Large-Scale RES Integration in Electricity Markets: Challenges and Potential Solutions

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Abstract—The increasing shares of renewable energy in power systems have a significant impact on the operation of electricity markets and grids worldwide. This paper provides an overview of the main challenges that high shares of renewable generation introduce in the power system management and electricity markets operation as well as a brief description of potential solutions for alleviating the negative implications caused by the large-scale renewable integration. Additionally, a summary of the core research activity that has been performed in the context of a relevant academic research project, called “Large-Scale Renewable Integration in Electricity Markets”, (acronym, “LaRInEM”), is presented and valuable conclusions regarding the efficient integration of large amounts of renewable energy in electricity markets are drawn.

Index Terms—CO$_2$ emissions, day-ahead market, electric vehicles, electricity markets, RES forecasting, unit commitment.

I. INTRODUCTION

In the absence of electricity generation from renewable energy sources (RES), the short-term scheduling and operation of a typical power system in either a regulated or a competitive market environment was based on relatively simple procedures. The main sources of uncertainty were limited to the uncertainty and variability of the system load in combination with the forced outages of the conventional generating units.

In this context, no particular operational problems arose, since both these challenges were well-addressed by the System Operators. However, the continuous installation and operation of large numbers of new RES plants (either large units connected to the transmission system or small dispersed units connected to the distribution network) during the last two decades, mainly due to strong environmental concerns worldwide, has been changing the way that the power systems and, subsequently, the modern electricity markets operate. Many of the established management methodologies need to be revised to optimally address the limited predictability and high variability of RES generation, features that make RES plants non-dispatchable or, at best, partially dispatchable.

The goal of this paper is to summarize the main challenges that high shares of RES generation introduce in the power system management and electricity markets operation as well as to provide a brief description of potential solutions for alleviating the negative implications caused by the large-scale renewable integration. Additionally, an overview of the activity that has been performed in the context of a relevant academic research project, called “Large-Scale Renewable Integration in Electricity Markets”, (acronym, “LaRInEM”), carried out at the Power Systems Lab, Aristotle University of Thessaloniki, Greece, is presented. LaRInEM aims at investigating the effects of large-scale RES integration on the operation of the electricity market and proposing measures for the efficient large-scale renewable integration [1].

In the following sections, all aforementioned issues are properly addressed and valuable insights regarding the efficient integration of large shares of renewable energy in modern electricity markets and power systems are drawn.

II. MARKET CHALLENGES

During the latest years, the high volatility of increasing renewable generation often introduces increased uncertainty in the short-term electricity market operation. The continuous variation of the conventional thermal units production to compensate for the high volatility of renewable injection in order to always maintain the supply-demand balance leads to more frequent start-ups and shut-downs (equivalently termed, “cycling”) of the conventional units, less efficient operation and increased wear-and-tear of the respective equipment as well as it causes substantial volatility in the market clearing prices [2]-[3].

In addition, since the energy injection coming from RES plants is considered as zero-cost energy and, thus, is usually prioritized in the day-ahead (DA) market clearing algorithm, large amounts of renewable energy often push conventional thermal units with high marginal cost (e.g. peak-load and/or mid-merit units) out of the market, leading to lower DA market clearing prices (see Fig 1) [4]. In this framework, it is usual that zero or even negative market clearing prices (in case it is allowed by the market regulatory framework, e.g. in the EPEX or Nord Pool markets) arise in periods where certain factors coexist, such as low load demand, increased RES production and inelastic production of conventional thermal plants (e.g. nuclear and large coal plants). Negative prices can be interpreted as the willingness of conventional plants to remain on-line, even by paying consumers to buy their energy, instead of being shut-down for a limited number of hours and start-up later, since the cycling costs are higher than the costs incurred due to the negative clearing prices.
Another challenge posed by the high uncertainty and variability of RES production is the need to maintain higher levels of operational reserves in order to preserve the supply-demand power balance in real-time. This is usually achieved by continuously maintaining flexible (and usually less efficient) thermal units committed in order to be able to provide fast regulation services [5]. This obviously results in significant increase of the total system operating cost, or equivalently, reduction of the total social welfare.

Regarding the impact that the high RES penetration usually has on the long-term electricity market operation, the unpredictable and non-dispatchable nature of RES makes the aggregated (over a wide geographic area) RES portfolio output more predictable and less variable.

III. EFFICIENT SOLUTIONS FOR LARGE-SCALE RES INTEGRATION

The negative impact that high shares of RES generation bring in the operation of the electricity markets call for new solutions that will allow for the efficient and reliable operation of the power system in conjunction with the full exploitation of the associated “green energy” benefits.

A key solution towards this goal is the amendment of the current regulatory and operating framework in order to adapt to the emerging requirements for optimal RES production management [6]-[7]. The proposed measures mainly focus on making RES fit to the market, thus limiting the market distortive effects of existing support schemes (e.g. feed-in-tariffs) and moving towards minimizing overcompensation schemes as well as exposing RES producers to market dynamics. In this context, an effective way is to incentivize RES plants to sell their energy in the wholesale market through priced energy offers and be subject to balancing mechanisms, similarly to conventional generation. It has been concluded that more flexible and market reflective operation of RES installations can lower the overall cost of the electricity system [8].

Regarding the short-term market operation, the development and use of advanced RES forecasting tools along with frequently updated forecasts aiming at the minimization of the forecast error lie among the most popular solutions to facilitate large-scale RES integration. In addition, the development of new sophisticated tools that incorporate the modeling of uncertainty in the decision-making models for the short-term power system scheduling (e.g. unit commitment algorithms), such as stochastic and robust optimization techniques, are now considered as suggested solutions to address the inherent uncertainty of RES production. In the same context, the adoption of multiple intraday markets (e.g. MIBEL currently operates 6 intraday markets within the day), where revised offers/bids are allowed and updated RES forecasts are considered in conjunction with real-time dispatch models with 5-min resolution and look-ahead capabilities so that the financially binding decisions of the first interval capture the forthcoming load and mainly wind energy variations, is the new trend in the electricity markets worldwide [9]. Shorter dispatch intervals along with moving the gate closure closer to the real-time operation has proved to be a plausible way to substantially reduce the system reserve requirements [10].

Another novel solution is the introduction of flexible ramping products that help the power system to maintain dispatchable flexibility in terms of ramping capability. This service was first launched in California [11] and MISO [12] markets, where an additional remuneration is provided through the respective ancillary service market clearing mechanism solely to those entities providing flexibility to the system.

The strengthening of interconnection lines connecting different control areas in order to take advantage of the RES portfolio effect[1] is also proposed as an effective means to allow for increasing RES hosting capacity, since the overall uncertainty and variability of RES generation are mitigated and, therefore, lower levels of operational reserves are required, leading to significant cost improvement.

Regarding the participation of the demand side in the optimal market operation, the incorporation of innovative de-

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[1] RES portfolio effect is the favorable effect of the geographic diversification of renewable resources, which makes the aggregated (over a wide geographic area) RES portfolio output more predictable and less variable.
mand-side management techniques can be regarded as another advantageous way to address the high uncertainty and variability of RES generation. The use of new technologies, intelligent control systems, bi-directional communications and advanced sensing technologies (e.g. smart meters, smart thermostats, smart appliances, etc.) allows for the flexible scheduling and optimal dispatch of large electricity consumers as well as the implementation of profitable demand response schemes to smaller flexible consumers that are represented in the market by load aggregators. In this way, the consumers turn from passive into active participants of the power system and help towards shifting energy usage to low net demand periods, enhancing the system reliability, lowering the total energy production cost and, thus, maximizing the social welfare. Storage, electric vehicles, and hybrid plants are expected to substantially contribute in this direction, since they are able to adjust their flexible operating schedules as well as to provide ancillary services in response to the high intermittency of RES production. Finally, the Virtual Power Plant (VPP) concept is a novel approach that aggregates diverse resources, including RES units, conventional power plants, demand response schemes and storage systems, and collectively behaves reliably as dispatchable thermal generation, providing valuable assistance to maintain the supply-demand balance of the power system.

All aforementioned solutions could be better exploited in combination with the efficient integration of electricity markets (such as the forthcoming implementation of the Internal Electricity Market in Europe [13]), which is expected to further facilitate the fulfillment of the ambitious energy and climate policy objectives in the near future.

IV. MAIN OUTCOMES OF LARINEM

In the aforementioned framework, LaRInEM focused on the analysis of the electricity market operation under the new emerging conditions of increased RES penetration. The research activity was oriented in three main axes, namely a) RES forecasting, b) market operation modeling and analysis, and c) participation of electric vehicles and Virtual Power Plants (VPPs) in the electricity market operation.

Almost all developed models and tools were tested on the Greek interconnected power system and electricity market. In the following, a brief description of the main outcomes in each of the three aforementioned axes is presented.

A. RES Forecasting

Various practical models for wind and photovoltaic (PV) generation forecasting were developed. Regarding PV forecasting, two practical methods for electricity generation forecasting of grid-connected PV plants were developed [14]. The first model was based on seasonal ARIMA time-series analysis and was further improved by incorporating short-term solar radiation forecasts derived from NWP models (SARIMA with exogenous factor). The second model adopted ANNs with multiple inputs, where two variants were considered regarding the inputs selection (ANN models A&B).

In order to evaluate the performance of the proposed forecasting models, they were all compared to the persistence model in terms of the Normalized (with respect to the PV installed capacity) Root Mean Square Error (NRMSE).

Test results from the application of all models in different PV plants of the Greek power system show that, in general, those models that make use of available external solar radiation data, namely the SARIMA model with exogenous factor and the ANN models are preferable, since they lead to considerably improved day-ahead forecasts and lower NRMSEs as compared to the persistence model or the pure SARIMA model (see Fig. 2). However, both the persistence model and the pure SARIMA model that do not take into account solar radiation data can be equally applied during summer, where the favorable weather conditions in Greece eliminate the need to use more sophisticated PV generation forecasting models.

B. Market operation modeling and analysis

The market operation modeling and analysis was the core part of the project and various key challenges were addressed in this framework, briefly described in the following.

1) Multiple time-resolution unit commitment for short-term operations under high RES penetration

Regarding the modeling of the short-term operation of an electricity market, the idea of a unified unit commitment and economic dispatch (UUCED) modeling within a unique tool that performs economic dispatch with up to 24-hour look-ahead capability was introduced [15]. The unique real-time tool uses an extended scheduling horizon of up to 36 hours and aims to better accommodate the increasing RES penetration in the short-term power systems operation. Variable time resolution is used in order to mitigate the computational burden. More specifically, finer time resolution (5-min, 15-min, 30-min) is used during the first hours, while coarser time resolution (60-min) is adopted during the last hours of the scheduling horizon. The dispatch and commitment decisions for the first interval are binding decisions, while the dispatch and commitment for the rest of the schedule are advisory (see Fig. 3).

2 In this paper, persistence is defined as if PV generation in each hour of the forecast day is equal to the real PV generation of the respective hour of the previous day.
In this way, the model increases the flexibility of the generation fleet by allowing total recommitment and redispach in each run. Ideally, the model uses frequently updated forecasts in order to provide robust real-time decisions in anticipation of an extended scheduling horizon.

Regarding the mathematical formulation, a variable-complexity MILP optimization model that comprises thermal unit operating constraints, such as minimum up/down constraints, ramping constraints, detailed (three-type) start-up and shut-down constraints as well as network security constraints was developed. The main drawback of the model is its high computational requirements that limit its applicability to medium-sized power systems, such as the Greek Power System.

The proposed model was tested via an annual simulation of the Greek power system short-term operations against two other models that were derived based on the current trends of the North-American ISO short-term operations [16]. The first model is a two-level model, comprising a rolling hourly unit commitment and real-time dispatch function. The second model is a three-level model comprising a DA unit commitment followed by an intra-day fast-start unit commitment and a real-time commitment-dispatch. The different models adopt different time resolutions and scheduling horizons as well as they have different forecast lead times and commitment/dispatch decisions. The annual simulations were performed for the actual wind energy production and the double of the actual wind energy production. Several performance indices were calculated, such as generation energy mix, thermal unit cycling and dispatch costs. Simulation results showed that the proposed UUCED model resulted in a more economic operation of the power system, especially for higher shares of wind installed capacity.

2) Determination of system reserve requirements

In order to determine the reserve requirements of the power system under high shares of RES generation, a probabilistic method adapted to the particularities of using a rolling variable time resolution unit commitment model, such as the proposed UUCED model, has been developed [17]. The method takes into account the duration and lead time of each interval as well as the specific hour of the day that corresponds to each interval. The method performs probabilistic analysis on the load and wind power forecasts and measurements of the Greek power system in order to calculate the standard deviation of the net load variability and the load/wind power forecast error uncertainty. All three reserve types (based on the ENTSO-E standards) are calculated, based on the load/wind power variability and uncertainty as well as the forced outage of the largest thermal generating unit.

A simplification of the proposed reserve quantification method was implemented in the proposed UUCED model. In this framework, load and wind power uncertainty is considered as the sole system uncertainty sources and, therefore, they are the only factors that affect the reserve needs. Annual simulation cases of the Greek power system short-term operations have been constructed for different reserve levels based on the 1σ, 2σ and 3σ rule, respectively. Based on the annual simulations results, several performance indices are calculated, such as the generation energy mix, thermal unit cycling and dispatch costs for all cases. Results show that the case that schedules reserves following the 1σ rule results in the most economic operation of the power system.

3) Scenario-based analysis of large-scale RES integration on the Greek electricity market

A scenario-based simulation analysis to evaluate the impact of RES integration on the operation of the Greek electricity market in terms of specific indicators was performed [18].

The simulation analysis was performed for the seven-year period 2014-2020 on an hour-by-hour basis considering five different RES technologies, namely wind, PV, small hydro, biomass and CHP. Two different models, regarding the organization of the Greek wholesale DA electricity market were considered: a mandatory power pool for 2014 and a power exchange for years 2015-2020 (aligned with the European “Target Model” [13]). Three different scenarios regarding the evolution of the installed capacity of the ground-mounted PV systems in the period 2015-2020 were considered.

The impact of the RES integration on the Greek electricity market was analyzed in terms of: a) the wholesale DA electricity market prices (SMPs), b) the total CO2 emissions and generation cost, c) the number of start-ups and shut-downs (cycling) of the thermal units, and e) the RES uplift charge, imposed by the Greek State for the payment of the (usually higher than the SMP) feed-in tariffs to the RES producers.
Simulation results showed that the wholesale market model transition from the mandatory pool to the power exchange in 2015 along with the abolition of favorable market rules for CCGTs that were in force up to the end of 2014 would lead to: a) an unambiguous increase in the resulting day-ahead SMP, b) a significant decrease of the CCGT total operating hours and energy production, and c) a notable increase of the CCGTs cycling in order to compensate for the large intermittent RES energy injection. In addition, the continuous increase of RES installed capacity would result in a notable decrease in SMP and CO₂ emissions (see Fig. 4).

Regarding the retail market operation, test results indicated that the increased PV penetration in the long-term would not affect substantially the RES uplift charge, since the FiTs of the new ground-mounted PV parks for years 2015-2020 were comparable to the resulting day-ahead SMP. However, additional financial measures (i.e. revenues from CO₂ emissions rights auctions and a special levy on RES producers), taken by the Greek government for the period 2014-2015 to eliminate the deficit on the payments balance of the RES Special Account, mitigated the economic impact of the imposed RES uplift charge on the electricity consumers.

4) Evaluation of the capacity credit of RES

In a different direction, the capacity credit of five different RES categories, namely wind, PV, small hydro, biomass, and cogeneration in the Greek power system was also investigated [19]. Widely accepted power system reliability evaluation techniques, such as the capacity outage probability table along with the Loss of Load probability (LOLP) and Loss of Load Expectation (LOLE) metrics were used. Test results showed the strong dependence of the capacity credit values on the RES penetration level for the majority of the RES technologies (see Fig. 5). In addition, the temporal correlation of the yearly RES production profile with the respective load demand profile may have a significant effect on the calculation of the capacity credit and, therefore, extended simulations with multiple years’ data are required to reach general conclusions. Finally, it was proved that the capacity credit of a given RES technology is highly influenced by the penetration level of other RES technologies.

![Fig. 4 Thermal production and CO₂ emissions](image1)

![Fig. 5 Capacity credit for variable RES penetration levels](image2)

C. Electric vehicles and VPP integration in electricity markets

1) Participation of electric vehicles in electricity markets

A complete framework for the optimal participation of plug-in electric vehicles, represented by electric vehicle (EV) aggregators, in electricity markets was proposed. Novel optimization tools were proposed for: a) the development of optimal bidding strategies for EV aggregators in the short-term markets (i.e. DA and real-time (RT) markets) [20]-[21], and b) the RT charging management of EV fleets [22].

An optimal bidding strategy of an EV aggregator participating in DA energy and regulation markets using stochastic optimization has been developed in [20]. Key sources of uncertainty have been identified and incorporated in the stochastic optimization model. The developed tool models also the inevitable deviations between the DA cleared bids and the actual RT energy purchases. The uncertainty regarding the energy content of the regulation signals has been modeled as a random variable and a model for the most common battery charging method (constant current – constant voltage) was also presented. Test results demonstrated that the careful consideration of the instructed and uninstructed energy deviations plays a key role in the design of the EV aggregator bidding strategy. Finally, changes in market rules influence the EV aggregator bidding strategy and profits.

The above DA optimal bidding strategy was extended to evaluate the opportunities for increased profits under a synergistic supply offer and demand bidding strategy of a wind energy producer and an EV aggregator that participate in the DA energy and regulation reserve markets, owing to the better management of energy deviations [21]. The new market player acts as a prosumer and participates in the market with synergistic offers and bids of the two entities. Indicative test results demonstrate that the benefits from the synergistic market participation are strongly dependent on the specific market rules of the energy deviation penalty scheme.

Besides the DA and RT market bidding strategies, a RT charging management framework for EV aggregators was also developed, including charging management in three control levels [22]. The proposed approach enables the EV aggregator to allocate set-points to the EVs every few seconds for participation in the provision of regulation services, while simultaneously interacting optimally with the closest market sessions.
The proposed models assign charging set-points to the EVs, based on evolving EV charging priorities and are solved very fast. The case study reveals the importance of adopting the dynamic regulation signal [23] for the reliable participation of EV aggregators in regulation markets. In addition, the impact of charging priority parameterization on the effectiveness of the RT charging management framework is presented.

2) Participation of VPPs in electricity markets

Regarding the emerging trend of VPPs participation in electricity markets, the optimal bidding strategy problem of a Commercial VPP (CVPP), which comprises distributed energy resources (DER), battery storage systems and electricity consumers and participates in the DA market, was addressed [24]. A three-stage stochastic optimization model was developed, enabling a CVPP to act as a price-maker in the DA market and aiming at the maximization of the DA profit in conjunction with the minimization of the anticipated RT generation and consumption imbalance charges.

The incorporation of demand-response schemes into the optimization model allows the CVPP to manage the DERs variability to its own profit. The CVPP owner is also able to decide the desired risk level prior to the construction of his bidding strategy by including the Conditional Value-at-Risk metric in the optimization model. Test results on the Greek system illustrate the substantial benefits of aggregating DERs and consumption imbalance costs.

V. CONCLUSION

In this paper, a brief overview of the main challenges introduced in the electricity markets operation due to high RES shares as well as key solutions that will allow for the efficient operation of the power system in conjunction with the full exploitation of the associated “green energy” benefits is presented. In addition, the core research performed in the context of LaRInEM project, comprising the development of novel simulation models as well as further analyses on the electricity market operation under large-scale RES integration, has been presented. All these contributions constitute useful tools that may help to formulate a generalized framework for designing and evaluating the future electricity markets, where renewable generation is expected to play a critical role.

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