# A Two-Stage Stochastic Unit-Commitment Formulation for Evaluating the Impact of Battery Energy Storage Systems on Reserve Requirements

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**Abstract**

In this paper, a suitable problem formulation is proposed to evaluate the effect of battery energy storage systems (BESSs) in reducing the reserve requirements of the power system. The problem is formulated as a two-stage stochastic unit-commitment problem. In the first stage, the commitment decisions, the energy dispatch and the reserve capacity needs are determined, while the second stage includes decisions that correspond to the real-time operation. The proposed optimization formulation follows a probabilistic approach and estimates the day-ahead reserve requirements that minimize the expected cost based on the uncertainty of renewable energy sources (RESs) generation. Moreover, the upward and downward regulation required to keep balance in the system are integrated for each scenario. To validate the proposed methodology, the updated version of the IEEE RTS 24-bus system for electricity market and power system operation studies is considered. As input data for the simulation, hourly time series provided by the Hellenic Transmission System Operator (TSO) are used to obtain realistic profiles for the RESs generation. An overall reduction in operational cost close to 2% was observed. Moreover, a significant reduction of over 20% was observed in reserve requirements. The results, therefore, indicate that BESSs installation can reduce reserve requirements by mitigating the deviation between forecasted and actual RESs generation.

## 1 Introduction

Achieving a certain percentage of renewable energy sources (RESs) integration into the power system is one of the primary goals in the electricity sector. However, electricity generation from RESs is constrained by their varying availability and uncertainty. In turn, this compels system operators to increase the reserve requirements in order to ensure sufficient balance between generation and demand in real-time, which in turn significantly increases overall cost of the power system [1, 2]. Battery energy storage systems (BESSs) with efficient controllers in RESs substations can provide flexible regulation and power management services to the system operators and therefore improve RESs energy share, shift RESs energy output and smooth RESs output [3, 4].

Different studies have been reported in the literature that consider BESSs for improving the operation of power systems. In [5], a reserve control level is proposed to be added in the conventional load-frequency control architecture to provide frequency support to disturbance-affected areas with the help of a set of BESS units available reserve capacity. In [6] a new methodology is proposed based on dynamic grid response and various BESS response characteristics to optimise the fast frequency response reserves and prevent the frequency from breaching the under-frequency load shedding thresholds. In [7] a novel framework and mathematical model are proposed for simultaneously procuring primary regulation and secondary regulation reserves alongside energy, in a BESS integrated, locational marginal price based real-time market. The study in [8] proposes a novel BESS operational cost model considering degradation cost, based on depth of discharge and discharge rate. The model is developed considering Lithium-ion batteries, and the approach can be applied to other conventional electrochemical batteries. The work in [9] proposes a power curve optimization strategy for RESs considering self-owned BESSs. The case study demonstrates that the dynamic setting method of assessment indicators can increase the revenue of RESs while ensuring that the penalty fees paid by RESs to the grid are sufficient to cover the reserve resource costs. Additionally, the power curve optimization strategy can help RESs further increase income and fully utilize BESSs to reduce power deviation. In [10] a control strategy to regulate the BESS output power is then proposed. It is shown that the frequency control action offered by the BESS complements amicably with that of conventional generators in enhancing the frequency regulation attribute of the grid system. In [11] a distributed optimization algorithm is developed with adaptive learning rates for the allocation of the ramping reserve. The algorithm restores a larger learning rate for compliance with the ramping needs upon detecting a potentially destabilizing event. Other works can be found in studies [12–17].

In this paper, a suitable problem formulation is proposed to evaluate the effect of BESSs in reducing the reserve requirements of the power system. The problem is formulated as a two-stage stochastic unit-commitment problem. In the first stage, the energy dispatch and the reserve capacity needs are determined, while the second stage includes decisions that correspond to the real-time operation. The proposed optimization formulation follows a scenario-based approach and estimates the day-ahead reserve requirements that minimize the overall cost, based on the uncertainty of RESs generation. Moreover, the upward and downward regulation required to keep balance in the system are integrated for each scenario. Additionally, loss of load and RESs curtailment are integrated in the objective function. Loss of load is taken explicitly into consideration into the optimization problem, by assuming high cost. The same applies for curtailment of RESs generation, thus ensuring that the optimization problem tries to maximize RESs generation.

To validate the proposed methodology, the updated version of the IEEE RTS 24-bus system for electricity market and power system operation studies is considered. As input data for the simulation, hourly time series provided by the Hellenic Transmission System Operator (TSO) are used to obtain realistic profiles for the RESs generation. The data was scaled appropriately to fit the network characteristics. Subsequently, different RESs scenarios generation were taken into account to integrate the effect of forecasting errors in the RESs generation. It is considered that BESSs are installed in all RESs substations, equal to 10% of the plant's nominal capacity. Moreover, the upward and downward regulation required to keep balance in the system for each scenario are estimated. From the analysis, an overall reduction in operational cost close to 2% was observed and a significant reduction of over 20% was observed in reserve requirements. In fact, this reduction in reserves is the main reason for the overall cost reduction. Our results, therefore, indicate the notion that BESSs installation can reduce reserve requirements by mitigating the deviation between forecasted and actual RESs generation.

Overall, the contribution of the paper can be summarized in the following: a) a mathematical approach is proposed to evaluate the effect of BESSs in the reserve requirements considering uncertainty on RESs power generation; b) the proposed approach was evaluated on the benchmark model of the updated version of the IEEE RTS 24-bus system in which realistic profiles for the RESs generation provided by the Hellenic TSO were utilized, thus obtaining more reliable and realistic results; c) since the increasing penetration of RESs in the system is expected to increase the need for reserves in the near future, it is examined how BESSs can contribute to reduce the reserve requirements of the system.

# 2 Methodology

In this section we provide a brief description of the two-stage stochastic unit commitment problem and the constraints included in this study. The problem is formulated as a mixed integer linear program. The objective is to minimize the total generation cost of the system and calculate reserve requirements given the uncertainty in the RESs generation forecast. The objective function which minimizes the total cost of operation is formulated as following:

$$\begin{aligned} &\underbrace{min \sum_{g\epsilon G}\sum_{t\epsilon T}(SU_{gt}v_{gt} + SD_{gt}w_{gt} + C_g P_{gt} +}_{Day-ahead} \\ &\underbrace{C_g^{RU}R_{gt}^U + C_g^{RD}R_{gt}^D) +}_{Day-ahead} \\ &\underbrace{\sum_{\xi\epsilon\Xi} prob^{\xi}(\sum_{g\epsilon G}\sum_{t\epsilon T}\left(C_g^U r_{gt}^{U,\xi} - C_g^D r_{gt}^{D,\xi}\right) +}_{Balancing} \\ &\underbrace{VoLL\sum_{i\epsilon I}\sum_{t\epsilon T}\left(L_{it}^{\xi} + W_{it}^{spill,\xi}\right))}_{Balancing} \end{aligned} \tag{1}$$

The first part of the objective function (1) refers to the day-ahead scheduling with $G$ denoting the set of available generators, $T$ the length of the generation planning horizon, $SU_{gt}$ and $SD_{gt}$ are the start-up and shut-down costs of unit $g$ at time $t$, $v_{gt}$ and $w_{gt}$ are binary variables that indicate the start-up or shut-down actions of unit $g$ at time $t$, $C_g$ is a coefficient for power, $P_{gt}$ is the power generation output of unit $g$ at time $t$, $C_g^{RU}$ and $C_g^{RD}$ are coefficients for the upward and downward reserve of generator $g$, respectively, while $R_{gt}^U$ and $R_{gt}^D$ correspond to the upward and downward reserve capacity of the same unit.

The second part of the cost function (1) refers to the balancing scheduling, which means adjustments that are being made closer to the real time after the uncertainty is realized for each scenario. For this purpose, different scenarios $\xi$ are being considered with $\Xi$ denoting the set of all scenarios that are involved, $i$ is the bus with $I$ the set of buses, the terms $C_g^U$ and $C_g^D$ represent coefficients of generator $g$ for upward and downward regulation, respectively, and $r_{gt}^{U,\xi}$ and $r_{gt}^{D,\xi}$ are the upward and downward regulation of unit $g$ at time $t$ under scenario $\xi$, $VoLL$ is considered the value of loss of load as well as RESs curtailment, $L_{it}^{\xi}$ is the load shedding loss at time $t$ in scenario $\xi$ at bus $i$, and $W_{it}^{spill,\xi}$ is the amount of the curtailed RESs generation at time $t$ in scenario $\xi$ at bus $i$.

## 2.1 Unit Commitment Constraints

The following equations (2) and (3) represent the constraints that affect the unit commitment decision. In particular, the minimum ON and OFF time constraints are given by:

$$u_{gt} - u_{g(t-1)} \leq u_{g\tau} \ \forall g\epsilon G, t\epsilon T, \tau = t,..,min\{t + L_g - 1, T\} \tag{2}$$

$$u_{g(t-1)} - u_{gt} \leq 1 - u_{g\tau} \ \forall g\epsilon G, t\epsilon T, \tau = t,..,min\{t + l_g - 1, T\} \tag{3}$$

where $u_{gt}$ represents the commitment decisions, parameter $\tau$ is the corresponding time period starting from time $t$ and limited by either the minimum time that generator $g$ should be up ($L_g$) or down ($l_g$) or the length of the generation planning horizon ($T$).

The start-up and shut-down action constraints can be expressed by the following equations (4) and (5):

$$v_{gt} \geq u_{gt} - u_{g(t-1)} \ \forall g\epsilon G, t\epsilon T \tag{4}$$

$$w_{gt} \geq -u_{gt} + u_{g(t-1)} \ \forall g\epsilon G, t\epsilon T \tag{5}$$

The level of generation and reserve provided by each unit is determined by the following constraints $\forall g\epsilon G, t\epsilon T, i\epsilon I$, which denote generator $g$, at timestep $t$, at $i$ bus:

$$\sum_{g\epsilon G} P_{gt} + \sum_{i\epsilon I} W_{it}^{S} \geq \sum_{i\epsilon I} D_{it} \; \forall g\epsilon G, t\epsilon T, i\epsilon I \tag{6}$$

$$P_g^{min} u_{gt} \leq P_{gt} \leq P_g^{max} u_{gt} \; \forall g\epsilon G, t\epsilon T \tag{7}$$

$$P_{gt} \geq 0 \; \forall g\epsilon G, t\epsilon T \tag{8}$$

$$P_{gt} - P_{g(t-1)} \leq P_g^{min}\left(2 - u_{gt} - u_{g(t-1)}\right) + RU_g\left(1 + u_{g(t-1)} - u_{gt}\right) \; \forall g\epsilon G, t\epsilon T \tag{9}$$

$$P_{g(t-1)} - P_{gt} \leq P_g^{min}\left(2 - u_{gt} - u_{g(t-1)}\right) + RD_g\left(1 - u_{g(t-1)} + u_{gt}\right) \; \forall g\epsilon G, t\epsilon T \tag{10}$$

Equation (6) denotes the system-wide constraint that generation ($\sum_{g\epsilon G} P_{gt}$) must equal demand ($\sum_{i\epsilon I} D_{it}$), given the scheduled RESs generation ($\sum_{i\epsilon I} W_{it}^{S}$). Equations (7) and (8) constrain the power generation to acceptable limits, where $P_g^{\max}$ and $P_g^{\min}$ are the maximum and the minimum power generation for unit $g$, respectively. Equations (9) and (10) concern the upward and downward ramping rate of each generator, where $RU_g$ and $RD_g$ is the upward or downward ramping limit, respectively .

For the reserve requirements the following constraints (11) and (12) must hold true:

$$R_{gt}^{U} + P_{gt} \leq P_g^{\max} \quad \forall g \in G, t \in T \tag{11}$$

$$P_{gt} - R_{gt}^{D} \geq P_g^{\min} \quad \forall g \in G, t \in T \tag{12}$$

According to this set of equations (11) and (12), the generator can provide upward reserve capacity ($R_{gt}^{U}$) such that the sum of this capacity with the actual power generation does not exceed the unit's maximum power generation ($P_g^{\max}$) and downward reserve capacity ($R_{gt}^{D}$) up to the point to which the capacity would be deducted from the actual power to still be equal or higher than the unit's minimum power generation ($P_g^{\min}$).

In this study, transmission network constraints are also considered, by assuming a DC approximation of the power flow. Specifically for day-ahead dispatch:

$$\sum_{(i,j)\epsilon A_i^+} f_{ijt}^{S} - \sum_{(i,j)\epsilon A_i^-} f_{jit}^{S} \geq \sum_{g\epsilon G_i} P_{gt} + W_{it}^{S} - D_{it} \; \forall (i,j)\, \epsilon A_i, g \in G, t\epsilon T, i\epsilon I \tag{13}$$

$$-F_{ij}^{max} \leq f_{ijt}^{S} \leq F_{ij}^{max} \; \forall (i,j)\, \epsilon A_i, t\epsilon T, i\epsilon I \tag{14}$$

where $f_{ijt}^{S}$ is the scheduled bidirectional flow between bus $i$ and $j$, at time $t$, $A_i^+$ the set of flow starting at bus $i$, $A_i^-$ is the set of flow ending at bus $i$, $G_i$ the set of generators at bus $i$ and $F_{ij}^{max}$ is the transmission flow limit between bus $i$ and $j$.

For each node at the system, as seen in Equation (13), we consider the generating power and forecast net load. The power flow between two nodes are constrained by the transmission line capacities (14).

Finally, Equation (15) below is an approximation of Kirchhoff's voltage law:

$$\left(f_{ijt}^{S} - f_{jit}^{S}\right) = B_{ij}\left(\beta_{it}^{S} - \beta_{jt}^{S}\right) \; \forall (i,j)\, \epsilon A_i, t\epsilon T, i\epsilon I \tag{15}$$

where $B_{ij}$ is the susceptance of transmission line $(i,j)$ and $\beta_{it}^{S}$ is the phase angle at interconnected bus $i$.

## 2.2 Real-Time Balancing Constraints

After the day-ahead dispatch is scheduled, generators offer upward and downward regulation in order to ensure real-time balancing for each scenario. The real-time decision variables are subject to the following constraints which provide the upward and downward boundaries:

$$r_{gt}^{U,\xi} \leq R_{gt}^{U} \; \forall g\epsilon G, t\epsilon T, \xi\epsilon \Xi \tag{16}$$

$$r_{gt}^{D,\xi} \leq R_{gt}^{D} \; \forall g\epsilon G, t\epsilon T, \xi\epsilon \Xi \tag{17}$$

$$L_{it}^{shed,\xi} \leq D_{it} \; \forall t\epsilon T, \xi\epsilon \Xi, i\epsilon I \tag{18}$$

$$W_{it}^{spill,\xi} \leq W_{it}^{\xi} \; \forall t\epsilon T, \xi\epsilon \Xi, i\epsilon I \tag{19}$$

$$r_{gt}^{U,\xi}, r_{gt}^{D,\xi}, L_{it}^{shed,\xi}, W_{it}^{spill,\xi} \geq 0 \; \forall g\epsilon G, t\epsilon T, \xi\epsilon \Xi, i\epsilon I \tag{20}$$

The balancing constraint (21) ensures that the increase or reduction in production from day-ahead scheduling equals to the corresponding change of RESs production:

$$\sum_{g\epsilon G}\left(r_{gt}^{U,\xi} - r_{gt}^{D,\xi}\right) + \sum_{i\epsilon I}\left(L_{it}^{\xi} - W_{it}^{spill,\xi}\right) = \sum_{i\epsilon I}\left(W_{it}^{S} - W_{it}^{\xi}\right) \; \forall g\epsilon G, t\epsilon T, \xi\epsilon \Xi, i\epsilon I \tag{21}$$

The transmission constraints (22) are required again in this balancing stage:

$$\sum_{(i,j)\epsilon A_i^+} f_{ijt}^{\xi} - \sum_{(i,j)\epsilon A_i^-} f_{jit}^{\xi} = \sum_{g\epsilon G_i}\left(r_{gt}^{U,\xi} - r_{gt}^{D,\xi}\right) + L_{it}^{\xi} - W_{it}^{spill,\xi} + W_{it}^{\xi} - W_{it}^{S} \; \forall (i,j)\, \epsilon A_i, g\epsilon G, t\epsilon T, \xi\epsilon \Xi, i\epsilon I \tag{22}$$

Due to the balancing actions that occur, the power flow deviates from the scheduled value, thus we must ensure that the new power flow does not exceed transmission constraints (23):

$$-F_{ij}^{max} \leq f_{ijt}^{S} + f_{ijt}^{\xi} \leq F_{ij}^{max} \; \forall (i,j)\, \epsilon A_i, t\epsilon T, \xi\epsilon \Xi, i\epsilon I \tag{23}$$

## 2.3 BESS Case

The operation of the BESSs requires three variables: $E$ describes the level of storage, $P^d$ the discharging power and $P^c$ the charging power. The following constraints define the BESSs operation:

$$E_{i(t+1)}^{\xi} = E_{it}^{\xi} - P_{it}^{\xi,d} + P_{it}^{\xi.c} \; \forall t\epsilon T, \xi\epsilon \Xi, i\epsilon I \tag{24}$$

For each BESS the boundaries for the variables are set as following:

$$E_{it}^{\xi} \leq E_{max} \; \forall t\epsilon T, \xi\epsilon \Xi, i\epsilon I \tag{25}$$

$$P_{it}^{\xi,d} \leq E_{it}^{\xi} \; \forall t\epsilon T, \xi\epsilon \Xi, i\epsilon I \tag{26}$$

$$P_{it}^{\xi,c} \leq E_{max} - E_{it}^{\xi} \; \forall t\epsilon T, \xi\epsilon\Xi, i\epsilon I \tag{27}$$

$$E_{it}^{\xi}, P_{it}^{\xi.c}, P_{it}^{\xi,d} \geq 0 \; \forall t\epsilon T, \xi\epsilon\Xi, i\epsilon I \tag{28}$$

The balancing constraint (21) will change in the BESS case to:

$$\sum_{g\epsilon G}\left(r_{gt}^{U,\xi} - r_{gt}^{D,\xi}\right) + \sum_{i\epsilon I}\left(L_{it}^{\xi} - W_{it}^{spill,\xi}\right) = \sum_{i\epsilon I}\left(W_{it}^{S} - W_{it}^{\xi} - P_{it}^{\xi,d} + P_{it}^{\xi.c}\right) \; \forall g\epsilon G, t\epsilon T, \xi\epsilon\Xi, i\epsilon I \tag{29}$$

Subsequently, the transmission constraints are formulated to accommodate for the BESS operation:

$$\sum_{(i,j)\epsilon A_i^+} f_{ijt}^{\xi} - \sum_{(i,j)\epsilon A_i^-} f_{jit}^{\xi} = \sum_{g\epsilon G_i}\left(r_{gt}^{U,\xi} - r_{gt}^{D,\xi}\right) + L_{it}^{\xi} - W_{it}^{spill,\xi} + W_{it}^{\xi} - W_{it}^{S} + P_{it}^{\xi,d} - P_{it}^{\xi.c} \; \forall (i,j)\, \epsilon A_i, g\epsilon G, t\epsilon T, \xi\epsilon\Xi, i\epsilon I \tag{30}$$

The new power flow is subject to the same constraints posed by the line capacity as shown in equation (23).

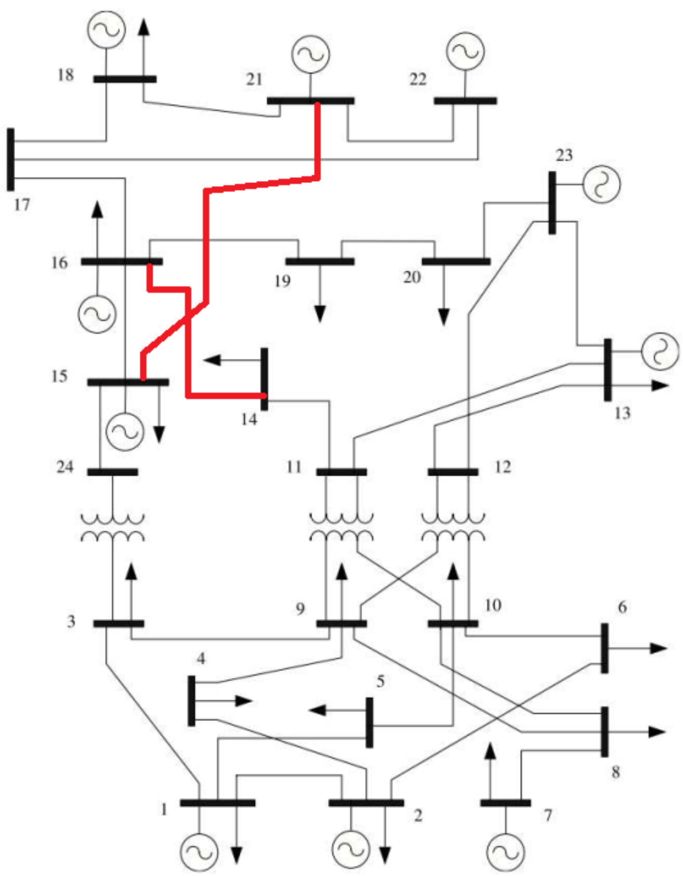


Figure 1: Modified IEEE RTS 24-bus system.

# 3 Test System

We consider the "Updated Version of the IEEE RTS 24-Bus System for Electricity Market and Power System Operation Studies" as the grid configuration [18]. This system is an updated version of the well-known single-area version of the IEEE reliability test system [19] and is proposed in the literature in order to be readily used for electricity market and power system operation studies. Additionally, it is properly modified to accommodate RESs in order to enable the use of the power system in case studies with high renewable energy penetration. Specifically, we identify two main issues with the tested network:

- High RESs penetration, produced by 6 Wind Power Plants of 200MW nominal capacity, located at the load buses.
- Two transmission lines that face congestion issues, namely the line from bus 16 to bus 14 and from bus 15 to bus 21. Both lines are highlighted with red in Figure 1.

These operational issues result in higher overall production cost, as some low cost units cannot reach full capacity due to congestion. Moreover, uncertainty in RESs generation requires higher reserve provision, in order to ensure real-time balance of demand and supply.

As input data for this simulation, we used the hourly time series for one year provided in [19] and wind generation data provided by the Hellenic TSO. Specifically, the time series of aggregated wind generation from 2018 were used, in order to obtain realistic profiles for the RESs generation. The data was scaled appropriately in order to fit the network characteristics. Subsequently, different RESs scenarios generation were considered to integrate the effect of forecasting errors in the RESs generation.

# 4 Results

One year of the system operation is simulated in MATLAB using the YALMIP toolbox [20] and solved with a commercial solver, with hourly resolution, with the system configuration already illustrated. Specifically, in each day, the day-ahead unit-commitment and the economic dispatch optimization problems are solved. For the purpose of this work, we assumed demand is perfectly forecasted and the market operates perfectly, i.e. each generator bids its marginal cost. There is, however, uncertainty to the wind power generation, in order to simulate more realistic network operation. The optimization algorithm is designed in such way in order to co-optimize generation and reserves similar to the current operation of the Hellenic electricity market. Furthermore, real-time rebalancing is considered, with dispatchable plants offering upward and downward regulation after the economic dispatch is issued, in order to maintain supply and demand balance, which stems from the uncertainty of wind generation. That inherent uncertainty requires expensive reserves in order to cope with any sudden changes. In this use case, we aim to evaluate the impact of BESSs in overall cost of the system, mainly by examining their impact on reserve requirements.

We formulate the day-ahead problem as a two-stage stochastic unit-commitment problem [21] with real-time rebalancing, which minimizes total production cost given the expected RESs generation. The optimization problem, therefore, follows a probabilistic approach and estimates the day-ahead reserve requirements that minimize the overall cost, based on the uncertainty of wind. Moreover, the upward and downward regulation required to keep balance in the system are estimated for each scenario.

Additionally, loss of load and RESs curtailment are integrated in the objective function. Loss of load is taken explicitly into consideration into the optimization problem, by assuming high cost. The same applies for curtailment of RESs generation, thus ensuring that the optimization problem tries to maximize RESs generation.

Two cases are tested:

- **Base case:** The network is simulated as is, without any BESSs.

- **BESS case:** In this case, BESSs are installed in all the wind power plants, equal to 10% of the plant's nominal capacity. The batteries are optimized for minimizing the total production cost.

The results of the two tests are presented in the Table 1 and Figure 2. It can be observed that the BESSs deployed, overall, had a positive effect on the system. Specifically:

- An overall reduction in operational cost close to 2% was observed.

- Moreover, a significant reduction of over 20% was observed in reserve requirements. In fact, this reduction in reserves is the main reason for the overall cost reduction.

Our results, therefore, indicate the notion that BESSs installation can reduce reserve requirements, by mitigating the deviation between forecasted and actual RESs generation, and also resolve congestion issues that leads to further reduction of the operational costs since low cost units can reach full capacity.

Table 1: Operational cost and reserves in the use case.

| **Case** | **Operation cost (MEur)** | **Reserves (TWh)** |
|---|---|---|
| **Base Case** | 74.8339 | 1.21593 |
| **BESS Case** | 73.34973 | 0.951087 |

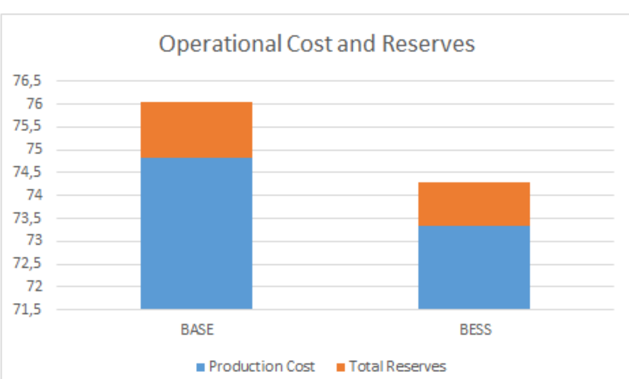


Figure 2: Operational cost and reserves of the use case.

# 5 Conclusion

In this paper, an appropriate mathematical approach was proposed to evaluate the effect of BESSs in the reserve requirements when considering uncertainty on RESs generation. The proposed method was tested in the updated version of the IEEE RTS 24-bus system for electricity market and power system operation studies. An overall reduction in operational cost close to 2% was observed. Moreover, a significant reduction of over 20% was observed in reserve requirements. The proposed methodology, therefore, showcases how BESSs can be exploited to reduce reserve requirements by mitigating the deviation between forecasted and actual RESs generation and also to resolve congestion issues.

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