ECONOMIC AND TECHNICAL ANALYSIS OF THE EUROPEAN SYSTEM WITH A HIGH RES SCENARIO

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1. Overview

Renewable energy sources (RES) are one of the main options towards long-term decarbonisation of electricity generation in Europe and variable generation, as wind and PV, will represent an important part of RES development. This type of generation presents some characteristics that create specific issues for its integration to the electricity system. These are its variable and not fully predictable output, its power electronics interface and a high modularity, a location not always coincident with demand centers and a close to zero marginal cost.

The present research, based on the results of long term electricity system studies, aims at improving the current understanding of the technical and economical issues of a massive deployment of wind and PV across the European system. The canvas for the work is a scenario with 60% renewable energy penetration in the European mix of which 40% are wind and PV generation. The scenario is based on the European Union (EU) Energy roadmap “High RES” scenario [1]. Several aspects of the system integration of variable generation are analyzed in this paper, including the characterization of variable RES generation variability for different time-scales (from inter-annual to hourly), the need for backup and interconnection infrastructure and the market profitability of variable RES. The present analysis is part of a wider study which includes more detailed analyses of the technical performance of the European electricity system in terms of impact of forecast errors on reserves and flexibility and the system dynamic frequency stability [2-3].

2. Methodology for the economic and technical analysis of the European power system with a large share of variable renewable generation

The approach used in this work simulates the development, operation and, as a result, we obtain the hourly system marginal costs across different European synchronous zones and countries [4]. This builds on a multi-area market equilibrium model developed by EDF R&D, Continental Model (CM) [5], with all units bidding their marginal costs and assuming perfect market competition. CM is part of a chain of tools that includes 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 a post-processing analysis to study marginal costs and generation revenues. With this whole system approach it is possible to perform detailed simulations of the European electricity system and the impact of the integration of variable RES on the load-generation balancing from long term planning to (close to) real-time operation time-scales (see Figure 1).

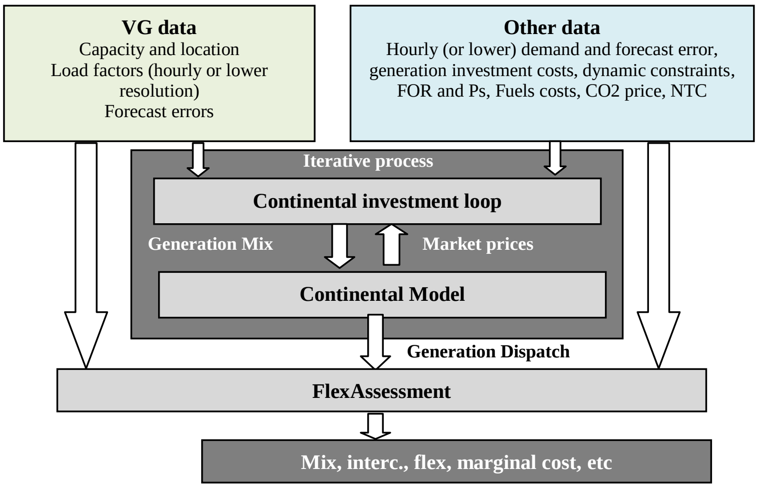

Figure 1 Structure of the whole system approach for the simulation of the European electricity system

CM simulates the hydro-thermal dispatch, for every hour of the year, given the interconnection constraints between the countries. The stochastic nature of variable RES, run-of-the river hydro, demand and generation availability is taken into account by using a large number of annual scenarios. Each scenario corresponds to an alternative realization of these variables, created using historic weather data, and is composed by annual time-series, with hourly resolution, for each country. The optimization of water reservoirs and pump storage is performed using dynamic programming. The thermal unit commitment and dispatch, solved using mixed integer linear programming (MILP), minimizes the thermal and hydro generation costs, being hydro represented by the water values (see [5] for additional details).

The multi-area investment planning problem is solved using an investment loop, Continental Investment Loop (CIL) [6]. The objective of CIL is to obtain, using an iterative process with CM, a thermal generation mix that minimizes system cost and ensures that the market revenue of every new unit is slightly higher than its annualized fixed and variable costs. The fixed costs include investment and O&M and the variable costs include start-up, fuel and CO_2 costs. An adequacy criterion, defined as the maximum expected number of hours per year with a marginal cost equal to the value of lost load (VOLL), needs to be respected. This approach is similar to other studies ([7], [8]) and ensures that only units that profitable (able to recover their costs from the hourly marginal costs) are built.

The outputs of the model include: generation mix, interconnection capacity, dispatched generation, interconnection use, system marginal costs, flexibility adequacy indicators and revenues from thermal and renewable generation.

3. Input scenario and input data

The scenario used as an input is based on the HighRES EU Energy roadmap 2011. The scenario assumes a mix where 60% of the European Union gross electricity consumption would be sourced from renewable technologies, with 40% coming from wind and solar technologies by 2030. 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 and installed capacity of nuclear) as well as the commodity and CO_2 prices. The TIMES model [9] that was used to develop the original scenario encompasses the whole European energy sectors and demands; therefore it cannot rely on the same level of details that is used in state-of-the-art studies of the power system ([10], [11]). 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.

A significant body of work was conducted to build a realistic representation of the future European interconnected system. The model used covers the main synchronous regions, which are the UK, Ireland, the Nordic system and the European continental area with a total of 17 countries. For each country we represent hydro-generation (run of the river and lake), pump storage, thermal generation, demand, variable RES (wind, PV), other RES (biomass, geothermal, etc) 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. 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/km^2 placed in farming land and swamps. 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. The results obtained are presented in Figure 2 and present a large concentration of offshore wind in the north of Europe where the more promising sites are located. Likewise, an important development of PV in the south of Europe is obtained. The hourly generation load factors for each scenario for wind, PV and run-of-the river hydro are constructed using projections of the development of the generation technology (type and location) and different historical years of meteorological data. Demand data is constructed using the same meteorological data, combined with load growth and new loads development assumptions. As a result, we obtain 30 scenarios of time-synchronized chronological data capturing the spatial and temporal correlations across the European system. The data set obtained is able to represent the impact of geographical diversity as well as the variability of the generation at different time-scales from hourly to seasonal and inter-annual. These are combined with randomly generated unit availability to obtain close to 100 scenarios.

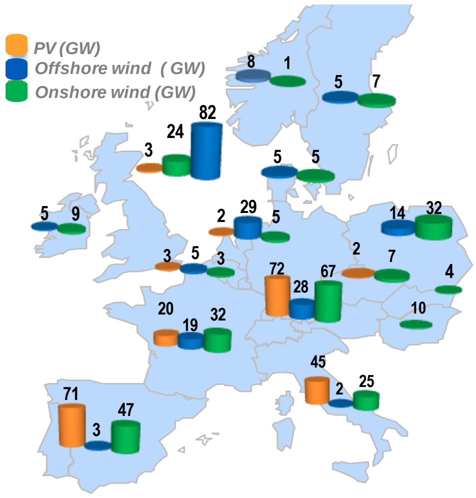

Figure 2 Variable RES geographical distribution and installed capacities

4. Generation and interconnection infrastructure for the European system with a 60% RES scenario

The data set and whole system approach presented in the previous sections allowed us to perform a detailed study of the European electricity system with 60% RES in particular issues as the characterization of variable RES and net demand variability, the structure of the conventional generation mix and average emissions from generation, flexibility issues and variables RES revenues. The results are detailed in the following sections.

4.1 Characterization of wind and PV variability across Europe

The analysis of the onshore and offshore wind and PV generation time-series allowed us to characterize the variability of its output. The first observation is the important 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. One can say that intermittency is a local issue at the level of an installation or farm. At system level variable generation presents a significantly smoothened profile. In order to benefit from this smoothing effect and facilitate the load-generation balancing the appropriate network infrastructure is required.

Figure 3 shows the important inter-annual variability of the onshore wind generation with respect to overall weather conditions in Europe. The degree of correlation of wind regimes across Europe shows that the availability of onshore wind generation, aggregated at the European level, is highly dependent on the atmospheric conditions. The simulation of a wind park with 280 GW of installed capacity, well distributed across the European system, showed that in winter the daily average power from wind varies between 40 and 170 GW depending on wind conditions during the different years. The same figure shows the “seasonality” of onshore wind generation. The average load factor (ratio between the generation output and the total installed capacity) varies from 15% in summer to 30% in winter.

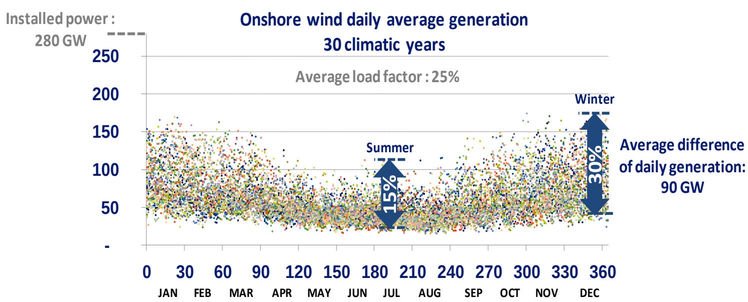

Figure 3 Wind generation for different climate years aggregated at the European interconnected system level

A similar analysis is performed for PV and Figure 4 shows that 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 (5%). These findings indicate that there is an important need for backup capacity in the mix in order to deal with the important inter-annual variability.

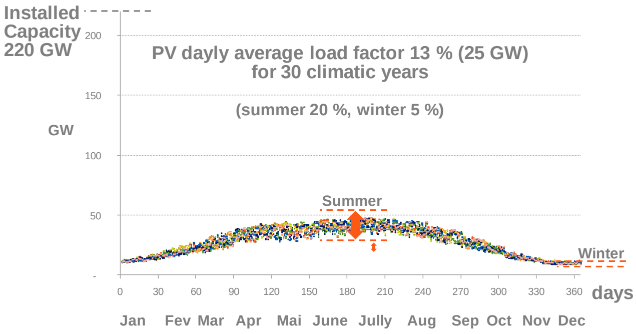

Figure 4 PV generation for different climate years aggregated at the European interconnected system level

4.2 Impact of 40% variable RES on interconnections infrastructure in Europe

In order to benefit from geographical diversity, optimize investments in generation and minimize operation costs an appropriate network infrastructure is required. In this study we performed a cost-benefit analysis (CBA) to quantify the needs for reinforcement of interconnections between countries. The CBA was performed using the tools described in section 2, and using as a starting point the existing capacity plus the reinforcements proposed in the European network of transmission system operators for electricity (ENTSO-E) ten year network development plan (TYNDP) of 2012. The basis of the 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 [10]. 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 that had a positive CBA are represented by the red lines Figure 5. These reinforcements are coherent with the ones published in the ENTSO-E TYNDP 2014 for a scenario with 60% RES by 2030 [12]. Please note that each country is represented as a single node based on the assumption that internal grid reinforcements will be done. In reality, failing to do so will represent an hindrance to the integration of 60% RES to the system.

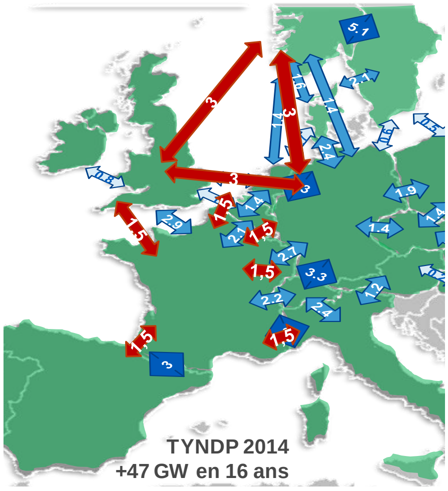

Figure 5 Interconnection infrastructure (blue lines correspond to the reinforcements predicted in the TYNDP 2012 and red lines are the new reinforcements required to accommodate 60% RES)

The results 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. Two main reinforcements areas are identified by the CBA: 1) the development of offshore wind in the North Sea should be accompanied by the adequate interconnection capacity to transport its production to demand centers; 2) an increase of the interconnection capacity around France helps to benefit from the diversity between PV in the south and wind in the north, as well as facilitates the access to low carbon conventional generation. 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. It is clear that a high RES scenario requires a joint geographical optimization of network and generation from RES. Infrastructure investment, however, faces acceptance problems and a slow development could pose challenges to the integration of high shares of RES.

4.3 Impact of 40% variable RES on the European Generation mix

For the load-generation balancing purpose (both long and short term) the RES variability is assimilated to demand variability in order to analyze the impact on the net demand (net demand is the demand that needs to be supplied by conventional plant and equals demand minus variable generation). The analysis of the net demand indicates that the development of a large share of variable RES entails an adaptation of the remaining generation mix. The conventional generation European fleet is likely to be different from the existing one and the results of our analysis of the optimized portfolio required to accommodate 60% RES is described in the next sections.

4.3.1 Structure of the mix

The two main consequences in terms of changes to the structure of the mix are: 1) a reduction of the need for base generation and 2) an increase of the need for backup capacity. The latter is composed of technologies able to recover their investment costs even with low load factors. These effects can be well illustrated by the load duration curves of Figure 6. From the figure one can see that the net load duration curve is not only depressed but also deformed when compared to demand. This entails the following consequences to the structure of the generation mix: 1) The energy produced by wind and PV displaces base load generation and the 700 GW of wind and PV displace 160 GW of base load generation equivalent to 40 % of the annual demand in energy; 2) A backup capacity increase in the order of 60 GW required to respect the capacity adequacy criteria of an expected loss of load of 3h/year. This higher backup need due to variable RES is explained by the presence of periods when wind and PV are not available; 3) 700 GW of wind and PV lead to a reduction in conventional generation capacity in the order of 100 GW (160 – 60 = 100 GW). This capacity credit comes solely from wind generation since PV generation in Europe is not present during winter peak.

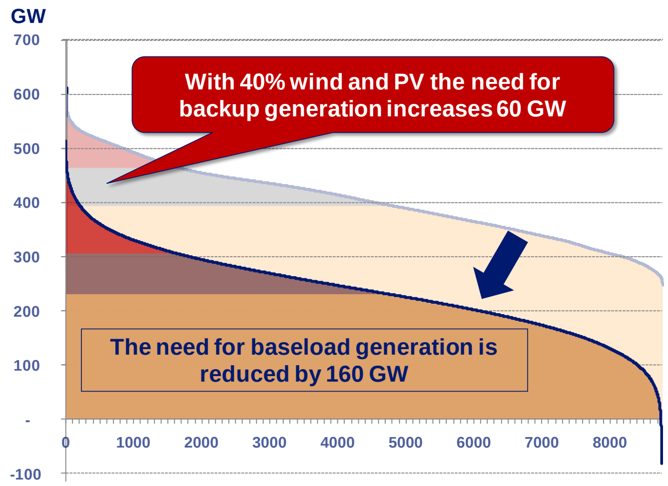

Figure 6 European Load duration curve of demand and net demand with 60% RES

The generation mix is optimized using the chain of optimization tools described in section 2. Low carbon generation, as RES and nuclear are defined in advance. RES energy and nuclear installed capacity are obtained directly from the EU energy roadmap 2030 for the HighRES scenario. This optimization uses as inputs the commodities and CO2 prices from the EU Energy Roadmap 2011 (Table 1).

Table 1 Commodity prices – projections for 2030 from the EU Energy Roadmap 2011

Commodity	Price
Coal	86 €/t
Gas	10 €/MBtu
Oil	107 €/baril
CO_2	35 €/t

For comparison purposes the same optimization is performed for a scenario without wind and PV. The results of the two cases are presented in Figure 7. The main observations from the load duration curve approach can be found in the optimized generation mix. In the mix with 40% variable RES, 352 GW of thermal generation are required to maintain security of supply. Wind and PV displace mostly coal. The presence of coal in the mix is mostly explained by the modest CO_2 price projected for 2030 by the EU Energy Roadmap 2011. The important inter-annual variability of variable RES is handled by backup generation (total of 99 GW) with a quite low utilization factor. The more competitive technologies to fulfill this role are currently open cycle gas or dualfuel thermal plant. The underlying question is how to ensure investments in backup capacity, given the revenue risks in a market environment dominated by variable generation, as seen in chapter 5.

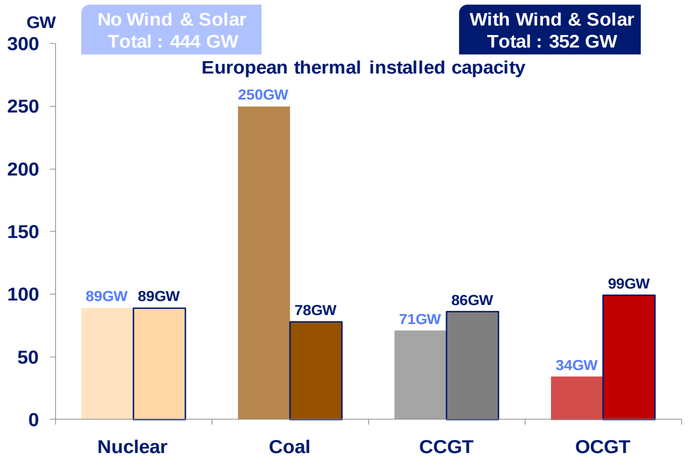

Figure 7 Structure of the European thermal generation mix with and without wind and PV generation

4.3.2 CO_2 emissions

The hourly generation dispatch permitted the calculation of the average CO_2 emissions. The results show that with 60% RES the average emissions are of 125 g CO_2 /kWh. This represents an important decrease from today's 350 g CO_2/kWh but a significant effort will still be required to reach full decarbonisation. The further replacement of coal with gas would allow us to reach 73 g CO_2 /kWh. This level of emissions is partly justified by the presence of low carbon base generation (89 GW of nuclear defined by the EU Roadmap) showing that a high decarbonisation level requires a significant share of carbon free base load.

4.3.3 Flexibility

The analysis of the hourly variability of net demand shows that net demand upward hourly variations larger than 20 GW and downward variations larger than 10 GW increase by 50% when compared to demand alone. Extreme hourly variations (>70 GW) that do not occur in demand can be found in net demand. This will lead to a need for more flexibility in the generation mix. The challenge of handling this variability is magnified by the fact that we are not able to have more than a statistical vision of variable RES generation until a few days before electricity delivery time. Recent and future improvements in forecast accuracy have a fundamental role to play and significant improvement has been observed in the last years, especially for the intra-day forecasts. However, at the European level a significant uncertainty remains, even in intra-day. The analysis of historic forecasts for wind and PV for the French system shows that the mean average error (MAE) in the intra-day forecasts of wind production is in the order of 2.5 % of the installed capacity. This corresponds to 12.5 GW when considering a park of 500 GW installed across Europe. For PV, the equivalent error is in the order of 5%, which for an installed park of 220 GW corresponds to 11 GW.

These observations clearly show that the system will require additional flexibility. In spite of the variability smoothing obtained thanks to geographical aggregation, high variations still remain at European level and these require significant ramping capability at different time-scales. In addition, forecast errors lead to an increase in the need for operation reserves and balancing [4].

This need for flexibility is addressed by the replacement of base load plant by more mid merit and peaking plant, as seen in Figure 7. This transformation of the mix enhances the flexibility of the system and its capability for handling variability and uncertainty. Our results show that the optimization of the generation mix naturally created a flexible mix without the need for an explicit representation of near term uncertainty in CM. Similar findings were reported in [13]. This result is adherent to the fact that the more economic technologies for backup capacity are also quite flexible and therefore able to cater for system's need for flexibility as well as adequacy.

The real-time load-generation balancing (frequency regulation) in the European system with high RES is a challenging issue, as shown by the stability study of the 60% RES scenario, presented in [3]. The power electronics interface of wind and PV and the fact that they do not currently contribute to frequency regulation could pose important challenges for the operation of the system. In order to ensure system security without excessive RES curtailment, variable RES will need to contribute to existing and new ancillary services.

5. Market value of variable RES

The market value of variable RES is studied by performing a targeted analysis of the hourly productions and system marginal costs results obtained with the detailed stochastic optimization model described in section 2. The hourly marginal costs are obtained for every zone and for the whole of Europe, considering the interconnection constraints, for close to 100 annual scenarios. The base case scenario is the 60% RES (40% wind and PV) scenario. The study of the base case is complemented by a set of sensitivity studies with scenarios with variable RES penetration between 0% and 80% of the energy demand. For the purpose of the sensitivity study none of the other parameters, such as the interconnections capacity, optimized for 60% RES, were modified.

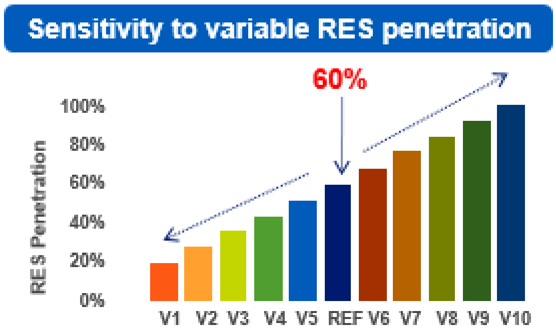

Figure 8 Base case (60% RES) scenario and sensitivity analysis scenarios

The first observation from the sensitivity analysis is a decrease of the yearly average system marginal cost when increasing the penetration of RES in the system. Notice that the drop in the annual marginal cost usually coincides with the first appearance of hours where the marginal cost equals zero as it is shown in Figure 9 for Germany. Please note that the zero marginal costs periods correspond to periods with RES curtailment. This curtailment is driven by two factors: 1) variable RES generation is higher than demand plus the export capacity in the area; 2) curtailment driven by economic factors such as avoiding start-ups costs.

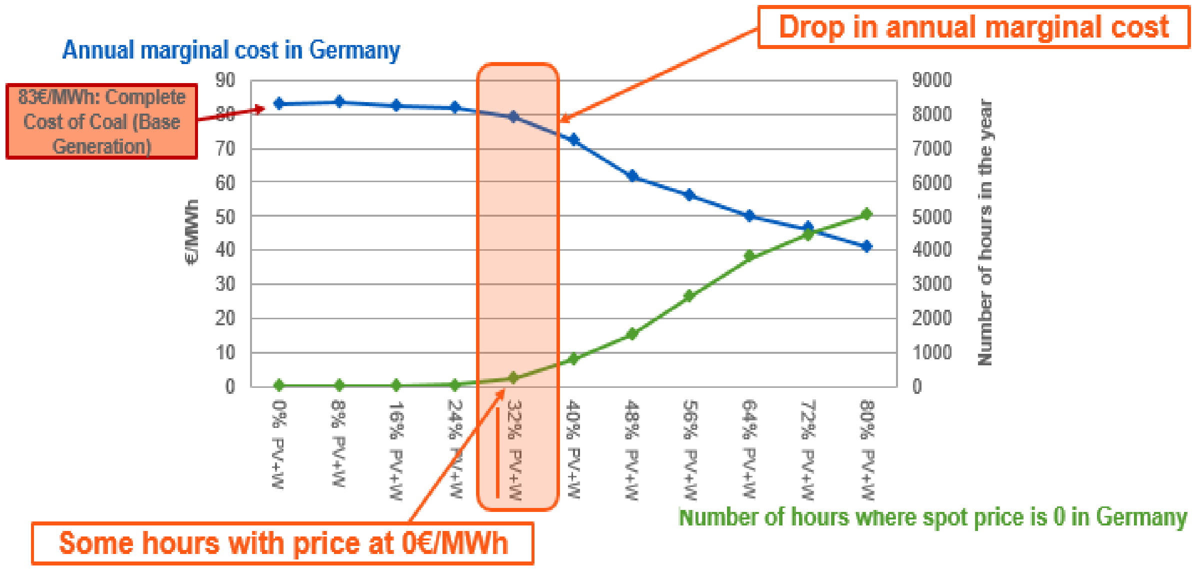

Figure 9 Drop of annual marginal cost for a high penetration of RES

For the scenarios with a low penetration of RES, the annual marginal cost corresponds to the Complete Cost of Base generation (CCBG), which are coal plants in Germany: this short term signal reflects the price that should be earned on average by a base generation plant to cover its costs (costs of capital and O&M). As the number of hours where variable RES are marginal increases, the annual marginal cost falls and no longer reflects the CCBG. However, since the thermal generation mix is optimized and all plants built are profitable, for example, coal plants in Germany operate on fewer hours but are still able to recover their costs. This is explained because the system marginal cost in these hours is sufficiently high. With high variable RES penetration the CCBG is no longer the right investment signal since the notion of base load is no longer present.

5.1 Market value of variable RES for the “60% RES scenario”

The analysis of the revenues touched by variable RES considering that they are paid 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”. Similar findings have been published in literature for the German, the British system and some parts of Continental Europe [14-16].

The analysis of the “market revenue gap” for wind and PV, for different countries, for the “60% RES” scenario, is presented in Figure 10. 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.

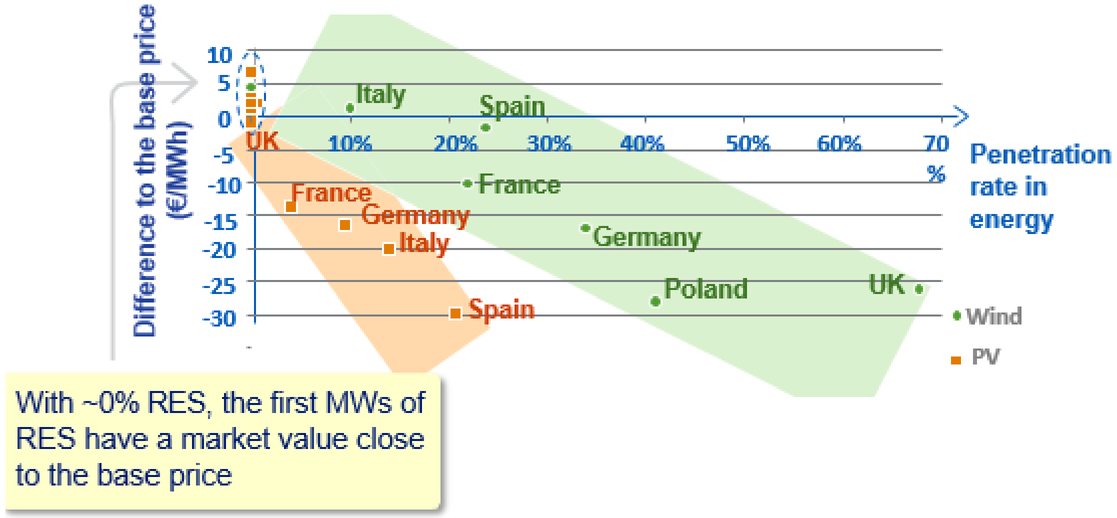

Figure 10 Market revenue gap of Wind and PV in the 60% RES scenario (y-axis shows the gap between the yearly base load price and the market revenues of wind and PV and the x-axis presents the relative penetration of wind and PV in the zone in question).

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 [14] 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 [15]). In our approach, we capture this effect since the system marginal costs are outputs of the CM 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.

5.2 Sensitivity analysis of the market value of variable RES to the variable RES penetration in Europe

The observations from the “60% RES scenario” are confirmed by the sensitivity analysis. This sensitivity analysis is based on the concept of value factor [15] that corresponds to the ratio between the RES revenue in €/MWh and the average annual marginal cost in the country. Figure 11 shows the value factor of wind and PV for different RES penetration in Europe. One can see that PV generation presents a drop in the value factor steeper than wind, since its generation is concentrated around a few hours of the day. A good example of this is the observation that with 20% penetration of PV in the Iberian Peninsula the value factor of PV is as low as 50%. Instead, in Great-Britain a similar value drop is attained only with 80% wind penetration in the country (see Figure 11).

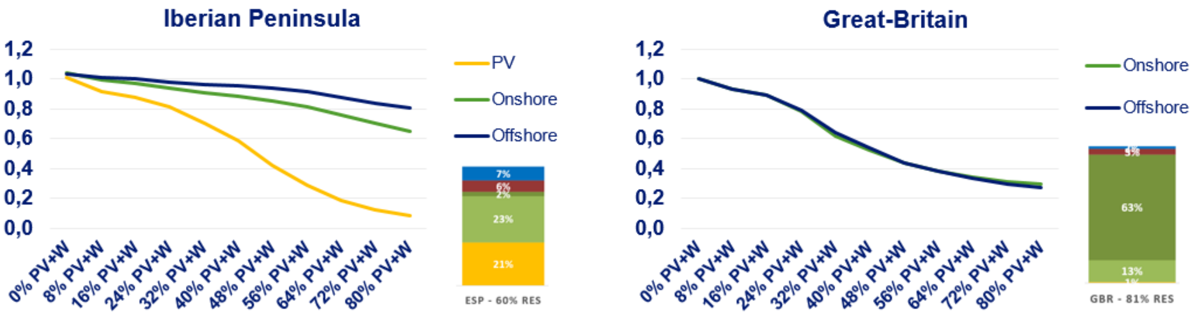

Figure 11 Sensitivity analysis of the value factor of wind and PV to the penetration of variable RES

These value factors represent significant revenue gaps for RES in spite of the assumption that their investment costs decrease significantly, as seen in the IEA projections for 2030 [17]. Similar findings were reported in [16]. Our analysis shows that for commodity and CO2 prices from the *EC Energy Roadmap 2011*, wind and PV are not able to recover their investment costs in the market (cf. Figure 12). The different between costs and revenues is not uniform for all technologies with onshore wind presenting the market value closest to its costs. Offshore wind is penalized by its high costs (around 350€/kW/year) and PV sees its market value drop very fast with the penetration rate, raising questions about the optimal penetration of the technology in the mix.

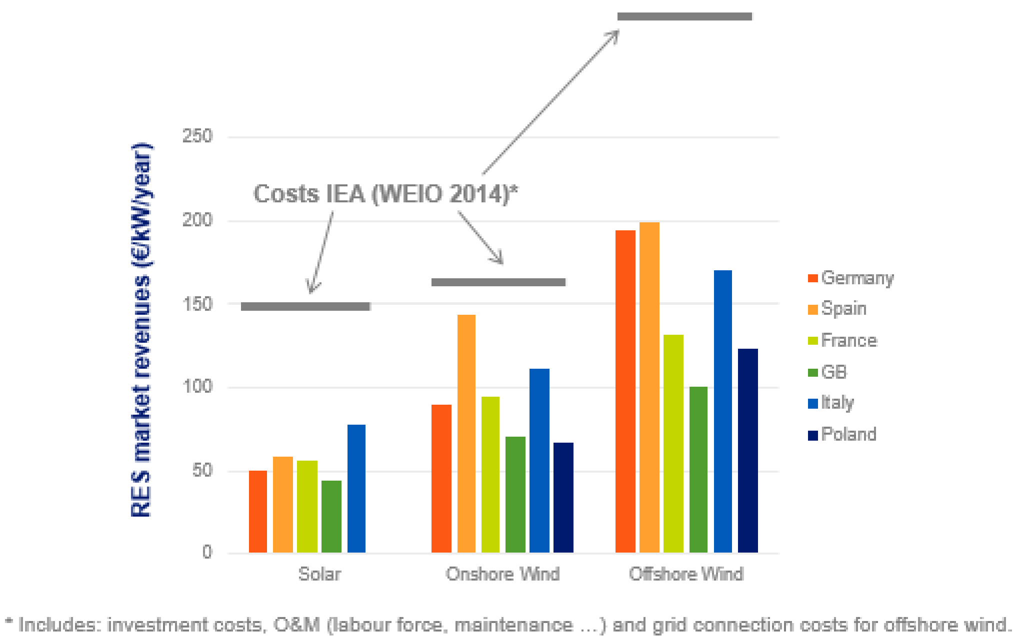

Figure 12 Average Cost/Benefit analysis for wind and PV in the 60% RES scenario

This is explained since the generation from renewable sources does not follow demand patterns. For a high volume of RES the additional amount of generation obtained from new capacity does not bring an equivalent value to the system since it is not available in the periods the system needs it. This can be easily understood since during periods of curtailment the additional energy produced does not bring value to the system. Moreover, the additional sensitivity analysis (Figure 13) shows how market revenues progressively decrease with RES development and how this behavior depends on the renewable technology and the country's mix. Our results indicate that offshore wind and PV are not able to recover their investment costs.

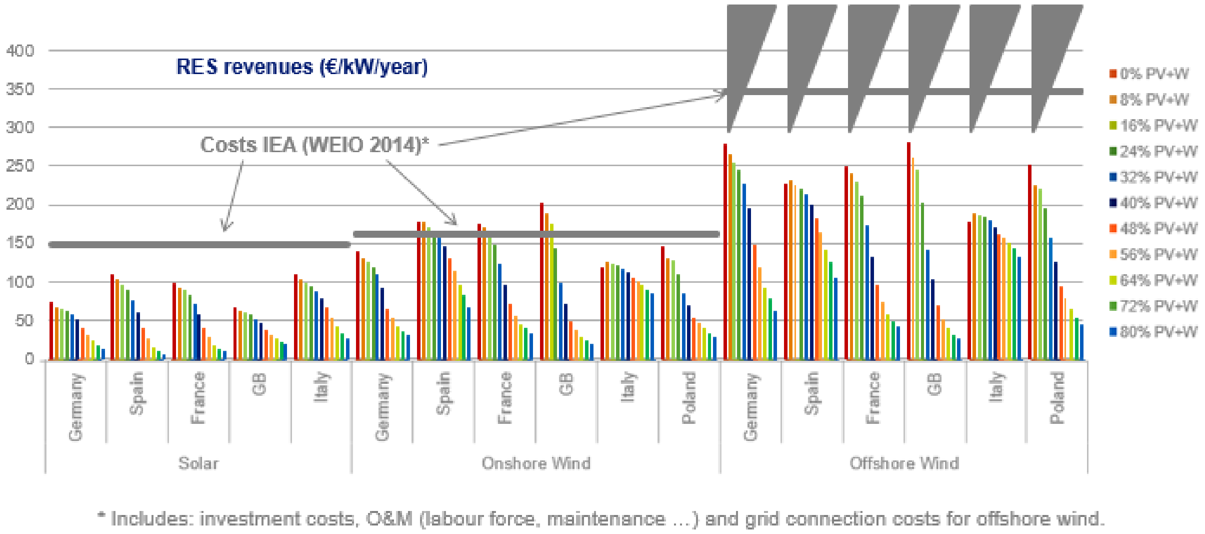

Figure 13: Average Cost/Benefit analysis for wind and PV in the sensitivity analysis

Conclusion

This paper presented the methodology, simulation approach and results of the study of the technical and economic issues of a scenario with 60% RES, of which 40% Are wind and PV, in the European electricity system.

The study shows that variable and conventional generation should be viewed as complementary. Wind and PV are an important component in the EU's 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.

Infrastructure, network and backup generation, will help mitigate the impact of the variability observed with 60% RES to a certain extent. However the infrastructure cannot cope with extreme Europe-wide climatic situations and is likely to become too costly if variable RES are developed too far away from consumption areas. A cost benefit analysis has shown that the development of offshore wind in the North Sea should be accompanied by the adequate interconnection and increasing the interconnection capacity around France helps to benefit from the diversity between PV in the south and wind in the north, as well as facilitates the access to low carbon conventional generation.

Assuming a clear decrease in investment costs and a large deployment of variable RES, we show that the energy market value loss renders difficult their market based development. This observation indicates that it might become too costly to develop variable generation, PV in particular, at a rapid pace as long as cheap storage has not been developed. The reason is that the larger the share of a variable technology in the mix, the smaller the market value of any new investment in this technology. The loss in value is going to be as high as 30% in some countries when intermittent penetration reaches 40%.

The pace of deployment of variable generation should be optimized. If it is too rapid, infrastructure and storage (or curtailment) costs and subsidies might become too high, while the value of variable generation decreases with its penetration rate.

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