UNIVERSIDADE DE
COIMBRA

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ENERGY STORAGE IN WIND FARMS

Dissertação no âmbito do Mestrado Integrado em Engenharia Eletrotécnica e de Computadores, na especialização de Energia, orientada pelo Professor Doutor Pedro Manuel Soares Moura e apresentada ao Departamento de Engenharia Eletrotécnica e de Computadores da Faculdade de Ciências e Tecnologias da Universidade de Coimbra.

Fevereiro de 2019

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CIÊNCIAS E TECNOLOGIA
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Fevereiro de 2019

“The measure of intelligence is the ability to change.”

– Albert Einstein

Agradecimentos

Em primeiro lugar, agradeço ao Professor Doutor Pedro Soares Moura por toda a ajuda e disponibilidade que sempre manifestou ao longo desta dissertação, sem a sua ajuda, tudo seria bem mais complicado. Obrigado por tudo.

Ao Departamento de Engenharia Eletrotécnica e de Computadores da Faculdade de Ciências e Tecnologias da Universidade de Coimbra, ao corpo docente da mesma, por toda a aprendizagem adquirida ao longo destes anos.

A todas as pessoas que esta jornada me deu hipótese de tornar amigas, principalmente à Joana e à Raquel por todos os bons momentos vividos durante estes 5 anos que vou sempre guardar na minha memória com muito carinho.

Ao António, por toda a ajuda e pela enorme paciência que teve comigo ao longo de todo o percurso.

E por fim, um enorme obrigado à minha família, principalmente aos meus pais, que sem eles nada disto seria possível, serão sempre as pessoas mais importantes da minha vida, o meu porto de abrigo. O meu sincero obrigada por tudo.

Abstract

In wind farms, due to the intermittency of the resource and to the fact that most wind parks have an installed power superior to the maximum power injectable into the grid, there is the need of curtailment, leading to resource and economic losses. Allied to these factors, in the future, wind generation should participate in the wholesale electricity market, being crucial the capacity to limit the generation in periods of low market price and to concentrate it in periods of higher price. In order to solve these issues, the use of energy storage systems is essential to store the power that otherwise would be wasted and to obtain a higher income to the wind farm. In this way, there is a need to develop algorithms able to correctly manage the energy storage system and also the wind resource.

The main objective of this dissertation was to analyze the impact of an energy storage system, based on batteries, in wind farms. For such purpose, a management system for a wind farm with energy storage was designed. In order to ensure it, two management algorithms developed in MatLab environment were implemented, one with the objective of reducing wind power curtailment and the other, maintaining the curtailment as a priority, but also with the objective of maximizing the economic income of the wind park.

The algorithms were tested and simulated for different scenarios and generation profiles and through the developed technical and economic analysis it was possible to verify the system viability. With the developed algorithms it was possible to reduce wind power curtailment and to increase the economic impacts of wind farms.

Keywords: wind farms, wind generation variability, curtailment, energy storage, management algorithms.

Resumo

Nos parques eólicos, devido à intermitência do recurso e ao facto de que, na sua maioria, possuem uma potência instalada superior à máxima potência injetável na rede, surge a necessidade de *curtailment*, resultando assim em desperdícios de geração e em perdas económicas. Para além de estes fatores, futuramente os parques eólicos serão renumerados em regime de mercado, sendo então crucial limitar a geração em períodos de preço baixo e concentrar a geração em períodos de preço elevado. De forma a resolver estes problemas, o uso de sistemas de armazenamento é essencial, para assim, armazenar a geração, que de outra forma seria desperdiçada e ao mesmo tempo aumentar o lucro do parque. Surge então a necessidade de desenvolver algoritmos capazes de fazerem a gestão correta, não só do sistema de armazenamento, mas também do recurso eólico.

O principal objetivo desta dissertação foi analisar o impacto de um sistema de armazenamento de energia elétrica composto por baterias em parques eólicos. Para tal, foi desenvolvido um sistema de gestão de um parque eólico com armazenamento de energia. Com esse intuito, foram desenvolvidos dois algoritmos em ambiente MatLab, um com o objetivo de reduzir curtailment e outro, mantendo a redução do curtailment como prioridade, com o objetivo de maximizar o lucro do parque eólico.

Ambos os algoritmos foram simulados e analisados em diferentes cenários e para diferentes níveis de geração, através da análise técnico-económica realizada foi possível verificar a viabilidade do sistema. Com os algoritmos desenvolvidos foi possível reduzir o curtailment assim como aumentar o impacto económico em parques eólicos.

Palavras Chave: Parques eólicos, variabilidade do recurso eólico, curtailment, armazenamento de energia, algoritmos de gestão.

Table of Contents

Index of Figures

Index of Tables

Acronyms

BESS	Battery Energy Storage System
CAES	Compressed Air Energy Storage
CES	Cryogenic Energy Storage
DC	Direct Current
DLSE	Decentralized Linear State Estimation
FES	Flywheel Energy Storage
FLC	Fuzzy Logic Controller
GHG	Greenhouse Gases
MAS	Multi-agent System
MIBEL	Mercado Ibérico de Eletricidade (Iberian Electricity Market)
OMIE	Operador do Mercado Ibérico de Energia (Iberian Energy Market Operator)
PHES	Pumped Hydro Energy Storage
RAS	Remedial Action Scheme
SC	Supercapacitor
SMES	Superconducting Magnetic Energy Storage
SNG	Synthetic Natural Gas
SOC	State of Charge
TES	Thermal Energy Storage
TSO	Transmission System Operator
VPP	Virtual Power Plant
VSWT	Variable Speed Wind Turbine

Variables

B_{cap}	Capacity of the storage system	MWh
$E_{\_excess}$	Power resultant from the difference between instantaneous electric power output and maximum power injectable into the grid	MW
$E_{\_needed}$	Power resultant from the difference between instantaneous electric power output and minimum power injectable into the grid	MW
$E_{sellprice}$	Tariff associated with the wholesale energy market	€/MWh
$E_{\_strd}$	Energy stored in the storage system	MWh
$E_{\_strd\_100}$	Electric power that can be stored in the storage system or electric power required to achieve a state of charge of 100%	MWh
$From_{\_bat}$	Electric power that is desirable to inject into the grid in higher price periods	MW
$Income$	Wholesale market prices for the periods that the battery tries to supply the maximum power of discharge	€
P_{bat}	Power resultant from the difference between the maximum power injectable into the grid and the instantaneous electric power output	MW
$P_{bat\_max\_charge}$	Maximum charge power	MW
$P_{bat\_max\_discharge}$	Maximum discharge power	MW
P_{max}	Maximum power injectable into the grid	MW
P_{min}	Minimum power injectable into the grid	MW
$P_{produced}$	Instantaneous electric power output	MW
SOC_{max}	Maximum state of charge	%
SOC_{min}	Minimum state of charge	%
$To_{\_bat}$	Electric power that is desirable to store in the battery in lower price periods	MW

Chapter 1 - Introduction

1.1. Motivation

Nowadays, climate changes and the need to reduce greenhouse gases (GHG) emissions have a strong influence on electric power systems, being the integration of renewable energy sources a major objective to achieve it. Therefore, new technologies and methodologies need to be adopted in order to integrate renewable generation into the system. These systems need to ensure security and reliability to the electric grid, to contribute to the reduction of the dependence in nonrenewable ways of electricity generation and to accomplish the reduction of greenhouse gases emissions.

The integration into the grid of renewable energy resources has been a challenge, due to the stochastic nature and variability of most renewable resources. In the specific case of wind farms, there is a strong dependence on climatic conditions, and the generation cannot be dispatched. This intermittence allied with the fact that the generation may occur in low demand periods, make the resource less appealing than dispatchable power plants. Another issue is the limitation of power injected into the grid, since most wind farms have an installed power superior to the maximum power injectable into the grid, which, in high generation periods leads to curtailment of generation. Curtailment is the term that designates the act of limit the wind farm generation, bringing not only generation losses and consequently economic, but also decreases the capacity factor of renewable energy projects, weakens investors' confidence in renewable revenues and make more difficult to meet carbon emissions targets. Additionally, in the future, wind generation should participate in the wholesale electricity market, being crucial the capacity to limit the generation in periods of low market price and to concentrate it in periods of higher price.

A possible solution to these issues may be the use of energy storage technologies. Nowadays, energy storage technologies, such as batteries, are already utilized in wind farms and present an increasing performance and decreasing costs. With the use of energy storage arises the need to develop an energy management system able to ensure technical and economic benefits for wind farms.

This management can be made, for example, by storing the surplus generation in high wind periods, being the surplus generation the energy that would otherwise be curtailed, storing the generation in lower price periods and inject the energy stored into the grid in high price periods. With this method, wind power curtailment would be reduced, and the wind farm would increase the economic profit.

1.2. Objectives

The main objective of the dissertation is to design the management of an energy storage system able to integrating wind farm generation, with the priority of reducing wind power curtailment. Another objective is to use such an energy storage management system to supply and store the generation according to the prices variation on the wholesale electricity market. In order to accomplish these objectives, two algorithms will be developed, one to the reduction of curtailment and other to ensure not only the curtailment, but also the maximum revenue possible to the wind park.

The first algorithm should be able of receiving the generation data, the energy storage system capacity, the maximum power injectable to the grid, the minimum power injectable to the grid and the minimum state of charge. Based on such parameters, the algorithm should be able to store when the generation is larger than the maximum power and inject when the generation is lower than the minimum power. The second algorithm should also be able to receive data from the wholesale electricity market, in order to reduce the curtailment, and to store energy in low price periods and inject energy into the grid in higher price periods.

In this way, both algorithms should allow to simulate the energy exchanges between the wind park and the battery, and the whole system with the grid. To analyze the impact of the algorithm, multiple scenarios must be tested considering different generation levels and different wholesale electricity market prices variations.

1.3. Structure

This dissertation is divided into six chapters. In the first chapter the introduction, which is constituted by the motivation and the objectives of the dissertation, is presented. In chapter 2, the main subject of the theme is presented, more specifically the wind farm generation variability, the curtailment and the methods of curtailment. In the third chapter, the different forms of energy storage are characterized, in particular, the ones more appropriated to wind farms. In chapter 4, based on all the conclusions from the previous chapters, the main objectives of the algorithms are presented, along with their structure and operation. In chapter 5, both algorithms are simulated in different scenarios, and the graphic and numeric results are presented. Finally, chapter 6 presents the conclusions and some subjects worth of future work.

Chapter 2 - Variability of Wind Power and Curtailment

Climate changes are a dramatic reality and the carbon emissions due to the combustion of fossil fuels for electricity generation represent a large share of the GHG released to the atmosphere. The energy sector accounted for 78% of GHG emissions in the 28 members of the European Union in the year of 2015 [1] and reducing carbon emissions is a goal to be reached in a short period of time, in order to do that the generation must rely on the renewable sources of producing energy. A high penetration of renewable energy can reduce massively these emissions and to ensure it wind power has a crucial role due to its high potential and reliability, as well as low costs [2].

2.1. Wind generation variability

Due is variability and stochastic nature wind power presents relevant challenges to the power systems. The wind power is proportional to wind speed cubed, so small variations of wind speed cause significant variations on wind power. Since this energy resource depends on climacteric characteristics, it is not possible to control the generation. This intermittency makes wind energy less appeal than the dispatchable energy to the system operators due to the fact that it cannot be controlled according to the system demand or economic requirements. Thus, integrating a considerable amount of wind generation in the grid is a challenge, since besides the variability, a large amount of wind generation occurs in hours of low demand and this generation is wasted if there are no methods of store this energy.

Predicting precisely wind generation is also challenging, since it is possible to predict the wind power generation for a whole year, but when it comes to hours or days is very unpredictable. Figure 1 presents the Portuguese total wind farm generation in a week of November of 2017.

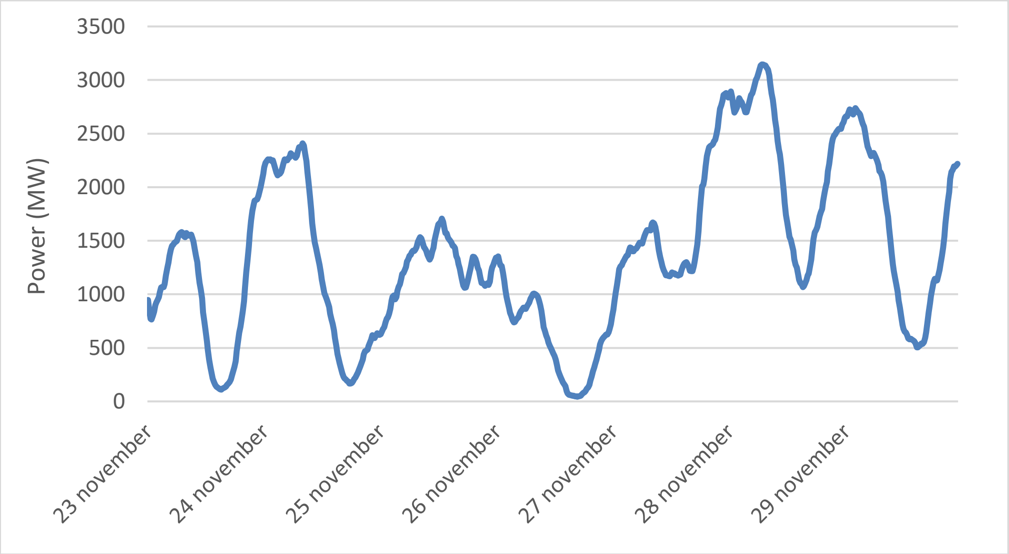


Figure 1-Wind generation variation in a set of wind parks of 4100 MW in a week of November of 2017[3].

As can be seen the wind generation varies significantly along the day and the week, causing problems to the system reliability. In day 28, for example, in the morning the wind farms generation combined produced approximately 3200MW, at the end of the day the production decreased drastically to 1000 MW. Therefore, it is hard for the system operators to predict and integrate this wind generation in the electric generation mix.

These variations are a problem not only when low power is reached, but also with a high power. With a low power the grid needs a reserve of power to compensate the power loss. When the generation exceeds the maximum injectable in the network the production needs to be reduced, being the curtailment one of the methods to ensure it.

The wind power variation can also degrade the grid voltage stability due to the surplus or shortage of power [4]. The non-dispatchability of wind power brings costs to the grid operators, rising such costs with the growth of wind generation integration in the grid in order to avoid a reliability degradation. To manage the intermittency of wind generation the system needs reserves. This reserve can be provided by dispatchable power plants, energy storage systems or demand-side management. In the absence of other flexibility resources, curtailment is the solution to maintain the balance between the supply and the demand.

2.2. Curtailment

Curtailment is a reduction of the output of a generator from what it could otherwise produce given available resources, imposed by certain conditions and grid limitations [5]. Curtailment of generators is a normal practice since the beginning of the electric power industry [5] and is one of the methods to maintain the stability and the control of the system in a minimum level of generation, even in periods of low demand. It typically occurs due to the congestion of the transmission and distribution network, in periods that the generation exceeds the necessary or during low load periods and to achieve system energy balance. It can also be used to maintain voltage requirements or due to interconnection issues [6]. To take better advantage of the renewable resource, most wind power plants (WPP) have installed a higher generation than the maximum injectable on the grid, so, in periods of high wind the curtailment is also required.

Curtailment is implemented by constraint the output of a set of wind turbines through pitch control of the wind turbine blades. The pitch of the blades is controlled through an electrical or hydraulic servo system. In [7] the modern variable speed wind turbine (VSWT) is presented. The control strategy diagram is represented in figure 2.

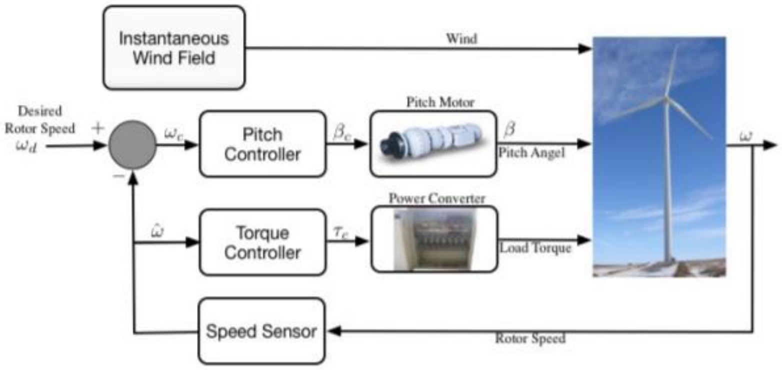


Figure 2-Variable speed wind turbine control diagram[7].

The torque and output power are regulated according to wind speed conditions. Torque control is mainly used in low rated wind speed region and is implemented by a frequency converter. The power output control is achieved by blade pitch control. The pitch control allows to turn in and turn out the angle of the blades in distinct wind speed conditions, ensuring that the output power is closer to the rated-power and reducing the aerodynamic load in high wind speeds.

Curtailment can be a valuable resource, helping stabilize the grid and improve system flexibility. The renewables can ramp up or down very quickly, so curtailment can help to relieve over-generation and potentially provide ancillary services. However, it can be problematic because it decreases the capacity factor of renewable energy projects, weakens investor confidence in renewable energy revenues, and, make more difficult to meet GHG emissions targets [8]. The use of curtailment brings not only generation losses but also economic, that must be considered in the wind park evaluation.

Nowadays the premium for renewable generators are based in Feed-in-Tariffs, dispatch-down wind power resources when they are available is a lost opportunity. In the future wind generation should be factored into balancing market prices, allowing producers to compete with other providers in a fair way [9]. With this market price change, it is profitable to inject energy to the grid in the hours of higher cost. Although, due to wind generation variability, the generation cannot be controlled, and this can induce to inject energy in the hours of low cost which leads to low profit in the wind park.

To improve and reduce the curtailment several methodologies have been proposed and will be discussed in subsection 2.2. 1..

2.2.1. Methods of curtailment

Latterly several methods of implementing curtailment are being developed and they vary significantly by cause, grid technology and grid operator [6]. These methodologies are divided into two types, one of them use and innovate curtailment to achieve a more efficient curtailed system, and the others developed strategies to minimize curtailment and take the most profit of wind resource available.

As explained in subsection 2.1. pitch control of the wind turbine blades is one of the technologies used to implement curtailment. An example of this method is given in [10]. Is considered a multi-megawatt turbine with double-fed induction generator and controllable pitch angle. The rotor of the generator is connected to the grid through a frequency converter which allows the control of the generator torque. A supervisory controller is related only to one turbine, but if the technology is applied to all the turbines in a wind farm it becomes a wind farm controller.

The control loop is presented in figure 3.

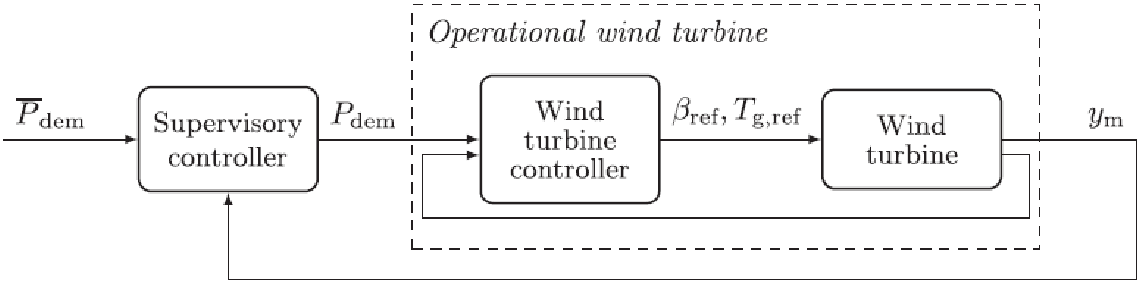


Figure 3-Supervisory control loop[10].

$\bar{P}_{dem}$ is the mean power that needs to be produced by the wind turbine and is determined by the wind farm controller, this value is fed to the wind turbine controller. The wind turbine controller set the pitch reference β_{ref} and the torque reference $T_{\mathrm{g,\ ref}}$. With this procedure and changing the power of the wind turbine in the proper manner, it is possible to overcome power fluctuations, which are one of the big issues of this energy resource.

By applying this supervisory controller in 10 or 20 wind turbines in a wind farm control system it is possible not only to reduce the generation in times of strong wind but also to appropriate the generation in the perspective of grid requirements.

In [11] is proposed another procedure of pitch control. In this example is suggested a novel pitch angle control, the system works in an outer open control loop and has an intrinsic hydro-mechanical position control loop that can improve the pitch angle control precision. This system allows smoothing the output power and torque fluctuation when compared to a conventional pitch system for a wind turbine.

Although these systems have a common disadvantage, the wind resource is not used to the maximum.

To overcome this energy waste methodologies to minimize curtailment are in development. In [12] is proposed a multi-agent system (MAS) based optimal wind power curtailment control strategy with the consideration of operating capacity credit to prevent the uncertain wind power curtailment, help to increase the wind power integration and minimize the system operation cost. The optimal operation control strategy is defined and implemented for hourly system operation and control. This system as a three-level hierarchical structure as can be seen in figure 4 which is constituted by distributed agent level, cooperation society level and central processing level. Every agent has three basic functions: information collection, decision making and decision execution. Unit agents on transmission lines and generators will monitor and send the state information of related power components to control centre.

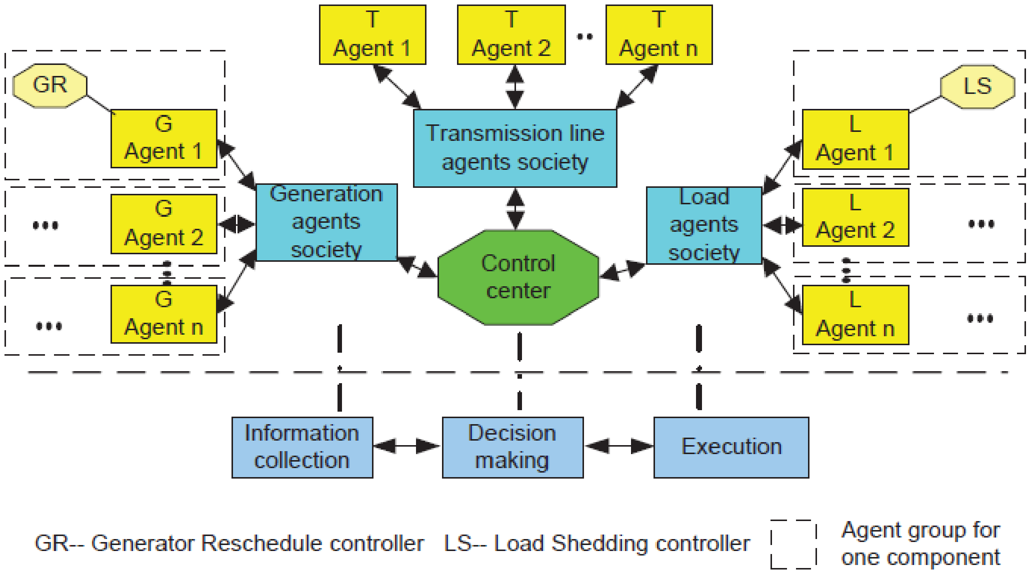


Figure 4-The structure of MAS based detection strategy[12].

Every hour the distributed unit agents and controller agents will send their present information to the upper layer agents. In the control centre the wind power and load demand will be predicted firstly for the next hour and then the best operation condition for that hour will be obtained based on an optimization algorithm. The distributed controller agents will then execute the related control strategy when the orders from the control centre have been received.

With this method the power balance of the system is improved, the difference between total available wind power and total dispatched wind power decreased, which means that the wind power loss has been minimized effectively and for that the generators have been limited significantly.

Another example is given in [13]. Remedial Action Scheme (RAS) is an automatic control mechanism made to detect the anomalous system conditions and act fast to obtain the system reliability. There are various types of RAS, dynamic RAS to minimize the cost of generation shedding, RAS to protect transmission lines from overloading, RAS to predict power flow scheduling limits on transmission lines and so on. In this particular case, a new RAS is used to minimize the wind curtailment and solve the overload condition on the transmission line at the same time. For this method, an advanced controller is installed in the wind farm substation and the wind power curtailment problem is considered as a linear programming problem.

There are two methods for this type of RAS:

- switching mode: RAS control to ON/OFF the wind generation using a relay installed in the substation;
- Generation reduction mode: RAS control the maximum generation of the wind farm resorting to an advanced controlled installed in the substation.

A Decentralized Linear State Estimation (DLSE) is utilized to provide fast data to RAS. Combining the two methods of RAS, and utilizing the information given by DLSE, RAS calculates the control action and some buses are shed and others suffer a generation reduction. This method can efficiently reduce wind power curtailment when solving the overload problem.

Even though these methodologies minimize curtailment and are technologically developed, wind resource still not used at the fullest potential. Therefore, the grid has to develop strategies and incentives to mitigate curtailment. Energy storage can be the solution, despite being already utilized nowadays, such as pumped hydro-storage, new strategies of storage can take the most profit of the renewable resource, and economic gain too.

Chapter 3 - Energy Storage

The electricity supply must ensure the balance between the energy supply and demand. Renewable resources only produce when the resource is available which imposes several challenges to the electricity supply system. Therefore, due to the lack of stability of the resource some actions must be taken to ensure a reliable electricity supply. Besides the stability, the generation surplus in periods of low load must be accounted too.

Storage may be one of the methods to reliably integrate power generated from renewable energy in the energy system and to store the surplus energy, that would typically have been wasted. In short, energy storage is a suite of technologies which can store energy in many forms[14]. The objective is to inject wind energy in periods of high demand or high cost and to store it in periods of high generation or low cost.

3.1. Energy storage technologies

The most mature energy storage technology nowadays is Pumped Hydro Energy Storage (PHES), representing the quantity of 99% of storage in use worldwide [14]. As referred in [15], PHES has developed worldwide due to its high-efficiency (75-85%), competitive costs (800-1500€/kW), large scale energy storage, long life-time and low self-discharge. Although, there are some barriers utilizing this technology. The first barrier is technological, in order to help the transmission system operator (TSO) mitigate the adverse effects caused by renewable energy on the grid power quality it is required to reduce the response time and extending the stable operating range of PHES units. The second is the geotechnical conditions required – an upper and lower water reservoir. And finally, the impact that PHES can cause on river ecosystems due to water management.

To overcome these issues and barriers other emerging storage technologies are in development.

Energy can be stored in different energy forms:

- Mechanical: PHES, Compressed Air Energy Storage (CAES), Flywheel Energy Storage (FES).
- Electro-chemical: Battery Energy Storage System (BESS).

- Chemical: Hydrogen, Fuel Cell, Synthetic Natural Gas (SNG).
- Electromagnetic: Supercapacitor Energy Storage System (SC), Superconducting Magnetic Energy Storage (SMES).
- Thermal: Cryogenic Energy Storage (CES), Thermal Energy Storage (TES)
- etc.

Each technology have is limitations and advantages, which make them more appropriate and profitable to certain applications. In figure 5 is possible to observe these technologies by discharge time and power rate.

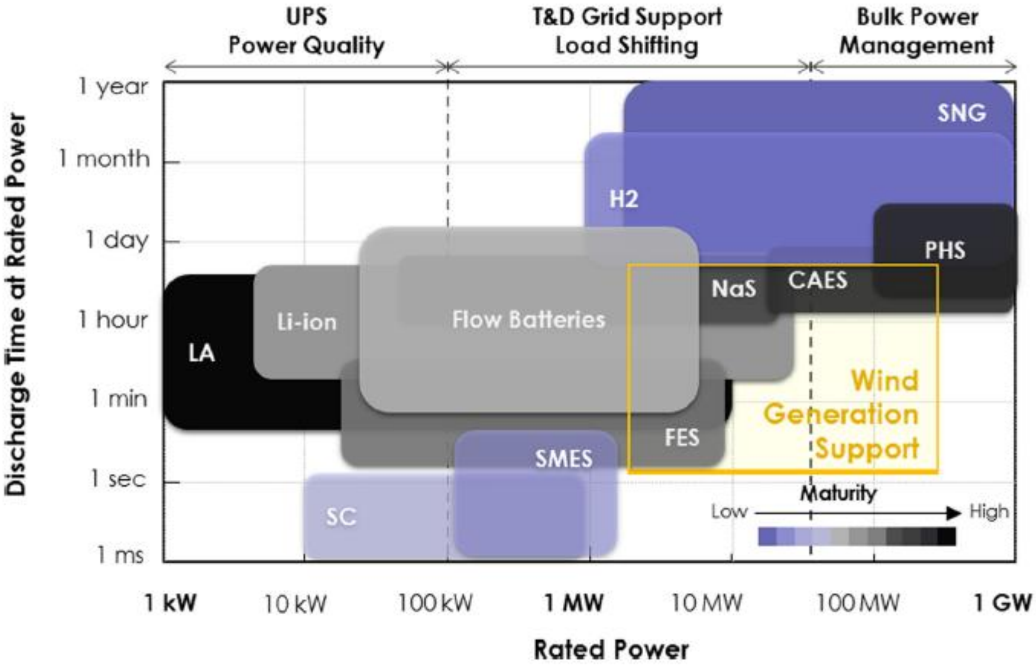


Figure 5-Power ranges and discharge power duration of different energy storage technologies[16].

3.2. Energy storage in Wind Farms

The target of wind farms storage is to minimize curtailment and mitigate wind power generation transients. Taking in count that in the future wind generation will be traded into market prices will be desired to inject on the grid in the hours of higher prices and store in the lower price hours.

Has mentioned in section 3, PHES are in used and have a high position of maturity and majority in the market. But due to its requirements, other solutions are more appropriated to some systems and locations. In [17] is proposed a CAES in parallel with a wind farm. The concept of CAES is relatively simple, being the storage charged using electrically driven compressors, which convert the electric energy into potential energy - pressurized air. The pressurized air is stored and then released to generate electricity by expansion of the air through an air turbine. The system is controlled based on wind speed conditions. Excess wind energy above “rated wind speed” would be stored and during below “rated wind speed” conditions, the stored compressed air would be expanded to produce the required power to supply the grid. The schematic diagram of this procedure is represented in figure 6.

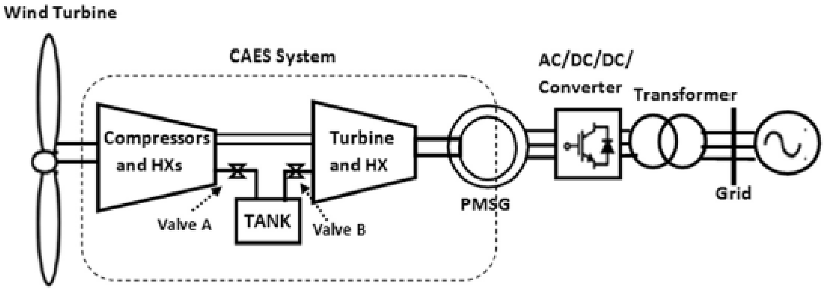


Figure 6-Schematic diagram of a parallel connected wind-CAES system[17].

However, this technology has an issue in common with PHES, the fact that needs a location to the air storage, and to that some geotechnical conditions are needed and are very difficult to obtain. Other disadvantages are that heat exchangers, compressor and expander trains, are expensive and some air compressors utilize fossil fuels [18].

In [19] is given an example of SMES in wind power generation. The system is based on storing energy in a magnetic field, created by a DC current that passes through a large superconducting coil at a cryogenic temperature. Using a fuzzy logic controller (FLC) SMES strategy to improve the performance of the grid in wind gust scenarios by controlling active and reactive power. The system presents a fast response charging/discharging, with an efficiency of about 90-98%. Despite these advantages and their good technological features, SMES is not very utilized [18].

Hydrogen storage is another example of a possible solution. Hydrogen can be obtained by water electrolysis using wind power and then stored in fuel cells. The system is composed of a water electrolyser system, a fuel cell system, hydrogen storage and a power converter (Figure 7).

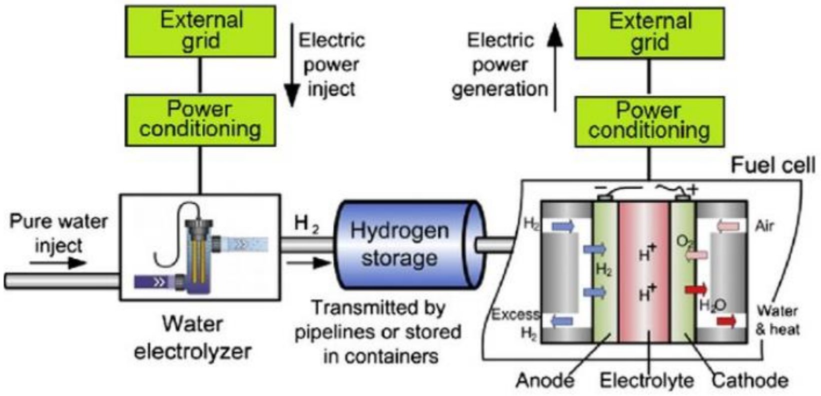


Figure 7-Hydrogen Storage system[20].

In [21] a hybrid system using hydrogen and battery storage is proposed. The hydrogen produced with the renewable energy source is compressed and fed into a gas grid. Renewable energy can be used directly in the electrolyser unit or stored in a battery before being used. These hybrid systems occur due to the minimum load requirement of electrolysers allowing to increase the efficiency of the system.

These technologies permit to store energy for long periods of time, but the major disadvantage is the low efficiency of approximately 42% [18]. In [22] a wind-hydro system is compared with the wind-battery system, the results showed that wind-battery systems are technically suitable for energy generation management and even more suitable, energetically and economically than wind-hydrogen systems.

3.3. Batteries in wind farms

Nowadays, besides PHES, battery energy storage system (BESS) is the new market in development, due to its high potential for wind power mitigation due to its fast response, high energy efficiency, large-scale grid applications and price decreasing [23]. The energy is stored in form of electrochemical energy, being the battery charged by an internal chemical reaction under a potential applied to both electrodes. This reaction is reversible and the energy absorbed can be discharged [24]. There are several types of batteries, such as low temperature batteries (lithium-ion, lead-acid, nickel-cadmium), high temperature (sodium nickel chloride, sodium-sulphur) and redox flow (vanadium, zinc bromine). In [14] a battery storage system is presented, including a battery, monitoring and control systems and a power conversion system (Figure 8).

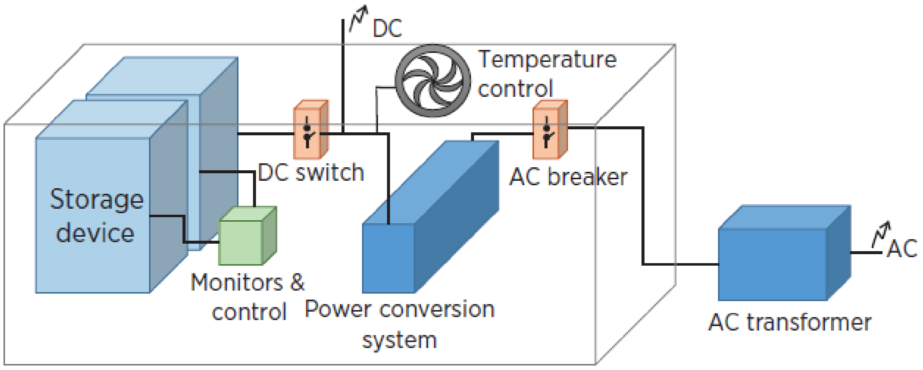


Figure 8-Battery storage system[14].

In [25] an optimal power dispatch strategy for wind power plants containing BESS is proposed. Utilizes a Dynamic Programming tool that incorporates simultaneously forecast information from wind power and market price as inputs, to determine the optimal capacity of BESS needed to maximize the overall revenue of the system. It was found by the results the effectiveness of the strategy to help power system operators to ensure an optimal energy dispatch, but it was not cost-effective without a subsidy (31.88€/MWh, in the Australian electric market).

In [22] an hourly management method for energy generated in grid connected wind farms using BESS is assessed from the technical and economic point-of-view. Energy is stored during low demand periods and then sold in high demand periods. The assessment used the data from the annual average demand in Spain and the price of electricity from the liberalized electricity market. The wind-battery system was simulated during a full year using hourly data and was compared with a wind-only system. One of the advantages is that the generation of energy can be managed, bringing it closer to the energy demand when compared with wind-only systems. From the several types of tested batteries, the results showed that NaS batteries were the most efficient in the group, with a longer lifespan and selling battery energy at prices of approximately 22-31c€/kWh, making the system more profitable than wind-only systems. However, lithium-ion batteries were not tested.

The economic potential for wind-battery-system and the use of a BESS for different energy market products was discussed in [26]. In this example is proposed a two-layer optimization structure to optimize the dimensional partition and the operation strategy of

BESS. The objective function of the algorithm is based on fundamental optimization principles, that regulate BESS to supply more energy during peak prices and prevent power delivery during low price periods. The method was simulated in a wind power plant of 238MW in different scenarios, being the best scenario marketing wind power with BESS in a mixed trading strategy, and the worst marketing without BESS. In a week, the income difference between the best case and the case without BESS was 26 thousand of euros, an increment of 9% in the profits. In the simulation, neither the cost of BESS or the effect of battery degradation is considered. Nevertheless, can be concluded that BESS system would give renewable energy resources the opportunity to participate in the market and take the most profit of the resource.

A multi-stage stochastic programming model to find the optimal operation of a VPP - an association of a wind power farm with a BESS in the day-ahead, intraday and secondary reserve markets while taking into account the uncertainty of wind power generation is presented in [27]. The data was taken from the Iberian electricity market and the results showed that the reserve market reshaped the charge/discharge profile and the optimal bid to the day-ahead market due to the high impact on the total profits. When the VPP is bidding only to the day-ahead and the intraday spot markets the total profit increases 10.4%, however, participating in the reserve market fourfold the profits in the case in study, that increase in profits is almost proportional to the increase of the capacity of BESS.

In [28] an optimal short-term wind farm dispatch scheduling method based on a model predictive control scheme is proposed. The target is to minimize energy loss of the wind farm and the battery usage while meeting the grid constraints. The method demonstrated that the optimal plan of charge/discharge helps to reduce the fast intermittency and high fluctuation of the wind power to meet grid requirements.

An optimization model to define the optimal hourly commitment of a BESS to increase the revenue of a wind farm while including relevant operational constraints of the battery was proposed in [29]. Two different batteries were used, one with a smaller and other with a larger capacity. The model was capable of avoiding imbalance costs for unstable wind power supply and show that the annual revenue of the wind farm is increased in the presence of BESS. When the state of charge of the batteries where restricted only the cases of the small battery lead to a profitable case since the lifetime is extended and the longer-term revenue of the wind farm is higher.

Chapter 4 - Algorithm

This is divided into two subsections. In subsection 4.1. an algorithm to prevent curtailment is presented and in 4.2. maintaining the curtailment as the major priority, another algorithm with the objective to obtain the maximum revenue possible for the wind park will be integrated.

4.1. Curtailment algorithm

Firstly, the objectives of the algorithm will be discussed followed by the structure and restrictions and, finally, the algorithm operation will be presented.

4.1.1. Objectives of the curtailment algorithm

In this section, the objective is to develop an algorithm able to reduce the power curtailment in a WPP. To ensure it, a maximum limit of the power injectable into the grid is set. In the periods of time that the generation overcomes this limit, if the battery system has enough capacity available, the difference between the generation and the limit is stored in the battery.

The energy stored in the battery in those periods of time is then used when the production is lower than a minimum power limit. If the battery system has power available in that instant, the difference between the minimum limit and the instantaneous power produced in that instant is calculated and supplied by the battery.

When the power generated is between these limits, the energy produced is directly injected into the grid. With this method, it is possible to smooth the curve of the energy injected into the grid, and by that means reduce the variability of wind resource, and above all, prevent the wind power curtailment, and its associated energy and economic losses.

4.1.2. Restrictions and structure of the curtailment algorithm

Firstly, the algorithm requires the user to provide some data, such as the battery capacity and the minimum state of charge, B_{cap} and SOC_{min}, respectively, which are the battery restrictions. Taking into account the associated losses of the battery storage system due to the charging/discharging cycles, an efficiency of 95% was considered.

The maximum power of charge/discharge depends on the values of SOC_{min} and B_{cap} chosen previously by the user, being considered as the maximum power of charge/discharge, $P_{bat\_max\_charge}$ and $P_{bat\_max\_discharge}$, respectively, 25% of the total capacity, B_{cap}.

Posteriorly, two more restrictions are required, the maximum power injectable into the grid, P_{max}, and the minimum power to be injected into the grid, P_{min}, representing the grid restrictions. After initializing all the variables associated with the storage system, and to the grid, the algorithm must collect the wind farm production data, $P_{produced}$. This data is defined in 15 min periods and represent a whole day of production.

Figure 9 and 10 present the structure and respective stages of the algorithm in the form of a flow chart.

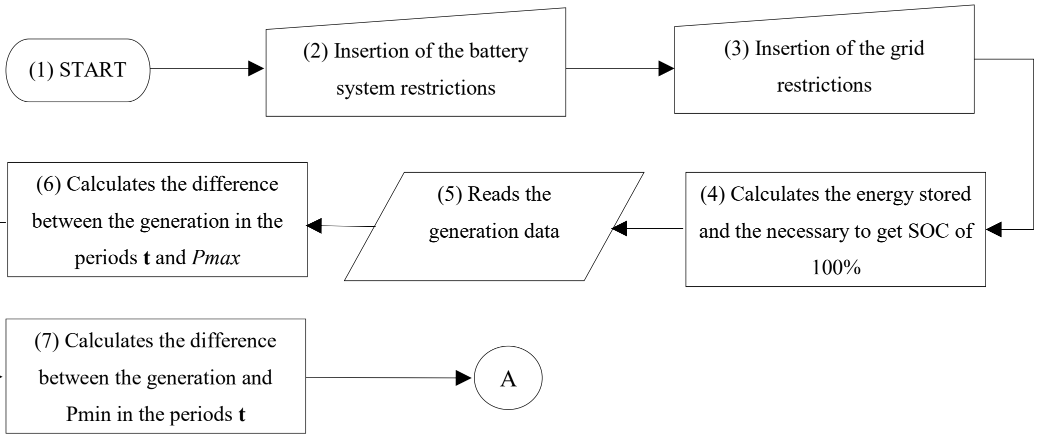


Figure 9-Flow chart of the stages 1 to 7 of the curtailment algorithm

In stage **1**, all the variables are clean and ready to be initialized. In stages **2** and **3**, it is required that the user inserts de battery capacity in MWh, the minimum state of charge, the maximum and minimum power injectable into the grid, both in MW. These values are allocated in the variables, B_{cap}, SOC_{min}, P_{max} and P_{min}, respectively.

Afterwards, in stage **4**, the energy stored in the battery and the energy necessary to the battery reaches a state of charge of 100% are calculated and allocated to the variables $E_{\_strd}$ and $E_{\_strd\_100}$, both in kWh. In stage **5**, after all the variables introduced and the energy of the battery calculated, the algorithm collects the data concerning to the generation of the wind farm, $P_{produced}$, being such values the instantaneous electric power for each 15 min of a day. The data is extracted in the form of a table and converted to a matrix and stored in 15 min periods.

In stage **6**, the difference between the instantaneous production in every instant ***t*** and P_{max} is calculated, being allocated to the variable $E_{\_excess}$. In **7**, the difference between the instantaneous production in every instant ***t*** and P_{min} is calculated and saved in the variable $E_{\_needed}$.

In stage **8** the algorithm must verify if in the instant ***t*** the difference between the instantaneous power and P_{max} is superior to zero. If the state is true the algorithm goes to stage **9**, and in such stage, it is verified if the state of charge is lower than 100%, in the event of being true, the algorithm advances to stage **10**, where it is checked if the battery system is capable of store $P_{bat\_max\_charge}$. If the battery has enough available capacity to the maximum power, in stage **11** is verified if the difference between $P_{produced}$ and P_{max} is equal or lower to $P_{bat\_max\_charge}$. If in stage **11**, the state is true, the algorithm advances to stage **12**, in this stage the surplus is stored and the remaining power (P_{max}) is injected into the grid, otherwise the algorithm advances to stage **13**, where the maximum power is stored and the remaining surplus is curtailed (difference between $E_{\_excess}$ and $P_{bat\_max\_charge}$), and similarly to stage **12**, the remaining power is injected into the grid (P_{max}). In the event of in stages **9, 10** and **11** the states are not verified, the algorithm goes directly to stage **14,** where all the excess is curtailed and P_{max} is injected into the grid.

If in stage **8** is verified that the difference between the instantaneous power and P_{max} is not positive, the algorithm advances to stage **15**. In the stage in question, the algorithm must determine if the difference between the instantaneous power and P_{min} is lower than zero, if it is, it goes to stage **16**, and in this point the algorithm checks if the state of charge is superior to SOC_{min}. Then, if SOC is superior to SOC_{min}, the algorithm advances to stage **17**, where it verifies if the battery system is capable of supply the maximum discharge power ($P_{bat\_max\_discharge}$) if it is, in stage **18** is verified if the difference between $P_{produced}$ and P_{min} is equal or lower than the maximum power of discharge**.** In case of a true state in stage **18**, the battery system supplies the energy needed and P_{min} is injected into the grid.

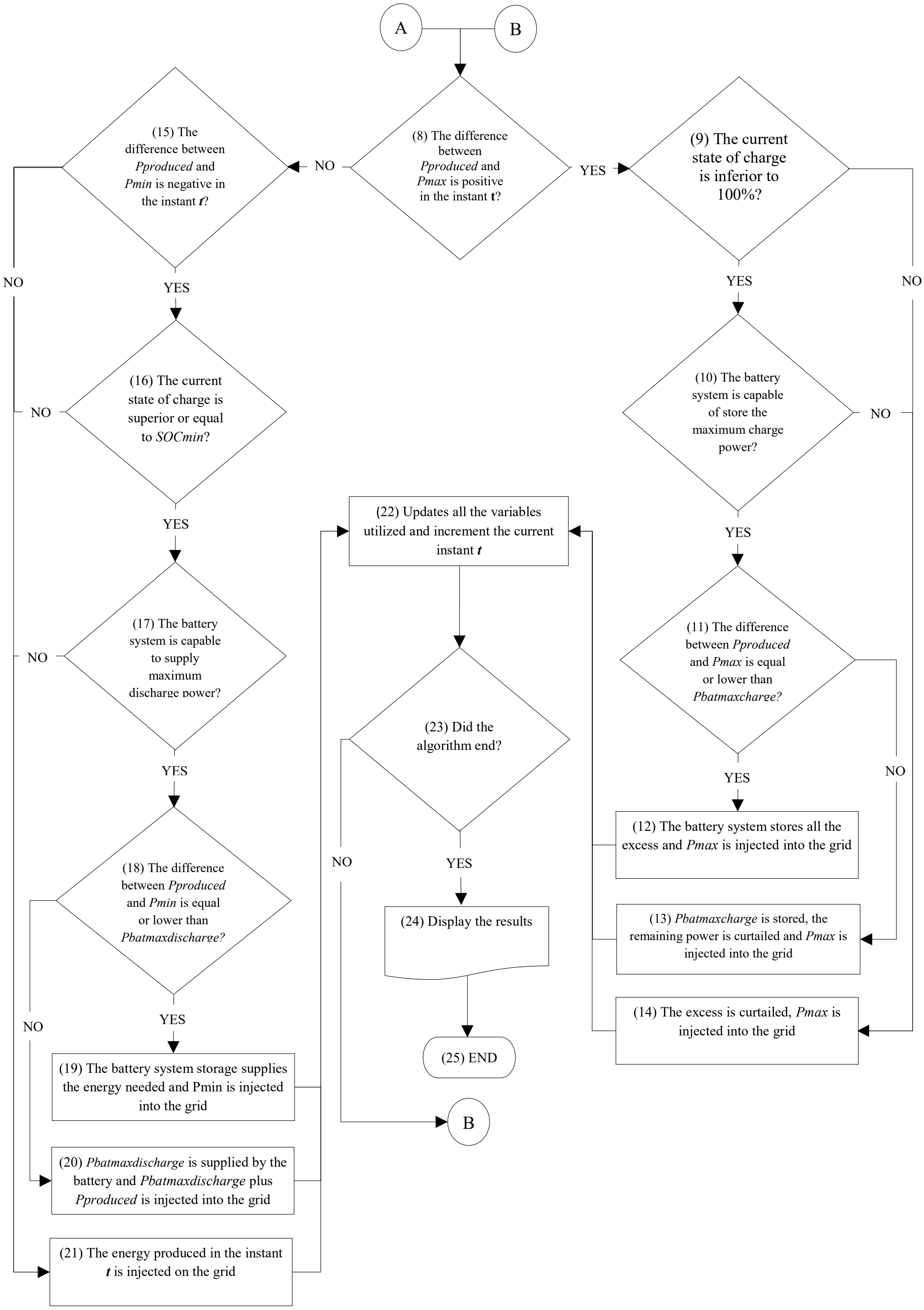


Figure 10-Flow chart from stages 8 to 25 of the curtailment algorithm

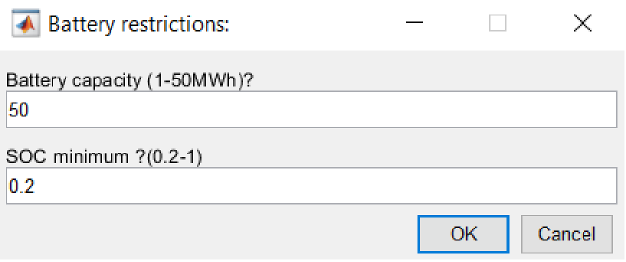
If in stage **18** is verified that the difference between the instantaneous power and P_{max} is superior than $P_{bat\_max\_discharge}$, the algorithm advances to stage **20**. In the stage in question, the battery system supplies the maximum power of discharge $P_{bat\_max\_discharge}$, and this power plus the instantaneous power produced in the instant ***t*** is injected into the grid. If in stages **15**, **16**, **17** the statements are verified as false, it advances to stage **21**, where the instantaneous power produced in that instant ***t*** is directly injected into the grid.

Regardless of the algorithm being in stage **12, 13, 14**, **19, 20** or **21**, it advances to stage **22** , where all the variables utilized are updated and the instant ***t*** is incremented to the next instant ***t***. Posteriorly, in stage **23,** the algorithm verifies if itself has ended, if the state is true, in stage **24** the results are displayed and in **25** the algorithm ends. If in stage **23**, the state is not true, the algorithm goes to stage **8** and repeats all the previously mentioned steps. The description of the variables and the mathematical equations of every stage of the curtailment algorithm are presented in annex A1 and A2, respectively.

4.1.3. Operation of the curtailment algorithm

The algorithm was developed in MatLab environment, and in this section, the interaction with the user and the algorithm operation will be presented.

In the beginning, a window appears for the input of the battery restrictions (figure 11). By default, the algorithm inserts the battery restrictions, but these can be modified by the user. The values boundaries must be respected, otherwise, a dialog box appears warning that the values limits have been exceeded, for example, in figures 12 and 13 it is possible to see what happens when the capacity value is exceeded, after the warning box, a new window appears for the user input the value again.


Battery restrictions:

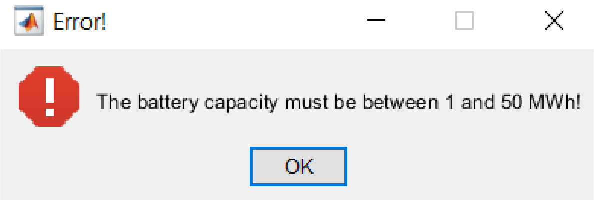
Battery capacity (1-50MWh)?

50

SOC minimum ?(0.2-1)

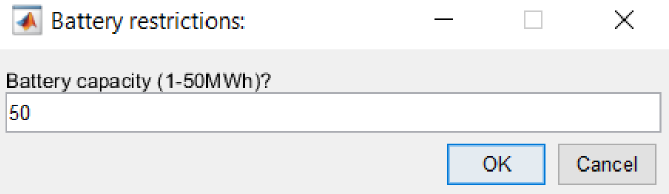
0.2

Figure 11-Dialog box to insert battery restrictions.



The battery capacity must be between 1 and 50 MWh!

Figure 12- Warning dialog box.

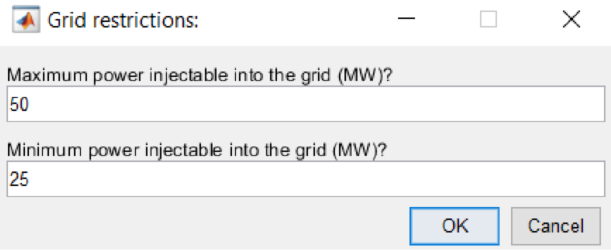


Battery capacity (1-50MWh)?

50

Figure 13- Dialog box to insert battery capacity.

After input the battery restrictions, the user must input the grid restrictions (figure 14). With all the inputs introduced, the algorithm simulates the energy exchanges with the battery system, the energy production of the wind farm, the wind power curtailment and the energy injected on the grid.



Maximum power injectable into the grid (MW)?

50

Minimum power injectable into the grid (MW)?

25

Figure 14- Dialog box to insert grid restrictions.

In figures 15, 16 and 17 is possible to see an example of the results simulated by the algorithm. Figure 15 presents the wind power production curve, the power injected into the grid and the wind power curtailment in function of the hour of the day. Figure 16 presents the input/output of power in the battery, according to the consumer criterion, and the battery SOC along the day. The algorithm also calculates in table form the total energy generated, stored and supplied by the battery, surplus, injected into the grid and curtailed for a whole day in MWh (table 1).

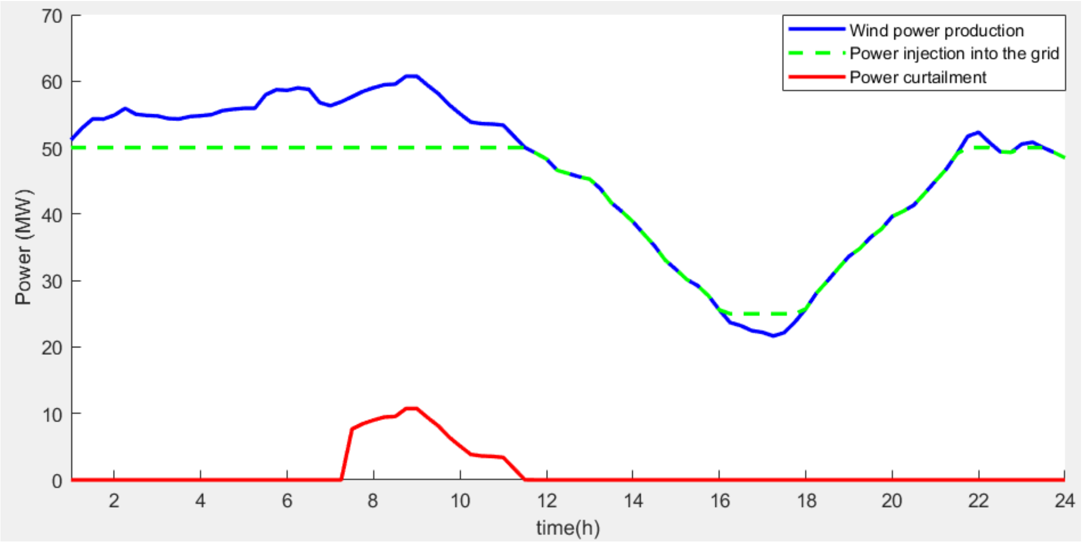
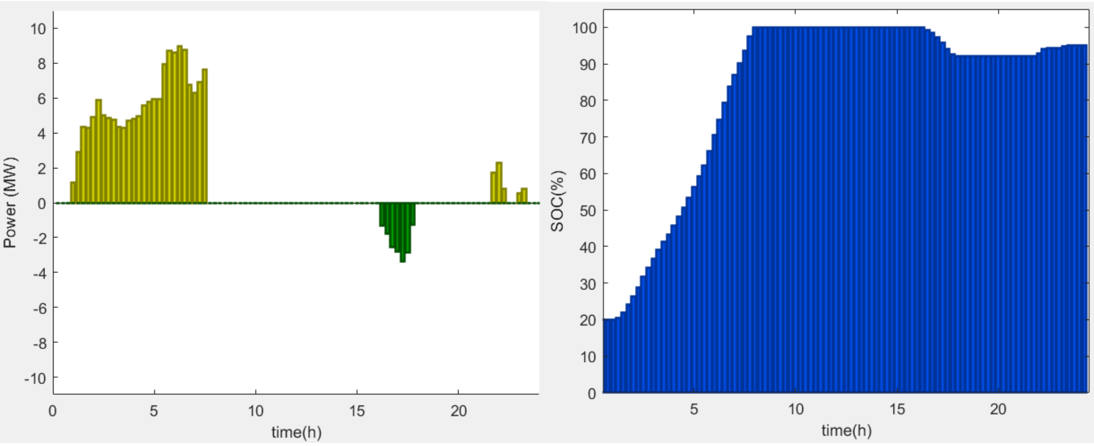


Figure 15-Wind power production, Power injected into the grid and Power curtailment.



(a) (b)

Figure 16- (a) Power in/out of the battery; (b) State of charge of the battery.

Table 1- Table of results of the algorithm

	Results (MWh)
Energy produced	1118
Energy surplus	66
Energy curtailed	26
Energy stored	40
Energy supplied by the battery	4
Energy injected into the grid	1056

4.2. Economic algorithm

Similarly, to the curtailment algorithm, this section will be divided into three subsections, being them the objectives of the algorithm, the restrictions and structure and finally the operation of the algorithm.

4.2.1. Objectives of the economic algorithm

In this algorithm, the purpose is to be able to reduce the power curtailment and simultaneously to ensure the maximum profit to the wind park. To guarantee the power curtailment reduction the algorithm maintains the structure of the curtailment algorithm, a maximum limit power injectable into the grid is set and the energy is stored in the battery in the surplus periods, in the case of available capacity.

When the generation is lower than the maximum power limit, three different situations can occur, these situations depend on the energy selling tariffs, being the price based on the MIBEL tariffs variation.

If the energy selling price is not appealing in that period of time and the battery has available capacity, the algorithm stores the maximum power of charge. If the selling price in that instant of time is profitable and the battery has enough energy stored to supply the maximum power of discharge, the battery supplies the available capacity to the grid and the instantaneous power produced in that period of time is injected into the grid, making sure that the minimum SOC and the maximum power injectable to the grid are maintained.

If none of these situations occurs, the energy produced is directly injected into the grid.

4.2.2. Restrictions and structure of the economical algorithm

The restrictions in this algorithm remain the same of the curtailment algorithm, such as battery restrictions and grid restrictions, with the difference that in the grid restrictions, in this case, no P_{min} is required, and in the battery restrictions, there is a new variable, SOC_{max}, that represents the maximum SOC. Similarly, to the previous algorithm, the maximum power of charge/discharge depends on the values of SOC_{min} and B_{cap} chosen previously by the user, being considered as the maximum power of charge/discharge, $P_{bat\_max\_charge}$ and

$P_{bat\_max\_discharge}$, respectively, 25% of the total capacity, B_{cap}. The battery systems efficiency remains the same as in the previous algorithm.

After initializing all the variables, the algorithm collects the wind farm generation data, $P_{produced}$, and the selling energy tariffs, $E_{sellprice}$. This data is defined in 15 min periods and represent an entire day of production and energy selling prices. In figures 17, 18 and 19 the structure and stages of the economical algorithm in the form of a flow chart are presented.

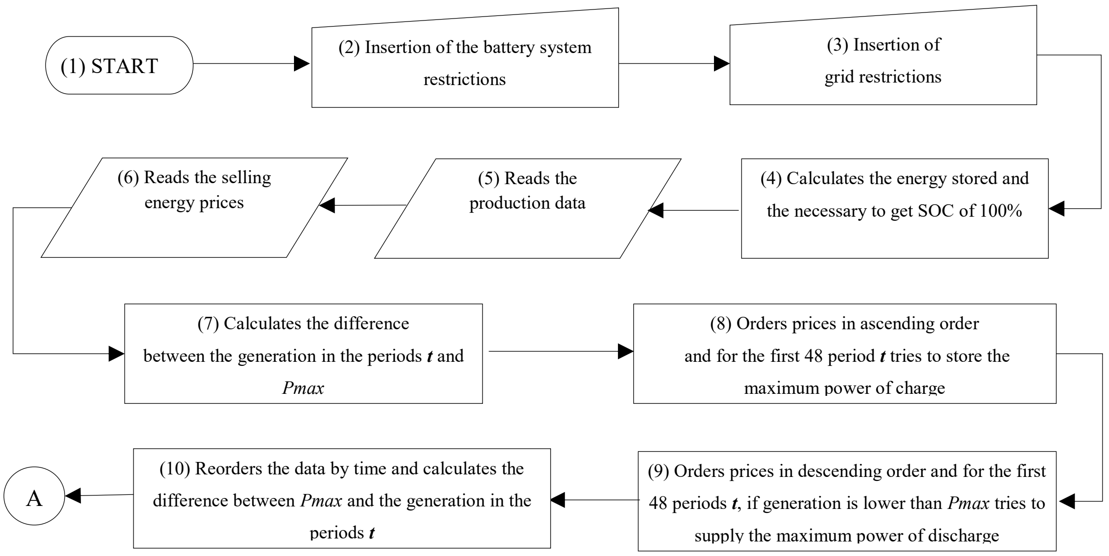


Figure 17- Flow chart of the stages 1 to 10 of the economic algorithm

From stages **1** to **5** there are none structural changes when compared to the previous algorithm. In stage **6** the MIBEL selling prices are read and allocated in the variable $E_{sellprice}$, and afterwards, in stage **7**, the difference between the instantaneous power produced in every instant ***t*** and P_{max} is calculated, being allocated in the variable $E_{\_excess}$. In stage **8** the matrix containing the variation of the prices along the day, $E_{sellprice}$, is ordered in ascending order. The first 48 periods ***t*** are selected, these values contain the periods with the lower price, and are allocated in the variable $To_{\_bat}$. For the 48 instants ***t*** selected, $To_{\_bat}$ is equal to $P_{bat\_max\_charge}$, and in the remaining periods $To_{\_bat}$ is equal to zero.

In stage **9** the opposite situation occurs, being the matrix ordered in descending order. The first 48 instants ***t*** are selected, in order to include the periods with the higher energy selling prices, and for the selected periods if $P_{produced}$ is lower than P_{max} the instants are allocated in the variable $From_{\_bat}$. In these periods, $From_{\_bat}$ is equal to the maximum power that the battery can supply, $P_{bat\_max\_discharge}$, and the other periods are set to zero. In this stage, for every period ***t*** selected, the energy sale prices for the corresponding periods ***t*** are saved and allocated to the variable *Income*. In stage **10** all the data from $To_{\_bat}$, $From_{\_bat}$ and *Income* is reordered by time and, for every instant ***t*** the difference between P_{max} and $P_{produced}$ is calculated and saved in the variable P_{bat}. In this way, the day is divided into two, with the battery system trying to store the energy produced in half of the day and trying to supply the energy previously stored in the other half.

From stages **11** to **17** the steps remain equal to stages **8** to **14** of the previous algorithm. When in stage **11** the statement is false the algorithm goes to stage **18** and **25**, but these stages are independent and never are true at the same instant ***t***, since they depend on the values of $From_{\_bat}$ and $To_{\_bat}$, and they never are positive at the same time, so do not intercept. If in stage **18** the current SOC is superior to SOC_{min} the algorithm advances to stage **19**, where, if the value in the matrix $From_{\_bat}$ is positive in that instant ***t***, meaning that in that instant, there are advantages from the economic point of view to supply energy, it progresses to stage **20** and it is verified if the battery system is able to supply $P_{bat\_max\_discharge}$ without trespassing SOC_{min}. If in stage **20** the state is true, it goes to stage **21**, where if P_{bat} (the difference between P_{max} and $P_{produced}$) is equal or inferior to the maximum power of charge, advances to stage **22**. In stage **22** P_{bat} plus $P_{produced}$ is injected into the grid. If in stage **21** P_{bat} is higher than $P_{bat\_max\_discharge}$, $P_{produced}$ plus $P_{bat\_max\_discharge}$ is injected into the grid in stage **23**. In stages **18, 19** and **20**, if the states are not true, the algorithm goes to stage **24**, and $P_{produced}$ is directly injected into the grid.

Returning to stage **11**, if the statement is not verified and in stage **25** the current SOC is inferior to SOC_{max} the algorithm advances to stage **26** where it is checked if it is possible to store in the instant ***t,*** depending on the value of $To_{\_bat}$ in the instant ***t*** being positive. If $To_{\_bat}$ is positive, in stage **27** is verified is the battery has enough capacity to store the maximum power of charge in the instant in question, and, in case of the statement being true, in stage **28**, the battery stores $P_{bat\_max\_charge}$ and the remaining power (difference between $P_{produced}$ and $P_{bat\_max\_charge}$) is injected into the grid, if the instantaneous power produced in the instant ***t*** is lower or equal to the maximum power of charge, all the generation is stored. It should be noted that the user can change the value of SOC_{max}, opting for a value lower than 100%, leaving a reserve for the surplus generation periods. In the case of the statements in stages **25**, **26** and **27**, are not verified, the generation is directly injected into the grid in stage **24**.

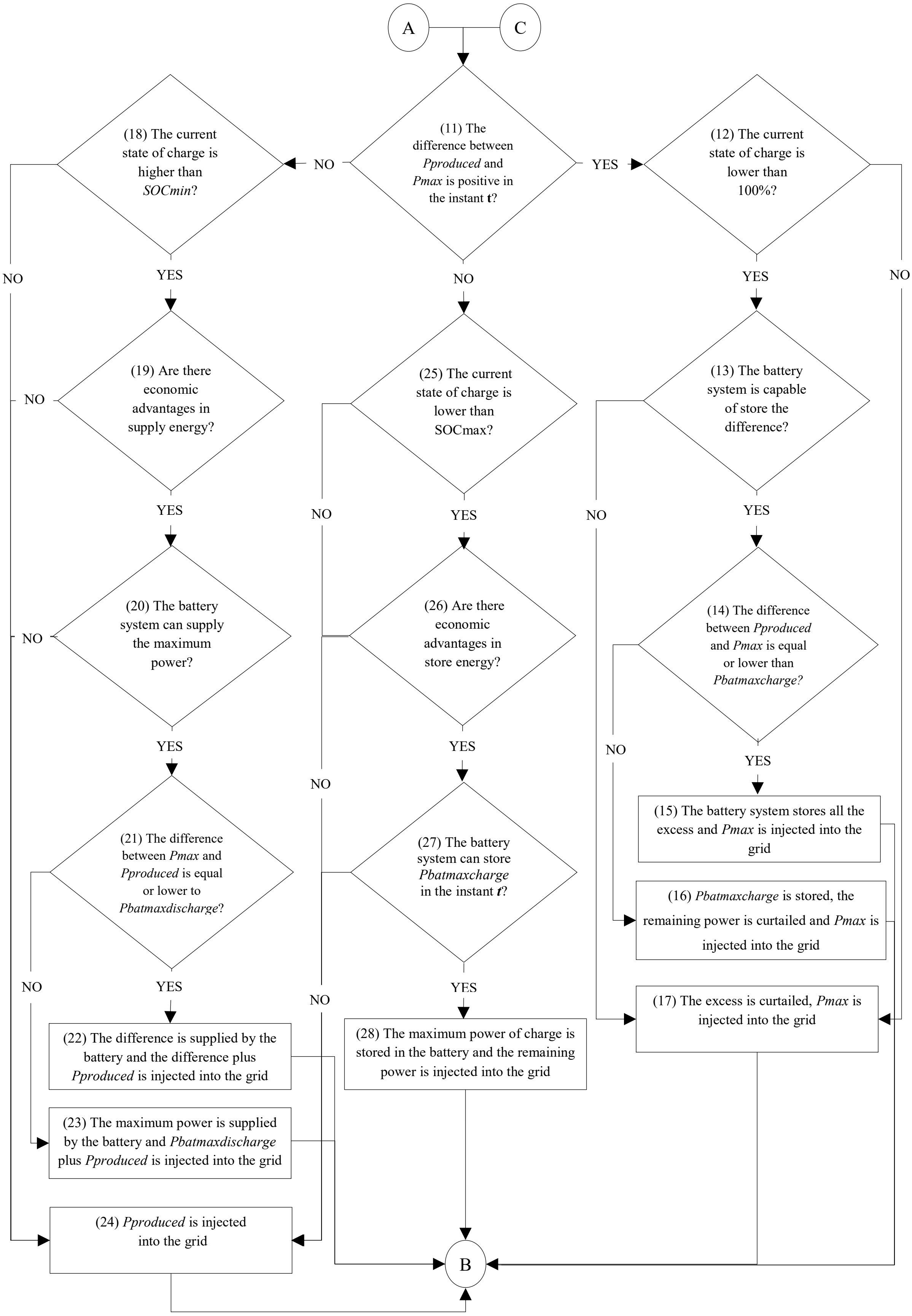


Figure 18-Flow chart of the stages 11 to 28 of the economic algorithm

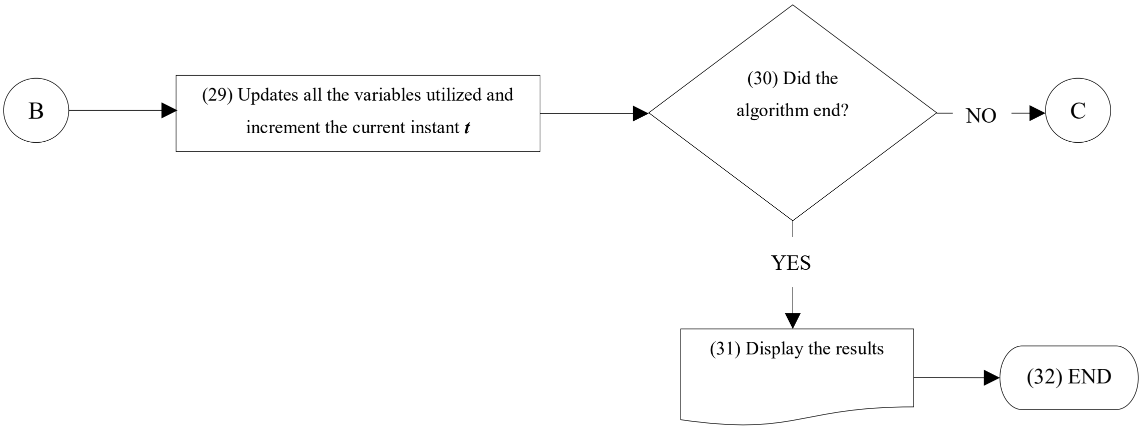


Figure 19-Flow chart of the stages 29 to 32 of the economic algorithm

If the algorithm is in stages **15**, **16, 17, 22, 23, 24** or **28**, it advances to stage **29**, where all the variables utilized are updated and the instant ***t*** is incremented to the next instant ***t***. Then in stage **30,** the algorithm verifies if the end has reached, and if the state is true, in stage **31** the results are displayed and in **32** the algorithm ends. If in stage **30** the algorithm did not end it goes to stage **11** and repeats all the steps referred previously. The description of the variables and the mathematical equations of every stage of the economic algorithm are presented in annex A1 and A3, respectively.

4.2.3. Operation of the economical algorithm

The algorithm operation remains similar to the curtailment algorithm. In the battery restriction insertion dialog box (figure 11), a new restriction is added for the user to select the maximum SOC. In the grid restrictions dialog box now no P_{min} insertion is required (figure 14). The simulation results display the same graphics, and, in the table, a new line is added with the total income resultant from the energy sold.

Chapter 5 - Simulation Results

The results will be divided into two subsections. In 5.1. the curtailment algorithm will be analyzed and in 5.2. the economic one. Considering a wind farm with an installed power of 60 MW, a maximum power injectable into the grid of 50 MW, a battery storage system with a capacity of 50 MWh and a minimum SOC of 20%.

5.1. Curtailment algorithm results

The algorithm will be tested in three distinct days with different values of generation surplus in a wind farm. With the objective to smooth the injection curve into the grid and to utilize the energy stored in the battery in the surplus periods, a minimum limit power injectable into the grid of 25 MW is considered. In 5.1.1., 5.1.2. and 5.1.3. three days with high, medium and low wind speed will be analyzed, respectively. The implemented curatilment algorithm is presented in Annex B1.

5.1.1. Low wind speed

The generation data, the power curtailment and the power injected into the grid for this day is shown in figure 20.

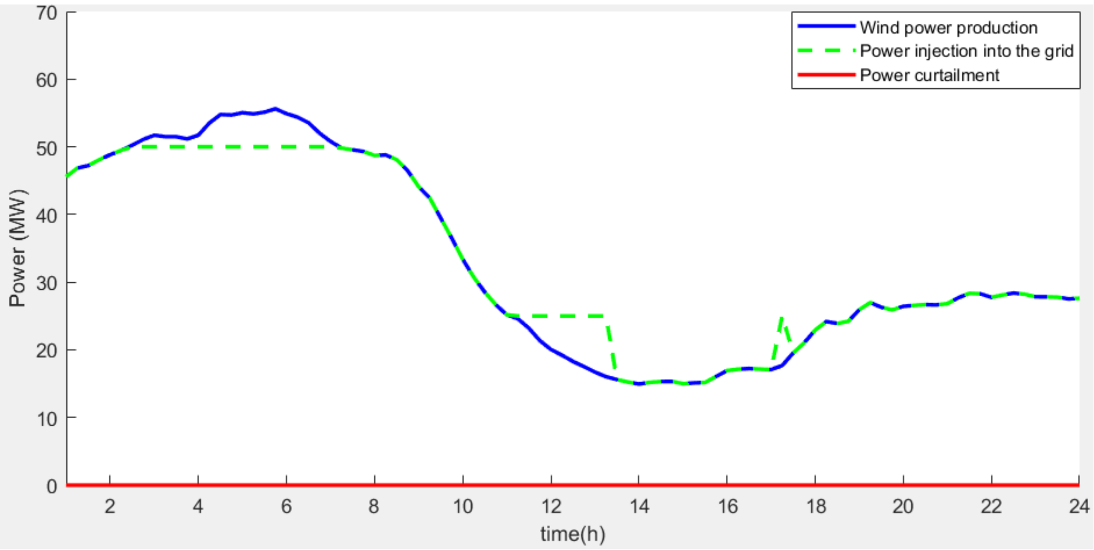
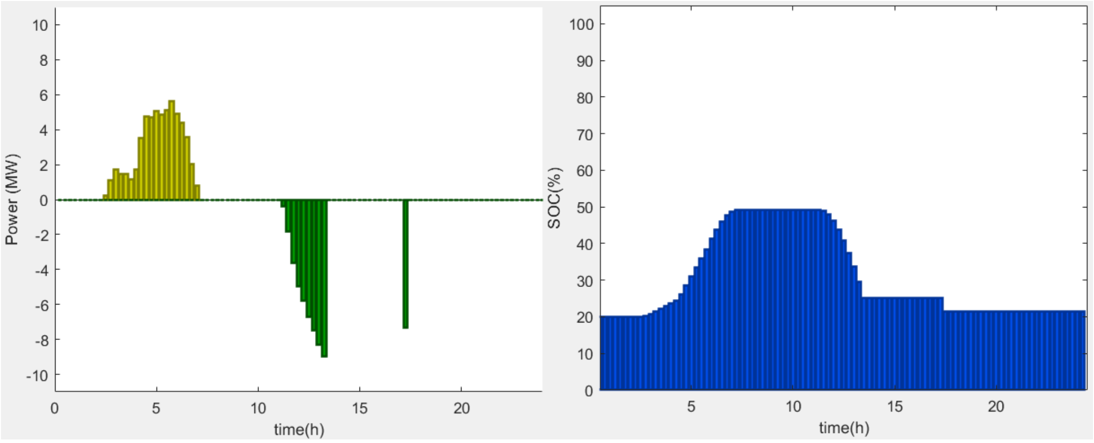


Figure 20-Wind power production, Power injected into the grid and Power curtailment for a low wind speed day.

Analyzing the curves, it is possible to observe that no power curtailment was necessary in this case. The periods of time that the generation overcomes 50 MW are between 2 and 6 a.m.

Between 12 and 2 p.m., approximately, the system compensates the energy necessary to maintain the power injection into the grid in the 25MW, utilizing the energy stored in the battery in the previous periods of overproduction. Between 2 p.m. and 6 p.m., the generation is lower than 25 MW, however, the battery does not have the energy necessary to compensate the generation and it is not possible to ensure the minimum power of 25 MW.

In the other periods of time the generation is between the defined boundaries, and therefore the power injected into the grid follows the generation. The power input/output in the battery and the SOC along the day are represented in figure 21.



(a)

(b)

Figure 21-(a) Power input/output of the battery and (b) State of charge of the battery for a low wind speed day.

These two graphics are only related to the battery, being possible to observe the input/output of power in the battery and simultaneously the SOC increasing/ decreasing.

Observing table 2, it is possible to verify that all the generation surplus was stored, meaning that no curtailment was necessary. In this day a total compensation of 14 MWh was supplied by the battery.

Table 2- Table of results of the curtailment algorithm for a low wind speed day.

	Results (MWh)
Energy produced	803
Energy surplus	15
Energy curtailed	0
Energy stored	15
Energy supplied by the battery	14
Energy injected into the grid	796

5.1.2. Medium wind speed

In this subsection a day with medium wind speed will be analyzed, being presented in figure 22 the generation data, the power curtailment and the power injected into the grid.

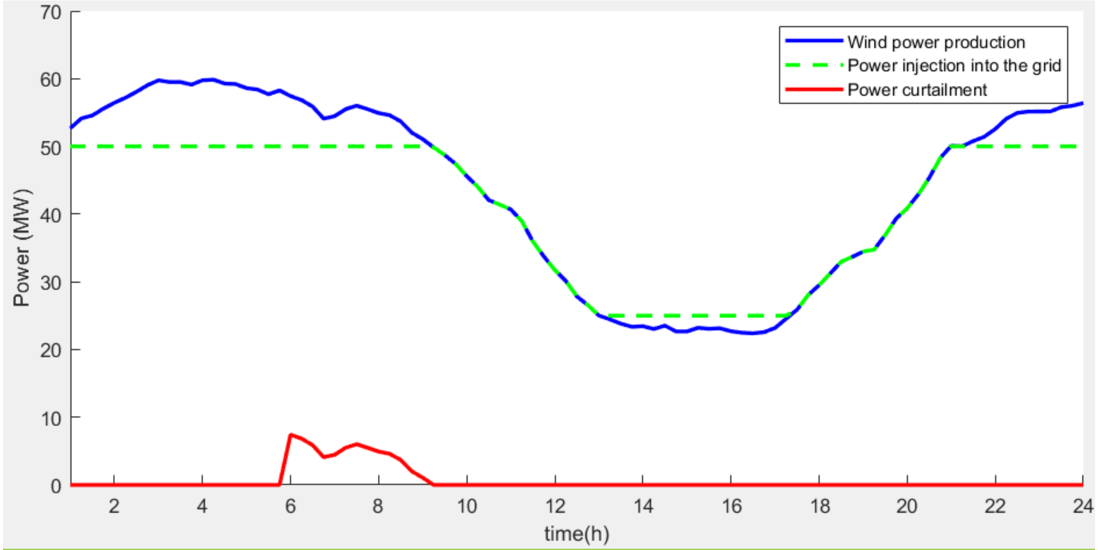
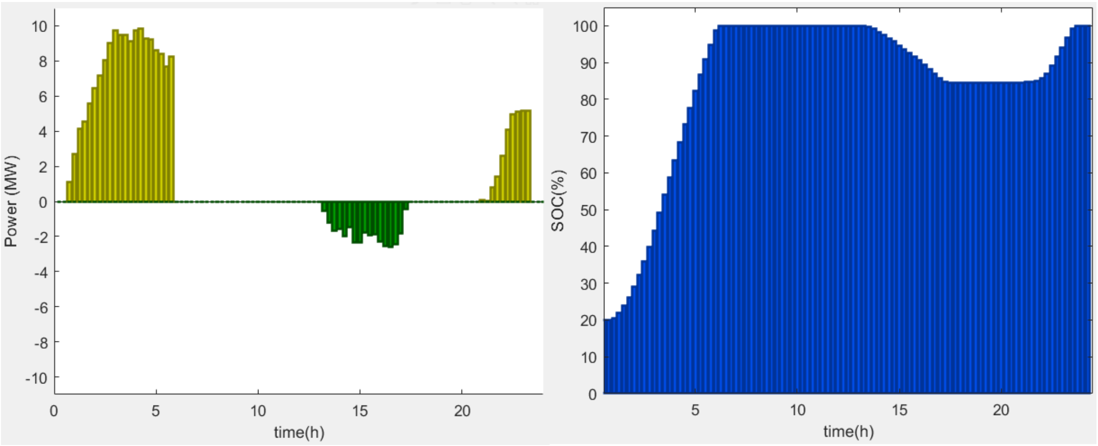


Figure 22-Wind power production, Power injected into the grid and Power curtailment for a medium wind speed day.

In this case, the battery system capacity was not enough to store all the generation surplus. It is easily visible the times periods with generation higher than 50 MW, being them between 1 and 9 a.m. and then between 9 and 12 p.m.. Between 1 and 5 p.m., approximately, the battery is able to compensate the low production and maintains the power injection into the grid in the 25 MW.

The charge/discharge power and the SOC along the day are represented in figure 23.



(a) (b)

Figure 23- (a) Power input/output of the battery and (b) State of charge of the battery for a medium wind speed day.

Analyzing the values of table 3, a total of 51 MWh was prevented from being curtailed, representing 76% of the total surplus. The total surplus was 67 MWh and a compensation of 8 MWh was possible to supply due to the energy stored in the previous periods of generation surplus.

Table 3- Table of results of the curtailment algorithm for a medium wind speed day.

	Results (MWh)
Energy produced	1056
Energy surplus	67
Energy curtailed	15
Energy stored	51
Energy supplied by the battery	8
Energy injected into the grid	996

5.1.3. High wind speed

In this subsection a strong wind speed day will be presented, being the generation data, the power curtailment and the power injected into the grid for this day represented in figure 24.

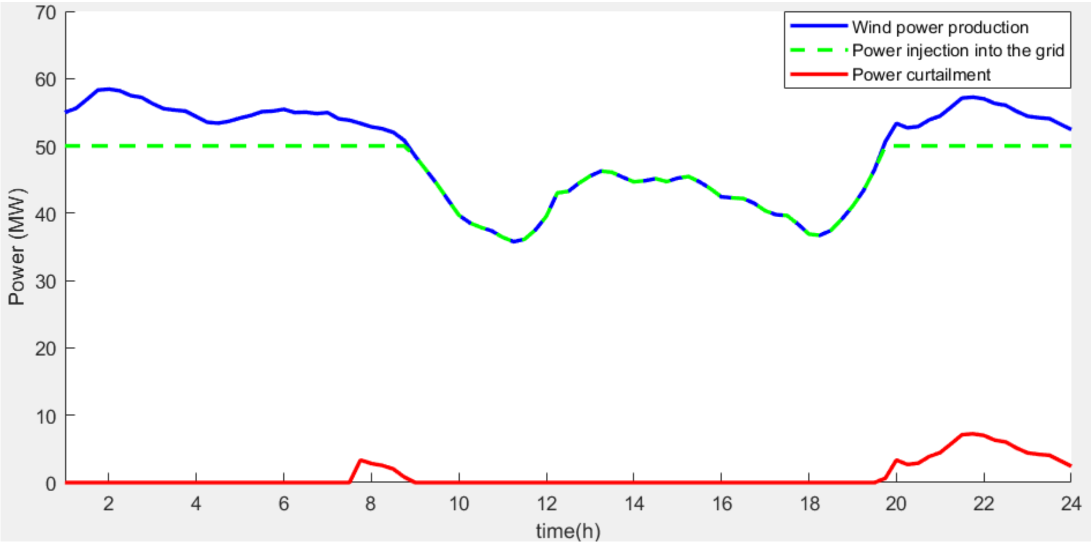
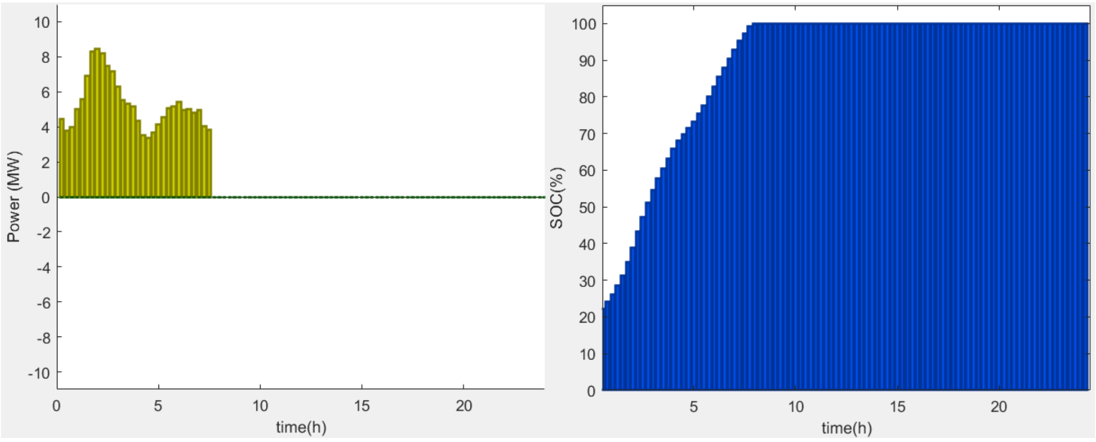


Figure 24-Wind power production, Power injected into the grid and Power curtailment for a high wind speed day.

The surplus generation periods are presented between 1 and 9 a.m. and then between 7.45 and 12 p.m., representing approximately 12 hours of the 24 hours of generation.

Analyzing figure 25 it is possible to verify that between 7 a.m. and 12 p.m. in the periods of generation surplus, there is the need of curtailment since the battery achieved the maximum SOC previously.



(a) (b)

Figure 25- (a) Power input/output of the battery and (b) State of charge of the battery for a high wind speed day.

Analyzing the values given in the results (table 4), 63% of the generation surplus was prevented from being curtailed. Comparing it with the medium wind speed day, the total generation surplus is lower, but, since the generation was never lower than 25 MW, the battery never discharges and consequently less energy was stored, being the energy stored along the day equal to the usable capacity of the battery. In such situations, it is considered that the battery discharges in the next day.

Table 4-Table of results of the curtailment algorithm for a high wind speed day

	Results (MWh)
Energy produced	1175
Energy surplus	63
Energy curtailed	23
Energy stored	40
Energy supplied by the battery	0
Energy injected into the grid	1113

5.2. Economic algorithm results

The algorithm will be tested in two different scenarios. In 5.2.1 a winter day will be simulated and in 5.2.2 a summer day. Different values of SOC_{max} will be simulated in both cases, in order to optimize the results for every scenario and to each day different values of energy selling prices are associated, depending on the typical price values for the different seasons. The implemented economic algorithm is presented in Annex B2.

5.2.1. Winter day

In figure 26, the variation of energy prices in the wholesale market (data from OMIE) along the day in a winter day is presented.

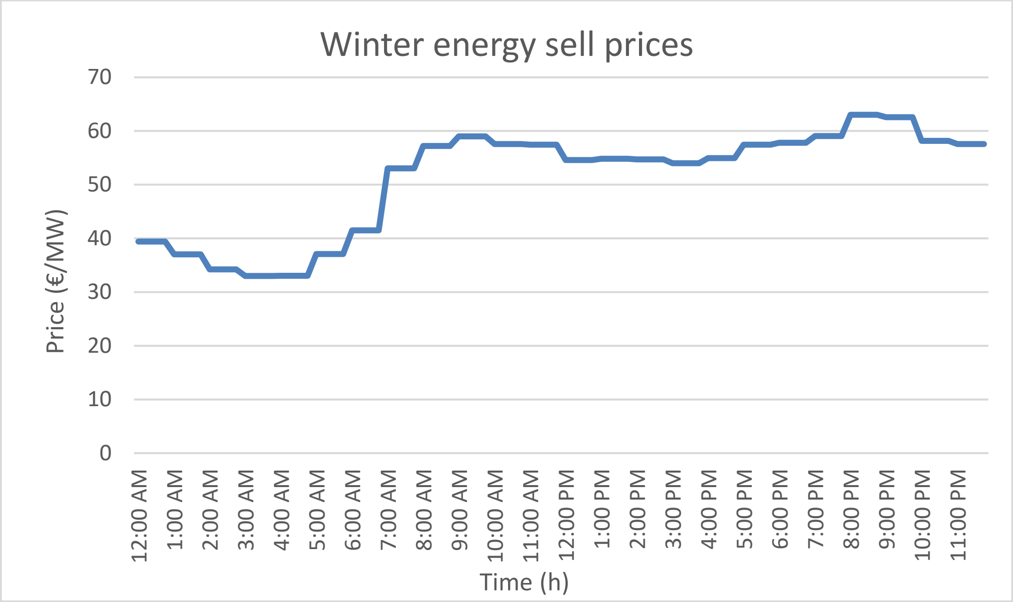


Figure 26- Energy sell prices variation on a winter day [30].

The wind power production, power injected into the grid and power curtailment for the first scenario are represented in figure 27.

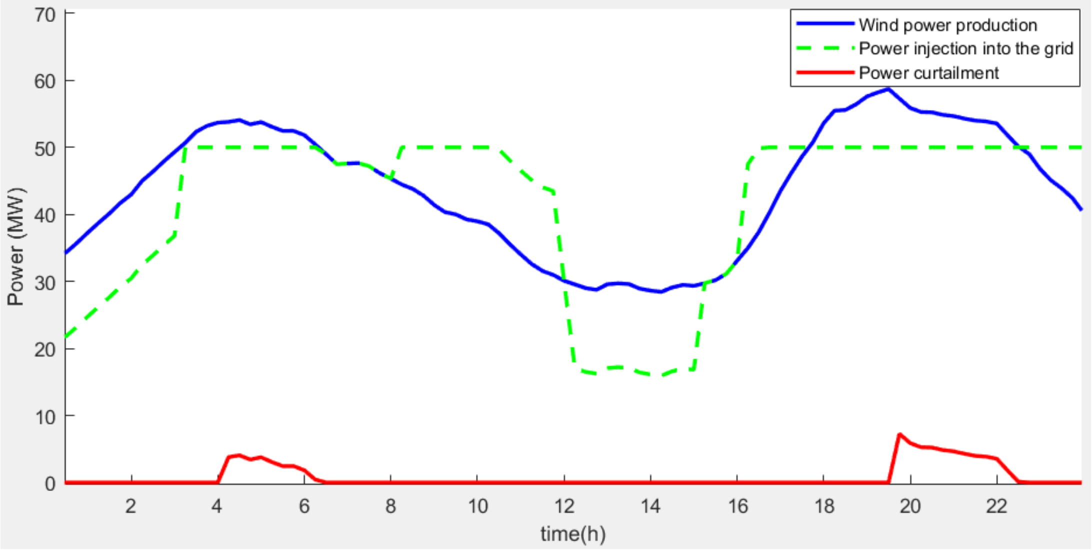


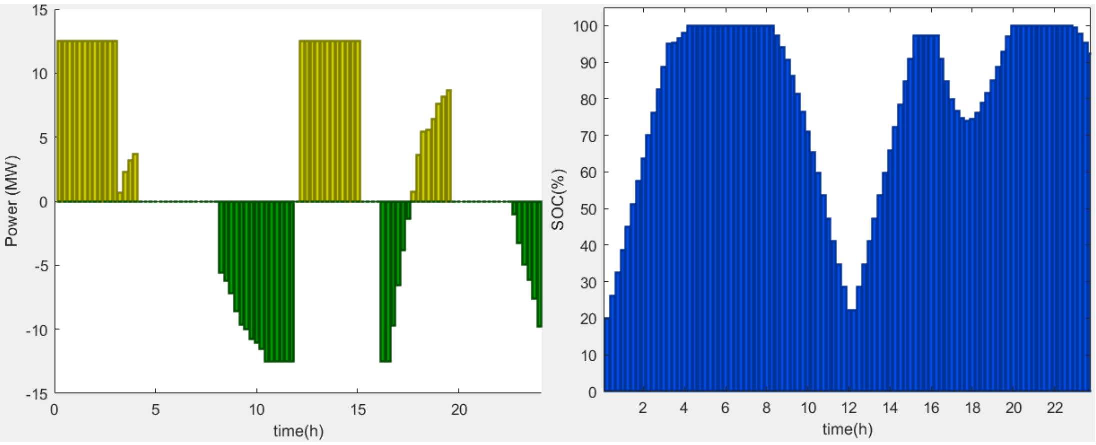
Figure 27- Wind power production, Power injection into the grid and Power curtailment for a winter day with SOC_{max} equal to 100%.

Observing the curves, it is easily noticed that the periods that the power injected into the grid is lower than the generation, represent the periods that the battery stores the maximum power of charge. These periods are represented between 12 p.m. and 1 a.m., and between 12 a.m. and 2.30 p.m.. Between 8 and 12 a.m., 4 p.m. to 5.30 p.m. and 10.30 and

12 p.m., approximately, the battery system supplies the energy previously stored in the battery.

The periods of generation surplus are represented between 3 and 6 a.m., and then between 7.30 p.m. and 10 p.m. and in such periods, a considerable amount of power was curtailment.

In figure 28, the charge/discharge power and the SOC along the day are represented.



(a) (b)

Figure 28- (a) Power input/output of the battery and (b) State of charge of the battery for a winter day with SOC_{max} equal to 100%.

Analyzing the power supplied by the battery is observable that the amount of energy supplied varies depending on the wind park generation in those periods, preventing the limit of power-injectable into the grid to be exceeded. To notice that, even though the battery has sufficient energy stored in some periods, the battery system waits to supply it only in the most convenient periods from the economic point-of-view.

In table 5 the numerical results are represented. In this day 42.4% of the total generation surplus was prevented from being curtailed. The percentage is lower than the previous results with the curtailment algorithm, this is justifiable due to be a day with high generation and to the fact that now the battery system also stores in the lower price periods, utilizing more capacity than before. From the total energy stored, 66.3% was supplied and sold in the more profitable periods, resulting in a total income of 3362 €. Even though this is a day with a considerable profit a significant amount of power was curtailed, and the economic losses associated with that may not compensate the energy sold. No limitation of

SOC_{max} occurred in this case, being equal to 100%, delimiting this value and leaving a bigger reserve in the battery capacity to the curtailment periods the losses may be attenuated.

Table 5- Table of results of the economic algorithm for a winter day with SOC_{max} equal to 100%.

	Results
Energy produced (MWh)	1050
Energy surplus (MWh)	33
Energy curtailed (MWh)	19
Energy stored (MWh)	89
Energy supplied by the battery (MWh)	59
Energy injected into the grid (MWh)	1001
Profit (€)	3362

The wind power production, power injected into the grid and power curtailment for a winter day with SOC_{max} equal to 70% is represented in figure 29.

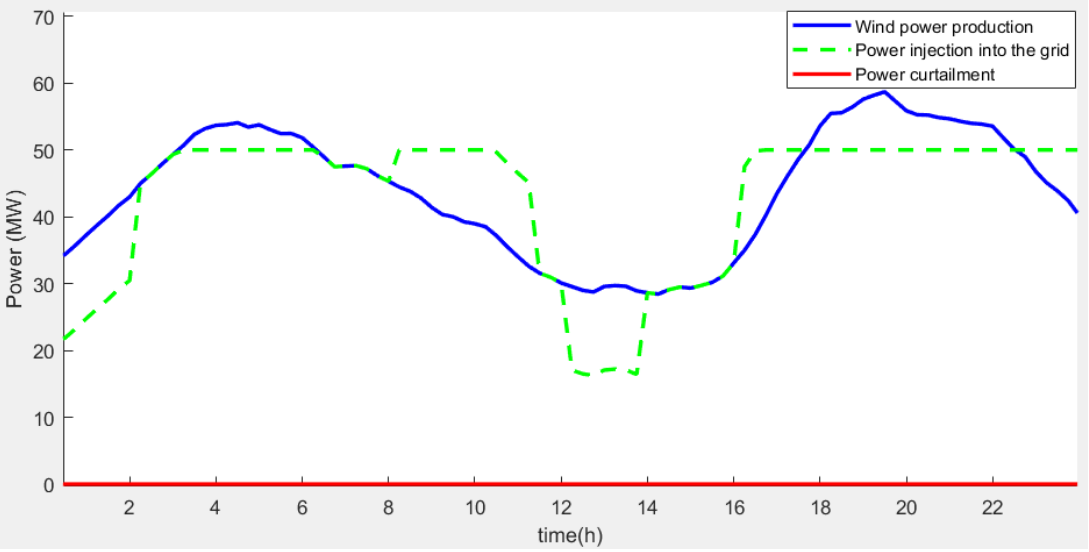


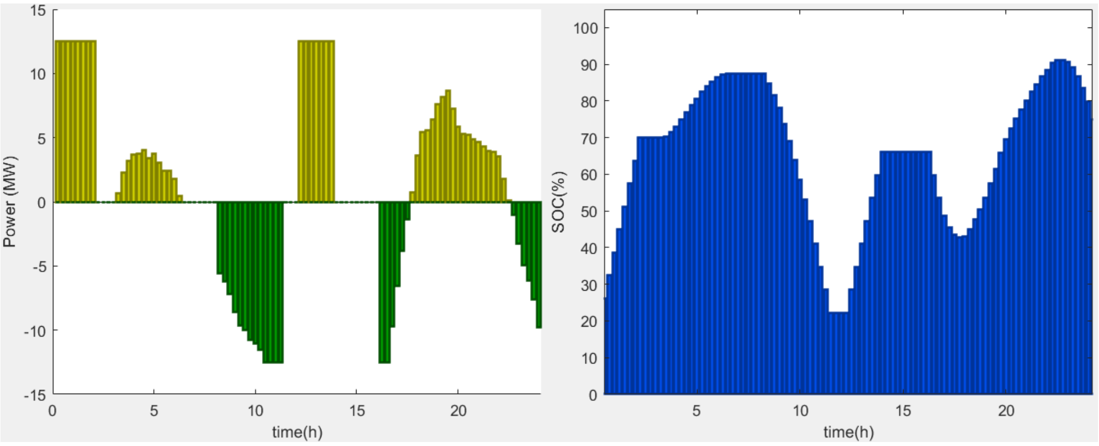
Figure 29- Wind power production, Power injected into the grid and Power curtailment for a winter day with SOC_{max} equal to 70%.

Comparing such results with the obtained results in the previous case, the major difference is the amount of power curtailed, that in this scenario was reduced to zero. This reduction was possible since the use of the battery system for economic purposes was limited until a maximum SOC of 70%, leaving more capacity available to compensate the surplus generation periods.

The periods that the battery stores are presented between 12 a.m. and 2 a.m. and between 12 p.m. and 2 p.m., being the above reduction notable in both periods of storage.

The generation surplus periods remain the same since there was no alteration in the generation. The periods with the battery supplying the stored energy are represented between 8 a.m. and 11.30 a.m. and suffered a small reduction in the first supply periods. This can be explained by the fact that less generation was stored previously. On the other periods no alterations occurred.

Figures 30 presents the charge/discharge power and the SOC along the day.



(a) (b)

Figure 30- (a) Power input/output of the battery and (b) State of charge of the battery for a winter day with SOC_{max} equal to 70%.

Analyzing the figures is even more noticeable the reduction in the energy stored, since the SOC only exceeds the maximum SOC in surplus periods, as intended. Additionally, as in the previous scenario, the battery only supplies and stores in the periods that are more economically convenient.

In table 6, the results for this scenario are presented. Observing the values, it is possible to notice that compared to the previous scenario, there was a reduction of 11.9% in the energy supplied by the battery, as consequence of the reduction in the energy stored. This situation leads to a decrease of 359 € in the profit. In this case, no power losses associated with curtailment occurred, and when compared with the previous case this is a positive point, but this reduction in the total income may not be economically profitable. In the preceding simulation the economic profits due to the energy sold where appealing, but this case has the advantage that no curtailment was required. Encountering a value of maximum SOC between these two may lead to a more convenient situation.

Table 6- Table of results of the economic algorithm for a winter day with SOC_{max} equal to 70%.

	Results
Energy produced (MWh)	1050
Energy surplus (MWh)	33
Energy curtailed (MWh)	0
Energy stored (MWh)	80
Energy supplied by the battery (MWh)	52
Energy injected into the grid (MWh)	1022
Profit (€)	3003

In order to find a better result between the two previous simulations, the winter day was tested with a maximum SOC of 80%. In figures 31, 32 and in table 7 the results for this simulation are presented.

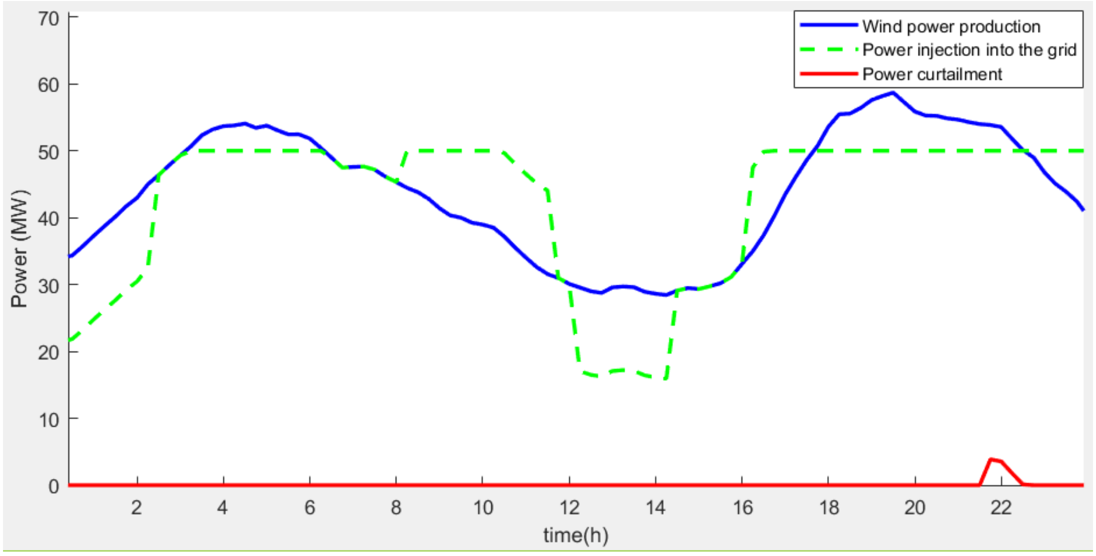
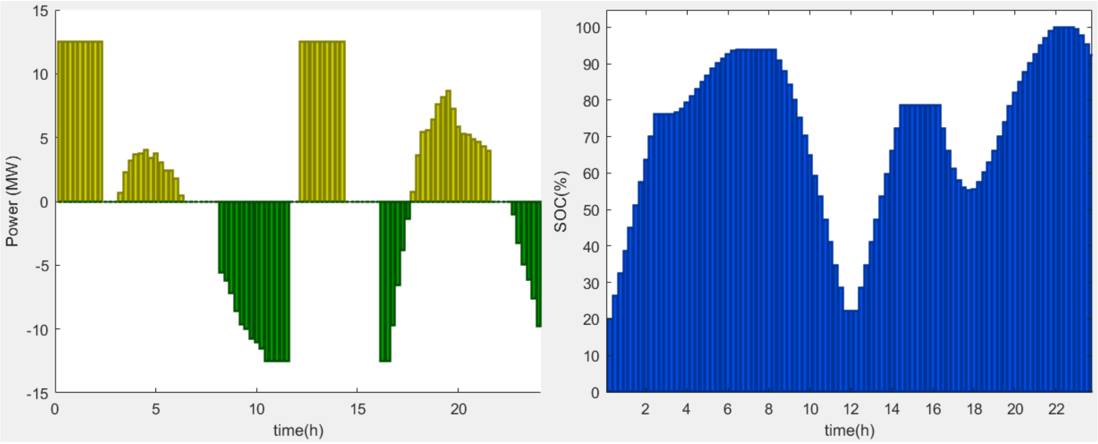


Figure 31- Wind power production, Power injected into the grid and Power curtailment for a winter day in the second scenario with SOC_{max} equal to 80%.



(a) (b)

Figure 32- (a) Power input/output of the battery and (b) State of charge of the battery for a winter day with SOC_{max} equal to 80%.

Table 7- Table of results of the economic algorithm for a winter day with SOC_{max} equal to 80%.

	Results
Energy produced (MWh)	1050
Energy surplus (MWh)	33
Energy curtailed (MWh)	2
Energy stored (MWh)	87
Energy supplied by the battery (MWh)	56
Energy injected into the grid (MWh)	1016
Profit (€)	3182

Observing the results given in this case, a power curtailment of 2 MW was required and with this new value of SOC_{max} an increase in profits of 5.6% was possible. These may not be the most convenient situation after all, since the losses in power may not compensate the increase in profits, being the second simulation the most profitable one. Adapting the SOC_{max} to the circumstance leads to the most convenient situation.

5.2.2. Summer day

The energy selling prices variation on a summer day (with data from OMIE) are presented in figure 33.

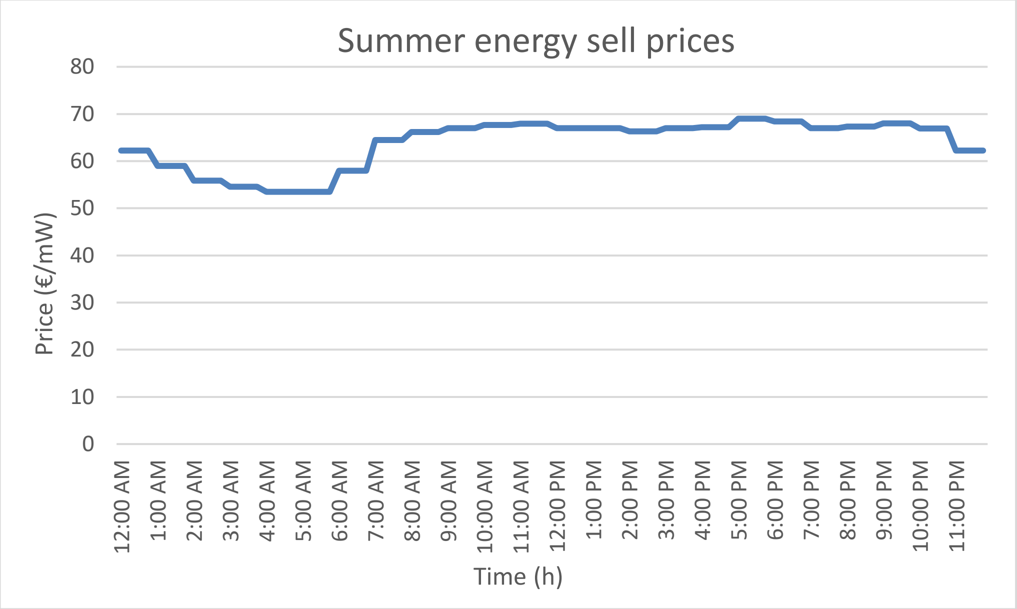


Figure 33- Variation of energy selling prices for a summer day [30].

The wind power production, power injected into the grid and power curtailment for the summer day are presented in figure 34.

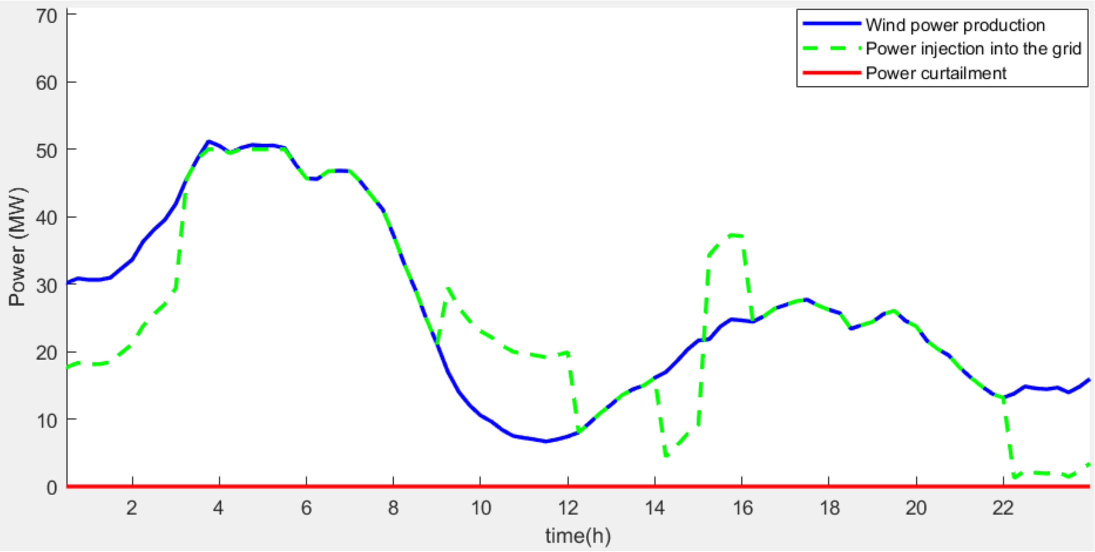


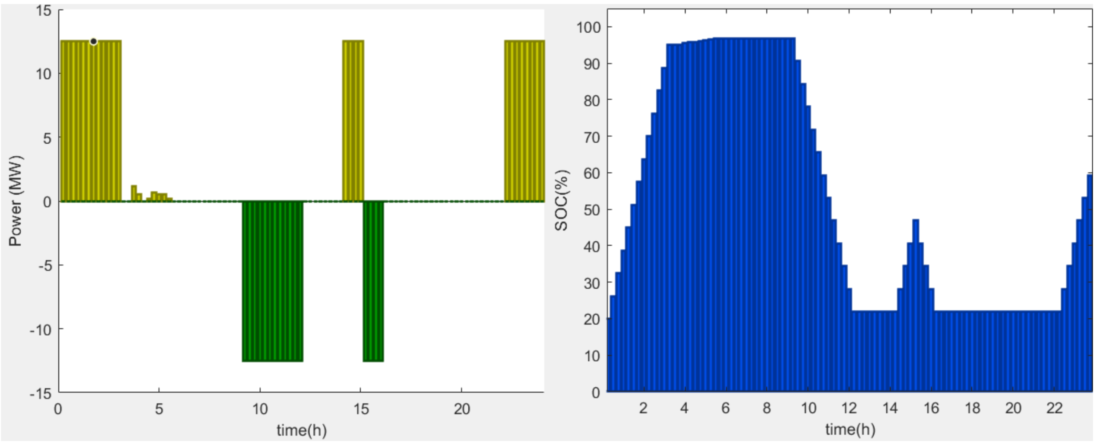
Figure 34- Wind power production, Power injected into the grid and Power curtailment for a summer day with SOC_{max} equal to 100%.

This is a day with low generation, and the only periods of surplus are between 3.30 a.m. and 5 a.m., leading to the fact that no curtailment was required in this day.

The periods when the battery stores are represented between 12 p.m. and 3 a.m., 2 and 3 p.m. and finally between 10 and 12 p.m..

Between 9 a.m. and 12 a.m. and then between 3.15 p.m. and 4.15 p.m., the energy storage system supplies the energy stored in the battery in the previous periods.

In figure 33 the charge/discharge power and the SOC along the day, respectively, are represented. Due to being a low generation day, in the higher price hours, the battery was always capable to supply the maximum power, contrary to the previous day.



(a) (b)

Figure 35- (a) Power input/output of the battery and (b) State of charge of the battery for a summer day with SOC_{max} equal to 100%.

In table 8, the results for this summer day are presented. Although a small percentage of surplus periods occurred in this day, due to the system store in low price periods, a total of 76 MWh was stored. In this day 50 MWh were supplied along the day by the battery, leading to a total income of 3370 €.

When compared to the previous day (Winter scenario), the difference in profits is not noticeable, since the periods of lower and higher prices are different, and less energy is stored to be supplied afterwards.

In days like this, it is more convenient to opt for a SOC_{max} equal to 100%. Since almost no generation surplus periods occur, the most profitable option to take is to store the maximum power possible in the lower price periods and to inject the maximum power possible into the grid in the most economically convenient periods.

Table 8- Table of results of the economic algorithm for a summer day with SOC_{max} equal to 100%.

	Results
Energy produced (MWh)	626
Energy surplus (MWh)	1
Energy curtailed (MWh)	0
Energy stored (MWh)	76
Energy supplied by the battery (MWh)	50
Energy injected into the grid (MWh)	600
Profit (€)	3370

The summer day will be tested with a SOC_{max} equal to 70%, but since no curtailment was required in the previous case, the simulation that leads to a most profitable situation was already encountered.

In figures 36, 37 and in table 9 the results for this simulation are presented.

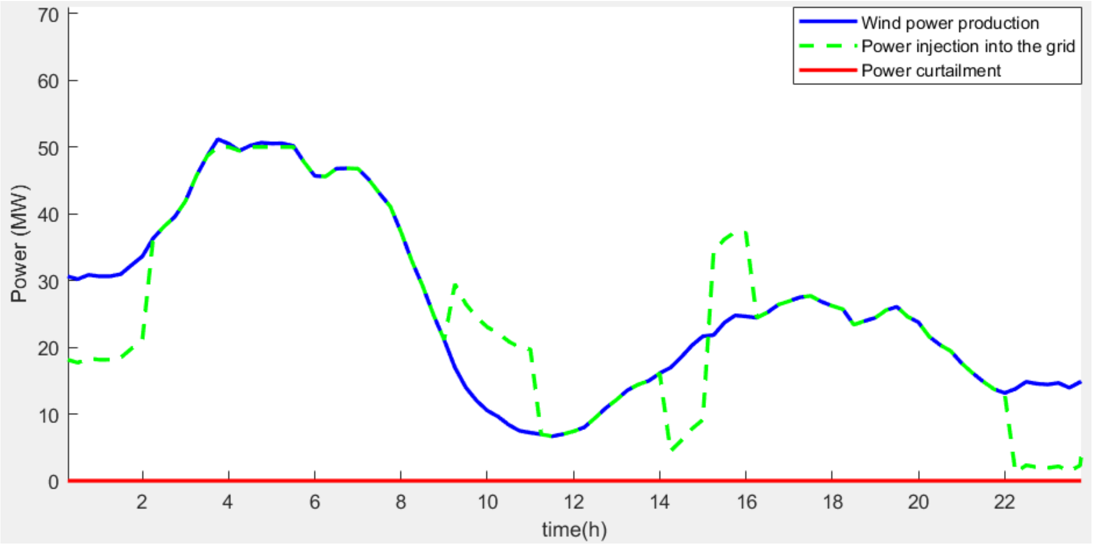
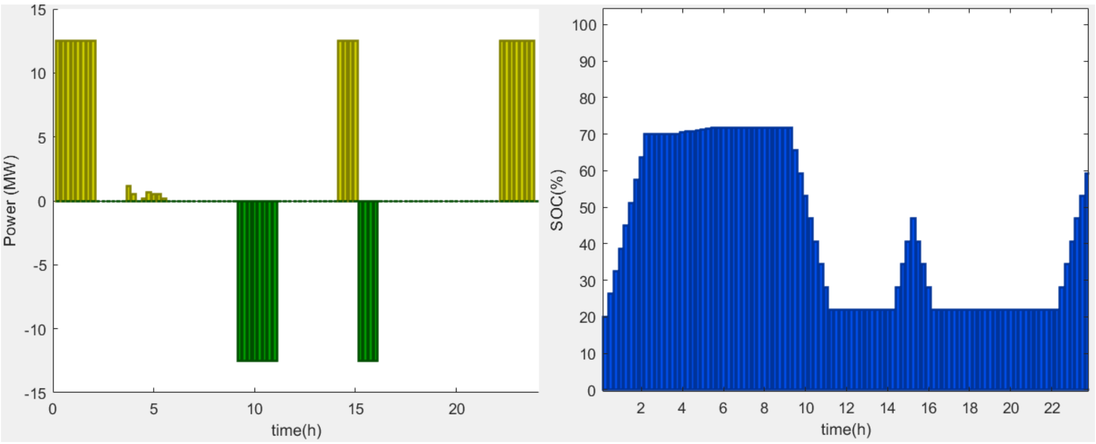


Figure 36- Wind power production, Power injected into the grid and Power curtailment for a summer day with SOC_{max} equal to 70%.



(a) (b)

Figure 37- (a) Power input/output of the battery and (b) State of charge of the battery for a summer day with SOC_{max} equal to 70%.

Table 9- Table of results of the economic algorithm for a summer day with SOC_{max} equal to 70%.

	Results
Energy produced (MWh)	626
Energy surplus (MWh)	1
Energy curtailed (MWh)	0
Energy stored (MWh)	60
Energy supplied by the battery (MWh)	38
Energy injected into the grid (MWh)	604
Profit (€)	2521

Evaluating the values resultant from this case when compared with the case simulated above, the reduction of SOC_{max} does not create any benefit, as expected, since there is no power curtailment to compensate. This reduction in the available capacity resulted in a reduction of the energy supplied by 24%, and, consequently, the total income decreased 849 €.

Chapter 6 - Conclusions and Future Work

6.1. Conclusion

The principal purpose of this dissertation was to develop an algorithm able to manage an energy storage system for wind parks. Most wind parks have an installed power superior to the maximum power injectable into the grid, leading to the need of curtailment, to limit the production of the wind park. With this method, a significant amount of power is wasted in periods of high wind velocity. Additionally, in the future, wind generation will participate in wholesale electricity markets, so allying the wind power curtailment and the variation of energy prices, the main objective of the algorithm was to store the generation surplus in curtailment periods and also to store in periods of low cost, to be injected into the grid in periods of higher cost.

In order to develop the algorithm, previous research about the wind farm resource and the different energy storage methods was realized. In the research made about energy storage technologies it was possible to conclude that batteries were more adequate to implement in this system. They ensure the needed technical requirements to manage the wind resource, are already used in several wind parks and present a decreasing cost.

After collecting all the information needed to implement the algorithm, in chapter 4, two different algorithms were designed, a curtailment algorithm and an economic algorithm, both developed in Matlab environment. In the curtailment algorithm, the main target was to reduce wind power curtailment and simultaneously smooth the power injection curve. The algorithm stores in surplus generation periods, reducing curtailment, and injects to the grid when the generation is inferior to a minimum power, selectable by the user. In the economic algorithm, maintaining curtailment as a priority, the objective was to store generation in lower price periods and inject into the grid, the energy previously stored, in higher price periods.

A virtual wind park with a power installed of 60 MW and a maximum power injectable into the grid of 50 MW was considered. The battery system was implemented with a capacity of 50 MWh and the algorithms were simulated considering different days.

For the curtailment algorithm three distinct days with different wind speeds (low, medium and high wind speed) were simulated. The results showed that it was possible to reduce wind power curtailment significantly and proved the efficiency of the algorithm. The obtained results are as follow:

- In low wind seep day, 2% of the total generation represented surplus generation periods, being the battery system able to store all the surplus.
- In medium wind speed day, the surplus periods represented 6.3% of the total generation, being the battery system able to store 77.6% of the surplus.
- In the high wind speed day, the surplus periods represented 5.9% of the total generation and the system was able to store 63.5% of the surplus generation.

In the economic algorithm, two different scenarios were simulated, a winter day and a summer day. These scenarios were simulated for different values of maximum SoC, in order to leave more capacity available to the curtailment periods. The results showed that the algorithm was able to ensure all objectives, with the following results:

- In a day with high generation during winter, in the worst-case scenario (SOC_{max} equal to 100%), the system was able to store 42.4% of the surplus generation and to make a total income of 3169 €
- Adapting to the circumstance and adjusting the restriction value, in the better case scenario for the winter day, no curtailment was required and a total income of 3003 € was possible.
- In the summer day, no curtailment was required and a total profit of 3170 € was obtained.

Taking into account all the presented results, the algorithms showed that an energy storage system in a wind park is able to minimize the power loss and to bring economic benefits. Even though, it is important to remember that all the conclusions and results depend on various factors, technical and economic, such as the tariffs value variation and the generation profiles. The cost of the battery storage system is an important economic factor that was not accounted and is crucial to validate the system.

6.2. Future Work

Even though the results given achieved the principal objectives, it is possible to adapt to new strategies and to develop the algorithm with new constraints and for different purposes.

Gathering more data and doing deeper research about the problem, more restriction could be applied. To be analyzed in a more realistic way, the use of data from an existing wind park would be interesting.

Another update may pass through the use of a degradation model of the battery system, in that way, the battery system would be more realist. Testing the algorithm in a larger period of time, for example, for a year would give interesting results, although, in order to do that, the generation data and the wholesale market prices for and whole year would need to be collected.

Adapting the algorithm to be integrated into a real wind park would be the most important step to make, and to do that, the algorithm should be modified to be applied in a real controller.

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Annex A – Variables Description

A.1 Storage system and grid restrictions for the curtailment and economic algorithms

Table 10 – Battery system restrictions, grid restrictions and generation data.

Battery system restrictions	
Energy storage system capacity (MWh):	B_{cap}
Minimum state of charge (%):	SOC_{min}
Maximum state of charge (%):	SOC_{max}
Maximum power of charge (MW):	$P_{bat\_\mathrm{max}\_charge}$
Minimum power of charge (MW):	$P_{bat\_\mathrm{max}\_discharge}$
Grid Restrictions	
Maximum power injectable into the grid (MW):	P_{max}
Minimum power injectable into the grid (MW):	P_{min}
Generation data	
Electric power produced (MWh):	$P_{produced}$

A.2 Variables and Mathematical equations of the curtailment algorithm

Table 11 – Variables description and mathematical equations utilized in every stages of the flow chart of the curtailment algorithm previously presented.

Stage	Variables and mathematical equations
1	$START$ n_{BS}
2	B_{cap} SOC_{min} $SOC_{aux} = SOC_{min}$ $P_{bat\_\max\_charge} = 0{,}25 \times B_{cap}$ $P_{bat\_\max\_discharge} = 0{,}25 \times B_{cap}$
3	P_{max} P_{min}
4	$E_{\_strd} = SOC_{min} \times B_{cap}$ $E_{\_strd\_100} = B_{cap} - E_{\_strd}$
5	$[P_{produced}] = ReadValues()$
6	$E_{\_excess}(t) = P_{produced}(t) - P_{max}$
7	$E_{\_needed}(t) = P_{produced}(t) - P_{min}$
8	$E_{\_excess}(t) \geq 0$
9	$SOC_{aux}(t) < 1$
10	$E_{\_strd}(t) + P_{bat\_\max\_charge} \leq B_{cap}$

11	$P_{produced}(t) - P_{max} \leq P_{bat\_\mathrm{max}\_charge}$
12	$E_{\_strd}(t+1) = E_{\_strd}(t) + E_{\_excess}(t)$ $E_{\_strd\_100}(t+1) = B_{cap} - E_{\_strd}(t+1)$ $SOC_{aux}(t+1) = E_{\_strd}(t+1) \div B_{cap}$ $E_{\_to\_bat}(t) = E_{\_excess}(t)$ $E_{\_to\_grid}(t) = P_{max}$
13	$E_{\_strd}(t+1) = E_{\_strd}(t) + P_{bat\_\mathrm{max}\_charge}$ $E_{\_strd\_100}(t+1) = B_{cap} - E_{\_strd}(t+1)$ $SOC_{aux}(t+1) = E_{\_strd}(t+1) \div B_{cap}$ $E_{\_to\_grid}(t) = P_{max}$ $E_{\_to\_bat}(t) = P_{bat\_\mathrm{max}\_charge}$ $E_{\_curtailed}(t) = E_{\_excess}(t) - P_{bat\_\mathrm{max}\_charge}$
14	$E_{\_strd}(t+1) = B_{cap}$ $E_{\_strd\_100}(t+1) = 0$ $SOC_{aux}(t+1) = 1$ $E_{\_to\_grid}(t) = P_{max}$ $E_{\_curtailed}(t) = E_{\_excess}(t)$
15	$E_{\_needed}(t) < 0$
16	$SOC_{aux}(t) > SOC_{min}$
17	$E_{\_strd}(t) \times n_{BS} + E_{\_needed}(t) \geq SOC_{min} \times B_{cap}$
18	$E_{\_needed}(t) \leq P_{bat\_\mathrm{max}\_discharge}$

19	$E_{\_strd}(t+1) = E_{\_strd}(t) + E_{\_needed}(t)$ $E_{\_strd\_100}(t+1) = B_{cap} - E_{\_strd}(t+1)$ $SOC_{aux}(t+1) = E_{\_strd}(t+1) \div B_{cap}$ $E_{\_from\_bat}(t) = E_{\_needed}(t)$ $E_{\_to\_grid}(t) = P_{min}$
20	$E_{\_strd}(t+1) = E_{\_strd}(t) + P_{bat\_\max\_discharge}$ $E_{\_strd\_100}(t+1) = B_{cap} - E_{\_strd}(t+1)$ $SOC_{aux}(t+1) = E_{\_strd}(t+1) \div B_{cap}$ $E_{\_from\_bat}(t) = P_{bat\_\max\_discharge}$ $E_{\_to\_grid}(t) = P_{bat\_\max\_discharge} + P_{produced}(t)$
21	$E_{\_strd}(t+1) = E_{\_strd}(t)$ $E_{\_strd\_100}(t+1) = B_{cap} - E_{\_strd}(t+1)$ $SOC_{aux}(t+1) = E_{\_strd}(t+1) \div B_{cap}$ $E_{\_to\_grid}(t) = P_{produced}(t)$
22	$t = t + 1$
23	$t \leq 96$
24	$plot\left(P_{produced}, E_{\_to\_grid}, E_{\_curtailed}\right)$ $bar(SOC_{aux})$ $bar\left(E_{\_to\_bat}, E_{\_from\_bat}\right)$
25	END

A.3 Variables and Mathematical equations of the economic algorithm

Table 12 – Variables description and mathematical equations utilized in every stages of the flow chart of the economic algorithm previously presented.

Stage	Variables and mathematical equations
1	$START$ n_{BS}
2	B_{cap} SOC_{min} SOC_{max} $SOC_{aux} = SOC_{min}$ $P_{bat\_\max\_charge} = 0{,}25 \times B_{cap}$ $P_{bat\_\max\_discharge} = 0{,}25 \times B_{cap}$
3	P_{max} P_{min}
4	$E_{\_strd} = SOC_{min} \times B_{cap}$ $E_{\_strd\_100} = B_{cap} - E_{\_strd}$
5	$[P_{produced}] = ReadValues()$
6	$[E_{sell\_price}] = ReadValues()$
7	$E_{\_excess}(t) = P_{produced}(t) - P_{max}$

8	$[E_{sell\_price}] = SortValues()$ $t \leq 48$ $To_{\_bat}(t) = P_{bat\_\max\_charge}$ $t > 48$ $To_{\_bat}(t) = 0$ $[To_{\_bat}] = UnsortValues()$
9	$[E_{sell_{price}}] = SortValues('descend')$ $t \leq 48$ $From_{\_bat}(t) = P_{bat\_\max\_discharge}$ $Income(t) = E_{sell\_price}(t)$ $t > 48$ $From_{\_bat}(t) = 0$ $Income(t) = 0$ $[From_{\_bat}] = UnsortValues()$ $[Income] = UnsortValues()$
10	$P_{bat}(t) = P_{max} - P_{produced}(t)$
11	$E_{\_excess}(t) \geq 0$
12	$SOC_{aux}(t) < 1$
13	$E_{\_strd}(t) + P_{bat\_\max\_charge} \leq B_{cap}$
14	$P_{produced}(t) - P_{max} \leq P_{bat\_\max\_charge}$

15	$E_{\_strd}(t+1) = E_{\_strd}(t) + E_{\_excess}(t)$ $E_{\_strd\_100}(t+1) = B_{cap} - E_{\_strd}(t+1)$ $SOC_{aux}(t+1) = E_{\_strd}(t+1) \div B_{cap}$ $E_{\_to\_bat}(t) = E_{\_excess}(t)$ $E_{\_to\_grid}(t) = P_{max}$
16	$E_{\_strd}(t+1) = E_{\_strd}(t) + P_{bat\_\max\_charge}$ $E_{\_strd\_100}(t+1) = B_{cap} - E_{\_strd}(t+1)$ $SOC_{aux}(t+1) = E_{\_strd}(t+1) \div B_{cap}$ $E_{\_to\_grid}(t) = P_{max}$ $E_{\_to\_bat}(t) = P_{bat\_\max\_charge}$ $E_{\_curtailed}(t) = E_{\_excess}(t) - P_{bat\_\max\_charge}$
17	$E_{\_strd}(t+1) = B_{cap}$ $E_{\_strd\_100}(t+1) = 0$ $SOC_{aux}(t+1) = 1$ $E_{\_to\_grid}(t) = P_{max}$ $E_{\_curtailed}(t) = E_{\_excess}(t)$
18	$SOC_{aux}(t) > SOC_{min}$
19	$From_{\_bat}(t) > 0$
20	$E_{\_strd}(t) \times n_{BS} - P_{bat\_\max\_discharge} \geq SOC_{min} \times B_{cap}$
21	$P_{bat}(t) \leq P_{bat\_\max\_discharge}$

22	$E_{\_strd}(t+1) = E_{\_strd}(t) - P_{bat}(t)$ $E_{\_strd\_100}(t+1) = B_{cap} - E_{\_strd}(t+1)$ $SOC_{aux}(t+1) = E_{\_strd}(t+1) \div B_{cap}$ $E_{\_to\_grid}(t) = P_{bat}(t) + P_{produced}(t)$ $Profit(t) = Income(t) \times P_{bat}(t)$ $E_{\_from\_bat}(t) = P_{bat}(t)$
23	$E_{\_strd}(t+1) = E_{\_strd}(t) - From_{\_bat}(t)$ $E_{\_strd\_100}(t+1) = B_{cap} - E_{\_strd}(t+1)$ $SOC_{aux}(t+1) = E_{\_strd}(t+1) \div B_{cap}$ $E_{\_to\_grid}(t) = From_{\_bat}(t) + P_{produced}(t)$ $Profit(t) = Income(t) \times From_{\_bat}(t)$ $E_{\_from\_bat}(t) = From_{\_bat}(t)$
24	$E_{\_strd}(t+1) = E_{\_strd}(t)$ $E_{\_strd\_100}(t+1) = B_{cap} - E_{\_strd}(t+1)$ $SOC_{aux}(t+1) = E_{\_strd}(t+1) \div B_{cap}$ $E_{\_to\_grid}(t) = P_{produced}(t)$
25	$SOC_{aux}(t) < SOC_{max}$
26	$To_{\_bat}(t) > 0$
27	$E_{\_strd}(t) + P_{bat\_\max\_charge} \leq SOC_{max} \times B_{cap}$

28	$P_{produced}(t) \leq P_{bat\_\max\_charge}$ $E_{\_strd}(t+1) = E_{\_strd}(t) + P_{produced}(t)$ $E_{\_strd\_100}(t+1) = B_{cap} - E_{\_strd}(t+1)$ $SOC_{aux}(t+1) = E_{\_strd}(t+1) \div B_{cap}$ $E_{\_to\_grid}(t) = 0$ $E_{\_to\_bat}(t) = P_{produced}(t)$ $P_{produced}(t) > P_{bat\_\max\_charge}$ $E_{\_strd}(t+1) = E_{\_strd}(t) + To_{bat}(t)$ $E_{\_strd\_100}(t+1) = B_{cap} - E_{\_strd}(t+1)$ $SOC_{aux}(t+1) = E_{\_strd}(t+1) \div B_{cap}$ $E_{\_to\_grid}(t) = P_{produced}(t) - To_{bat}(t)$ $E_{\_to\_bat}(t) = To_{bat}(t)$
29	$t = t + 1$
30	$t \leq 96$
31	$plot\left(P_{produced}, E_{\_to\_grid}, E_{\_curtailed}\right)$ $bar(SOC_{aux})$ $bar\left(E_{\_to\_bat}, E_{\_from\_bat}\right)$
32	END

Annex B – Algorithms Developed in MatLab

For a better interpretation of the codes it is recommended to copy it to MatLab.

B.1- Curtailment Algorithm

```
%% 1- start

clear
clc

%% 2- Insertion of the battery restrictions

prompt = {'Battery capacity (1-50MWh)?', 'SOC minimum ?(0.2-1)'};
title = 'Battery restrictions:';
dims = [1 60; 1 60];
definput = {'50', '0.2'};
bat_aux = inputdlg(prompt, title, dims, definput);

%difining data and validating it
B_cap = str2double(bat_aux(1));
SOC_min = str2double(bat_aux(2));

%verifies if capacity is in the interval
while((B_cap < 1)|| (B_cap > 50) || (isfinite(B_cap)~=1))
     waitfor(msgbox('The battery capacity must be between 1 and 50 
MWh!', 'Error!','error'));
     B_cap = str2double(inputdlg(prompt(1), title, dims(1,:), 
definput(1)));
end
%verifies if SOC minimum is in the interval
while((SOC_min < 0.2)|| (SOC_min > 1) || (isfinite(SOC_min)~=1))
     waitfor(msgbox('The SOC minimum must be between 0.1 and 1 !', 
'Error!','error'));
     SOC_min = str2double(inputdlg(prompt(2), title, dims(2,:), 
definput(2)));
end

B_cap = B_cap*(1000)*4; % converting the battery capacity to kW
pause(1);
n_BS = 0.95; %efficiency of the battery system

P_bat_max_charge = B_cap*(1/16);
P_bat_max_discharge = B_cap*(1/16);

%% 3- Insertion of the grid restrictions

prompt = {'Maximum power injectable into the grid (MW)?', 'Minimum 
power injectable into the grid (MW)?'};
```

```
title = 'Grid restrictions:';
dims = [1 60; 1 60];
definput = {'50', '25'};
grid_aux = inputdlg(prompt, title, dims, definput);

Pmax = str2double(grid_aux(1));% maximum power injectable into the
grid
Pmin = str2double(grid_aux(2));% minimum power injectable into the
grid

P_max = Pmax*1000;
P_min = Pmin*1000;

%% 4- calculates the energy in the battery and the necessary to
reach SOC of 100%

E_strd = zeros(96,1);%pre allocation of matrix
E_strd(1,1) = B_cap * SOC_min; %energy in the battery
E_strd_100 = B_cap - E_strd; %energy necessary to SOC = 100%

SOC_aux = zeros(96,1);%pre allocation of matrix
SOC_aux(1,1) = SOC_min; %SOC



%% 5- Reads the production data

P_produced = readtable('Example_day.xlsx');
P_produced = table2array(P_produced);

E_to_bat = zeros(96,2);%pre allocation of the matrix of energy
that goes to the battery
E_excess = zeros (96,2);%pre allocation of matrix of the energy
that overcomes P_max
E_to_grid = zeros (96,2);%pre allocation of matrix of the energy
that goes to grid
E_curtailed = zeros (96,2);%pre allocation of matrix of the energy
curtailed
E_needed = zeros (96,2);%pre allocation of matrix of the energy
needed from the battery
E_from_bat = zeros (96,2);%pre allocation of the matrix of energy
that comes from the battery
dif_1 = zeros (96,1); %pre allocation of the matrix of the
difference between Pproduced and Pmax
dif_2 = zeros (96,1);%pre allocation of the matrix of the
difference between Pmin and Pproduced

for i = 1:96

    P_produced(i,1) = i;
    E_excess(i,1) = i;
    E_to_grid(i,1) = i;
    E_to_bat(i,1) = i;
```

```
    E_curtailed(i,1) = i;
    E_needed(i,1) = i;
    E_from_bat(i,1) = i;

%% 6- Calculates the difference between the production in the
periods t and Pmax

    dif_1(i,1)= P_produced(i,2) - P_max;

%% 7- Calculates the difference between the production in the
periods t and Pmin

    dif_2(i,1) = P_produced(i,2) - P_min;

%% 8- The difference between Pproduced and Pmax is positive in the
%% instant t ?

    if(dif_1(i,1) >= 0)

        E_excess(i,2) = dif_1(i,1);

        %% 9 and 10 - The current state of charge is inferior to
100% and
        %% the battery is capable of store the P_bat_max_charge ?

        if(SOC_aux(i,1) < 1 && E_strd(i,1) + P_bat_max_charge <=
B_cap)

            %% 11 - The difference between Pproduced and Pmax is
equal or
            %% lower than Pbat_max_charge ?

            if (E_excess(i,2)<= P_bat_max_charge)

                % 12- The system stores all the excess and Pmax is
injected
                % into the grid

                E_strd(i+1,1) = E_strd(i,1) + E_excess(i,2);
                E_strd_100(i+1,1) = B_cap - E_strd(i+1,1);
                SOC_aux(i+1,1) = E_strd(i+1,1)/B_cap;
                E_to_grid(i,2) = P_max;
                E_to_bat(i,2) = E_excess(i,2);

            else
                % 13 - The system stores Pbat_max_charge, the
remaining
                % power is curtailed and Pmax is injected into the
grid

                E_strd(i+1,1) = E_strd(i,1) + P_bat_max_charge;
                E_strd_100(i+1,1) = B_cap - E_strd(i+1,1);
                SOC_aux(i+1,1) = E_strd(i+1,1)/B_cap;
```

```
                E_to_grid(i,2) = P_max;
                E_to_bat(i,2) = P_bat_max_charge;
                E_curtailed(i,2) = E_excess(i,2) - 
P_bat_max_charge;

            end

        else
            % 14 - The excess is curtailed and Pmax is injected 
into the
            % grid
            E_strd(i+1,1) = B_cap;
            E_strd_100(i+1,1) = 0;
            SOC_aux(i+1,1) = 1;
            E_to_grid(i,2) = P_max;
            E_curtailed(i,2) = E_excess(i,2);

        end
    end

    % 21- The energy produced is injected into the grid

    if (dif_2(i,1)>= 0 && dif_1(i,1)< 0)

            E_strd(i+1,1) = E_strd(i,1) ;
            E_strd_100(i+1,1) = B_cap - E_strd(i,1);
            SOC_aux(i+1,1) = E_strd(i,1)/B_cap;
            E_to_grid(i,2) = P_produced(i,2);

    end

    %% 15- The difference between Pproduced and Pmin in negative 
in the
    %% instant t ?

    if(dif_2(i,1) < 0)

        E_needed(i,2) = dif_2(i,1);

        %% 16/17 - The current state of charge is superior than 
SOCmin and
        %% the battery is capable of supplying P_bat_max_discharge
?

        if (SOC_aux(i,1) > 0.2 && E_strd(i,1)*n_BS + 
E_needed(i,2)>= 0.2*B_cap)
           %18- The difference between Pproduced and Pmin is equal 
or lower
           %than P_bat_max_discharge?

            if (-(E_needed(i,2))<= P_bat_max_discharge)
                % 19 - The battery system supplies the energy 
needed and
```

```
                % Pmin is injected into the grid
                E_strd(i+1,1) = E_strd(i,1) + E_needed(i,2);
                E_strd_100(i+1,1) = B_cap - E_strd(i+1,1);
                SOC_aux(i+1,1) = E_strd(i+1,1)/B_cap;
                E_from_bat(i,2) = E_needed(i,2);
                E_to_grid(i,2) = P_min;

            else
                % 20 - The battery suplies P_bat_max_discharge and
                % Pproduced is injected into the grid
                E_strd(i+1,1) = E_strd(i,1) - P_bat_max_discharge;
                E_strd_100(i+1,1) = B_cap - E_strd(i+1,1);
                SOC_aux(i+1,1) = E_strd(i+1,1)/B_cap;
                E_from_bat(i,2) = P_bat_max_discharge;
                E_to_grid(i,2) = P_bat_max_discharge +
P_produced(i,2);

            end

        else
            %21 - The power produced in the instant t is injected
into the
            %grid

            E_strd(i+1,1) = E_strd(i,1);
            E_strd_100(i+1,1) = B_cap - E_strd(i,1);
            SOC_aux(i+1,1) = E_strd(i,1)/B_cap;
            E_to_grid(i,2) = P_produced(i,2);

        end
    end

    % 22 - Updates all the variables utilized and increments to
the next
    % instant t

end

 %% 23- Did the algorithm end?

 %% 24- Display the results
disp('Algorithm executed! Calculating the results...');

x1 = P_produced(:,1)*(1/4);
y1 = P_produced(:,2)/1000;
y2 = E_to_grid (:,2)/1000;
%y3 = E_to_bat(:,1)/1000;
y3 = E_curtailed(:,2)/1000;
orange = [1 0.65 0];

%% Power injected, produced and curtailed graphic
figure('Name', 'Power injection into the grid, energy stored in
the battery and power curtailment')
```

```
set(gcf, 'Position', [300, 300, 900, 400])
hold on
plot(x1,y1,'LineWidth',2,'Color', 'blue');
plot(x1,y2,'--','LineWidth',2 ,'Color', 'green');
%plot(x1,y3,'LineWidth',2,'Color', 'red');
plot(x1,y3,'LineWidth',2, 'Color','red');
hold off
xlim([1 24])
ylim([0 70])
ylabel('Power (MW)');
xlabel('time(h)');
legend('Wind power production','Power injection into the
grid','Power curtailment');

%% energy in/out battery graphic

figure('Name', 'Power input/output the battery')
hold on
x = E_to_bat(:,1)*(1/4);
y = E_to_bat(:,2)/1000;
y1 = E_from_bat(:,2)/1000;
bar(x,y, 'FaceColor',[0.8 0.8 0],'EdgeColor',[0.5 .5
0],'LineWidth',1.5);
bar(x, y1, 'FaceColor', [0 .6 0], 'EdgeColor', [0 .3 0],
'LineWidth', 1.5);
hold off;
ylabel('Power (MW)');
xlabel('time(h)');
xlim([0 24])
ylim([-11 11])


%% SOC graphic
figure('Name', 'Battery state of charge')
subplot(2,1,1:2);
x = (1:97)*(1/4);
y = SOC_aux(:,1)*100;
bar(x,y, 'FaceColor',[0 .3 .9],'EdgeColor',[0 .2
.6],'LineWidth',1.5);
ylabel('SOC(%)');
xlabel('time(h)');
xlim([0.5 24.5])
ylim([0 105])


%% calculates the results
VariablesNames = {'Energy produced (MWh):';'Energy stored
(MWh):';'Energy injected into the grid (MWh):';'Energy needed
(MWh):';'Energy curtailed (MWh):';'Energy surplus (MWh):'};
Results =
[round(sum(P_produced(:,2))*(1/4000));round(((sum(E_to_bat(:,2)))*
(1/4000)));round(sum(E_to_grid(:,2))*(1/4000)); round(-
```

```
(sum(E_from_bat(:,2))*(1/4000)));round(sum(E_curtailed(:,2))*(1/40
00)); round(sum(E_excess(:,2)*(1/4000)))];

T = table(Results,'RowNames',VariablesNames);

disp(T);
%% 25- END
% waits for the user to confirm that the algorithm ended:
waitfor(msgbox('Algorithm run without any errors!!'));
```

B.2- Economic Algorithm

```
%% 1- start

clear
clc

%% 2- Insertion of the battery restrictions

prompt = {'Battery capacity (1-50MWh)?', 'SOC minimum ?(0.2-1)',
'SOC maximum ?'};
title = 'Battery restrictions:';
dims = [1 60; 1 60; 1 60];
definput = {'50', '0.2', '1'};
bat_aux = inputdlg(prompt, title, dims, definput);

%difining data and validating it
B_cap = str2double(bat_aux(1));
SOC_min = str2double(bat_aux(2));
SOC_max = str2double (bat_aux(3));

%verifies if capacity is in the interval
while((B_cap < 1)|| (B_cap > 50) || (isfinite(B_cap)~=1))
     waitfor(msgbox('The battery capacity must be between 1 and 50
MWh!', 'Error!','error'));
     B_cap = str2double(inputdlg(prompt(1), title, dims(1,:),
definput(1)));
end
%verifies if SOC minimum is in the interval
while((SOC_min < 0.2)|| (SOC_min > 1) || (isfinite(SOC_min)~=1))
     waitfor(msgbox('The SOC minimum must be between 0.1 and 1 !',
'Error!','error'));
     SOC_min = str2double(inputdlg(prompt(2), title, dims(2,:),
definput(2)));
end

while((SOC_max < 0.6)|| (SOC_max > 1) || (isfinite(SOC_max)~=1))
     waitfor(msgbox('The SOC minimum must be between 0.1 and 1 !',
'Error!','error'));
     SOC_max = str2double(inputdlg(prompt(3), title, dims(3,:),
definput(3)));
```

```
end

B_cap = B_cap*(1000)*4;
pause(1);

n_BS = 0.95; %efficiency of the battery system

P_bat_max_charge = B_cap*(1/16);%maximum power of charge
P_bat_max_discharge = B_cap*(1/16);%maximum power of discharge

%% 3- Insertion of the grid restrictions

prompt = {'Maximum power injectable into the grid (MW)?'};
title = 'Grid restrictions:';
dims = [1 60];
definput = {'50'};
grid_aux = inputdlg(prompt, title, dims, definput);

Pmax = str2double(grid_aux(1));% maximum power injectable into the
grid
P_max = Pmax*1000;

%% 4- calculates the energy in the battery and the necessary to
reach SOC of 100%

E_strd = zeros(96,1);%pre allocation of matrix
E_strd(1,1) = B_cap * SOC_min; %energy in the battery
E_strd_100 = B_cap - E_strd; %energy necessary to SOC = 100%

SOC_aux = zeros(96,1);%pre allocation of matrix
SOC_aux(1,1) = SOC_min; %SOC


%% 5- Reads the production data

P_produced = readtable('summer_day.xlsx');
P_produced = table2array(P_produced);

%% 6- Reads selling prices data

E_sell_price = readtable('E_sell_summer.xlsx');
E_sell_price = table2array(E_sell_price);

To_bat = zeros (96,2);%pre allocation of the matrix of energy that
goes to the battery in lower price periods
From_bat = zeros (96,2);%pre allocation of the matrix of energy
that comes from the battery in higher price periods
Income = zeros (96,2);%pre allocation of the matrix of income in
higher price periods
E_excess = zeros (96,2);%pre allocation of the matrix of
generation surplus
E_grid = zeros (96,2);%pre allocation of the matrix of energy that
goes to the grid
```

```
E_to_bat = zeros (96,2);%pre allocation of the matrix of energy
that goes to the battery
E_from_bat = zeros(96,2);%pre allocation of the matrix of energy
that goes to the battery
E_curtailed = zeros (96,2);%pre allocation of the matrix of energy
that is curtailed
P_produced_unsorted = P_produced;%pre allocation of the matrix of
Production ordered by time
I = zeros(96,2);%pre allocation of the energy that is supplied by
the battery in higher price periods reorder by time
profit = zeros(96,2);%pre allocation of the matrix of profit
T = zeros(96,2);%pre allocation of the energy that is stored by
the battery in lower price periods reorder by time

%% 8 - orders prices in ascending order and for the first 48 t
tries to store maximum power of charge
for k = 1:96

    A = [P_produced(:,1) P_produced(:,2) E_sell_price(:,2)];

    B = sortrows(A,3);%ordena valores de hora por ordem crescente
de preço

    P_produced = [ B(:,1) B(:,2)];
    E_sell_price = [B(:,1) B(:,3)];

    To_bat (k,1) = E_sell_price(k,1);%ordenada por ordem de preços
crescente
    To_bat (k,2) = P_bat_max_charge;%vai para a bateria a energia
produzida nas horas ordenadas por ordem crescente de preço

    if (k <=48)

        T(k,1) = To_bat(k,1);
        T(k,2) = To_bat (k,2);
    else
        T(k,1) = To_bat(k,1);
        T(k,2) = 0;
    end
    %% 10- reorders data
    X = sortrows(T);
end

%% 9- Orders prices in descending order and for the first 48
instant t if the Pproduced < Pmax, tries to supply maximum power
of discharge

for a = 1:96

    E = [P_produced(:,1) P_produced(:,2) E_sell_price(:,2)];

    C = sortrows(E,3, 'descend');%ordena valores de hora por ordem
crescente de preço
```

```
    P_produced = [ C(:,1) C(:,2)];
    E_sell_price = [C(:,1) C(:,3)];

    From_bat (a,1) = E_sell_price(a,1);%ordenada por ordem de 
preços decrescente
    From_bat (a,2) = P_bat_max_discharge;%retira da bateria e 
energia pretendida

    Income(a,1) = From_bat (a,1);
    Income(a,2) = E_sell_price(a,2);

    if (a <=48 && P_produced(a,2) < P_max)

        I(a,1) = Income(a,1);
        I(a,2) = Income (a,2);
    else
        I(a,1) = Income(a,1);
        I(a,2) = 0;
    end
    %% 10 - reoders data
    D = sortrows(I);
end

dif_1 = zeros (96,1); %pre allocation of the matrix of the 
difference between P_produced and P_max
P_bat = zeros(96,1); %pre allocation of the matrix of the 
difference between P_max and P_produced

for i= 1:96

    E_excess(i,1) = i;
    E_grid(i,1) = i;
    E_to_bat(i,1) = i;
    E_curtailed(i,1) = i;
    profit(i,1) = i;
    E_from_bat(i,1) = i;

    %% 10- Calculates the difference between Pmax and Pproduced

    P_bat(i,1) = P_max - P_produced_unsorted(i,2);

    %% 7 - calculates the difference between P produced and Pmax

    dif_1(i,1)= P_produced_unsorted(i,2) - P_max;

    %% 11- The difference between Pproduced and Pmax is positive 
in the
%% instant t ?

    if (dif_1(i,1) >= 0)

        E_excess(i,2) = P_produced_unsorted(i,2) - P_max;
```

```
    %% 12 and 13 - The current state of charge is inferior to
100% and
    %% the battery is capable of store the P_bat_max_charge ?

    if(SOC_aux(i,1) < 1 && E_strd(i,1) + E_excess(i,2) <=
B_cap)
      %% 14 - The difference between Pproduced and Pmax is
equal or
      %% lower than Pbat_max_charge ?
      if (E_excess(i,2)<= P_bat_max_charge)
        % 15- The system stores all the excess and Pmax is
injected
        % into the grid
        E_strd(i+1,1) = E_strd(i,1) + E_excess(i,2);
        E_strd_100(i+1,1) = B_cap - E_strd(i+1,1);
        SOC_aux(i+1,1) = E_strd(i+1,1)/B_cap;
        E_grid(i,2) = P_max;
        E_to_bat(i,2) = E_excess(i,2);

      else
        % 16 - The system stores Pbat_max_charge, the
remaining
        % power is curtailed and Pmax is injected into the
grid
        E_strd(i+1,1) = E_strd(i,1) + P_bat_max_charge;
        E_strd_100(i+1,1) = B_cap - E_strd(i+1,1);
        SOC_aux(i+1,1) = E_strd(i+1,1)/B_cap;
        E_grid(i,2) = P_max;
        E_to_bat(i,2) = P_bat_max_charge;
        E_curtailed(i,2) = E_excess(i,2) -
P_bat_max_charge;

      end

    else
      % 17 - The excess is curtailed and Pmax is injected
into the
      % grid
      E_strd(i+1,1) = B_cap;
      E_strd_100(i+1,1) = 0;
      SOC_aux(i+1,1) = 1;
      E_grid(i,2) = P_max;
      E_curtailed(i,2) = E_excess(i,2);

    end
  end

  if (dif_1(i,1) < 0)

    %% 25 and 26 and 27 - The SOC <  SOCmax and Are economic
advantages in store energy? and the battery can store the maximum
power of charge?
```

```
         if( SOC_aux(i,1)< SOC_max && E_strd(i,1) + 
P_bat_max_charge <= SOC_max*B_cap && X(i,2) > 0)
             % 28 - Stores Pbat_max_charge and the remaining power 
goes to grid
             if P_produced_unsorted(i,2) <= P_bat_max_charge

                E_strd(i+1,1) = E_strd(i,1) + 
P_produced_unsorted(i,2);
                E_strd_100(i+1,1) = B_cap - E_strd(i+1,1);
                SOC_aux(i+1,1) = E_strd(i+1,1)/B_cap;
                E_to_bat(i,2) = P_produced_unsorted(i,2);

             end

             if P_produced_unsorted(i,2) > P_bat_max_charge

                E_strd(i+1,1) = E_strd(i,1) + P_bat_max_charge ;
                E_strd_100(i+1,1) = B_cap - E_strd(i+1,1);
                SOC_aux(i+1,1) = E_strd(i+1,1)/B_cap;
                E_to_bat(i,2) = P_bat_max_charge ;
                E_grid(i,2) = P_produced_unsorted(i,2) - 
P_bat_max_charge ;

             end

        %% 18, 19 and 20 - SOC < SOCmin and are economic 
advantages in supply energy and the battery can supply maximum 
power of discharge

         elseif ( SOC_aux(i,1) >= SOC_min && E_strd(i,1)*n_BS - 
From_bat(i,2) >= SOC_min*B_cap  && D(i,2) > 0 )
             %21- the difference between pmax and Pproduced is 
equal  or
             %lower than P_bat_max_discharge
             if (P_bat(i,1) <= From_bat(i,2))
                   % 22- the system supplies the difference and 
Pproduced
                   % is injected into the grid
                    E_strd(i+1,1) = E_strd(i,1) - P_bat(i,1);
                    E_strd_100(i+1,1) = B_cap - E_strd(i+1,1);
                    SOC_aux(i+1,1) = E_strd(i+1,1)/B_cap;
                    E_grid(i,2) = P_bat(i,1) + 
P_produced_unsorted(i,2);
                    profit(i,2) = D(i,2)*(P_bat(i,1)*(1/4000));
                    E_from_bat(i,2) = P_bat(i,1);
             end
              % 23 - Pbat_max_discharge is supplied, and Pproduced 
is
              % injected into the grid
             if (P_bat(i,1) > From_bat(i,2) )

                    E_strd(i+1,1) = E_strd(i,1) - From_bat(i,2);
```

```
                    E_strd_100(i+1,1) = B_cap - E_strd(i+1,1);
                    SOC_aux(i+1,1) = E_strd(i+1,1)/B_cap;
                    E_grid(i,2) = From_bat(i,2) +
P_produced_unsorted(i,2);
                    profit(i,2) = D(i,2)*(From_bat(i,2)*(1/4000));
                    E_from_bat(i,2) =  From_bat(i,2);
             end

         else
             % 24- Pproduced is injected into the grid
             E_strd(i+1,1) = E_strd(i,1);
             E_strd_100(i+1,1) = B_cap - E_strd(i+1,1);
             SOC_aux(i+1,1) = E_strd(i+1,1)/B_cap;
             E_grid(i,2) = P_produced_unsorted(i,2);

         end

    end
    % 29 - Updates all the variables utilized and increments to
the next
    % instant t
end


 %% 30- Did the algorithm end?
 %% 31- Display the results
disp('Algorithm executed! Calculating the results...');

x1 = P_produced_unsorted(:,1)/4;
y1 = P_produced_unsorted(:,2)/1000;
y2 = E_grid (:,2)/1000;
y3 = E_curtailed(:,2)/1000;
orange = [1 0.65 0];

%% Power injected, produced and curtailed graphic
figure('Name', 'Power injected into the grid, energy stored in the
battery and power curtailment')
set(gcf, 'Position', [300, 300, 900, 400])
hold on
plot(x1,y1,'LineWidth',2,'Color', 'blue');
plot(x1,y2,'--','LineWidth',2 ,'Color', 'green');
%plot(x1,y3,'LineWidth',2,'Color', 'red');
plot(x1,y3,'LineWidth',2, 'Color','red');
hold off
xlim([1 24.5])
ylim([0 71])
ylabel('Power (MW)');
xlabel('time(h)');
legend('Wind power production','Power injection into the
grid','Power curtailment');

%% Energy in/out battery graphic
figure('Name', 'Power input/output the battery')
```

```
hold on
x = (1:96)*(1/4);
y = E_to_bat(:,2)/1000;
y1 = -(E_from_bat(:,2)/1000);
bar(x,y, 'FaceColor',[0.8 0.8 0],'EdgeColor',[0.5 .5
0],'LineWidth',1.5);
bar(x, y1, 'FaceColor', [0 .6 0], 'EdgeColor', [0 .3 0],
'LineWidth', 1.5);
hold off;
ylabel('Power (MW)');
xlabel('time(h)');
xlim([0 24.1])
ylim([-15 15])


%% SOC graphic
figure('Name', 'Battery state of charge')
subplot(2,1,1:2);
x = (1:97)*(1/4);
y = SOC_aux(:,1)*100;
bar(x,y, 'FaceColor',[0 .3 .9],'EdgeColor',[0 .2
.6],'LineWidth',1.5);
ylabel('SOC(%)');
xlabel('time(h)');
xlim([0.5 24.2])
ylim([0 105])


%% Calculates the results
VariablesNames = {'Energy produced (MWh):';'Energy stored
(MWh):';'Energy injected into the grid (MWh):';'Energy from
battery (MWh):';'Energy curtailed (MWh):';'Energy excess (MWh):';
'Income (€):'};
Results =
[round(sum(P_produced_unsorted(:,2))*(1/4000));round(((sum(E_to_ba
t(:,2)))*(1/4000)));round(sum(E_grid(:,2))*(1/4000));
round((sum(E_from_bat(:,2))*(1/4000)));round(sum(E_curtailed(:,2))
*(1/4000)); round(sum(E_excess(:,2)*(1/4000)));
round(sum(profit(:,2)))];

T = table(Results,'RowNames',VariablesNames);

disp(T);
%% 31- END
% waits for the user to confirm that the algorithm ended:
waitfor(msgbox('Algorithm run without any errors!!'));
```