# FEASIBILITY STUDY ON THE USE OF LARGE-SCALE LITHIUM-ION BATTERIES TO PREVENT ENERGY WASTES DUE TO CURTAILMENTS IN OFFSHORE WIND FARMS

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## ABSTRACT

The challenging goals of the energy transition set for 2030 are prompting Mediterranean countries to pay increasing attention at planning significant offshore wind production. However, due to the growth of intermittent renewables and the large scale of offshore wind farms, grid operators may be forced to introduce energy curtailments, since grid revamping could require more time than new installations. This study aims to evaluate the possible management of curtailed energy in a specific installation site to assess the impact of these events on the revenues of a wind farm. To this end, Li-ion batteries are adopted as energy storage systems (ESS) to reduce energy waste. The first step of the analysis has been the optimization, by means of the levelized cost of energy (LCOE) minimization, of the layout of a floating offshore wind farm located in Sicily. Then, a sensitivity analysis is carried out by varying the assumptions on curtailed energy remuneration and the daily and monthly distribution of curtailments. The second step of the study is the management of the curtailed power, in order to evaluate if the adoption of Li-ion batteries is more cost-effective than the base plant. In this regard, different ESS costs and curtailment scenarios are considered to account for the uncertainties of the energy and component markets. In all scenarios, results show that batteries, if correctly sized, lead to an increase in the revenues from the considered 1 GW wind farm that ranges between 130 and 240 M€.

## 1 INTRODUCTION

The reduced visual and acoustic impact, coupled with increased restrictions imposed on available onshore sites for the installation of renewable energy facilities, promotes a progressive rise in the deployment of offshore technologies within the European energy landscape in the coming years (Castro-Santos et al., 2016). Despite the crucial role of power production from renewable energy sources (RES) in the energy transition, the integration of a relevant number of large-scale facilities in the national electrical grid poses significant challenges. In particular, for Mediterranean countries, and specifically for Italy, large-concentrated installations of renewable energies can: i) affect the stability and reliability of the power grid, due to significant fluctuations associated with the non-dispatchable RES; ii) generate grid congestions during peak hours production; iii) lead to the planned reduction of renewable plants' power output, namely curtailments. As described in the scenarios presented in (Terna, 2022), a massive increase in installed RES capacity by 2030 or 2050, may result in significant energy waste owed to curtailments. To this end, the development of advanced energy storage systems (ESS) and grid management solutions becomes imperative. Lots of research efforts were spent to study the coupling between offshore wind farms and Li-ion batteries in order to store and shift the use of energy surplus. In (Esteban and Leary, 2012; Ikni et al., 2015) batteries are selected as potential ESS to be employed for mitigating short-term fluctuations in renewable production and to increase power quality. Moreover, the results presented in (Jafari et al., 2020) show that, despite the higher grid losses, locating the battery onshore, near the point of delivery, contributes to increasing the earnings from the system.



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Finally, according to (Buhagiar et al., 2019) batteries are located directly in turbines to minimize the temporal misalignment between production and demand. In spite of the reduction of land occupation and grid losses, the results of the above-mentioned study show a high rate of degradation due to the relevant number of charging and discharging cycles. However, despite the significant number of studies on the coupling of offshore wind farms and batteries and on the use of hydrogen to reduce energy wastes (Travaglini et al., 2023), the utilization of those ESS to mitigate the effects of curtailments represents a gap in the literature. Most of the studies focus on power quality and load shifting for relatively small plants, often lacking detailed analyses on how to consider and reduce the impact of curtailments on the economy of large-scale wind farms. To this end, this present study aims to fill this gap. After a description of the methods adopted to estimate the power production of a floating offshore wind farm in the western marine area of Sicily with a minute resolution, this work showcases the assumptions made to analyze energy reductions and the revenues introduced by the adoption of Li-ion battery ESS. Furthermore, a new cost metric has been introduced. Relying on the LCOE standard formulation, a market-dependent levelized cost of energy (mLCOE) has been considered to account for the decreased power production due to the energy market. Both cost metrics, along with the net present value (NPV), are used for the techno-economic analyses in this paper.

## 2 METHODS

### 2.1 Wind Turbines

In this current study, the 15 MW reference wind turbine (WT) proposed by IEA for offshore installations (IEA, 2020) is adopted. Despite the early commercial stage experienced by those turbines, this choice is consistent with a time scale starting in 2030, when it is foreseen that these turbine sizes will have attained complete maturity and undergone extensive commercialization. Table 1 depicts the reference data for the adopted WT.

**Table 1:** IEA 15 MW reference data.

| Hub height | Rotor diameter | Rated power | Cut in/out wind speed | Rated wind speed |
|---|---|---|---|---|
| 150 m | 242 m | 15 MW | 3/25 m/s | 10.6 m/s |

Recent findings (IEA, 2022) established a lifetime of 30 years for those WTs. Planned extraordinary maintenance could extend the operation for an additional five years, instead of the 25 commonly considered, without significantly affecting the performance. This assumption, considering a lifetime of 30 years also for the whole power plant, leads to avoiding replacement costs for the generators. Regarding floating platforms, mooring systems, and energy delivery to shore, herein the same assumptions extensively described in (Travaglini et al., 2023) are adopted. Specifically, due to the height of the seabed and the metocean conditions characteristic of the site, the semi-submersible platform with catenary moorings is selected. Finally, intra-array electric cables with a capacity of 90 MVA and HVAC export cables are adopted as the most cost-effective solution in this specific case.

### 2.2 Wind Farm Layout and Installation Site

This study is focused on a sea lot located approximately 60 km from the western shores of Sicily, where previous feasibility projects were presented to the Italian authorities (MASE, 2023). This study aims to estimate the LCOE for a wind farm with the potential integration of Li-ion batteries in a time horizon starting in 2030. In order to minimize the costs associated with energy production, a layout optimization is needed.

**Table 2:** Wind farm layout spacing description.

| Layout L-l | 13d-5d | 13d-6.25d | 13d-7.5d | 13d-10d | 14d-7.5d | 15d-7.5d |
|---|---|---|---|---|---|---|
| Intra-array distance [km] | 3.25-1.25 | 3.25-1.56 | 3.25-1.87 | 3.25-2.5 | 3.5-1.87 | 3.75-1.87 |
| Sea lot extension [km$^2$] | 292.5 | 365.04 | 437.58 | 585 | 471.24 | 504.9 |

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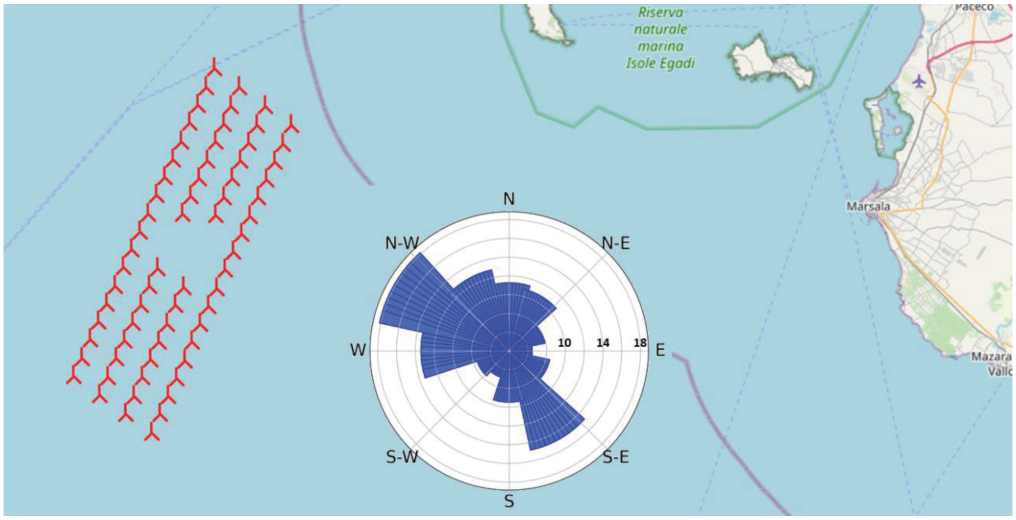


**Figure 1:** Example of wind farm layout with wind rose of the specific site in terms of frequency [%].

Wind farms are composed of sixty-seven 15 MW WTs, for an overall rated power of 1.005 GW. The optimal layout of offshore wind farms poses significant challenges, including submersible cables and moorings. Furthermore, wake effects significantly affect power production, as most of the rotors work at suboptimal efficiency due to slower and more turbulent wind, thus reducing the revenues from wind farms. For these reasons, an extensive sensitivity analysis on WT distance is performed to find the optimal tradeoff between the increasing capital costs in ancillary devices and the decreasing wake effects associated with more distanced configurations. The LCOE minimization is achieved by adopting a rectangular-shaped layout and varying the intra-array distance, as shown in Table 2, where the configurations are described using the spacing in the wind (L) and crosswind (l) direction expressed in WT diameters (d). Moreover, to maximize the energy capture while minimizing wake effects on downstream wind generators, the orientation of the cluster of rotors was set considering the prevalent wind direction from the west-northwest, as depicted in Figure 1. Finally, the environmental footprint of each configuration, described in Table 2 by means of occupied surface, ranges from approximately 290 to 504 km$^2$.

### 2.3 Wind Data

The adoption of detailed battery models in smart energy system analyses requires power inputs with an appropriate time resolution, to account for a realistic behavior of the storage device. In particular, a one-minute resolution has been considered a good tradeoff between accuracy and computational cost to properly assess the effects of charge and discharge cycles on the state of health (SOH) and efficiency of the component (Superchi et al., 2023). However, the use of wind data with this time resolution could lead to significant errors in wind power production assessment. Wind power curves provided by WT manufacturers are typically averaged over ten-minute intervals (Sohoni et al., 2016), and using wind data on a minute basis would prevent an accurate evaluation of the real performance of the generator, which fluctuates significantly on such small-time scales due to turbulence in the incident flow. Therefore, while a ten-minute scale is adopted in order to correctly estimate the wind power generation from the available wind speed, a subsequent refinement strategy is used to obtain the time-varying power output on a one-minute basis. Nevertheless, obtaining wind data with a ten-minute resolution at the typical hub height of modern rotors is challenging, considering the lack of offshore direct measures, the reduced elevation of measurement stations and the hourly resolution of reanalysis databases.

Considering the lack of detailed guidelines on how to refine the coarse wind dataset to match the desired time resolution, the authors adopted a strategy based on the variability of the measured data at mast elevation with respect to the hourly average. As described in Figure 2, both the ERA5 database (Hersbach et al., 2020) and measured data from an existing offshore mast near the site (Serri et al., 2021) are used.



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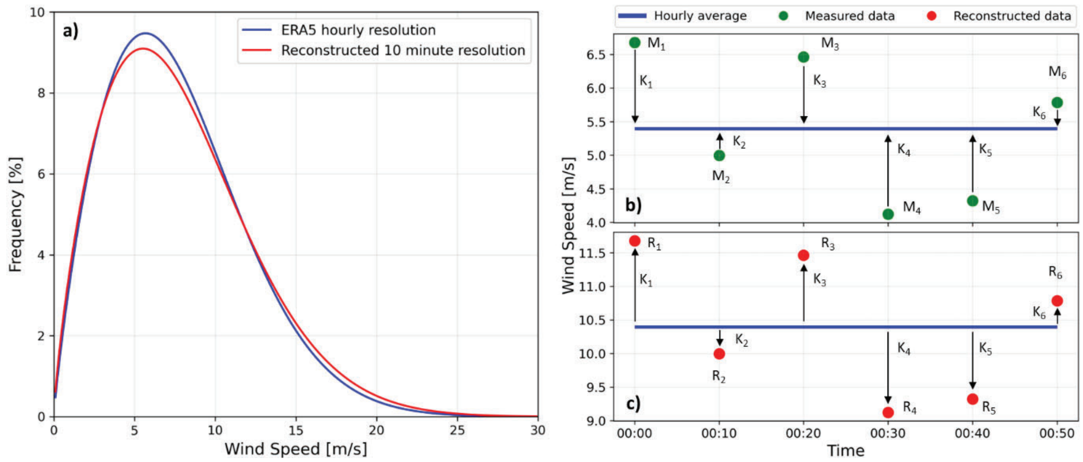


**Figure 2:** a) Comparison between Weibull curves of ERA5 and the reconstructed data at 100m a.s.l: b) procedure to evaluate the wind variation of the measured data; c) evaluation of the ten minutes series at 100m a.s.l.

The first one provides the hourly average wind speed in the selected site. The second one, which includes the mean, minimum, and maximum wind speed on a ten-minute basis, provides the wind variation with respect to the mean. The refinement process for those three wind velocities can be outlined in two steps:

- Figure 2a: Extrapolation of the wind variation ($k_i$) from the measured data as the ratio between each value ($M_i$) and their hourly mean (blue line)
- Figure 2b: Application of the extrapolated variation to the reanalysis data, by multiplying hourly data of ERA5 at 100 m above sea level (a.s.l.) (blue line) by $k_i$.

Despite the conservation of the average wind speed, this approach results in increased variability of the source, as depicted by the red line in Figure 2a, and in a slight decrease in the median velocity. However, given the cubic dependence between wind speed and WT power production, the refinement to the ten-minute resolution leads to a difference of 4.3% in the annual energy production (AEP). Considering that the loss of such information is intrinsic to the refinement process, and according to the authors' experience, the introduced error is deemed acceptable for conducting detailed analyses based on coarse databases. Furthermore, to accurately define the wind source, the following assumptions are made:

- Wind direction is considered constant with the elevation, and the measured data from the buoy are used.
- The hourly atmospheric temperature of ERA5 is kept constant, considering the reduced variation rate of this quantity.

## 2.4 Power Production Calculations

In this study, the commercial software windPRO (EMD International, 2022) was adopted due to its wide utilization in the design, development, and evaluation processes of wind projects. Time-dependent analyses are conducted to evaluate the ten-minute power production starting from the data described in the previous section. For this work the authors adopted the procedure extensively described in (Travaglini et al., 2023), adopting the N.O.J. wake model (Katic et al., 1987) and neglecting factors such as the surface roughness and orography due to the offshore site. Finally, given the need to conduct analyses over time horizons longer than the two years provided by measurements, with periods of interest spanning ten years, the estimated power dataset at ten-minute intervals is extended to achieve the desired length. Specifically, considering the peculiar behavior of wind in certain months of the year, it was chosen to reconstruct the missing months by randomly shuffling the days from those same months computed in previous years. With respect to a simple repetition of the available years to reach the required ten-year time span, this randomization allows for increased variability in the repeated periods, while statistically respecting the seasonal variability of the wind resource. However, although the wind


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power reconstructed dataset has a duration of a decade, a plant lifetime of thirty years is assumed. For simulating the entire operational period of the plant,therefore, it was decided to rely on the available dataset to extrapolate the final results. This choice is due to the reduction of computational efforts and is consistent with the lifespan of the battery, which is considered the most critical component.
In order to accurately estimate the cyclic wear of the battery, once the ten-minute mean ($P_{AVG}$), minimum ($P_{MIN}$), and maximum ($P_{MAX}$) power productions are estimated relying on the resource above, an additional refinement process is adopted to obtain a power resolution of one minute. To this end, as adopted by some of the authors in previous works (Galli et al., 2024), an iterative procedure based on the random generation in a range limited by $P_{MIN}$ and $P_{MAX}$ of eight power values, whose average is $P_{AVG}$. This approach, considering that the average power generation is preserved, prevents the errors that would have been included in the production estimation based on a minute resolution of the wind source.

### 2.5 Curtailments

Curtailments represent the planned reduction of power output from wind farms during periods of electrical grid congestion, predominantly impacting non-programmable renewable energy sources. The "Global Ambition Italia" scenario depicted by TERNA for 2040 (Terna, 2022) anticipates a substantial adoption of these sources, leading to an estimated 11 TWh/year of curtailed energy, constituting around 5% of the projected renewable energy production. However, this percentage is indicative, given the significant variability in grid capacity across different regions. Hence, this study examines three scenarios are, varying annual curtailed energy from 5% to 10% or 15% of the plant AEP. Additionally, the planned power output reduction is estimated as a percentage of the farm's nominal power, as described in table 2, in order to match the target annual curtailed energy. Those reductions are scheduled throughout daylight hours, with a distribution centered on 1:00 p.m., and modeled with two distinct time-dependent approaches:

- *Homogeneous distribution (S1)*: the curtailed energy is equally distributed throughout the year. Over the 24 hours, the curtailed energy is concentrated during the six central hours of the day, typically when the grid congestion is higher. This reduction is applied to all days of the year without distinctions.
- *Seasonal distribution (S2)*: the planned reduction of power output is concentrated during the summer, with peaks of eight hours per day, six hours in spring and autumn, and minimums in winter (four hours). In this case, both the potential issues induced by the seasonal fluctuation of renewables and the daily trend of grid conditions are accounted for. Additionally, in order to consider weather variability, a randomization process that preserves the mean hours per day has been applied for winter months.

**Table 2:** Curtailment description in terms of power reduction.

| Scenario | | 5% | 10% | 15% |
|---|---|---|---|---|
| S1 | Power reduction [%] | 12 | 27 | 47 |
| S2 | Power reduction [%] | 12 | 29 | 51 |

Furthermore, in this work, the curtailed energy is assumed to be remunerated ($E_{cost}$) as a percentage of the LCOE. This assumption is consistent with the present regulation and, even if it will be probably changed in the future, it is considered in this study as an incentive to promote the installation of large capacities of renewable power plants. According to authors' experience, three different scenarios are considered, assuming an $E_{cost}$ is equal to 0%, 25%, and 50% of the LCOE.

### 2.6 Battery Modelling

Among the existing electro-chemical ESS technologies, this study considers Li-ion batteries due to their high round-trip efficiency and ability to withstand charge and discharge cycles (Divya and Østergaard, 2009). Specifically, the Nickel-Manganese-Cobalt (NMC) Python-based model developed by the authors in the past (Superchi et al., 2023) was employed. To this end, the battery is charged when the



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wind farm power generation is limited by curtailments and discharged when the production is lower than the 1 GW nominal output. In order to obtain accurate results, a degradation model is also considered, accounting for the reduction in available capacity due to cyclic wear. Finally, given the continuous use of the battery, a self-discharge model is not included, as it refers to situations where the state of charge (SOC) of the component remains high, without undergoing discharging cycles for extended periods. Moreover, in order to obtain a more conservative assessment of the battery degradation, a new fitting for the estimation of the end-of-life cycles (EOL) is adopted with respect to the one in (Superchi et al., 2023). Specifically, the resulting coefficients A and B reported in equation (1) are equal to 2944.4 and -1.24, respectively.

$$EOL_{cycles} = A * (\Delta SOC)^B \tag{1}$$

A decrease in SOH leads to lower performance of the battery, consistent with energy and economic losses. Moreover, the SOH reflects the residual life of the component. To this end, SOH equal to 70% or operation time of ten years (Ferrari et al., 2018) are set as constraints to determine the lifetime of the BESS.

### 2.7 Metrics for Cost Estimation

The estimation of costs related to the generation of electricity is key for this work. Specifically, the levelized cost of energy (LCOE) is employed as the primary metric for the evaluation of the layout optimization of the wind farm. LCOE represents the cost associated with the production of a single unit of energy with a specific technology and the price at which energy must be sold to recover capital (CAPEX) and operational (OPEX) expenditures during the plant's lifetime. Notably, as depicted by equation (2), this metric is obtained with the ratio between the actualized sum of costs projected throughout the lifespan of the plant and the actualized sum of energy ($E_{prod}$) that the plant will generate within the same timeframe.

$$LCOE = \frac{\sum_{t=1}^{n} \frac{(CAPEX_t + OPEX_t)}{(1+i)^t}}{\sum_{t=1}^{n} \frac{E_{prod,t}}{(1+i)^t}} \tag{2}$$

Where t represents the present year, n is the plant lifetime and i is the discount rate. Furthermore, the same metric can be used to accurately consider the impact of curtailments on the revenues of the wind farm. The inclusion of the grid constraints in the estimation of the producibility leads to a decrease in the amount of $E_{prod}$ to account for the non-production due to curtailments. In this case, considering the unchanged CAPEX and OPEX, the costs for energy production would experience a relevant increase. To this end, in this study, the market-dependent LCOE (mLCOE), is used to estimate the real minimum price at which energy should be sold assuming no remuneration for curtailments.
The other metric used to estimate the impact of the adoption of an energy storage system is the NPV. This parameter allows for the evaluation of the profitability of a planned investment by assessing its present value through the difference between the future discounted cash flows (CF) and the initial CAPEX, as specified in equation (3). Specifically, CFs are estimated as the sum of the revenue obtained from energy input to the grid and the remuneration expected for the energy not injected during curtailment. The difference between the plant with and without an ESS is considered in the increase in the initial capital cost and the replacement expenditures for the battery over the system lifespan.

$$NPV = \sum_{t=1}^{n} \frac{CF_t}{(1+i)^t} - CAPEX \tag{3}$$

### 2.8 Component Costs

The accurate estimation of CAPEX and OPEX is crucial for computing the LCOE and NPV of a wind-powered energy system. However, due to the limited number of existing plants, estimating the actual and projected costs of floating offshore wind turbines (FOWTs), floating platforms, and all related


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components is complex. In this work, the authors adopted the same assumptions and methodology described in (Travaglini et al., 2023), with the specific capital expenditures described in table 3. In detail, to account for the size of the wind farm, a scale factor that reduces the installation costs as the number of installed turbines increases was included. Finally, in the analyzed case study, wind turbines, floaters, and intra-array cables constitute more than 70% of the total plant cost breakdown.
To deal with the uncertainty related to the costs of Li-ion batteries for analyses conducted over a timeframe starting from 2030, it has been decided to perform sensitivity analyses by varying the battery cost, with values per unit of capacity ranging from 110 to 190 €/kWh.

**Table 3:** Specific Expenditures for the case study.

| Component | Capex |
|---|---|
| Wind turbines [M€/MW/unit] | 1.034 |
| Platform [M€/MW/unit] | 0.696 |
| Intra array cables [M€/kW/km] | 0.008 |
| Export cables [M€/MW/km] | 0.011 |
| Moorings [M€/MW/unit] | 0.035 |
| Installation [M€/MW] | 0.169 |

This assumption is consistent with the future projections presented by (Chen and Hsieh, 2023; Morten Lybech, 2021). Furthermore, a replacement cost of the storage system at the end of its life equal to 70% of the capital cost has been adopted (Fisher et al., 2019), assuming that the auxiliary components do not need to be replaced for the entire operational period of the plant.

# 3 RESULTS

This section presents an overview of the wind farm performance in different configurations and scenarios. The outcomes for the analyzed layouts are described in terms of AEP and LCOE to highlight the effects of wake losses and component costs in the optimization. Furthermore, mLCOE is adopted to estimate the real costs per unit of energy in each curtailment scenario for the specific installation case. Finally, concerning the utilization of batteries, the results of the time-dependent analyses are presented to estimate the size that maximizes the wind farm NPV. In this study, a sensitivity analysis on the interest rate (i) is performed to account for the uncertainties in the component and energy market for a time horizon starting from 2030. To this end values of 5%, 7%, and 9% are adopted.

## 3.1 Wind Farm Layout Optimization

This section shows the results in terms of energy production and cost of energy, considering aerodynamic losses and cable costs. Optimizing the wind layout to minimize the LCOE means finding the best trade-off between higher energy production and higher installation costs. As expected, upon examination of table 4, an increase in wind turbine intra-array spacing enhances the energy production, due to the decrease in wake effects. However, despite the 13d-10d layout is not the most spaced in the along-wind direction, the increased distance in the cross-wind direction promotes a reduction of wake losses, which results in the highest AEP.

**Table 4:** Wind farm AEP and LCOE for the analyzed layouts with different i.

| Layout L-l | i | 13d-5d | 13d-6.25d | 13d-7.5d | 13d-10d | 14d-7.5d | 15d-7.5d |
|---|---|---|---|---|---|---|---|
| AEP [GWh/y] | - | 3268.5 | 3308.3 | 3334.7 | 3368.9 | 3341.0 | 3347.3 |
| LCOE [€/MWh] | 5% | 107.20 | 106.61 | 106.18 | 106.77 | 106.04 | 106.17 |
| LCOE [€/MWh] | 7% | 121.67 | 121.00 | 120.52 | 121.19 | 120.36 | 120.51 |
| LCOE [€/MWh] | 9% | 137.28 | 136.52 | 135.98 | 136.73 | 135.79 | 135.97 |



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The adoption of L equal to thirteen WT diameters leads to an almost full wake recovery, resulting in small improvements with a further increase of this parameter. As depicted by table 4, an increase in AEP is not necessarily related to a decrease in energy costs. Despite the minimum wake losses and higher capacity factors, higher WT spacing leads to enhanced CAPEX and OPEX. For this specific installation site, the optimal wind farm layout is represented by the 14-7.5 configuration.

### 3.2 mLCOE

Based on the outcomes of the previous section, the optimal layout has been chosen to investigate the effects of curtailments on energy costs. To this end, the time-dependent analysis enables the estimation of the yearly impact of curtailments on energy production. Without an ESS, non-production affects the revenues of the wind farm. The accurate estimation of curtailments is crucial. Figure 3a shows the net yearly energy production and the curtailed AEP for both S1 and S2 in the different scenarios. The Figure represents both the seasonal and homogeneous scenarios because, as mentioned in the previous sections, despite the different distribution of daily curtailments in S1 and S2, the total amount of non-produced energy is equivalent.

Figure 3b shows the mLCOE for the considered curtailment scenarios with different discount rates. As expected, the decrease in energy production results in a relevant increase in generation costs. Curtailment scenarios of 5%, 10%, and 15% lead to a rise in energy costs of 5%, 11%, and 18%, for all the considered interest rates. Low values for $E_{cost}$ lead to relevant economic losses in the revenues of the wind farm, especially if the price of the energy sold to the grid is close to the LCOE. To this end, the inclusion of the mLCOE results in more accurate cost projections to attend to the tender system of the energy market.

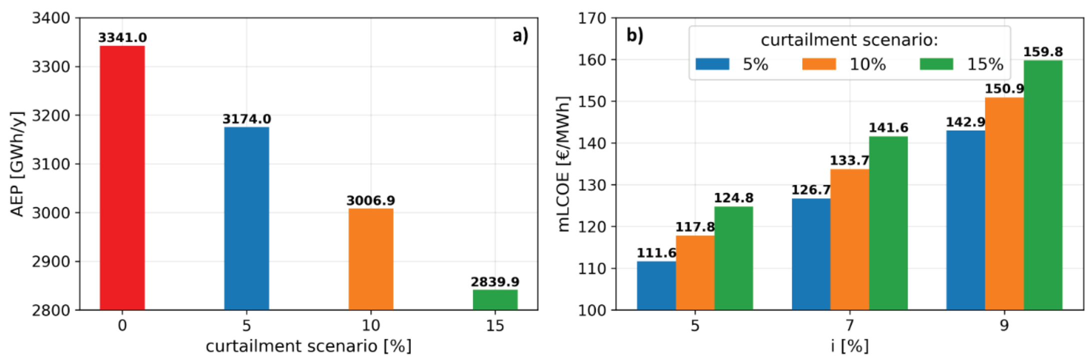


**Figure 3:** AEP (a) and mLCOE (b) in different curtailment scenarios for the analyzed discount rates.

### 3.3 NPV

This section describes the assumptions made and the results of the previously mentioned scenarios for the estimation of the Li-ion ESS contribution. In order to compare the storage plant with the base one, an accurate description of the energy remuneration scheme is needed. For the curtailed energy, the same $E_{cost}$ is assumed for both plant configurations. This approach allows for considering the potential revenues from curtailments as a positive cash flow. The base plant does not generate energy during hours of curtailment. On the other hand, the ESS can store the energy produced in such moments and further inject it into the grid, when the system is allowed to. This additional source of income may contribute to enhancing the NPV, when higher than the additional installation and substitution costs of the BESS. For the NPV calculation, some hypotheses about the electricity pricing are required. The presence of a feed-in tariff is assumed, valuing the energy injected into the grid at €185/MWh. Considering the absence of an existing incentive policy in Italy for offshore wind farms, this value was estimated relying on the authors' experience in the field. Finally, in this section, only the results for i equal to 7% are shown, while an LCOE of 120.36 €/MWh is considered.

Figure 4 shows the influence of Li-ion ESS costs on the NPV of the wind farm after 30 years of operation in different curtailment scenarios. Specifically, an $E_{cost}$ of 0% (a), 25% (b), and 50% (c) of the plant LCOE is reported for the S1, S2, and no ESS scenarios.


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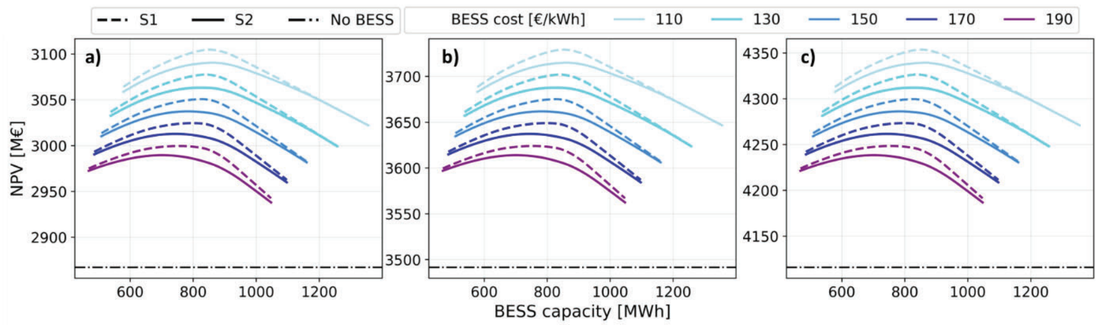


**Figure 4:** NPV of the wind farm in the 5% curtailment scenario and a curtailed energy remuneration of 0% (a), 25% (b), and 50% (c) of the LCOE.

It is apparent how the base plant (dash-dot black line at the bottom) experiences lower revenues over the plant lifetime in all the configurations analyzed. A seasonal scenario (continuous line) results in a lower contribution of the storage system, if compared to the S1 condition (dashed line), where a homogeneous power flux to the battery improves the performance of the component increasing the amount of exploited energy. Furthermore, an increase in storage costs (different colors) leads to a relevant decrease in the wind farm NPV and the battery's optimal size. Specifically, a rise of 20% in BESS cost results in a reduction of the revenues of 1%. This is due to an enhanced capital expenditure for the system with the same energy available for storage. Regarding $E_{cost}$ variation, while an increase in the remuneration of curtailed energy enhances the absolute value of the NPV, it does not affect the relative revenues with respect to the base plant. Specifically, an optimal range of BESS capacity between 700 and 900 MWh is estimated, which leads to maximum NPVs ranging from 3000 to 3100 M€, from 3600 to 3730 M€, and from 4240 to 4350 M€ for $E_{cost}$ values of 0%, 25% and 50% of the LCOE, respectively.
In figure 5 the effects of a curtailment scenario of 5% (blue), 10% (orange), or 15% (green) of the AEP are shown. In detail, the results show that the adoption of a storage system is always convenient regardless of the curtailment distribution throughout the year. Moreover, an increased reduction of the wind farm output leads to a decreased amount of energy valued at the market energy price, assumed to be equivalent to 185€/MWh. This is consistent with the decrease of the NPV shown in the plot for the base plant (solid line) with all the $E_{cost}$ assumed. In addition, the revenues in S2 (circles) are 0.4% lower than those in S1 (triangles). This trend is consistent with the lower ESS contribution shown in figure 6, where the impact of the storage systems is depicted in terms of additional energy exploited per year.

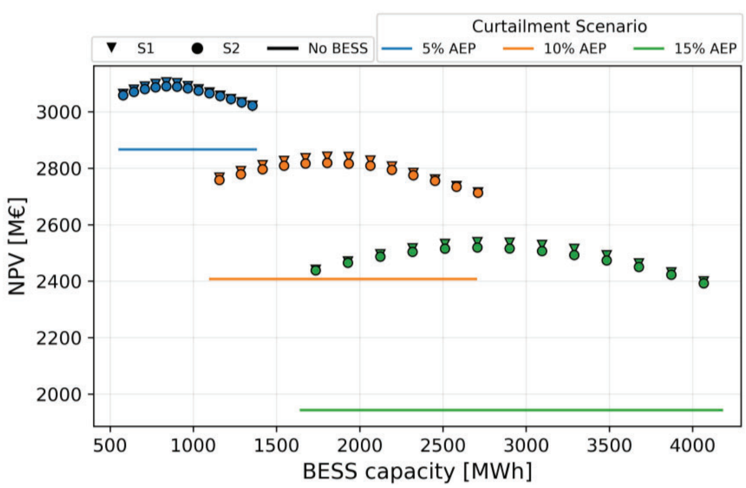


**Figure 5:** NPV of the wind farm with an $E_{cost}$ of 0% of the LCOE and an ESS cost of 130 €/kWh.



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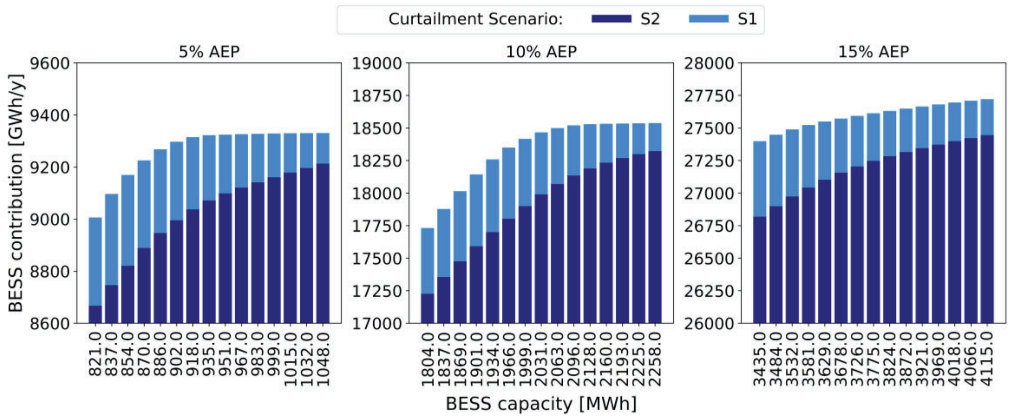


**Figure 6:** Yearly battery contribution with the different curtailment scenarios in S1 and S2.

An increase in curtailed energy leads to lower storage effectiveness and a reduction of the gap between the two scenarios from 2% to 1% for a power reduction of 5% and 15% on the AEP, respectively. As expected, the optimal size of the storage, depicted in the outcomes above, is about 9%, 16%, and 38% smaller than the one that leads to the minimum energy waste.

Figure 7 shows how the increased remuneration for the curtailed energy affects the increase in the NPV (ΔNPV) due to the battery, varying the ESS cost. The results demonstrate that, while the remuneration of 50% of the LCOE leads to an overall higher income, the ΔNPV is not affected by increases in the price of curtailed energy, due to the proportional increase in revenues from the base plant. On the other hand, a higher amount of curtailed energy results in enhanced ΔNPV due to the increased weight of energy exploitation. As expected, while the most cost-effective case is characterized by a low percentage of energy allocated to curtailments, valued with the highest remuneration and low battery costs, the higher impact on the revenues is obtained in a curtailment scenario where the energy reduction is equivalent to 15% of the AEP. One last consideration can be made on battery SOH after ten years of operation. Results show that with the correct sizing of the component, the degradation experienced is lower than the maximum allowed for this study, which leads to a replacement after the time limit of a decade set for safety issues, as per standard practice. To this end, with the technical development of the Li-ion batteries, enhanced reliability could result in increased revenues due to fewer replacements. Figure 8 depicts how in S1, because of the higher exploitation of curtailed energy, the increased number of cycles enhances the impact of degradation. Finally, with an increase in planned power output from wind farms, the sensitivity of SOH to a homogeneous or seasonal distribution of curtailments decreases, showing a trend similar to the one depicted by the storage contribution.

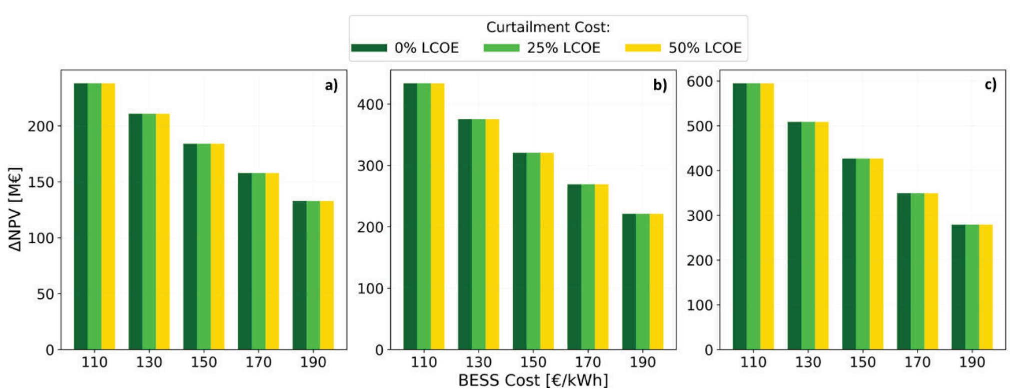


**Figure 7:** Increase in NPV produced by the configuration characterized by optimal ESS size varying battery cost for different curtailed energy remuneration and wind farm output reduction of 5% (a), 10% (b), and 15% (c) of the AEP.


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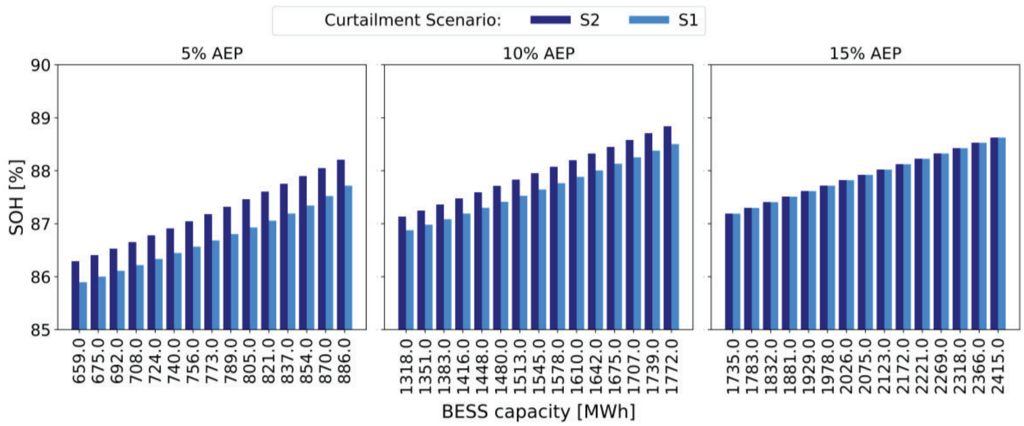


**Figure 8:** Battery SOH after ten years of operation in different curtailment scenarios.

## 4 CONCLUSIONS

This study aims to investigate the effects of curtailments on the revenues of wind farms for an installation site in the Mediterranean Sea, adopting Li-ion batteries as ESS to avoid energy waste. Different curtailment scenarios are simulated to evaluate the optimal layout for the floating offshore wind farm located near the western shores of Sicily and quantify the energy losses. Furthermore, the optimization of the size of the ESS and the estimation of its economic contribution to the system are presented. For large-scale farms, such as the 1 GW plant considered in this study, curtailments represent a significant issue, especially in installation contexts where grid requirements are particularly strict. To this end, the adoption of storage systems is essential to prevent the increase in energy production costs, as demonstrated by the new cost metric implemented. In this regard, an LCOE of 120.36€/MWh for a discount rate of 7% has been estimated. On the other hand, considering the impact of the energy market, the mLCOE shows increases in production costs of 5% 11%, and 18% for a curtailment scenario of 5%, 10%, and 15% of the AEP. The results obtained, despite the uncertainty associated with the techno-economic assumptions made to predict the development of technologies and market evolution, show production costs lower than the selling price, assumed as a feed-in tariff imposed by the grid operator. Finally, it is possible to assess the impact of adopting the storage system in terms of the NPV at the end of the plant's lifetime. Considering the optimal size obtained for each configuration, the increase in NPV due to the battery ranges from 5% to 30%, disregarding curtailed energy remuneration and considering BESS prices of 190 €/kWh and 110 €/kWh, respectively.

The improvements due to the adoption of BESS showcased in this work can significantly influence policymaking by demonstrating the efficiency and reliability of energy storage systems coupled with RES. This can lead to the development of supportive regulations, incentives, and subsidies that promote RES adoption, accelerating the global transition towards sustainable energy systems.

Future developments of this work will include the comparison of Li-ion batteries with different storage technologies, such as hydrogen, to assess the strategy to avoid energy waste. Moreover, the introduction of the hydrogen and electricity market could be interesting to define the guidelines for large renewable installations in the Mediterranean Sea.

## NOMENCLATURE

| | | |
|---|---|---|
| AEP | Annual Energy Production | (GWh/y) |
| BESS | Battery Energy Storage System | (-) |
| $E_{cost}$ | Energy cost | (€/kWh) |
| LCOE | Levelized Cost Of Energy | (€/MWh) |
| NPV | Net Present Value | (€/MWh) |
| mLCOE | market Levelized Cost Of Energy | (€/MWh) |


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