The role of the energy storage and the demand response in the robust reserve and network-constrained joint electricity and reserve market

[a]*Marko Mimica*, [c]*Zoran Sinovčić*, [b]*Andrej Jokić*, [a]*Goran Krajačić*

[a]Department of Energy, Power Engineering and Environment, Faculty of Mechanical Engineering and Naval Architecture, 10 000 Zagreb

[b]Department of Robotics and Production System Automation, Faculty of Mechanical Engineering and Naval Architecture, 10 000 Zagreb

[c]Croatian Transmission System Operator, 10 000 Zagreb

e-mail: mmimica@fsb.hr

Abstract

Increase of the variable renewable energy sources in the power system is causing additional needs for the reserve in the system. On the other hand, the integration of energy storage and the demand response offers additional sources of flexibility in the system. Most of the current studies that model energy systems do not model the reserve market. Because of this, these studies eliminate the possibility to assess the full benefits of energy storage and demand response. The method proposed in this study enables the comparison between the two approaches and evaluates the benefits of energy storage and demand response for both approaches. The case study was conducted on the power system consisted of 13 interconnected nodes. The results showed that the operation cost of the system was 28.1% higher when the reserve constraints were imposed for the most pessimistic scenario. Moreover, the results showed that energy storage and flexible loads achieved significantly higher revenues when they were able to participate in the reserve market. The results indicated the need for the development of the reserve market as well as frameworks that will enable the energy storage and the demand response to participate in the reserve markets.

Keywords

Energy storage; Demand response; Power system analysis; Flexibility; Reserve markets

1. Introduction

The recent objectives set by the European Union (EU) in [1] described the necessity for the green energy transition. This is another document in a series of regulations regarding energy (e.g. [2] for energy balancing, [3] regarding the electricity market design) and other memorandums [4] and initiatives (e.g. Smart Islands initiative [5] and Clean Energy for all Europeans [6]) that emphasize the fact that the green energy transition is one of the top EU strategic objectives. Decarbonization of the electricity sector represents perhaps the most challenging issue. As the conventional generators that run on coal and gas are starting to phase out, the new variable renewable energy sources (VRES) such as wind and photovoltaic (PV) power plants are being integrated in the system. This results with additional uncertainty in the power system operation because VRES production depends on the current weather conditions in contrast to the coal and gas power plants that are controllable.

Many studies analysed the operation of future systems with high VRES share. The authors in [7] presented a case for complete decarbonization of the South-East Europe energy system. A subsampling method applied at the United Kingdom (UK) power systems over 36 year period in [8] resulted in significantly less variation in terms of system cost and hours of unmet demand in comparison to the models that observe individual years. The UK power system was also modelled in [9] but with consideration of different time resolutions, concluding that the systems with high wind and solar penetration should be modelled on a resolution finer than a one-hour resolution. Different tools for analysing the energy systems were developed over the years as well (e.g. EnergyPLAN used in [10], or H2RES applied in [11]). The value of interconnection was demonstrated in [12] where the authors analysed the islands of Korčula, Hvar, Lastovo and Vis. The results showed that Critical Excess Electricity Production decreased by 22% when the interconnection was considered for the most optimistic scenario. Another study [13] proposed a 30 MW solar and 22 MW wind energy mix for the island of Korčula. A 100% renewable energy system of island La Gomera was modelled in [14]. Similar results that indicate that it is possible to achieve 100% renewable production were achieved for the Åland Islands in [15]. The Markal model was coupled with the load flow model in [16] and showed that the integration of a 100 MW wind power plant resulted in a maximum of 21% line overload. Multi-energy microgrid operation was investigated in [17] where authors showed the flexibility benefits when different sectors are jointly integrated. The possible pricing strategies for the battery storage in the residential microgrid with the photovoltaics were analysed in [18] and concluded that it would be optimal to apply the volumetric and the capacity tariffs. Different demand response models and energy storage systems were considered in the study [19] where authors concluded that optimal integration of renewable units with energy storage and the demand response results in a lower cost of the system. A multi-objective framework with AC OPF model was developed in [20] that analysed the operation of the demand response and the energy storage in the reconfigurable heat and power microgrid, however without including the reserve market. A similar study was conducted in [21] with a focus on including environmental aspects in the modelling and without the consideration of the reserve constraints. A soft-linking approach presented in [22] proved the necessity of more detailed modelling as there was grid code violation for the analysed energy planning scenario, however, the authors also did not include the reserve markets in the study. The studies [7-22] did not consider any kind of reserve constraints and used hourly time resolution (except [9] which compared different time resolution approaches). This paper presented a method that considered the reserve constraints incorporated in a DC OPF model on a 15-min time resolution. Moreover, the results of this study were obtained under demand uncertainty which is not considered in studies [7-22]. The proposed method filled in this research gap and the results demonstrated the necessity for more detailed modelling of the energy system.

Several studies proposed more detailed energy system models that included the reserve requirements. The authors in [23] analysed the Western Europe power system using the Dispa-SET tool. The study showed that the system can operate securely with a decrease in electricity price by 46.5% with an increase in renewable production of 11.7% by 2020 and 28.7% by 2030. The study did not, however, use a grid model where the power flow is a function of voltage angle difference between the two nodes. Another study [24] presented a joint energy and reserve model that did not include energy storage systems (ESS) and demand response (DR) as well as aggregated all technologies in one node. Joint energy and reserve model was presented in [25] where authors observed the influence of electric vehicle (EV) fleet on the system operation. Between the scenarios with 5, 50 and 500 EVs in the fleet, the lowest cost was achieved for the scenario with 50 EVs. However, the study did not consider the grid constraints which would enable better utilization of a fleet with a higher number of EVs. Another study [26] included EVs in the optimal management strategy of the energy and reserve markets, however without modelling of the grid constraints. A DC OPF model with reserve saturation was presented in

[27] where the authors provided a novel method for generator production and reserve provision control. The study does not consider the influence of ESS and DR on the system operation in the proposed model. The DR model was proposed in [28] in the AC OPF model, however, the reserve market was not modelled in this study.

The analysed studies indicated that the integration of VRES in power systems is increasing substantially. For these reasons, higher amounts of the reserve are required, while at the same there are fewer units that can provide the reserve as underlined in [29]. However, one of the solutions to this problem is the integration of flexible technologies such as ESS and DR [30]. The recent study [31] showed that ESS can successfully provide ancillary services to the system and maintain the voltage level below 1.05 p.u. However, the study focuses only on ancillary services regarding nominal voltage preservation. The study [32] considered an energy hub with included reserve constraints, however without enabling the possibility of reserve provision by the energy storage and without the comparison analysis to models without the reserve constraints. Another recent study [33] proposed a stochastic framework for integrating ESS as a reserve provider and compared four ESS reserve models. Both studies [31] and [33] used hourly time resolution and did not consider flexible load for providing reserve. Moreover, the studies did not provide insight into what benefits does reserve modelling offer in comparison to the existing energy system models. This paper analysed the differences between the two modelling approaches and quantified the impact on the overall system operation when the ESS and DR are included in the reserve market. The analysis of the previous studies shows that there is a research gap as there is no method that enables the comparison of different modelling approaches and that enables the comparison of the ESS and DR in such different models. This study fills this research gap by providing such robust method that enables the quantification of ESS and DR role under the uncertainty.

To the knowledge of the authors of this paper, no study compares the differences of the DC OPF model with and without the reserve constraints and includes ESS and DR reserve models under the demand uncertainty. A novel and original method for the comparison of energy system models is presented in this study. In addition, the presented method enables the comparison of ESS and DR roles in different models, thus provides an insight into the possible business models for providing flexibility on electric energy and reserve markets. This study hypothesises is that the inclusion of the reserve market in the power system modelling has a significant impact on the operation cost of the system as well as the operation and revenue of different stakeholders in the power system. The contributions of this study are listed below:

- A robust power system model under the demand uncertainty that includes the reserve market was modelled. The model includes the reserve models of ESS and DR.
- A comparative analysis between the joint model of electricity and reserve market and only electricity market was conducted
- A sensitivity analysis concerning different VRES share in the power system was conducted

This paper is organised in the following manner: an introduction and literature review are followed by the materials and methods section. The case study is described in the third section, the results are provided in the fourth section, the discussion in the fourth section and, in the final section, the conclusion is provided.

2. Materials and methods

This section provides a general overview of the proposed approach, a detailed mathematical representation of the models used in the paper, as well as a method for solving the proposed optimization problem.

2.1.General

The method developed in this study enables a comparison between the power system modelling with and without the reserve market. The method is designed for closed power systems, meaning that import and export were not allowed. This assumption was made because the method intends to demonstrate the operation of future power systems. These systems will include a high share of variable renewable energy sources (VRES) which means that it is assumed that the grid surrounding the observed system is also characterised by the high share of VRES. As similar VRES production can be expected for the observed system and the surrounding grid, energy exchange between the observed system and the surrounding grid is not considered.

It is assumed that the market price is equal to the marginal cost of production and reserve. The presented model is a network-constrained market clearing problem with energy dispatch as well as joint energy and reserve dispatch. The method offers the possibility to observe the impact of the corrective actions that occur as a result of reserve market inclusion in the model. This enables the evaluation of the benefits when the reserve market is included in the energy system models that are being extensively discussed in the scientific community.

It should be noted that the study intends to focus on the role of ESS and DR in the power systems. The study aims to demonstrate the differences in the power system operation when ESS and DR are considered only in the environment of the electricity market in comparison to the case when joint electricity and reserve market. It is assumed that the transmission system operator (TSO) knows the parameters in equations (1) – (30) and that the joint electricity and reserve market is implemented. The overview of the proposed method is provided in Figure 1.

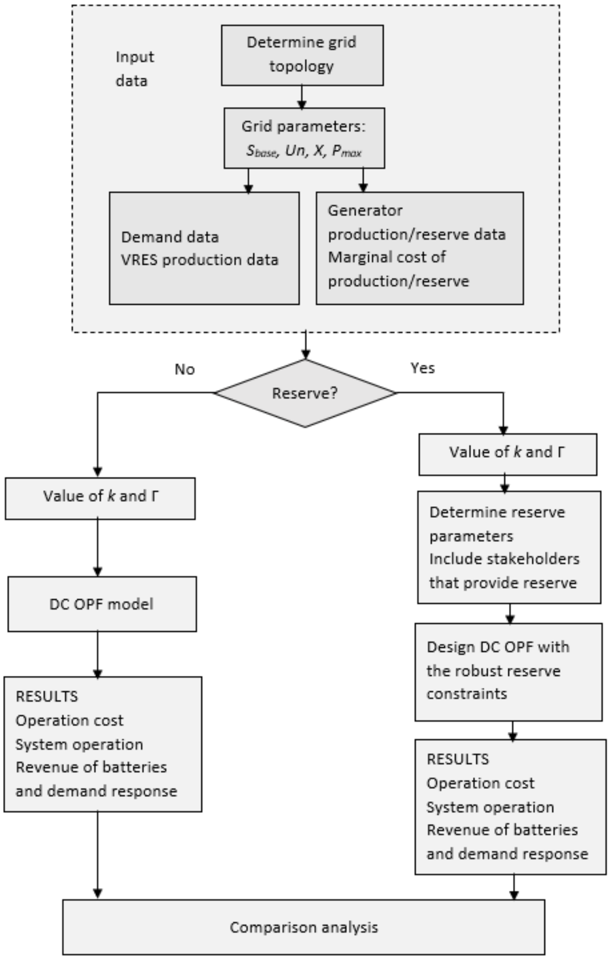


Figure 1. Flow diagram of the proposed method

2.2. Power system model without reserve market

The power system network is considered to be an undirected graph $\mathcal{G} = (\mathcal{N}, \mathcal{E})$ where $\mathcal{N}$ is a set of nodes and $\mathcal{E}$ is a set of transmission lines or edges in the observed system. Other sets include generators ($\mathcal{R}$), loads ($\mathcal{L}$), wind power plants ($\mathcal{W}$), photovoltaic power plants ($\mathcal{S}$), energy storages ($\mathcal{B}$) and flexible demand ($\mathcal{V}$). Set of all generation units is denoted as $\mathcal{G} := \mathcal{R} \cup \mathcal{W} \cup \mathcal{S}$. The power system operation is observed for the set of periods $\forall t \in \mathcal{T}$. The reactance of the transmission lines is represented with X_{ij} $(= X_{ji})$. The nomenclature can be found at the end of the paper.

Equation (1) presents the objective function of the problem. The objective function includes the cost of energy production from the regular generators and VRES, cost of load shedding (LS) and the cost of curtailed energy ($p_{i,t}^{curt}$) from the VRES. The objective of the proposed problem is to minimize the system operation cost as defined in equation (1). It should be noted that (1) will be changed when the reserve market is considered. The model includes grid constraints (2), (9) and (10), power balance at each node constraint (3), generator constraints (4)-(6), VRES constraints (7) and (8), ESS constraints (11)-(14) and DR constraints (15)-(17). The generation constraints define the ramping possibilities for the two consecutive time periods, equations (5) and (6), as well as minimum and maximum production from the units (4). The benefit of this model is that power flow balance needs to be satisfied in each node of the grid, as defined with equation (3), which is different from many other energy planning studies that do not consider the power grid as elaborated in the Introduction section. The ESS constraints (11)-(14) regulate the state of charge of the ESS at the given time period and limit the charging and discharging power of the ESS. Equation (17) ensures that the same amount of energy that is reduced as a consequence of the DR programme is retrieved. In other words, equation (17) ensures the preservation of energy. Binary variable $y_{i,t}$ was introduced to prevent simultaneous charging and discharging of the ESS, while binary variable $z_{i,t}$ was introduced to prevent simultaneous demand reduction and demand retrieval of the flexible loads. It should be noted that the constraints for the ESS and the DR will change as the reserve requirements will be included in the model. This can be seen in section 2.3. The k parameter associated with equations (7) and (8) was used to model the sensitivity analysis concerning the VRES share in the system. This will enable to observe the operation of the ESS and DR for the different share of renewables penetration in the system. For the sake of simplicity, the cost of generator production is assumed to be linear.

$$\min f \triangleq \min \sum_{t\in\mathcal{T}} \left(\sum_{i\in\mathcal{G}} p_{i,t}^{G} \cdot b_i + \sum_{i\in\mathcal{L}} LS_{i,t} \cdot VOLL + \sum_{i\in\mathcal{G}\setminus\{\mathcal{R}\}} CE \cdot p_{i,t}^{curt} \right) \cdot \Delta t \tag{1}$$

$$p_{ij,t} = \frac{\delta_{i,t}-\delta_{j,t}}{x_{ij}}, \quad i,j \in \mathcal{N}, \forall ij \in \mathcal{E}, \forall t \in \mathcal{T} \tag{2}$$

$$p_{i,t}^{R} + p_{i,t}^{S} + p_{i,t}^{W} + p_{i,t}^{d} - p_{i,t}^{c} + p_{i,t}^{drr} - p_{i,t}^{dr} - L_{i,t} = \sum_{j\in\mathcal{E}} p_{ij,t} : \lambda_{i,t}, \quad \forall i \in \mathcal{N}, \forall t \in \mathcal{T} \tag{3}$$

$$P_i^{min} \le p_{i,t}^{R} \le P_i^{max}, \quad \forall i \in \mathcal{R}, \forall t \in \mathcal{T} \tag{4}$$

$$p_{i,t+1}^{R} - p_{i,t}^{R} \le RU_i, \quad \forall i \in \mathcal{R}, \forall t \in \mathcal{T} \tag{5}$$

$$p_{i,t-1}^{R} - p_{i,t}^{R} \le RD_i, \quad \forall i \in \mathcal{R}, \forall t \in \mathcal{T} \tag{6}$$

$$p_{i,t}^{W} + p_{i,t}^{W,curt} \le k \cdot \Lambda_{i,t}^{W}, \quad \forall i \in \mathcal{W}, \forall t \in \mathcal{T} \tag{7}$$

$$p_{i,t}^{S} + p_{i,t}^{S,curt} \le k \cdot \Lambda_{i,t}^{S}, \quad \forall i \in \mathcal{S}, \forall t \in \mathcal{T} \tag{8}$$

$$-\frac{\pi}{2} \le \delta_{ij,t} \le \frac{\pi}{2}, \quad \forall ij \in \mathcal{E}, \forall t \in \mathcal{T} \tag{9}$$

$$-P_{ij}^{max} \le p_{ij,t} \le P_{ij}^{max}, \quad \forall ij \in \mathcal{E} \tag{10}$$

$$soc_{i,t} = soc_{i,t-1} + \left(p_{i,t}^{c} \cdot \eta_i^{c} - \frac{p_{i,t}^{d}}{\eta_i^{d}}\right) \cdot \Delta t, \quad \forall i \in \mathcal{B}, \forall t \in \mathcal{T} \tag{11}$$

$$SOC_i^{min} \le soc_{i,t} \le SOC_i^{max}, \quad \forall i \in \mathcal{B}, \forall t \in \mathcal{T} \tag{12}$$

$$p_{i,t}^{d} \le P_i^{d-MAX} \cdot y_{i,t}, \quad \forall i \in \mathcal{B}, \forall t \in \mathcal{T} \tag{13}$$

$$p_{i,t}^{c} \le P_i^{c-MAX} \cdot (1 - y_{i,t}), \quad \forall i \in \mathcal{B}, \forall t \in \mathcal{T} \tag{14}$$

$$p_{i,t}^{dr} \le DR_{i,t}^{max} \cdot z_{i,t}, \quad \forall i \in \mathcal{V}, \forall t \in \mathcal{T} \tag{15}$$

$$p_{i,t}^{drr} \le DRR_{i,t}^{max} \cdot (1 - z_{i,t}), \quad \forall i \in \mathcal{V}, \forall t \in \mathcal{T} \tag{16}$$

$$\sum_{t\in\mathcal{T}} p_{i,t}^{dr} = \sum_{t\in\mathcal{T}} p_{i,t}^{drr}, \quad \forall i \in \mathcal{V} \tag{17}$$

2.3.Power system model with reserve market

The complete DC OPF problem with reserve constraints included is given with the equations (2) – (30) and they form a joint electricity and reserve market clearing. It can be observed that the objective function (1) is now transformed into (18). The objective function (18) is expanded by including the cost of providing the up ($r_{i,t}^{UP}$) and down ($r_{i,t}^{DO}$) reserve from the generators, ESS and flexible loads. The objective of the problem remains to minimize the system operation costs but is defined as in equation (18). It is assumed that the marginal cost of the reserve for regular generators and ESS changes with respect to the change in the demand in the node where generators and storage are connected. The intention is to model a simple bidding strategy that generators and storage would use to increase their revenues. Equations (19) and (20) describe the constraints for reserve requirements. Reserve requirements are defined with the current demand, wind and solar generation in the system. An increase of these values leads to higher requirements for the reserve. It should be noted that the system considers the demand to be uncertain. This means that the uncertain parameter is included in equations (19) and (20) which is why the robust model was developed as described in chapter 2.4. This allows the model to see the result parameters sensitivity with the respect to the different demand values in the system. Equations (21)-(24) are constraints for reserve provision from the regular generators, (25)-(28) are constraints for reserve provision from the ESS and (29)-(30) are constraints for reserve provision from the flexible load. It can also be seen that the generator, ESS and DR constraints were also modified in the model with included reserve constraints. Because these stakeholders (generators, ESS and DR) are participating in the reserve market, this has to be represented mathematically as well. Part of their capacity should be saved in case of reserve requirements defined by the model.

$$\begin{aligned}\min f \triangleq \min \sum_{t\in\mathcal{T}} \Bigg[& \sum_{i\in\mathcal{G}} p_{i,t}^{G} \cdot b_i^{G} + \sum_{i\in\mathcal{L}} LS_i \cdot VOLL \\ & + \sum_{i\in\mathcal{G}\setminus\{\mathcal{R}\}} CE \cdot p_{i,t}^{curt} + \sum_{i\in\mathcal{V}} r_{i,t}^{DRR,UP} \cdot b_i^{DRR,UP} \\ & + \left(\sum_{i\in\mathcal{R}} r_{i,t}^{R,UP} \cdot b_i^{R,UP} + \sum_{i\in\mathcal{B}} r_{i,t}^{d,UP} \cdot b_i^{d,UP} \right) \left(1 + \frac{L_{i,t}}{L_i^{MAX}} \right) \\ & + \sum_{i\in\mathcal{V}} r_{i,t}^{DR,DO} \cdot b_i^{DR,DO} \\ & + \left(\sum_{i\in\mathcal{R}} r_{i,t}^{R,DO} \cdot b_i^{R,DO} + \sum_{i\in\mathcal{B}} r_{i,t}^{c,DO} \cdot b_i^{c,DO} \right) \left(1 + \frac{L_{i,t}}{L_i^{MAX}} \right) \Bigg] \cdot \Delta t \end{aligned} \tag{18}$$

$$\begin{aligned} \sum_{i\in\mathcal{R}} r_{i,t}^{R,UP} + \sum_{i\in\mathcal{B}} r_{i,t}^{d,UP} + \sum_{i\in\mathcal{V}} r_{i,t}^{drr,UP} \geq J_L^{UP} \sum_{i\in\mathcal{L}} \widetilde{L_{i,t}} + J_W^{UP} \sum_{i\in\mathcal{W}} p_{i,t}^{W} + J_S^{UP} \sum_{i\in\mathcal{S}} p_{i,t}^{S} \\ : \ \mu_t^{UP}, \forall t \in \mathcal{T} \end{aligned} \tag{19}$$

$$\begin{aligned} \sum_{i\in\mathcal{R}} r_{i,t}^{R,DO} + \sum_{i\in\mathcal{B}} r_{i,t}^{c,DO} + \sum_{i\in\mathcal{V}} r_{i,t}^{dr,DO} \geq J_L^{DO} \sum_{i\in\mathcal{L}} \widetilde{L_{i,t}} + J_W^{DO} \sum_{i\in\mathcal{W}} p_{i,t}^{W} + J_S^{DO} \sum_{i\in\mathcal{S}} p_{i,t}^{S} \\ : \ \mu_t^{DO}, \forall t \in \mathcal{T} \end{aligned} \tag{20}$$

$$r_{i,t}^{UP} \leq P_i^{max} - p_{i,t}^R, \qquad \forall i \in \mathcal{R}, \forall t \in \mathcal{T} \tag{21}$$

$$R_i^{UP-MIN} \leq r_{i,t}^{R,UP} \leq R_i^{UP-MAX}, \qquad \forall i \in \mathcal{R}, \forall t \in \mathcal{T} \tag{22}$$

$$r_{i,t}^{DO} \leq p_{i,t}^R - P_i^{min}, \qquad \forall i \in \mathcal{R}, \forall t \in \mathcal{T} \tag{23}$$

$$R_i^{DO-MIN} \leq r_{i,t}^{R,DO} \leq R_i^{DO-MAX}, \qquad \forall i \in \mathcal{R}, \forall t \in \mathcal{T} \tag{24}$$

$$r_{i,t}^{d,UP} \leq \frac{SOC_i^{max} - soc_{i,t-1}}{\Delta t} - \frac{p_{i,t}^d}{\eta_i^d}, \qquad \forall i \in \mathcal{B}, \forall t \in \mathcal{T} \tag{25}$$

$$r_{i,t}^{c,DO} \leq \frac{soc_{i,t-1} - SOC_i^{min}}{\Delta t} - \eta_i^c \cdot p_{i,t}^c, \qquad \forall i \in \mathcal{B}, \forall t \in \mathcal{T} \tag{26}$$

$$r_{i,t}^{d,UP} \leq P_i^{d-MAX}, \qquad \forall i \in \mathcal{B}, \forall t \in \mathcal{T} \tag{27}$$

$$r_{i,t}^{c,DO} \leq P_i^{c-MAX}, \qquad \forall i \in \mathcal{B}, \forall t \in \mathcal{T} \tag{28}$$

$$r_{i,t}^{drr,UP} \leq DRR_{i,t}^{max} - p_{i,t}^{drr}, \qquad \forall i \in \mathcal{V}, \forall t \in \mathcal{T} \tag{29}$$

$$r_{i,t}^{dr,DO} \leq DR_{i,t}^{max} - p_{i,t}^{dr}, \qquad \forall i \in \mathcal{V}, \forall t \in \mathcal{T} \tag{30}$$

2.4. Uncertainty modelling

This paper used a robust approach for interpreting the uncertainty of the demand in the observed system. The robust approach presents an effective possibility for uncertainty modelling as it eliminates the need for modelling a large set of scenarios as is the case in the stochastic approach. It is considered that the demand value at node *i* and time *t* obtain the value in range between the minimum and maximum possible value of the demand as defined with the equation (31). This means that the minimum and maximum demand are the only input data that need to be known to model the uncertainty of the demand by using the robust approach. The input data is available from historic data as described in the Case study section.

$$\widetilde{L_{i,t}} \in U\left(\widetilde{L_{i,t}}\right) = \left\{\widetilde{L_{i,t}} : \ L_{i,t}^{min} \leq \widetilde{L_{i,t}} \leq L_{i,t}^{max}\right\}, \qquad \forall i \in \mathcal{L}, \forall t \in \mathcal{T} \tag{31}$$

Modifying the equations (19) and (20) with the robust model results with the following equations (32) – (33). By introducing the auxiliary variables σ_i and $\varphi_{i,t}$ as well as conservativeness factor Γ_i the uncertain variable $\widetilde{L_{i,t}}$ can be replaced with the value $L_{i,t}^{min}$, $\forall i \in \mathcal{L}$, $\forall t \in \mathcal{T}$. This approach is described in [34]. The market-clearing process in a practical context is based on expected demand values as well as bids from different generators. It is considered that the generators bid based on their marginal cost. In order to achieve a higher level of physical representation of the method, the market-clearing is conducted with deterministic demand values as is the case in real-time operation. The presented method allows observation of the system behaviour for various demand values when the ESS and DR are included in the joint electricity and reserve market.

Another assumption in this paper is that the perfect competition was considered. This assumption can be found in many publications, for example [35], and represents a market where all buyers and consumers have full and symmetric information. With this assumption, the Lagrange multiplier of the power balance constraint represents the electric energy price. In practical implementation, the energy prices are formed based on producers bids and expected demand. Thus, this model considers deterministic values in the power balance equation, while the uncertainty is implemented in the reserve constraints by the introduction of the auxiliary variables. This model aims to compare cases under the demand uncertainty controlled with the conservativeness factor Γ_i. Auxiliary variables σ_i and $\varphi_{i,t}$ change values as the conservativeness factor changes. For example, if the value of Γ_i is equal to zero, all the values will be contained in σ_i because of equation (34) and the most optimistic case will occur.

$$\sum_{i\in\mathcal{R}} r_{i,t}^{R,UP} + \sum_{i\in\mathcal{B}} r_{i,t}^{d,UP} + \sum_{i\in\mathcal{V}} r_{i,t}^{drr,UP} \geq J_L^{UP} \sum_{i\in\mathcal{L}} (L_{i,t}^{min} + \sigma_i \cdot \Gamma_i + \varphi_{i,t}) + J_W^{UP} \sum_{i\in\mathcal{W}} p_{i,t}^{W} + J_S^{UP} \sum_{i\in S} p_{i,t}^{S} \,:\, \mu_t^{UP}, \forall t \in \mathcal{T} \tag{32}$$

$$\sum_{i\in\mathcal{R}} r_{i,t}^{R,DO} + \sum_{i\in\mathcal{B}} r_{i,t}^{c,DO} + \sum_{i\in\mathcal{V}} r_{i,t}^{dr,DO} \geq J_L^{DO} \sum_{i\in\mathcal{L}} (L_{i,t}^{min} + \sigma_i \cdot \Gamma_i + \varphi_{i,t}) + J_W^{DO} \sum_{i\in\mathcal{W}} p_{i,t}^{W} + J_S^{DO} \sum_{i\in S} p_{i,t}^{S} \,:\, \mu_t^{DO}, \forall t \in \mathcal{T} \tag{33}$$

Equation (34) has to be considered so that the uncertainty range can be accounted for. With this equation (34), the auxiliary variables are assigned values greater or equal to the set range of the uncertain variable and the uncertainty range.

$$\sigma_i + \varphi_{i,t} \geq \left(P_{i,t}^{max} - P_{i,t}^{min}\right), \qquad \forall i \in \mathcal{L}, \forall t \in \mathcal{T} \tag{34}$$

The variables of the described robust joint electricity and reserve market are provided with the (35).

$$Q = \begin{Bmatrix} p_{i,t}^{R}, p_{i,t}^{S}, p_{i,t}^{W}, LS_{i,t}, p_{i,t}^{curt}, \delta_{i,t}, p_{ij,t}, \\ p_{i,t}^{drr}, p_{i,t}^{dr}, soc_{i,t}, y_{i,t}, z_{i,t}, p_{i,t}^{d}, p_{i,t}^{c}, r_{i,t}^{R,UP}, \\ r_{i,t}^{R,DO}, r_{i,t}^{d,UP}, r_{i,t}^{c,DO}, r_{i,t}^{drr,UP}, r_{i,t}^{dr,UP}\ \sigma_i,\ \varphi_{i,t} \end{Bmatrix} \tag{35}$$

The formulated model represents a mixed-integer problem and was solved with the CPLEX solver for continuous and discrete problems in the GAMS programming language on a 16 GB RAM machine. The model includes 6155 single variables and 144 binary variables.

2.5.Revenues for the ESS and DR under the marginal pricing

The proposed model suggests that three different commodities exist at each node. The three commodities are energy, up reserve and down reserve. Regular generators, wind and solar power plants sell the energy and the reserve can be offered by regular generators, ESS and flexible load (FL).

The defined robust optimization problem defines the market clearing process and results with the energy production and consumption of all units as well as with the up and down reserve values. The revenue of ESS and flexible load can be defined with the equations (36) and (37). The DR and ESS revenue is obtained as a sum of provided up and down reserve multiplied with the price of up and down reserve ($\mu_{i,t}^{UP}$ and $\mu_{i,t}^{DO}$) and the difference of sold and bought electricity on the market multiplied with the energy price ($\lambda_{i,t}$).

$$R_i^{ESS} = \sum_{t \in \mathcal{T}} \Delta t \cdot \left[\lambda_{i,t}\left(p_{i,t}^{d} - p_{i,t}^{c}\right) + \mu_{i,t}^{UP} \cdot r_{i,t}^{d,UP} + \mu_{i,t}^{DO} \cdot r_{i,t}^{c,DO}\right], \qquad \forall i \in \mathcal{B} \tag{36}$$

$$R_i^{DR} = \sum_{t \in \mathcal{T}} \Delta t \cdot \left[\lambda_{i,t}\left(p_{i,t}^{dr} - p_{i,t}^{drr}\right) + \mu_{i,t}^{UP} \cdot r_{i,t}^{drr,UP} + \mu_{i,t}^{DO} \cdot r_{i,t}^{dr,DO}\right], \qquad \forall i \in \mathcal{V} \tag{37}$$

3. Case study

The case study was conducted on the network consisted of 13 nodes and 15 transmission lines represented in Figure 2. Loads, generators (marked with the symbol for AC source), wind power plants (W), photovoltaic power plants (PV) and energy storages (ESS) can be connected to the node. The parameters for energy production units, ESS and flexible load are provided in Table 1 -Table 3. The production cost data in Table 1-Table 3 was obtained based on the report on energy production technologies [36] and [37] as well as the report on ESS [38]. The reserve costs were based on the report [39] that proposed margin cost values of the reserve for the peak and off-peak periods. It was assumed that the reserve cost from the flexible loads is significantly higher than the reserve from generators and the storage, especially for down reserve. This can be justified by the fact that the activation of the down reserve from the flexible loads would cause discomfort or loss for the industry or citizens providing it. The grid parameters for the observed system are provided in Table 4 calculated for the base power of 100 MVA. The grid parameters were obtained from [40] and represent the standard parameters of the transmission grid that include elements that operate on 110 kV voltage or higher. The reserve requirements for up and down reserve are equal and provided in Table 5. These values are specific for different parts of the grid and determined by the TSO. However, it can be assumed that these values depend on the demand, wind and PV production in the system as in [41].

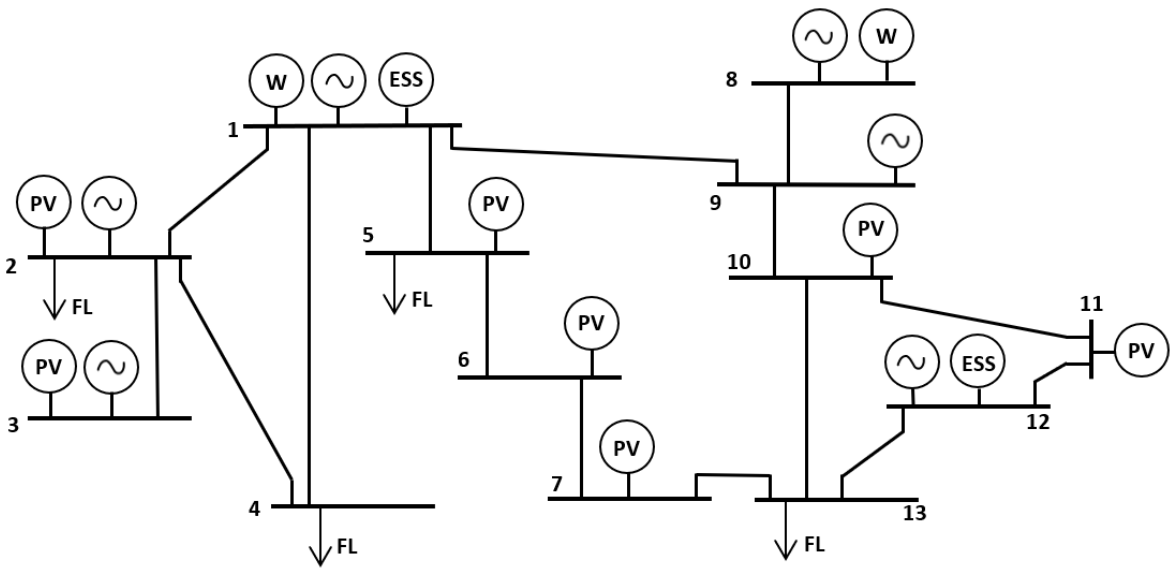


Figure 2. Grid topology of the analysed system with connection points of the production units, storage units and flexible load. The non-flexible load is present in every node but was not shown to preserve the clarity of the figure [40]

Table 1. Production unit data

Production unit	**Node**	**P_{min} [MW]**	**P_{max} [MW]**	**RU [MW]**	**RD [MW]**	**b [€/MWh]**	**b^{UP} [€/MWh]**	**b^{DO} [€/MWh]**
G1	1	10	35	17	17	65	12	8
G2	8	3	12	7	7	49	16	12
G3	9	2	10	6	6	51	18	14
G4	12	2	6	3	3	53	18	14
G5	3	2	10	6	6	55	17	11
G6	2	2	9	5	5	55	18	11
W1	1	0	12	-	-	6.8	-	-
W2	8	0	14	-	-	6.8	-	-
S1	2	0	4	-	-	5.3	-	-
S2	3	0	4	-	-	5.3	-	-
S3	5	0	6	-	-	5.3	-	-
S4	6	0	6	-	-	5.3	-	-
S5	7	0	4	-	-	5.3	-	-
S6	10	0	5	-	-	5.3	-	-
S7	11	0	3	-	-	5.3	-	-

Table 2. Energy storage system data

	Node	SOC_0 [MWh]	SOC_{min} [MWh]	SOC_{max} [MWh]	P^c_{max} [MW]	P^d_{max} [MW]	η_d	η_c	b^{UP} [€/MWh]	b^{DO} [€/MWh]
ESS1	1	4	0.8	7.2	4	4	0.97	0.98	11	11
ESS2	12	4	0.8	7.2	4	4	0.97	0.98	11	11

Table 3. Flexible load data

Flexible load	Node	DR_{max}	b^{UP} [€/MWh]	b^{DO} [€/MWh]
FL1	3	10%	30	55
FL2	9	12%	30	55
FL3	10	11%	30	55
FL4	20	10%	30	55

Table 4. Line parameters for the DC OPF model

N_i	N_j	X [p.u.]	P_{max} [MW]	N_i	N_j	X [p.u.]	P_{max} [MW]
1	2	0.0066	300	8	9	0.03388	110
2	3	0.01355	110	9	10	0.02711	110
2	4	0.03388	110	10	11	0.01694	110
1	4	0.03388	110	11	12	0.08471	110
1	5	0.08471	110	12	13	0.03388	110
5	6	0.13554	110	10	13	0.05083	110
6	7	0.23719	110	7	13	0.12149	80
1	9	0.02372	110				

Table 5. Reserve requirement parameters

Reserve requirement parameters	
J_L^{UP}, J_L^{DO}	0.05
J_W^{UP}, J_W^{DO}	0.1
J_S^{UP}, J_S^{DO}	0.05

The behaviour for the observed power system was obtained from the historical records [42], while the load data was obtained from [40]. The calculations are completed for one day on a 15-min level. The lower and upper boundaries of the load can be seen in Figure 3. The load range boundaries were set to the 5th and 95th percentile of the analysed historical data. This ensures that 5% of the cases are under the lower boundary and that 95% of the cases are under the upper boundary. The production from renewable sources is presented in Figure 4 based on the historical values provided in [22].

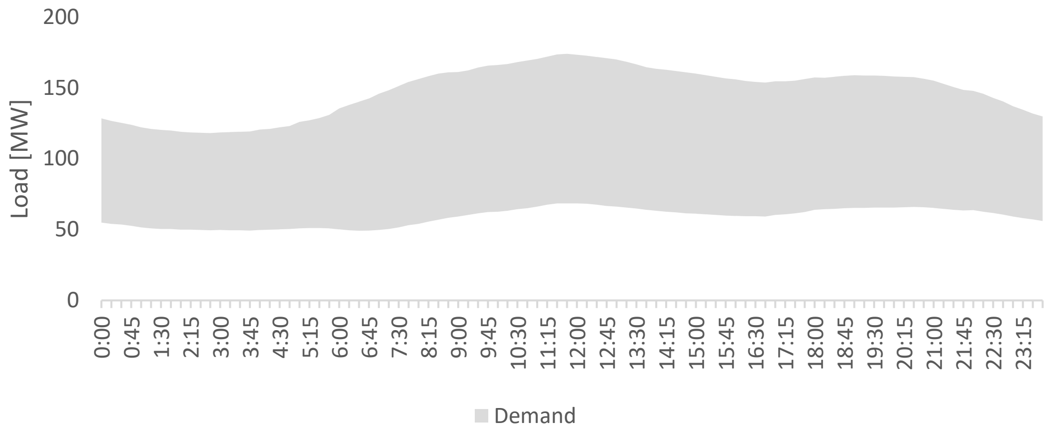


Figure 3. Load range for the observed power system

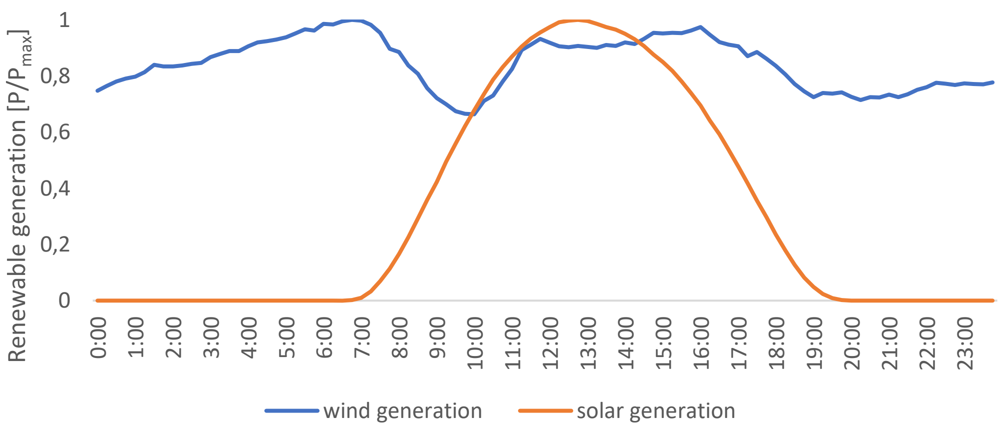


Figure 4. Generation from the renewable units

The penalty for the energy curtailment from the wind and photovoltaic power plants was assumed to be 45 €/MWh. The cost of the load shedding was set to a very high level of 10 000 €/MWh, thus ensuring the feasibility of the model.

Three different levels of VRES penetration were examined. This was modelled by adjusting the value of the *k* parameter. The three scenarios were the lowest VRES share (k = 0.5), the original scenario (k = 1) and the high VRES share (k = 1.5).

4. Results

The obtained results showed that there are significant differences in the power system operation for cases with and without the reserve market. The differences are visible for several parameters of the power system which are reported below. The results are presented in two sub-sections. The first sub-section presents the results of the comparison between models with and without the reserve market. The observed parameters include the operation cost of the system, marginal prices of energy as well as up and down a reserve, operation of the observed units in the system and detailed operation of the ESS. The second sub-section shows the revenue and the operation of ESS and DR when different levels of VRES are present in the system. The key results of the study show the necessity for reserve modelling for a more accurate representation of the energy systems as well as the need for the development of financial and regulatory frameworks for the inclusion of ESS and DR in the reserve markets.

4.1.Comparison between the model with and without RM

The operation cost of the system is illustrated in Table 6. When observing the difference between the modelling approaches, it can be seen that the inclusion of the reserve market caused the increase of the operation cost for all Γ values. This can be explained by the fact that the reserve requirements caused additional expenses because some of the capacities had to be reserved in case there would be the need for reserve activation. The reserved capacities may be used for electric energy production in the case when the reserve market is neglected. The difference in the operation cost between the modelling approaches became more expressed for more pessimistic scenarios. The maximum difference occurred for the most pessimistic scenario and increased by 28.1% in comparison to the scenario without consideration of the RM. The operation cost increased with the increase in demand conservativeness factor. This result was expected as the most optimistic case was presented for $\Gamma = 0$, while the most pessimistic case occurred for $\Gamma = 1$. The demand uncertainty had a lesser influence on the operation cost as the difference between the most optimistic case and most pessimistic was 6 095 €, while the difference for the most optimistic case when RM was considered in comparison with the case when RM was not considered was 16 836 €. This result further underlines the need for the inclusion of the RM in the energy system models. This will also become more important as the participation of different stakeholders in the provision of flexibility services will increase as a result of sector coupling.

Table 6. Operation cost for scenarios with and without RM

	Without RM	**With RM (Γ = 0)**	**With RM (Γ = 0.5)**	**With RM (Γ = 1)**
Operation cost [€]	59868	70609	73980	76704
Percentage change	-	17.9%	23.6%	28.1%

Figure 5 presents another interesting result of the study regarding the marginal price of power balance. Since the observed system is well interconnected, there was no congestion in the power system. As a result, the local marginal cost of the power balance was equal for each particular case. The differences in the dual variable of the power balance equation for different modelling approaches can be observed. The highest difference was equal to 0.5 €/MWh, with the highest energy cost of 13.75 €/MWh. The price difference is not significant as the market clearing was based on the deterministic demand values so that the optimization problem would have a better physical representation. However, if higher demand values would occur with less production from the renewables, one could expect higher prices of energy as marginal DR loads would have to be activated.

It should also be noted that this can influence the final electric energy price for the consumer. This price is usually dependent on many factors that include market price, taxes, distribution and transmission operator fee as well as any other fees set by the government, Increase in reserve requirements will make flexibility services more expensive which can lead to the increase of different fees as well as influence the market price of electric energy. In order to avoid dramatic increases, it is necessary to include the consumers in the energy transition process so that they are flexibility providers and that they can make revenue from providing the flexibility services. However, it is necessary to create proper regulatory and market mechanisms to enable such features. The technology for enabling such possibilities is already available as demonstrated on many research and innovation projects (e.g. [43]), however, it is necessary to invest efforts in the creation of the regulatory frameworks that will help to include consumers in the energy transition towards the decarbonised systems.

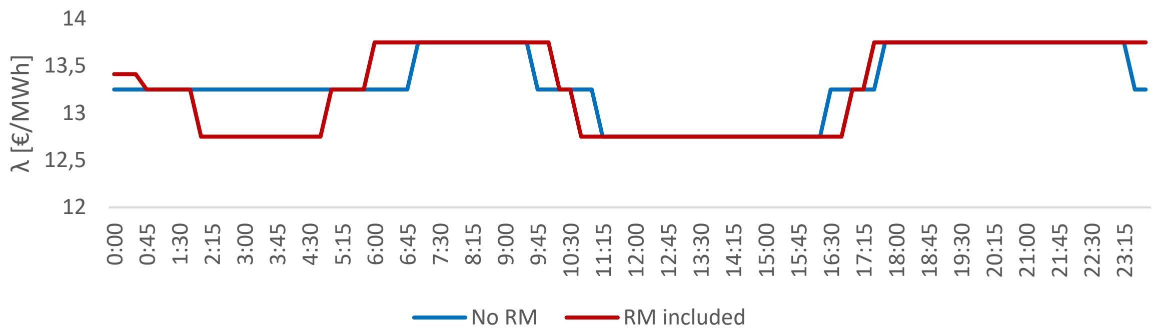


Figure 5. Marginal energy price of the observed system with and without the reserve market under the different robustness levels

Figure 6 and Figure 7 present the dual variables for the up and down reserve constraints. These dual variables represent the marginal cost of the reserve and can only be non-negative. The marginal cost of the reserve was significantly higher for the down reserve than for the up reserve. The more expense controllable generators were mostly operating at their minimum due to the high penetration of the cheaper VRES units. Because of this, generators units were not able to provide the down reserve which means that the reserve requirements had to be met with the ESS and DR units. Although ESS units offer cheaper reserve, their capacity was not sufficient and the DR units have to be occupied for the provision of the reserve which resulted in a higher marginal cost of down reserve. This result is in line with other studies that showed that the down reserve will be more expensive than the up reserve and this is more detailly elaborated in the Discussion section.

Another finding of the paper revealed that the price of the reserve increased for more pessimistic scenarios (Figure 6 and Figure 7). For more pessimistic scenarios ($\Gamma \geq 0.5$), a sharp increase in up reserve price can be seen. The increase in marginal price occurred as the increased demand caused that units with more expensive up reserve had to provide it for that particular period.

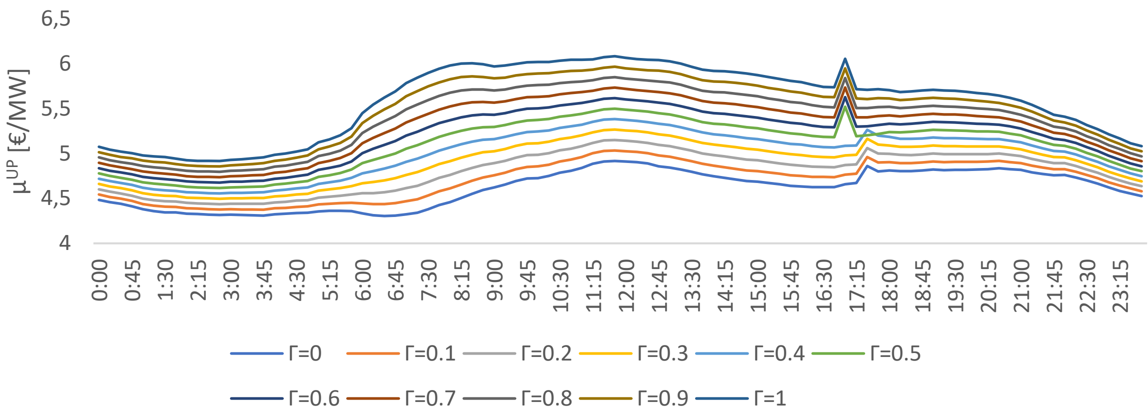


Figure 6. The marginal cost of upper reserve provision for different robustness levels

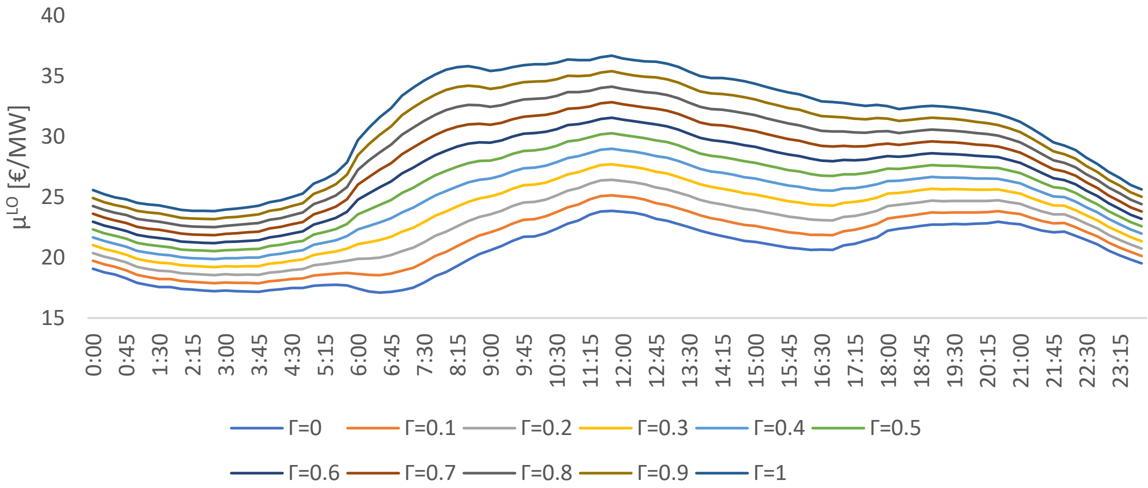
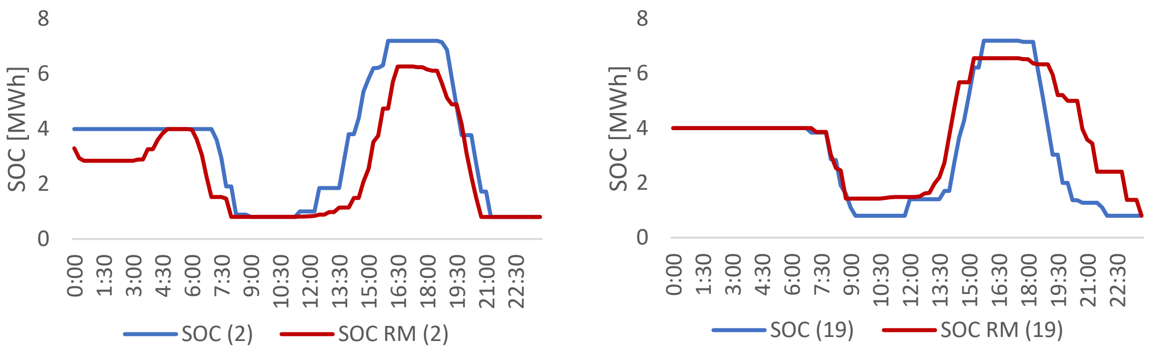


Figure 7. The marginal cost of lower reserve provision for different robustness levels

The ESS operation differs for models with and without the reserve market. Moreover, the presented spatially distributed model enables the observation of ESS units in different locations (Figure 8). This result showed that the inclusion of the reserve market in the modelling of the energy system would change the operating regime of the system as well. This means that many studies that deal with energy systems would produce different results if the reserve constraints were not neglected (e.g. [7-17]). The ESS operated differently when RM was considered as part of its capacity was preserved in order to be able to offer cheaper up reserve.



(a) (b)

Figure 8. ESS operation at node 1 (a) and node 12 (b) for cases when the reserve market is considered (red line) and when the reserve market is not considered (blue line)

Figure 9 and Figure 10 show the overall system operation for cases with and without the RM for conservativeness factor 0.5. For the case without the RM, the DR was activated only for the marginal cases because of its' high marginal cost. The DR was not activated for the model with the reserve market because it is the marginal reserve provider. This result also showed that the model used the DR retrieval (increased demand) and charged battery during the periods of high wind and solar production. This indicates the need for flexible technologies in the systems with high VRES share.

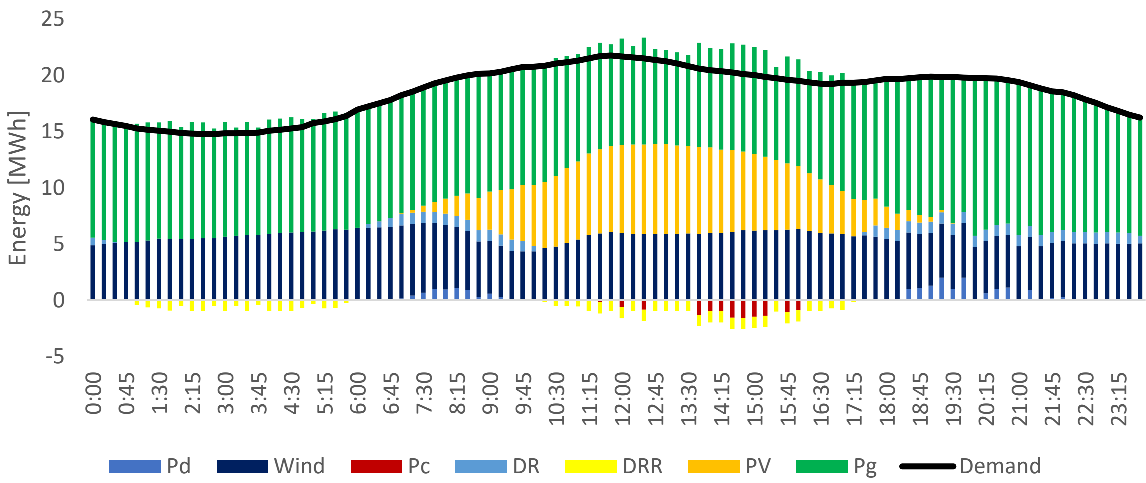


Figure 9. Energy system operation without the reserve market

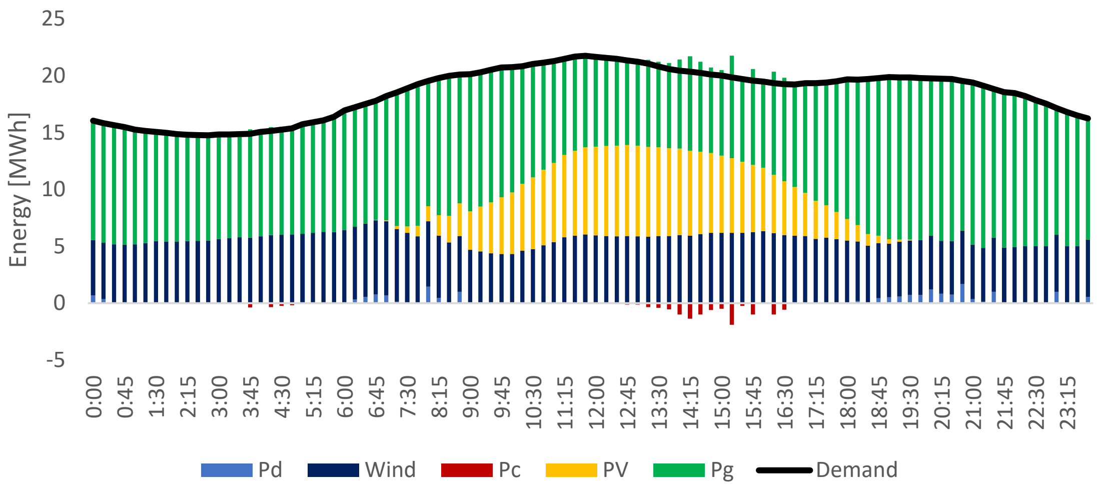


Figure 10. Energy system operation with the reserve market and conservativeness factor 0.5

4.2.Sensitivity analysis – different installed amounts of VOIE

The operation of the system was observed for three different levels of VRES installed power. The operation cost of the system was the highest for the case with the lowest share of VRES (Figure 11). This result was expected as the VRES are the cheapest units in the system although they create additional reserve requirements. Moreover, a higher share of VRES results in lower operation cost. The difference between the operation cost of the high VRES scenario (k=1.5) and the original scenario (k=1) was 15.2% for lowest demand (Γ=0) and it was 13.53% for the highest demand value (Γ=1). The results indicate that the share of VRES had a higher influence on the operation cost of the system than the demand uncertainty.

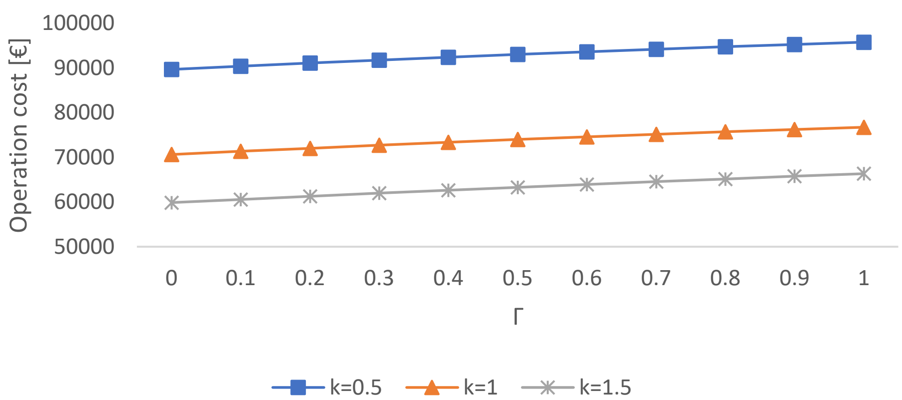


Figure 11. The operation cost of the power system for three different levels of VRES under the demand uncertainty

Another important finding of this study was that the ESS and the DR achieved significantly higher revenues when they were included in the RM. Figure 12 illustrates this result. It can be observed that the revenue increase from the reserve provision is more significant for the increase in the demand uncertainty than for the increase of VRES share. This is especially visible for the DR where the share of VRES did not significantly affect the revenue from the reserve provision. This result indicates that there is a need for sooner development of the reserve markets and the inclusion of the ESS and the DR as they can successfully contribute to the system operation even with the lower share of VRES. Additionally, frameworks that would enable the DR participation in the reserve markets would accelerate the inclusion of the citizens in the energy transition, which is one of the EU objectives.

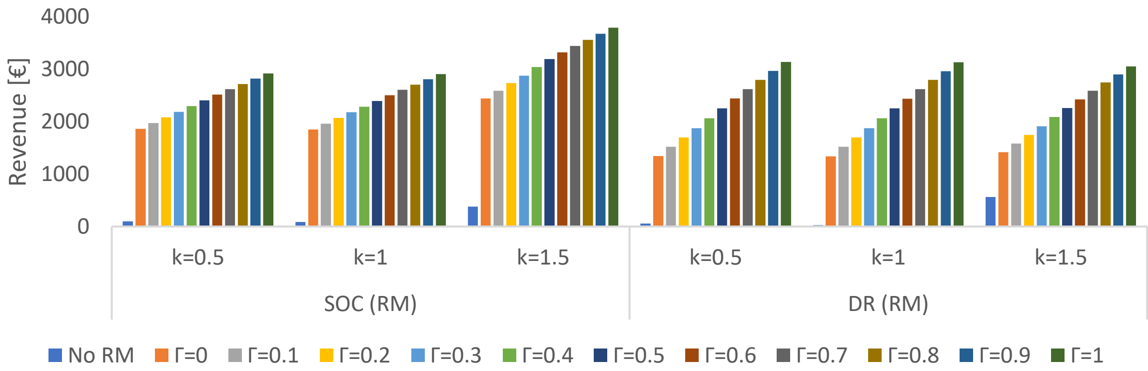


Figure 12. Energy storage and DR revenue from participation on the electric energy market and the reserve market under the demand uncertainty for different VRES levels

A complete schedule for reserve provision is provided in Figure 13 for the highest amount of VRES. It can be observed that the marginal reserve provider for the down reserve was the DR during most of the observed period. The up reserve is provided mostly from the ESS except for nine time periods (two hours and fifteen minutes) when the conventional generators participated in the reserve provision as well. The amount of required reserve does not change significantly for different periods which was expected because this was a direct consequence of the equations (19) and (20).

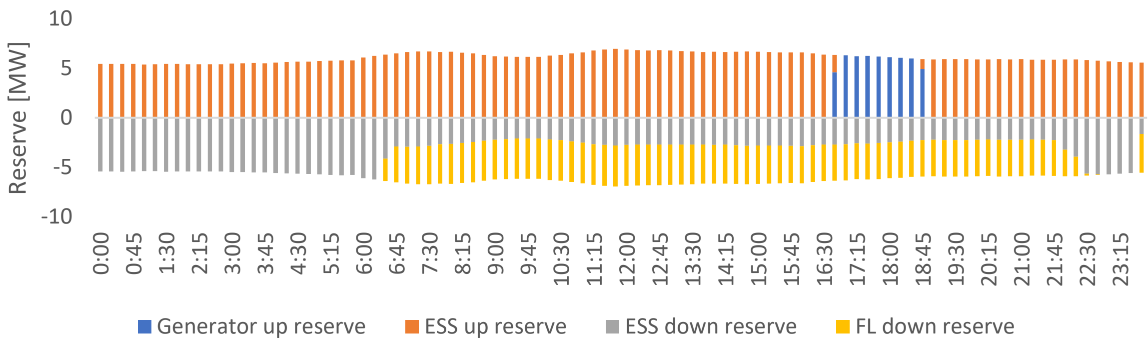


Figure 13. The reserve schedule for the observed period (k=1.5)

A detailed operation of the ESS in node 1 is provided in Figure 14. Interestingly, the ESS operation differs significantly for the different VRES shares. The SOC of the ESS was higher on average for the higher VRES share because there was a higher need for a down reserve. The upper reserve was provided mostly from the ESS because it can provide the cheapest reserve in comparison with the conventional generators and the DR.

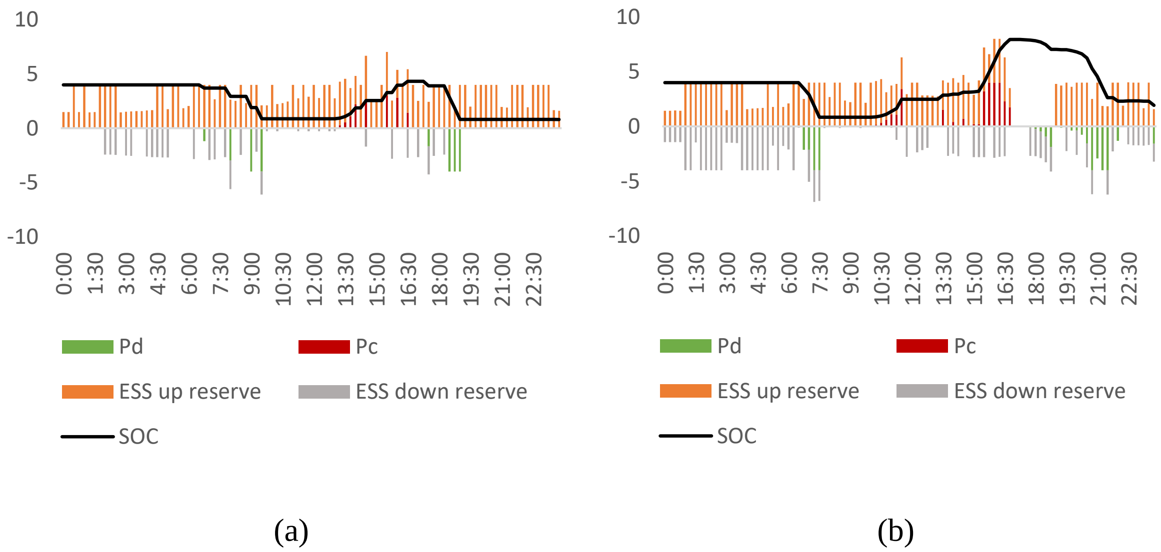


Figure 14. Battery storage operation in node 1 for different VRES shares k=0.5 (a) and k=1.5 (b) where SOC is measured in MWh and other parameters in MW

5. Discussion

One of the main objectives of this paper was to quantify the differences in power system modelling with and without the reserve market. There were three key findings of this study.

Firstly, the results showed that the inclusion of advanced technology such as the ESS and the DR in the reserve market resulted in significantly increased revenues for these stakeholders regardless of the VRES share in the system. Secondly, the proposed approach that incorporated the reserve market modelling resulted in significantly different operating parameters of the system. Finally, the results indicate the need for the development of legal and financial frameworks for the development of the reserve markets and the inclusion of different stakeholders in these markets.

To the best of the knowledge of the authors of this paper, the most extensive study on power system operation under reserve constraints was carried out in [44]. The authors found that 70% of the reserve was provided by the ESS while the marginal reserve provider for the observed period was flexible load and supplied 10% of the reserve. In this study, 69% of the overall reserve was provided by the ESS (for the Γ=0.5). However, the share of flexible demand in the overall reserve was 29% which is slightly different from the findings in [44].

The relation between the electric energy market and the reserve market in the high VRES share was investigated in [45]. The authors found that the total operation cost of the system changed between 2% and 2.5% when the PV share changed from 0-30%. The results of this study showed that the increase of VRES (PV and wind) for 50% (between k = 1 and k= 1.5 scenarios) would result in 15.2% - 13.53% lower operation cost depending on the level of conservativeness. This study also showed that the decrease of operation cost was more significant between the low share VRES scenario (k = 0.5) and original scenario (k =1) than between high VRES (k = 1.5) and the original scenario. The operation cost was 21.2% lesser for the original scenario in comparison to the low VRES share scenario for the most optimistic case. This indicates that the integration of VRES in the systems with a low share of VRES would have a greater effect on the operation cost reduction than in the systems with a higher VRES share.

The changes that occurred in the operation of the observed system indicate the need for more detailed modelling of the energy systems. Current studies that offered different possibilities for the DR provision by the integration of different sectors (e.g. [46] for transport and electricity, [47] for water and electricity) illustrated the benefits of these technologies. However, the results from these studies could be expanded by applying the model from this paper. According to the results from this study, the DR technology can achieve significantly higher revenue from participation in the reserve market than in the electric energy market. This is partially related to the fact that the price of the down reserve, provided only from ESS and the DR, is significantly higher than the upper reserve. This finding underlined the results of another study [48] that showed that the price of the down reserve can reach 93 €/MWh. The findings of this paper indicate the need for down reserve in future power systems with a high VRES share.

Moreover, this study showed that the ESS and DR achieve significantly higher revenues when they are allowed to provide the reserve. This is a valuable finding as it suggested that the inclusion of the ESS and DR on the reserve market is beneficial for all three stakeholders – ESS, DR as well as TSO. ESS and DR would be able to generate additional profit, while the TSO would have additional reserve providers.

One could argue that different reserve requirements that are dependable from one TSO to another would influence the final results of this study. Although this is a reasonable argument there are at least two reasons why this does not affect the key message of this study. First, the proposed method can be applied to any zone controlled by any TSO because the reserve requirements parameters can easily be changed. This allows any interested party can obtain its results. Second, the reserve requirements in the analysed case were set to a low value. Higher values of reserve would only increase the revenues from the reserve market, further emphasizing the findings of this study. Thus, it can be concluded that the system would operate similarly under different reserve requirements with ESS and flexible loads being significant reserve providers.

There are several limitations present in this study. Although this study introduced up and down reserve, additional types of the reserve were not considered. It can also be expected that the future energy system will be highly interconnected. This implicates that additional means of flexibility will emerge from the integration of an electric system with transport, heating, water system etc. Thus, there will be a possibility for reserve provision from a diverse spectrum of stakeholders. The representation of these stakeholders would require a more detailed model.

Finally, this study contributes to the understanding of the advanced technology role in future energy systems. The study underlines the necessity for the creation of the proper framework for the development of the reserve market, for the inclusion of the citizens in the electric energy and reserve markets and the more detailed energy and power system models.

6. Conclusion

This paper presented a novel method for the evaluation of the energy models that include the reserve market in comparison to the models without the reserve. The results of the study revealed significant differences in the two modelling approaches. Inclusion of the reserve constraints caused changes in the operating parameters of the system, marginal cost of electric energy production and revenues of the stakeholders in the system. The key findings of the study can be summarized as follows:

- The operation cost of the system increased by 16 836 € for the most pessimistic scenario with reserve market included in comparison to the scenario without the reserve market.
- The marginal cost of electric energy changed as a result of the inclusion of the reserve constraints
- The marginal cost of the down reserve was significantly higher than the marginal cost of the up reserve for all levels of VRES share in the system, which leads to the conclusion that there will be higher requirements for the down reserve units in the future due to the high excess production from the VRES
- The results showed that the revenue of ESS and flexible loads was significantly higher when they were allowed to participate in the reserve market. This indicates the need for the development of the reserve markets and the benefits of inclusion of the ESS and flexible load in the reserve market.

Future research will include more detailed modelling of different types of the reserve. It can also be expected that there will be requirements for a certain amount of inertia in future power systems with a high share of variable renewable energy sources. The inclusion of such requirements will also be a part of future research.

Acknowledgement

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Nomenclature

Sets

$\mathcal{N}$	Set of nodes
$\mathcal{E}$	Set of edges
$\mathcal{R}$	Set of regular generators
$\mathcal{W}$	Set of wind power plants
$\mathcal{S}$	Set of PV power plants
$\mathcal{G}$	Set of all production units
$\mathcal{L}$	Set of loads
$\mathcal{B}$	Set of ESS
$\mathcal{V}$	Set of flexible loads
$\mathcal{T}$	Set of observed periods

Variables

$p_{i,t}^{G}$	Production from generators at node *i* at time *t* [MW]
$LS_{i,t}$	Load shedding value [MW]
$p_{i,t}^{curt}$	Curtailed power [MW]
$p_{ij,t}$	Power flow from node *i* to node *j*
$p_{i,t}^{d}, p_{i,t}^{c}$	Discharge and charge power from the ESS [MW]
$soc_{i,t}$	State of charge of the ESS[MWh]
$p_{i,t}^{drr}, p_{i,t}^{dr}$	Demand response retrieval and demand response power [MW]
$\delta_{i,t}$	Voltage angle at node *i* [rad]
$y_{i,t}$, $z_{i,t}$	Binary variables for ESS and flexible load
$r_{i,t}^{UP}, r_{i,t}^{DO}$	Up and down reserve at node *i* and time *t* [MW]
$\lambda_{i,t}$	The dual variable of the power balance equation
$\mu_{t}^{UP}, \mu_{t}^{DO}$	Dual variable of up and down reserve requirements equation

Parameters/notations

Δt	Difference between the two periods [h]
f	Objective function
b_i	The marginal cost of energy production [€/MWh]
$VOLL$	Value of lost load [€/MWh]
CE	Curtailed energy value [€/MWh]
X_{ij}	Reactance between node *i* and node *j* [p.u.]
S_{base}	Base power [MVA]
U_n	Nominal voltage [kV]
P_i^{min}, P_i^{max}	Minimum and maximum generator *i* power [MW]
RU_i, RD_i	Ramp-up and ramp-down values of the generator *i* [MW]
k	Sensitivity parameter related to the share of VRES
$\Lambda_{i,t}^{W}, \Lambda_{i,t}^{S}$	Forecasted wind and PV production [MW]
P_{ij}^{max}	Maximum power from node *i* to *j* [MW]
η_i^c, η_i^d	Charging and discharging efficiency of ESS
SOC_i^{min}, SOC_i^{max}	Minimum and maximum state of charge of ESS [MWh]
P_i^{c-MAX}, P_i^{d-MAX}	Maximum charging and discharging power of ESS [MW]
$DR_{i,t}^{max}$, $DRR_{i,t}^{max}$	Maximum demand response and demand response retrieval [MW]
b_i^{UP}, b_i^{DO}	The marginal cost of up and down reserve [€/MWh]
J_L^{UP}, J_L^{DO}	Reserve requirements parameters concerning current demand in the system
J_W^{UP}, J_W^{DO}	Reserve requirements parameters concerning wind production
J_S^{UP}, J_S^{DO}	Reserve requirements parameters concerning PV production
R_i^{UP-MIN}, R_i^{UP-MAX}	Minimum and maximum up reserve values of generators [MW]
R_i^{DO-MIN}, R_i^{DO-MAX}	Minimum and maximum down reserve values of generators [MW]

$\widetilde{L_{\iota,t}}$	Uncertain load variable	Γ_i	Conservativeness factor
φ_{ij}, σ_i	Auxiliary variables	R_i^{ESS}, R_i^{DR}	Revenues of ESS and flexible loads [€]

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