The effects of renewable energy integration on price volatility in electricity markets: the dampening potential of storage technologies.

Tomás Reilly-Rockett[1], Jorge Cano-Martínez[1,2], Arturo Vivancos-Grau[1], Alfredo Quijano-López[1,2], Vicente Fuster-Roig[1,2]
[1] Instituto Tecnológico de la Energía, ITE
[2] Universitat Politècnica de València
Valencia, Spain
tomas.reilly@ite.es

Abstract—The integration of variable renewable generation (VRE) has transformed the intrinsic behavior of electricity markets: while average electricity prices are decreasing, the volatility of these prices is increasing. In this paper, the volatility-affordability trade-off of high VRE penetrated systems is addressed. A scenario-based forecast on electricity price trends for future energy systems is presented using ASSUME, an open-source agent-based simulation environment. In the first part of this paper, the year 2019 Spanish electricity market model is created and validated under ASSUME's environment. In the second part, two synthetic scenarios with high VRE integration and storage capacity deployment are created based on Spanish national plans. Results show that high VRE penetrated systems experience an increase in price volatilities and a decrease in the average electricity price. Storage systems' potential to dampen volatility is also assessed as their deployment result in price stabilization and market liquidity increase.

***Index Terms*-- Agent-based modeling, power markets, renewable energy sources, storage batteries.**

I. INTRODUCTION

In the past decades, many power systems have experienced important transformations due to an increasing penetration of VREs and a progressive phase-out of thermal units such as coal power plants. The National Energy and Climate Plans (NECP) of each member state in the European Union sets out an objective.

While VREs contribute towards a more sustainable system, new challenges arise due to their intrinsic behavior. Firstly, they rely on meteorological phenomena, making them non-dispatchable. This requires careful planning and forecasts to ensure an optimal operation of the power system. Additionally, their low operating costs make them the cheapest technologies in the energy mix. Therefore, in power systems with high percentage of VREs, price signals of the wholesale energy market can experience an increase in volatility. Lower prices will occur during periods of high renewable generation while higher prices will be observed when demand must be met by more expensive thermal units. This paper addresses this issue, focusing on the impact the transformation of power systems will have on wholesale energy markets. New technologies such as storage are also considered as possible solutions to this problem, providing flexibility to the system.

The modeling of the electricity market is based on the ASSUME environment [1], an agent-based modeling tool that incorporates the complex interactions between market participants, obtaining realistic results of market outcomes. As a benchmark, the Spanish electricity system is considered as a case study with scenarios based on the past, present and future states of the system.

This paper is structured as follows, in section II, assumptions and methodology followed for scenario definition and modeling are discussed, section III centers on the scenario definition adequacy and accuracy validation. In section IV, the synthetic scenarios results are shared. Results are evaluated and discussed in Section V. Finally, section VI contains this work's conclusions.

II. METHODOLOGY

This paper's objective is to evaluate price volatility in electricity markets caused by high VRE integration and the potential that energy storage solutions have towards dampening of price volatility. The evaluation is performed through market modeling and simulation of three annual scenarios. Each scenario is modeled with the ASSUME environment.

The scope of this analysis is centered on the Spanish electricity market. For simplicity of the analysis and access to data, only the Spanish part of the Iberian power system has been considered, leaving the Portuguese power system out of the scope of this paper. Spain has experienced a significant growth in renewable energy technologies in the past decades, lead by onshore wind and photovoltaic solar technologies. According to the last available annual report [2] of Red Eléctrica de España

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(REE), the Spanish Transmission System Operator (TSO), Spain had a total renewable installed capacity of 77,039 MW in 2023, accounting for 50.3% of the total electricity generated throughout the year. 95% of the renewable energy capacity is composed of hydro (17,097 MW), wind (30,810 MW), and photovoltaic solar (PV) (25,549 MW). Wind and PV generation technologies have experienced significant growth in the las decade, adding 28 GW during that period. Between 2014 and 2023, wind passed from 22,987 MW to 30,810 MW, and PV from 4,797 MW to 25,549 MW.

According to decarbonization plans, this tendency is expected to be maintained in the next decades. Following the last update of the Spanish NECP (the PNIEC) [3], renewable energies aim to generate 83% of the electricity share in 2030. This objective is based on the massive deployment of renewable energies and storage systems, a deployment of renewable generation capacity of 160 GW and 22,5 GW of storage are planned.

To evaluate the market volatility induced by VRE generation, three scenarios are modeled and simulated. The reference scenario is based on the 2019 Spanish market. Two synthetic scenarios are generated based on the reference scenario and the PNIEC forecast for 2030.

A. *Reference case modelling (Case 0)*

A simplified model of the 2019 Spanish market is modeled for the reference scenario. The year 2019 is chosen for the reference case as it is the last year with stable market dynamics before COVID-19 pandemic and EU energy crisis due to Ukraine invasion. The data required to model the reference scenario in ASSUME are:

- Generation units
- Renewable resources availability
- Demand
- Fuel prices

1) *Generation units*

To accurately replicate the complex environment of the electricity market, the generation units are created from real generation units' data available at OMIE [4], the designated Iberian Peninsula market operator. The generation units are modified to match the installed power capacities at the end of the year 2019 (from Red Eléctrica 2019 annual report [5]), and adjusted to ASSUME's format. Only the technologies covered in the ASSUME example cases have been considered, ignoring technologies such as solar thermal or geothermal, among other residual technologies with a minor impact on Spanish market dynamics.

In Table I, the Spanish and the reference scenario modeled total capacities at the end of 2019 are shared. Technologies considered covered more than 95% of the installed capacity in the Spanish generation structure. The following assumptions are made to generate ASSUME's model: i) All coal generation plants are assumed to use lignite, ii) solar thermal and other renewable energies are ignored, iii) several biomass technologies are gathered, iv) each renewable energy technology is considered as single unit. Finally, a total of 423 generation units are used, with a total of 380 operators. The number of units per technology are shared in Table II.

TABLE I. REE 2019 AND REFERENCE MODEL INSTALLED CAPACITY

Technology	Installed capacity (MW)	
	2019 REE Report	*2019 Reference model (Case 0)*
Biomass	650	650
Combined cycle gas turbine	26,284	24,560
Hydro	17,096	17,096
Lignite	9,683	9,683
Nuclear	7,117	7,117.2
Oil	2,447	2,447
Open cycle gas turbine	5,677	5,546
Solar	8,913	8,913
Wind onshore	25,799	25,799
Pumped hydro	3,329	3,329
Thermal solar	2,304	0
Other renawables	1,076	0
Total	**110.376**	**105,140.2**

TABLE II. NUMBER OF GENERATION UNITS PER TECHNOLOGY

Technology	Number of units
Biomass	1
Combined cycle gas turbine	50
Hydro	1
Lignite	4
Nuclear	7
Oil	2
Open cycle gas turbine	356
Solar	1
Wind onshore	1
Pump	1

2) *Renewable resources availability and demand*

Renewable resource availability is estimated as the hourly energy generated per technology over the total installed power at the end of the year. The hourly generation data is obtained from E·SIOS [6], the REE information system operator. The hourly annual demand for 2019 is also obtained from E·SIOS.

3) *Fuel prices*

The model definition needs fuel prices and further technical parameters for the generation units, such as emission factors, efficiency and additional costs. This data is highly sensitive to the actors involved in the energy market, its availability and obtention or estimation is highly challenging. In this work, fuel prices and technology technical parameters are estimated from ASSUME's examples and reference cases; especially the cases studied in [7]. In the case of the generation units parameters, they are estimated as the mean of the units defined in [7].

B. *Synthetic cases modelling (Case A & B)*

The synthetic scenarios are based on the 2019 market model (Case 0). The reference scenario is modified and adapted to replicate some of the PNIEC 2030 estimations. In particular, the electricity demand is increased, and the total renewable and storage capacity expanded. Two additional scenarios are modeled, in both, the demand is increased according to the PNIEC.

In the first synthetic scenario, named Case A, the PV and wind capacity is expanded. Additionally, other technologies installed power are adapted. Following the most ambitious PNIEC forecasts for 2030, the total power for coal, open cycle gas turbine and oil are set to 0. According to the PNIEC and the Spanish nuclear phaseout plan, 3 nuclear reactors will be remaining in 2030. The second synthetic scenario, Case B, is based on Case A, adding the PNIEC forecast for storage system deployment. The total installed power per technology and case is shown in TABLE III. The storage is modelled as a single unit in the market representing the total forecasted capacity. The storage's charge and discharge efficiency has modelled to 0.86 and 0.9, respectively.

TABLE III. INSTALLED POWER PER TECHNOLOGY AND SCENARIO

Technology	**Installed capacity (MW)**		
	Case 0	***Case A***	***Case B***
Biomass	650	650	650
Combined cycle gas turbine	24,560	24,560	24,560
Hydro	17,096	17,096	17,096
Lignite	9,683	0	0
Nuclear	7,117.2	3,040	3,040
Oil	2,447	0	0
Open cycle gas turbine	5,546	0	0
Solar	8,913	57,000	57,000
Wind onshore	25,799	62,000	62,000
Pump	3,329	3,329	3,329
Storage	0	0	22,500
Total	**98,023**	**167,675**	**190,175**

In Case A & B, the number of generation units is reduced to 57 and the operators to 21. In both cases, the hourly demand has been augmented by 34%, as estimated in the PNIEC for 2030.

In the following all simplifications and assumptions made to model all cases are shared:

- A selective approach was applied, prioritizing the most influential technologies, which account for 95% of the actual installed capacity in Spain.
- Non-renewable technologies are considered always available for the period of study.
- Renewable energy availability has been estimated as 2019 availability.
- The number of generation units and the technological capacity are considered invariant over the analysis period.
- Renewable energy is aggregated into a single generation unit for each technology.
- Fuel prices, generation unit parameters and CO_2 prices are estimated.
- The Spanish market is considered isolated from Portugal's market.
- Cross-border flows are omitted, due mainly to the singularity of the Iberian power system, with few interconnections with other countries.

III. MODEL VALIDATION

The reference ASSUME's market model is validated prior to the synthetic scenario's simulation and analysis. To evaluate the model definition and adequacy, the reference scenario model (Case 0) is simulated and compared to real market results. Hourly real market results are obtained from E·SIOS.

Two analyses are performed to evaluate Case 0 model's adequacy and ASSUME performance. In the first place, the daily average energy cost is compared between real market data and ASSUME's Case 0 simulation. In Figure 1, 2019 real market and Case 0 daily average energy prices are shown. Case 0 results match real prices, although its peaks vary more abruptly. The simulation's daily prices follow real data tendency throughout the year. However, the simulation data tends to underestimate the resulting market price. According to REE 2019 annual report [5], Spanish mean electricity price for the year 2019 was 47.68 EUR/MWh. Case 0 mean annual price was 42.62 EUR/MWh, differing -10.6% from the real price. Among other factors, this underestimation can be influenced by not considering the unavailability of some power plants throughout the year, due to maintenance.

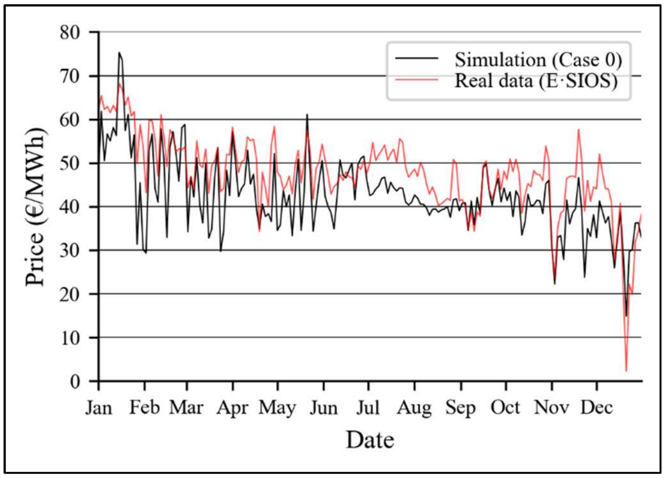

Figure 1. 2019 Spanish spot electricty maket mean daily cost

Considering the previous results, along with the model's simplifications and assumptions, the definition of Case 0 and the performance of ASSUME are deemed sufficiently valid for the intended analysis. Although the mean average price differs around -11% and some daily deviations can be higher. This work's objective is not to replicate the market behavior, but to evaluate the market response to the integration of VRE and storage technologies.

IV. RESULTS

Once the Case 0 model has been validated, Case A and Case B synthetic models are simulated, and the results are evaluated and compared to Case 0 (reference).

The daily average electricity price has been analyzed as a preliminary indicator for Cases 0 and A. Figure 2 illustrates these results, providing insight into the market response to the modifications introduced in Case A. Case B is excluded from the figure, as its results are nearly identical to those of Case A.

Table IV provides the annual mean electricity cost and standard deviation for all simulations. The substantial integration of renewable resources in Cases A and B leads to a mean annual cost reduction of approximately 6 €/MWh relative to Case 0. As for the standard deviation, it rises from 12.30 €/MWh in Case 0 to 24.51 €/MWh in Case A, and 24.12 €/MWh in Case B.

Price volatility is analyzed for Cases 0, A, and B through hourly electricity prices. As shown in Figure 3, the interquartile range for Cases A and B is wider than that for Case 0, suggesting an increase in price volatility.

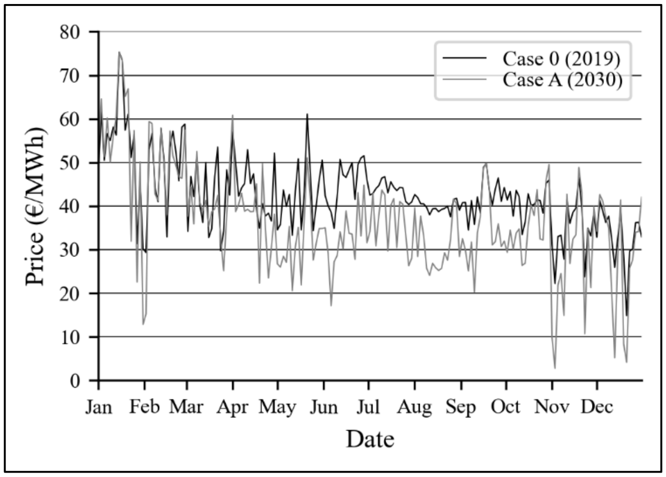

Figure 2. Average daily simulation results for Case 0 and Case A

TABLE IV. SIMULATION'S ANNUAL MEAN COST AND STANDARD DEVIATION

Metric	Case 0	Case A	Case B
Annual mean cost (€/MWh)	42.62	36.28	36.04
Standard deviation (€/MWh)	12.30	24.51	24.12

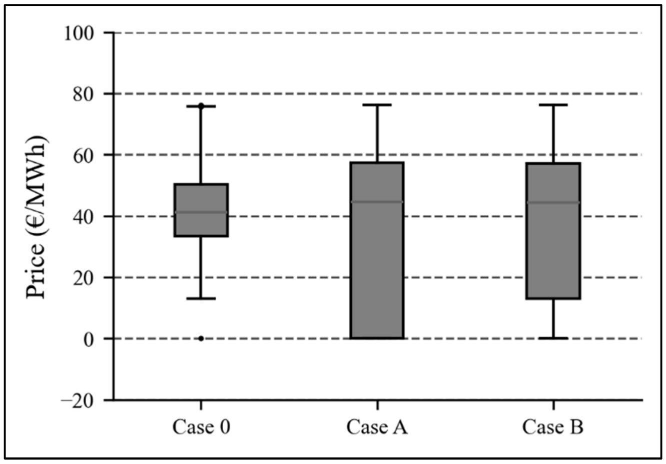

Figure 3. Hourly prices for each scenario

Finally, Figure 4 illustrates an hourly price detail comparing Case 0 and A (top illustration), and Case A and B (bottom illustration). This illustration is shared to evaluate the storage systems' response and impact on the market.

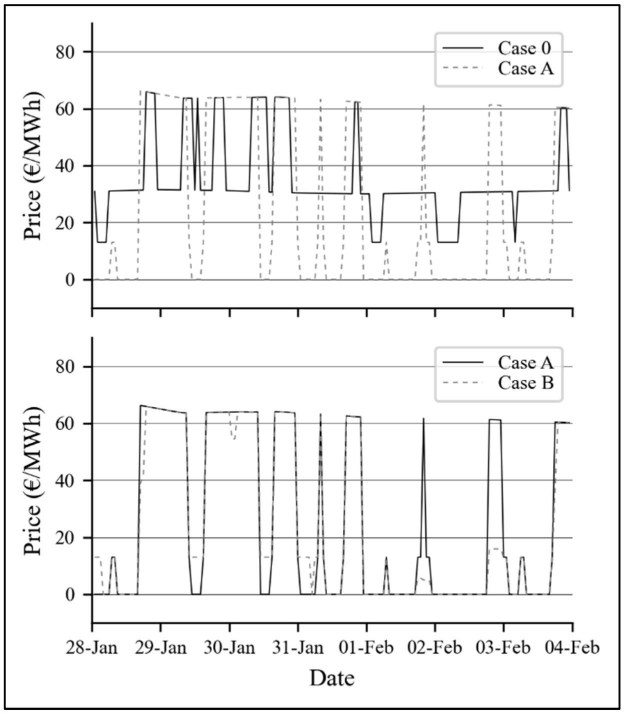

Figure 4. Comparison of hourly price of electricity between cases. Above: Case 0 and Case A. Bottom: Case A and Case B

V. DISCUSSION

The daily average prices and price trends for Cases 0 and A, shown in Figure 2, indicate the good performance of the Case A model simulation. From February until the end of the year, the trendline for Case A shows lower electricity prices; in the spring, summer and early autumn, the gap widened. In Case A, there are more price peaks, and these peaks are typically sharper and lower. Case A typically has lower prices from June to November.

Based on the analysis of Figure 2, The integration of VRE in Case A, in conjunction with the reduction of non-renewable capacity, resulted in lower electricity prices and increased price volatility. The volatility increase is due to both peaks over the trendline and under the trendline, although peaks under the tendency tend to be more acute. This interpretation is backed by results shared in Table IV, which indicates that mean annual prices are lower for Case A and B. The higher standard deviation in Case A and B also indicates higher price volatility. Table IV also indicates that Case B average annual price and volatility is slightly lower than Case A.

The higher price volatility in Case A and B is easily observable in Figure 3. Case 0 boxplot shows price concentration around the mean annual price and a relatively even distribution around the median. Additionally, in Case 0 the 0 EUR/MWh prices are considered outliers. Case A boxplot has a large interquartile range, reflecting an acute volatility increase compared to Case 0. Case A hourly prices are more dispersed towards higher and lower prices. In Case A, the lower value of the interquartile range coincides with a price of 0 EUR/MWh. Low hourly prices, even 0 EUR electricity prices, are common in Case A. Analyzing Case B box, electricity prices volatility is reduced as the interquartile range is shortened from Case A. The upper interquartile boundary is maintained, and the lower boundary has raised. Although 0 EUR electricity prices are not outliers in Case B, electricity prices are less spread than in Case A, and thus prices are less volatile.

Battery intervention and influence on the market is shown in Figure 4, which shows the hourly electricity prices between the 28th of January and the 4th of February. On the top illustration, Case 0 and Case A prices are shown. This illustration reflects the volatility increase in Case A with respect to Case 0. In Case 0, the price range is lower (between 15 and 65 €/MWh) with many hours at an intermedium price around 30 €/MWh. In Case A, the lower boundary is decreased to 0 €/MWh. The price volatility does not only increase in range, the number of peaks and transitions between prices are larger. Additionally, the hourly mid-price range is highly reduced, which denotes the influence of the elimination of mid-price technologies such as nuclear or coal generation (peak prices correspond to gas-fueled technologies).

In the bottom illustration of Figure 4, the battery intervention and influence on prices is perceived. The storage system avoids some 0 €/MWh prices, as can be observed before the 2nd and 3rd of February.

VI. CONCLUSION

In this paper, the effect of future power grids towards high penetration of renewables has been analyzed, with a special focus on the Spanish electricity system.

With a reliable market modeling environment, it has been possible to view the clear effect VRE generation has towards price volatility and 0 € electricity prices. This is one of the challenges that should be addressed in the coming years to ensure efficient system planning and guarantee adequate resource availability. With elevated volatility and near-0 price signals, investment won't be incentivized towards new generation projects, which can compromise the adequacy of future power grids. In this sense, power markets in Europe are implementing Capacity Markets to guarantee optimal investments in mid to long term planning. Other power systems such as the Australian National electricity Market (NEM) implements an energy-only market as a mechanism to incentivize investments.

Price volatility also incentivizes technologies with inherent flexibility capabilities. In this sense, specific analysis has been conducted in this paper towards the effect battery storage has on the electricity market. In future power grids with high VRE generation, flexible technologies such as batteries play a crucial role in reducing price volatility while increasing market liquidity. From the results obtained in this paper, batteries charge during low-price low-demand periods, reducing the occurrence of 0 € electricity prices. During high-demand high-price periods, batteries discharge supplying energy thus reducing the final price of electricity.

The objective of this paper has been achieved by quantifying the effect VRE generation has on electricity markets while also evaluating the potential of batteries towards addressing this challenge. Additionally, by taking the Spanish market as a case study, the implications of the analysis have been directly applied to a real power system. The 2030 scenario without batteries (Case A) shows a clear tendency towards high-volatility low-liquidity market. On the other hand, the incorporation of batteries to the 2030 scenario (Case B) has a partial effect on reducing price volatility. In order to significantly address the challenges of future power systems, the installed capacity objective of batteries for 2030 (22.5 GW) should be reevaluated and increased, ensuring a market that incentivizes optimal investment with adequate price signals.

The transformation of power grids toward more sustainable systems brings new challenges that need to be carefully analyzed and addressed. This paper has focused on price volatility and the capability of batteries towards reducing it. Many other technologies and mechanisms (e.g. Demand-side response, capacity markets, etc.) can be implemented to resolve these challenges and will have to be analyzed in future studies.

VII. ACKNOWLEDGMENTS

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