Improving Wind Power Market Value with Various Aspects of Diversification

Preprint

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Improving wind power market value with various aspects of diversification

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***Abstract*—The wind generation share in many European bidding zones is now large enough to affect the market value of wind power, and wind energy is getting less-than-average market price in day-ahead markets. As alternatives to investing in dedicated energy storage, there are two main ways to mitigate the decreasing market value trend. The first is employing different diversification measures (geographical spread, alternative wind turbine technologies, integration with solar). The second is implementing demand flexibility measures. Examples of these measures from some European and USA studies are given in this article, which stems from the international collaboration under IEA Wind TCP Tasks 25 and 53.**

***Index Terms*—Generation mix diversification, power system economics, power system planning, variable renewable energy sources, wind energy integration**

I. INTRODUCTION

The amount of wind power in the European power system is increasing, and towards 2030 a doubling of capacity to more than 400 GW is expected. The Europe-wide share of wind power is already approaching 20% of demand on a yearly average. During windy days and hours, the generation in many European bidding zones will exceed demand [1]. The so-called merit-order effect (i.e., a decrease of electricity prices at the power exchange due to an increased supply of renewable generation in the market pushing out conventional generation stacks) has been evident in current electricity market situations [2] and its relevance is being discussed for future electricity market scenarios [3] [4]. This effect is impacting the market value of wind power – wind energy is receiving less than the average market price in day-ahead markets [3].

The EU-SysFlex study has shown that the market value factor can drop sharply with increasing Variable Renewable Energy (VRE) shares, in particular for solar [5]. The solar market value factor was found to drop from 93%, at a VRE share of 23%, to 36%, at a VRE share of 55%. This is because solar production is concentrated in the middle of the day, which leads to a drop in system marginal costs. Wind generation is more spread during the day, and the market value for wind power drops only from 97% (onshore) and 98% (offshore), at a VRE share of 23%, to 76% and 81% respectively, at a VRE share of 55%, in the same study [5]. Flexibility of demand was only moderately considered in these scenarios, but the study's results show why market integration and cost recovery of VRE have become significant concerns in future energy systems [6].

These developments show that the LCoE-centric approach towards wind power, which served the industry well for decades, needs to be equipped with additional measures. The relation between *electric power produced* and its *marginal value created* is declining as the relation between wind power output and power market price gets stronger [7].

There are three general ways to mitigate the merit-order effect and decreasing market value:

- Diversification of the weather-driven generation fleet reduces power output fluctuations and thereby mitigates (negatively correlated) market price fluctuations
- Flexibility of demand can compensate for weather-driven power output fluctuations and thereby reduce their impact on market prices
- Storage of electric energy, such as pumped hydro and batteries can shift energy in time and thereby match supply and demand.

These measures can be seen as complementary solutions to the same problem: diversification reduces the size of the balancing problem, flexibility and storage solves the problem. The energy storage option has received a lot of attention, both previously [8] [9] and currently [10] [11]. It will play an important role in future energy systems, but it comes at significant investment cost, and it is outside the scope of this article. The flexibility that will be needed for balancing, will mainly come from the demand side. This is because the flexibility of the generation fleet is reduced with the ongoing Energiewende, in which resources from a stored primary energy carrier are displaced with weather-driven resources. As demand flexibility will likely be the main source of price stabilisation in future sustainable power systems, it is discussed in Section V.

The main part of this article, however, addresses various diversification measures, which can be categorised as follows:

- Spatial diversification: building wind parks on new sites where the wind resource is not strongly correlated with existing wind power plants to exploit geographical smoothing (Section II)
- Wind turbine technology diversification: using a mix of different wind energy converters, such as low-wind and high-wind turbines (Section III)
- Generation mix diversification: building wind and solar power plants, as well as other VRE sources, such as run-of-river hydroelectric, tidal, and wave power (Section IV)

This article is an outcome of international collaboration under IEA Wind TCP Task 25 (Design and operation of energy systems with variable generation) and Task 53 (Wind energy economics).

II. SPATIAL DIVERSIFICATION

Spatial diversification is based on the fact that wind speed fluctuations decrease when not considering a point measurement but an average in space. This effect, which already smooths the harvested wind power across the rotor area of a single wind turbine, or between different wind turbines within a wind power plant, works in the same manner for different wind power plants within a given region, country, or continent. As the size of the considered area increases, smoothing becomes relevant for longer time scales. Spatial diversification exploits the benefits of geographical smoothing for wind park siting. Building wind parks at new sites where the wind resource is not strongly correlated with existing generation can increase the value of generation considerably. Value can also be increased by combining offshore and onshore sites. The concept of spatial diversification only works if the transmission capacity in the grid is sufficient to allow for geographical smoothing. Examples from selected European regions and countries are presented in this section, for both market value through smoothing the hourly generation, and increase in value through decreasing balancing costs.

A. Nordic countries

Examples of market value of wind energy are shown for the seven price areas of Finland (FI), Denmark (DK1-2) and Sweden (SE1-4) for years 2019 and 2020 in Figure 1. As a comparison, the total aggregated wind power in Nordic countries (Finland, Sweden, Norway, and Denmark), valued at market system price is shown as markers. This total Nordic market value is a measure that indicates the theoretical maximum for geographic benefits – with no bottlenecks in transmission to split the Nordic area into price areas.

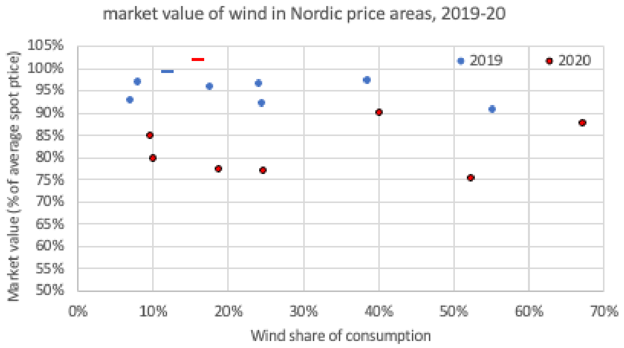

Figure 1: Wind energy income from day-ahead markets relative to average day-ahead price in Nord Pool for the Nordic price areas of Finland, Denmark, and Sweden (Source data from Nord Pool, energia.fi, and SvK)

The total Nordic market value for wind power was 102% in 2020, compared to 75%-90% for the individual price areas. In 2019 the market value for Nordic-wide wind power was 99%, compared with 91%-97% in the individual price areas. In 2020 the global pandemic caused lockdowns, and consumption was lower resulting in low market prices; accordingly, the market price for wind power relative to the average market price was lower than usual. The share of wind power was also higher, especially in Northern Sweden.

B. Norway

Norway's new target of 30 GW of offshore wind power by 2040 will result in a similar size of offshore generation capacity as its current hydropower dominated generation capacity. The correlation in hourly power production between different candidate offshore wind power locations has been analysed to give indications on opportunities for spatial diversification [12]. In total, 18 locations were selected in the study; 15 locations were identified by the Norwegian Water and Energy Directorate in 2012, along with 3 British, Danish, and German locations (Figure 2, right side). Wind power output was estimated using 29 years of MERRA2 reanalysis wind speed data and a Gauss-filtered power curve to represent a large wind park [13]. Correlation coefficients were computed from these timeseries and are shown in Figure 2, left side. Locations farther north were identified as better, because they correlate less with the large-scale wind power developments in the North Sea, with very low correlations for wind parks 0-8.

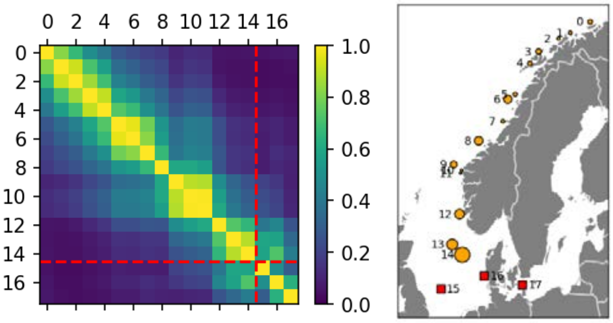

Figure 2: Correlation coefficients for estimated hourly power output from Norwegian offshore wind power sites (0-14), and three sites further south (15-17)

C. Portugal

The technical-economic impact of aggregation as a way to minimize the costs of deviations for wind power producers in the balance market has been analysed in Portugal [14]. Aggregation strategies are applied to 8 wind parks that have a total of 116 wind turbines and a maximum distance between each wind park of nearly 50 km. In terms of normalized root mean square error (RMSE) covering the forecast for the day-ahead market period, a reduction of nearly 2.3% was achieved in the best scenario compared with a passive approach in which each wind park performed its own forecast. The added market revenue of using the aggregation approaches for forecasting vary from 0.40% to 1.47%. In the best case, it was possible to reduce penalties paid by 34%. However, it was also shown that aggregation strategies may lead to worse results (up to a 19% increase in penalties) compared to a passive approach. Even for a small region studied here, results highlighted the advantage of enhancing the statistical power smoothing effect in the wind power forecast—not only for the power system operations but also for the participation in electricity markets.

D. Ireland

At present, the majority of wind generation in Ireland is located on the western coast, recognising that the dominant wind direction is from the southwest. [15]. As part of reducing the aggregated wind variability and locating wind parks closer to the load centres, there are plans for new offshore wind parks mostly off the eastern coast. The possibility to increase the effective “geographical size” of the Irish power system by adding offshore wind power, reducing wind power variability, while also recognising the effects of climate change is examined [16]. The analysis shows that the winter will become “windier”, with the reverse for the summer, while east coast offshore wind speeds will also be more adversely affected than for west coast or onshore wind generation. The extended low-wind periods for onshore and offshore do occur in the same season, but not always at the same time, improving system resilience. Particularly, for the summer period, diversity away from only wind generation is likely to be favoured.

E. North and Central Europe

The spatial correlations between North and Central European countries for wind power vary between 0 and 0.88 [17] (simulated hourly data over tens of years). This shows that the distances are large enough to decrease variance of the aggregate generation. In comparison, solar PV correlations between the same countries vary between 0.75 and 0.96, showing that increasing the spatial distribution of solar PV installations has less impact on the aggregate generation. The results also show that increasing the share of offshore wind power and spreading the installations away from areas that already have large quantities of VRE (especially Germany) decrease variance of the aggregate VRE generation.

III. WIND TURBINE TECHNOLOGY DIVERSIFICATION

Optimization of wind turbine design has led to a convergence towards an LCoE-optimal design, leaving only small differences between individual turbine types available on the market. This is disadvantageous from a diversification perspective because similar turbines will increase power output correlation between them.

A. Higher Hub Heights

Increases in market value have been shown for lower specific power turbines placed on higher hub heights. A potential benefit in Europe of up to 4.3 €/MWh relative to a Business-as-Usual scenario has been identified [18]. Regions with 20% wind energy share experience 2-3 \$/MWh increase in market value and an additional 2 \$/MWh greater value from transmission, balancing, and financing benefits. This drives a combined aggregate value boost of 4-5 \$/MWh [19]. For purposes of comparison, these value potential increases equate to approximately 10%-15% of estimated LCoE.

B. LowWind Turbine Concept

Modern turbines at high hub heights can provide higher capacity factors compared to existing installations, which tends to reduce variability in relation to harvested energy [20]. In addition, lower variability can be accomplished by using different wind energy converter technologies, i.e., combining turbines designed for low- and high-wind sites. Low-wind turbines have increased generation during low-wind hours when market value tends to be high. To reduce the cost of such turbines, the LowWind technology studied in [21] shuts off at high winds when market value tends to be low. In the studied scenarios in North and Central Europe, the LowWind technology would obtain significant market share by 2050, if CAPEX can be kept competitive compared to traditional turbine design. The introduction of LowWind both reduced required transmission investments and generated increased revenues. These results indicate that market signals can drive design beyond LCoE and lead to more system-friendly generation patterns. Compared to turbines installed in Denmark in 2018, which had a mean specific power of 330 W/m^2, the LowWind turbines could produce double the revenue per MW in 2045 in Denmark [21].

C. Airborne Wind Energy

Airborne wind energy converters (e.g., [22]) are still in rather early phases of development, but if maturity and competitiveness can be achieved, they could possibly provide a great source of diversification. As they can operate at significantly higher altitude than regular wind turbines, they can access winds that are less correlated with regular wind power plants, and steadier than at lower altitudes. However, it is still uncertain if airborne wind energy converters will reach commercial deployment within the foreseeable future.

IV. GENERATION MIX DIVERSIFICATION

The main opportunity for diversification lies, of course, not within wind power itself, but in the mix of different variable renewable energy sources that are combined. Solar power can complement wind power and vice versa. Consider a mix of windy overcast days and sunny calm days as well as windy nights when solar output is zero. Moreover, average wind speeds in Europe are highest during wintertime [23].

A. Wind & solar

Negative correlation is found between wind and solar PV generation across the countries in Northern and Central Europe, and a mixture of wind power and solar PV provides the lowest variance of the aggregate VRE generation. This situation indicates that increasing the share of offshore wind power and spreading the installations away from areas with a lot of VRE (especially Germany) decrease variance of the aggregate VRE generation [17].

A detailed assessment of wind and solar PV complementarity by assuming the hybridization of existing Portuguese wind parks was performed in several studies, e.g. [24], [25]. Figure 3 depicts the Pearson correlation values for the location of existing wind power plants in Portugal. The hourly complementarity levels are lower than the values observed at a daily scale. Inner parts of the country in the central and northern regions are the ones with the highest level of wind power and solar PV generation complementarity (some locations show correlation values of nearly -0.6).

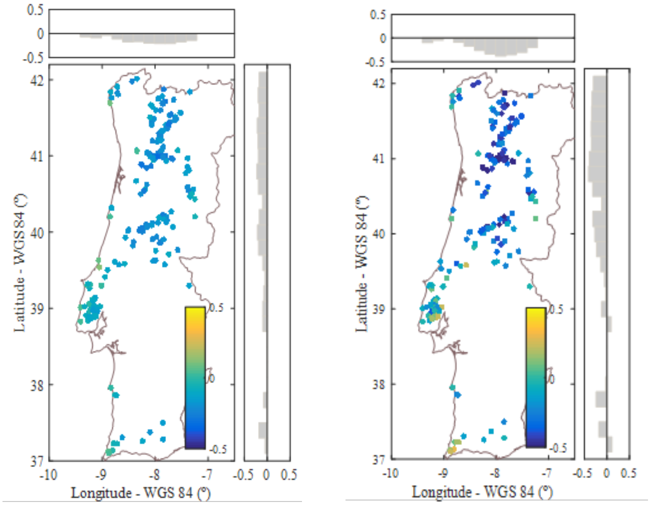

Figure 3: Pearson correlation coefficients between wind and solar generation for each location of existing wind power plants using hourly (left) and daily (right) data. The upper left grey bar plot corresponds to the mean values of correlation using a 0.2° spatial resolution [24]

Combining wind and solar power will increase the market value, especially where their outputs are more complementary. In a studied case for Portugal, the market revenues from spot markets including balancing costs can increase between 15.59% to 30.14%, representing a market value increase between 2.97% to 4.94% [26].

B. Hybrid power plants

If wind and solar power are co-located and operated together as one power plant sharing the same busbar, it is referred to as a Hybrid Power Plant (HPP). This can be beneficial from several perspectives. However, the system benefit of diversification does not depend on if the wind and solar power assets are operated as one hybrid power plant or as two individual power plants. Battery energy storage systems, which also can be included in a HPP, are not a means of diversification but rather a means of flexibility. Currently, there is not yet a high level of operational experience in this type of power plant, despite the theoretical recognition of the benefits of HPPs [27].

In case of a congested grid connection, an "overplanting" tactic can be utilized to increase the capacity factor of the grid connection; however it would be at the cost of curtailments during favourable weather conditions. (This would lower the capacity factor of the generation assets overall.) These undesirable curtailments can partly be mitigated by generation mix diversification within the oversized power plant, leading to a hybrid power plant. In order to assess the potential of HPPs in existing wind parks, three overplanting solutions are analyzed for cases in Portugal [24] [25]. Research in the United States has similarly found an increase in the grid connection usage of hybrid wind-PV plants compared to stand-alone wind or PV resources [28].

C. Combination with non-PV renewables

The advantages of generation mix diversification increase with the availability of more generation technologies. Future power systems with very large shares of wind and solar power might see high electricity prices during calm overcast days, paving the way for additional sources such as wave power or tidal power. Even though these technologies are not (and may never be) competitive on a LCoE basis, they might benefit from wind and solar power-induced price fluctuations by enabling better generation mix diversification [7].

V. DEMAND FLEXIBILITY

For future systems, market challenges are discussed where the system can be foreseen to only have two states:
are considering future market challenges that reflect a system that has only two states:

- overproduction and potential curtailment of variable renewables with very low electricity prices
- under-supply of renewables with very high electricity prices from thermal backup generation

However, this assumes inflexible demand and extrapolates the merit-order effect [29] [4]. The Energiewende puts electricity systems at the core of a clean energy supply. At the same time, indirect electrification, with a potential uptake of hydrogen or derived fuel economy, plays a crucial role in achieving sustainability of the energy supply and industrial processes in hard-to-abate sectors, including the production of ammonia, steel, cement, and plastics. The direct or intermediate electrification of end-use demands challenges the assumption of inflexible electricity demands in future markets.

Flexible demand allows consumption of available generation on windy days and no consumption when there is scarcity of electricity in the system. Sources of flexible demand may submit demand bids based on their actual opportunity costs in sustainable electricity markets in the future, influencing the market clearing and partly alleviating close-to-zero price situations. The flexibility may come from demand that is by nature more flexible because of access to some kind of storage, such as temporal shifting of demand (e.g., heat storage), fuel-switching (e.g., hybrid boilers) and Power-to-X fuel conversion (e.g., electrolysers) [29]

A. Germany

Recent work on wholesale market clearing prices in sector-integrated sustainable energy systems [4], shows that, instead of the two-state system for market prices, there is a more nuanced and stepped picture. The merit-order effect may not extend to market outcomes of future sustainable electricity markets because cross-sectoral demand bidding can impact market-clearing outcomes and price-setting effects. Figure 4 gives an example for Germany. The figure indicates that hybrid technology combinations (e.g., hybrid boilers, hybrid heat pumps, multivalent CHP systems) and electricity-based fuel production (electrolysers and potential post-processing plants) with traceable opportunity costs and marginal values of consuming electricity, may enter the market with bidding signals from the demand side. This situation can impact the capture prices of wind power and increase the market values in the much-discussed situations with close-to-zero or even negative prices. Note that cross-border integration still plays a crucial role, especially in the German bidding zone that has many transit flows.

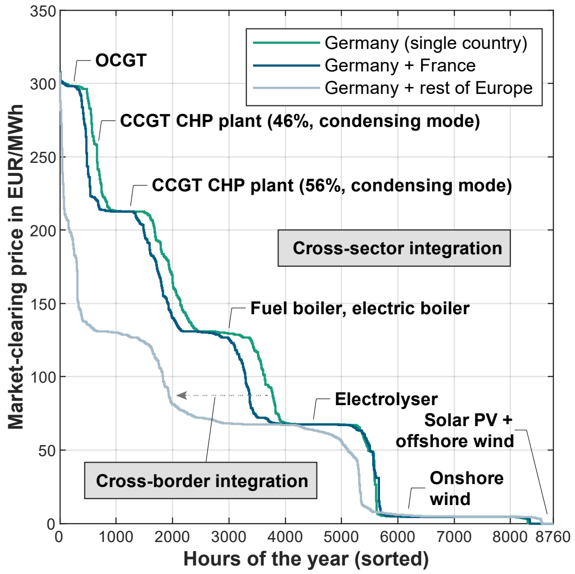

Figure 4: Market clearing price duration curve of Germany in a sustainable European energy system with different levels of cross-border integration, based on [4]

B. USA

An indication of added market value due to flexibility is the added wind power in optimal capacity expansion simulations of future power and energy systems (Figure 5). In the United States, future system buildouts under various cost assumptions for hydrogen electrolysis show that more economic hydrogen production leads to greater wind power deployment [30]. The study used capacity expansion and production cost modeling to explore the impacts of wind and solar power on generator deployment and operations. Assuming low temperature electrolysis, the study found that hydrogen can provide an additional income stream to drive greater deployment of wind power and, to a lesser extent, solar PV resources. While these resources were not modeled as hybrid systems, this study shows how wind power deployment could increase more than any other generation options under electricity system future scenarios with cost-effective hydrogen production. This is because electrolytic hydrogen production can balance wind's seasonal availability. Furthermore, hydrogen transmission infrastructure can overcome geographic limitations. Similar conclusions were derived from a hydrogen energy study for Texas [31].

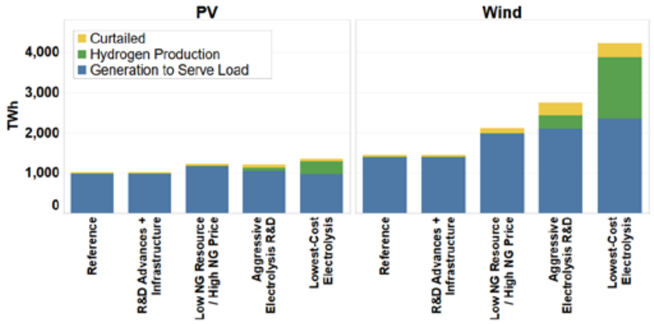

Figure 5: Wind and solar generation under different economic assumptions for electrolytic hydrogen [30]

VI. CONCLUSION

Various aspects of diversification benefits to market value have been studied. Regarding spatial diversification, correlation coefficients down to zero have been identified in Northern Europe, indicating significant advantages of spreading wind power developments away from the dominant North Sea region. Additional benefits of spatial diversification have been identified regarding reduced forecast errors. When considering wind turbine technology diversification, the LowWind turbine presents an interesting concept for the future. Generation mix diversification has even more potential; the "right" mix of solar and wind power may help to keep power output variability low. This relatively low variability is enabled by negative correlation coefficients between wind and solar power. However, diversification alone will likely not be sufficient to balance future energy systems, and demand flexibility, at daily and weekly time scales, may be the most powerful mitigation for market value reduction of wind energy.

Even though the aspects of diversification are subject to increasing general interest, the amount of available data quantifying direct economic effects is still limited. This indicates that persistent research is needed on measures to increase the value of variable renewable energy; this subject will need to be addressed thoroughly as part of sustainable energy system planning.

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