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Energy Department "Galileo Ferraris"

Master's Degree in Energy and Nuclear Engineering

Optimal sizing and techno-economic analysis of a utility-scale wind-battery energy system for grid-level wholesale energy arbitrage service

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Abstract

The modern electricity grid is composed by an increasing percentage of renewable energy installations. Given the intrinsic unpredictable nature of these sources of power generation, it is essential to integrate battery energy storage systems (BESS) so as to ensure stability of power grids. This work proposes a techno-economic analysis of the integration of a BESS into a wind power plant, useful for performing grid-level wholesale energy arbitrage. The purpose of the analysis is to optimize the size of the battery so as to ensure the greatest possible profit from its use. To do this, a mixed integer linear programming (MILP) optimization algorithm is used. Its objective function seeks to maximize the gains achievable by performing arbitrage with energy taken from both the wind system and the grid. For optimal battery operation, the degradation that is caused by the charge and discharge cycles performed is also taken into account. The algorithm inputs are historical data related to the wind farm examined, that include wind speed, energy prices, and dispatch orders. Using this data, scenarios were created to represent different conditions under which the system might operate. The analysis was then performed going for maximum NPV by running a sensitivity on battery price, energy price and weighted average cost of capital (WACC). The results show that with favorable energy price conditions, thus with sufficiently high and variable prices, profits can be made from the implementation of these storage systems. In a business-as-usual scenario of energy prices and dispatch orders, an optimal battery size of 30MW and 60MWh was obtained with an NPV of 4.177.589 € after 15 years of battery life. This work therefore shows the possibility of being able to implement storage systems in renewable energy production facilities, leaving opportunities for more future research.

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Chapter 1

Introduction

1.1 Renewable energy overview

Climate change poses an imminent threat to the planet and our society. The main cause of this phenomenon is the emission of greenhouse gases, mainly resulting from the use of fossil fuels for energy production. The consequences of climate change are already visible and steadily intensifying. Every day we are dealing with: extreme weather events, desertification, rising sea levels, loss of biodiversity and worsening health conditions of people [1].

The Intergovernmental Panel on Climate Change (IPCC) has played a key role in charting a direction regarding the behaviors that need to be put in place to try to mitigate the rise in global average temperature. The objective is to keep the increasing temperatures below 1.5 degrees Celsius compared to pre-industrial levels. This goal was highlighted in the "Special Report on 1.5°C Global Warming" released in 2018 [2]. One of the main points highlighted by the IPCC is that even a seemingly modest increase in global average temperature can have dramatic effects on the planet. For example, the risk of severe extreme weather events, such as heat waves, floods and prolonged droughts, with significant impacts on agriculture, water supply and food security. The IPCC special report stresses that limiting temperature rise below 1.5 degrees will require decisive and immediate global action to drastically reduce greenhouse gas emissions. This implies a comprehensive transformation of energy, industrial, agricultural and transportation systems to renewable and low-carbon energy sources. Effective adaptation policies are therefore needed to address climate impacts and seek to achieve climate neutrality by 2050.

The report also points out that achieving this goal requires a decisive policy stance and consequent joint work by all nations of the world. This means that is needed a significant investment in research and development of clean and sustainable technologies. In order to succeed in achieving this goal, an increase in the share of renewable energy is crucial; in fact, all member countries of the United Nations (UN) in 2015 adopted the 2030 Agenda for Sustainable Development. This document includes the goal of "ensuring access to affordable, reliable, sustainable and modern energy for all" (Goal 7) [3]. The use of energy from renewable sources, thus seems to be a fundamental way to try to stem the irreparable damage that global warming would cause. The use of renewable energy would contribute to reducing the use of fossil fuels, which currently emit 75% of global greenhouse gas emissions and 90% of global carbon dioxide emissions [4]. The presence of these greenhouse gases in the atmosphere results in the creation of the greenhouse effect, which is known to generate an increase in the temperature of the atmosphere. Thus, the use of fossil fuels and the resulting greenhouse gases are the direct cause of global warming.

Renewable sources, on the other hand, generate zero greenhouse gas production during their use by going to exploit natural phenomena that occur on a daily basis. Examples include photovoltaic power generation and wind power generation. These are among the most common sources of production and in 2022 produced 1300 and 2100 TWh, respectively [5],[6]. In addition to these, there are somewhat less common sources of production such as geothermal energy, tidal and ocean energy, or energy production from biofuels. The latter is experiencing a significant increase in demand and production, in fact a record production of 1195 TWh was reached in 2022. However, a significant margin of increase from this value is needed. According to the Net zero scenario forecast, it is expected to more than double the current value, reaching 2778 TWh of energy production from this source by 2030 [7].

Finally, as the last renewable energy source, it is essential to mention a technology that has been established for decades. It turns out in fact to be the one that produces more energy than all other renewable sources combined, namely hydroelectricity. This technology in fact does not work by combustion but by exploiting the kinetic energy of water, thus producing energy without emitting greenhouse gases. Its production values are remarkable, reaching 17% of the total energy produced globally, surpassed only by the energy produced by burning gas and coal. With this technology 4300 TWh were produced globally in 2022 [8].

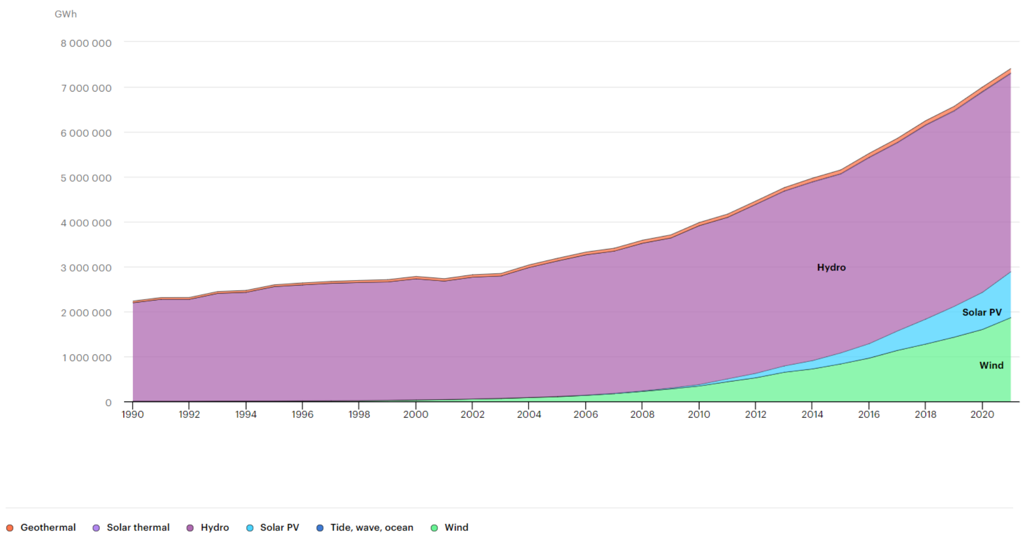

Figure 1.1: Renewable energy produced globally distinguished by source [9].

Now is important to give some numbers regarding the energy produced from these renewable sources. According to the International Renewable Energy Agency (IRENA) [10] the global installed renewable power capacity in 2022 was 3381 GW with energy production in the order of magnitude of thousands of TWh per year. To give an example in 2021 production of 7858 TWh was recorded. These values, notable as they are, still appear to be a long way off from being able to hope to reverse the trend of global warming. According to the Global energy outlook report [11] by the International Energy Agency (IEA), in order to achieve the targets set for decarbonization the power installed will have to more than triple. In fact, based on their predictions installed power is expected to increase to 11000 GW in 2030.

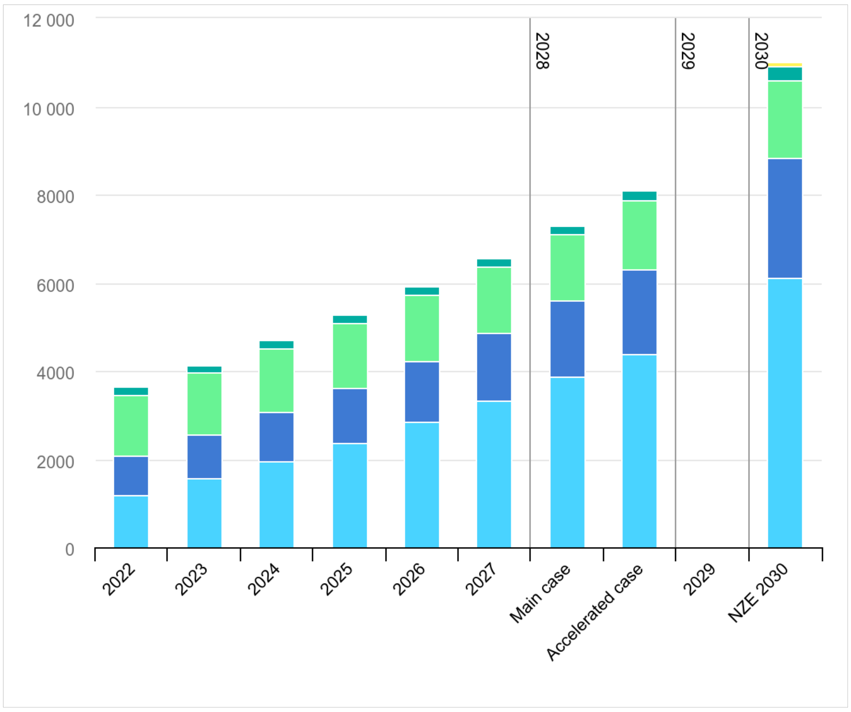

Figure 1.2: Global Renewable electricity generation by source [12].

1.1.1 Global Wind energy production

As described above, wind power generation is among the major renewable energy sources presently globally, and projected to be among the major technologies in the future. The operation of wind power technology at its base is simple: the force of the wind turns the rotor blades, which are connected to a shaft which in turn is connected to a speed increaser that generates a faster rotation of the shaft. This rotation is then transformed from kinetic energy to electrical energy through a power generator.

Nowadays turbines still have this basic operation, although in other technical aspects, it has become extremely more sophisticated over the years. This evolution is both because of the use of increasingly advanced materials and because of the refinement of technology at the aerodynamic level and at the system control level. One example is the implementation of the yaw and pitch control systems.

Wind power plants, specifically can be divided into two main categories: onshore and offshore.

The development of onshore plants nowadays has been more developed, as there are decades of knowledge that have enabled these plants to be developed extensively. The difference with offshore plants, which have matured less globally, is due to the fact that the installation of offshore turbines poses numerous technical challenges. These problems are mainly related to the fact that the installation of large turbines at sea requires enormous costs and numerous technical difficulties.

However, over the years, the number of wind turbines has steadily increased as technology has been consolidated and improved. With technological development, turbines composed of lighter and stronger materials have been built. Figure 1.3 represents the average size of the turbines which is shown to be increasing over the years. This is due to the fact that by increasing the size of the turbines, higher powers can be achieved [13]. This scaling up is most exploitable in the case of offshore turbines, which by being able to take advantage of wind conditions on the sea, which are generally more constant and stronger. In this way is possible to build more large and powerful plants [13].

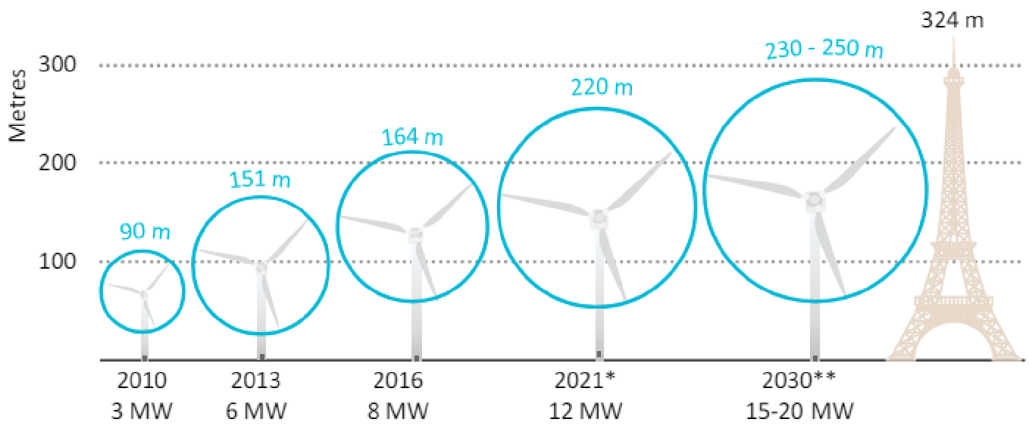

Figure 1.3: Average turbine size increase during years [13].

According to IRENA, global installed wind power capacity in 2022 amounted to 899 GW [10]. Of these, new installations in 2022 amounted to 78 GW of new power capacity including 68,8 GW onshore, according to the Global Wind Energy Council (GWEC) report [14]. The leading nation globally is China, which installed more than half of this value, or 52%. Europe, on the other hand, contributed a total of 16,7 GW of installed power in 2022, with the nations contributing the most being Germany, Sweden, Poland and Finland [14].

Global onshore installation in 2022 are in line with what GWEC predicts for the coming years, as their scenarios predict an increase in annual installed capacity of between 60 and 65 GW per year.

Regarding offshore, as mentioned, there are very high costs and technical difficulties, which obviously cause a slowdown in the installation of new power. Despite this, 8,8 GW of new power was installed in 2022, bringing the total globally installed power to 64,3 GW for this year. Globally, the continents with the largest offshore installations are Asia-pacific and Europe, specifically with the largest concentration of installations located in northern Europe. It is also important to point out that on the offshore side, Italy is also moving in trying to approve some projects in its seas.

Wind power generation, however, still needs to drastically increase its annual growth, as forecasts show that in order to fall within the IEA's net zero scenario targets, 2 TW of cumulative installed capacity should be reached. However, as can be seen from the figure 1.4 that at current rates this would not be achieved, but would need to be accelerated [14].

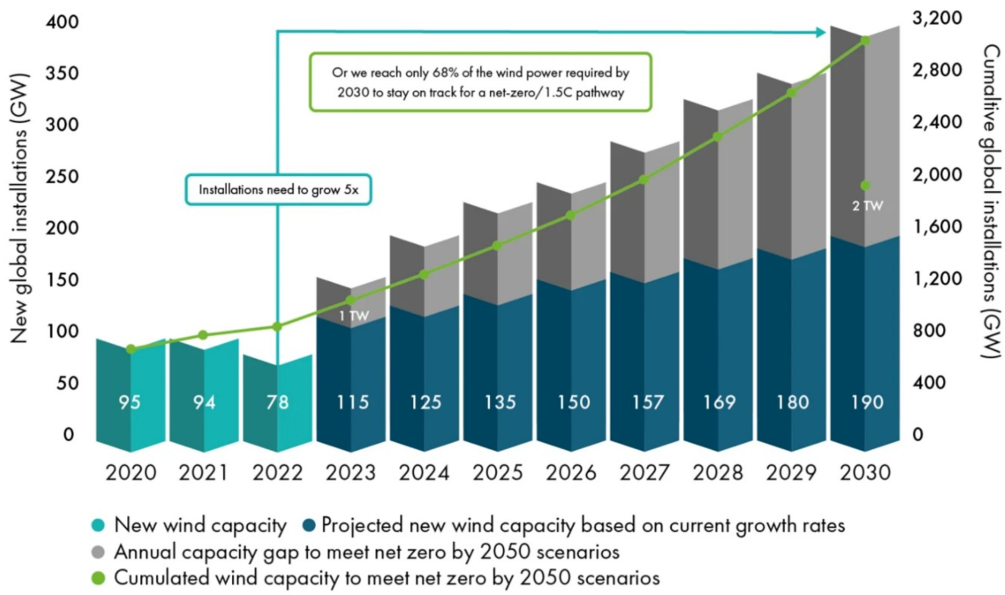

Figure 1.4: Global wind power installations Scenario [14].

The use of renewable energies such as wind power also entails some problems, related to their intermittent nature. Unlike conventional non-renewable energy sources, such as coal or natural gas, wind power generation depends on weather conditions and cannot be scheduled or controlled directly by grid operators. This variability poses a major challenge for power grid management, as it requires proper balancing of supply and demand in real time.

Intermittent production from wind power plants can cause sudden fluctuations in power generation, which can overload existing transmission and distribution infrastructure. This phenomenon requires more sophisticated and flexible grid management systems to ensure the stability and security of the power system [15].

The listed problems related to renewable generation facilities will be amplified in the future in view of their increased presence in power grids. The increase in renewable generation will lead to an intensification of the energy curtailment problem, which will be explained in detail in the following chapter.

1.1.2 Wind energy curtailment

The energy curtailment, represents that condition in which reasons of various kinds make it necessary to totally or partially shut down power production by a given plant. In this way is possible to avoid problems that power production might cause to the power grid. This is a common condition for renewable energy production facilities, specifically in wind power plants.

The most common example of the need to subject a plant to curtailment is that of grid congestion. This means that it may happen that the output of a renewable plant may exceed what the grid could accept, thus causing blackouts or damage to grid components. This condition can be attributed to renewable generation plants, as they have intermittent and unpredictable energy production. This, when combined with low energy demand from users, can cause imbalances and difficulties in grid management. The consequence is that plant shutdowns are called by the grid operator, thus generating episodes of curtailment, which are necessary to safeguard the power system. [16].

The congested condition of the grid is also due to the fact that the grids in a specific area were often designed and commissioned before the construction of the plants, which were connected to the power grid later. This, therefore, means that the grids often have difficulty handling the intermittency and variability of these sources, due to a lack of infrastructure [17].

Other causes that can cause curtailment include, for example:

Frequency stability problems, it can happen that with power inputs into the system, imbalances can be generated on the frequency. Since grids are designed to work on precise frequencies, intermittent inputs can create imbalances that affect their equilibrium. Given the variability of power produced by renewable plants, it can be common for them to create variations in synchronization. To avoid this therefore, curtailment is necessary.

Another cause can be the minimum operating levels of thermal plants. It means that thermal base load plants cannot be turned off and on quickly, so they should always be kept at a minimum power level. In case there is low power demand and at the same time high renewable production, to avoid shutting down thermal plants, it is preferable to subject renewable plants to curtailment [17].

During curtailment episodes, the plant operator can choose whether to curtail all generating units, or only some, the number obviously depending on the degree of grid imbalance. Generally, only some units can be curtailed, leaving others to produce instead so as to ensure dynamic grid stability [16].

Considering all these different factors, it is easy to understand that curtailment represents a highly variable factor depending on the context. In fact, curtailment rates as a function of the plant's energy production can vary from values that reach peaks above 10%, to values below 1%, but on average curtailment rates are between 1 and 3% [17].

As a result, curtailment represents a complex problem. On the one hand, it wastes valuable renewable energy resources and can undermine greenhouse gas emission reduction and climate change mitigation goals. On the other hand, it can have negative economic consequences for wind operators, who see their revenues reduced when production is interrupted or curtailed. Currently, however, in Italy this economic loss is still remunerated by the grid operator, namely Terna.

Addressing the problem of curtailment requires an integrated and coordinated approach acting on several fronts. The upgrading and modernization of electricity grids and all the dedicated transmission infrastructure connected to them is essential. The development of diversified storage technologies to recover energy that would otherwise be wasted is also crucial. Upgrading and modernizing the transmission grid could be the effective solution to increase energy transport capacity and reduce grid congestion. This needs to be coupled with an implementation of various strategically placed storage systems to function as reserve capacity. This then allow excess energy produced during periods of overproduction to be stored and used when demand is higher [18].

1.1.3 Italian framework

In the Italian context, the situation regarding the scope of wind energy production is continuously growing, in Italy there was an installed capacity of 11,86 GW in 2022 and an annual production of 20.494 GWh, with a trend that continues to increase over the years [19].

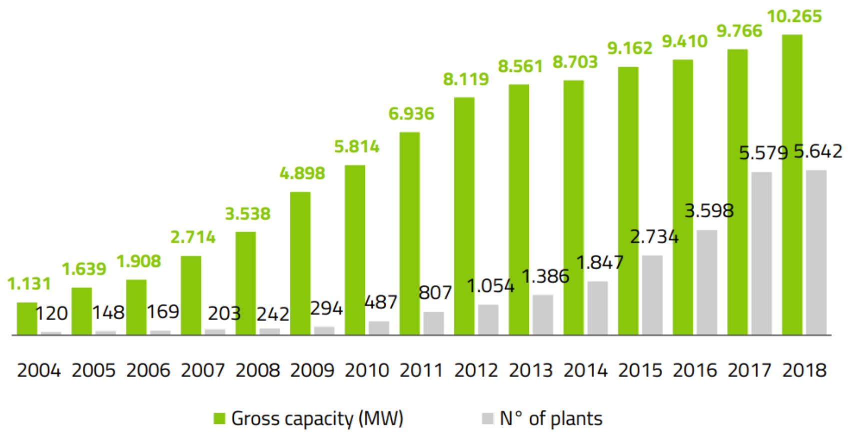

Figure 1.5: Wind plants installation trend in Italy [20].

In the country, the disposition of plants, for obvious geomorphological reasons, is mainly in the south of the nation, particularly in Apulia, Campania, Basilicata, Calabria, Sicily and Sardinia where there is a good wind resource [20]. In the northern part of the country, on the other hand, there is difficulty in establishing plants. This happens because due to orographic obstacles such as the Alps, there is not good wind circulation. Having a low wind energy resource means that there is no economic return from the presence of these plants. In the following figure there is a representation of the wind capacity distribution in Italy in 2018 divided by region.

Figure 1.6: Percentage of wind energy produced over the total for each Italian region [20].

At the national level, curtailment is regulated by law (Annex A ARG/elt 5/10) [21] which states: "Wind power producers who have had their input power curtailed by Terna must submit a request for remuneration to the GSE, which calculates the amount of electricity that can be produced using forecasting models that replicate the operation of the generating unit." To better determine the amount of electricity produced by wind units, the GSE carries out several actions:

- Identifies reference wind units for wind data collection.
- Installs, maintains, and certifies reference anemometers and instruments to process and transmit data without manipulation.
- Develops and validates forecast models to estimate the energy pro-

duced by reference units.

- Develops and validates forecast models to estimate energy produced by non-reference units, based on anemometer data or energy already produced.

In addition, the GSE can redefine and revalidate the forecast models to improve the results. On a monthly basis, the GSE goes to calculate the wind production loss for each generating unit using the following formulas:

$$MPE_{i,h} = 0 \quad \text{se} \left\{ \sum_{n=1}^{h} \max\left[0; E_{\text{producibile },n} - \max\left(E_{\text{immessa },n}; E_{\text{limitata },n}\right)\right] \right\} * IA \leq F; \tag{1.1}$$

$$\begin{aligned} MPE_{i,h} = & \left\{\max\left[0; E_{\text{producibile, }h} - \max\left(E_{\text{inmessa, }h}; E_{\text{limitata },h}\right)\right]\right\} \cdot IA \\ & \text{se} \left\{ \sum_{n=1}^{h} \max\left[0; E_{\text{producibile, }n} - \max\left(E_{\text{inmessa },n}; E_{\text{limitata, }n}\right)\right] \right\} \cdot IA > F \end{aligned} \tag{1.2}$$

- MPE is the total wind production loss of the wind production unit that implemented Terna's dispatch orders in relation to the period under analysis by the GSE;
- $E_{\text{producibile,h}}$ is the electricity that can be produced by wind generation unit i in hour h, as calculated by GSE;
- $E_{\text{immessa,h}}$ is the electricity that wind generation unit is actually fed into the grid in hour h;
- $E_{\text{limitata,h}}$ is the maximum electricity that wind generation unit i should have injected into the grid in hour h;
- IA is the reliability index;
- F is the electricity for which generating units are not entitled to remuneration;
- $MPE_{\text{i,h}}$ is the hourly wind generation shortfall of wind generation unit

(i) that implemented Terna's dispatch orders related to hour (h).

As explained in previous analyses, there is expected to be a significant increase in the presence of renewable energy in the global and Italian electricity system in the coming years.

This then leads to the understanding that energy subject to curtailment could increase proportionally. Therefore, with a view to the future, there is a need for an upgrading of the electric grid, but above all a widespread implementation of storage systems.

1.2 Battery energy storage systems

Energy Storage Systems (ESS) represent a key infrastructure that enables the efficient conversion of energy from one form, typically electricity, to another form suitable for storage. This conversion and storage process makes it easier to dynamically manage energy supply and demand, ensuring a stable balance within electricity grids [22].

A key aspect of ESS is its ability to store electricity when demand is low and release it when demand is high. This functionality provides crucial operational flexibility that can mitigate the intermittent variations that characterize many renewable energy sources, such as wind and photovoltaics. Through temporary electricity storage, ESSs act as dynamic stabilizers of power grids, helping to ensure a continuous and reliable supply of power [22].

Applications of ESS range across several sectors, like the automotive, but also including a wide range of devices that we use every day. Taking in consideration the grid-scale storage systems , the major categories used are:

- Pumped Hydro Energy Storage: these are mechanical storage systems that exploit the principle of potential energy storage using water reservoirs located at different elevations. During periods of low energy demand, water is pumped from lower to higher reservoirs, storing energy in the form of gravitational potential energy. When there is a high energy demand, water is released from the upper reservoirs, running it through hydraulic turbines to generate electricity. This represents the most mature and established storage technology.
- Flywheel energy storage: those type of systems uses a rotating flywheel to store kinetic energy. During periods of energy overproduction, electrical energy is used to rotate the flywheel at high speed, storing kinetic energy. When there is a demand for energy, the flywheel is braked, transferring the stored kinetic energy into electrical energy.
- Compressed Air Energy Storage: those systems, work by taking advantage of air compressors that are activated when there is an over-

production of electricity, or when energy has a low cost. Compressed air is stored, then will be released when needed, going to power turbines that will produce electricity.

- Battery energy storage systems: these are batteries that use electrochemical processes to store and release electrical energy. These include lithium-ion batteries, lead acid batteries, and redox flow batteries.
- Supercapacitors: these are capacitors that can store an extremely higher amount of electrical charge than regular capacitors; it is a growing technology that still has many limitations, particularly in terms of storable energy [23].

Each type of ESS has specific advantages and limitations, and the choice of the most suitable system depends on the application needs and the characteristics of the context under consideration. The variety of different storage technologies can help create more robust and resilient energy systems that can meet the growing needs of a renewable energy economy.

Energy storage systems can help to reach the decarbonization future goals, so, in fact, ESS are expected to increase to 200 GW by 2030 and 600 GW by 2050 of installed capacity at the European level [24].

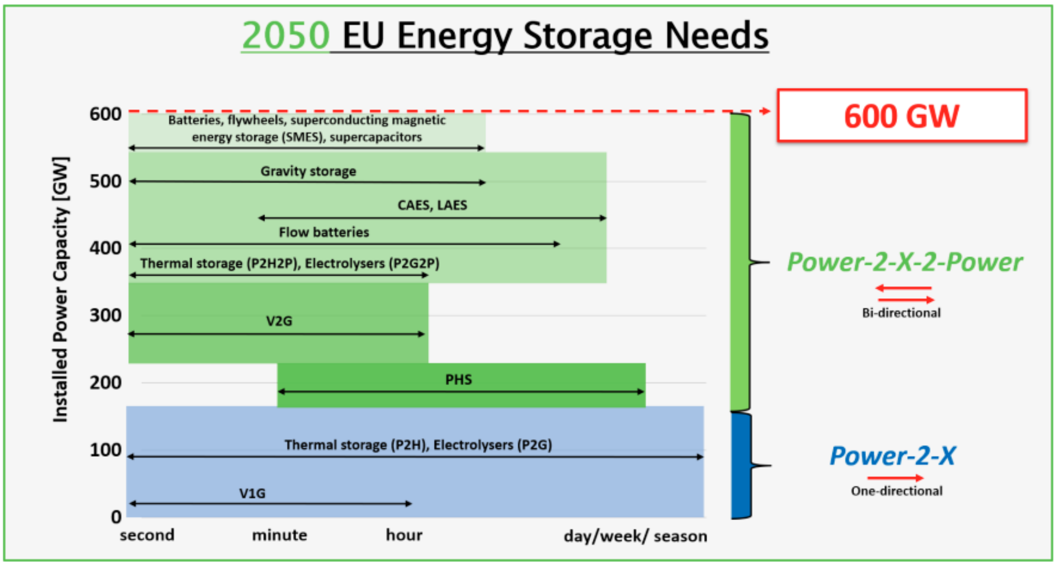

Figure 1.7: European energy storage needs to 2050 [24].

It is easy to find many articles in the literature regarding the implementation of storage systems in new or existing installations. Batteries can be implemented for a variety of purposes. They can do numerous services that can represent a good diversification of uses. In this way batteries can represent a diversified source of remuneration.

From the studies [25][26] a high number of possible uses have emerged, the main and most common among them are:

- Energy Arbitrage Services: batteries can be used to take advantage of fluctuations in electricity prices in the market, buying energy when prices are low and selling it when prices are high, thus generating profit.
- Reserve capacity: batteries can be used as reserve capacity to provide additional power during sudden spikes in demand or unforeseen events in the electricity system, ensuring system stability and safety.
- Frequency management services: storage systems can be used to provide system frequency regulation services, keeping the frequency of electricity in the grid within acceptable limits and ensuring stable and reliable operation of the power system [27].
- Compensation of demand fluctuations: batteries can be used to compensate for fluctuations in energy demand within the system, ensuring a constant flow of energy and reducing the need to use external resources to meet demand variations.
- Optimizing resource utilization: Batteries can be used to optimize the use of available energy resources, enabling more efficient distribution of energy according to the specific needs of the plant and its production processes.
- Voltage and transmission support: an important use that can be made of storage systems is to support the transmission grid by providing additional voltage that is useful for maintaining stable grid voltage levels.
- Reducing forecast errors: another use is to compensate for forecast errors in renewable energy production by ensuring power continuity

through the help of battery power [28].

These are only few possible uses that can be done with storage systems. From [23] is reported this list, which can summarize more clearly all the possible applications.

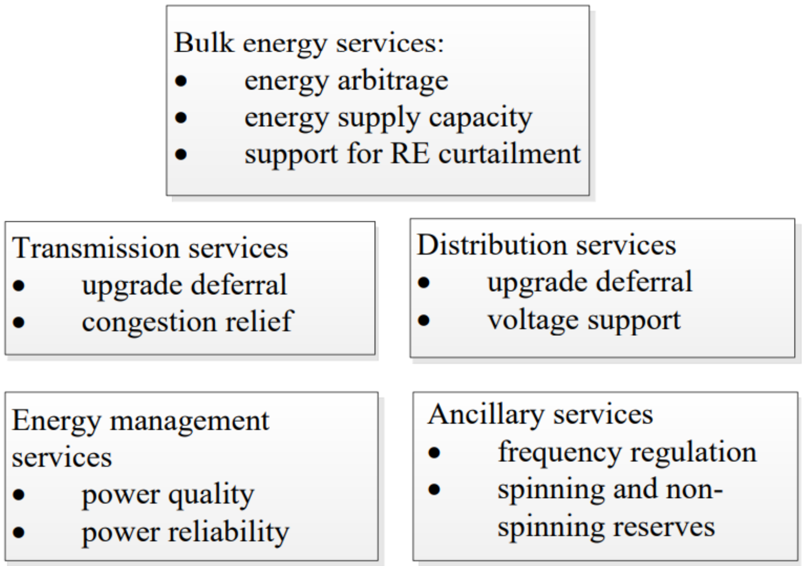

Figure 1.8: List of possible uses of an energy storage system [23].

1.2.1 Lithium batteries overview

Lithium batteries are a key part of the evolution of energy systems, offering an advanced and versatile solution for energy management. Lithium batteries have become a key technology for integrating intermittent renewable energy sources into energy systems, as they enable more efficient and flexible balancing of energy supply and demand. The distinctive characteristics of lithium batteries, such as high energy density, light weight, fast charging capability, and long life associated with low self-discharge losses, make them ideal for a wide range of applications. Lithium battery technology has reached a point where it is cost-effective for large-scale use in power plants, enabling greater penetration of renewable energy into global energy markets [29].

Lithium batteries are known for their reliability and durability. However, it is important to understand how the useful life of these batteries can be affected by various factors. The most relevant are the usage regime, the intensity of charge-discharge operations, and the environmental conditions to which they are subjected.

In particular, factors such as ambient temperature can affect lithium battery performance and longevity. Temperatures that are too high or too low can affect performance and reduce battery life, indicatively, the optimal battery use should be between 20°C and 30°C, as an increase in operating temperature of 10°C above the design value, can result in a 50% reduction in battery life [29]. Therefore, it is important to store and use batteries in appropriate environments, avoiding prolonged exposure to extreme conditions.

In general, the lifespan of a lithium battery is closely related to the percentage of residual capacity it retains over time. It is generally considered that a battery can operate up to 80% residual capacity for electric vehicle batteries. In contrast, for batteries that have less intensive use such as batteries connected to systems, the residual capacity can be made to reach 70% [30].

Several field studies have shown that, with optimal use and proper care, a lithium-ion battery can achieve an operating life of up to 15 years [31]. This figure is based on the assumption of an average use of about one charge and discharge cycle per day, which would allow for more than 5.000 cycles over the life of the battery [32]. However, this value is highly context-dependent, as battery life is closely related to the environmental conditions in which the battery is operated, and especially the intensity of its use. In fact, other studies state that the battery can vary its life in a range from 500 to a maximum of 20.000 equivalent cycles for Lithium-titanate batteries [29].

It is therefore critical to understand that battery longevity also depends on how it is used. Conservative use can contribute significantly to preserving battery capacity in the long term. This involves avoiding fully discharging the battery and leaving it completely discharged for long periods of time. Ideally, one should keep the battery charge between 20% and 80% of its maximum capacity in order to keep it healthy [30]. This reduces stress on the battery and minimizes phenomena such as "depth discharge," which can compromise the life of the battery.

1.2.2 BESS in wind plants, literature review

Several applications of storage systems in wind power plants can be found in the literature. Bera et al. [33] have tested a sizing approach for a BESS coupled with a wind turbine to provide inertial support and minimize the amount of energy lost due to curtailment. The optimization is done using an algorithm that exploits a MonteCarlo method (MCS), and as a result, different battery sizes are obtained that vary depending on the case under consideration.

Fan et al. [34] explain the case of a BESS connection to a wind farm located in England. The purpose of the connection is to provide enhanced frequency control. The optimization is done through a particle swarm optimization (PSO) algorithm that is used specifically to determine the size of the BESS and the other variables related to the state of charge (SOC). They go to maximize the NPV related to this case. The study shows that the case of a wind farm coupled with a BESS results in a 1% loss in profitability compared to the case where only the wind farm is considered. It is important to note, that by avoiding construction and connection costs, the profitability of the BESS coupled with the wind farm increases significantly compared to the case of the presence of the wind farm alone.

Mokhtare and Keysan [35] performed an analysis related to wind farms present in Turkey. The analysis is carried out with a mixed integer non-linear programming (MILNP) which is useful to do a two-level technical-economic optimization. This algorithm is useful to maximize the annual profit by finding the optimal capacity of the storage system. The optimization has achieved good results since that the global annual profits have increased.

Das et al. [28] used an approach related to day-ahead prices (day ahead market) thus going to exploit for recharging, the best price available in the market, in order to ensure the highest possible profit. With this method, very satisfactory results were obtained, yielding a 10% higher gain than in the case without batteries.

Lobato et al. [36] on the other hand, analyze a case related to the Spanish market in which a BESS is coupled to a 30 MW wind power plant. In this study the storage is used for different market applications, such as: utilization in the balancing market, use for day-ahead price arbitrage, schedule tracking by reducing wind deviations. The results obtained showed that only the balancing market could make the battery profitable as far as the Spanish case is concerned. Instead, the other market approaches examined, did not show a significant increase in revenues.

Frate et al. [37] proposed a study of an Italian wind farm placed in Sicily, coupled with a Li-ion battery. This analysis consists in a techno-economic optimization of the battery, which is done by taking into account the day-ahead market prices. The optimization is done by scheduling the wind production with a MILP (mixed integer linear programming) algorithm using a 24-hour rolling horizon. Taking into account the BESS degradation related to the number of cycles, this study concludes that an optimal size of the battery is approximately of 4h of discharge duration for a battery lifetime of 6-7 year.

Rayit et al. [38], carried out a study related to the implementation of a battery in a wind power plant which is useful for covering peak electricity demand. This application can reduce the utilization of gas turbines for cover the peaks. It was shown that under certain favorable conditions, this can be an economically favorable use.

Chapter 2

Methodology

2.1 MILP algorithm

The leading process of the work was based on the use of a Mixed Integer Linear programming (MILP) optimization algorithm, which by taking the input data provided, goes to get as output the optimized BESS operation over a specific time window. The optimization consists in an optimal management of the battery, maximizing the profits achievable by doing energy arbitrage. The Python-based algorithm was taken and adapted from the work proposed by Grimaldi et al. [39].

Specifically, it consists of working with an optimization window of 168h corresponding to one week, with a time resolution of 1h. In this way, the actual behavior of the battery can be evaluated. Characteristic data, such as residual capacity, can be obtained from the analysis, which would be difficult to take into account in the case of simulations made on a single-year basis.

The simulations receive as input data files containing: the hourly price, the power that can be produced by the system as a function of wind velocity, and the dispatch order. The battery works with a charging efficiency equal to the discharging efficiency. Both have a value of 0.9, so the total AC/AC round-trip efficiency of charging and discharging amounts to 81%.

What is done in the concrete to perform the optimization is to maximize the objective function. It is composed by the revenues, formed by the gains obtained by selling energy to the grid from wind plant $\mathbb{R}_{\text{exp}}^{\text{wind}}(t)$ and from the BESS $\mathbb{R}_{\text{exp}}^{\text{BESS}}(t)$.

These revenue flows are diminished by the following costs:

- $\mathbb{C}_{\text{imp}}(t)$ which is the cost of importing the energy to charge the battery from the grid.
- $\mathbb{C}_{\text{deg}}(t)$ which is the cost of battery degradation, since over time the battery loses capacity and will no longer be able to accumulate the same amount of energy as at the beginning of its use.
- $\mathbb{C}_{\text{curt}}(t)$ which is the cost of curtailment. It represents the cost of the energy that neither be sold to the grid (due to a dispatch order) nor be charged into the battery, which is therefore considered a loss.

Among these factors, revenues are put positive, while instead costs are put negative, so that the objective function goes to maximize revenues and minimize costs, thus maximizing the overall profit of the battery installation.

$$\begin{aligned}\max\{obj\} &= \max\left\{\sum_{t=1}^{T}\mathbb{P}(t)\right\}\\ &= \max\left\{\sum_{t=1}^{T}\mathbb{R}_{\text{exp}}^{\text{wind}}(t)+\mathbb{R}_{\text{exp}}^{\text{BESS}}(t)-\mathbb{C}_{\text{imp}}(t)-\mathbb{C}_{\text{deg}}(t)-\mathbb{C}_{\text{curt}}(t)\right\}\end{aligned} \tag{2.1}$$

Taking into account the individual factors in detail, we can report that revenues can be obtained in two ways: the wind revenues, obtained multiplying the energy price EP(t) times the wind power flow $\mathbb{R}_{\text{exp}}^{\text{wind}}(t)$ discharged to the grid for each timestep Δt, and the BESS revenues $\mathbb{R}_{\text{exp}}^{\text{BESS}}$, which are obtained by multiplying the energy price to the BESS discharged power $P_{dh}^{\text{BESS}}(t)$ for each timestep Δt.

$$\mathbb{R}_{\text{exp}}^{\text{wind}}=\sum_{t=1}^{T}EP(t)\cdot P_{grid}^{\text{wind}}(t)\cdot\Delta t\quad\forall t\in T\ [€] \tag{2.2}$$

$$\mathbb{R}_{\text{exp}}^{\text{BESS}} = \sum_{t=1}^{T} EP(t) \cdot P_{dh}^{\text{BESS}}(t) \cdot \Delta t \quad \forall t \in T \text{ [€]} \tag{2.3}$$

The cost of importing energy $\mathbb{C}_{imp}(t)$, on the other hand, is calculated by multiplying EP(t) times the charging energy of BESS from the grid $P_{ch-grid}^{\text{BESS}}(t)$ for each timestep Δt. The equation (2.5) is simply calculated by multiplying the energy price times the power loss.

$$\mathbb{C}_{imp}(t) = \sum_{t=1}^{T} EP(t) \cdot [P_{ch-grid}^{\text{BESS}}(t) \cdot \Delta t] \quad \forall t \in T \text{ [€]} \tag{2.4}$$

$$\mathbb{C}_{\text{curt}}(t) = \sum_{t=1}^{T} EP(t) \cdot P_{loss}(t) \quad \forall t \in T \text{ [€]} \tag{2.5}$$

Regarding the study on battery aging, the following work was taken into consideration [40]. The degradation cost is calculated multiplying a degradation factor $\mu_{\text{deg},j}$ to the charge and discharge power of the BESS. The charging power is composed by the two charging sources of the BESS, so the charging from the wind $P_{\text{ch-wind}}^{\text{BESS}}(t)$ and the charging from the grid $P_{\text{ch-grid}}^{\text{BESS}}(t)$. Also in this case, all the factors are evaluated for each time step.

As mentioned, in the degradation cost a degradation coefficient $\mu_{\text{deg},j}$ is reported, as a representation of battery degradation after each time step j corresponding to the 168h optimization interval. This coefficient is calculated by multiplying the degradation cost DEG_{cost} times the difference between the capacity of the battery at the start of the episode j ($E_{\text{start},j}^{\text{rem}}$) and at the end ($E_{\text{end},j}^{\text{rem}}$). Those two terms are divided by 100 and multiplied to the BESS nominal capacity $E_{\text{nom}}^{\text{BESS}}$ (because they are defined as a percentage of the initial capacity). All is divided by the power of the previous episode P_{prev}.

$$\mathbb{C}_{\text{deg}}(t) = \sum_{j=1}^{T} \mu_{\text{deg},j} \cdot [P^{\text{BESS}}_{\text{ch-wind}}(t) + P^{\text{BESS}}_{\text{ch-grid}}(t) + P^{\text{BESS}}_{\text{dh}}(t)] \cdot \Delta t \quad \forall t \in T \text{ [€]} \tag{2.6}$$

$$\mu_{\text{deg},j} = [\frac{\left(\frac{(E^{\text{rem}}_{\text{start},j} - E^{\text{rem}}_{\text{end},j})}{100} \cdot E^{\text{BESS}}_{\text{nom}}\right)}{\sum_{j=1}^{T} P_{\text{prev}}(t)}] \cdot DEG_{\text{cost}} \tag{2.7}$$

The degradation function DEG_{cost} is calculated by dividing a standard battery investment cost of 200 €/kWh by the expected number of years of the lifetime of the battery (which is considered to be 15 years). The obtained value is then multiplied to the remaining capacity minus the end-of-life capacity (70%) and all divided by the maximum capacity loss acceptable for a stationary battery, equivalent to the difference between 100% (beginning-of-life condition) and 70% (remaining capacity at end-of-life condition).

$$DEG_{\text{cost}} = 13333 \cdot (\frac{E^{\text{rem}}_{\text{end},j} - 70}{100 - 70}) \tag{2.8}$$

Regarding the battery degradation trend, a degradation curve was used, which as mentioned, allows for a remaining battery capacity of 70%. This curve was derived and adapted from [39] [41]. Specifically, what was done was to study the aging and degradation of batteries. From this the characteristic curve representing this trend was derived. The curve is a 6^{th} degree equation that varies according to the number of cycles performed by the battery. This curve, however, was designed to go up to a degradation of 80%, which can be reached by performing a number of 3771 cycles. As mentioned, however, in our case it was decided that the battery should be exploited up to 70% remaining capacity. Therefore, the original 6^{th} degree curve was modified into a 9^{th} degree equation, capable of reaching 70% capacity remaining at 6147 cycles.

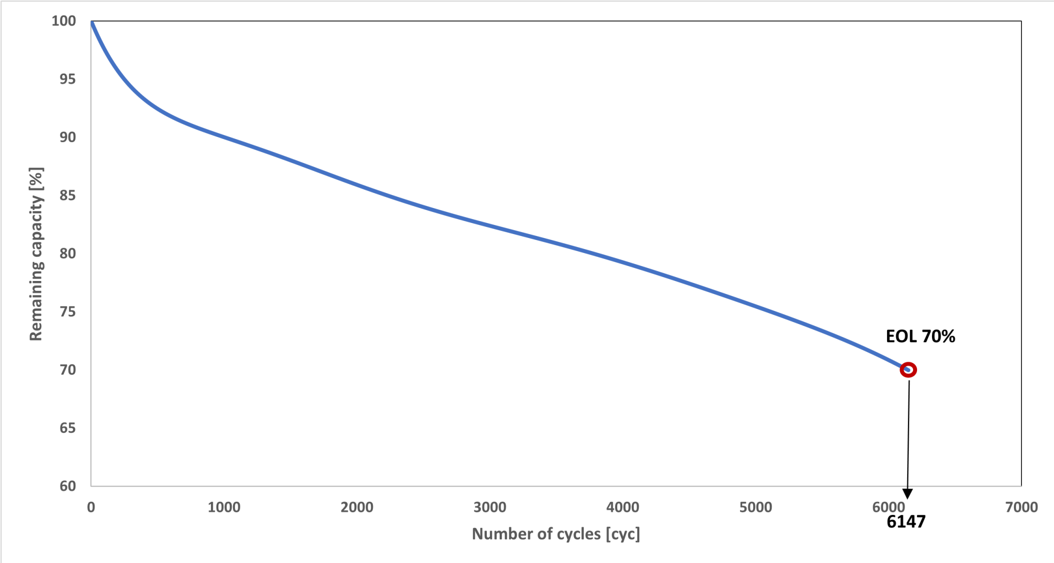

Figure 2.1: 9^{th} degree degradation function.

Continuous constraints represent those referring to continuous variables that impose limits on the algorithm regarding plant-related values that must be met. The equation (2.9) says that the power injected to the grid by the sum of the wind power and the BESS discharge, as to be lower or equal to the dispatching order power $P_{odd}(t)$ requested by the grid transmission operator.

$$P_{grid}^{\text{wind}}(t) + P_{dh}^{\text{BESS}}(t) \leq P_{odd}(t) \quad \forall t \in T \tag{2.9}$$

The following equations (2.10) (2.11) represent the constraints related to the maximum power of the BESS: the power charged by the BESS from the wind plant $P_{\text{ch-wind}}^{\text{BESS}}(t)$ and the power discharged by the BESS $P_{\text{dh}}^{\text{BESS}}(t)$ to the grid must be lower than or equal to the BESS nominal power $P_{\text{nom}}^{\text{BESS}}$, and higher than equal to the BESS minimum power (that is assumed equal to zero).

$$0 \leq P_{\text{ch-wind}}^{\text{BESS}}(t) \cdot \beta_{\text{ch-wind}}^{\text{BESS}}(t) \leq P_{\text{nom}}^{\text{BESS}} \quad \forall t \in T \tag{2.10}$$

$$0 \leq P_{\text{dh}}^{\text{BESS}}(t) \cdot \beta_{\text{dh}}(t) \leq P_{\text{nom}}^{\text{BESS}} \quad \forall t \in T \tag{2.11}$$

Whereas the equation (2.12) says that when the BESS charges from the grid, the power charged has to be higher or equal than the minimum power value, and lower or equal to BESS nominal power $P_{\text{nom}}^{\text{BESS}}(t)$.

$$0 \leq P_{\text{ch-grid}}^{\text{BESS}}(t) \cdot \beta_{\text{ch-grid}}^{\text{BESS}}(t) \leq P_{\text{nom}}^{\text{BESS}} \quad \forall t \in T \tag{2.12}$$

Taking into account the values of the state of charge of the battery, the following equation represents the values in between the state of charge (SOC) of the battery as to be maintained. Particularly, it is important to avoid a discharge of the battery to a value lower than the 20% because depth of discharges too high will accelerate the degradation of the storage system.

$$0.2 \cdot E_{\text{BESS}}^{\text{nom}} \cdot (E_{\text{end},j}^{\text{rem}}/100) \leq \text{SOC}(t) \leq E_{\text{BESS}}^{\text{nom}} \cdot (E_{\text{end},j}^{\text{rem}}/100) \quad \forall t \in T \tag{2.13}$$

These next two equations represent a single one that is divided into two. The first one represents the initial state of charge of the battery. The second represents all subsequent states of charge that update based on the previous one. Particularly these equations represent the evolution of the state of charge of the BESS, which varies in function of the energy flows that affect the battery. This equation also features the efficiencies of charge $\eta_{\text{ch-wind}}^{\text{BESS}}$, $\eta_{\text{ch-grid}}^{\text{BESS}}$ and discharge $\eta_{\text{dh}}^{\text{BESS}}$ to take into account the losses which can be present during the charging and discharging phases, and also the self-discharge losses $\eta_{\text{self}}^{\text{BESS}}$.

$$\mathrm{SOC}(t) = 0.5 \cdot E_{\text{nom}}^{\text{BESS}} + \left[P_{\text{ch-wind}}^{\text{BESS}}(t) \cdot \eta_{\text{ch-wind}}^{\text{BESS}} \cdot \Delta t\right] + \left[P_{\text{ch-grid}}^{\text{BESS}}(t) \cdot \eta_{\text{ch-grid}}^{\text{BESS}} \cdot \Delta t\right] \\ - \left[\left(P_{\text{dh}}^{\text{BESS}}(t) / \eta_{\text{dh}}^{\text{BESS}}\right) \cdot \Delta t\right] \quad \forall t \in T : t = 0 \quad [\text{MWh}] \tag{2.14}$$

$$\mathrm{SOC}(t) = \mathrm{SOC}(t-1) \cdot \eta_{\text{self}}^{\text{BESS}} + \left[P_{\text{ch-wind}}^{\text{BESS}}(t) \cdot \eta_{ch-\text{ wind}}^{\text{BESS}} \cdot \Delta t\right] + \left[P_{\text{ch-grid}}^{\text{BESS}}(t) \cdot \eta_{\text{ch-grid}}^{\text{BESS}} \cdot \Delta t\right] \\ - \left[\left(P_{\text{dh}}^{\text{BESS}}(t) / \eta_{\text{dh}}^{\text{BESS}}\right) \cdot \Delta t\right] \quad \forall t \in T \geq 1 \quad [MWh] \tag{2.15}$$

The equation (2.16) calculates the fractional number of cycles with respect to a complete cycle (represented by one full charge and one full discharge) performed over time Δt.

$$Cyc_{rate}(t) = \left[\frac{(P_{\text{ch-wind}}^{\text{BESS}}(t) + P_{\text{ch-grid}}^{\text{BESS}}(t) + P_{\text{dh}}^{\text{BESS}}(t)) \cdot \Delta t}{E_{\text{BESS}}^{\text{nom}}}\right] / 2 \quad [-] \tag{2.16}$$

Instead, the equations (2.17) and (2.18) represent the calculation of the cumulative number of cycles done by the battery. The first equation is related to the first-time step, whereas the second equation is related to all the following timesteps.

$$Cyc_{\text{rate}}^{\text{cum}}(t) = Cyc_{rate}(t) + cycle_{num} \quad \forall\, t \in T:\ t = 0 \tag{2.17}$$

$$Cyc_{\text{rate}}^{\text{cum}}(t) = Cyc_{\text{rate}}^{\text{cum}}(t-1) + Cyc_{rate}(t) \quad \forall\, t \in T:\ t \geq 1 \tag{2.18}$$

At this point it is important to represent the integer constraints: these constraints are important to restrict the feasibility region of the MILP-based algorithm solution. Particularly avoid cases which the BESS execute charging and discharging processes at the same time, but allows it to execute them one at a time through the help of the previously mentioned booleans $\beta_{\text{ch}}(t)$ and $\beta_{\text{dh}}(t)$. They can assume the value of 1 when the energy flow is allowed, otherwise they assume a value equal to 0. In the optimization algorithm it is necessary to use the bigM method [42] which would be an extension of the simplex algorithm. To apply it, it is necessary to start from an initial feasible solution, which is taken as a very large integer value of 5.000.000. This is taken because it represents a value that cannot be reached by the variables processed in the problem. This is entered into inequality constraints as a negative or positive value that cannot be reached, so it will always remain greater or less than the values being considered.

The equations (2.19) (2.20) refer to the BESS charge power from the wind farm or from the grid. They say that the BESS is in discharging phase $\beta_{\text{ch}}(t)$=0, its charging power flow $P_{\text{ch}}^{\text{BESS}}(t)$ must be no less than zero. If, on the other hand, the BESS is charging $\beta_{\text{ch}}(t)$=1, its charging power flow $P_{\text{ch}}^{\text{BESS}}(t)$ must be greater than or equal to a redundant negative lower limit (-bigM =-5.000.000) that is at least two orders of magnitude lower than any feasible value. Is important to notice that also in the following equations, when we refer to the bigM factor, it will have these dimensions.

$$P_{\text{ch-wind}}^{\text{BESS}}(t) \geq 0 - \text{bigM} \cdot \beta_{\text{ch-wind}}^{\text{BESS}}(t) \quad \forall t \in T \tag{2.19}$$

$$P_{\text{ch-grid}}^{\text{BESS}}(t) \geq 0 - \text{bigM} \cdot \beta_{\text{ch-grid}}^{\text{BESS}}(t) \quad \forall t \in T \tag{2.20}$$

Equation (2.21) represents an inequality constraint that in the case of discharge, $\beta_{\text{dh}}^{\text{BESS}}(t)$=1, the charging power flow of the BESS must be less than or equal to zero. Whereas in the case of charging, we will have $\beta_{\text{dh}}^{\text{BESS}}(t)$=0, and at the same time we will have the charging power of the BESS which must be less than or equal to a positive upper limit (bigM = 5.000,000).

$$\left(P^{\text{BESS}}_{\text{ch-wind}}(t)\cdot\beta^{\text{BESS}}_{\text{ch-wind}}\right)+\left(P^{\text{BESS}}_{\text{ch-grid}}(t)\cdot\beta^{\text{BESS}}_{\text{ch-grid}}(t)\right)\leq 0+\text{ bigM }\cdot\left(1-\beta^{\text{BESS}}_{\text{dh}}(t)\right)\quad\forall t\in T \tag{2.21}$$

The equation (2.22) refers to the discharge power of the BESS $P^{\text{BESS}}_{\text{dh}}(t)$, which in the case of discharge, $\beta^{\text{BESS}}_{\text{ch}}(t)$=0, will have to be greater than or equal to a negative lower limit (-bigM = -5.000,000). Instead, in case of BESS charge phase, $\beta^{\text{BESS}}_{\text{ch}}(t)$=1, the BESS discharge power flow will have to be greater than or equal to zero.

$$P^{\text{BESS}}_{\text{dh}}(t)\geq 0-\text{bigM}\cdot(1-\beta^{\text{BESS}}_{\text{ch-wind}}-\beta^{\text{BESS}}_{\text{ch-grid}})\quad\forall t\in T \tag{2.22}$$

The equation (2.23) refers to the discharge power of the BESS $P^{\text{BESS}}_{\text{dh}}(t)$ that in the case of discharge, $\beta^{\text{BESS}}_{\text{dh}}(t)$=1, the discharge power will have to be less than or equal to a positive upper limit (bigM = 5.000.000). In case of charge, $\beta^{\text{BESS}}_{\text{dh}}(t)$=0, the discharge power flow of the battery must be less than or equal to zero.

$$P^{\text{BESS}}_{\text{dh}}(t)\leq 0+\text{bigM}\cdot\beta^{\text{BESS}}_{\text{dh}}(t)\quad\forall t\in T \tag{2.23}$$

As a last, equation (2.24) represents the constraint that makes the sum between the charging $\beta^{\text{BESS}}_{\text{ch-wind}}$, $\beta^{\text{BESS}}_{\text{ch-grid}}$ and discharging $\beta^{\text{BESS}}_{\text{dh}}(t)$ booleans always less than or equal to one. This ensure that the battery does not perform simultaneous charging and discharging operations.

$$\beta^{\text{BESS}}_{\text{ch-wind}}+\beta^{\text{BESS}}_{\text{ch-grid}}+\beta^{\text{BESS}}_{\text{dh}}(t)\leq 1\quad\forall t\in T \tag{2.24}$$

2.2 Case study

Taking into consideration all the aspects mentioned in the previous chapters, the purpose of this thesis work, will be to analyse a future scenario in which Terna no longer goes to remunerate lost production. This scenario would obviously result in a loss of renewable energy produced. This looking to a future scenario, where is predicted a significantly greater amount of energy generated from wind power plants, could result in a significant loss in environmental and economic terms.

To carry out this analysis, a wind field located in Southern-Italy was considered. The wind plant consists of several turbines, with a total rated field power of 38 MW. The wind plant has been selected as representative of the average curtailment behaviour of the Italian on-shore wind park in the period 2015-2023 (approximately 3% of curtailed energy, with respect to the overall wind production). Taking into account the historical data recorded from 2018 to 2022, this percentage, corresponds approximately to 2,8 GWh of energy curtailed.

Table 2.1: Wind farm data.

Description	Value
Wind farm rated capacity	38 MW
Acquisition history	2015 - 2023
Average yearly curtailment (2018-2022)	2.8 GWh

The purpose of the work will be to process real data for the plant under investigation. Those datasets contain recordings of the power produced by each individual turbine with 10-minute detection intervals. For the same fraction of acquisition time, we also have data on: wind speed in m/s, temperature in degrees Celsius, and any dispatch order requested by Terna in MW. Using these data and the zonal prices downloaded from the Gestore dei mercati energetici (GME) website [43], an optimization related to battery operation will be performed. The optimization will be processed through the previously described MILP algorithm that will take the input files and process them to obtain as output parameters that will represent the optimal wind-battery system operation in a given time frame. These factors will be explained in detail in the following chapters.

The output data obtained, will then be processed in an economic analysis, to evaluate the possible profitability of this investment. Particularly in the first instance, also considering similar analysis in the literature, it was considered reasonable to carry out an analysis to calculate the Net Present Value (NPV). In addition, it was considered appropriate to also evaluate the value of the Levelized Cost Of Storage (LCOS) so as to have a second evaluation useful to have a broader view of the case. For the input data of the simulations, it was deemed more sensible to use real data recorded over the years in the plant under consideration. This choice is preferable rather than using scenario data that being only assumptions, could generate not very reliable results. Therefore, the data used are historical data recorded in the plant, ranging from 2015 to 2023. A 15-year profile has then been constructed by repeating them over the years in order to have more complete series, the specific techniques of assembling the data will be explained later in this thesis work.

At this point it is worth to introduce a description of the scheme of the entire plant designed for this thesis work to represent more clearly the logic behind the system and the assumptions that were made.

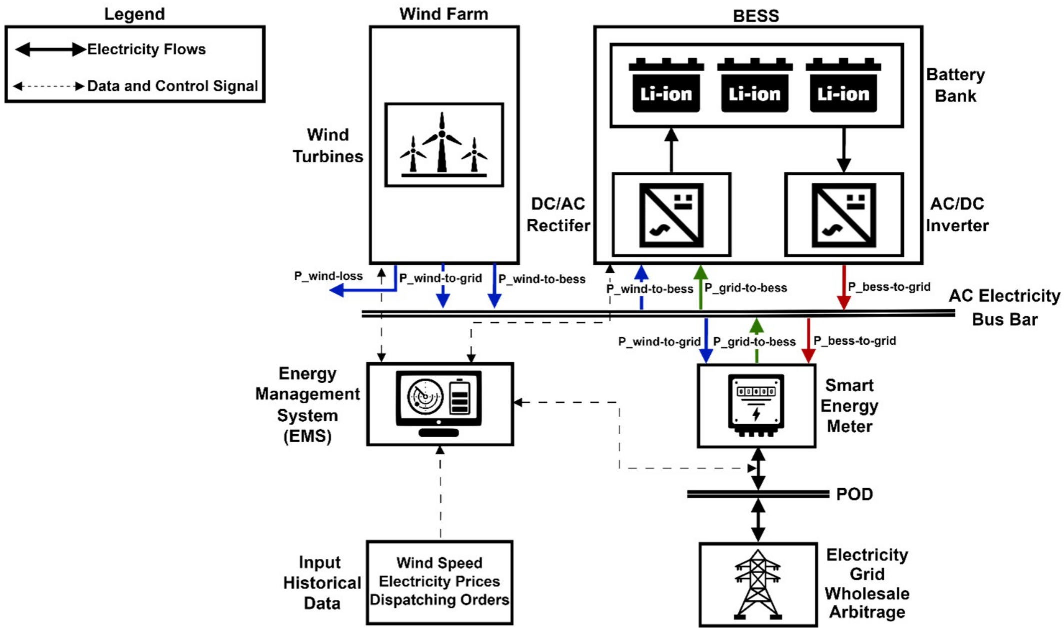

Figure 2.2: Wind plant and BESS system layout.

The schematic shown represents the plant under analysis. It consists of the wind power plant that is schematized in the upper left corner. From it three blue-colored streams depart to the AC electricity bus, which go to represent the flows of electricity produced that go to the battery and the power grid. Moreover, a third blue flow represents residual wind-farm energy losses due to curtailment orders. The purpose of this work is to reduce as much as possible this energy flow. However, there are few cases when there is a curtailment request, and at the same time, the battery is already charged. In this situation it is impossible to force a further battery charge, thus the system is forced to accept an energy loss.

The BESS system is connected in parallel to the wind farm; it is composed of the battery bank, connected to a bidirectional inverter (AC/DC rectifier used during charge phase and DC/AC inverter for the discharge phase). At the connection point between the renewable plant bus and the grid, is placed a smart energy meter, which allows to measure the electricity exchanged.

All system operation is driven by an Energy Management System (EMS) that makes the whole system run as efficiently as possible. Specifically, it takes as input data: wind speed, electricity prices, and dispatch orders given by the power grid operator. Based on the continuous and integers constraints of the optimization algorithm, the EMS goes about coordinating the system in the most efficient way possible. The battery has been programmed to work by performing energy arbitrage. It means, going to charge the battery when the energy price is low and discharging it when the energy price is high. This makes the battery utilization optimal to ensure the highest possible gains.

It is important to note that there are three different colors of flows in the schematic. This coloring was applied to easily distinguish the blue flows, which are those produced by the wind farm. The red flows, on the other hand, are those coming out of the battery. The green flows represent the flows taken from the grid that go to charge the battery.

Importantly, figure 2.2 shows the layout in which the battery can be recharged both from the wind and from the grid, in the case where it is cost-effective. In this thesis work, two configurations will be studied: one corresponding to the case just mentioned, while the other consists of a layout that does not allow charging from the battery from the grid. In this way, it will be possible to compare the results in the two cases and to evaluate the economic impact of the contribution of charging from the grid in an energy arbitrage application of a real wind farm.

In the next chapters there will be explained a statistical analysis done on the occurrences of curtailment phenomena. Now it is deemed appropriate to consider a battery that could also be charged from the grid. This configuration is necessary, as the low frequency and intensity of curtailment phenomena, did not allow the full potential of the storage system to be exploited. At the current conditions, the battery results underutilized, thus making the battery installation unprofitable. The configuration with charging also from the grid, on the other hand, made it possible to guarantee a much higher number of cycles of battery use. This is due to the fact that the battery can be charged at any time, not only during curtailment phenomena. Thus guaranteeing, a use that try to justify the investment of its purchase.

2.3 Data sources and inputs

As previously announced, the data used for this analysis came from a real plant placed in Southern Italy.

The work began by taking the historical data of the plant and subjecting it to preliminary cleaning and filtering in order to eliminate errors in the data files. Analysis of the available power data showed congruence with the power curves provided by the manufacturer. The recorded operating points showed very good overlap with the power curve, confirming the quality of the data available, and the correctness of scaling up a correlation between generated power and wind speed from a single turbine to the overall wind farm.

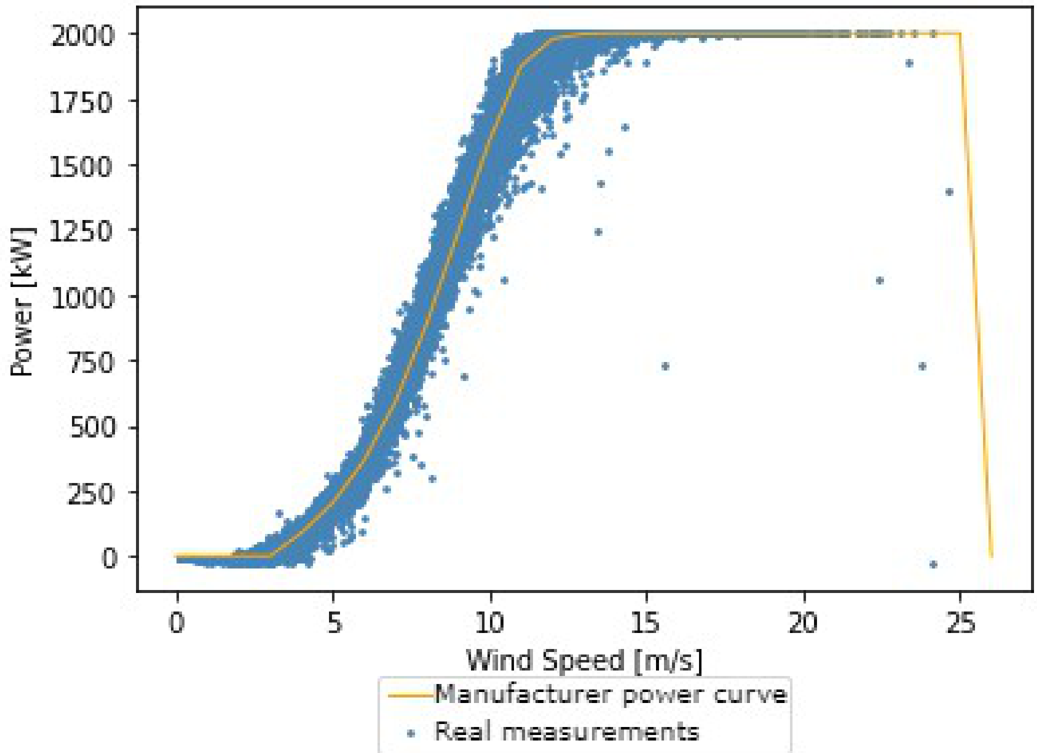

Figure 2.3: Power curve fitting with data.

From a subsequent statistical analysis on the historical data present, the following cumulative distribution showing the required powers for the curtailment events was obtained. From it can be deduced that with a 19 MW battery power, 95% of the curtailment requests could be covered. Therefore, at the initial stage of the feasibility study, the battery power was taken as the reference, which corresponds to exactly half of the field power.

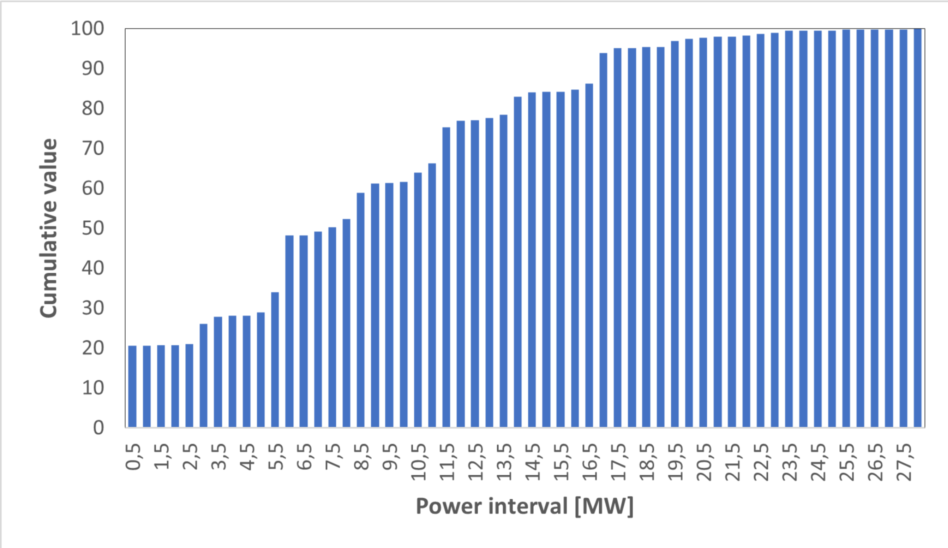

Figure 2.4: Maximum power required during curtailment events [MW].

Following this initial analysis, which was necessary to understand what the possible dimensions of the BESS, the following step are to process the input data needed by the algorithm. Before entering the data within the optimization algorithm, work had to be done to reformulate the data so that it would be congruent with how the optimization code would work.

It is important to note that an approximation was made for the input data, which was necessary to have a data set that was not compromised by errors of various kinds. Specifically, as producible power was considered the theoretical power, that means the power relative to the wind speed measured by the SCADA sensing system implemented on each turbine.

It was preferred to consider this power rather than the power recorded from the field, as this resulted in numerous errors that did not give an accurate representation of the field's production potential. Some of these measurement errors include, for example: recording errors, fault and maintenance related error codes.

This decision made it possible to give a clearer representation of what the wind field production could be as a function of wind force alone.

Other key data for the simulations that were obtained from this prior analysis are those related to the dispatch order required by the grid operator. For simplicity in the remainder of this thesis work they will be referred to as “ODD” which is the acronym of the Italian definition "ordine di dispacciamento".

It is important to note that dispatch orders have values ranging from 0 to the rated power of the plant. A value of 0 represents a total blocking of energy input to the grid, so it means 100% curtailment value, where the plant blades must all be blocked. In the case that there are values greater than zero but less than the nominal power, this means that if there is a wind resource greater than this value, the system will have to work at partial load. This means that either the turbines will have to be limited to produce, but with less power than can be delivered at that time. Alternatively, only some of them will have to be stopped, while the others can produce at maximum power. This situation can occur in case of maintenance to individual turbines.

On the other hand, when there are no dispatch orders from the grid operator, the allowable power is considered to be equal to the rated power of the wind turbine plus the rated power of the battery. In this way, the optimization code can recognize the possibility of feeding the maximum deliverable power into the grid without limitation, obviously in the presence of a favorable price match.

As for battery utilization, there were several attempts to figure out what would be its best use, so as to optimize costs as much as possible and avoid underutilization of the battery. Initially, as announced earlier, the purpose of the analysis was supposed to be to implement the battery to go to recover the energy lost in curtailment events, so as to reduce the loss of renewable energy produced.

To do this, the algorithm in its initial form, written to take as key inputs the power producible from the wind called “wind” and the dispatch order required by the operator Terna, was used. Based on these two data, the algorithm then goes to charge or discharge the battery in the most efficient configuration possible. In fact, as shown in the figure 2.5, it is possible to note the constant compliance with the ODD value in the battery discharge and wind energy feeding phases. In contrast, in cases where a wind resource is present, and at the same time there is a dispatch order, there are green columns representing the battery charging phase. These represent battery utilization that goes to avoid wasting wind power.

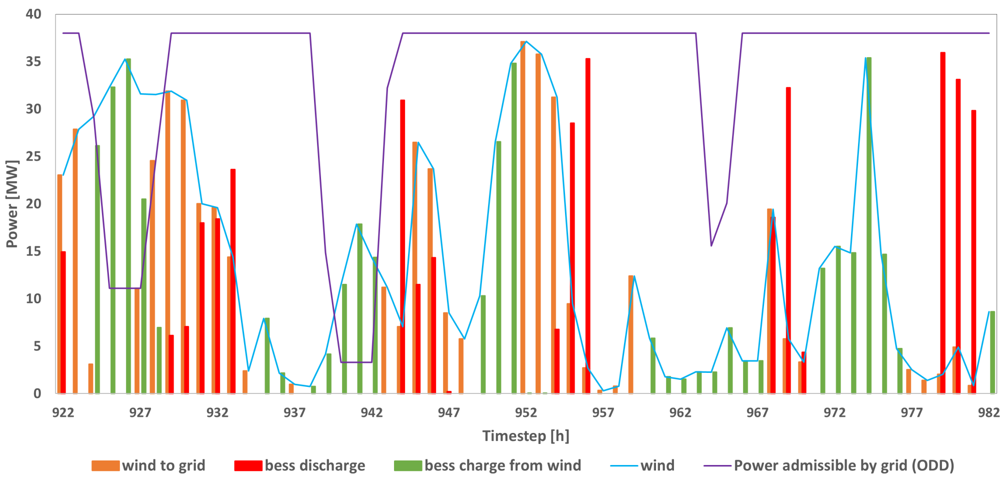

Figure 2.5: BESS operation with only curtailment.

At this point the algorithm worked properly allowing the optimal use of the battery so as to recover all the energy subject to curtailment. However, it was deemed reasonable to try to expand the range of use of the battery. The idea was to exploit it even at times when there is no demand for curtailment, and find other alternative uses so as to create a profit from its use. Therefore, it was decided to try to implement an additional use chosen from those described in the literature review conducted in this thesis work 1.2.2.

Among all the alternative utilization modes, the arbitrage use was chosen. This BESS application consists of going to charge the battery when there is a low energy price, so as to recharge it while spending as less as possible. After that, wait until the energy price reaches a higher level and discharge the battery. In this way with a simple charge and discharge, a guaranteed net profit is achieved. In the figure 2.6 is represented an example of the BESS working doing arbitrage. It is clear to see that the storage system tends to recharge when the energy price is low and discharge when the energy price is high.

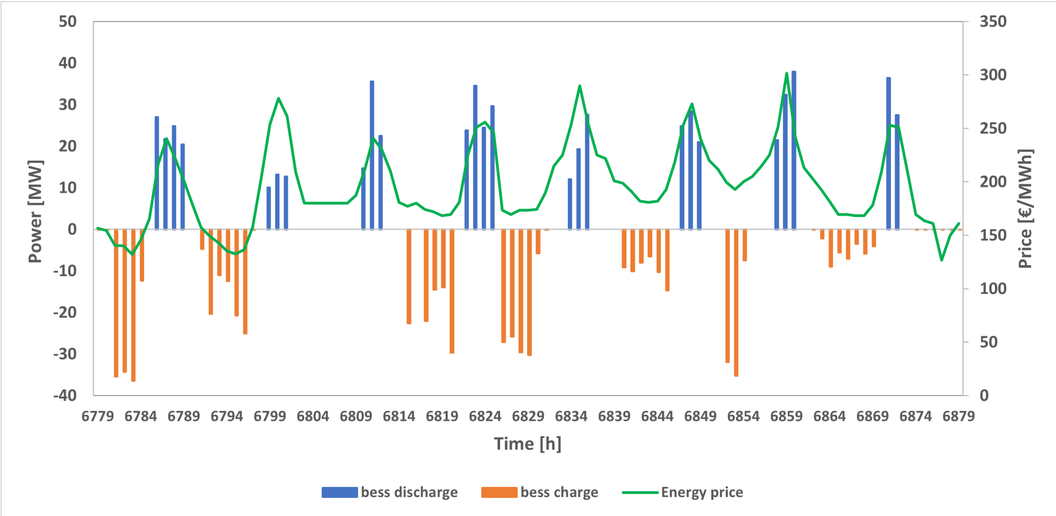

Figure 2.6: BESS price arbitrage operation.

The application of arbitrage thus results in a better utilization of the battery. This is because it is allowed to charge no longer exclusively from the energy subject to curtailment, but also from the energy produced in general by the wind farm. This obviously results in significantly greater battery utilization, which can then complete a much higher number of cycles.

The following figure shows an example comparing different battery use cases. Specifically shown is an example with a 6h battery discharge with price, wind and ODD data from 2021. From these the different cases considered were calculated. The "No battery" case, refer to the case where only the wind farm is present without the battery: good portion of the total energy that is lost can be clearly seen in red, called Ploss which represents 2% of the total.

Next, the case in which the battery is used for the "only curtailment" case is reported, in which a significant reduction in lost Ploss power can be seen compared to the case in which there is no battery installed in the system, thus ensuring a rescue of energy that would otherwise be lost.

The remaining two cases shown are those for arbitrage taken individually, and arbitrage combined with energy recovery subjected to curtailment. From these two columns, it can be seen that the choice to use the battery also for alternative uses such as arbitrage is a good strategy. In fact, the battery is used more frequently, thus helping to exploit the storage system to its fullest by having it perform a greater number of cycles. This means being able to better amortize the cost of buying the battery due to the net gain from this use, and also opening up the possibility of making a net profit, thus making the battery an investment.

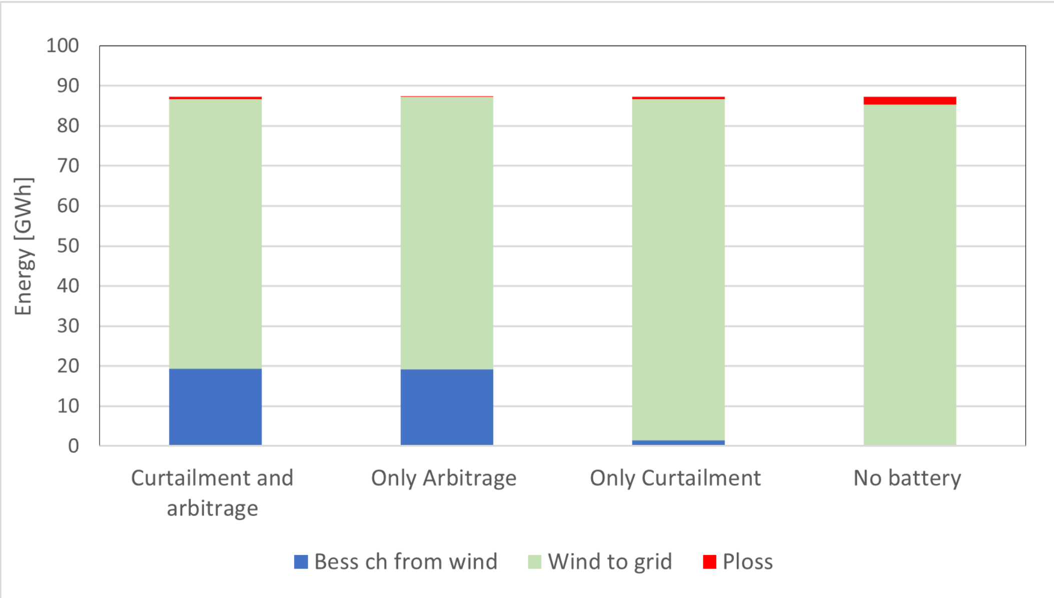

Figure 2.7: Different BESS operation comparison with data of 2021 and 6h discharge battery.

In the following analyses the simulations performed with this configuration, will be labeled as "no grid charging" so called to distinguish them from the other examined case that will be explained later.

Obviously, in order to be able to employ this technique, it is necessary to know the energy price profile well, so that the optimization algorithm knows perfectly which are the most pronounced peaks and valleys in the price profile. In this way it will be possible to perform charging and discharging with the largest possible price spread and ensure the highest possible gain. It is crucial to point out that the price profile can guarantee optimal battery performance, in the presence of a price that has high average values, but above all highly variable values. This in fact turns out to be the key factor for the optimal functioning of the algorithm. It is also important to point out that the need for prior knowledge of the profile implies a limitation in view of the application of the algorithm to future cases, as it is necessary to know a well-defined price profile. This means that a price scenario study will be necessary, which given the uncertainty intrinsic to scenarios, there can be no guarantee of certain optimal operation.

From the first analyses performed, however, it quickly became apparent that although the battery was functioning as expected, thus succeeding in operating optimally to maximize profit. It was noted that the battery was performing a limited number of cycles compared to those that had been set. This reduction in number of cycles, is related to the fact that there is not always a sufficient wind resource to charge the battery. Therefore it appeared that they were not exploited to their full potential. In fact, it is recalled that it was initially assumed that the battery should operate until it reached a remaining capacity value of 70%. According to the degradation curve, this value should have been reached after 6147 cycles.

In consideration of the obvious insufficient wind resource to be able to exploit the battery to its intended limits, it was deemed appropriate to develop a second case, that is a configuration in which the battery is connected to the grid for charging. With this new configuration, it would have been possible to charge the battery even at times when there was not a sufficient wind resource. It would have been possible to charge with only favorable price conditions, in other words, finding a low price, and then discharging it once prices went up during the normal daily variation. This means performing arbitrage from the power grid. With this new configuration, it was then possible to increase the number of cycles performed by the battery, arriving at percentages of remaining capacity much closer to the 70% target than in the no grid charging layout. This new configuration will be referred to in the remainder of this thesis work as the grid charging layout.

The table 2.2 reports an example regarding the difference in the number of cycles that can be obtained for each individual year by comparing grid charging and no grid charging layouts. Specifically, a standard battery size of 5MW power and 10 MWh capacity was examined as an example.

Its operation was simulated for individual years using historical data from the plant under consideration. From the table, it is clear that with the grid charging layout, the battery performs a greater number of cycles every single year. Repeating this for all years of battery life results in a substantially greater number of cycles for the grid charging case.

Year	No grid charging	Grid charging
2015	319	382
2016	290	345
2017	278	335
2018	271	315
2019	311	369
2020	350	422
2021	295	346
2022	329	377
2023	351	402

Table 2.2: Comparison between number of cycles completed for each year by a battery of 5MW and 10MWh in No grid charging and grid charging cases.

Regarding the simulations performed on battery operation, as previously announced, historical wind and ODD data were available in the period between 2015 and 2023. As a result, since not enough data were available to simulate the entire expected battery lifetime of 15 years, it was deemed necessary to reassemble the data in order to have a sufficiently long series to represent lifetime years. During the initial analysis, many attempts were made to obtain sufficiently long time series of data, but due to the presence of the 2020 pandemic, altered price and curtailment data compared to average values resulted. In particular, 2020 was found to be a year in which there were very low energy prices, and at the same time much higher curtailment rates than in other years due to the low energy demand due to the pandemic. Also from a price point of view, there were years, particularly the end of 2021, but especially the 2022 year when due to the beginning of the war between Russia and Ukraine, energy prices, turned out to be extremely high.

From the table 2.3 it is possible to see the values of energy subject to curtailment regarding the examined wind field reported by single year.

Figure 2.8, on the other hand, shows the trend of hourly energy prices divided by year, reported by the Energy Markets Manager for the southern zone of Italy. From this graph, it is easy to see the large difference in energy prices present between pre-war and post-war years, particularly from the end of 2021 until 2022, where a sharp increase in energy prices can be seen.

Year	ODD (MWh/year)
2015	107
2016	670
2017	2882
2018	2831
2019	2890
2020	5090
2021	2114
2022	1465
2023	382
ODD mean	2048

Table 2.3: Annual energy subjected to curtailment (MWh/year) from 2015 to 2023.

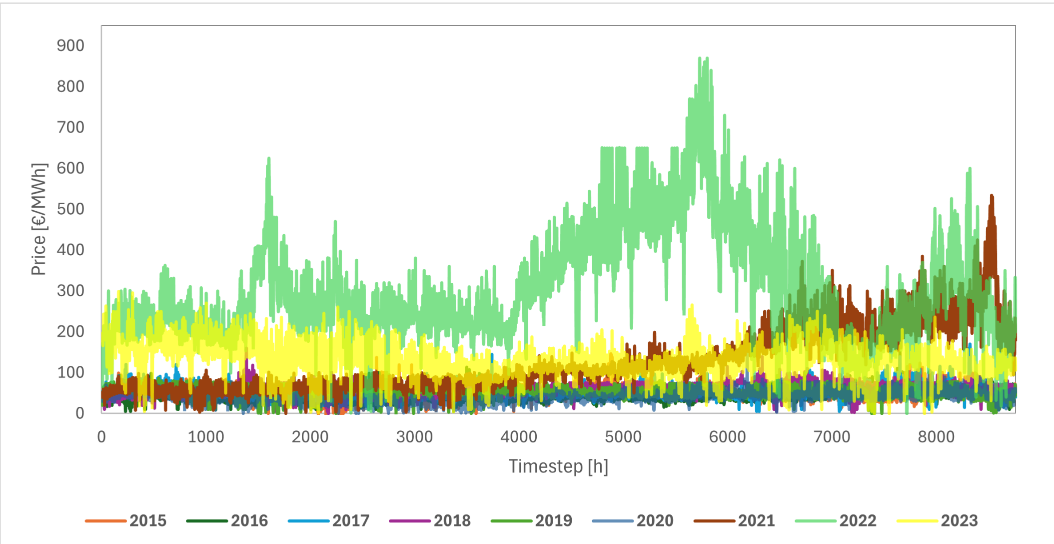

Figure 2.8: Energy price trend for each year between 2015 and 2023.

So, due to the high variability in the data, it was considered appropriate to perform an analysis of the possible operation of the battery in three representative situations by going to a single year's data and repeating it 15 times:

- An optimal scenario (called "Best"), where the highest and most variable prices ever recorded among all-time series were set, namely 2022. To which the highest recorded dispatch order values were coupled, so the 2020 curtailment requests. With this case it was thought to go and simulate what the behavior of the battery could be in terms of cycles made and the economic profit that could be obtained in the case of the best possible conditions.
- An intermediate scenario (called "Medium") where average values of price and curtailment requests were selected. Therefore, the annual data sets of 2023 price and 2021 curtailment requests were chosen for this case. This case could be considered as the most representative of current conditions, as last year's energy prices were included, so they appear to be similar to current energy prices.
- A worst scenario (called "Worst") where the time series of 2018 price and curtailment claims from 2015 were taken. With this case finally, we therefore want to go to represent what the battery's and investment performances could be if during its operating life, there were the worst possible conditions.

The analysis of battery operation was then based on the three representative scenarios explained. On these was then based a sensitivity analysis that was used to go and explore the possible combinations of characteristics that the battery can take on. The objective was to find the optimal ones that can guarantee the greatest possible return on battery-related expenses, and in the most virtuous cases try to achieve economic gain as well. The sensitivity analysis was therefore based on distinguishing grid and no-grid layouts, on differentiating between Best, medium, worst scenarios, and also by going to test various power and battery capacity sizes.

Initially, regarding battery capacity, the analysis started with large sizes (above 8 hours). The initial idea was to ensure that the storage system could be classified as long duration energy storage. However, it quickly became apparent that installing a battery that had such a large capacity could pose a huge problem in terms of cost. According to some analyses found in the literature, such as the analysis by Hou et al. [44] and that of Frate et al. [37]. Initially, therefore, it was decided to choose initial analysis sizes of 2 and 4 hours.

Regarding the power size on the other hand, from the analysis of studies reported in the literature, it was found that generally battery sizes below the rated power of the system were used. Specifically, from the cases reviewed in [45] [44], battery sizes were used that were between about 1/5 and 1/10 of the wind farm rated power. Therefore, in our case study, for a 38 MW wind power plant it was decided to perform an analysis on batteries with sizes close to these ranges: a 2 MW size, a medium 5 MW size, and a larger 10 MW size.

As regards the economic analysis, it was carried out by calculating, the net present value (NPV) and the levelized cost of storage (LCOS). The NPV was obtained by subtracting from the revenues of the BESS, its own cumulative costs. More specifically, the costs are obtained by adding to the BESS CAPEX costs, the actualized costs of the BESS OPEX, and the energy import costs.

$$NPV = \sum_{n=1}^{N} \frac{\mathrm{R}_{\mathrm{exp}}^{bess}}{(1+r)^n} - \mathrm{C}_{\mathrm{cum}}^{\mathrm{BESS}} = \mathrm{R}_{\mathrm{cum}}^{bess} - \mathrm{C}_{\mathrm{cum}}^{bess} \ [€] \tag{2.25}$$

$$C_{\mathrm{cum}}^{\mathrm{BESS}} = C_{\mathrm{capex}}^{\mathrm{BESS}} + \sum_{n=1}^{N} \frac{C_{\mathrm{opex}}^{\mathrm{BESS}}}{(1+r)^n} + \sum_{n=1}^{N} \frac{C_{\mathrm{imp}}^{\mathrm{BESS}}}{(1+r)^n} \ [€] \tag{2.26}$$

Then the levelized cost of storage (LCOS) [46] is calculated with the equation 2.27 which says that the LCOS as to be calculated by adding the BESS CAPEX to the BESS Operation and mainteinance costs and the costs of the imported energy actualized. All these terms then are divided by the energy discharged from the BESS to the grid. In this way is possible to evaluate which has to be the cost of the energy to recover battery costs.

$$LCOS = \frac{\text{CAPEX} + \sum_{n=1}^{N} \frac{O\&M}{(1+r)^n} + \sum_{n=1}^{N} \frac{\text{import cost}}{(1+r)^n}}{\sum_{n=1}^{N} \frac{\text{BESS\_to\_grid}}{(1+r)^n}} \tag{2.27}$$

The following data were used to perform the economic evaluations: the CAPEX was calculated as the sum of the cost of the battery, the cost of connecting the battery to the grid and the installation costs, which specifically took on these values. The cost of the battery was set starting from Bloomberg data [47] with a cost of 350 $/MWh which at the exchange rate of 28 March 2024 corresponds to 323.81 €/MWh. This cost corresponds to the total cost of the battery stack, to which all other costs relating to it are added, therefore for example the cost of the transformer, the balance of systems, the energy management system, engineering procurement and construction, and others. The cost of connecting the battery to the electricity grid, was set at 4.000 € for each MW of battery power. The installation cost was set as 2% of the battery purchase cost as reported by Dufo et al. [48]. As regards the calculation of OPEX, however, a percentage value of the purchase cost of the battery was used, which according to internal evaluations stands at 2.4%. Finally, a WACC of 4% was considered for the analysis.

Description	Value
BESS total cost	324 €/kWh
Cost of connection	4000 €/MWh
Installation costs	2% of BESS cost
BESS opex	2,4% of BESS cost
WACC	4%

Table 2.4: Economic analysis values.

Chapter 3

Results and discussion

This section will describe the results obtained from the various analyses performed on the batteries.

The analysis will be structured by dividing the no grid charging and grid charging layouts and analyzing them separately. For each layout there will analyzed the three scenarios Best, Medium, Worst.

3.1 No grid charging layout

Sensitivity will then be performed on each individual scenario, first the case that yielded the best results, so the "best scenario," will be analyzed.

3.1.1 No grid charging layout: Best scenario

Just as a reminder, this scenario was composed by going for the highest annual price values ever recorded in the history from 2015 to 2023, thus using the prices of 2022. These prices were influenced by the post-pandemic global uncertainty and the start of the war between Ukraine and Russia, caused energy prices to rise to very high levels. These prices were coupled with the 2020 ODD profile, which turn out to be by far the highest of all ODD values among the historical data. This was due to the presence of the covid 19 pandemic, as with the stop of production activities, energy demand was very low. In the meantime however, wind plants have continued to produce energy due to the presence of wind, so it has often been necessary to subject these plants to curtailment.

Initially, an analysis was made regarding the maximum NPV value obtained after a simulation period of 15 years with different battery power sizes, a WACC value of 4% and a battery price of 324 €/kWh was used in these simulations. The simulations were divided into two series where each represents a battery discharge duration, entering the 2h and 4h datasets.

Due to the very high energy prices used, always positive NPVs were obtained with very high gain values. In fact, it was observed that by increasing the battery power, an increasing gain could be obtained. Therefore, the evaluation did not stop at the initially choose sizes of 2 MW 5 MW and 10 MW. It was decided to run simulations with increasing battery sizes so as to understand up to what size could go while continuing to guarantee an increasing profit.

As can be seen in Figure 3.1 it was possible to go as far as extremely higher power values, reaching the peak gain with an 80MW battery and 160 MWh. This is obtained with batteries with 2h discharge duration, achieving an NPV of 41.938.638 €. On the other hand, with regard to batteries with 4h discharge, the peak was achieved with a smaller power size, the best result was achieved with a 40MW and 160 MWh battery, obtaining an NPV of 33.254.934 €. The maximum value with a discharge duration of 4h was achieved with a lower power size since the cost of the battery is evaluated according to its capacity; therefore, the longer the discharge duration the higher the cost of the battery. This obviously goes to the economic balance of the battery that will suffer a reduction in NPV.

Beyond 80 MW for the 2h battery and 40 MW for the 4h battery, the cost of the battery has too significant an influence compared to the gains that can be made by selling the battery power, so the NPV value reports a decline.

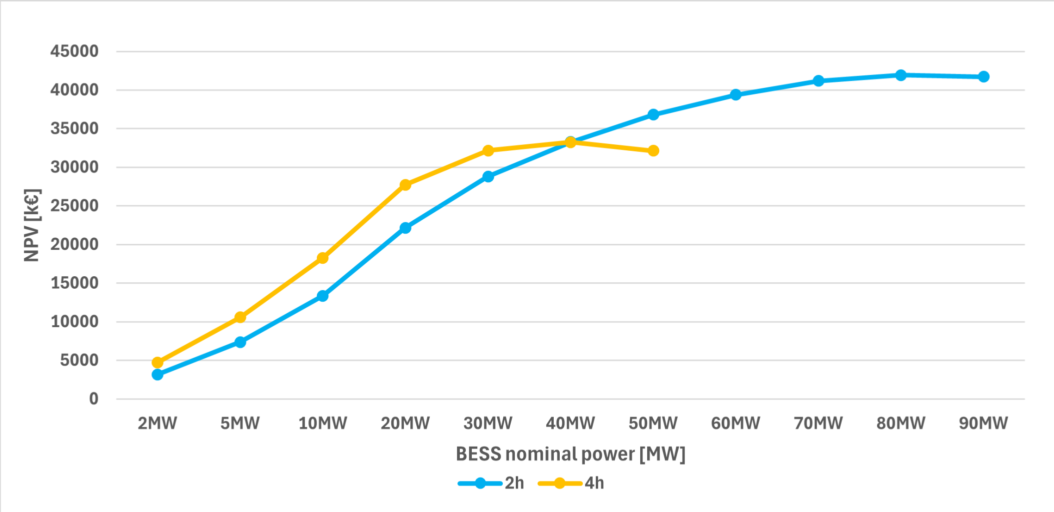

Figure 3.1: No grid charging layout: Best scenario BESS cost 324€/kWh and WACC 4%. NPV evaluation varying BESS power size with 2h and 4h discharge duration.

Using the same battery price variables of 324 €/kWh and a WACC of 4%, the other economic variable considered in this work, the LCOS, was then analyzed.

The figure 3.2 therefore shows an analysis of the LCOS in which the value of the average energy price calculated in the year 2022 was reported, which is 295.81 €/kWh. With the average energy price are reported the LCOS values calculated for the different battery sizes analyzed. From the graph it is possible to see that the calculated LCOS values always show a lower value than the average energy price. This confirms that the battery can be a good investment under these conditions, as to repay all the costs of the battery it is necessary to have an energy cost that is lower than the average annual energy cost obtained.

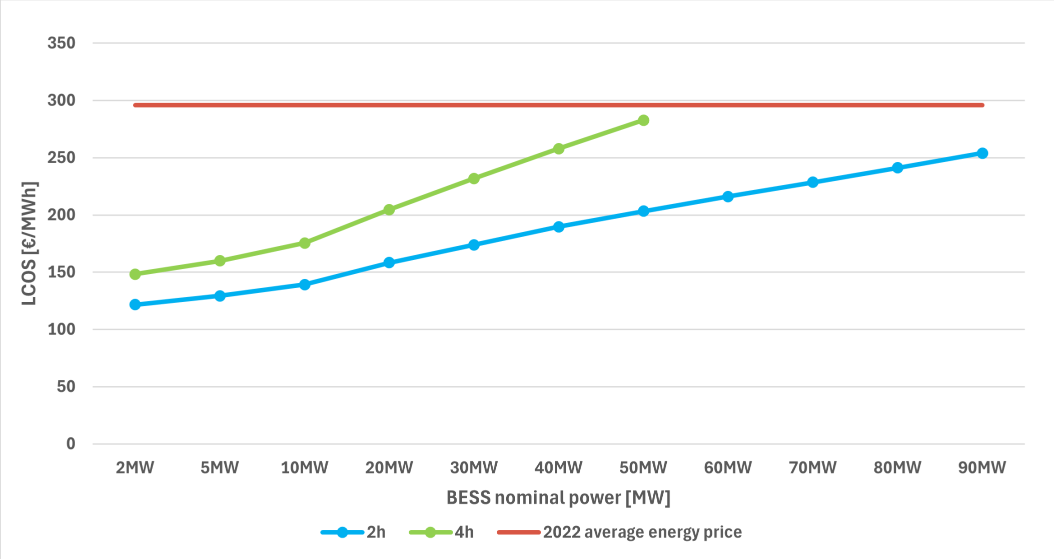

Figure 3.2: No grid charging layout: Best scenario, BESS cost 324€/kWh and WACC 4%. LCOS values with respect to 2022 annual average energy price.

As a final analysis with regard to this case, a sensitivity was performed on the value of the WACC used. Particularly it was done starting from the base value of 4% and increasing it to higher values such as 6% and 8%. These values are more representative of which that might be found in the case of battery installation in a real system.

The results obtained show a similar trend among the three cases, with significantly lower NPV values as the WACC increases. The optimal battery size at which the maximum NPV is achieved also decreases. This is due to the fact that an increase in WACC results in less favorable economic conditions, leading to a faster decline in NPV values.

The graph is divided according to colors, with each color going to represent a different value of WACC. The sizes are separated according to discharge duration, with the dashed lines representing batteries with 2h of discharge, while the continuous lines represent batteries with 4h of discharge. The best results achievable with a WACC of 4% have already been described in figure 3.1, instead for the case with WACC 6% is obtained an optimal value of battery with 2-hour discharge at 70 MW 140 MWh. For the 4-hour battery the maximum NPV is reached at 30 MW 12 0MWh. Instead, regarding the battery with WACC 8% the maximum is reached with a 60MW

120 MWh battery regarding 2 hours discharge, and similarly to the previous case for the 4-hour battery the maximum is reached with a 30 MW 120 MWh battery.

Even using a higher WACC, in despite of the decrease in NPV, is still achieved significantly positive economic results. However, it is important to point out that such advantageous conditions in battery installation have been favored by the very high energy prices.

This then points to the fact that is possible to believe in being able to install a battery for this purpose, but should also be conscious that is needed to find favorable conditions. In fact, it is evident that energy prices can play a key role in making these investments feasible.

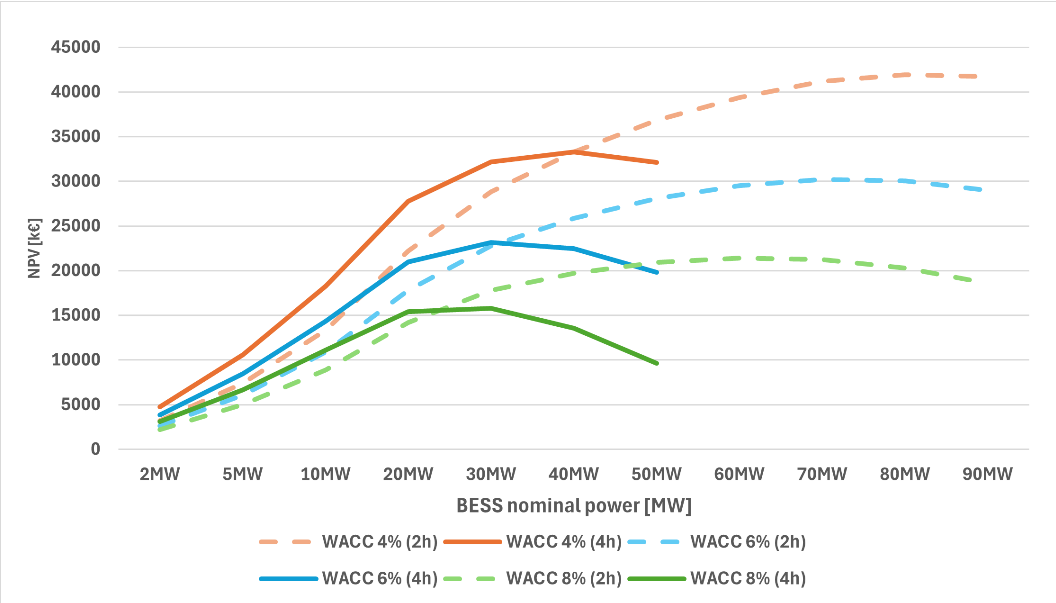

Figure 3.3: No grid charging layout: Best scenario, BESS cost 324€/kWh. WACC sensitivity.

3.1.2 No grid charging layout: Medium scenario

This medium scenario was composed of the 2023 Southern Italy area electricity market prices combined with the 2021 curtailment requests. These data were selected because they represent values in the average in the data history.

This scenario represents good conditions, as energy prices are more stable than 2022 and report a higher average value than in pre covid years.

From the first analysis performed by going to evaluate the NPV obtained for batteries with costs of 324 €/MWh and WACC at 4%, some very interesting results can be found. As in the case of the Best scenario, largely positive NPV values were obtained with the standard battery sizes. Therefore, also in this case to find the maximum NPV, it was possible to increase the size of the batteries with 2h discharge duration to a size of 30 MW and 60 MWh managing to obtain an NPV of 4.177.589 €.

With batteries of 4h discharge duration, on the other hand, the analysis stopped by finding a maximum for the 10 MW and 40 MWh battery size obtaining an NPV of 1.929.150 €. With this discharge duration it is not possible to increase the battery size more than 20 MW and 80 MWh because a negative NPV of -124,738 € was obtained demonstrating the influence of battery cost on economic balances.

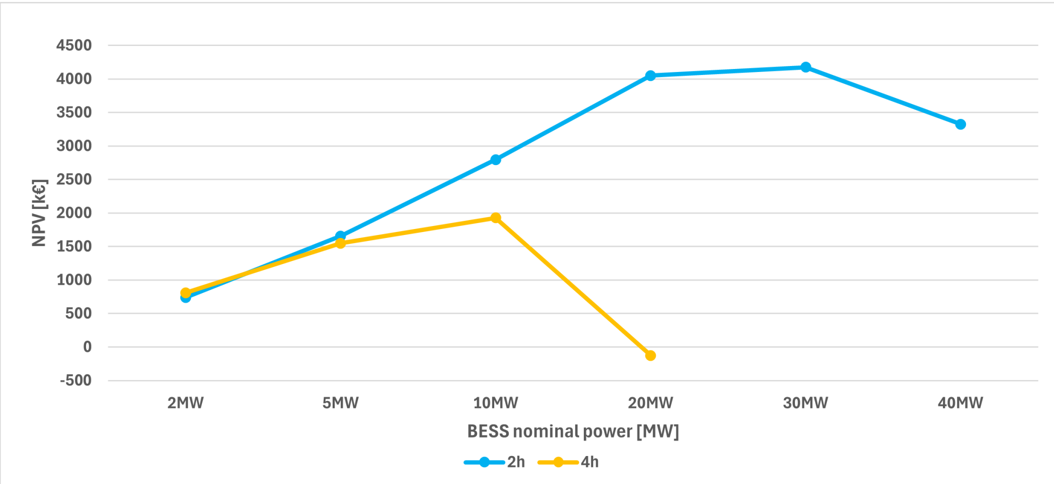

Figure 3.4: No grid charging layout: Medium scenario, BESS cost 324€/kWh and WACC 4%. NPV evaluation varying BESS power size with 2h and 4h discharge duration.

Next, the LCOS values for the same battery sizes selected for NPV calculation were evaluated. The results are shown in figure 3.5, from which it can be seen that for batteries with 2h of discharge, only the 2 MW and 5 MW sizes yield an LCOS lower than the average cost of energy in 2023, which stands at 125 €/MWh. The other sizes show a linear LCOS growth to reach 161 €/MWh for the 40MW and 80MWh battery.

On the other hand, for batteries with a discharge duration of 4h, an LCOS was obtained that is always higher than the average energy price for all sizes analyzed.

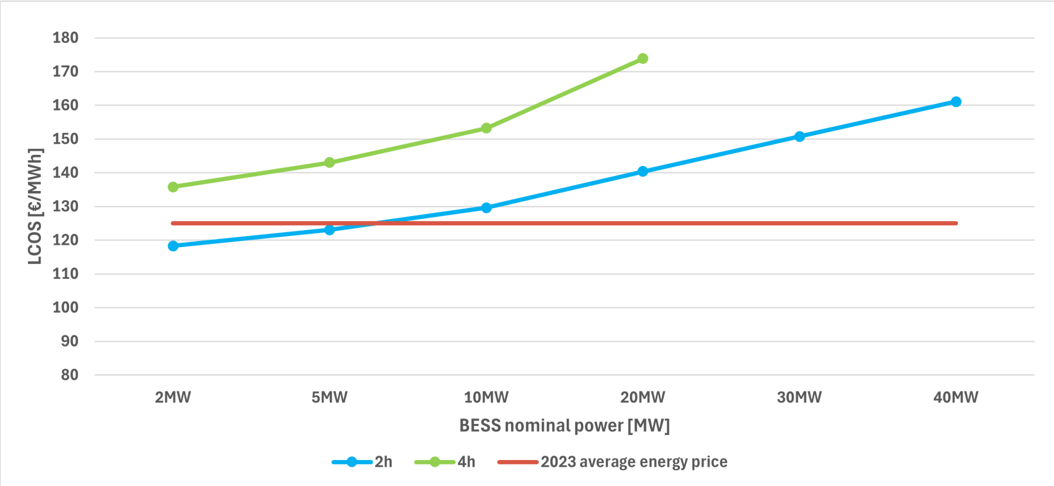

Figure 3.5: No grid charging layout: Medium scenario, BESS cost 324€/kWh and WACC 4%. LCOS values with respect to 2023 annual average energy price.

In the face of these results, it might therefore be thought that the energy price is not sufficient to repay the battery costs, going against what was obtained from the NPV analysis described above. However, it should be noted that the difference between the values of LCOS and average energy price still remains very small, on the few tens of €/MWh.

This price difference therefore has little influence, as it must be considered that the comparison is made between LCOS and an average price, which therefore does not report the variability of the energy price that characterizes 2023.

The wide variability favors battery operation in performing arbitrage, thus ensuring large profits obtainable by exploiting price spreads. This thus goes to justify the contrast between these two analyses, highlighting the good economic results obtainable from the installation of these storage systems.

As pointed out, the present conditions make results that turn out to be very positive, however, it must be taken into account that the value of the

WACC in a real application case could reach higher values than the 4% used.

Therefore, the sensitivity analysis on this case was focused on assessing the impact of WACC on NPV, while keeping the battery price constant. In this analysis, which is shown in figure 3.6, the changes in NPV that could be obtained in the case of having an increasing WACC at 6% and 8% were analyzed.

Obviously, an increase in this value does not benefit the final results because it places the analysis in worsening conditions, so the values obtained report a negative trend as one increases with the value of WACC.

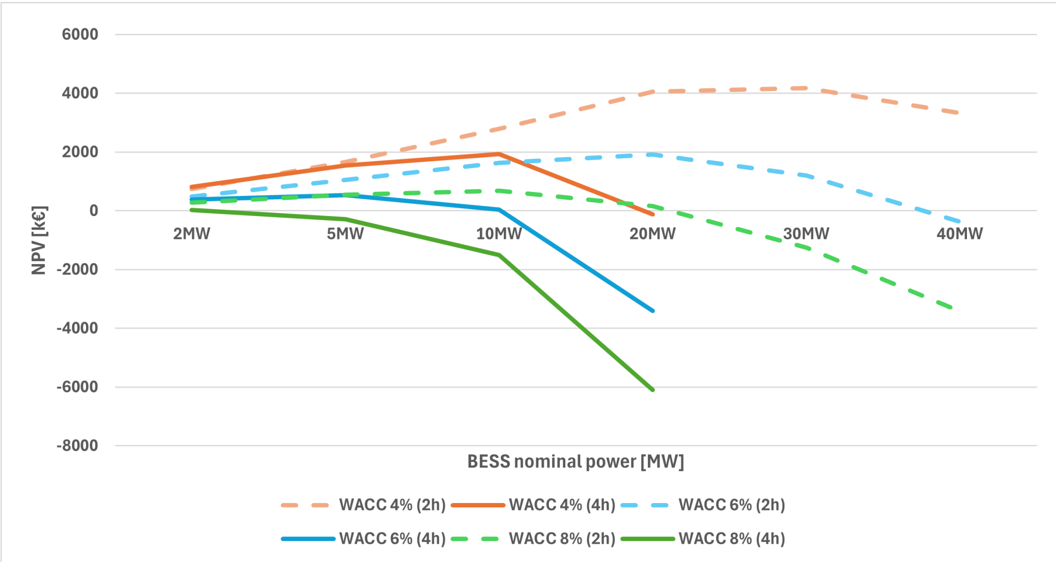

Figure 3.6: No grid charging layout: Medium scenario, BESS cost 324€/kWh. WACC sensitivity.

From the figure 3.6 it can be seen that in this case with an increase in WACC, worse results would be obtained than in the base case.

Specifically, with an increase in WACC to 6%, results in NPVs that report a significant lowering, but still go to positive values for almost all sizes analyzed. Specifically, negative NPV values would be obtained only with the 40 MW and 80 MWh sizes with a value of -376,224 €. Also with a 20 MW 80 MWh battery size a negative NPV of -3.407.868 € is obtained. However, for this case is important to consider that this size had already reported a negative NPV value even while keeping the WACC at 4%.

On the other hand, regarding the case with the WACC at 8%, significantly worse results are obtained, specifically with the 2h discharge duration batteries. NPVs close to zero are obtained for the 20 MW battery and negative for the 30 MW and 40 MW batteries.

Instead, the case of the 4h discharge batteries, significantly worse results were obtained. All the sizes analyzed resulted in negative NPVs, except for the 2 MW and 8 MWh battery alone, which resulted in an NPV of 29.826 € thus reporting a negligible value.

This indicates that under current price conditions, in the case of battery installation in an economic environment where there is a WACC of 8%, there would be difficulties in being able to make a profit on the investment in the battery. In particular, with 4h discharge duration it would be impossible to be able to repay the investment, thus forcing the choice on the 2h discharge duration.

3.1.3 No grid charging layout: Worst scenario

This worst scenario is composed through the combination of the 2018 energy price data, which turned out to be low and not very variable on average. These prices are combined with the values of dispatch orders recorded in 2015, which report very low values, with very few curtailment requests throughout the year. This scenario represents the most unfavorable conditions possible among the historical data considered.

The first analysis was performed by considering the standard battery values that were named in this thesis work, thus using a battery price of 324 €/kWh and a WACC of 4%. The analyses were performed on the previously mentioned battery sizes, thus 2 MW 5 MW and 10 MW.

From the NPV analyses, however, it was immediately evident that under these battery price conditions always negative NPVs were obtained. Unlike the Best and the Medium scenarios, the price of energy sold does not turn out to be high enough to be able to guarantee a profit that would ensure a positive net economic balance.

In fact, it became evident that with these energy prices, the battery cost has too great an influence on the economic balance.

This can be deduced by looking at the results obtained from the analysis shown in the figure 3.7 from which it can be seen that as the size of the batteries used increases, there is a sharp decrease in the NPVs obtained.

This indicates that energy sold at the 2018 price, does not generate sufficient earnings to repay the battery costs. The reason for this is that the price of energy is very low on average, and also has low variability that does not allow for large profits from the arbitrage function.

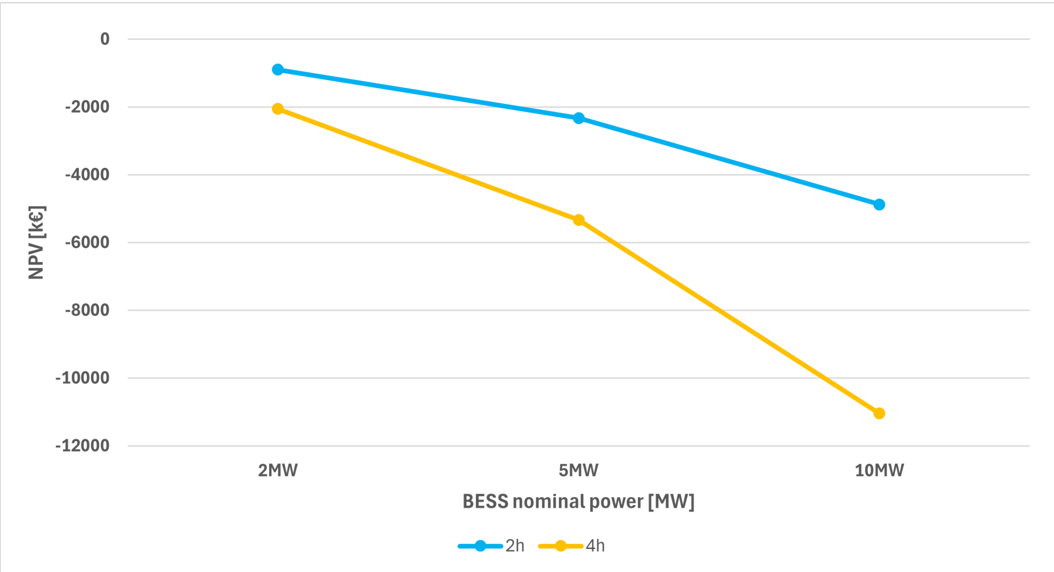

Figure 3.7: No grid charging layout: Worst scenario, BESS cost 324€/kWh and WACC 4%. NPV evaluation varying BESS power size with 2h and 4h discharge duration.

On the other hand, with regard to the analysis related to the value of LCOS obtained with the different battery sizes, the results go to confirm what was obtained from the previous analysis on NPV.

In fact, from this analysis, it can be seen that even when analyzing the LCOS, a difficulty in being able to repay the battery investment under these energy price conditions can be deduced.

The average value of energy in 2018 was 59 €/MWh but the LCOS obtained for the different sizes are largely higher, with values ranging from

160 to 179 €/MWh for 2h discharge batteries thus representing a price difference greater than 100 €/MWh. Moreover, with 4h discharge batteries the results are even worse, with values ranging from 190 to 218 €/MWh.

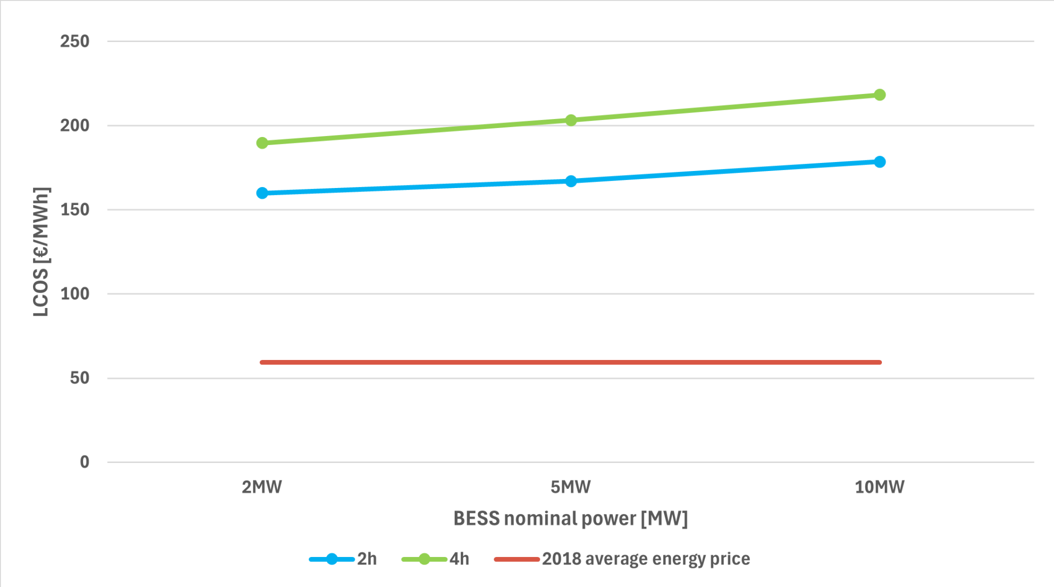

Figure 3.8: No grid charging layout: Worst scenario, BESS cost 324€/kWh and WACC 4%. LCOS values with respect to 2018 annual average energy price.

On the other hand, as far as sensitivity analyses are concerned, in this scenario, it was deemed unreasonable to perform an analysis on the change in WACC as it would only lead to a worsening of the results obtained, which already with a 4% WACC are all negative.

Since the value of the sold energy price used is not sufficient to ensure positive NPV values, it was deemed appropriated to perform a sensitivity analysis on the battery price. This decision was made because the cost of the battery is a key determinant of the final economic outcome of such projects.

In recent years, the price of batteries has shown a downward trend, suggesting a continuous reduction in costs. Therefore, the analysis attempted to determine the future price needed to ensure an economic profit by considering projected cost reductions.

For this analysis, price values predicted by Bloomberg for 2030 and 2033 were used, with a cost of 253 €/kWh and 238 €/kWh respectively. These values were chosen because they represent realistic estimates based on historical trends and market projections. In addition, two other assumed future prices were considered: one corresponding to half of the current price, so, 162 €/kWh, and another corresponding to one-third of the current price, therefore 108 €/kWh. These hypothetical values were included in the analysis to explore optimistic cost reduction scenarios and to assess the impact of these reductions on the overall economics of the storage system.

The objective of this analysis was to identify the turning point at which the price of batteries falls enough to make investment in storage systems profitable. Thus, Bloomberg's forecast for 2030 and 2033 was an important baseline, while the assumptions of further price reductions allowed to hypothesize potential future scenarios of technology and market development.

For this analysis, it was decided to represent the 2h and 4h discharge duration sizes separately so that all cases could be represented more clearly. Particularly were used continuous lines to represent the 2h BESS and dashed lines to represent 4h BESS. Figures 3.9,3.10 shows the values of the sensitivity analysis on battery price, specifically the NPV values obtained for each battery size analyzed. Each color, reports the cost associated with the storage system.

Thus, it can be seen from the results that as the price decreases, there are NPV values that are consistently better. It should be noted, however, that almost all of the prices used result in a negative NPV for all sizes analyzed.

Therefore, the price that must be reached at to obtain positive results is 108 €/kWh, so one third of the current price. Specifically with this price, NPVs on the order of hundreds of thousands of euros are obtained. The threshold values were both obtained with the 10 MW size battery with the maximum being obtained with the 10 MW and 20 MWh battery with an NPV of 682.668€. At the contrary, the minimum value that was obtained with the 10 MW and 40 MWh battery with an NPV of 67.776 €.

This last analysis therefore opens up the possibility of being able to install a battery in the future, even with very low energy prices, hoping, however, that the costs associated with the storage system will decrease significantly.

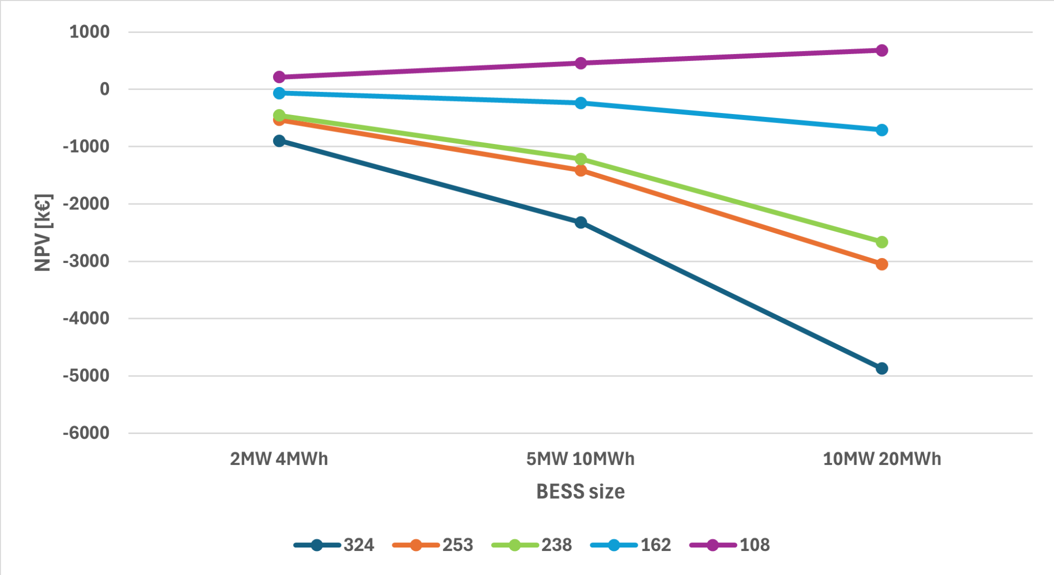

Figure 3.9: No grid charging layout: Worst scenario. BESS price sensitivity with a WACC of 4% for 2h BESS.

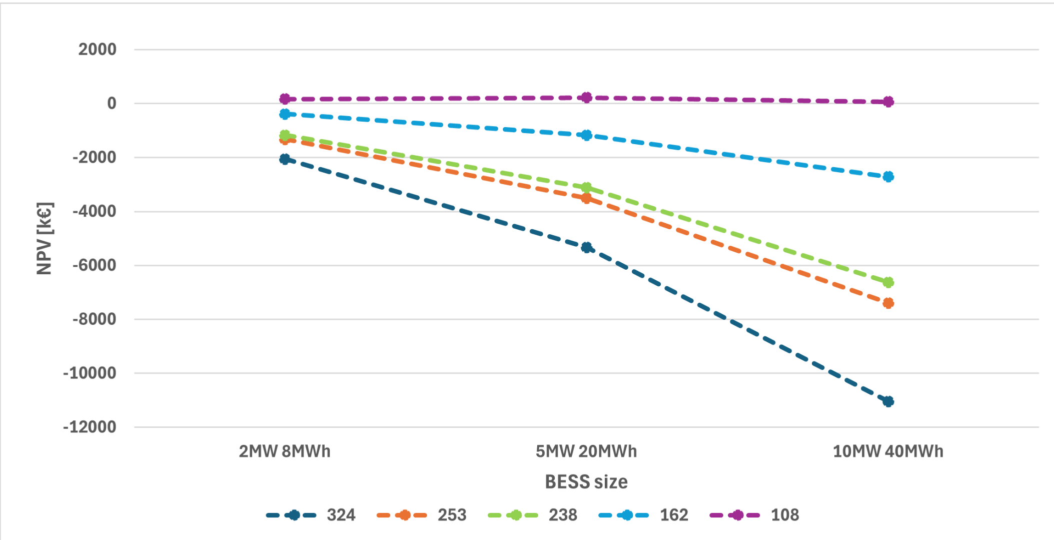

Figure 3.10: No grid charging layout: Worst scenario. BESS price sensitivity with a WACC of 4% for 4h BESS.

3.2 Grid charging layout

As announced at the beginning of this chapter, following the analysis done concerning exclusively the no grid charging layout, this section will examine the corresponding results of the case that also includes battery charging from the grid.

It is important to point out, that initially, when comparing the results obtained in the sensitivity analysis performed between the grid charging and no grid charging layouts, it was noticed that the case of the battery charging from the grid made NPV economic results lower than the no grid charging case, under the same analysis conditions.

This turned out to be counterintuitive since the case of charging the battery from the grid as well as from wind was designed precisely to go for higher battery utilization and a consequent increase in achievable profits. The battery with the grid charging layout was actually used more, performing more cycles during its operation over 15 years.

However, when analyzing the cycles that were performed by the battery, it was noted that it would go charging from the grid even in situations where a wind resource was present. Thus, charging the battery from the grid and at the same time selling the wind power to the grid. This operation although counterintuitive from a deterministic point of view, turned out to be correct from an algorithm operation point of view. This is because there is no difference in energy price between charging from the grid and selling energy to the grid, so the algorithm evaluates the costs of the two energy flows as equivalent.

Therefore, the difference occurs due to the discontinuity of the wind resource, a discontinuity in terms of power available for battery charging also follows from it. Contrary to charging from the grid, it allows the battery to be charged by providing always maximum and continuous power availability over time.

Since for the algorithm the cost of recharging energy is the same regardless of whether it recharges from the grid or the wind plant, it prefers to recharge from the grid.

The imbalance in the economic accounts between the grid charging and no grid charging layouts is therefore created because the economic evaluation is based only on the operation of the battery. Therefore, the flows that go from the wind farm to the grid are not considered, this is because the analysis only relates to the battery. Also considering the flows that go from the plant to the grid would mean also considering the costs of the wind farm, but it would introduce evaluations that are not the subject of this thesis work.

Since the grid charging layout places the calculations under unfavorable conditions, a post-production calculation technique was therefore used to deterministically balance the accounts. Specifically, the net amount of energy charged into the battery from the grid was calculated. This means that when the battery is charged from the grid and at the same time the wind power is discharged to the grid, the net value of the energy is calculated according to the following conditions useful for balancing the system:

$$\boldsymbol{IF}: \; P_{ch-wind}^{BESS} = 0$$

$$\boldsymbol{IF}: \; (P_{grid}^{wind} \geq P_{ch-grid}^{BESS}) \rightarrow P_{ch-grid\,(NEW)}^{BESS} = 0$$

$$\boldsymbol{ELSE}: \; P_{ch-grid\,(NEW)}^{BESS} = P_{ch-grid}^{BESS} - P_{grid}^{wind}$$

$$\boldsymbol{ELSE}: \; P_{ch-grid\,(NEW)}^{BESS} = P_{ch-grid}^{BESS}$$

Figure 3.11: Equations used for the post-production process.

Specifically, the conditions consist of two IF cycles. The first tells us that if there is no battery charging from the wind plant, then the second condition can be checked. The second condition is characterized by a second IF cycle that states: in the case where there is a value of energy discharged from the wind plant to the grid that is greater than the value of energy charged to the battery from the grid, the new value of charge from the grid should be considered zero.

On the other hand, if occurs the situation where the value of the energy charged from the battery to the grid is greater than the value of the energy discharged from the wind plant to the grid. In this case the new value of the energy charged from the grid to the battery will be equal to the difference between the value of the energy charged from the grid to the battery, and the value of the energy discharged from the plant to the grid.

In the event that the first condition is not met, so, if the battery charging from the wind plant is not zero, then the new battery charging flow from the grid will be equal to the previous battery charging flow from the grid.

As a result of this data processing, it was then possible to obtain much more similar NPV values between the layouts of charging from the grid and no charging from the grid.

Before describing the step-by-step analysis, it is also important to pre-announce that from the results obtained, it appears that however the NPV values are still in favor of the no grid configuration compared to grid charging.

This is due to the fact that the layout with charging from the grid performs a greater number of cycles compared to the no grid layout. The majority of these cycles performed, as mentioned above, are performed by charging the battery from the grid, thus needing a cost to charge the battery. In contrast, for the no grid layout, despite the lower number of cycles, they are performed entirely by charging the battery from the wind system, thus performing recharges without any cost.

Thus, it can be said that in the no grid charging case per single cycle a higher gain is guaranteed. This goes to have a greater weight in the economic balances than the higher number of cycles performed, thus making the no grid charging layout more cost-effective than the grid charging one.

3.2.1 Grid charging layout: Best scenario

Similar to the analysis of the no grid charging layout, the best scenario is taken as the first case analyzed.

As a first analysis, an assessment is made regarding the NPV trend under standard conditions of € 324 €/kWh of the battery and WACC at 4%, the assessment was performed by going through various power dimensions of the battery examining it with two discharge durations for each size, namely 2h and 4h.

Similar to what was seen for the best scenario of the no grid charging layout, it was possible to extend the power analysis from the 2 MW base power to much higher powers. Increasing the power was seen to increase the gains due to the particularly favorable energy prices related to the best scenario. From the results obtained it is possible to see that the NPV peak of 16.554.462 € over 15 years of useful life was reached for storage systems with 2h discharge, with the 40 MW battery and 80 MWh. On the other hand, with regard to the maximum value obtained for batteries with 4h of discharge, the maximum was reached for the 30 MW and 120 MWh size, achieving an NPV value of 17.638.086 €.

By comparing the same scenarios between grid charging and no grid charging layouts, it can be seen that as predicted, the grid charging one presents less performing results. In fact, the maximum NPV value is achieved for lower battery sizes, presenting an early decrease in earnings already from smaller battery sizes. This worse performance is attributable to the higher costs involved in grid charging for this new configuration.

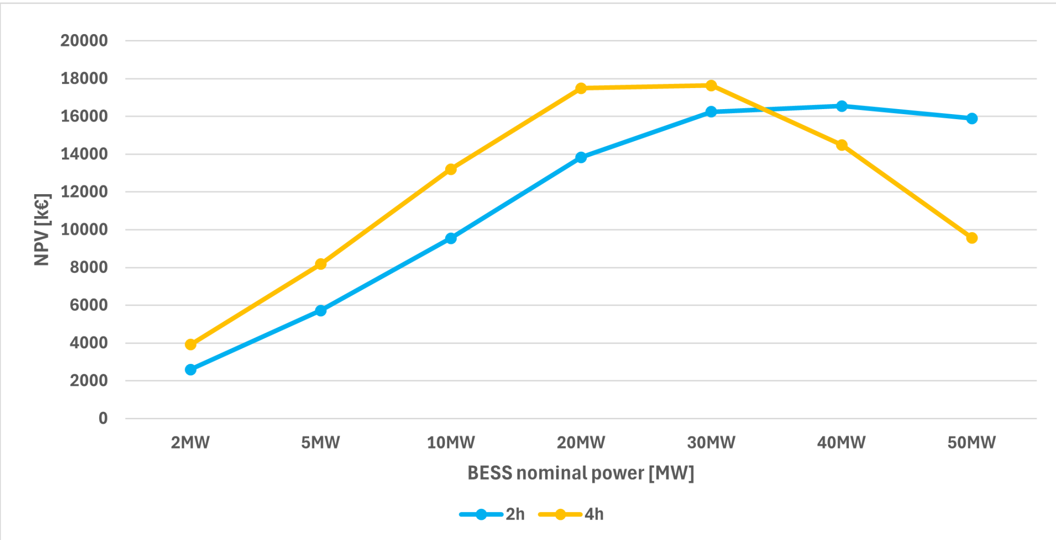

Figure 3.12: Grid charging layout: Best scenario BESS cost 324€/kWh and WACC 4%. NPV evaluation varying BESS power size with 2h and 4h discharge duration.

Next, the other economic analysis performed on the different battery sizes for operation under baseline conditions was the LCOS. This evaluation also yielded very promising results for battery operation at these energy price conditions.

From the figure 3.13, it can be seen that as the power of the batteries increases, they show a linear trend of increasing LCOS, with the highest values being recorded by the 4h hours of discharge batteries.

The results obtained show that almost all of the battery sizes analyzed yielded a lower LCOS than the average 2022 energy price of 296 €/MWh.

The only sizes that yielded a higher LCOS than the average energy value for both the 2h and the 4h discharge battery were the 40 MW and 50 MW powers. It should be noted, however, that similarly to the no grid charging case, the obtained values of LCOS are greater than the cost of energy by very little. Just consider that the largest value obtained was from the 50 MW and 200 MWh battery, which yielded an LCOS of 344 €/MWh.

The very small difference leads to the conclusions mentioned in the no grid charging layout for the best scenario, namely that for such a small price difference, the investment would still be advantageous. The results thus go to confirm the possibility of making a very substantial profit from the installation of these storage systems under the price conditions of 2022. That being very high and variable, they make large profits from the arbitrage function.

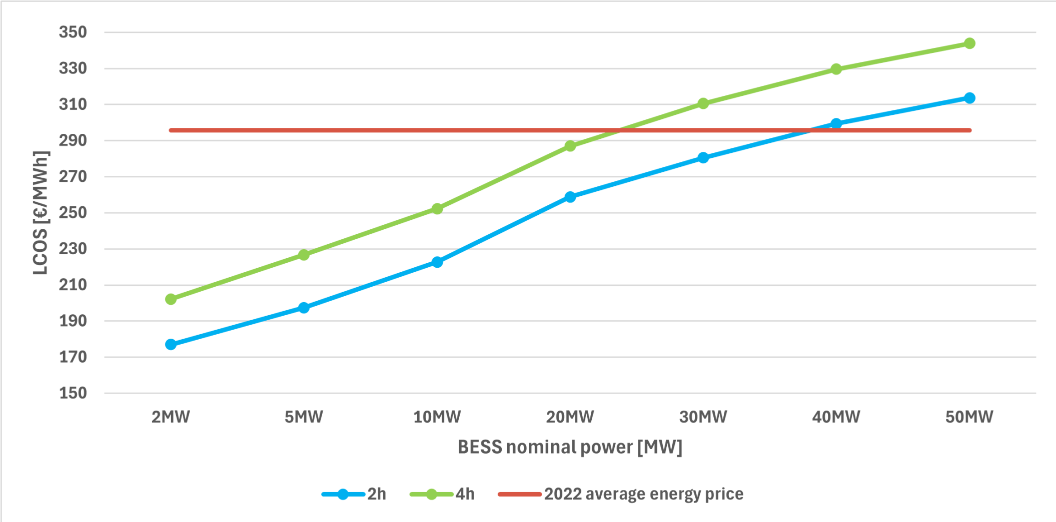

Figure 3.13: Grid charging layout: Best scenario BESS cost 324€/kWh and WACC 4%. LCOS values with respect to 2022 annual average energy price.

Similar to what was done in the analogue case of no grid charging, it was deemed appropriate to perform a sensitivity analysis on the possible change in WACC.

Also in this case, the graph was represented by using different colors to indicate the different value of WACC, and also by differentiating the battery discharge durations through the use of a different line. Specifically, the dashed line was used for batteries with 2h discharge duration, and the continuous line was used with batteries with 4h discharge duration.

The results show a symmetrical trend between the three curves representing the three WACC values examined. With a predictable decrease in the NPVs obtained for each specific size as the WACC value increases. A clear difference can be seen between the 2h discharge and 4h discharge batteries. In particular, taking into consideration the 2h batteries consistently positive NPV values were obtained for all sizes examined even considering the most disadvantageous conditions of WACC at 8%.

On the other hand, with regard to the batteries with 4h of discharge, a more curved trend of NPV value among the power sizes was obtained. Presenting a NPV maximum of 12.069.344 € with the 20 MW and 80 MWh battery in the case of WACC at 6%, a maximum NPV of 7.611.849 € with the same battery size, for the case of WACC at 8%. Using a WACC at 6% yields positive NPVs for all battery sizes used, in contrast, using a WACC of 8% yields negative NPVs for the 40 MW 160 MWh size (-653.796 €) and also for the 50 MW 200 MWh size (-7.431.014 €). This indicates the important influence that an increase in WACC could have although it should be considered that negative values are reached only with very large battery sizes.

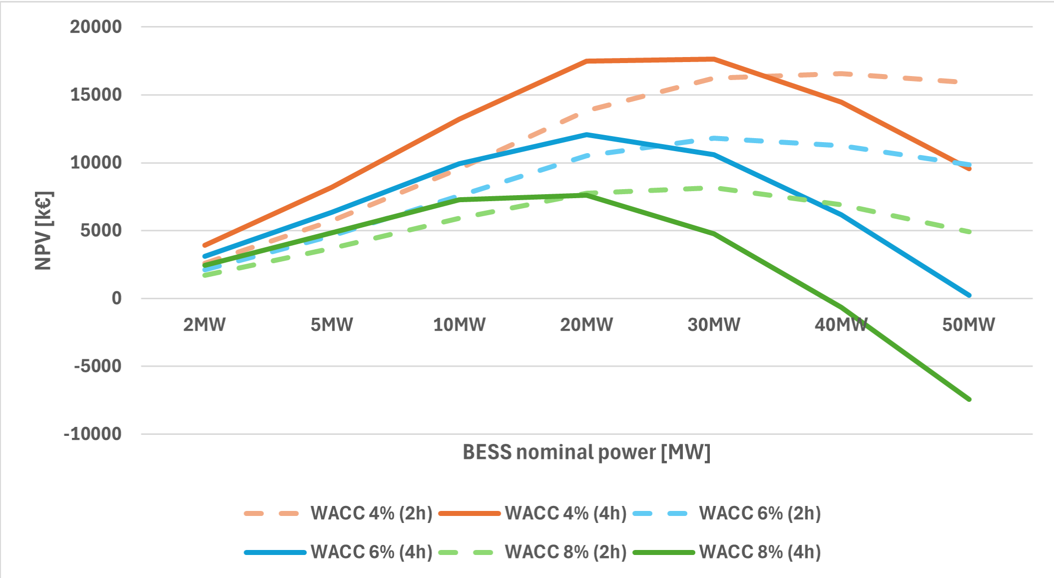

Figure 3.14: Grid charging layout: Best scenario BESS cost 324€/kWh. WACC sensitivity.

3.2.2 Grid charging layout: Medium scenario

For the continuation of the analysis on the grid charging layout, the case for the medium scenario was analyzed.

The analysis in this case reported less optimal values than the similar scenario for the no grid charging layout. In fact, the number of sizes studied is less extensive than those considered in the no grid charging layout, as the maximum NPV value was found with lower sizes.

The results are shown in Figure 3.15, it shows that in this case the absolute optimal size corresponds to the 10 MW and 20 MWh, with which an NPV of 956.486 € was obtained. On the other hand, if batteries with 4h discharge duration are considered, the optimal size corresponds to 2 MW 8 MWh with which an NPV of 427.808 € was obtained. The analysis thus goes to show a clear change between the no grid charging and the grid charging layouts, from which lower net profits were obtained.

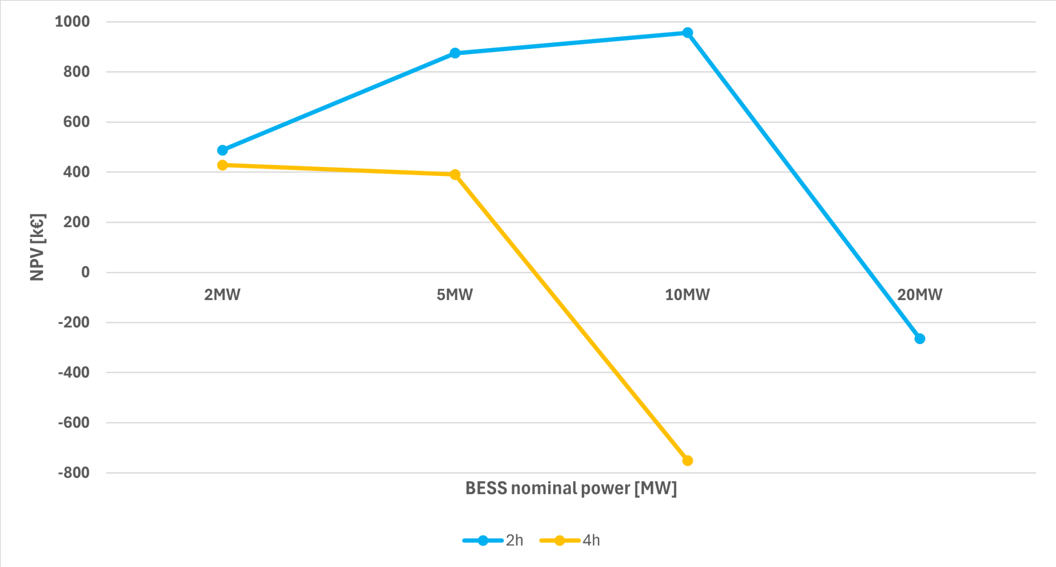

Figure 3.15: Grid charging layout: Medium scenario, BESS cost 324€/kWh and WACC 4%. NPV evaluation varying BESS power size with 2h and 4h discharge duration.

Next, the LCOS value is analyzed, which unlike the similar analysis for the no grid charging layout, does not result for any battery size in an LCOS value that is lower than the 2023 average energy price value. Even in this case, however, the difference still turns out to be small at a few tens of €/MWh so at least for the smaller sizes it could be considered negligible.

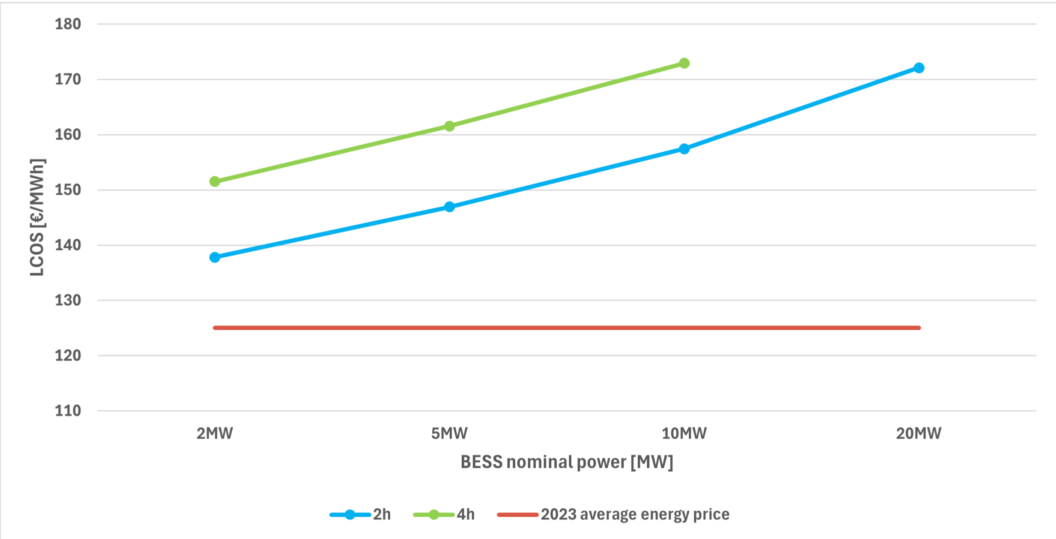

Figure 3.16: Grid charging layout: Medium scenario, BESS cost 324€/kWh and WACC 4%. LCOS values with respect to 2023 annual average energy price.

Similar to the other cases analyzed for the Best and Medium scenarios, it was also deemed sensible to perform a sensitivity analysis here by evaluating the value in NPV as a function of the increase in WACC value.

From this analysis, it was found that an increase in WACC with the price conditions of 2023 could be problematic in being able to achieve a positive NPV.

From the figure 3.17, it can be seen that with an increase to 6%, only batteries with 2h discharge duration achieve a positive NPV value. On the other hand, as far as 4h batteries are concerned, the only size that gets a positive NPV is the 4h one, which however turns out to be only 49.685 € so very close to zero.

On the other hand, in the case where the WACC value is 8%, the only size that gets a positive NPV was the 2 MW and 4 MWh one obtaining a value of 85.241 €. All the other sizes examined, yielded negative values. This goes to that in case there is an increase in WACC, the energy prices recorded in 2023 turn out to be insufficient to succeed in the battery investment in most of the examined configurations.

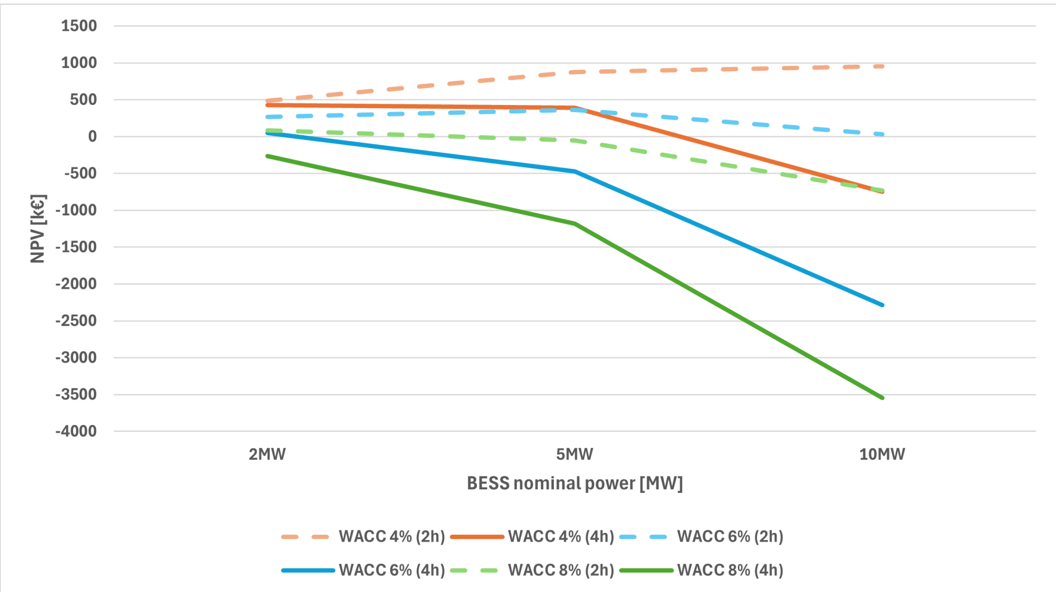

Figure 3.17: Grid charging layout: Medium scenario, BESS cost 324€/kWh. WACC sensitivity

3.2.3 Grid charging layout: Worst scenario

Finally, the worst scenario for the grid charging layout is analyzed. The analysis of this scenario reported similar results to those obtained for the worst scenario that was analyzed for the no grid charging layout. In this case slightly more negative NPV results were obtained due to the issue related to the charging from the grid already explained.

In the first instance, the analysis performed for the NPV evaluation yielded the results that are shown in Figure 3.18. They are similar to what has already been described for the worst scenario analyzed for the no grid charging layout. This means that due to the low energy prices present, the investment does not turn out to be cost-effective for any battery size.

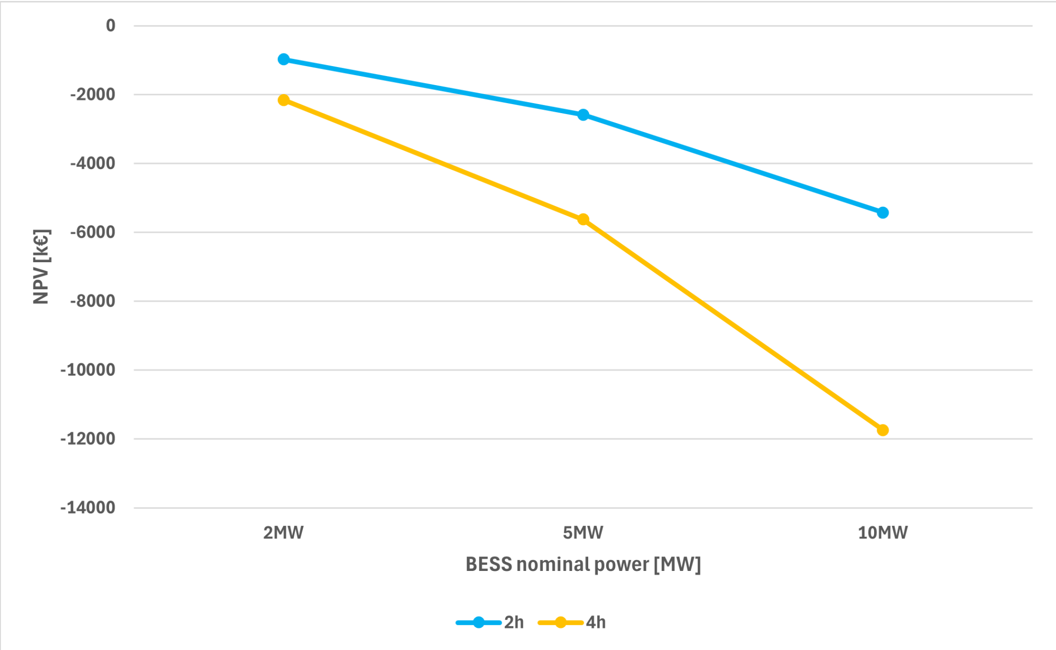

Figure 3.18: Grid charging layout: Worst scenario, BESS cost 324€/kWh and WACC 4%. NPV evaluation varying BESS power size with 2h and 4h discharge duration.

The same is true for the LCOS analysis, where the values obtained with all sizes of batteries, are largely above the value of the 2018 average annual cost of energy. The minimum difference is 100 €/MWh for the smallest size analyzed, and by increasing the size, this difference turns out to be larger. Taking into account that the average energy price in that year is 60 €/MWh, it means that the value of the energy cost would have to at least double to break even with the value of the LCOS.

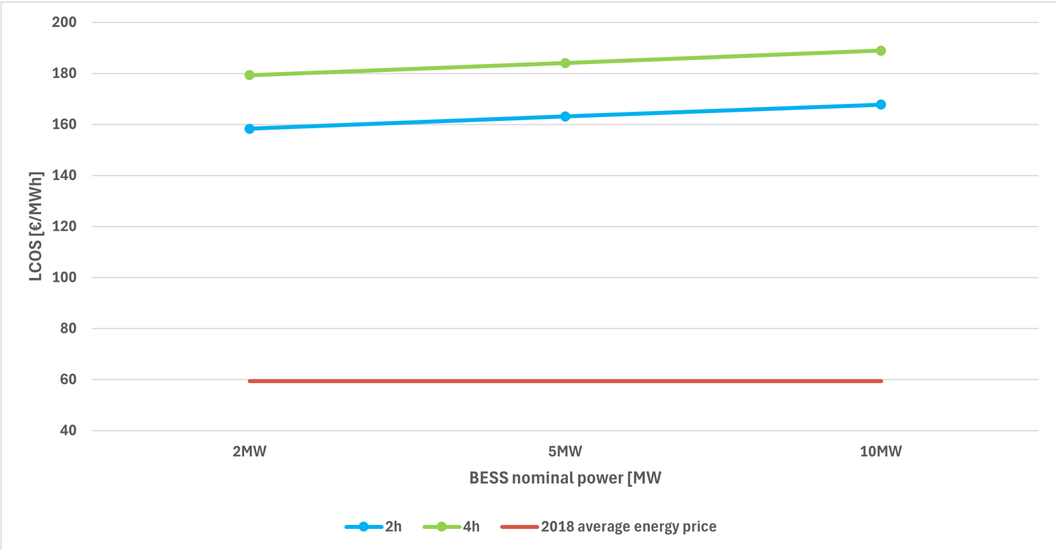

Figure 3.19: Grid charging layout: Worst scenario, BESS cost 324€/kWh and WACC 4%. LCOS values with respect to 2018 annual average energy price.

Finally, again as a sensitivity analysis, it was found to make relatively poor sense to perform an analysis on the increase in WACC. Instead, it was deemed more sensible to perform a sensitivity analysis on battery prices so as to understand what the cost associated with the storage system should be in order to be able to guarantee a positive NPV value at the end of the battery life.

Similar to what was obtained in the Worst scenario for the no grid charging layout, this analysis also obtained that the battery cost should reach the value of one-third of the current cost. Thus, it is necessary that it should come down to 108€/MWh.

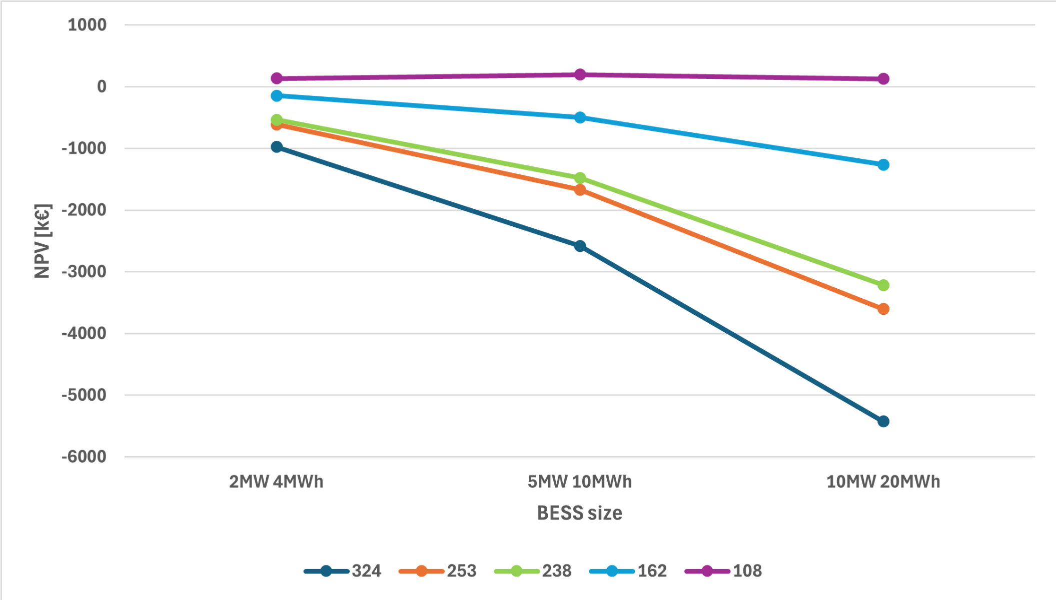

Figure 3.20: Grid charging layout: Worst scenario. BESS price sensitivity with a WACC of 4% for 2h BESS.

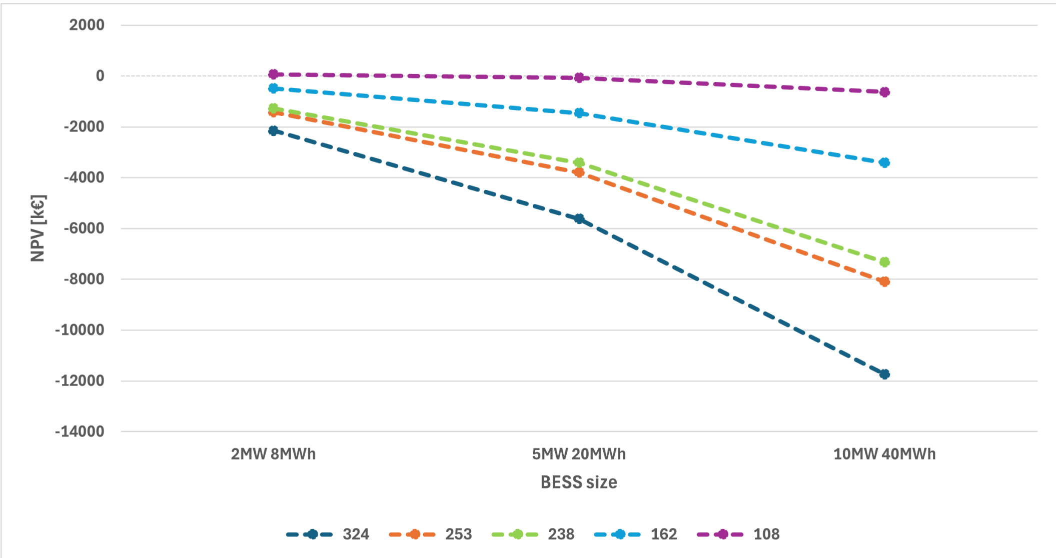

Figure 3.21: Grid charging layout: Worst scenario. BESS price sensitivity with a WACC of 4% for 4h BESS.

With this cost, positive but low values were obtained with almost all battery sizes analyzed. In this case, however, there were two sizes that reported a negative NPV despite the lower battery price. The first being the 10 MW and 40 MWh battery, which has reported a negative result of -631.071€. In addition to this, however, there is also a second battery, also with 4h of discharge duration, the 5 MW and 20 MWh battery, which recorded an NPV value of -68.671 €.

This could be a further indicator that batteries with 4h discharge duration present too high capital cost compared to the gains that can be obtained from them. Therefore, it seems that an investment on a 2h discharge battery is more recommended.

In fact, even in this case the optimal NPV value was obtained with a 2h discharge battery, more specifically with the 5 MW and 10 MWh battery, where an NPV of 196.616 € was obtained.

Chapter 4

Conclusions

The present work proposes a techno-economic analysis of the integration of a BESS into an existing wind power plant used to perform grid-level wholesale energy arbitrage.

The primary objective is to conduct a sensitivity analysis on battery sizes aimed at finding the optimal size in terms of maximum profitability. A mixed integer linear programming (MILP) optimization technique is used. The objective function of the optimization problem is the maximization of the profit achievable from battery operation in performing energy arbitrage. Additionally, a cycle-counting degradation model is implemented to account the degradation effect induced by the battery charge and discharge cycles.

Two different configurations are simulated: one which charges energy from the wind farm only ("no grid charging" layout), and another that also charges energy from the grid ("grid charging" layout). The analysis is performed using real historical data from a plant located in Southern-Italy.

To perform the analysis, three scenarios are assumed to represent three different conditions (Best, Medium, Worst). It is important to note that in the three different scenarios analyzed, the profits obtained considering the grid charging layout are lower than the profits of the no grid charging layout. This finding is in line with that obtained by Di Orio et al [49]. The root cause could be the larger amount of energy charged from the grid in the grid charging layout. This results in an additional cost for charging from the grid compared to charging exclusively from the wind farm, thus generating lower profits overall.

Different results are obtained from the analysis depending on the scenario analyzed. For the Best scenario, since high and variable energy prices are present, very high final gains are achieved for all battery sizes analyzed. In both grid charging and no grid charging layout, gains on the order of millions of euros are obtained. This underscores the possibility of obtaining large gains from the installation of these technologies in case there are favorable price conditions. However, it should be noted that the price values used are very high, so similar conditions are difficult to repeat. As for the Medium scenario, energy price values of 2023 are used, so they can be considered comparable to current prices. This scenario yields very promising results, as positive NPVs are obtained with almost all combinations of battery sizes. The maximum value for the no grid charging case is obtained with a battery size of 30MW and 60MWh with which 4 M€ is achieved. Similarly, positive values given by battery use are also obtained for the grid charging scenario, even though they are smaller than in the no grid charging case. In this configuration, the maximum NPV value of 0.9 M€ is obtained with a 10MW/20MWh battery size. Finally, regarding the Worst scenario, negative results are obtained with all sizes examined. The results can be attributed to the low energy prices used that do not allow for a profit from the arbitrage operation. However, from this last analysis, positive NPV values can be obtained considering lower battery investment costs. This implies good results in view of the future, as battery prices are expected to gradually decrease over the years, which could make their investment profitable even in the face of low and little variable energy prices.

Based on this master thesis work, further studies related to the use of different optimization algorithms could be prospected. In this way, it would be possible to carry out a more detailed analysis to try to find which algorithm could be the most effective in obtaining the maximum profit.

In addition, it would be interesting to expand the case studies by going to evaluate the inclusion of a storage system in other plants with different characteristics. In this way, a broader and more robust analysis could be created that would support the inclusion of BESS in wind power plants.

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