Received: 23 June 2023 | Revised: 10 January 2024 | Accepted: 12 February 2024

IET Renewable Power Generation

DOI: 10.1049/rpg2.12970

The Institution of Engineering and Technology WILEY

ORIGINAL RESEARCH

Optimal sizing of battery energy storage system for a large-scale offshore wind power plant considering grid code constraints: A Turkish case study

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Funding information
Danish International Development Agency, Grant/Award Number: 19-M03-AAU; Türkiye Bilimsel ve Teknolojik Araştirma Kurumu

Abstract

Integration of large-scale wind farms (WFs) into the grid has to meet the critical constraints set in the national grid code. Wind farm operators (WFOs) are inclined to comply with these constraints and avoid heavy penalty costs for violating such regulations. However, this may result in reduced power sent to the grid. Moreover, the addition of new rules to account for the increased penetration of WFs brings challenges to the profitability of the WFs. A battery energy storage system (BESS), if sized optimally, can be a reliable method to fulfill the grid code requirements without sacrificing profit. This paper provides a techno-economic model to find the optimal rated capacity and power for a BESS in WFs. This optimization model takes the absolute production and delta production constraints into account. Two approaches are studied for integrating these constraints into the grid code. It is shown that the flexible strategy financially outperforms the strict addition of the new rules. This will be useful, especially to attract investments in wind energy projects despite the abovementioned limitations in the grid code. All the modeling and analysis are done for a potential offshore wind power plant (OWPP) in Turkey. Simulation results show the effectiveness of the optimal BESS in increasing the amount of energy delivered to the grid and improving the profitability of the OWPP.

1 | INTRODUCTION

Turkey has increased its installed wind power capacity from 1.73 GW in 2011 to 10.67 GW in 2021. Accordingly, the share of wind energy in electricity generation has improved from 3.27% to 10.63% [1]. The total energy demand in Turkey is predicted to rise from 324.5 TWh in 2022 to 452.2 TWh by 2031 [2]. Hence, Turkey needs to increase its renewable energy generation capacity even further to meet this demand increase and reduce its carbon emissions [3]. While the total installed wind energy power in Turkey has reached 11.4 GW by the end of 2022 with 358 onshore wind farms [4], Turkey's very first OWPP is yet to be installed [3, 5].

A review of the integration issues specifically for offshore WFs is presented in [6]. Uncertainty is inevitable in wind energy due to its innate variability, which needs to be considered for economically optimal and technically stable operation of power grids [7]. Although uncertainty in small-scale WFs can be ignored, its presence in large-scale WFs can cause serious power quality and power stability problems for the transmission system operator (TSO). Installing auxiliary ESSs for the WFs is one of the proposed methods in the literature to address these challenges [6, 8]. Grid code is a set of rules defined by the responsible legislator for the secure operation of the power system. Violating the grid code requirements could lead to penalties for the power plant operator. In the past, with low shares of wind energy in power systems, the grid code regulations were rather simple for WFs. However, with the accelerated installation of WFs, especially large ones, grid code requirements were updated accordingly. New grid codes required WFs to contribute to grid support actions instead of disconnection.

Frequency support is one of the essential functions for power system stability. Simply put, it requires the total generation to be increased during under-frequency conditions and to decrease the generation during over-frequency periods to create a balance between generation and demand. Frequency support, in this context, is achieved by keeping a certain level of reserve capacity in the power grid. This is commonly provided by conventional power plants since it would negatively affect the financial revenue of WFOs because they would be required to consistently reduce their generation even under normal frequency conditions. However, in the future, WFs are expected to be one of the main components contributing to frequency support due to their faster response times than most traditional power plants [9, 10]. For instance, in Denmark where the penetration level of wind energy is already high, strict requirements are set in the Danish grid code for the output active power of WFs. These include absolute production, delta production, and power gradient constraints. In this paper, the first two requirements are considered and further explained in section 3. Similar requirements exist in the Korean grid code [11, 12]. A comprehensive study on Turkish grid-code requirements for integrating OWPPs is presented in [13].

Studies on the optimal sizing of ESSs for WFs can be found in the literature. Research on optimal BESS for profit maximization of a WF in the day-ahead market for an Italian case study is presented in [14]. In [15], authors have developed a mixed-integer nonlinear model to optimize an ESS for neighboring WFs by considering forecast errors. Optimal sizing and management of an ESS for a South Korean case are studied in [16]. Authors in [17] have optimized a Lithium-ion BESS for WFs considering the costs of auxiliary services, namely peaking and reserve capacity. A control strategy is designed in [18] for offshore WFs coupled with ESSs. The proposed method combines the WF control layer with local controllers of individual wind turbines to achieve higher efficiency and profitability. A framework for optimizing ESS capacity and location in a transmission-constrained network to support WFs is presented in [19]. Optimizing ESS size for inertial support from WFs is studied in [20]. Network constraints, wind generation uncertainty, and conventional unit outages are considered. Optimization of ESSs for WFs considering the Korean grid code is studied in [12]. In [21], authors have optimized a hybrid ESS consisting of batteries and supercapacitors to achieve a smooth output power from the WF according to the 1-min and 10-min ramp rate limits.

It is evident that ESSs are advantageous for WFs. These benefits include but are not limited to reduced power curtailment, increased revenue, inertial support, filtering high-frequency fluctuations, and complying with grid code requirements. Although the BESS technology has matured considerably in the past few years, it is still deemed expensive for utility-scale installations. So, given their positive impacts on the integration of WFs, optimization is needed to find a balance between financial costs and performance enhancements introduced by the BESS. In this paper, a two-layer techno-economic optimization framework is presented. The goal is to find the optimal BESS that increases the annual profit of the WFO by minimizing violations of the grid code constraints on active power defined for the integration of WFs by the TSO.

The contributions of this paper are to demonstrate the impacts of applying flexibility while introducing new rules namely absolute and delta production constraints into the grid code by the Turkish TSO.

With increased penetration of large-scale WFs in the main grid, the Turkish TSO is considering introducing new regulations into the national grid code for the stability and integrity of the grid. However, since offshore wind energy in Turkey is an untouched area, adding new rules will most likely disturb future investments. The new rules under consideration will most likely include limitations on the active power production of the WFs. In other countries with already high levels of wind energy, absolute and delta production constraints are integrated into their grid codes. In this paper, the introduction of these rules into the Turkish grid code is considered. The large-scale BESS technology is analyzed as a viable solution to counteract these constraints. The contributions are to show BESS technology as a viable solution to counteract new regulations while maintaining financial profitability. By analyzing two strategies, namely strict and flexible, it is demonstrated how the inclusion of flexibility in the introduction process of active power constraints can increase the profits of the WFO. The case study is done to advocate for Turkey's very first potential OWPP.

The research presented in this paper is performed in contribution to the Offshore WFs Large-Scale Integration project in Turkey (WindFlag) [22]. In [3], authors have conducted extensive research to identify suitable sites for installing OWPPs in Northwest Turkey, and the Kıyıköy region was introduced as one of the candidates for this purpose. The proposal for Kıyıköy OWPP includes two phases with 60 wind turbines in each. The 15 MW offshore wind turbine reference model from the National Renewable Energy Laboratory (NREL), defined in [23], is considered in this project. So, the Kıyıköy OWPP is aimed to have a 1.8 GW installed power. Integration of the Kıyıköy OWPP into the Turkish grid, mainly considering compliance with grid code requirements related to voltage and frequency, is thoroughly analyzed in [5].

The remainder of this paper is organized as follows: Section 2 provides the wind speed and power data extraction procedure for the Kıyıköy OWPP. The details of selected grid code constraints are described in Section 3. The proposed techno-economic optimization approach is presented in Section 4. Section 5 provides simulation results of the case study and discussions. Finally, Section 6 concludes the paper.

2 | WIND DATA

The chosen wind turbine model for the Kıyıköy OWPP has a hub height of 150 m. Historical wind data with hourly, daily, monthly, and annual temporal resolutions for single point coordinates around the world are available at NASA's Prediction of Worldwide Energy Resources (POWER) Application Programming Interface (API) [24]. Hourly wind speed data for the year 2022 at 50 meters above sea level for the Kıyıköy OWPP coordinates are extracted from the POWER platform.

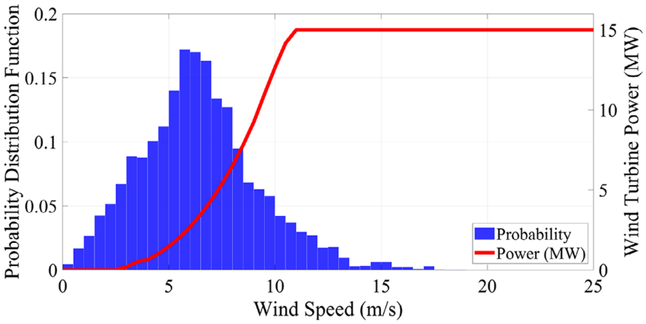

FIGURE 1 Probability distribution function of wind speed in Kıyıköy in the year 2022 and output power curve of an individual 15 MW reference offshore wind turbine.

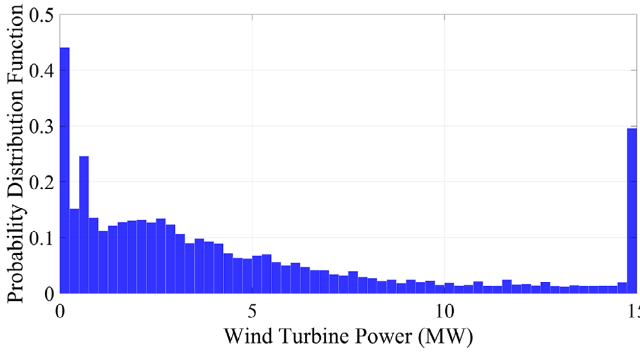

FIGURE 2 Probability distribution function of an individual 15 MW reference offshore wind turbine power in Kıyıköy in the year 2022.

TABLE 1 Parameters of wind speed profile.

Parameter	Value
Maximum wind speed	17 (m/s)
Average wind speed	5.76 (m/s)
Weibull distribution shape parameter	2.422
Weibull distribution scale parameter	6.486 (m/s)

Two mathematical methods can be used to calculate wind speed at an elevation different from the measurement height. These techniques include the logarithmic profile and the power law profile [25]. In this paper, the power law profile method is utilized to find wind speed data at the desired hub height of 150 m. The power law profile equation is shown below [24, 25]:

$$V_w^H = V_w^M \times \left(\frac{h_H}{h_M}\right)^{\alpha}. \tag{1}$$

The wind turbine reference model used in this study has a hub height (h_H) of 150 m, and the wind measurement height (h_M) is 50 m. The surface roughness parameter (α) of the open water surface is taken as 0.1006, according to [24]. The probability distribution of wind speed for the proposed Kıyıköy OWPP location is illustrated in Figure 1. It can be seen that wind speed data follow the Weibull distribution function. Important parameters of the distribution function are listed in Table 1.

The power vs. wind speed curve of the 15 MW reference wind turbine model is plotted in Figure 1. The power output of an individual wind turbine is obtained, and its distribution function is shown in Figure 2.

3 | GRID-CODE CONSTRAINTS ON OUTPUT ACTIVE POWER

Two of the regulations for the active power output of WFs applied in the Danish grid code are explained here [7, 10, 12]. These regulations ensure stable grid operation in terms of supply and demand balance despite uncertainties in wind energy. In addition, they motivate WFOs to adopt solutions that bring stronger contributions to the energy supply chain and, eventually, higher economic returns.

3.1 | Absolute production constraint

As the name suggests, this constraint limits the WF's output power to avoid overloading. The predefined power limit can be set to a constant value for small-scale WFs or grids where the wind energy penetration is small. However, for large-scale WFs, especially those integrated into grids with high wind energy potential, the WF would be required to enter the day-ahead market like any other power plant. In this scenario, the output power limit for every hour should be assigned separately based on the available power. In other words, the output power limit is also the committed power for that specific hour.

Due to the uncertainty in wind energy, the realistically available power from the WF can be higher or lower than the predefined power limit. Without any ESS, curtailment is the only tool for the WFO to decrease the available power to the committed power level. If the available power is below the committed power, the WFO will be fined for the power mismatch. On the contrary, the presence of an ESS allows the WFO to store the extra power and utilize it in periods of lower available power. Hence, it is evident that the installation of ESS can significantly reduce power curtailment and power mismatch, which leads to higher financial profit for the WFO.

In this paper, the absolute production limit or the committed power in each hour is derived from the original hourly wind speed data extracted in the previous section.

3.2 | Delta production constraint

Based on grid code requirements for active power, WFs must hold a certain amount of reserve power while connected to the grid to contribute to the power system stability during emergencies, similar to the spinning reserve in traditional power plants. This constraint is normally defined as a percentage of the output power.

Without any ESS in place, the WFO is forced to constantly decrease the output power. In this way, the required reserve power is kept in the form of a spinning reserve in wind turbine generators. Investing in installing an ESS helps the WFO to fulfill a part of the required reserve power by the energy stored in the ESS. Hence, the output power of the WF and its financial profit increase significantly if the ESS is optimally selected.

4 | TECHNO-ECONOMIC OPTIMIZATION MODEL FOR SIZING OF THE BESS

4.1 | Control methodology

Based on the constraints explained in the previous section, two strategies can be developed for the united operation of OWPP and ESS. In the first strategy, the WFO is expected to deliver the required power based on the committed power, no more and no less. In other words, the absolute production constraint level equals the committed power at each hour. So, any deviation, whether higher or lower than the committed value, is grounds for the penalization of the WFO by the TSO. So, when the total available power from the WF and ESS exceeds the sum of committed output and reserve powers, all of the extra power must be kept as reserves and cannot be injected into the grid as it will surpass the committed output power. This is the strict strategy in this paper.

The second strategy represents a more flexible market environment toward renewable energies. Here, the WFO is charged with fines only if the power delivered to the grid is below the committed output power. Hence, under situations where available energy is more than required, the WFO is permitted by the TSO to inject more power into the grid under the condition that the provided reserve capacity is updated accordingly. Going forward, this strategy will be cited as the flexible strategy.

Needless to say, any shortage of reserve power in either one of the strategies leads to penalties for the WFO.

A block diagram of the proposed techno-economic model is illustrated in Figure 3.

4.2 | Technical algorithm

The inner layer of the two-level techno-economic model consists of a technical algorithm. The proposed mixed-integer nonlinear programming (MINLP) based technical algorithm is developed and presented in Algorithm 1. A nomenclature including definitions of abbreviations and parameters is included in Table 2. Initially, based on the state of charge (SOC) of the BESS and its rated output power, the amounts of powers available for charge and discharge are calculated. Next, the total available power from the OWPP and BESS is obtained. If the available power is more than enough to deliver the committed output power and fulfill the committed reserve power, then the output power can be readily identified as equal to the committed power. However, for the flexible strategy, the committed powers need to be updated beforehand, as shown in Algorithm 1. On the other hand, if the available power is below the sum of committed powers, then optimization is performed to find the optimal output power. The upper and lower limits of the output power are given in Algorithm 1. So, an exhaustive search with a simple loop function is integrated to find the optimal output power that gives the maximum profit at the hour under analysis.

Once the output power is determined, BESS power and SOC are obtained accordingly. Furthermore, provided reserve capacities in the BESS and spinning forms are calculated. Finally, violations in each one of the constraints are assessed.

ALGORITHM 1 The proposed mixed-integer nonlinear algorithm

```
for h = 1 : H do
  P_{B,C}(h) = min{[SOC_{Max} − SOC(h − 1)] × C_{B,R}/(η_C × 100), P_{B,R}/η_C}
  P_{B,D}(h) = Max{[SOC_{min} − SOC(h − 1)] × C_{B,R} × η_D/100, P_{B,R} × η_D}
  P_{Avl}(h) = P_{OWPP}(h) − P_{B,D}(h)
  if P_{Avl}(h) ≥ [P_{Com}(h) + P_{Com−Res}(h)] then
    if Strategy = }}Flexible'' then
      P_{Com}(h) = P_{Avl}(h) × [1/(1 + RR)]
      P_{Com−Res}(h) = P_{Com}(h) × RR
    end if
    P_{Out}(h) = P_{Com}(h)
  else
    Find Optimal Output Power :
    Max[P_{Avl}(h) − P_{Com−Res}(h), 0] ≤ P_{Out}(h) ≤ min[P_{Avl}(h), P_{Com}(h)]
  end if
  if P_{OWPP}(h) ≤ P_{Out}(h) then
    P_B(h) = Max[P_{OWPP}(h) − P_{Out}(h), P_{B,D}(h)]
  else
    P_B(h) = min[P_{OWPP}(h) − P_{Out}(h), P_{B,C}(h)]
  end if
  P_{B−R}(h) = −{P_{B,D}(h) − min[P_B(h), 0]}
  P_{SR}(h) = Max{[P_{OWPP}(h) − P_{Out}(h)], 0}
  if P_B(h) ≥ 0 then
    SOC(h) = SOC(h − 1) + [P_B(h) × η_C/C_{B,R}] × 100
  else
    SOC(h) = SOC(h − 1) + [P_B(h)/(η_D × C_{B,R})] × 100
  end if
  P_{V,AP}(h) = |P_{Com}(h) − P_{Out}(h)|
  P_{V,DP}(h) = Max{P_{Com−Res}(h) − [P_{Avl}(h) − P_{Out}(h)], 0}
end for
```

4.3 | Economic sub-model

The economic sub-model is programmed as the outer layer of techno-economic optimization. The equivalent annualized cost (EAC) method is adopted. EAC takes both capital and maintenance costs into account. The annualized cost of BESS is then calculated by considering the expected lifetime as shown

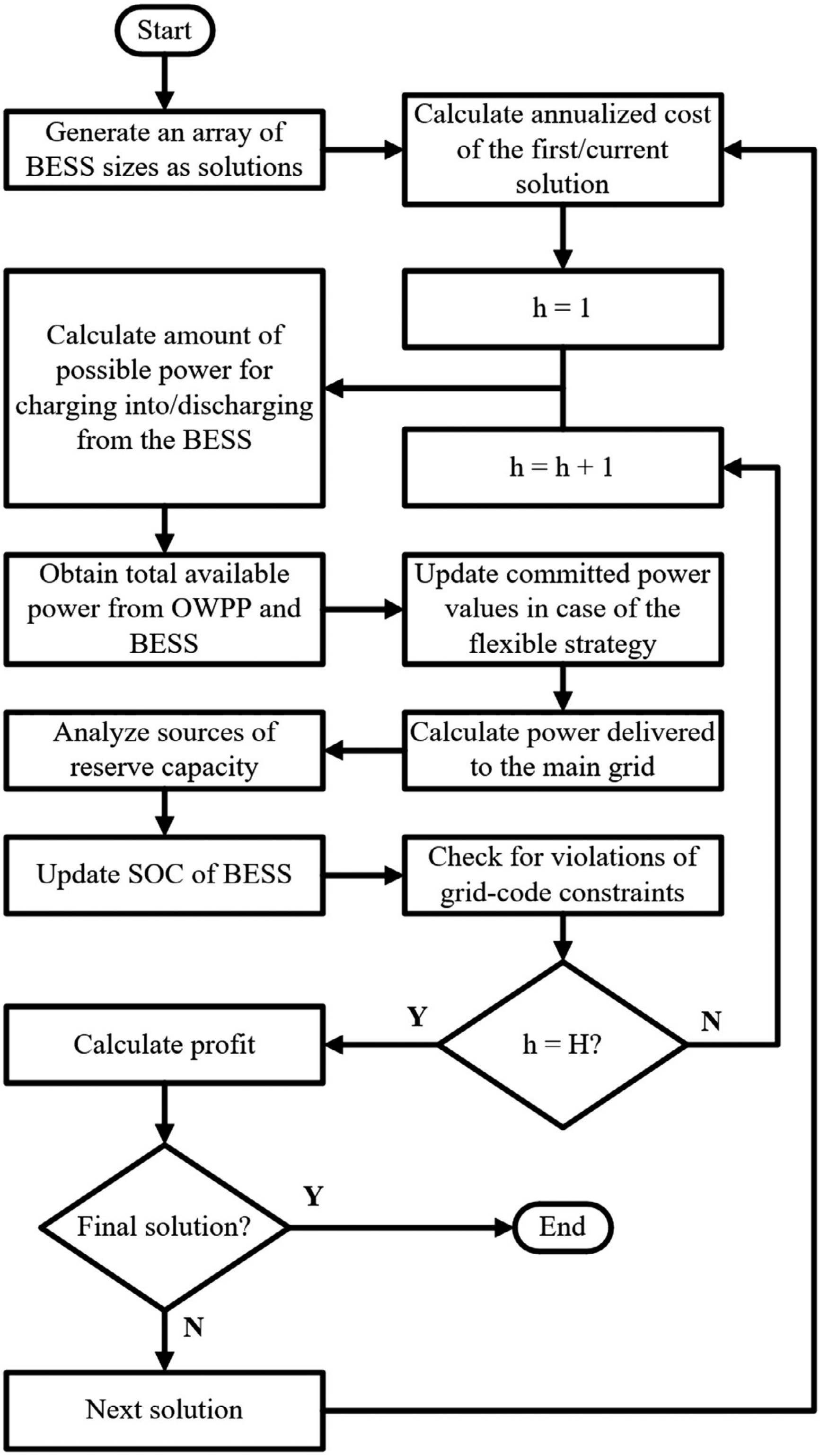

FIGURE 3 Block diagram of the proposed techno-economic model.

in (2) [12]. The capital recovery factor (λ) used for calculating the annualized form of capital costs from the lifetime (L) and interest rate (r) parameters is obtained as follows [12, 17]:

$$Cost^{B} = \left[(Cost^{B,C} \times C_{B,R}) + (Cost^{B,P} \times P_{B,R})\right] \times \lambda + (Cost^{B,O\&M} \times P_{B,R}), \tag{2}$$

$$\lambda = \frac{(1+r)^{L} \times r}{(1+r)^{L} - 1}. \tag{3}$$

The optimization problem in this study is formulated as a maximization. The annualized cost of the BESS and penalty costs for violations of the grid code are subtracted from the annual revenue from selling power to the grid. Hence,

TABLE 2 Nomenclature.

Abbreviation	Definition
BESS	Battery Energy Storage System
EAC	Equivalent Annualized Cost
ESS	Energy Storage System
MINLP	Mixed Integer Nonlinear Programming
NREL	National Renewable Energy Laboratory
OWPP	Offhore Wind Power Plant
SOC	State of Charge
TSO	Transmission System Operator
WFO	Wind Farm Operator
Parameter	**Definition**
α	Surface roughness parameter
η_C	Charge efficiency
η_D	Discharge efficiency
λ	Capital recovery factor
$Cost^B$	BESS cost ($)
$Cost^{B,C}$	BESS capacity cost ($)
$Cost^{B,O\&M}$	BESS operation and maintenance cost ($)
$Cost^{B,P}$	BESS power cost ($)
$C_{B,R}$	Rated capacity of BESS (MWh)
F_{AP}	Penalty factor for violating absolute production constraint
F_{DP}	Penalty factor for violating delta production constraint
h	index of time steps
H	Number of time steps
h_H	Wind turbine hub height
h_M	Wind measurement height
L	BESS lifetime (years)
P_{Avl}	Available power (MW)
$P_{B,C}$	Power available for charge into the BESS (MW)
$P_{B,D}$	Power available for discharge from the BESS (MW)
$P_{B,R}$	Rated power of BESS (MW)
P_B	BESS power (MW)
P_{B-R}	BESS reserve power (MW)
P_{Com}	Committed output power (MW)
$P_{Com-Res}$	Committed reserve power (MW)
P_{Out}	Output power (MW)
P_{OWPP}	OWPP power (MW)
P_{SR}	Spinning reserve power (MW)
$P_{V,AP}$	Power violating absolute production constraint (MW)
$P_{V,DP}$	Power violating delta production constraint (MW)
r	Interest rate (%)
RR	Reserve ratio
S	Electricity selling price ($/MWh)
SOC_{Max}	Maximum permitted SOC for BESS (%)
SOC_{min}	minimum permitted SOC for BESS (%)
V_w^H	Hub-height wind speed (m/s)
V_w^M	Measured wind speed (m/s)

TABLE 3 BESS parameters.

Parameter	Definition	Value
$Cost^{B,C}$	BESS capacity cost	1 (M$*/MWh)
$Cost^{B,O\&M}$	BESS operation and maintenance cost	0.015 (M$*/MW)
$Cost^{B,P}$	BESS power cost	0.3 (M$*/MW)
r	Interest rate	2%
L	BESS lifetime	10 years
η_C	Charge efficiency	0.895
η_D	Discharge efficiency	0.895

*Million US dollars.

the total profit as the objective function for maximization is mathematically defined (see (4)).

$$Profit = \left[\sum_{h=1}^{H} P_{Out}(h) \times S(h)\right] - Cost^B - \left[F_{AP} \times \sum_{h=1}^{H} P_{V,AP}(h) \times S(h)\right] - \left[F_{DP} \times \sum_{h=1}^{H} P_{V,DP}(h) \times S(h)\right]. \tag{4}$$

5 | SIMULATION RESULTS

Simulations are performed in the MATLAB environment. The proposed technical algorithm based on MINLP is implemented in the inner layer of the optimization model, and the economic sub-model is placed in the outer layer. The BESS optimization is presented in the first subsection. Then, a sensitivity analysis considering variations in three parameters is presented. The parameters for the BESS are tabulated in Table 3.

5.1 | Optimization results

The selected battery module has a rated capacity of 3 MWh and a power rating of 1.5 MW. The wind generation uncertainty is taken as 2%. Standard practice in optimization studies is to run simulations under the worst-case scenario. So, the available power from OWPP is considered to be 2% below the wind power profile found in Section 2 for the entire 8760 h of the year. Penalty factors are both taken equally as 5. In addition, the committed reserve power is set to be 10% of the committed power for delivery to the grid. The selling price of electricity is set as 100 $/MWh.

In this subsection, the optimal number of battery packs is identified. Due to the limited number of options for the single optimization parameter, an exhaustive search method is adopted to find the global maxima. The optimal BESS capacity under the aforementioned conditions was found to be 33 MWh for the strict strategy and 27 MWh for the flexible strategy.

Figure 4 illustrates the annual generation during the optimization process. It is evident that the increase in total generation for the flexible strategy is much higher compared to the strict one. This is because the output power is limited by the committed power in the strict strategy, but in the flexible

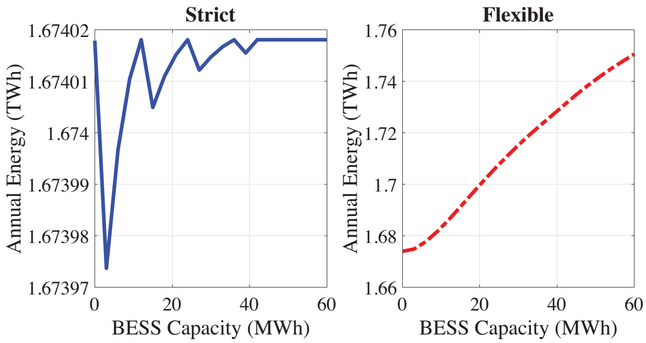

FIGURE 4 Annual generation during the optimization process.

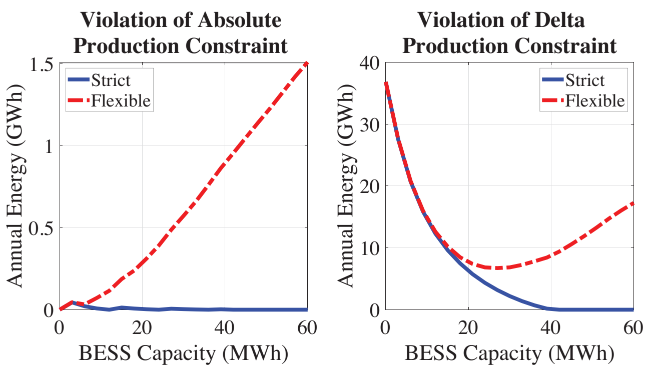

FIGURE 5 Constraint violations during the optimization process.

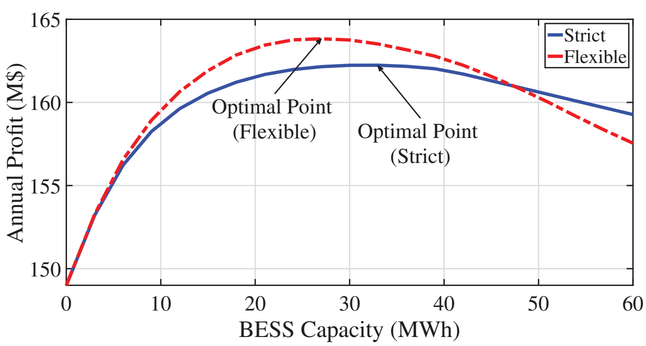

FIGURE 6 Annual profit during the optimization process.

strategy, the committed power is updated based on the available power.

Variations of the constraint violations and annual profit during the optimization process are shown in Figure 5. For the strict strategy, violations in both constraints decrease with the number of BESS modules, eventually reaching zero at 42 MWh BESS capacity. In contrast, violations in the flexible strategy start increasing after a certain number of BESS modules. The annual profit curves in Figure 6 show that the flexible strategy is more profitable than the strict strategy at their respective optimal points. Numerical results are summarized in Table 4 to show the effects of installing a BESS and the choice of strategy.

It can be seen from Table 4 that without any BESS, the penalty cost for violating the grid-code constraints is quite high

TABLE 4 Optimization results.

	Without BESS	With optimal BESS (strict)	With optimal BESS (flexible)
Optimal number of BESS modules	–	11	9
Optimal capacity of BESS (MWh)	–	33	27
Optimal rated power of BESS (MW)	–	16.5	13.5
Annual energy delivered to the grid (TWh)	1.674	1.674	1.711
Annual energy violating the constraint (GWh)	36.8	1.38	3.28
Annual revenue from selling power to the grid (M$)	167.4	167.4	171.1
Annual penalty for violating the constraint (M$)	18.4	0.69	1.64
Annual cost of BESS (M$)	–	4.47	3.66
Annual profit (M$)	149	162.24	165.8

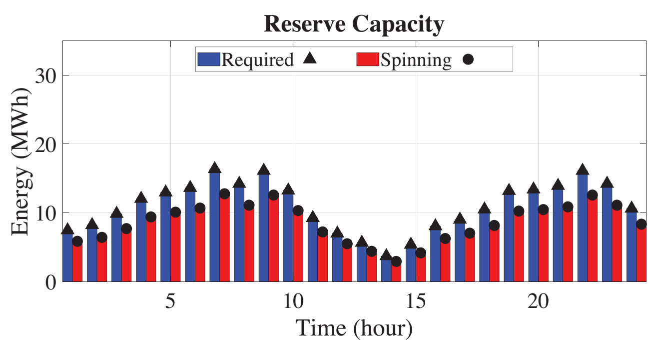

FIGURE 7 Reserve capacity for the first day without BESS.

and considerably decreases the profit. In contrast, BESS can clear the violations to a substantial extent depending on the permitted strategy. Ultimately, the annual profit is increased by 13.24 M$ for the strict strategy and 16.8 M$ for the flexible strategy.

The reserve capacity graphs for the first day are shown in Figures 7–9. As shown in Figure 7, without BESS, the spinning reserve is inadequate to match the required reserve capacity. With the optimal BESS in place and the strict strategy in operation, the total reserve capacity provided by the BESS and spinning reserve is either equal to or more than the required amount (see Figure 8). In the last scenario, with the optimal BESS and the flexible strategy, the energy stored in BESS can contribute to the output energy after the committed power and committed reserve capacities are modified. In this way, as shown in Figure 9, the total provided reserve capacity meets

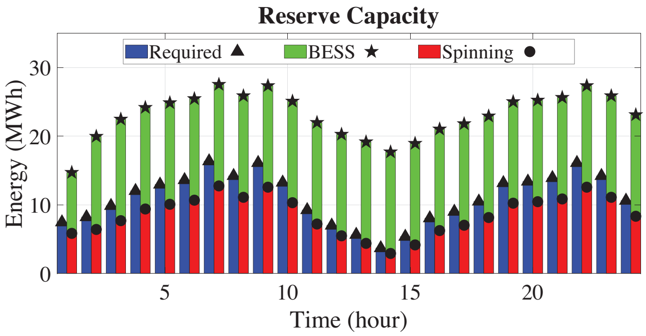

FIGURE 8 Reserve capacity for the first day with the optimal BESS and strict strategy.

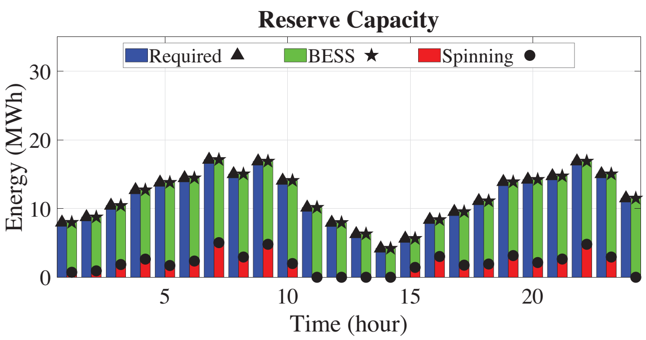

FIGURE 9 Reserve capacity for the first day with the optimal BESS and flexible strategy.

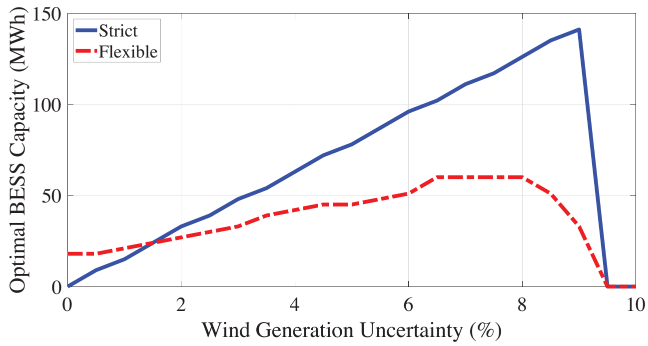

FIGURE 10 Sensitivity analysis on wind generation uncertainty.

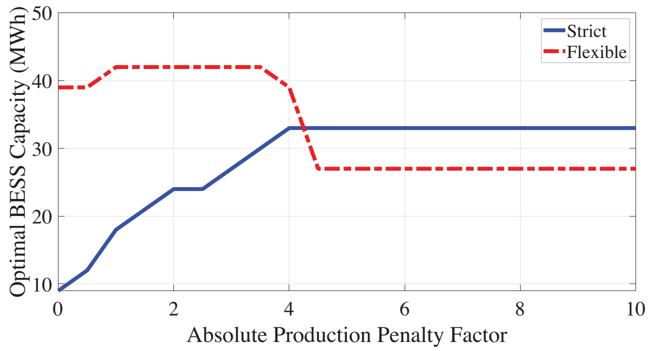

FIGURE 11 Sensitivity analysis on absolute production constraint.

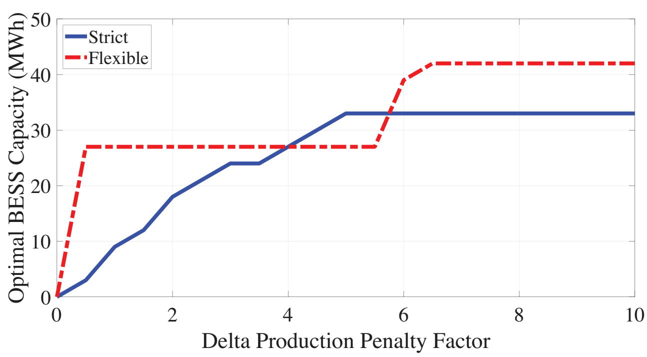

FIGURE 12 Sensitivity analysis on delta production constraint.

the updated but slightly higher required values. This is advantageous because the spinning reserve is decreased, and more of the available OWPP power can be delivered to the grid.

In the strict strategy, having lower wind power than expected due to uncertainty, energy stored in batteries helps the spinning reserve fulfill the required reserve capacity. However, in the flexible strategy, the power commitments to the electricity market are updated according to uncertainty. During hours 11–14 of Figure 9, a portion of the energy stored in batteries is enough to fulfill the required reserve capacity, and there is no need to keep a spinning reserve, so the entire wind power is delivered to the grid.

5.2 | Sensitivity analysis

During simulations, three parameters have the most impact on the optimal capacity of BESS. These parameters include wind generation uncertainty, absolute production penalty factor, and delta production penalty factor. Results of the sensitivity analysis by changing these parameters from the aforementioned conditions one at a time are presented in Figure 10.

It can be seen from Figure 10 that the optimal capacity of BESS starts increasing for both strategies. For the strict strategy, beyond 9% uncertainty, the available power from the OWPP in the worst-case scenario is so low that any BESS would not get the chance to be charged efficiently and contribute to the process enough to compensate for its cost. As opposed to the strict strategy, the optimal BESS capacity under the flexible strategy starts decreasing gradually from 8% uncertainty and reaches 0 at 9.5% uncertainty, where installation of BESS becomes economically unreasonable.

As illustrated in Figures 11 and 12, in the strict strategy, the change in the optimal battery capacity against penalty factors is always increasing until reaching a point where batteries become too expensive for their technical contributions, and hence, the curves in these figures are constant thereafter. The higher the penalty factors, the higher the necessity for batteries to compensate for the reserve capacity requirement.

Installation of more BESS modules is justified because the penalty costs of violations have risen.

The results for the flexible strategy are different. Here, the BESS is not just another source of reserve capacity but also contributes to the output energy. So, even with zero penalty factors, installing a BESS is deemed more beneficial for the flexible approach than the strict one. Also, contrary to the strict strategy, a steady increase or decrease in the optimal capacity of BESS is not observed.

A similar analysis can be performed for the amount of wind generation uncertainty. With zero uncertainty, BESS is obsolete in the case of a strict energy market environment. In contrast, since BESS can help increase revenue from the power sold to the grid, it is found to be a reasonable choice in the flexible strategy. It is interesting to note that in the case of flexible grid-code regulations, which is the basis for the development of the second strategy, a smaller BESS capacity is required for the majority of uncertainty values.

6 | CONCLUSION

This paper presented an optimization approach for sizing BESS coupled to WFs. The techno-economic framework was designed to maximize the annual profit of the WFO by avoiding violations in the relevant grid-code constraints on the active power, including absolute and delta production constraints. The proposed mixed integer nonlinear technical algorithm quickly found the global maxima.

Two different methods were studied for adding the absolute and delta production constraints. The strict method represents the rigid and sudden inclusion of these constraints, and the flexible technique provides a smoother transition toward new regulations. These led to two strategies being defined for the combined operation of the WF and BESS in the day-ahead market environment. The strict strategy limited the power output of the OWPP to a previously committed value, but the flexible approach was open to modifying the permitted power output from WF to increase the share of renewable energies on the generation side and decrease carbon emissions even further. An easy-to-implement MINLP-based technical algorithm, which can model both strategies, was proposed. The proposed algorithm was then utilized in a two-layer techno-economic optimization to maximize annual profit by finding the optimal BESS capacity.

Simulation results were provided for the first potential OWPP in Turkey. The strict strategy resulted in an optimal BESS with 33 MWh capacity, which led to a 13.24 M$ increase in the annual profit. As expected, the flexible strategy reached a higher increase of 16.8 M$ in the annual profit with a smaller optimal BESS capacity of 27 MWh.

In a nutshell, optimization results showed that installing an economically reasonable and optimally chosen BESS can help the WFO effectively address the abovementioned active power restrictions that might be set by the TSO in the future and ultimately improve its annual profit. Moreover, it was presented how flexibility in the process of introducing new grid code constraints can maintain an active interest in investments by providing a higher profit margin. Hopefully, this will increase interest in financial investments in the proposed Kıyıköy OWPP.

AUTHOR CONTRIBUTIONS

Mohammad Hossein Mokhtare: Conceptualization; formal analysis; methodology; software; visualization; writing—original draft; writing—review and editing. **Ozan Keysan**: Conceptualization; supervision; writing—review and editing.

ACKNOWLEDGEMENTS

The authors would like to thank for the support from the Danish International Development Agency (DANIDA) Fellowship Centre and the Ministry of Foreign Affairs of Denmark (Grant No: 19-M03-AAU), project title “Offshore Wind Farms Large-Scale Integration in Turkey – WindFlag”. Scientific and Technological Research Council of Turkey, Türkiye Bilimsel ve Teknolojik Araştirma Kurumu, TUBITAK, TÚBİTAK.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Mokhtare, M.H., Keysan, O.: Optimal sizing of battery energy storage system for a large-scale offshore wind power plant considering grid code constraints: A Turkish case study. IET Renew. Power Gener. 1–10 (2024). https://doi.org/10.1049/rpg2.12970