TECHNICAL AND ECONOMIC ANALYSIS OF THE EUROPEAN ELECTRICITY SYSTEM WITH 60% RES

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EDF R&D

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This document examines the impacts of the integration of a large share of variable renewable generation into the generation mix of the European interconnected electricity system. The analysis, which is based on the results of long term studies performed by EDF R&D, aims at improving the current understanding of the technical and economical feasibility of a massive deployment of wind and PV across the European system. The document addresses several aspects of the system integration of variable generation in particular, including the characterization of variable RES generation, the need for generation and interconnection infrastructure, the impacts on short-term system operation and market profitability.

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Cover : Chemin D'Ablis Wind farm – EDF@Didier-Marc

I. CONTEXT AND MAIN ISSUES ANALYSED

As part of the effort to reduce carbon emissions from the energy sector, the European Union (EU)'s energy strategy envisages the development and wide-scale deployment of low-carbon electricity generation from renewable energy sources (RES). According to the current EU Climate and Energy package the proportion electricity generation obtained from renewable energy sources (RES) should increase from 20% in 2010 to 30–45 % in 2020 with a target of 55% by 2050[1].

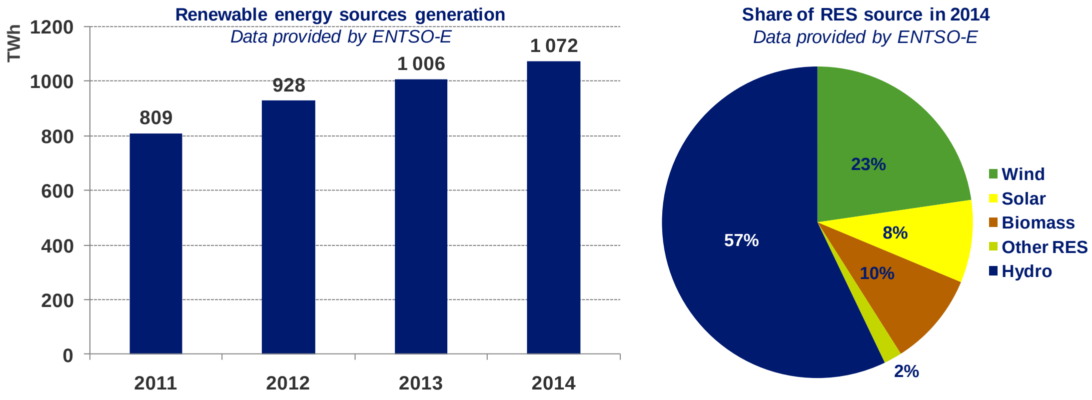


FIGURE 1: **ELECTRICITY GENERATION FROM RENEWABLES IN EUROPE**

Today the main RES contributor to electricity generation is hydro generation (Figure 1). In Europe its potential is already being well exploited and there is limited opportunity for further development. Meeting European RES targets will require the development of new sources of RES generation such as wind, PV and biomass. In this context, the **European RES strategy will be strongly based on the development of wind and PV generation.** Starting from an energy share of 10% of electricity demand in 2014, the share of variable RES such as wind and PV in the European mix is expected to reach 20% in 2020 and around 30% in 2030.

The leading countries in the development of variable generation (Denmark, Germany, Ireland, Portugal, Spain, etc.) have had to deal with a range of technical challenges to connect and integrate this type of generation to their systems. These challenges are linked to the **power electronics interface** of the generation units and to the **variable nature** of their output. Previous experience has proven that the development of wind and PV has a significant impact on power system operation since the **system needs to handle the intermittency of these generation sources**.

From a long-term perspective, the massive integration of variable generation will require profound changes in power system operation and market design, important infrastructure developments and the transformation of the conventional generation mix.

[1] EU Energy, Transport and GHG Emission - Trends to 2050 - Reference Scenario 2013, European Commission

II. KEY RESULTS AND LESSONS LEARNED FROM THE TECHNICAL AND ECONOMIC STUDIES

A. INTERMITTENCY IS A LOCAL PROBLEM THAT BECOMES A VARIABILITY PROBLEM AT SYSTEM LEVEL

Before analyzing the impact of wind and PV on the electricity system, it is important to understand the nature of their intermittency in terms of variability and uncertainty. The term intermittency has been used in the past and refers to the fact that the production from wind and PV generation presents a stochastic nature. This stochastic nature comprises variability, which is the variation over time of the wind and PV generation output, and the uncertainty associated to this variability, related to the generation output forecast errors. Wind and PV generation depend on atmospheric conditions that control the availability of their primary energy source, i.e. wind and sun. Their output of these energy source is intermittent and non-dispatchable. This creates significant exposure within the electricity system to the uncertainties of climate conditions.

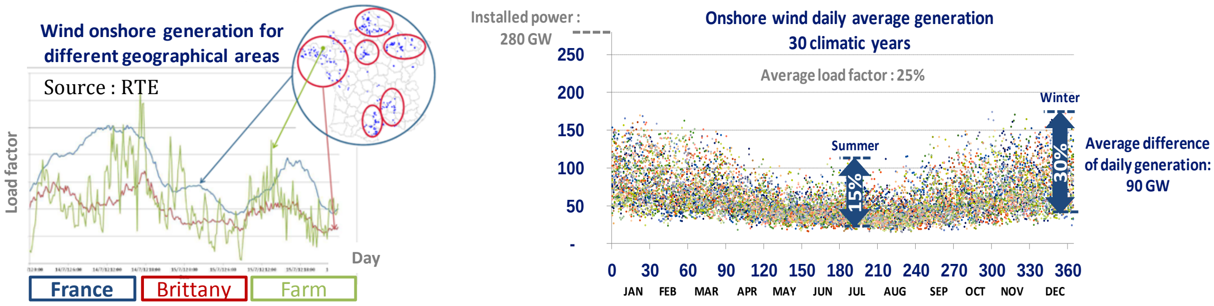
Detailed work was conducted to develop a model of the generation of a wind and solar fleet spread across the European territory. This was based on a dataset of 30 years of detailed weather observations that allowed us to generate, for every country, time series of onshore and offshore wind and PV generation with hourly intervals, using a bottom-up approach. Using this approach we were able to represent spatial and temporal correlations across the European system in order to capture the impact of geographical diversity as well as the variability of the generation at different time-scales from hourly to seasonal and inter-annual. This work provided a unique dataset of wind and PV generation, able to capture with a level of detail that has not been observed in previous studies the characteristics of wind and PV generation across the whole of Europe with a rigorous representation of spatial and temporal effects relevant to power system planning and operation.

The analyses of the wind and PV generation time series allowed us to characterize the variability of this type of generation. The first observation is the significant reduction of the intermittency in wind and PV generation when their outputs are aggregated over a wider geographical area, as a result of the diversity of the outputs. Taking the illustrative example of onshore wind and the data for the French system (**Figure 2**, image on the left) one can see that at a wind farm level the generation profile is intermittent with rapid variations but this variability is smoothed when wind farms in the region of Brittany are aggregated, with a further significant smoothing effect observed when all wind farms in France are aggregated. However, due to the coupling of climate regimes and events at the level of the European continent, a significant variability in production is still observed even if production is aggregated at the European interconnected system level[2] (see **Figure 2**, image on the right). In this image, each dot corresponds to the average power output from the European wind fleet on a specific calendar day. The different points observed for the same calendar day correspond to the value observed for each of the 30 weather-years. The image clearly shows the significant variability of onshore wind generation with respect to overall weather conditions in Europe. In the same image, one can also observe “seasonality” in the output of the onshore wind fleet, such that the average load factor[3] varies from 15% in summer to 30% in winter.

[2] The simulation is performed for an onshore wind generation fleet spread across the European territory, in agricultural areas and wetlands, considering a density of 160 kW/km^2. This density level has already been exceeded in certain regions in Germany. The onshore wind fleet obtained has a total installed capacity of 280 GW, representing an important increase from the existing 100 GW.

[3] The load factor corresponds to the ratio between the generation output and the total installed capacity.

FIGURE 2 : WIND GENERATION PROFILE AGGREGATED AT THE EUROPEAN INTERCONNECTED SYSTEM LEVEL

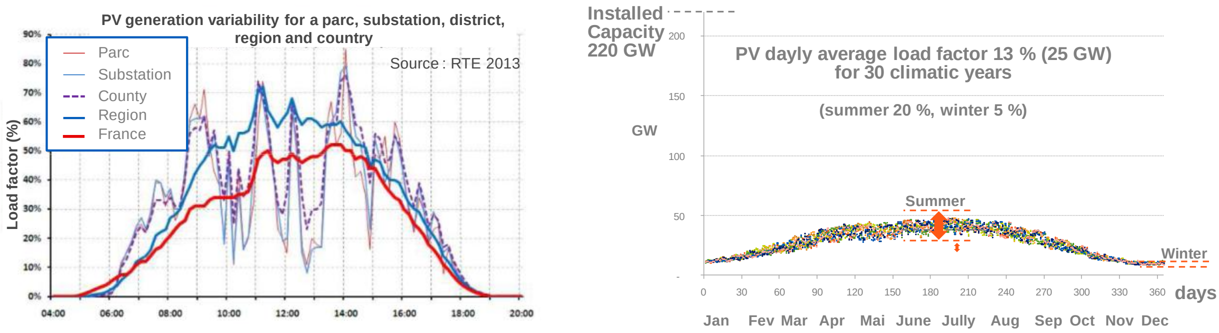


☛ Wind and PV generation present an intermittent generation profile at site level but as a result of natural geographical diversity this intermittency can be reduced when total production is considered at regional or national level. This smoothing, however, is contingent on an appropriate electrical network infrastructure.[4]

☛ We observe, however, that wind regimes are often somewhat correlated across Europe. Thus at the European system level we observe a significant variability in the output of wind generation as a function of atmospheric conditions. The simulation of a wind fleet of 280 GW of installed capacity, well distributed across the European system, showed that in winter the daily average power generation from wind varies between 40 and 170 GW depending on wind conditions!

A similar analysis was performed for PV generation. As for wind, PV also benefits from a smoothing of the intermittence of its output as a result of geographical diversity (see **Figure 3** image on the left) starting from the PV farm level up to the national level. When considering production at the level of the European interconnected system (**Figure 3** image on the right), the variability of the daily PV energy with weather conditions is lower than the one observed for wind. Unsurprisingly, the average load factor in winter is quite low in Europe.

FIGURE 3: PV GENERATION PROFILE AGGREGATED AT THE EUROPEAN SYSTEM LEVEL



PV generation differs from wind in terms of level of its grid connection. A significant proportion of installations, including small roof-top arrays, are connected at low voltage with low observability and little or no controllability.

☛ **The integration of wind and PV to the power system poses a twofold challenge of managing intermittency at the local distribution network level (HTA/BT) and handling variability at the level of the European interconnected system.**

[4] We observe here the natural phenomenon of diversity, well known in electricity demand. This represents an incentive to system-wide aggregation of generation rather than a management of intermittency at local level in strongly meshed networks.

B. RELEVANT ISSUES FOR THE EUROPEAN INTERCONNECTED ELECTRICITY SYSTEM OF WIND AND PV LARGE SCALE DEPLOYMENT

Our study focuses on the issues related to the integration of variable RES at the scale of the European interconnected system. The integration of variable RES within distribution and national transmission grids should be the object of dedicated studies and as such lie outside the scope of this publication.[5]

The object of the current study is to understand and characterize the main impacts on the power system of integrating a large share of variable RES, and the need for the system's transformation.

While RES remain an emerging source of production, with deployment at volumes which have had marginal impact on the system, it has been possible to pursue a development using a "*Fit and forget*" logic where this type of generation is not integrated into the electricity market and has priority dispatch as well as access to the network.

Large-scale deployment of variable RES, however, will have a marked impact on the structure and operation of the electricity system at all levels. In such a case it is important to consider the following: What network infrastructure will be required? What is the impact on the conventional generation mix? What flexibility will be required to handle variability and uncertainty? And finally, What is the cost-benefit balance associated with the development of RES? These questions, summarized in Table 1, will be addressed in this study in order to examine the need for transformation of the electricity system for it to integrate a large share of variable RES.

TABLE 1: **QUESTIONS ADDRESSED IN THIS STUDY**

What are the flexibility needs in order to handle variability introduced by wind and PV	How will the security and dynamic robustness of the European power system be affected?	What will be the role required of the network and interconnections?	What is the value of RES and flexibility sources in a market context?
• How does the generation mix need to evolve in order to maintain demand-generation balancing in a system with a large share of variable generation? • What is the role of enabling flexible technologies such as storage and flexible demand as a means of managing variability?	• What is the impact of uncertainty in variable generation production on the needs for operation margin and reserves? • Will frequency stability still be maintained in spite of the reduction of generation inertia due to the large-scale deployment of producers with power electronics interfaces?	• What is the need for transmission network reinforcement? • How much interconnection capacity will be required to benefit from the geographical diversity of variable RES at the European level?	• Will wind and PV generation be profitable in electricity markets?

[5] The network integration issues concern distribution and transmission network reinforcement, protections and automation and supervision (smart grids) and well as grid access feed and connection rules and grid codes …

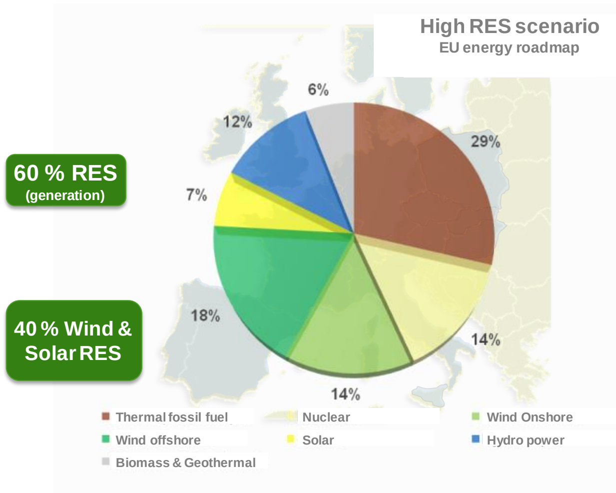
C. DRIVERS FOR THE CHOICE OF A SCENARIO WITH A HIGH SHARE OF RENEWABLES IN THE GENERATION MIX

The scenario used is inspired in the EU *Energy Roadmap* 2011, more precisely the High RES scenario that gives a level of 60% RES in terms of electric energy share by 2030. Of this 60%, 40% is represented by wind and PV generation, meaning that 40% of the annual energy demand would be supplied by these sources. We have used the assumptions provided for this scenario for total demand, commodities and CO2[6] prices. These are presented in Figure 4. To ensure the consistency of our inputs with the EU roadmap High RES scenario, we respected the technology energy shares in the mix proposed in the document, specifically those for nuclear, thermal, biomass, hydro, wind and PV. This scenario represents a more ambitious development of RES than the target set up by the European Council in the Energy and Climate Framework, which aims for a 27% energy share for wind and PV by 2030.

The choice of scenario was made with the objective of identifying the feasibility conditions and possible limits to the integration of a massive share of variable RES in the European power system.

As such, the role of the scenario is to obtain representative orders of magnitude of the issues related to a large-scale development of variable RES in the European system.

FIGURE 4: **EUROPEAN UNION ENERGY ROADMAP**



High RES 2030	GW	Load factor (h/yr)
Solar (PV)	220	1100
Onshore wind	280	1900
Offshore wind	205	3200
Hydro	120	3800

Within this context, EDF R&D constructed a detailed dataset for the European energy mix respecting the global energy volumes per energy source described in *EU roadmap* including the geographical distribution of the development of the different technologies. The underlying assumption used to obtain the development of onshore wind across Europe is that there will be a homogeneous distribution of new capacity considering an equipment density of 160 kW/km2[7] placed in farming land and wetlands. The placement of off-shore wind and PV is based on the identification of sites offering the greatest potential from a technical point of view. Consequently, this results in a large concentration of offshore wind in the north of Europe where the more promising sites are located. Likewise, a significant development of PV in the south of

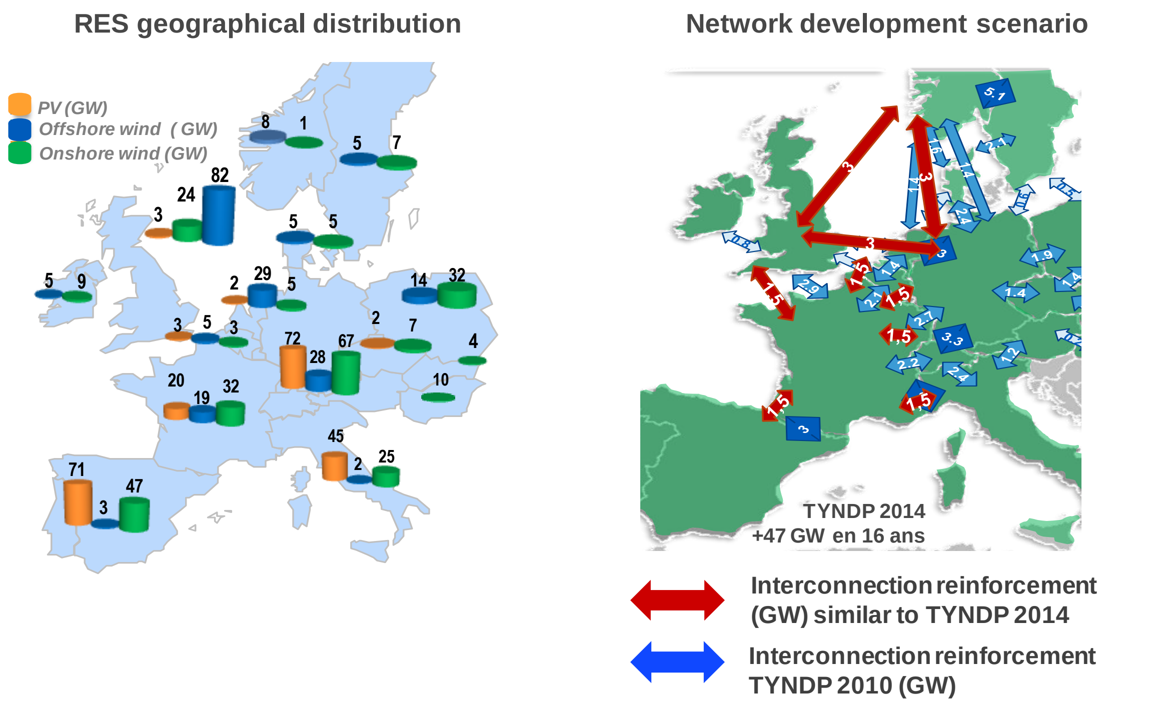
[6] The electricity demand in the area studies is of 3600 TWh/year with a peak demand of 600 GW. The variable RES capacity of 700 GW. The oil price is of 107 $2011/bl, the CO2 price of 35 €2011/t. The coal and gas prices in the roadmap make coal more competitive than gas, what results in the use of coal plant as base load rather than gas. These assumptions date from 2011, however, they are still coherent with the more recent ones in the document *EC Trends to 2050 - Reference Scenario 2013*.

[7] The geographic distribution of RES takes into account the existing plants that will still be working by 2030. This results in an adaptation of the amounts of wind and PV in France and Germany, in order to maintain their export energy balance.

Europe is obtained. The geographical distribution of variable RES obtained is presented in Figure 5 (image on the left).

The needs for interconnection capacity expansion in the scenario[8] are determined using a cost-benefit analysis, performed using the tools described in the next section, and using as a starting point existing capacity, plus the reinforcements proposed in the European network of transmission system operators for electricity (ENTSO-E)'s ten-year network development plan (TYNDP) of 2011. The basis of the cost-benefit analysis was that reinforcements would be accepted if the reduction of generation investment and operation costs was higher than the investment cost of the reinforcement. More specifically, the savings in generation investment costs are the costs of avoided backup capacity and the economies of fuel costs across the whole European system. The interconnection reinforcements with a positive cost-benefit analysis are represented by the red lines in Figure 5 (image in the right). These reinforcements are similar to the ones published in the ENTSO-E TYNDP 2014 for a scenario with 60% RES by 2030.

FIGURE 5: **WIND AND PV INSTALLED CAPACITIES AND INTERCONNECTION REENFORCEMENT NEEDS**



The results clearly show that the development of offshore wind in the north of Europe and the development of PV in the south will require the development of interconnections to enable the transport of this production to the demand centers. This additional interconnection capacity will also permit the sharing of thermal generation capacity between countries, reducing the need for backup capacity and better capitalizing on the diversity of both demand and variable RES generation across the system. This in turn will reduce variability at system level.

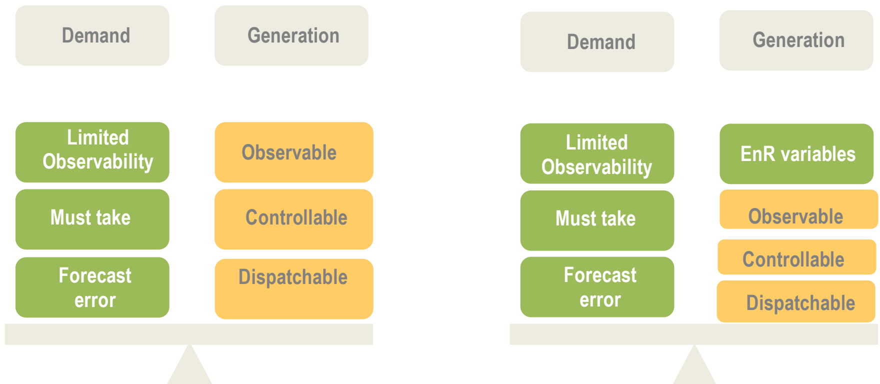
☛ **The integration of a large share of variable RES is facilitated by a coordinated development of RES capacity and network infrastructure.**

[8] The reinforcement of the national transmission network was treated in a simplified fashion taking into account the need for national transmission network reinforcement required when interconnection capacity is increased.

D. A SYSTEM WIDE APPROACH BASED ON A CHAIN OF ADVANCED POWER SYSTEM SIMULATION AND OPTIMISATION TOOLS

Wind and PV generation share many characteristics with electricity demand. As illustrated in Figure 6, like demand, wind and PV generation represent non-dispatchable contributions to the generation-load balance. Both are variable and difficult to forecast, with an important dependency on weather. Since electricity cannot be easily stored and as the load-generation balance needs to be maintained in real time, it is apparent that the integration of variable RES will pose a number of challenges across the entire electrical system.

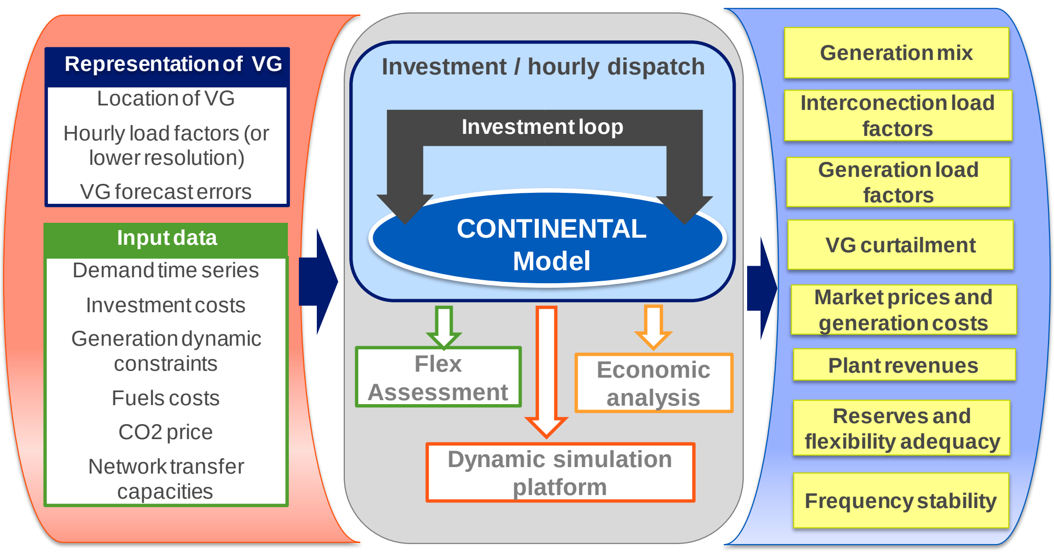
Figure 6: **VARIABLE RES REPRESENTS A NEW SOURCE OF UNCERTAINTY IN THE ELECTRICITY SYSTEM**



This study made extensive use of an optimisation tool, CONTINENTAL[9], developed by EDF R&D, to perform European electricity system-wide studies. The tool CONTINENTAL simulates the hydro-thermal dispatch of generation across the full European system, including interconnection constraints. The optimisation tool is complemented by several other tools, including an investment loop to evaluate generation expansion, a dynamic simulation platform to study frequency stability, a probabilistic tool to perform the near-term flexibility assessment and post-processing analysis to study market prices and generation revenues. This whole system approach permitted by this set of tools allows a detailed simulation and quantification of the impact of integrating variable RES in the load-generation balancing (see Figure 7).

The main results of the study are described in the following sections.

FIGURE 7 : **SYSTEM-WIDE APPROACH STRUCTURE AND TOOLS**



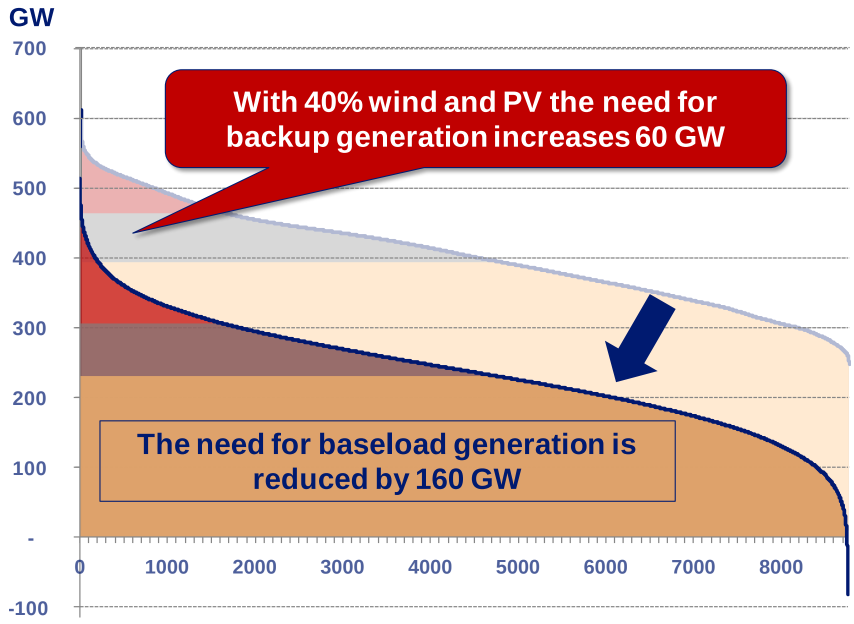
[9] The geographical area studied includes the whole of the European electricity system with the exception of the Balkans, Greece and the Baltic countries.

E. MAIN FINDINGS OF THE STUDY

a. With a high share of variable RES the European generation mix requires less conventional base units and more peaking units

Generation from wind and PV contributes mainly to the supply of energy. The stochastic nature of this production means that its output does not always coincide with periods of high demand and as a consequence it makes a minor contribution to capacity. A simple statistical calculation, based on a load duration curve[10] at the European system level, can illustrate this issue. Figure 8 (image on the left) illustrates demand by a stack of conventional generation technologies (thermal and hydro) without variable generation in the mix. Figure 8 (image on the right) illustrates the same but with the presence of 40% variable RES. In this case the conventional technologies stack aims at covering net demand (demand minus variable RES). The conventional generation technology stack is represented in the area below the duration curve of demand (figure on the left) and net demand.

FIGURE 8 : **EUROPEAN LOAD DURATION CURVE OF DEMAND AND NET DEMAND WITH 60% RES**



From the previous image one can observe the following:

- The **energy produced by wind and PV displaces base load generation**[11]: the 700 GW of wind and PV displace 160 GW of base load generation, equivalent to 40% of the annual demand in energy[12].
- The development of variable RES entails a need for backup capacity, required during the periods when wind and PV are not available: in the 60% RES scenario, 60 GW of

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[10] The load duration curve represents the probability of reaching a specific level of net demand (demand-wind-PV). This probability is expressed as the annual expected value (probability x 8760h) of reaching at least this demand level. In practice this curve is constructed using 30x8760 points, corresponding to the hourly realisations of demand and variable generation for the 30 weather years used. It is important to highlight that the data in the blue line on the left (load duration curve) and the data on the blue line of the image on the right (net load duration curve) do not correspond to the same calendar periods.

[11] This result might seem surprising for PV generation since one might expect that it would have displaced backup plants thanks to its coincidence with periods of high demand during the day.

[12] 40% variable RES means that 40% (1,430 TWh) of European electricity demand (3,545 TWh) is covered by wind and PV, and a further 20% covered by other RES (hydro, biomass, etc.) making up 60% RES penetration.

additional backup capacity (called on for very short durations) are required to respect the capacity adequacy criteria of an expected loss of load of 3h/year.

- Overall, the development of 700 GW of wind and PV would lead to a reduction in conventional generation capacity in the order of 100 GW (160 – 60 = 100 GW[13]). This capacity credit comes solely from wind generation[14], since in Europe PV generation is not present during winter peak[15].
- Saying this, periods with an offer of variable RES higher than 100% of demand are observed at the European level. During these periods, when all demand can be covered by must-run RES, **curtailment may be required to maintain demand-generation balance** as well as to allow the **provision of reserves and ancillary services, required to ensure the security of the system**.

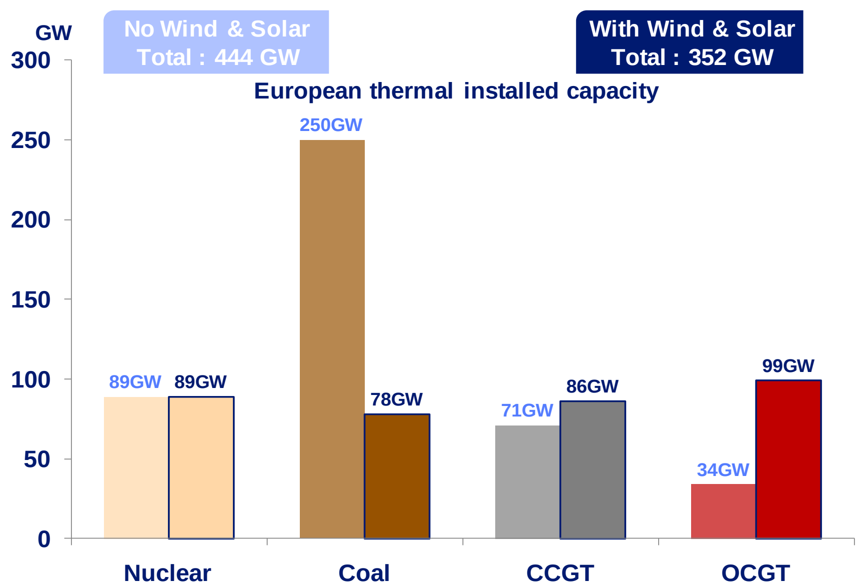
☛ **Wind and PV generation** lead to a transformation of the structure of the conventional generation mix with a **reduction of base load generation and an increase in peaking plants ("back-up")** which will be required during periods with low wind and PV across Europe.

☛ The situations with **high variable RES generation** are **challenging for the operation of the system**, since **traditional flexibility sources are no longer available** and there are **limited providers of the ancillary services which are essential for the security of the system.**

b. CO_2 emissions are significantly reduced thanks to RES and low-carbon base generation

The 60% RES scenario, represents an annual CO_2 savings in the order of 1 Gt when compared to a scenario without variable RES[16]. These savings come from wind and PV generation and from the reduction of carbon-emitting base load plants in the conventional generation mix[17] (See Figure 9).

FIGURE 9 : **STRUCTURE OF THE GENERATION MIX WITH AND WITHOUT WIND AND PV GENERATION**



[13] Amount of capacity required to maintain the loss of load probability (LOLP).

[14] The capacity credit obtained is in the order of 20% for wind generation in the "60% RES scenario" (100/485 GW). The capacity credit drops with the increase of the wind penetration in the system.

[15] The capacity credit of PV is zero. The development of 200 GW PV in our scenario displaces 22 GW of base plant and leads to an equivalent increase in backup capacity.

[16] We recall the calculations are performed considering the CO_2 price EC Energy *Roadmap* of 35 €/t.

[17] The generation mix described is the generation mix obtained using continental model and its investment loop, taking into account the interconnection capacities between countries and an optimised dispatch of hydro-generation. The nuclear generation capacity in the mix is an input and its value if defined by the *EC Energy Roadmap 2011*.

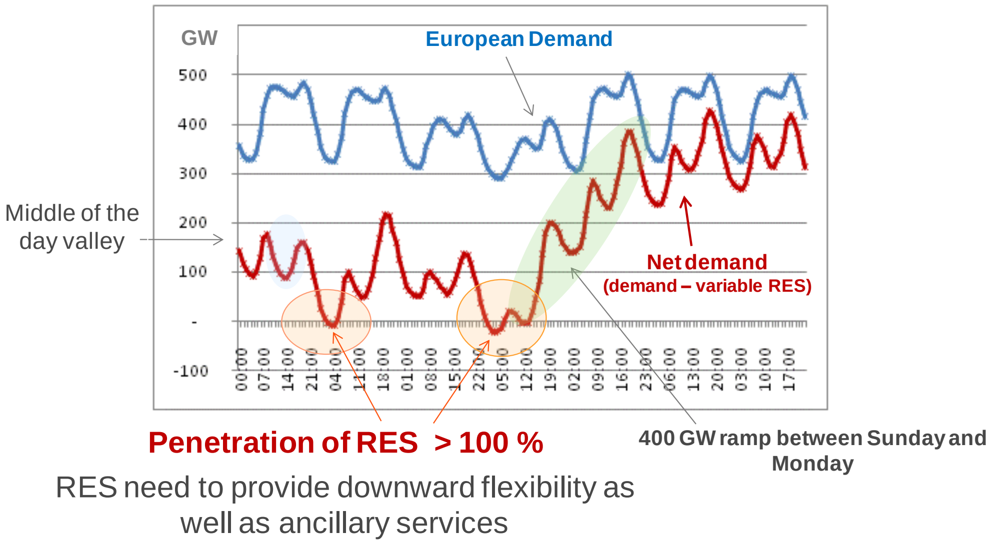
☛ The **decarbonisation of European base load generation is achieved with a mix of RES and nuclear plant**. The **average CO_2 content per kWh produced with 60% RES is 125 gCO_2/kWh, a value significantly lower than today's 350 gCO_2/kWh**[18]. **The additional replacement of coal with gas plants would allow CO2 output to be reduced to as low as 73 gCO_2/kWh.**

☛ **Above a certain share of RES, however,** the **marginal efficiency of CO_2 reductions** drop and **the marginal cost of this reduction increases** (as a result of an increase in curtailment of wind and PV and the reduction of capacity credits and of fossil fuel savings)[19].

c. The flexibility of conventional plants is essential to handle net demand variability

Wind and PV generation increase the variability that needs to be managed by conventional generation. The net demand profile, supplied by conventional generation, is more variable than demand alone, increasing the solicitation of the flexibility of conventional plants (see Figure 10). This impact on flexibility needs is expressed mainly in terms of a higher frequency of large variations in net demand. At European level, upward hourly variations larger than 20GW and downward variations larger than 10 GW increase by 50% and extreme hourly variations (>70GW) which do not happen for demand are present in net demand.

FIGURE 10 : **LOAD-GENERATION BALANCING BECOMES QUITE COMPLEX FOR PERIODS WITH HIGH NET DEMAND VARIABILITY**



☛ The solicitation of the **manoeuvrability of conventional generation plants** is higher with an increase exposure to higher and less predictable ramps.

☛ **Above a certain instantaneous penetration,** the ability to **dispatch variable RES becomes crucial to maintain the load-generation balance**. During these periods, **system security can be maintained only if variable RES contribute to ancillary services and reserves**.

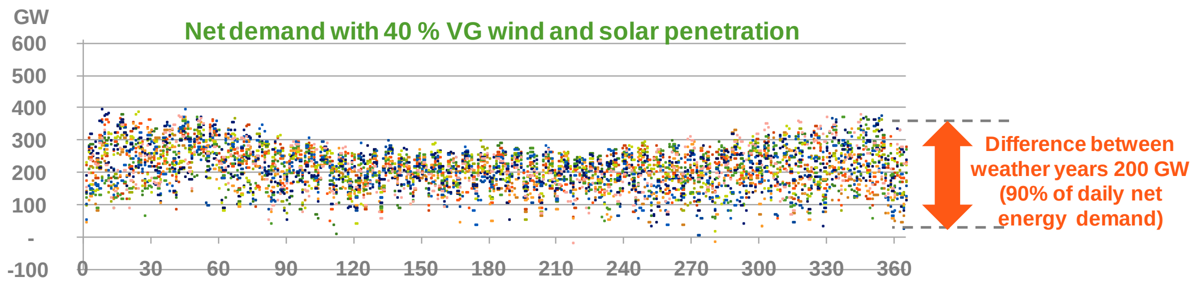
[18] With the commodity prices assumed in the EU *Roadmap* coal enters the mix as base generation and the average emissions are of 400 gCO_2/kWh for an hypothetic case with no wind and PV generation.

[19] This effect can be taken into account in the cost-benefit analysis of RES using the CO_2 price.

d. Load generation balancing becomes significantly exposed to weather conditions

In a scenario with 40% variable RES, the results in this study have shown that for the same calendar day, the average daily energy generated from **wind and PV aggregated at the European system level can vary by 5 TWh between climate years, depending on the weather conditions.** This is equivalent to 200 GW on average, for the same calendar day, depending on the annual weather conditions (Figure 11). By way of comparison, the temperature-sensitivity of the European demand is no more than 2 TWh during the periods of high demand in winter and is only 0.7 TWh on average across the entire year. This clearly shows the significant increase of the exposure of the load-generation balancing to climatic conditions.

FIGURE 11: **INTER-ANNUAL NET DEMAND VARIABILITY**

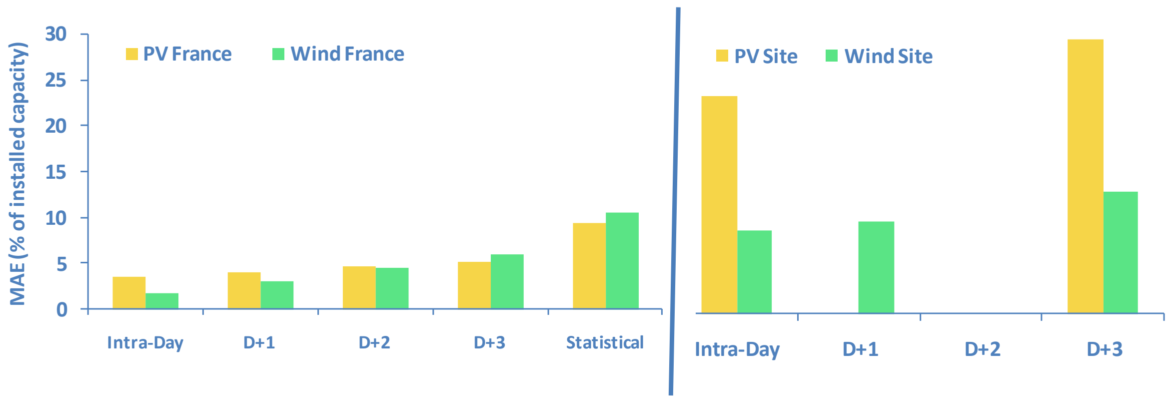


☛ **In order to handle the increase of the exposure of the system to climate conditions and its associated uncertainty, the system will require significantly increased operating margins.**

e. Observability and forecasting will play a major role for a cost effective short term load-generation balancing

Improving accuracy in RES production forecast has a fundamental role to play in reducing the needs for the operating margin and reserves required to cover the uncertainty in the output from RES. Based on historic forecasts for wind and PV for the French system, presented in Figure 12, the mean average error (MAE) in the intra-day forecasts of wind production is in the order of 2.5% of installed capacity. This corresponds to 12.5 GW for a fleet of 500 GW installed across Europe. For PV, the equivalent error is in the order of 5%, which for an installed fleet of 220 GW corresponds to 11 GW.

FIGURE 12 :**WIND AND PV HISTORICAL FORECAST ERRORS FOR INCREASING LEAD-TIMES FOR A SINGLE SITE AND FOR THE FRENCH SYSTEM**

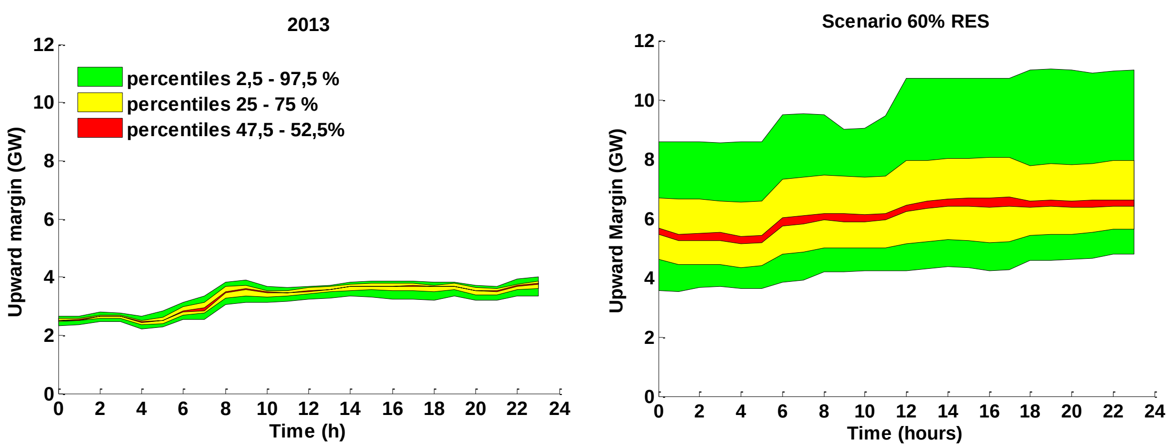


☛ **As is the case for temperature, a coupling of meteorological forecast models to the real-time measure of production will permit a reduction in the uncertainty in wind and PV** production at a day and eventually intra-day time horizons.

☛ It should be noted that the forecasts at a local level are of lower quality – **the forecast error at the level of a site of production is 3 to 4 times larger than the error at a national scale**. This implies that there will be a value in integrated management in those systems which benefit from a natural reduction of the uncertainty when they are considered as a whole (as opposed to island systems where this natural smoothing is less pronounced).

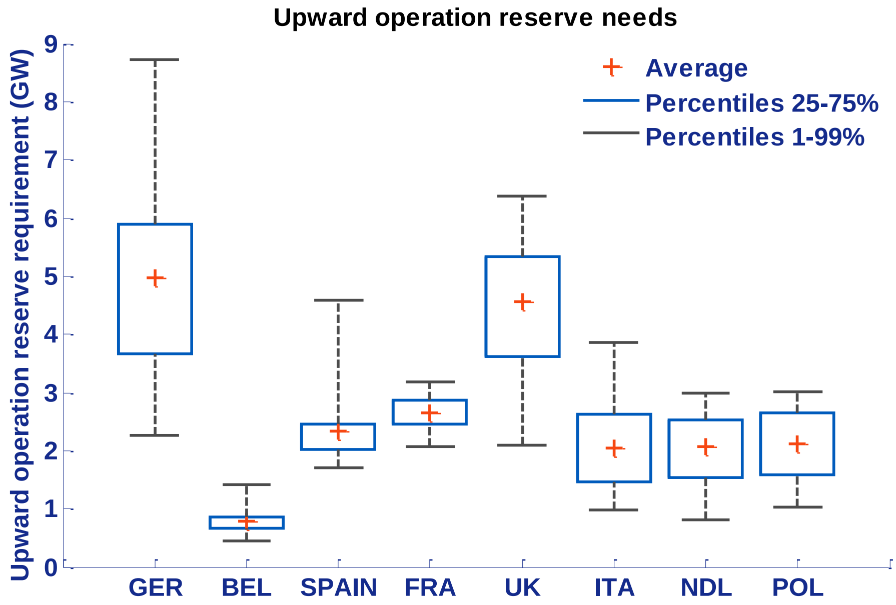
The forecast error depends on the variability of production and forecast errors are lower the higher the geographical diversity of the wind and PV fleet. Forecast errors at local level are 3 to 4 times larger than at country level (Figure 12). By taking account the possibility to reduce uncertainty in short-term RES production, it is possible to limit the increase in the need for operating margin. In spite of this, a significant increase in both upward and downward is observed for the "60% RES" scenario due to the added uncertainty from wind and PV. The comparison of day-ahead operating margin needs for 2013 and for the "60% RES" scenario for France is presented in Figure 13. In the image in the left the need for operating margin is dominated by demand and run-of-the river hydro forecast errors and generation outages. The image in the right presents the operating margins for the scenario with "60% RES". Due to the integration of 30% wind and PV penetration in the French mix, day-ahead upward operating margins increase by a factor of 3 to 4. The magnitude of the increase is similar for downward margins.

FIGURE 13 : **DAY-AHEAD OPERATING IN 2013 AND THE SIMULATED OPERATING MARGIN FOR THE SCENARIO "60% RES" FOR FRANCE DURING SUMMER**



At the moment, a figure for operating margin is calculated for each country in order to manage the uncertainty within their boundaries. Currently, the differences in the needs for operating margin in the different countries are due to the size of the respective demands. In the case of a high penetration of RES, the differences in operating margin will be due more to the relative penetration of RES rather than the relative sizes (i.e. demand) of the different systems, as shown in Figure 13. This could pose particular difficulties for the management of operating margins and reserves in some countries, such as the UK.

FIGURE 14: **OPERATING RESERVES AND BALANCING REQUIREMENTS IN THE DIFFERTN EUROPEAN COUNTRIES**



If the needs for operating margins can be mutualized between countries, the overall need in the mutualized zone will be half that of the systems when considered separately. This reduction is due essentially to the smoothing of the overall output of intermittent RES that occurs over wider geographic areas. In order to exploit this, the calculation of the requirements, associated services and their procurement and activation would need to be performed at European level. Such transformation of current practices needs to be supported by a robust cost-benefit analysis.

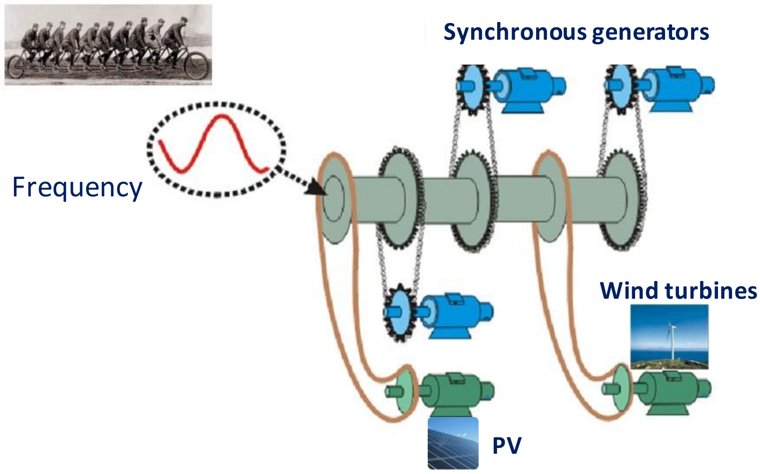
☛ The management of uncertainty (in RES output) will be facilitated by an increasing near real-time management of operating margins in order to capitalize on the benefits of near-term forecasts and system monitoring.

For operation, time-scale decisions can be greatly supported by variable RES forecasts, these forecasts however degrade rapidly when looking a horizon of several days. For load-times higher than 3-4 days the forecast errors converge on the statistical climate observations. This statistical information is the only one available for mid- and long-term decisions.

f. The contribution of variable RES to inertia and ancillary services will be essential to ensure power system dynamic stability and reliability

Wind and PV farms differ from conventional generation and other RES since these have a power electronics interface with the system, often designated as asynchronous (Figure 15). The connection of wind farms and PV via power electronic interfaces will lead to a reduction in the inertia of the system.

FIGURE 15 : **INERTIA AND SYSTEM FREQUENCY STABILITY**



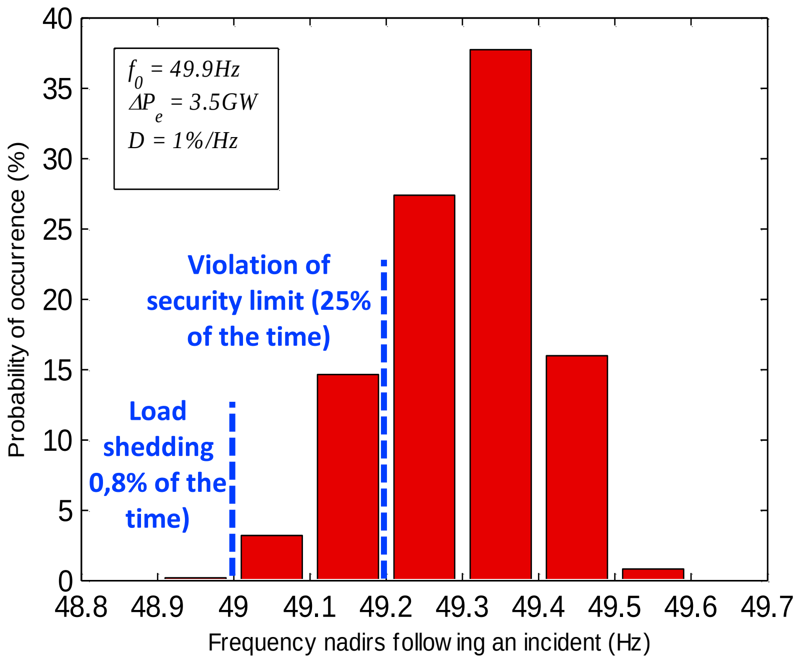
This reduction of inertia impacts the dynamic robustness of the system, namely the frequency following an incident. For low to moderate penetration of variable RES the synchronously interconnected European grid today has high inertia, which ensures that it has the capacity to accept a significant number of sources of production connected through power electronics interfaces. In order to quantify the impact of close to 40% variable RES in the European synchronous system, we have performed a large number of dynamic simulations. With 40% variable RES, for the majority of cases, the overall European network appears to be sufficiently robust, as illustrated in Figure 16. The figure presents the frequency nadir, following a reference incident of 3.5 GW, for all hours of the studied years (close to 100 resulting from combining 30 weather years with generation availability scenarios).

That said, critical situations equivalent to a frequency nadir lower than the 49 Hz that trigger under frequency load shedding and lower than the security level of 49.2 Hz could arrive. These are observed for periods with 25% instantaneous penetration of RES[20], when the overall system demand is low (<250 GW). A similar incident occurring during periods of high demand would not seem to pose a problem even for instantaneous penetration of RES as high as 70%, given that the load self-regulating effect[21] will contribute naturally to the re-establishment of the system frequency.

[20] The instantaneous penetration of variable RES corresponds to the penetration observed in a single operation period (in this case the hour) and is obtained by dividing the variable RES production during this period by the demand in the same periods.

[21] The load self-regulating effect is the natural contribution of the load to frequency recovery following an incident. Demand is sensitive to frequency and evolves in a sense favorable to the reestablishment of load-generation balancing. The loads that have this natural capability are industrial motors and some domestic loads as washing machines. The increase of electronic loads is likely to reduce this effect in the future. For the purpose of this study we used a load self-regulating effect of 1%/Hz, recommended by the ENTSO-E.

FIGURE 16: ANALYSIS OF FREQUENCY STABILITY IN THE EUROPEAN CONTINENTAL SYNCRONOUS AREA WITH 35-38% SHARE OF VARIABLE RES



☛ The most critical periods for frequency stability are those when the demand is low. During these periods, **it will be necessary to limit the instantaneous penetration of RES in order to maintain the security of the system.**

☛ That said, **innovative solutions such as the creation of synthetic inertia from wind farms or the contribution of wind generation to frequency regulation** are expected to reduce the severity of some of these limits.

☛ Smaller systems such as Ireland limit already the instantaneous penetration of RES in order to preserve the security of their system and are looking to require new wind generation capacity to provide synthetic inertia and frequency regulation services.

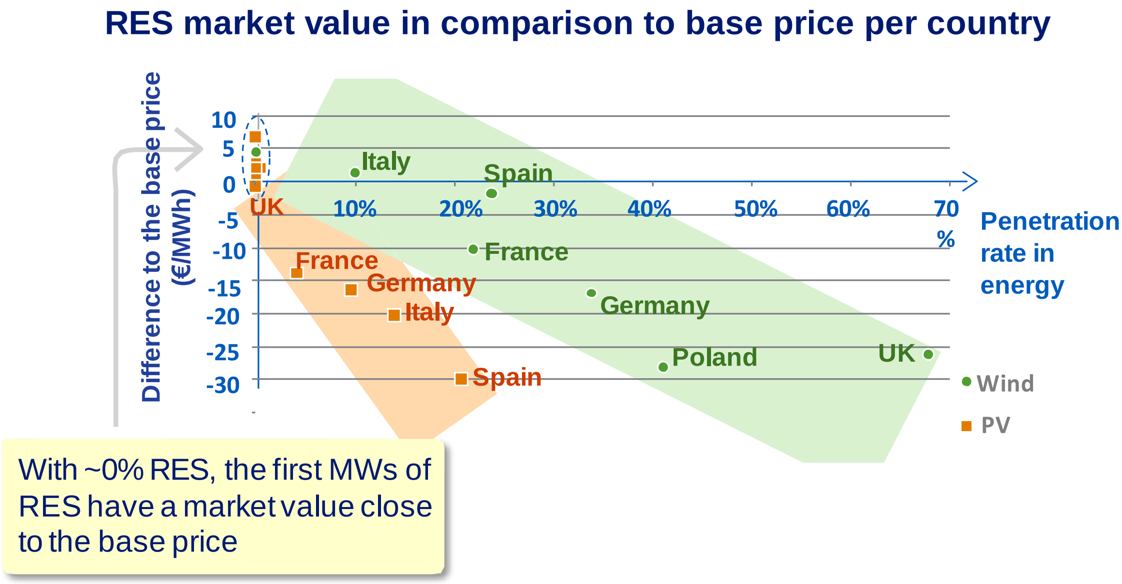
☛ **It is essential that the variable RES production which is displacing conventional generation is also able to contribute to the provision of ancillary services and also potentially provide new services (e.g. inertia).**

g. The market value loss of wind and PV increases with their penetration in the mix raising an important question concerning the existence of economic limits to high shares of variable renewable generation

In this section, the question of the economics of wind and PV production is reexamined from the perspective of a cost-benefit analysis. This question is commonly addressed in the literature by comparing the cost of the production of the different types of generation. This comparison, however, would only be possible if all types of generation provided exactly the same service to the system. The variable nature of wind and PV generation means that its generation output does not always coincide with demand. This means that the value of the service that they provide to the system is affected by the so called "intermittency cost".

This impact can be analyzed by comparing the difference between the yearly base load price, calculated as the time average system marginal cost, and the market revenue of wind and PV. Taking the scenario "60% RES" we analyzed the gap between the yearly base load price and the average revenue of wind and PV, for different countries. The incremental value of the service provided by variable RES to the system is evaluated by comparing the marginal value of the first kW with the value of "40% variable RES". Figure 17 presents in the y-axis the gap between the yearly base load price and the market revenues of wind and PV. The x-axis presents the relative penetration of wind and PV in the system. From the figure we can see that this value gap is very low or negative for the first MW of wind or PV (while their presence is marginal to the formation of the system marginal cost). Instead, for the relative penetrations of wind and PV observed in each country, for the "60% RES" scenario the gap becomes significant. This gap exists because the drop in the market revenues of variable RES is higher than the decrease in the yearly base load price that they create. The value gap is a function of the variable RES technology, its production profile when compared to the marginal system cost, and its penetration. One can see that PV generation presents a value gap higher than wind, since its generation is concentrated around a few hours of the day.

FIGURE 17 : MARKET REVENUE GAP OF WIND AND PV



☛ We showed earlier in this document that variable RES displaces base generation and increase the need for flexible backup. This **difference in the service provided to the system is translated by a market value loss when compared to other technologies**. This effect is quantified in terms of the gap between the average system marginal price and the average market revenue of wind and PV.

☛ Our results show that for the "60% RES" scenario this **value gap for wind and PV ranges from 10 to 30 %[22] depending on the country**. The gap presents a degree of correlation with the penetration rate of variable RES. Moreover, this **energy value gap increases with the variable RES penetration ("cannibalisation" effect). In Europe, this "cannibalisation" effect is more pronounced for PV[23].**

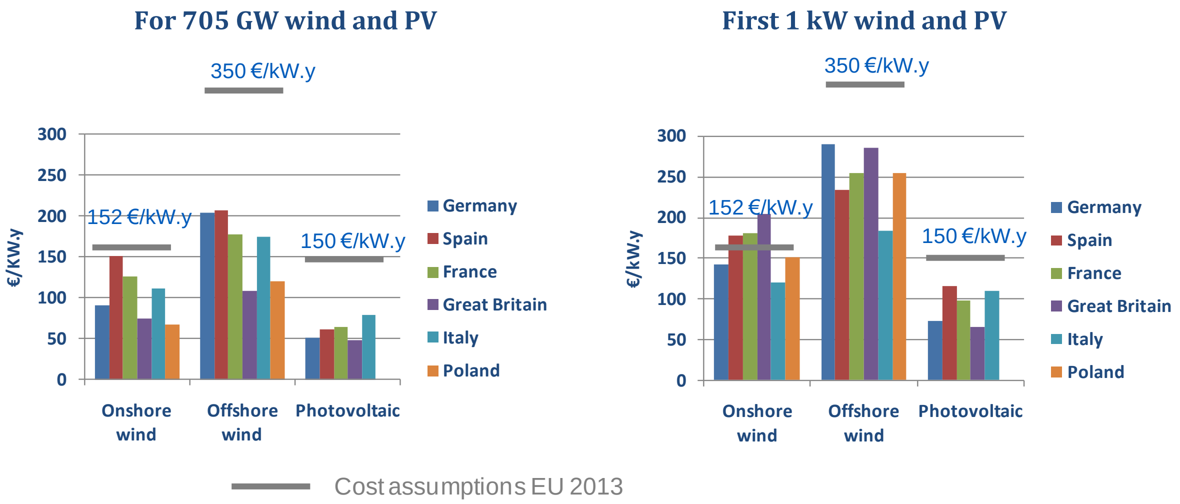
The competitiveness of wind and PV is accessed using a simple cost-benefit analysis comparing its market revenues with its investments costs. Our analysis shows that for commodity and CO_2 prices from the *EC Energy Roadmap 2011*, wind and PV need to be subsidised to cover their cost in the scenario. This cost-benefit analysis for onshore, offshore and PV is presented in Figure 18 with the value of the first kW installed (right image) and the value for the "60% RES" scenario (left image). Onshore wind is the technology with an economic value closest to its costs. Offshore

[22] These numbers to not include the costs resulting for forecast errors, often called balancing costs.

[23] The concentration of the production over a limited number of hours of the day tends to saturate the ability of the system to accommodate the production of PV faster than what is observed for wind.

wind is penalized by its high costs. PV sees its energy value[24] drop very fast with the penetration rate, raising questions about the optimal penetration of the technology in the mix.

FIGURE 18 **AVERAGE AND MARGINAL COST[25]/BENEFIT OF WIND AND PV FOR A SCENARIO WITH 60%RES[26]**



h. Storage and flexible demand contribute to the flexibility required for balancing demand and generation but do not replace the need for backup generation essential to handle inter-annual weather uncertainty

The results of the performance of the European system integrating a high penetration of variable RES do not provide clear economic justifications for further wide-scale development of centralized storage for managing the generation-demand balance, given the volume of storage that already exists.

The potential for development in storage will vary across the different zones in the European systems. Figure 19 presents value of storage (40h reservoir). This net value is obtained using a cost-benefit analysis where the cost of storage is subtracted to the gross value of storage. The gross value is obtained in terms of system cost savings (fixed plus variable costs) obtained when comparing a scenario with a scenario without storage. The net value is represented in the Figure using a yellow band that presents the interval of the net value as a function of the storage cost assumptions. We have considered different scenarios of this cost and the band represents the potential net value depending on the cost assumptions. The results indicate that current capacity of storage in France seems well adapted to the optimization of the generation-load balance. The region of Germany/Austria does not seem to hold great promise for the development of storage. This is in contrast to the UK in which the strong potential for offshore wind generation could make storage an interesting proposition. The interest in such deployment can only increase if storage contributes to ancillary services and reserves. The conclusions are similar if we consider smaller storage with a 2h reservoir (Figure 20) with slightly better perspectives for intra-day storage in Germany.

[24] To this we need to add the location costs quantified as network reinforcement costs. Its quantification lies outside the scope of this work.

[25] Outside of the cost of network reinforcement – Assumption of the European Commission "Trends to 2050 update 2013".

FIGURE 19: **EVOLUTION OF NET AND GROSS STORAGE BENEFITS IN MD€/AN FOR WITH A 40H RESERVOIR**

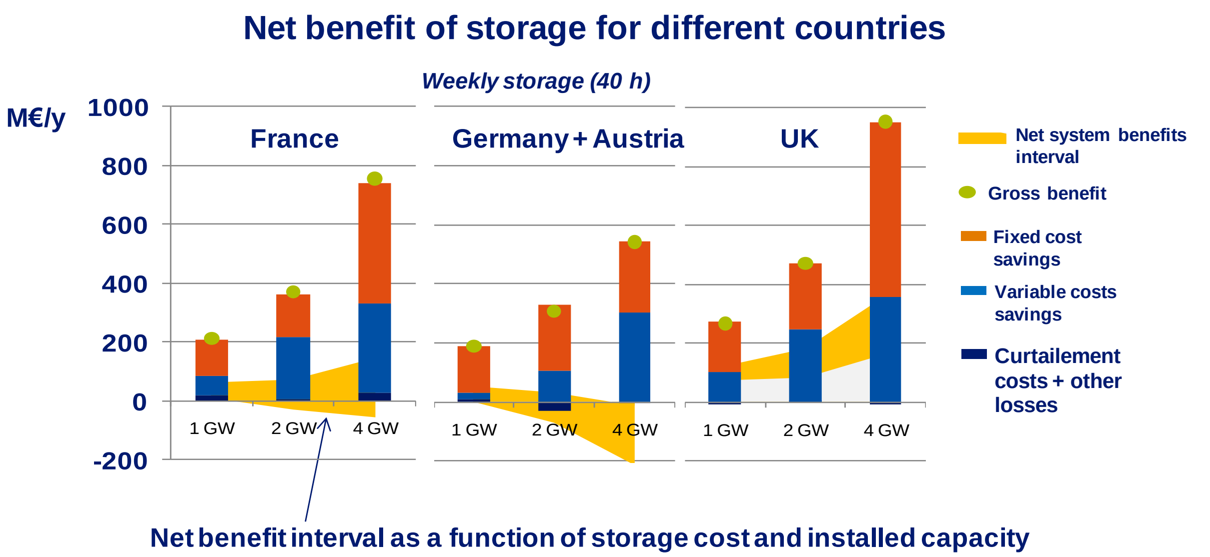
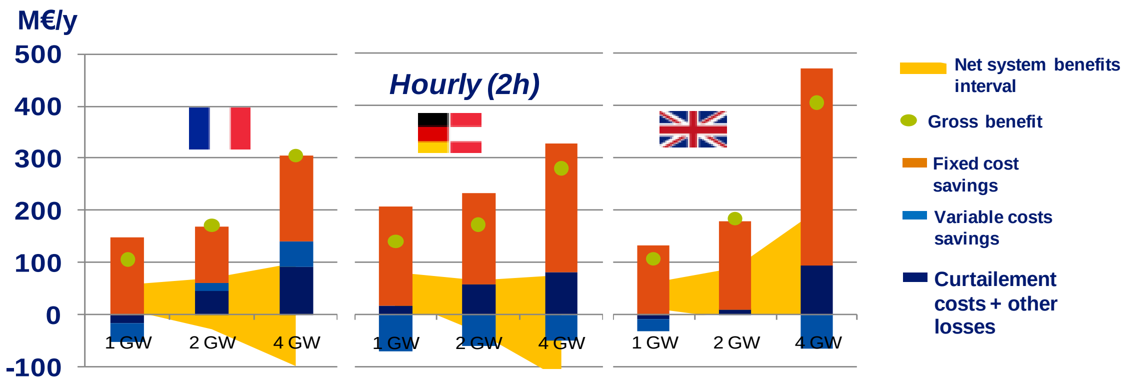


FIGURE 20: **EVOLUTION OF NET AND GROSS STORAGE BENEFITS IN MD€/AN WITH A 2H RESERVOIR**



☛ **Demand response mechanisms and decentralized storage can respond in only a limited way to the needs at a system level for back-up capacity driven by wide-spread wind and PV development.**

☛ **In contrast, storage and active demand can contribute to the dynamic management of the load/generation balance by providing flexibility and ancillary services (frequency and voltage control and *balancing,*) that supplement those provided by conventional generation and RES production.**

F. SUMMARY OF KEY FINDINGS

Variable RES and conventional generation will play complementary roles in the European interconnected electricity system. While wind and PV production have key roles to play in the European strategy for the decarbonisation of electricity production, thermal generation remains necessary in order to ensure system stability and security of supply. A contribution of nuclear to this thermal production would seem necessary in order to obtain the required CO2 reductions.

It will be necessary to develop new mechanisms for providing flexibility within the system, which must operate in complement to existing flexibility, in order to manage the variability of wind and PV production. That said, back-up thermal generation will continue to be needed in order to ensure security of supply.

- **If RES penetration reaches 60%, out of which 40% is variable RES, close to 500 GW of conventional generation (thermal, hydro and biomass) will still be required.**
    - **The European electrical system will be required to cope with the variations in variable RES production.** For instance, an installed capacity of 705 GW of wind and PV could see its daily production vary by a volume equivalent to 50% of total European demand within a 24 hour period**.**
        - For an installed on-shore wind capacity of 280 GW, the average hourly generation on a winter's day could vary from one year to the next between 40 and 170 GW depending on specific weather conditions.
        - Near-term flexibility needs will be important since for example, net demand upward hourly variations larger than 20GW and downward variations larger than 10 GW increase by 50% when compared to demand alone. Extreme hourly variations (>70GW) that do not occur in demand can be found in net demand.
- **Network developments at a local level within the distribution network, at a national level within the transmission networks along with new interconnectors** may be needed if it is wished to capitalize on the natural diversity in demand and the production from the different RES sites. Nevertheless, climatic phenomena, which can have a simultaneous impact across the European continent, can result in marked changes in wind production as seen across the entire system. In addition, network development costs may be too high if variable RES is developed too far away for the load centers.
- In addition to backup capacity, **demand response mechanisms** should also be developed to contribute to generation/load balancing. Nonetheless, while load shifting could play a role in extreme situations as means to limit peak demand, it will not be capable of dealing solely with the variability introduced by wind and PV production.
- There does not appear to be a business case in the next 15-year for **a wide-scale development of storage** as a means to manage intermittency, given the existing volume of storage in the European electrical system.

The rhythm with which variable RES are deployed needs to be optimized.

- An overly rapid development of variable RES will result in elevated costs of storage infrastructure (or overly conservative curtailment of variable RES) while at the same time the market value of variable RES will decrease as penetration levels increase.
- In addition, security of supply issues are also likely to increase as a result of the reduced dynamic stability of a system in which conventional spinning generation has been replaced by generators using power electronics interfaces.

III. PUBLICATIONS FROM THIS STUDY

Tools and methodology

G. Prime, V. Silva, J. M. Schertzer, M. Lopez-Botet Zulueta, *Integration of flexibility assessment to generation planning of large interconnected systems*, submitted for publication to IEEE Transactions on Power Systems.

M. Lopez-Botet, T. Hinchliffe, P. Fourment, C. Martinet, G. Prime, Y. Rebours, J-M. Schertzer, V. Silva, Y. Wang, *'Methodology for the economic and technical analysis of the European power system with a large share of variable renewable generation'*, presented at IEEE PES General Meeting, Washington, USA, 27-31 July, 2014.

Langrene, N., van Ackooij, W., Breant, F., 'Dynamic *Constraints for Aggregated Units: Formulation and Application*', IEEE Transactions on Power Systems, vol.26, no.3, Aug. 2011.

Frequency stability studies

Y. Wang, V. Silva, M. Lopez-Botet Zulueta, *Impact of high penetration of variable renewable generation on frequency dynamics in the continental Europe interconnected system*", IET Renewable Power Generation (shortcoming)

Y. Wang, V. Silva, A. Winkels, *'Impact of high penetration of wind and PV generation on frequency dynamics in the continental Europe interconnected system*', 13th International Workshop on Large-scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, Berlin, October 2014.

Presentations and exchanges with external experts

Analysis of the European power system with a large share of variable renewable generation,
IEA Task 25 – Wind integration, Meetings Munich September 2014

Flexibility assessment of scheduling solutions for systems with a high variable generation share,
Utilities variable generation integration group (UVIG), Fall Technical workshop, San Antonio, TX, October 2014

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