Chapter 9
Anticipating Some of the Challenges and Solutions for 60% Renewable Energy Sources in the European Electricity System

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Abstract In this study, EDF R&D used the EU "high RES" (RenewableEnergy Sources) scenario of the 2011 European Energy Roadmap, reaching 60% of renewables generation by 2030 including 40% from variable RES (such as wind and solar), and analysed its implications on system development and operation. The analysis was based on an in-house chain of power system planning, dispatch and simulation tools. The study indicates that a strong development of variable RES generation would imply significant changes to the thermal generation mix required to balance supply and demand, with the need for less base load power plants and for more flexible units. The study shows that conventional plants are still required to ensure security of supply and, in order to reach a high level of decarbonation, low carbon base plants are essential. Furthermore, the results also underline the strong interest of deploying a certain level of interconnections, especially around the North Sea and France: it is a very efficient way to optimize the systems costs since these ensure that electricity generated by RES can reach demand and curtailment can be avoided, while also enabling the sharing of backup plants and of RES and demand diversity. Storage and flexible demand play a complementary role as flexibility providers, as a complement to thermal plants and RES curtailment. The potential for cost effective additional storage will however depend on the zone and on the possibility to deploy the other existing levers. Storage is particularly interesting in island systems with limited flexibility such as the UK. Load generation balancing will be highly dependent on weather conditions and its associated uncertainty that will increase the need for operation margins at different lead times and reserves. In order to limit the

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impact of this uncertainty, forecasting tools and the operational practices will play an important role. An increase of variable RES in the mix leads to challenges in terms of dynamic stability, with frequency excursion potentially reaching security limit. These challenges are linked to the fact that variable RES are interfaced with the system by power electronics and do not naturally contribute to system inertia, which is a key factor in maintaining system security. In order to maintain system security, some curtailment or the deployment of innovative solutions such as fast frequency response from battery storage and RES are required. Lastly, the economics of such a system would be a significant challenge, as the cost of the infrastructure is high while the market profitability of RES decreases with RES penetration since it is exposed to a "cannibalisation effect".

Keywords Renewable energy · Low-carbon Europe · Roadmap 2050 · RES-E variability · Power system reliability · Dynamic stability · Thermal backup Storage · Active demand response · Interconnections · Synthetic inertia

9.1 Introduction and Hypotheses

European countries have committed to an important change in their energy system to reduce carbon emissions and foster greater energy efficiency. The power sector will be a key contributor namely with an increase of renewables for many decades to follow. The European Union has issued a series of climate and energy packages that define milestones until 2050.

The HiRes scenario of the EC Energy Roadmap 2011 [1] constitutes the base of the hypotheses used in this paper. The share of renewables in the mix reaches 60% of the European Union gross electricity consumption by 2030.[1] Unlike today where the largest share of renewable energy is produced by hydraulic plants, in 2030, the highest share of renewable production will come from wind and solar plants. This comes from the fact that there are very few new sites where hydraulic plants could be built and the costs of wind and solar are plummeting, allowing for a mass development of these technologies for the next decades. In this scenario, 40% of the European Union gross electricity consumption would come from wind and solar technologies. This quantitative scenario is used to illustrate the issues of the large deployment of variable renewable generation in the European system.

The original HighRES scenario is the result of a global energy modeling exercise commissioned by the EU. The EU roadmap also provides the electricity generation from low carbon sources (energy generation for wind, PV, biomass, hydro, other RES (Renewable Energy Sources) and installed capacity of nuclear) as well as the commodity and CO2 prices. The TIMES model [2], used to develop the original scenarios, is a bottom-up model that produces least-cost energy systems under a given

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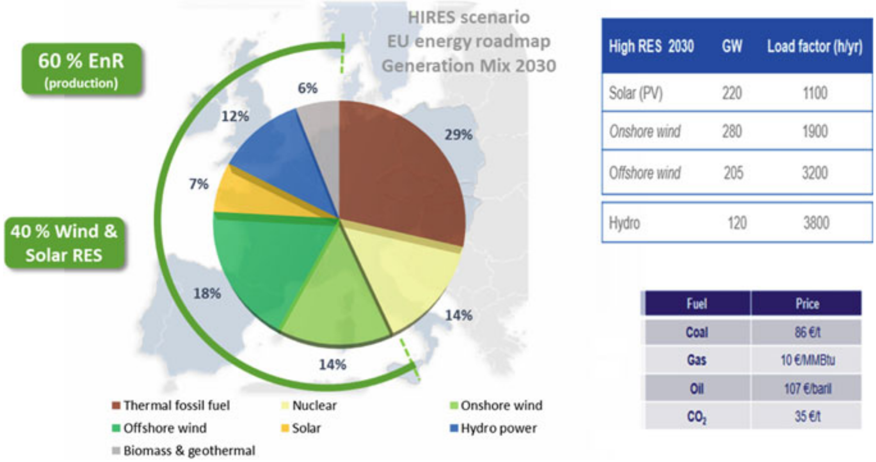
[1] This is to be compared to a share of 29.6% of renewable energy in the EU28 power system in 2016 (Eurostat, SHARES 2016).



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

Fuel	Price
Coal	86 €/t
Gas	10 €/MMBtu
Oil	107 €/baril
CO_2	35 €/t

Fig. 9.1 European union energy roadmap

set of constraints at different time horizons, using linear programming. Therefore, it encompasses the whole European energy sectors and demands, and it cannot rely on the same level of details that is used in state-of-the-art studies of the power system [3, 4]. In particular, it provides an average view for the contribution of variable RES to demand supply using few time-slices, while in reality, the supply and demand must be balanced for every hour (and less) whatever the weather conditions and resulting RES generations happen to be.

EDF R&D constructed a detailed dataset for the European energy mix respecting the global energy volumes per energy source described in EU energy roadmap 2050 [1] including the geographical distribution of the development of the different technologies. A significant body of work was conducted to build a realistic representation of the future European interconnected system. The model used covers 17 countries: the European continental area, the UK, Ireland, and the Nordic system. For each country, we represent hydro-generation (run of the river and lake), pumped storage, thermal generation, demand, variable RES (wind, PV), other RES (biomass, geothermal,) and the interconnection capacity between countries. The geographical distribution and installed capacity of variable RES (onshore wind, offshore wind and PV) are optimized given the resource potential, land usage and social acceptance using a TIMES based model. We find that the level of wind and PV reaches 705 GW as detailed in the table of Fig. 9.1 with 220 GW of Solar, 280 GW of onshore wind and 205 GW of offshore wind. This brings new challenges to the operation of the power system through the variability of the wind and solar generation and the interface with power electronics. It will lead to new ways of operating the power system as well as new market designs, and will require important infrastructure developments and a transformation of the conventional mix. A complete report with the details of the modelling is available in [5] and also in [12–14] and [15].

The four main challenges of integrating a high level of renewables in a mix, that will be developed in this paper, are:

- Connecting RES and load: Renewable generation potentials do not coincide with demand location. Therefore, infrastructures need to be developed to bring renewable generation to where the power is used. Having these additional networks will help smooth the renewable generation by allowing for a bigger geographical diversity. The generation remains, however, highly variable which requires more flexibility.
- Bringing flexibility to handle variability: The net demand (the total demand minus the variable RES production) that has to be met by conventional plants is exhibiting new features and becoming increasingly variable. Storage technologies can help but the conventional mix will also see profound changes.
- Keeping the lights on: To keep the same level of reliability that consumers have come to expect, RES-E will need to provide new services since conventional plants that have historically ensured the stability of the network will not always be online at the most delicate times unless RES-E are curtailed.
- Balancing the economics: Finally, the integration of massive RES-E also changes the economics of the system with the marginal prices exhibiting the shape of a duck curve or Nessie curve, as already seen today in California and Hawaii.

9.2 Connecting RES and Load

9.2.1 Integrating a Large Share of Variable RES Requires a Coordinated Development of RES and Networks

Renewable generation potentials do not coincide with power needs. Solar potential are highest in the south of Europe and wind potential are highest around the North Sea. EDF R&D constructed a detailed dataset where the wind and solar capacities were distributed by country. Interconnections are necessary to connect production and load, pool thermal backup and share the variability of intermittent RES-E. EDF R&D performed a cost-benefit analysis to assess the reinforcements required by the new generation mix (see Fig. 9.2). This analysis finds similar reinforcements to the ones planned in the TYNDP 2014 [6]. In particular, as exhibited in other studies such as e-Highways 2050 [7], we see a North-South corridor[2] going through France to link electric peninsulas and share wind in the north and solar in the south, as well as a triangle around the North Sea to bring back the offshore wind to the continent.

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[2] From the UK and the Netherlands all the way to Spain and Italy.

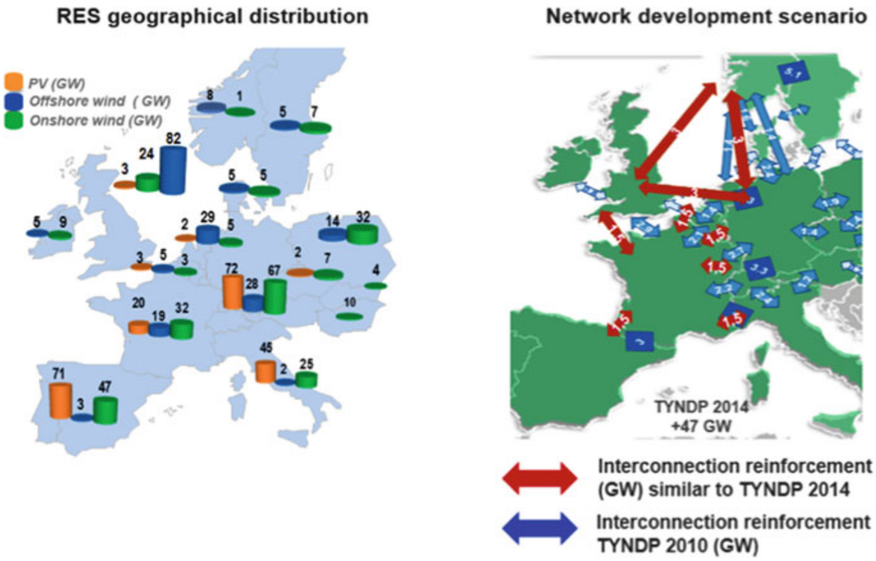

Fig. 9.2 Geographic distribution of RES and network development

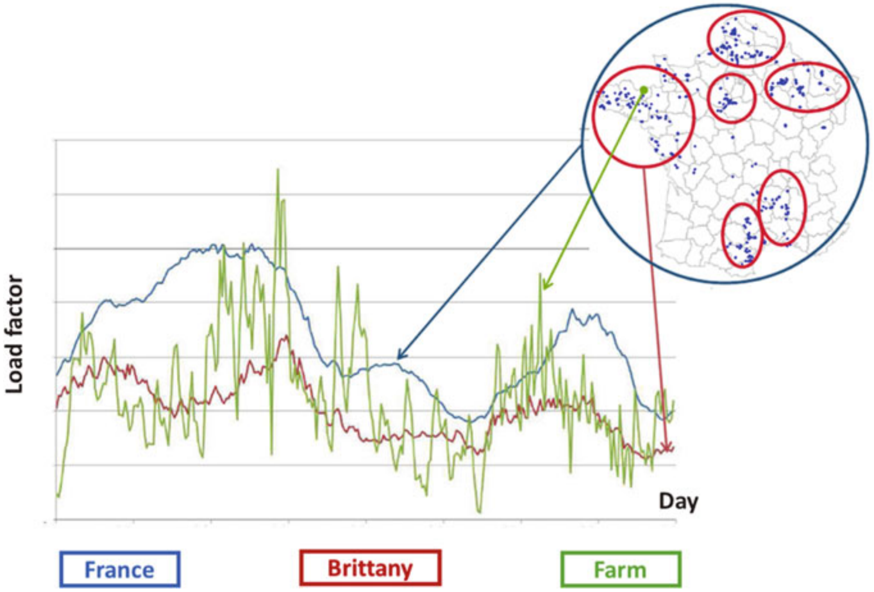

Fig. 9.3 Onshore wind generation for different geographical scales. (source RTE)

9.2.2 Geographical Diversity Does Help, but There Is Still Significant Variability at European Level

The development of infrastructures to bring the renewable generation to where the power is used will also help smooth out the renewable generation by allowing for a bigger geographical diversity as shown on Fig. 9.3. The generation is very uneven on the scale of a wind farm (green curve). It becomes smoother when aggregated over a region (red curve) and even smoother when aggregated over the entire country (blue curve).

Despite the generation becoming smoother, the variability remains significant at the European level as shown on Fig. 9.4. The figure represents the daily onshore wind generation for 30 different climatic years. A climatic year is created by using climate characteristics of a year in the past, such as wind speeds and solar radiation and temperature, to project the generation of wind and solar plants into the future. It therefore preserves the correlation with demand.[3] In the figure, there are 30 dots for each day of the year. We can observe a very large dispersion from one year to the next, as well as from one day to the next. It is largest over the winter where wind production is highest with 90 GW on average and still reaches a significant level over the summer. The same can be observed for solar plants with the highest dispersion occurring over the summer where the production is largest.

9.3 Flexibility to Handle the Variability

9.3.1 Not only Conventional Generation, but also Variable RES, Will Contribute to Balancing and Ancillary Services

Wind and PV generation increase the variability that needs to be managed by conventional generation. The net demand[4] profile, supplied by conventional generation, is more variable than demand alone, increasing the solicitation of the flexibility of conventional plants (see Fig. 9.5). 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 20 GW and downward variations larger than 10 GW increase by 50% and extreme hourly variations (>70 GW), which do not happen for demand, are present in net demand.

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[3] For the rest of the dataset, the climatic year will take into account the rain and snow patterns of the year for hydraulics, as well as load pattern.

[4] Net demand = Demand − Variable RES.

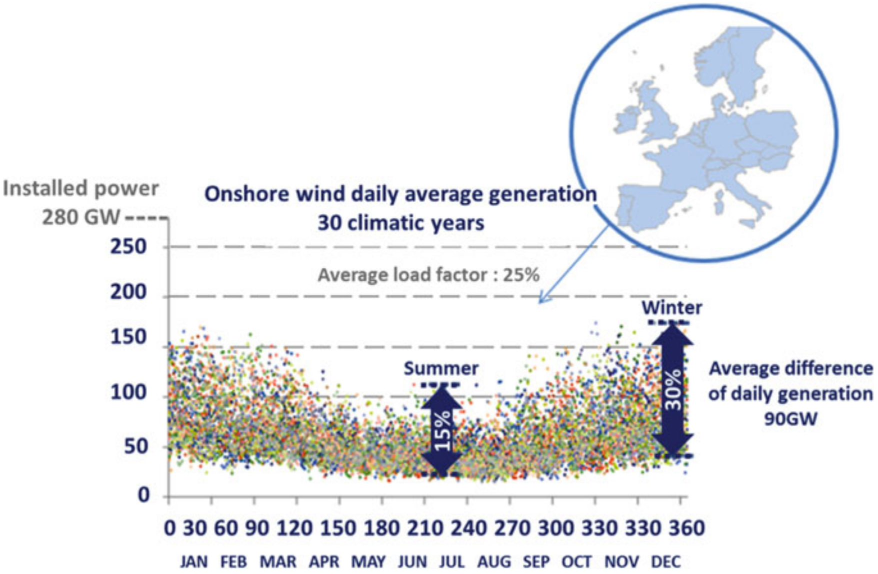

Fig. 9.4 Dispersion of daily onshore wind generation for 30 climatic years for the European power system. The average load factor (ratio between the generation output and the total installed capacity) varies from 15% in summer to 30% in winter

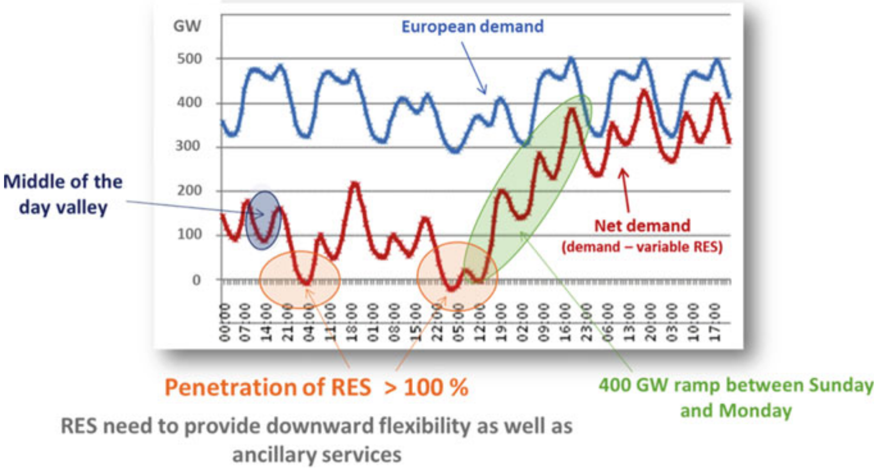

Fig. 9.5 Load-generation balancing becomes quite complex for periods with high net demand variability

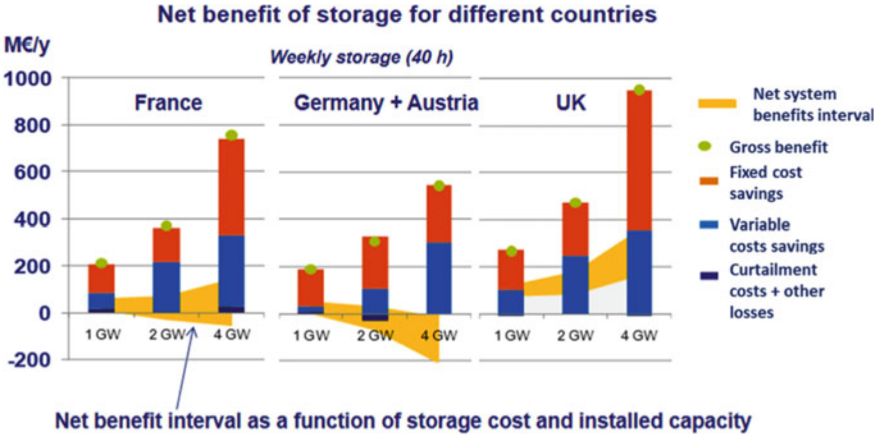

Fig. 9.6 Evolution of net and gross storage benefits in md/year for with a 40 h reservoir

9.3.2 Storage and Active Demand May to a Certain Extent Supplement Generation to Balance Supply and Demand

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 of storage will vary across the different zones in the European systems. Figure 9.6 presents the net value of storage for a 40 h 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 (see for example [8]) and the band represents the potential net value depending on the cost assumptions. The results indicate that the 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 a smaller storage with a 2 h reservoir, with slightly better perspectives for intra-day storage in Germany.

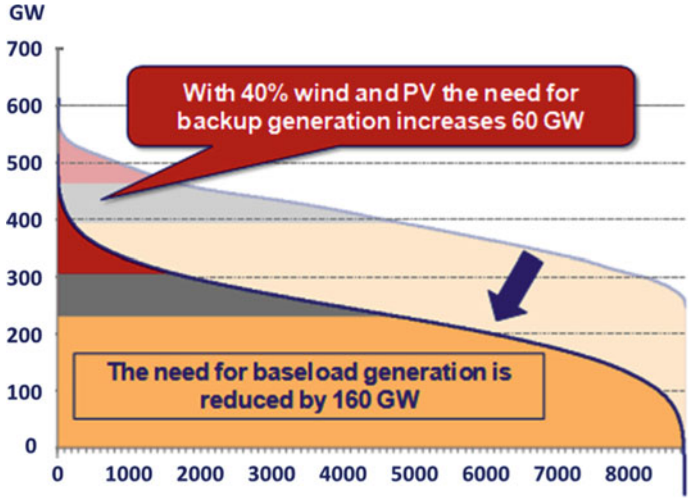

Fig. 9.7 European load duration curve of demand and net demand with 60% RES. Baseload generation = orange, semi-baseload generation = grey, peaking generation = red

9.3.3 Fuel Plant Are Needed for Backup Capacity for Security of Supply with High Level of Decarbonisation

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 at the European system level, can illustrate this issue. Figure 9.7 (transparent colors) illustrates demand by a stack of conventional generation technologies (thermal and hydro) without variable generation in the mix. Figure 9.7 (solid colors) 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 and net demand.

From the Fig. 9.7, one can observe the following:

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

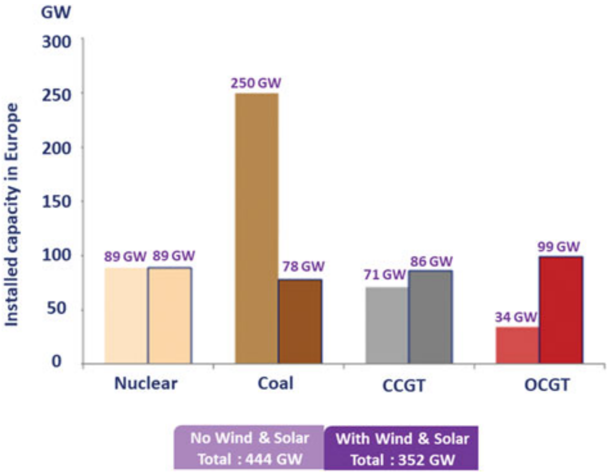

Fig. 9.8 Structure of the generation mix with and without wind and pv generation. CCGT = Combined Cycle Gas Turbine, OCCGT = Open Cycle Gas Turbine

This capacity credit comes solely from wind generation, since in Europe, PV generation is not present during winter peak.

- 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.

The 60% RES scenario, represents an annual CO2 savings in the order of 1 Gt when compared to a scenario without variable RES. These savings come from wind and PV generation and from the reduction of carbon-emitting base load plants in the conventional generation mix (See Fig. 9.8). The decarbonisation of European base load generation is achieved with a mix of RES and nuclear plants. The average CO2 content per kWh produced with 60% RES is 125 gCO2/kWh, a value significantly lower than todays 350 gCO2/kWh. The additional replacement of coal with gas plants would allow CO2 output to be reduced to as low as 73 gCO2/kWh. Above a certain share of RES, however, the marginal efficiency of CO2 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).

9.4 Keeping the Lights on: Variable RES Production Should Potentially Provide New Services Like Fast Frequency Response (Inertia)

Wind and PV farms differ from conventional generation and other RES because of their power electronics interface with the system, often designated as asynchronous (Fig. 9.9). The connection of wind farms and PV via power electronic interfaces will lead to a reduction in the inertia of the system.

This reduction of inertia impacts the dynamic robustness of the system, namely the frequency[5] 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 Fig. 9.10. 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).

However, critical situations with a frequency nadir lower than 49 Hz, triggering under frequency load shedding, and with a frequency lower than the security level of 49.2 Hz could happen. These are observed for periods with 25% instantaneous penetration of RES, 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 will contribute naturally to the re-establishment of the system frequency.

9.5 Balancing the Economics: The Pace of Deployment of Variable RES Should Be Optimised in Order to Limit Costs of Storage or Excessive Curtailment

The analysis of the revenues touched by variable RES, considering that they are paid at the system marginal cost, shows their revenue decreases with the scale of their deployment. This effect has been designated in literature as the "cannibalization effect". This is translated by a difference between the system yearly base load price and the average revenue of variable RES, designated here as "market revenue gap".

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[5] Keeping the frequency within a prescribed range is essential for the safety of the electric grid. The power that is received by a consumer stems from generators several hundreds of kilometers away sending electricity through a maze of lines at a given frequency. If the frequency shifts, there can be serious consequences for the network and consumer equipments, as well as for the electric grid, that can lead in the most extreme case to a blackout.

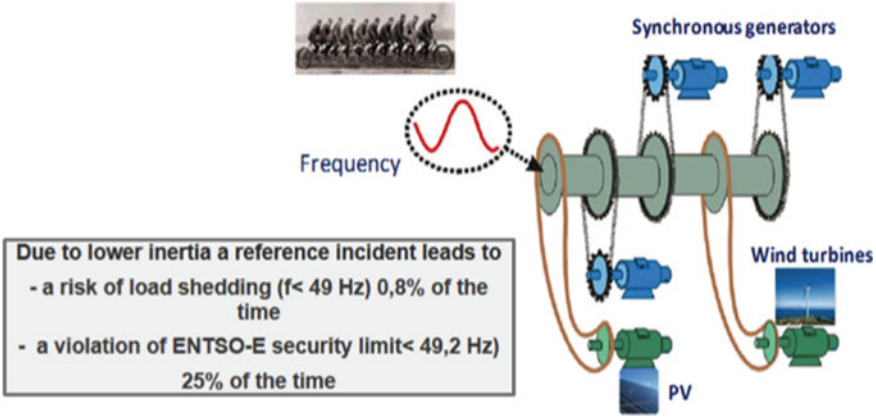

Fig. 9.9 Inertia and system frequency stability. Wind turbines and PV differ from synchronous generators in part because their power electronics interface is decoupled from the grid

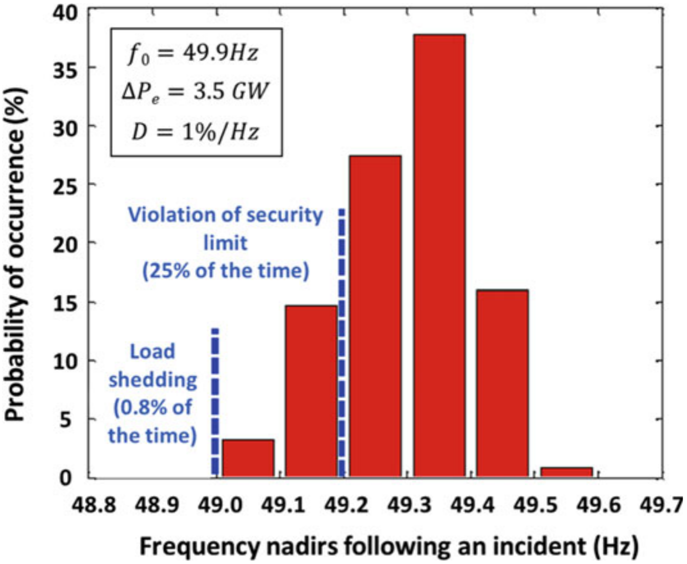

Fig. 9.10 Analysis of frequency stability in the European continental synchronous area with 35–38% share of variable RES

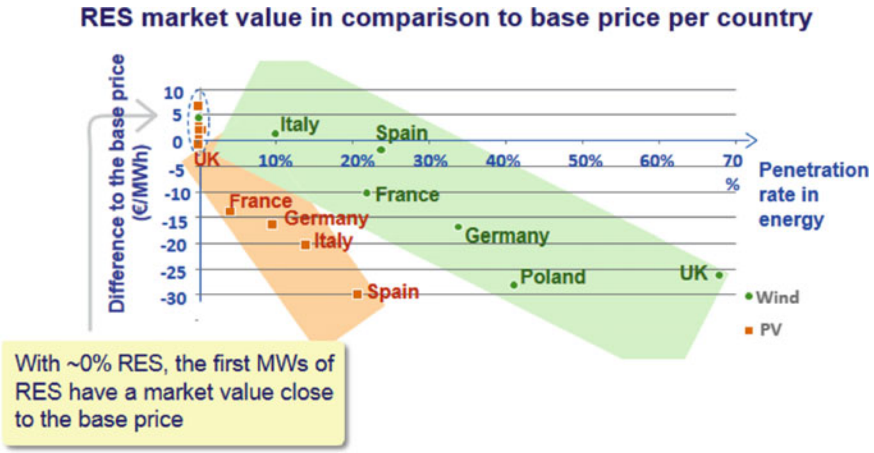

Fig. 9.11 Market revenue gap of Wind and PV in the 60% RES scenario (y-axis shows the gap between the yearly base load price and the market revenues of wind and PV and the x-axis presents the relative penetration of wind and PV in the zone in question)

Similar findings have been published in literature for the German, the British system and some parts of Continental Europe [9–11].

The analysis of the "market revenue gap" for wind and PV, for different countries, for the "60% RES" scenario, is presented in Fig. 9.11. The figure presents the evaluation of the incremental value of the service provided by variable RES to the system by comparing the marginal value of the first kW with the value of "40% variable RES". We can see that the value gap is very low or positive for the first MW of wind or PV (while their presence is marginal to the formation of the system marginal cost). Instead, for the higher penetrations of wind and PV for the "60% RES" scenario the gap becomes significant.

This result, which may seem counterintuitive, is easily explained. A technology is usually said to be mature when its levelised cost of production appears competitive compared with traditional thermal technologies or with a benchmark price for electricity. Joskow [9] notes however that for variable RES this comparison is misleading because the variable generation of a RES unit may be statistically biased towards periods when wholesale spot prices are higher or lower than the benchmark (see also [10]). In our approach, we capture this effect since the system marginal costs are outputs of the model and depend on the amount of RES capacity and on their generation patterns. A noticeable contribution of our approach is to reveal a telling pattern for how market value for RES decreases with their deployment.

9.6 Summary and Conclusion

Europe is leading an energy transition to lower carbon emissions. The HiRes scenario of the EU Energy roadmap 2050 is based on the introduction of massive volumes of renewable energies with a share reaching 60% in 2030, with 40% wind and solar in the mix. Such levels of wind and PV bring new challenges to the operation of the power system with the four main challenges being:

- **Connecting RES (Renewable Energy Sources) and load**
  Network developments at a local level within the distribution network and 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.
- **Bringing flexibility to handle the variability**
  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, and extreme hourly variations (>70 GW) that do not occur in demand can be found in net demand.
  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. 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.
- **Keeping the lights on: variable RES production should potentially provide new services like fast frequency response (inertia)**
  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. 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).

- **Balancing the economics: the pace of deployment of variable RES should be optimised in order to limit costs of storage or excessive curtailment**
  We showed earlier in this document that variable RES displace 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% 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.

The study shows that variable and conventional generation should be viewed as complementary. Wind and PV are an important component in the EUs decarbonisation strategy, thermal generation is necessary to maintain system reliability and security of supply. Furthermore, low carbon base load generation is needed in order to deliver the reduction in the average carbon factor of European electricity.

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