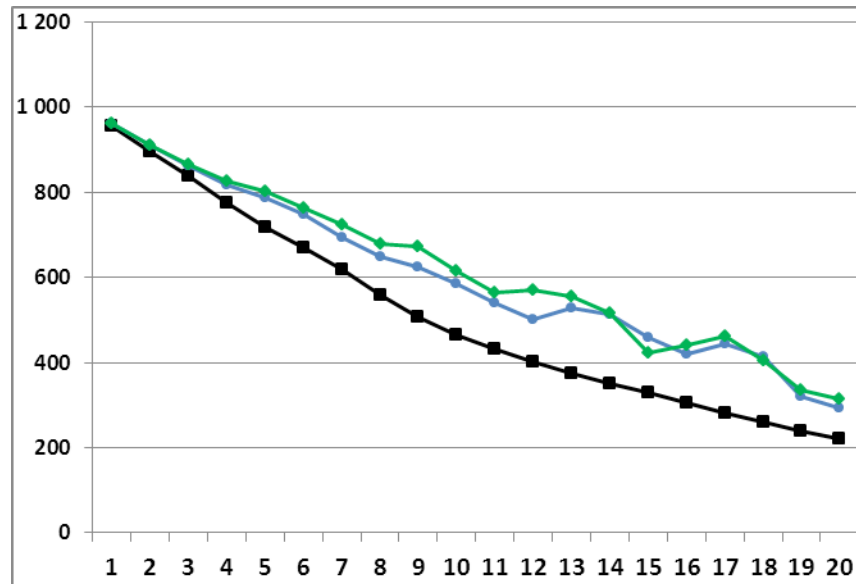


Fig. 16. CO₂ mass emission (in kt) which each new GW of installed wind power may have prevented over the *semester*. The black, blue and green curves correspond to Stages I, II and III of the calculation, respectively.

With the full calculation, Stage I + II + III, (green curve) the addition of the first GW of wind turbines allows a reduction of CO₂ emissions slightly larger than 0.96 Mt while the twentieth GW only saves approximately 0.32 Mt of GHG⁴⁴. Of course, the energy still saved in the reservoirs and the STEPs at the end of February can be used later (March, April) to replace coal, gas or oil productions⁴⁵. Very much depends on whether the limitation discussed in item 5) of Sect. C.4 is takes place or not.

In a calculation restricted to Stage I and II, when the goals of the Grenelle are reached (25 GW), about 11% of wind energy (2.9 TWh over the *semester*) would have to be compensated by slowing down nuclear plants. Of course, these 11% yield no reduction of GHG emissions. Moreover, they do not permit to decrease the installed nuclear power which remains essential to balance production against consumption during the winter cold waves. The nuclear fuel saving corresponds to about 300 kg of fissile material, a smaller mass of high level radioactive waste and to about 50 t of natural uranium (about 0.6% of French consumption). The economic benefit is negligible since the entire nuclear fuel cycle (from the mine to waste disposal) weighs less than 15% in the cost of the nuclear MWh. For the same 25 GW of installed wind power, introducing the STEPs would also not modify the need to keep the entire nuclear fleet in operation. It would only decrease the amount of saved fissile material to 200 kg. It then makes more economical sense for the nation to turn off the wind turbines and to keep the nuclear plants running undisturbed.

In addition, the 0.723 energy efficiency of the STEPs induces a 1.5% loss of the wind electric production when the installed wind power is larger than 15 GW.

⁴⁴ For any installed wind power, the total CO₂-emission reduction (integral of the curves in Fig.16 up to that power) is always larger in Stage III than it is in Stage II. On the other hand, for a given additional GW of wind power, the blue and green curves in Fig.16 may sometimes cross depending on whether the introduction of a new GW of wind power, allowed to stop a coal plant in stage II preventing from using the STEPs for that usage in Stage III. STEPs may then have to use their energy to replace gas production. The green and blue curves do not cross if we assume that all fossil-fuel-fired plants emit the same mass of CO₂ per MWh.

⁴⁵ Up to 12 additional GW of wind power, there is no energy left in the dam reservoirs and the steps at the end of February. It is 0.5 TWh when 20 GW of wind turbines have been added to the fleet.

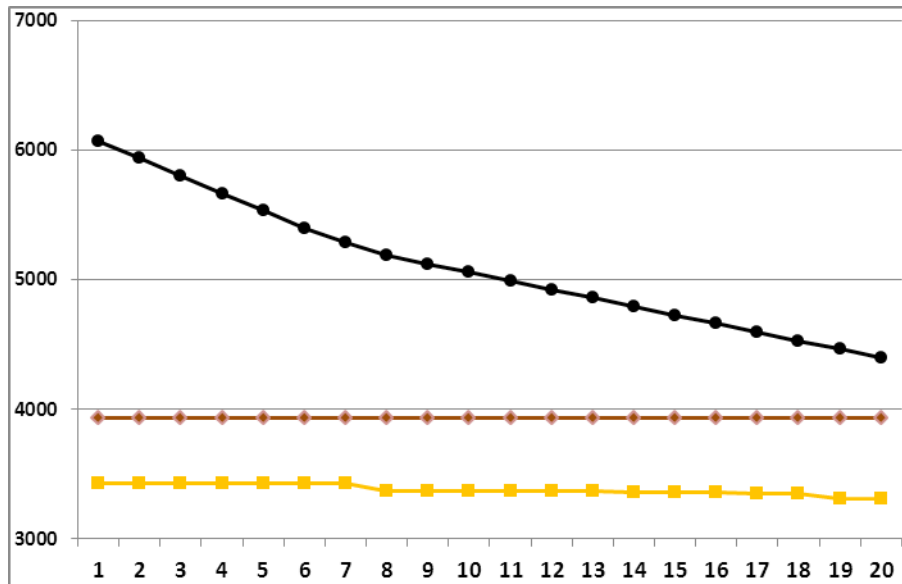


Fig. 17. Fossil-fuel-burning-plant power (MW) which must remain available as a function of the additional wind power. The values are those yielded by the full calculation (Stages I+II+III). The horizontal axis gives the power in GW of the additional wind-turbine fleet. The black, gold and brown curves correspond to coal, gas and oil fired plants, respectively.

Another interesting quantity to follow is how much fossil-fuel-burning power must remain operational for those periods when the wind is weak and when the water preserved in the dams and the STEPs from earlier windy periods has been spent. We thus look at the maximal power of each type of plant that one still has to call upon during the *semester*. The result is shown in Fig.17. It is seen that out of the 6 GW of coal-fired plant which RTE data shows that had to be called upon at least once during the *semester* only about 500 MW could be saved by the installation of a new 5 GW wind turbine fleet. When the Grenelle goal is reached with a 25.24 GW total, about 1.7 GW of coal power plant can be turned off. One also observes a small reduction of the total power of the gas plants. All oil power must be kept.

Figure 18 displays the same information with a different presentation. It shows (in %) the amount of coal + gas + oil power which can be pulled back with the introduction of each new GW of installed wind power⁴⁶. Thus the first GW of wind turbines can eliminate about 135 MW of fossil fuel burning power. For the twentieth GW of additional wind power, the number drops to 98 MW. We thus recover a value similar to the small percentage of power which is “warranted” by the present French wind fleet as mentioned in the discussion of Fig.2

⁴⁶ The kink observed From 7 to 8 GW or 18 to 19 GW of installed wind power is associated with the stopping of some gas power in addition to the regularly decreasing trend of coal power (see Fig.17).

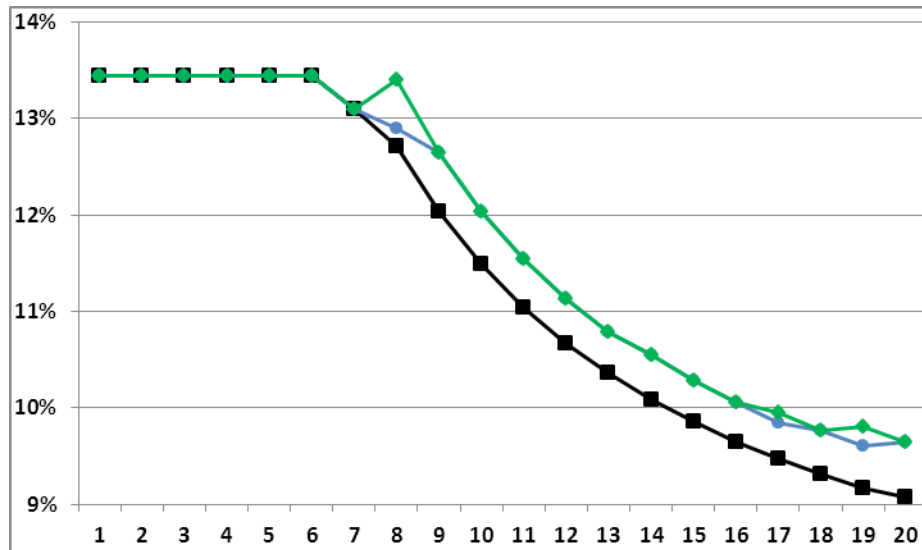


Fig. 18. Ratio (in %) of the fossil burning power that each new GW of installed wind power allows to withdraw. The black, blue and green curves correspond to Stages I, II and III of the calculation respectively.

E) Additional considerations

Now that we have produced an estimate of the maximal CO₂ emission reductions that the deployment of wind energy according to Grenelle planning can achieve, we can perform some small numerical exercises, still based on RTE data. We ask whether, by other ways, a similar or better environmental performance could not be obtained without the recourse to wind energy and by means which would either require a smaller public spending (subsidies) and/or a less complex reorganization of the global electric network .

Table 2 contains some of the RTE data which we will work with

	coal	gas	Oil	Wind (1 GW power)	Export
Energy (TWh)	10.59	9.33	1.08	1.06	14.80
CO ₂ emissions (Mt)	10.17	2.80	0.86	-	-

Table 2 RTE data on the delivered energy and the associated CO₂emissions of several productions over the *semester*. The wind energy production is given for 1 GW of installed power. According to RTE, the production of 1 TWh of electric energy by a coal plant produces 0.96 Mt of CO₂. For gas and oil plants, the corresponding values chosen by RTE are 0.30 Mt and 0.8 Mt respectively.

Although we believe that it underestimates the CO₂ emissions of gas-fired power plants by at least 30%, our calculations use the value given by RTE on its website (0.3 t/MWh). For some reason RTE has chosen to give this electricity production mode a very favorable rating. In particular, this value takes into account neither the CO₂-equivalence of the methane (CH₄; another potent GHG) which is released during the extraction and transport of natural gas, nor the energy required to transport the natural gas from the gas fields to the generation plants.

In the three scenarios sketched below, we take into account that, according to Fig. 17, over the *semester*, it was at one moment necessary to call 6 GW of coal power and 3.5 GW of gas power. Table 2 shows that the mass of CO₂ emissions of coal, gas and oil plants over this period was 13.83 Mt. Table 3 presents the integrals of the black, blue and green curves in Fig.16: the total of CO₂ emissions which, according to three stages of our calculation, the deployment of a given additional GW of wind power could spare.

Additional wind power (GW)	2	4	6	8	10	12	14	16	18	20
Avoided CO ₂ Mass Stage I (Mt)	1.85	3.47	4.85	6.03	7.00	7.83	8.56	9.19	9.73	10.19
Avoided CO ₂ Mass Stage II (Mt)	1.87	3.55	5.09	6.43	7.64	8.68	9.72	10.60	11.45	12.07
Avoided CO ₂ Mass Stage III (Mt)	1.87	3.56	5.13	6.53	7.82	8.50	10.02	10.88	11.75	12.40

Table 3 Maximal mass of the CO₂ emissions which the deployment of an additional wind power in continental France could prevent according to the hypotheses and the three stages (I, II and III) of the calculation described in Sect. A and C.2 and C.4

We now introduce several options which do not involve the deployment of any new wind turbines and we estimate what they may achieve.

- First, instead of being used to support the construction of the Grenelle wind fleet, the public money is entirely spent to increase the performances of the French hydraulic storage system. This improvement is anyhow required by the deployment of 20 GW of wind turbines. It is an externality of renewable energies which just begins to be investigated⁴⁷. Let us assume that French consumer contributions serve to improve the storage capacity in France. One can now imagine utilizing this high quality storage system to preserve the 14.8 TWh surplus of electricity (Table 2) which was exported over the *semester*. According to Table 2 this energy, instead of being sold abroad⁴⁸ could cover all of the coal production and 45% of the gas production. The resulting total reduction of CO₂ emissions is 11.93 Mt. Table 3 tells that, given the most favorable assumptions made in this calculation, this is about all that can be expected from the full deployment of wind power scheduled by the Grenelle. Of course, this does not make the hypotheses presented in Sect C.4 technically or financially easier to satisfy.
- Second, the French government authorizes the construction of 6 EPR nuclear reactor (nominal power 1.55 GW each) in order to replace the coal and the gas plants. If the load factor of these reactors is taken to be no larger than 80%, these six EPRs (total power 9.3 GW) can produce 32.6 TWh over the *semester*. This dependable electricity would be cheaper to French consumers than what they have to pay to support that which is produced by wind. It would eliminate all the CO₂ emissions of coal and gas plants, a much better result than the best that can be hoped from 20 GW of wind turbines. The cost of the EPR presently under construction at Flamanville may reach 5 G€. The more recent EPR reactors built at Taishan (China) are most likely going to be cheaper by several tens %. With the Flamanville figure, six EPRs cost about 30 G€. A low estimate for the average cost of a wind turbine fleet comprising 14 GW of onshore and 6 GW of offshore is 1.6 G€ per GW leading thus to a total cost of 32 G€⁴⁹. The controllable energy delivered by the nuclear reactors does not require a major reinforcement of the network as compared to what a 20 GW wind fleet demands.

⁴⁷ For instance, one can consult the 2011 Accenture-Barclays report “Carbon capital, financing the low carbon economy”.

⁴⁸ Presently, a significant fraction of the exported electricity is sold to Switzerland. This country uses it to pump up some water into the reservoirs of one of its many mountain dams. It is later sold as “green” energy.

⁴⁹ It is estimated that today, in Europe (in China it is cheaper), onshore wind investment cost is about 1.5 G€ per GW. For offshore wind power, values twice higher are mentioned. Weighed with 14 GW and 6 GW respectively, the average cost of the future wind fleet in today currency could then be as high as 1.9 G€ per GW leading thus to 38 G€ total cost.

- A third option simply authorizes the replacement of the 6 GW of coal plants by 6 GW of gas powered plants. This also does not require any additional spending on boosting the network and improving hydraulic storage⁵⁰. With the RTE value of 0.3 t/MWh for a gas fired plant, this would lead to the savings of 6.3Mt of CO₂ emissions that is the best performance that could be expected from a 8 GW fleet of wind turbines. Assuming this option to be more acceptable to those for which nuclear energy is evil, although less performing, it could still allow us to lower the goals (and costs) of the Grenelle wind energy program to 17 GW without sacrificing any of the ambitions in the environmental fight.

We do not present these options as fully thought-out solutions to replace those propounded by the Grenelle. They just seem to us to be at least as realistic alternate routes deserving to be considered before committing large amounts of public money to support an inefficient energy such as wind.

F) Conclusions

In the first part of this report, we analyze what the recently published RTE data tells us about the wind production for a period covering the end of summer, the fall of the year 2010 and the first part of the winter 2011. We have found the same limitations of this mode of production which could be established from earlier investigations on Danish, Spanish or German wind production.

The delivered power is wildly fluctuating (Fig.2). It is bound to have a negative impact on the stability of the network (discussion of Fig.6). The production has no relation with the electricity needs of the French society (fig.7). It does not yield much in those cold anticyclone periods when both the country's electricity request and the CO₂-emissions of the electric sector, are at a maximum (comparison of Fig.2 and Fig.3 for the second part of November and the first half of December). In this six month period which is traditionally more favorable to wind production than the other half of the year, the average load factor of the turbines was smaller than 25%. It reached 70% for less than 10 days (Fig.2 and 4). The predicted smoothing of wind power fluctuations thanks to some hypothesized beneficial geographical averaging specific to our country is not detectable (Fig.2).

The long awaited publication of French electric data has thus shown that, as far as wind is concerned, France is not significantly different from its neighbors (see for instance Appendix B in the reference listed in footnote 8). Thus, the country could have gained a lot from studying the foreign experience before trying to emulate it. Similarly, before embarking into the construction of 6 GW worth of offshore wind turbines, it appears worthwhile to follow closely the performances and the possible difficulties of the offshore wind parks already in operation in other European countries. Since the construction of the turbines themselves is not going to generate jobs within France, at the very least, one would like to be convinced by data that these machines are going to be useful either to the country electric production or to the environment.

The French electric production system has some unique features. In contrast with a majority of countries, it does not rely much on fossil fuel burning power plants (less than 10% over the *semester*). A comparison with the two other European nations which generate their electricity without emitting much CO₂, Sweden and Switzerland, also shows major differences. Indeed, geography allows these two countries a large fraction of hydraulic production which contributes as much as nuclear energy. In France, the ratio is closer to 1/8. Everywhere, hydro-electricity is used to balance the most rapid instances of the evolution of the consumption. Because, French hydraulic resources are limited⁵¹, they must be employed with discernment and sparingly. As a matter of fact, in France, in extreme cold situations, all controllable means of production, coal, gas, oil and nuclear have to be called in order to

⁵⁰ Although, it must be clear by now, that the author strongly supports a resolute public policy in this domain.

⁵¹ They are likely to remain so. According to the Centre d'Analyse Stratégique, the still untapped French hydraulic potential is estimated to be only few GW. Moreover, the flooding of mountain valleys it requires is likely to generate strong opposition from environmental organizations.

stabilize the network. The addition, even in modest proportions, of a fickle and poorly predictable production such as that by wind is not going to improve a situation which, during the winter months, can become very tense.

The possibility to decrease the CO₂ emissions of the French electricity sector appears to be the strongest, if not the sole, justification of the ambitious deployment of wind energy decided by the government. To check how the estimates of this potential are vindicated by actual data, we have designed an algorithm which calculates the maximal reduction of GHG emissions that can be expected from the realization of the Grenelle ambitions. The calculation starts with an on-time cancellation of coal, gas and oil productions by an equivalent wind-produced amount. In a second and third stage, we assume that any remaining wind energy can be preserved under the form of water inside the dam reservoirs or the STEPs. This fraction of the wind energy is later transformed into hydraulic energy which is used to cancel some more production from fossil-fuel powered plants.

The main outcomes of the calculation are plotted in Fig. 16 and 18. Fig.16 shows that the first GW of wind turbines beyond the present fleet saves about 1 Mt of CO₂ while the twentieth will only avoid the production of 0.3 Mt. It takes the last three GW to achieve as much as the first. This is preliminary evidence that the cost of the avoided ton of CO₂ may increase three fold as the wind fleet expands⁵². From fig.18 we draw the conclusion that the first GW of wind turbines would allow pulling back from operation about 140 MW of mostly coal plants. For the twentieth GW the value drops to 95 MW. In both cases, we are observing an illustration of the law of diminishing returns.

As all prospective or scenario studies, this work is mostly an exercise in number manipulation. The worth of its results is no greater than that of its hypotheses. Here, we have adopted those which wind energy proponents usually introduce in their estimates. Quite naturally, they are selected to put the performances of wind electricity production in the most favorable light. It is all the more remarkable that, in the end, when actual data on wind production instead of imaginary ones are introduced in the calculation, the results are not especially outstanding.

Indeed, it is worthwhile putting in perspective the significance of the suppression of 1 Mt of CO₂ emission by a country which belongs to the first ten economies of the world. Such an amount can be compared to the mass of the 2008 world CO₂ emissions: 30 Gt, or to the value that the UNO International Panel on Climate Change would prefer: 10 Gt. Thus, within the Grenelle wind program, one is at best dealing with quantities which are four orders of magnitude smaller. As a matter of fact, from the start one knows that wind (or solar photovoltaic) cannot lead to a significant improvement since the yearly total CO₂ emissions of the French electricity sector are about three orders of magnitude smaller than what the world emits. By emphasizing wind energy, one is obviously diverting the attention of the country from questions which may have a quantitative influence on its GHG emissions. French efforts should rather be focused on improving building insulation, efficient heating (heat pumps) and the public as well as the private transportation economies. These three domains will require increasing the electric production with an efficient and dependable non-CO₂-emitting electric production. This is a task to which renewables energies can only be poor contributors as Fig.2 clearly demonstrates for the case of wind⁵³.

Moreover in Section C.4, we have discussed the wind-favorable hypotheses of our calculation and shown that in many respects they are seriously flawed. They are not compatible with several technical or economic facts. Another way of saying this is that adjusting the electric system to the wishes of the wind industry is going to be long, difficult and costly. Some recent analyses at the European level have already pointed out this sad fact⁵⁴. Taking into account the constraints of the real world can only lead to smaller environmental performances of wind energy than those reported in this work.

⁵² Offshore turbines are not going to improve the situation. Indeed, while it is expected that their efficacy will be 60% to 80% larger than onshore machines, their cost appears to be at least twice higher.

⁵³ No solar photovoltaic data has been made public.

⁵⁴ See footnote 47.

The “problem” of France is that, for its electricity, it relies on CO₂-emitting means of production for only about 10%. This leaves little room for improvement. It also explains why a NGO like Greenpeace which tries to justify massive deployment of renewables, first requires that civilian nuclear energy be replaced by imported gas. In fact, this sort of reasoning corresponds to the following motto: “Let us first make things worse, to show that we can later improve”⁵⁵.

The conclusions drawn here are only valid for continental France which provides both the context and the data on which this analysis is founded. For instance, they do not apply to the “gas-less”, “nuclear-less”, almost “hydraulic-less” and trade-wind-blessed French Caribbean Islands. They are also not applicable to many of our European neighbors. The uniqueness of the situation of every country justifies a specific analysis for each one.

Coming back to France, given the ineffectiveness of wind energy at delivering economical, dependable electricity and, as importantly, at improving the environmental performances of the French electric sector, it appears that decreeing the use of French consumer money for the sole benefit of foreign industry and of investors⁵⁶, does really a poor service to the nation⁵⁷.

F) Acknowledgements

The author is indebted to his SLC colleagues, J.J. Hérou, J.P. Le Gorgeu, Ph. Hansen, H. Nifenecker, J.P. Pervès, F. Poizat, S. Savarèse, J. Treiner as well as well to members of the SLC Scientific Committee for useful information and fruitful discussions which helped orient this work as well as for suggestions and comments on this text.

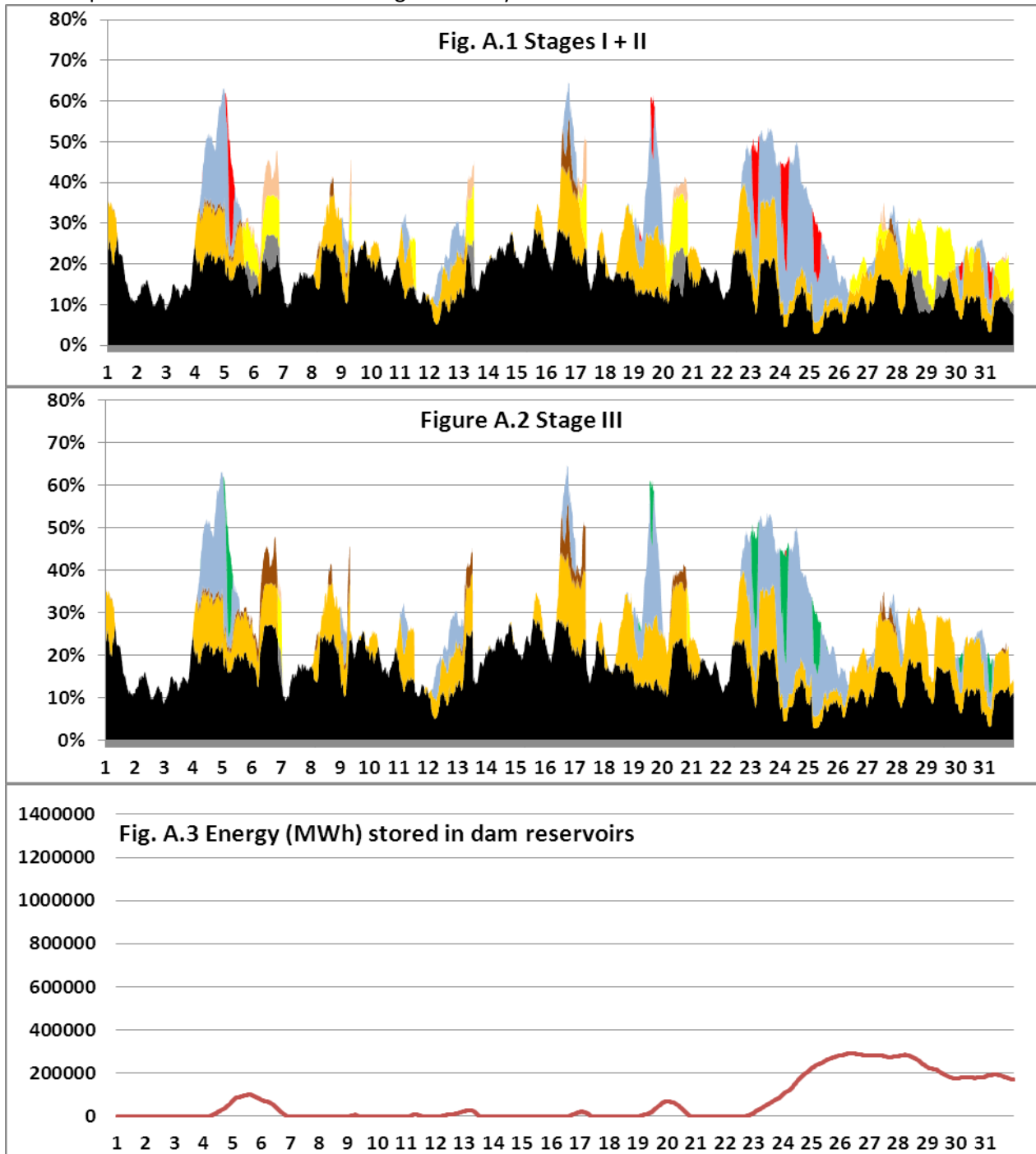
⁵⁵ This might well be the case for France in the decade to come. Indeed, in its “Bilan prévisionnel 2009” (revised 2010), RTE forecasts the construction of 4.8 GW of Gas Power Plants. Thus, despite the wind turbines and solar photovoltaic deployment decided after the Grenelle, one can expect an increase of the CO₂ content of the French produced electric MWh.

⁵⁶ As a matter of fact, the word “investor” is not really appropriate here. Indeed, French regulation allows that most of the capital cost be borrowed on the financial markets (all of it in the case of the recent offshore-wind call for proposals). Therefore, the amount of equity required from constructors of wind parks can be very small, even zero. Thanks to the guarantee offered by the French government via high tariffs (often those asked by the constructors themselves) plus the obligation for EDF to buy the electricity, small interests rates can be secured from banks. Returns up to several ten per-cents can be expected. By definition, returns are infinite when all the capital can be borrowed.

⁵⁷ The second part of this report will appear September 2011. It will analyze a full year of RTE published electric production. We also would like to remove some of the less credible hypotheses listed in Sect.C.4.

**Appendix A
December 2010**

The figures A.1, A.2 and A.3 are the analogs of Figs. 11, 12 and 13. In Sect C.3, they were drawn for the month of November 2010. The total installed wind power is again assumed to be 25.2 GW. However, here the STEP energy capacity is taken to be 120 GWh (instead of 240 GWh in Sect.C.3) as in the section D which presents our results. Abscissae give the day of the month.



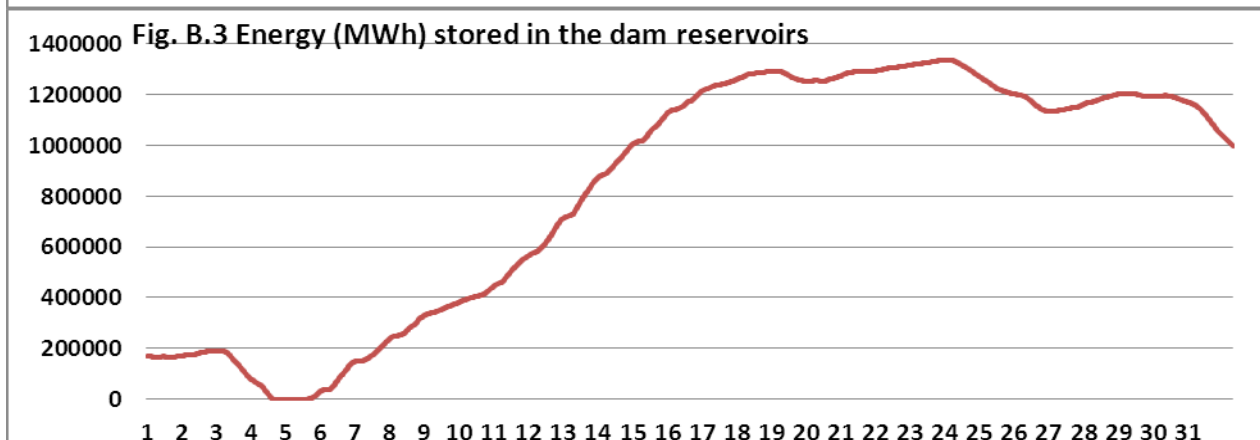
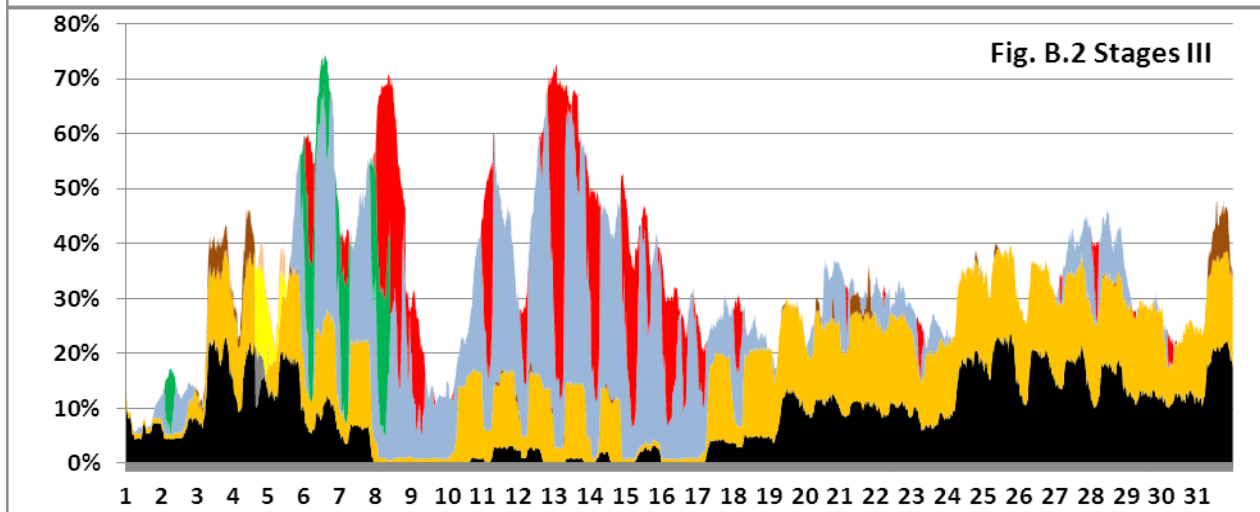
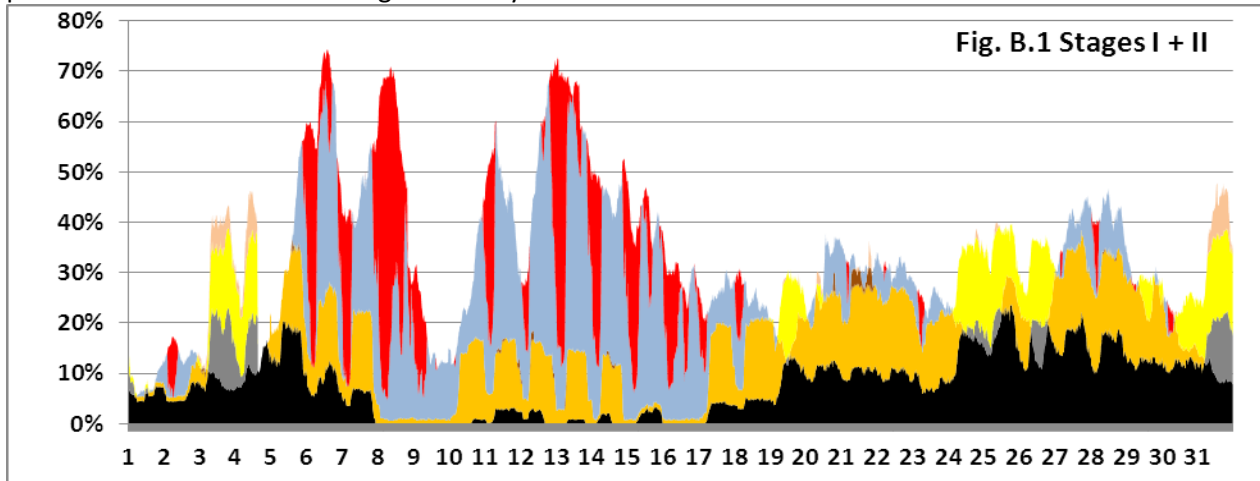
From the discussion in Section C.2 we know that the envelope of the black + gold + brown + blue + red zones in Fig. A.1 (Stage I+II) gives the efficiency of the wind fleet observed by RTE. During the month of December 2010, whose first part witnessed a severe cold wave, it rarely exceeded 50%. Thus, until the 22nd, almost no energy could be preserved in the dam reservoirs. The small sized pale gray, pale yellow and pink zones show that most of this energy was spent before the end of the month and didn't suppress much CO₂ emitting electricity production. The fact that, often, the black or gold zones are not topped by any brown, blue or red colors while no energy remains in the reservoirs (Fig. A.3), indicates that some of the coal or gas production could not be eliminated by the 25 GW wind fleet in either Stage I or Stage II.

Fig. A.2 (Stage III) differs from Fig.A.1 mostly in that the small zones that were red are now green. Some energy has been saved by the STEPS. It has no significant effect on the reduction of CO₂ emissions (there are almost no pale gray or yellow zones in Fig. A.2).

Fig. A.3 shows that often only a small amount of energy could be preserved in the reservoir before the Xmas season. The quantities, which could be saved early in December during the short spikes of wind, were almost immediately spent. Only at the end of the month a small amount of energy could remain under the form of water in the dam reservoirs till the end of the month.

**Appendix B
January 2011**

The figures B.1, B.2 and B.3 are the analogs of Figs. 11, 12 and 13. In Sect C.3 were drawn for the month of November 2010. The total installed wind power is again assumed to be 25.24 GW. However, here the STEP energy capacity is taken to be 120 GWh (instead of 240 GWh in Sect. C.3) as in the section D which presents our results. Abscissae give the day of the month.



The month of January 2011 began with a short cold period. Then, during the first half of the month, two Atlantic depressions flew over France bringing with them mild temperatures and strong winds. The second half of the month was colder.

Fig.B.1 shows first that the water remaining in the reservoirs was used during few days to stop coal production and most of gas production. By day 4 (see Fig.B.3) there was no preserved energy left. Then the wind started blowing strongly. In the stage I of our calculation, not only all coal, gas and oil production⁵⁸ was stopped but also a significant amount of energy could be stored. The amount of energy reached almost 1.4 TWh. It started being released during the second half of the month eliminating all fossil-fuel production. At the end of the month 1 TWh was still available. It has been “spent” to cancel coal and fuel production during the month of February when the wind load factor substantially dropped.

Fig.B2 shows that it took only a few days to fill the STEPS. None of 120 GWh they contained could be used before the month of February.

⁵⁸ As a matter of fact, for several days, there was no coal production at all.