Faculdade de Engenharia da Universidade do Porto

Integrating Hybrid Off-grid Systems with Battery Storage: Key Performance Indicators

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Resumo

Os elevados custos de geração das redes isoladas e as grandes emissões de gases efeito de estufa levaram à necessidade de integrar fontes de energia renovável na rede elétrica. A geração através das fontes de energia renovável tem custos operacionais reduzidos e têm poucas ou nenhumas emissões de gases efeito de estufa mas impõe alguns desafios que o operador do sistema tem de resolver, tais como a intermitência e a limitada previsibilidade. A integração de sistemas de armazenamento na rede elétrica permite aumentar a integração de produção através de fontes de energia renovável, valorizar os ativos da rede e aumentar a eficiência e flexibilidade da rede.

Assim, neste trabalho são identificados indicadores de performance chave de forma a avaliar a integração de sistemas de armazenamento de energia em sistemas isolados híbridos. Tendo em consideração a avaliação realizada através dos indicadores, é desenvolvida a metodologia DIOPHOS. Esta metodologia tem como principais objetivos a realização do planeamento do dia seguinte e a realização de despachos intra-diários para o sistema produtor da rede isolada com a integração de sistema de armazenamento de energia por baterias. A metodologia é implementada na perspetiva do operador da rede isolada e, através da otimização da estratégia de funcionamento do sistema, a metodologia pretende minimizar os custos operacionais e aumentar a integração das fontes de energia renovável, garantindo as restrições de segurança do sistema e considerando a degradação do sistema de armazenamento de energia.

A metodologia desenvolvida é aplicada a um caso de estudo em que a principal dificuldade é a falta de flexibilidade na operação das centrais térmicas para a integração de grandes níveis de energia renovável. Através dos resultados obtidos, é verificado que a integração do sistema de armazenamento de energia a baterias melhora a flexibilidade da rede isolada enquanto integra de forma eficiente a produção através das fontes de energia renováveis. Além disto, a coordenação do sistema de armazenamento de energia com as centrais térmicas, melhora o ponto de funcionamento das centrais térmicas conduzindo a um menor consumo de combustível fóssil.

Abstract

The high generation costs of off-grid systems and their large greenhouse gas emissions led to the need to integrate renewable energy sources into these electric grids. The generation from renewable energy sources has low operational costs and has few or zero greenhouse gas emissions but imposes some challenges that the system operator must address, such as intermittence, limited predictability and controllability. The integration of energy storage systems into the isolated grid allows increasing the integration of production based on renewable energy sources, enhancing the value of the grid assets and increasing the efficiency and flexibility of the grid.

In this work key performance indicators are identified in order to assess the integration of battery energy storage systems in hybrid off-grid systems. Regarding the assessment performed through the key performance indicators, the DIOPHOS (Day-ahead and Intra-day Operational Planning for Hybrid Off-grid Systems) methodology is developed. The methodology is implemented from the perspective of the system operator and, through the optimisation of the operating strategy, the methodology aims to minimise the operational costs and increase the integration of renewable energy sources, ensuring the system security constraints while considering the performance and degradation over time of the battery energy storage system.

The developed methodology is applied to a case study in which the main challenge is the lack of flexibility in the operation of the thermal power plants for the integration of high levels of renewable energy. Through the results obtained, it is verified that the integration of the battery energy storage system improves the flexibility of the off-grid system while efficiently integrating the production through renewable energy sources. In addition, the coordination of the energy storage system with the thermal power plant improves the operating point of the thermal units leading to a lower fossil fuel consumption and, thus, lower GHG emissions.

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Abbreviations

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ACE	Area Control Error
ADP	Adaptative Dynamic Programming
AGC	Automatic Generation Control
BESS	Battery Energy Storage System
BMS	Battery Management System
CHP	Combined Heat and Power
DER	Distributed Energy Resources
DG	Distributed Generation
DIOPHOS	Day-ahead and Intra-day Operational Planning for Hybrid Off-grid Systems
DoD	Depth of Discharge
ECD	Equivalent Cycles per Day
EMS	Energy Management System
EU ETS	European Union Emissions Trading System
EV	Electric Vehicles
EWMA	Exponential Weighted Moving Average
FC	Fuel Cells
GHG	Green-House Gas
HVAC	Heating, Ventilation and Air Conditioning
ICT	Information and Communication Technology
ISO	Independent System Operator
KPI	Key Performance Indicator
LP	Linear Programming
LV	Low Voltage
MILP	Mixed Integer Linear Programming
MPC	Model Predictive control
MV	Medium Voltage
NLP	Nonlinear Programming
OPEX	Operational Expenditure
PCC	Point of Common Coupling
PCS	Power Conversion System
PV	Photovoltaic

R&D	Research and Development
RES	Renewable Energy Sources
RL	Reinforcement Learning
SoC	State of Charge
SoH	State of Health
TSO	Transmissions System Operator
UC	Unit Commitment
UPS	Uninterruptible Power Supply

Chapter 1

Introduction

This work proposes a set of Key Performance Indicators to assess the integration of hybrid off-grid systems with battery energy storage systems. Furthermore, considering these KPIs, a multi-stage methodology is developed, consisted of day-ahead planning of operation and intra-day dispatch, in order to reduce the Operational Expenditure of off-grid systems and maximize the share of renewable energy sources in the electrical grid.

1.1. Motivation

The existence of islands, natural barriers and environmental restrictions do not allow the connection of some electric grids to the interconnected grid. Because these obstacles are related to the geographical location, fuel costs are remarkably high and, due to low installed power, the integration of Distributed Generation (DG), namely renewable generation, presents some challenges to the system operator. From the perspective of the system operator, in which the main purpose is to maintain high levels of reliability and quality, the integration of DG does not contribute to these goals. However, the concern for the reduction of oil reserves and the need to reduce the emission of Greenhouse Gas (GHG) makes this integration mandatory. Therefore, power systems are expressing a growing interest in connecting DG to the distribution network, which contributes to a new paradigm in the electrical energy production and consumption but faces some challenges as networks behave as active networks contrarily to the previous paradigm in which the networks were passive.

The major advantage of the use of DG is the possibility to produce electricity through RES because these sources have low operating costs and low GHG emissions. But, due to the inherent characteristics from RES, the integration into the distributions networks causes several challenges to the operation of the electric system.

The changing paradigm of distribution networks contributed to the current relevance of energy storage systems. These systems have unique characteristics such as the capability to store energy and to inject energy into the distribution network. Thus, these abilities allow the increase of the system's flexibility and the provision of system services, e.g., primary reserve and voltage regulation, in order to increase the performance of the entire system and value of the existing assets. Therefore, in off-grid systems with high operating costs and limited flexibility, energy storage systems operating in coordination with other generating sources have a great the potential to optimise the operation of thermal units and increase the share of RES.

The use of Key Performance Indicators allows the continuous evaluation of a project or operation. Due to the great complexity of power systems, the use of KPIs simplifies the overview of the system and detects weaknesses and areas for improvements. The KPIs should provide objective evidence of progress towards achieving a desired result, and in self-adaptative software systems, the KPIs perform as monitored variables and determine whether a system is working as expected relative to its mandate or whether it should adapt its behaviour [1].

1.2. Thesis Scope and Objectives

Given the needs of the problem described in the previous section and the challenges encountered throughout the dissertation process, this work aims to address the following objectives:

- Perform a comprehensive literature review on the areas of off-grid systems, the integration of renewable energy into the distribution network, applications for energy storage systems in isolated networks, as well the constitution and characteristics of battery energy storage systems;
- Identify, describe and model Key Performance Indicators that allow the technical and economic assessment of off-grid systems and battery energy storage systems;
- Develop a methodology, with these KPI reflecting the potential impacts of battery Storage within a Hybrid Off-grid system, that will enable the assessment of the business case of the BESS integration;
- Validate the developed methodology in a case study, to analyzing the results in detail and assessing the impact of each step of the methodology.

1.3. Publications

During the course of this dissertation it was submitted and accepted a conference paper titled: “Integrating Hybrid Off-grid Systems with Battery Storage: Key Performance Indicators” for the IEEE conference: 2019 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe), Bucharest, Romania from September 29 to October 2, 2019.

1.4. Dissertation’s Structure

The Dissertation is structured in six chapters, reflecting the methodological steps followed.

- Chapter 2 presents the paradigm shift in the distribution networks motivated by the need to integrate distributed energy resources. Also, this chapter presents the applications, the characteristics and the typical structure of BESSs.
- Chapter 3 identifies and fundaments the KPIs to assess the BESS integration in hybrid off-grid systems.
- Chapter 4 describes the methodology developed, DIOPHOS (Day-ahead and Intra-day Operational Planning for Hybrid Off-grid Systems), regarding the assessment performed by the KPIs.

- Chapter 5 applies the methodology to a case study, presents the results and their assessment.
- Chapter 6 highlights the main conclusions of this dissertation and point out some lines for future works.

Chapter 2

Integrating Hybrid Off-grid Systems with Battery Storage – Literature Review

There is a clear need to introduce technologies that will assist in reducing GHG emissions and global warming [2]. One of the technologies to achieve such goal are DER technologies based on RES. Their main advantages are the modularization, short building time, electrical proximity to demand and reduction of GHG emissions [3]. However, incorporating RES leads to flexibility challenges issues, therefore, what is required is a transitional path that supports development of RES, while cooperating with the existing infrastructure. The most promising approach is the concept of renewable energy based hybrid electric energy system [4]. This hybridization consists on coupling a battery storage device to a conventional thermal power plant or to a RES.

2.1. The Distribution Network

In the first years of electricity supply, each town had its own generation station supplying local loads. However, the electrical system evolved to have large central generators up to 1000 MW feeding an interconnected transmission system, which carries the energy to consumers through a distribution network. From power plants to consumers, the electricity goes through a transmission system with a large extension and a distribution system where it passes through a series of transformers to the final distribution network [5] as seen in the Figure 2.1.

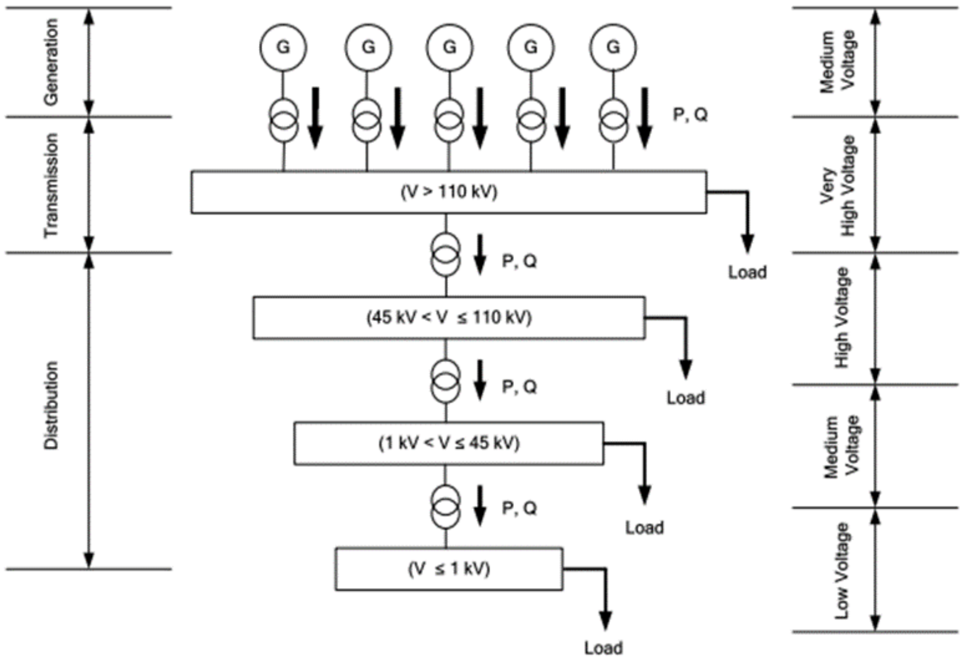

Figure 2.1 - Conventional Distribution Network Architecture [6].

This type of electric grid architecture presents several advantages such as [7]:

- Combined cycle power plants have high levels of energy efficiency;
- With centralized production, maintenance and investment costs are lower in relative terms;
- The use of an interconnected transmission system with low losses and high stability;
- The planning and operation of the distribution network are simple due to the existence of a unidirectional power flow.

However, it also has disadvantages, among which the following stand out [7]:

- The negative environmental impacts resulting from the use of fossil fuels;
- In the event of a disturbance at higher voltage levels, the whole grid may be affected due to the hierarchical structure being radial, which may result in reduced reliability;
- High investment costs for the construction of a long transmission network.

In some places, it is not possible to connect to an interconnected network due to natural obstacles, located in islands and environmental restrictions. Therefore, this type of electrical grid is considered as an isolated grid. Due to its geographical location, there are several types of problems that impact the definition of an appropriate solution for the distribution system including: poor communities, environmental and meteorological problems and hazardous environment [9]. Because of the low installed power, isolated networks have low amount of ancillary services, i.e. reserves and voltage support, which leads to problems with fuel cost, performance and reliability.

From 1990, the interest in integrating DG at the distribution network level increased and changed the paradigm of the electric sector, which brought the attention of electric system operators, distributed generation promoters and policy makers. One of the main contributors to the integration of DG in the network are Governments in order to reduce CO_2 emissions and the need for diversifying the energy sources mix [10].

DG is a generating power plant that has a power range from less then to kW to tens of MW [11]. The connection to the electrical grid is typically made at the distribution level, thus being electrically closer to the electric demand [12]. This means that the initial distribution network architecture is changed, Figure 2.2.

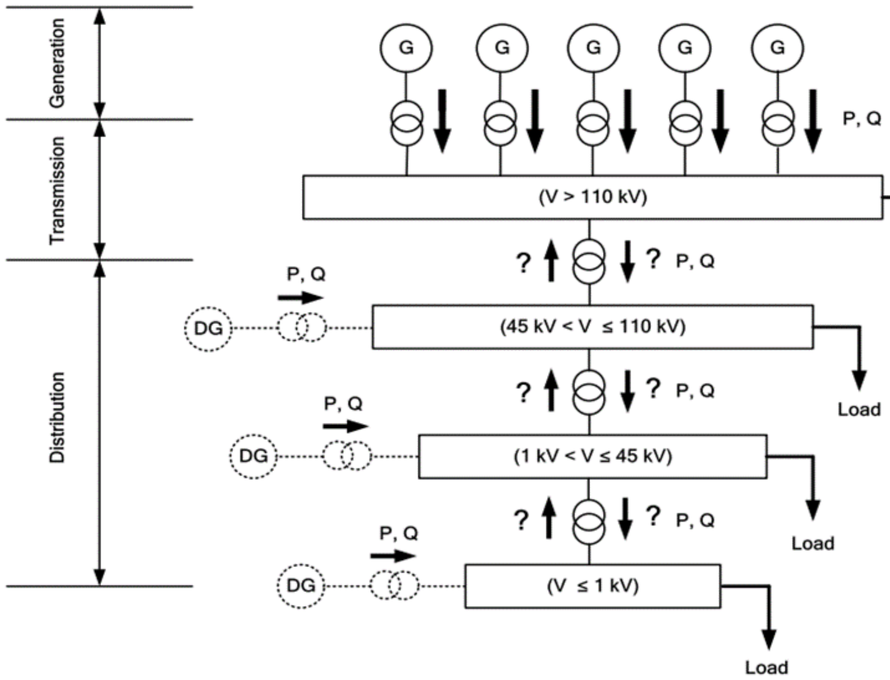

Figure 2.2 - Integration of DG in the Distribution Network architecture [6].

This paradigm shift is the result of DG being connected in places where power injection was not planned, in particular, the fact that the infrastructure is designed for unidirectional power flows, from primary substations until consumers, which may not happen with a significant integration of distributed generation units [13].

2.1.1. The Smart Grid Concept

The smart grid may be defined as an electricity network that can integrate the behaviour and actions of all users (producers, consumers and prosumers), connected to it in a cost-efficient manner [14]. In order to ensure the economic efficiency, the distribution network must have low losses, high levels of quality and security of supply and safety [15]. This concept is associated with the production of energy through RES as the smart grid promotes social benefits like reduced emissions, lower energy costs and greater flexibility to accommodate new renewable distributed energy resources. This is achievable by introducing advanced automatic control and communications techniques in the electric power grid, namely at the distribution level [16].

The most relevant features of the smart grid concept are given by the following list [17]:

- *Advanced monitoring and diagnostics*: monitoring and state estimation capability and real-time condition monitoring of components;
- *Optimisation capabilities*: fluctuating electricity generation from renewable sources requires the ability to optimise the operation. Flexible loads and storage systems add additional degrees of freedom;

- *Automatic topology reconfiguration*: support of automatic or semiautomatic adjustment of the distribution grid topology due to optimisation purposes, fault management and power system restoration;
- *Adaptive protection*: automatic or semiautomatic adaption of protection devices with respect to the actual power grid conditions;
- *Distributed power system management*: distributed control with automatic decision finding processes and proactive fault prevention;
- *Islanding possibilities/microgrids*: improve the reliability of supply due to failures on higher voltage levels;
- *Distributed generation with ancillary services*: usage of ancillary services provided by DER improves power grid optimisation;
- *Demand energy management*: this feature provides additional flexibility in power system operation;
- *Advanced forecasting support*;
- *Self-healing*: Automatic or semiautomatic restoration of grid operation in case of component faults;
- *Asset management power system maintenance*: preventive maintenance according to component conditions and remaining lifetime.

To accommodate services and functionalities with different requirements in what concerns data rates, delays and losses among many others, communications infrastructures are regarded as an essential support for the information exchange [19].

Therefore, due to the need to increase the devices of ICT and automation solutions in the smart grids, standardization is essential so that it is possible to comply with the inter-operability and scalability requirements [17].

Smart Grid's implementation should be based on platforms with functionalities of the Supervisory Control and Data acquisition (SCADA) system such as the Energy Management System (EMS), the Distribution Management System (DMS) and the Outage Management System (OMS) that support the operation of the utilities, the system operator and consumers demand. These centralized functionalities must be able to interoperate with the Substation Automation Systems (SAS) and with the Advanced Metering Infrastructures (AMI), such as Smart Metering Systems.

The constituent elements of a smart grid and its architecture are presented in the Figure 2.3.

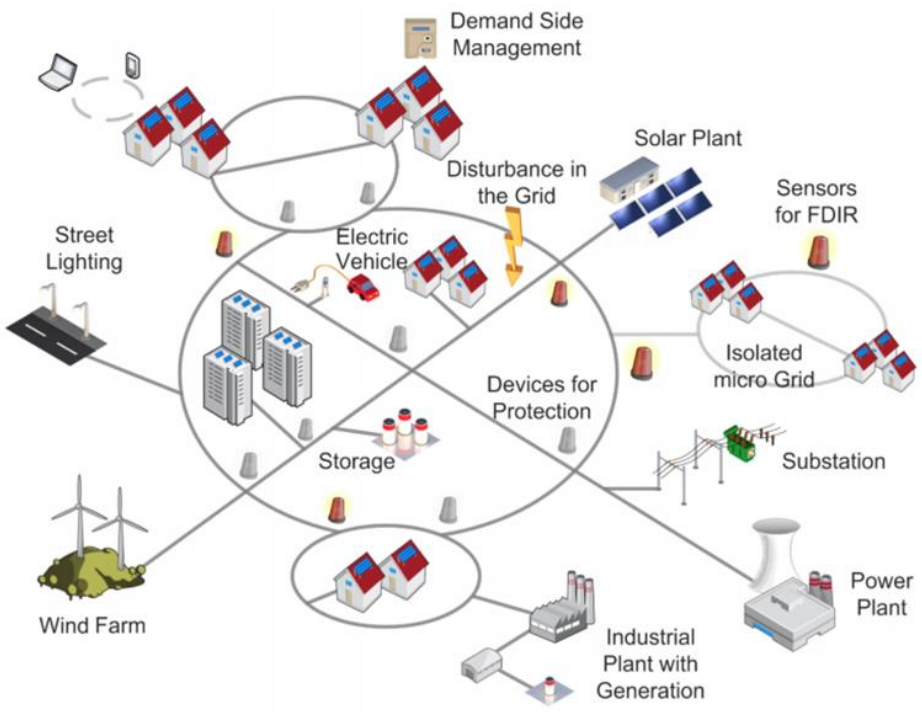

Figure 2.3 - The Smart Grid Paradigm.

At its core, a smart grid is the aggregation of complementary components, subsystems and functions under control of a distributed intelligent system. Furthermore, the growth and evolution of the smart grid is expected to be achieved through the integration of structures such as microgrids. A smart microgrid network that can operate in both grid-tied as well as islanded modes typically integrates the following seven components: power plants capable of meeting local demand, variety of loads, makes use of local and distributed power-storage capability to smooth the performance of RES, smart meters and sensors, communication infrastructure, smart terminations and energy management systems [20].

The operation of the microgrid must be able to perform the voltage control and the frequency/load-generation balance. When in grid-connected mode, the voltage control is the main problem and can be performed through the control of MV/LV on load tap changing and control of the active power of the microgeneration units. When in islanding mode, frequency and voltage control is the main concern. In the island mode, microgrids require some form of energy buffering to ensure initial energy balance, which can be achieved by generation units and active loads using a droop control approach or by energy storage systems [21].

Due to low operating costs and being a solution to reduce emissions of GHG, EVs are considered as economically and environmentally friendly [22]. Moreover, because of EVs' controllable charging rates [23], the EVs can even provide regulation services to the grid [24]. However, unregulated EV charging can cause system overloading or even a breakdown in the power grid [25]. In order to bring benefits for both users and the grid, a load aggregator can act as an interface between the users and the grid operator so that the vehicles are charged in a regulated way [26].

2.2. Integration of Distributed Energy Resources in electrically off-grids

The relatively high operational costs of isolated networks and large emissions of GHGs have led to the need to integrate DER, and particularly distributed RES, into the electrical grid. This occurs because there are several DER technologies and each one with its characteristics that must be considered in the planning and operation of the electrically isolated grid.

From a technical point of view, the integration of DER in isolated grids may allow the reduction of network losses, improved voltage profiles, as well as the reduction of operation costs, environmental costs and, ultimately, the electricity tariff [27]. However, the integration of DER, and particularly distributed RES, in isolated grids also imposes challenges that need to be tackled by the system operator in order to keep high system performance indexes such as the SAFRI (System Average RMS variation Frequency Index).

2.2.1. Distributed Energy Resources Technologies

DER are small generating units installed in strategic points of the power system, and especially close to load centers [28]. The most common DER technologies consist of renewable generations, such as photovoltaic, wind and small hydro, biomass/waste, small CHP, fuel cells and energy storage devices.

Usually, micro-turbines are the main source of generation in isolated grids. They are small capacity combustion turbines, which can operate using natural gas, propane, and fuel oil. Due to its compact size and low weight, micro-turbines can be installed in places where space is limited [29]. The capital cost is lower than the cost of other DG technologies [30]. If the grid interface is performed by modern electronic power, the flexibility is increased [31].

A major advantage of the use of distributed generation, is that it is possible to produce electricity through RES. The advantages are mainly in reducing operating costs and reducing greenhouse gas emissions into the atmosphere. There is a lot of investment in this area in order to reduce their cost of capital and increase their performance. The main RES are PV and wind power technologies. Due to the inherent characteristics of these technologies, renewable generation has limited dispatch and is intermittent with high fluctuations [32].

The PV power technology uses semiconductor cells (wafers), generally several square centimetres in size. The cell converts solar radiation into DC power and numerous cells may be assembled in a module in order to generate larger amounts of power [33].

The wind turbine captures the wind's kinetic energy in a rotor consisting of two or more blades mechanically coupled to an electrical generator and the turbine is mounted on a tall tower to enhance the energy capture [33].

FC are electrochemical devices that convert the chemical energy contained in a wide variety of fuels directly into electric energy [34]. Unlike batteries, FC does not need to be charged for the consumed material during the electrochemical process since these materials are continuously supplied [35]. FC technology is based on an electrochemical process in which hydrogen and oxygen are combined to produce electricity without combustion [36].

In an overview, the energy storage devices, by charging and discharging, may time-shift the use of energy from the periods in which the demand is low to the periods where the demand is high. It is usually combined with other kinds of DG types for a better integration of these units and valuation of assets. Within energy storage devices there are several types of technologies and the choice of technology depends on the application for which it is intended [37]:

- Batteries;
- Hydrogen;
- Flow Batteries;
- Supercapacitors;
- Superconducting magnetic energy storage;
- Flywheels;
- Compressed air.

2.2.2. Operational challenges in off-grid power systems

The connection of DER in isolated networks has impact on the operation of the network and imposes technical challenges that must be taken into account in the planning and operation of the electric system.

In both isolated and interconnected grid, the main technical aspects that need to be evaluated due to the presence of DER units in the grid are [10]:

- Voltage profile;
- Power quality;
- Protection schemes;
- Stability;

During steady state operating conditions, the voltage must be maintained between the limit values (e.g. -10% and +6% of the nominal value) everywhere in the distribution grid [39]. The contribution of DER plants to the voltage regulation in the distribution network is worrying the system operator and must be taken measures of voltage and reactive power control. Through deterministic methods, considering the “worst case scenario”, it is determined the maximum capacity of distributed generation [40].

The system operator must ensure coordination of distributed generation sources so that they can address power quality problems such as: voltage flicker, voltage fluctuations and harmonic distortion [41].

With the inclusion of DGs in the distribution network, protection schemes may have to be changed and must be coordinated with the DG unit so that the selectivity and sensitivity are not impaired and, thus, maintaining safety and high reliability rates.

The conventional distribution network does not consider stability problems because the connection to the transmission network makes it stable. Even with distributed generation in the interconnected distribution network, stability is hardly considered [42], however being a problem to be taken into account in isolated networks because of the network’s fragility.

In isolated networks, one of the most limiting factors for the penetration of RES are the technical limits of the small-scale thermal generators and the reserve requirements in the presence of RES [43]. These limitations of the thermal generators are related with their production technical minimum, their starting and shut down processes as well as their ramping capabilities [44].

The need to fulfil reserve requirements leads to lower operating points of the thermal generators, as the electric load of the islanded system has to be allocated to more generators. This means that the power produced by thermal generators is lower, leading to lower operating point which causes the generator to work less efficiently, which means a higher fuel consumption per unit of produced energy. It may also happen that it is no longer possible to reduce the operating point of the generators, which leads to the need to make renewable curtailment in order to maintain the reliability and spinning reserve criteria of the system [44].

During the process of start-up and shutdown of the thermal generators, other generators operate in a lower operating point which means that there is a need for spinning reserve and, thus, there is renewable curtailment so that the generators stay above their minimum technical limits [44].

As in an isolated system there is typically a lower number of generating units, the participation of each unit in the primary frequency control is high and this affects the integration of intermittent sources in the network. The main limitation comes from the ramp response limits to power fluctuations. The constant rapid response needed to reduce the frequency deviations leads to more fuel consumption, more degradation, and reduced lifetime [45].

Therefore, although it is possible to reduce fuel consumption with the introduction of RES in the distribution network, the integration cannot reach its potential due to inherent characteristics of the isolated systems and, particularly, its generation system that is based on thermal generators with limited flexibility [44].

2.3. Applications of energy storage systems

Energy storage systems, such as BESS, are an interesting component to integrate into the electrical grids because they are able to counterbalance the intermittent nature of renewable production, stabilizing microgrids, increasing the flexibility and grid efficiency due to the high storage capacity and high charge and discharge rates [46]. These improvements that energy storage systems can bring to the network are achieved through one or a stack of services that it is able to perform.

2.3.1. Electric Supply Services

2.3.1.1. Electric energy time-shift

The Electric energy time-shift corresponds to charge the BESS, in periods when the demand is lower or when the RES production is higher, and to discharge that energy in periods when the demand is higher or when the RES production is lower, Figure 2.4. Therefore, the objective of this application is to sell cheap electric energy in intervals of time when the price is higher. The price differences occur because the demand for electricity is not the same at all periods of the day and the increase in price happens with the increase in demand. So, with this application the storage system will do the time-shift for the periods when there is more demand [44].

Entities that take advantage of this application should be regulated utilities or non-utility merchants. It is important to highlight that the purchase and sale of energy has to be made in the wholesale electric energy market [47].

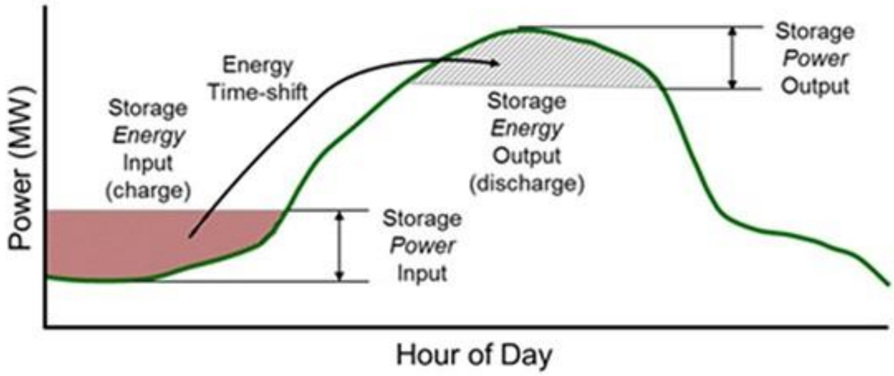

Figure 2.4 - Electric Energy Time-shift application [47].

The BESS can also provide a time-shift similar by store excess energy produced, otherwise it would be cut off (e.g. renewable sources, wind and PV).

Due to the performance of the entire BESS cycle, this application requires that the price difference be significant because, with a minimal difference, time-shift is not profitable. The increase of the sources of storage in the grid causes that the prices of the market are leveled, what takes this application loses its profitability.

2.3.1.2. Electric supply capacity

Depending on the circumstances in a given electrical system, the BESS can be used to defer and/or reduce the need to purchase a new central station generation capacity and/or to purchase generation capacity in the wholesale electricity marketplace, Figure 2.5. In order to reduce overload on equipment, this application can extend the life of an asset and thus delay its replacement [10]. This application is similar to and also referred in the literature as peak shaving [48].

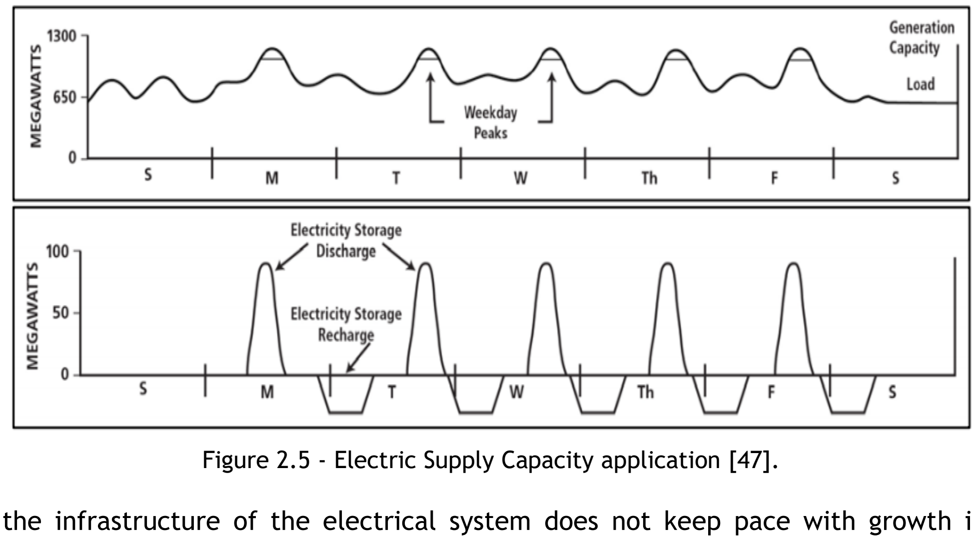

Figure 2.5 - Electric Supply Capacity application [47].

If the infrastructure of the electrical system does not keep pace with growth in peak demand, the electric system may become congested [44], leading to transmission costs during peak periods increase. Energy storage systems can be used to avoid the costs related to congestion. In this service, energy storage systems would be installed at locations that are electrically downstream from the congested portion of the distribution network [47].

2.3.2. Ancillary Services

2.3.2.1. Load Following

Power balancing between generators and loads, Figure 2.6, is the most critical task in isolated networks since available generators designed for grid regulations are limited [49]. In isolated grids, the diesel gensets are typically used for this type of service but this mode uses more fuel and results in more emissions. Also, the constant changes in production also results in additional maintenance costs [50].

Due to the ease of changing their operating point, the storage systems have the ideal feature to perform the following load. For this application, storages systems must be reliable in order to ensure the contractual obligations and must be able to communicate with the independent system operator to access the AGC.

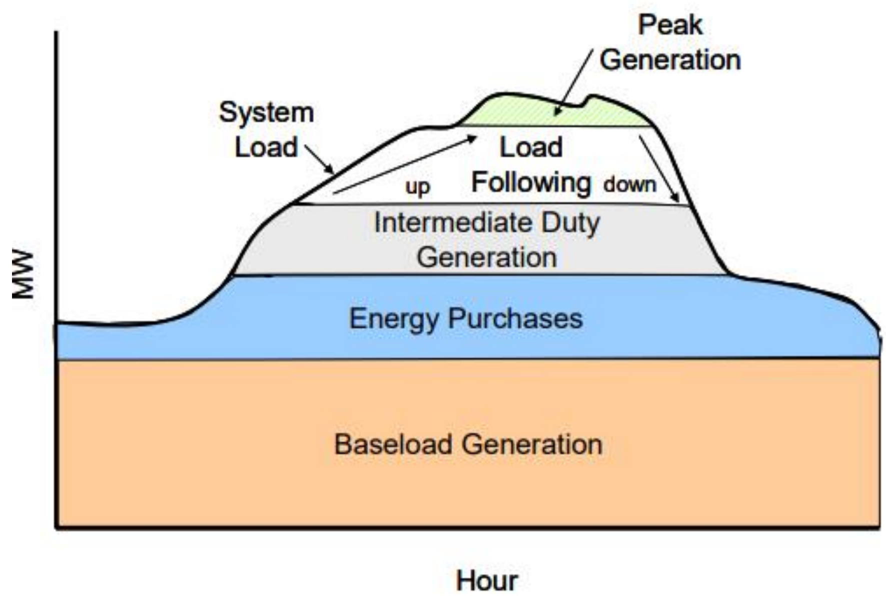

Figure 2.6 - Load Following application [47].

2.3.2.2. Electric Supply Reserve Capacity

The control scheme of the electrical systems is presented in the Figure 2.7. The primary control is automatic and decentralized. This control is provided by the speed droop of loads and generators connected to the grid. It aims to stabilize the system frequency, maintain the balance between generation and demand. This control operates a few seconds after the incident and ends after 30 seconds if the disturbance is the size of the required primary reserve [51].

The secondary control is automatic and centralized TSO-equipment (AGC) that controls secondary control power. It aims to restore system frequency to its set-point value and maintain a balance between generation and demand within the control area [51].

The tertiary control consists of actions centralized by the TSO, namely: connection/tripping of units capable of providing 10/15 minute reserve, re-dispatch among generation units, change the programmed value of power interchange with neighboring control areas/blocks and load shedding. This control complements the reserve value of the secondary control in the control area or restore the same reserve by following economic considerations [51].

Most of storage systems have quick response characteristic, therefore, the storage systems are a valuable source of regulation. The energy storage used for this control must have access and be able to respond to the signal of the ACE. Also, it is not necessary that the storage is charging or discharging to perform the regulation, just need to be in a state of stand-by [47].

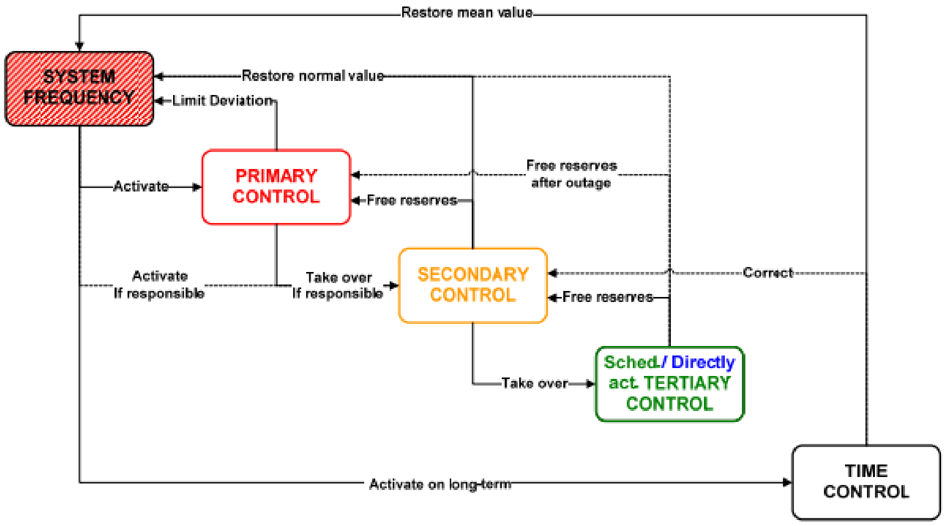

Figure 2.7 - Control scheme and actions starting with the system frequency [51].

2.3.2.3. Voltage Support

To maintain acceptable voltage levels under normal operating conditions and contingency conditions, each control area shall implement voltage control strategies. One of the reasons for voltage problems is the excess reactive power in the grid and it is necessary to place devices that compensate this energy. Because the reactive power transmission is complicated, the reactive resources must be placed in specific locations. When the reactive resources are insufficient, the system operator must take other corrective actions (e.g. the load shedding) to prevent the collapse of the voltages [52].

Due to the existence of the PCS, the energy storage systems can perform a dynamic supply of reactive power for the voltage support, responding immediately to the voltage variations [53,54] represented in the Figure 2.8.

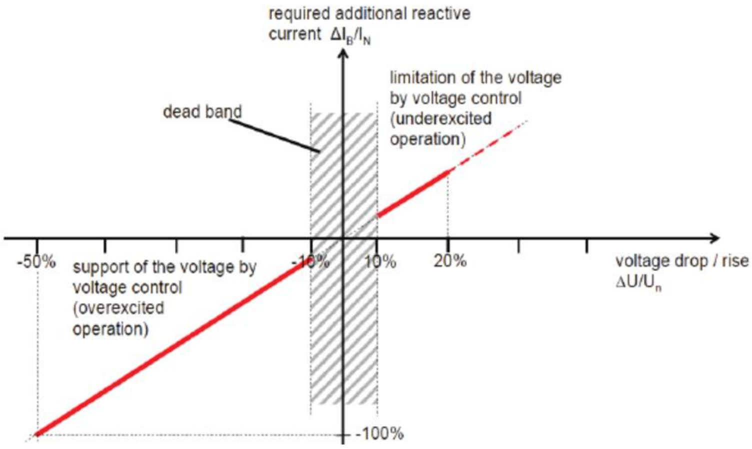

Figure 2.8 - Voltage Support application [52].

2.3.2.4. Black Start

The process of restoring the system back to normal operation involves crucial steps and considerations [56]. The energy storage is able to participate in black start because it does not need special equipment and does not need to operate while waiting for the dispatch. Thus, a restoration strategy in a microgrid may be: the energy storage system is selected as the main power source of the black start to establish the voltage and frequency; after this, loads and micro-sources are connected in sequence; after it's all connected, the voltage and frequency are stabilized and microgrid enters stable operation mode [57]. The BESS output during the Black Start application is presented in the Figure 2.9.

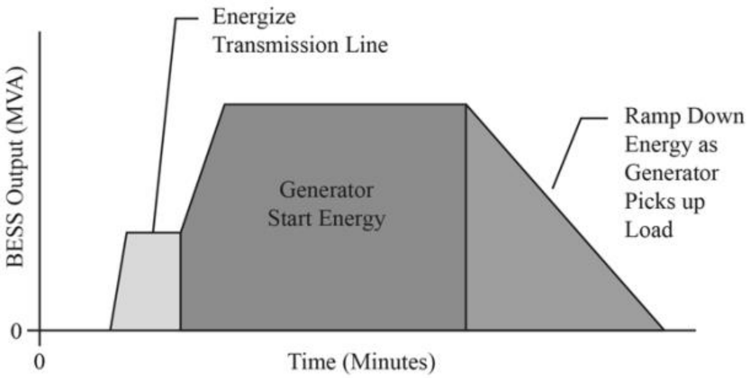

Figure 2.9 - Black Start application [47].

2.3.3. Costumer Energy Management Services

2.3.3.1. Power Quality

The importance of power quality issues will increase with the energy systems decentralization, as competition between suppliers will require high quality standards [58]. The power quality service of a BESS is the use of energy storage to protect consumers from some short-term events that affect the quality of the delivered power. Some manifestations of poor power quality include the following: voltage level fluctuation, frequency fluctuation, harmonic distortion, low power factor, transient overvoltage and unbalance load [59]. By monitoring the quality of electric power, energy storage operates so that the disturbances are mitigated or eliminated.

2.3.3.2. Power Reliability

Under the right circumstances, this application ensures that there is no loss of power supply after the loss of a major grid component (e.g. primary substation transformer) [44]. Through a regulator, the network operator has to guarantee its delivery rates below the stipulated. Thus, the energy storage is able to keep the loads supplied for a certain time in isolated mode until the main supply is restored ensuring a higher reliability of the network [60].

2.4. Hybrid Off-grid Power Systems

Hybrid power systems consist of two or more different types of generation technologies, typically with one or more renewable energy sources combined with conventional technologies, such as diesel generators [61] as seen in Figure 2.10. Because of the flexibility that a BESS can bring, the integration of RES in distribution networks with BESS is performed in a more responsible and sustainable way, thus allowing a greater share of RES.

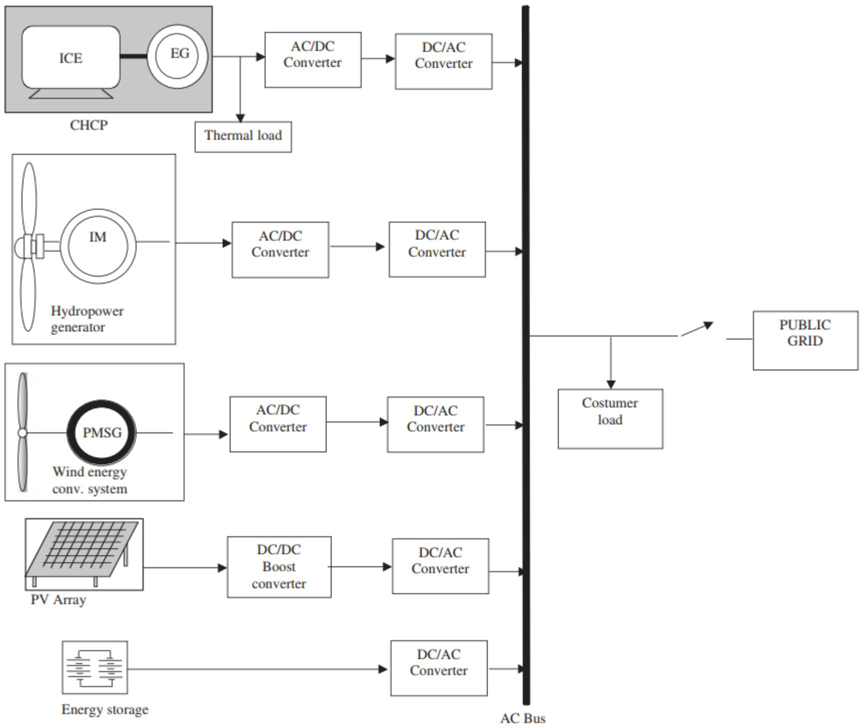

Figure 2.10 - Example of a Hybrid System [59].

2.4.1. Renewable Energy Sources

In systems where RES penetration is high, mostly wind generation, operators must provide ancillary services such as primary frequency control [63]. For this purpose, wind generators have to operate at a lower point of the optimal curve, in order to provide upward adjustments, resulting in lower efficiencies. With a BESS coupled to a wind plant, the wind generators work at a higher operation point and the primary frequency control is provided by BESS, increasing the share of RES [44].

As RES are variable, particularly wind and PV systems, rapid power output variations have an impact on power systems. With a BESS coupled and with the application of short-term fluctuations smoothing, the rapid variations are counteracted by charging or discharging and the need for primary frequency reserve is reduced [64].

In order to increase the predictability of RES and enhance participation in electricity markets, with the capacity firming application, the BESS is used to ensure that the combined power output of the RES and the BESS is constant during a certain time period. The target value for the combined output is often based on forecasts of the renewable production [65].

In systems where the share of RES is limited, it may be necessary to make renewable curtailment. With a BESS coupled, renewable curtailment minimisation can be achieved by storing excess energy or by performing services that increase the penetration of RES, i.e. reactive power management [66].

2.4.2. Thermal Power Plants

In addition to the RES, the use of a hybrid thermal generator + BESS in an isolated network also has benefits, among which the optimisation of the operating point of the thermal generators. Typically, thermal generators reach the optimum operating point near their rated power but, due to the characteristics of the producer system and the system's required reserves, it is necessary that the operating point is lower than the nominal. Thus, with a BESS coupled, the BESS charges when the operating point is low and discharges when the generators are at high operating points. This application increases the system's efficiency, so fuel consumption is lower.

Due to the obligation to provide primary frequency control, thermal generators are subject to large variations of power output. With a BESS coupled, BESS can provide this service and thereby reduce the fuel consumption spent on accelerations in the thermal generators and reduce maintenance costs.

When it is necessary to start or shut-down generators, the start and shut-down times affect the electrical system and, with a BESS coupled, these transitions become smoother.

2.5. Battery Energy Storage Systems

2.5.1. Structure

The structure of a typical BESS is presented in Figure 2.11. The BESS includes components such as the battery pack, BMS, bi-directional ac/dc converter and the control unit that acts as the EMS of the complete solution [67].

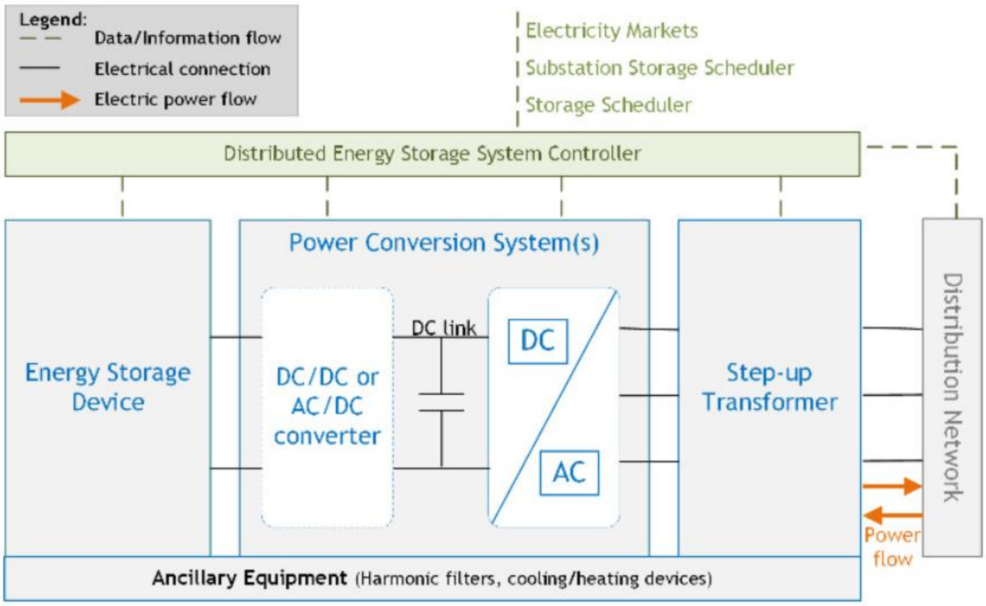

Figure 2.11 - BESS structure [44].

The energy storage device is composed by batteries and a BMS. The batteries are the bridge of energy store and conversion, which can convert chemical energy to electrical energy and vice versa [68]. They are rated in terms of their chemistries, capacity, power, nominal voltage, C-rate, operating temperature, self-discharge, life span, energy density, efficiency and DoD [68,69]. The aging of the batteries depends mainly on three parameters namely SoC, DoD and temperature.

BMS is the management platform of each battery cell, ensuring that all cell voltages are within limits for safety operation cycle life [67], and protects the battery module from short-circuit and high temperature [70]. To manage and control module performance the BMS includes cell voltage, module current and temperature measurements [70] and estimates the SoC and SoH of each battery cell in the pack [67]. This increases the lifetime of the batteries and optimises their performance [71].

In the PCS is performed the AC conversion of DC power input / output through a converter based on power electronics that provides a set of features and controls (i.e. 4-quadrant power flows) that allows a very fast response to power, frequency and voltage changes [46]. It may also be necessary to include an additional converter to match the output voltage level of the energy storage device to the DC bus, or to control power flows in parallel multi-string or multi-storage configurations [60].

If there are differences in nominal voltages between the side of the energy storage system and the side of the grid, or there is the need to provide galvanic isolation, a step-up power transformer is required for a proper connection at the PCC [72]. Since the waveforms originated in the PCS are not pure sinusoids, the transformer, together with the ancillary equipment, allows the reduction of harmonics in the current and voltage waveforms [44].

The Distribution Energy Storage System Controller presents functionalities of monitoring, control and communication [73]. This controller enables the continuous monitoring of AC and DC magnitudes from the electric grid and battery system and, through the BMS, monitors the battery device [46]. Its control is performed by sending active and reactive power set-points to the PCS in order to perform different services [44]. To perform the optimisation of the system, the controller communicates with other systems of other electric sector stakeholders to obtain technical and economic information, i.e. renewable forecast. Therefore, the controller also integrates algorithms to optimise the operation of the global system, defining the schedule of the battery system.

The BESS also incorporates ancillary equipment for proper operation. Some of the equipment are metering and power quality systems, harmonic filter, UPS, protection devices, HVAC and fire detection and suppression systems.

2.5.2. Characteristics

2.5.2.1. Rated Power and Energy

The rated power of a system indicates the maximum power it is capable of discharging into or charging from the network under normal operating conditions. It is expressed in W.

The nominal energy capacity of the battery corresponds to the amount of energy that can be stored during the charge [74]. It is expressed in Wh.

2.5.2.2. Battery Gravimetric Energy Density

The gravimetric energy density of a battery is the total amount of energy which a battery can store at a specific unit mass. It is also known as battery specific energy. It is expressed in Wh/kg [75].

2.5.2.3. C-rate

The C-rate is the total rate at which a battery is charged or discharged relative to its capacity [75].

2.5.2.4. Efficiency

The efficiency is defined by the ratio between released energy and stored [76]. The efficiency of the system consists in two components: the efficiency of the storage technology and the efficiency of the interface with the electric network.

2.5.2.5. State of Charge

The estimation of the SoC is among one of the most important functions of the BMS because it indicates the remaining autonomy system until the discharge is complete [76]. In (Eq. 2.1) the SoC is the ratio of the available energy capacity in a storage system to its nominal capacity.

$$SoC = \frac{Q}{Q_0} \tag{Eq. 2.1}$$

Where Q is the amount of charge at a given moment and Q_0 is the nominal capacity of the battery [77].

2.5.2.6. Depth of Discharge

The DoD is the ratio of the energy discharged from the last charge to the nominal power capacity of the storage system, or, equals to the change in the SoC in one discharge cycle as in (Eq. 2.2).

$$DoD = \Delta SoC = \frac{1}{Q_0}\int I(t)dt \tag{Eq. 2.2}$$

Where I is the discharge current [77]. It is a characteristic that is directly linked to the lifetime of the battery system, since cycling the battery at high DoD can reduce the number of lifetime cycles dramatically for batteries [78].

2.5.3. Battery Energy Storage Technologies

One of the most relevant components that may vary between the various projects is the battery technology depending on technical, operational and economic requirements. Different types of battery technologies exist, with different levels of application and different stages of maturity. Some of the technologies are already available commercially as Lead-Acid, Nickel-Cadmium, Nickel-Metal, Lithium-ion and Sodium-Sulphur but others are still being developed in the laboratory as Zinc-air [44].

The battery consists of one or more electrochemical cells, each cell being constituted by an electrolyte with two electrodes, one positive (anode) and the other negative (cathode) [79]. The electrolyte, which separates the electrodes, allows the transfer of ions between electrodes, where the redox reactions occur. When the electrodes are connected externally, there are chemical reactions between the two electrodes and the battery is discharged. If an external voltage is applied to the electrode terminals, the reactions are reversed, and the battery is charged [80].

The oldest type of rechargeable batteries is Lead-acid (Pb-acid) and with lower capital costs compared to other types of batteries. Each cell has its electrodes built in lead and immersed in an aqueous solution and it can be divided in two types: flooded type and valve regulated type. This technology main limitations are the low energy and power densities, limited charging and reduced cycle life [81]. Besides that, this technology is also being continually improved to reduce the need for maintenance and with good battery management and a well optimised operational regime, these systems have been shown to be financially competitive [82].

With 100 years of development, there are Nickel based batteries. Nickel Cadmium (NiCd) battery systems rank alongside lead-acid systems in terms of their maturity [82]. It is constituted by a nickel hydroxide anode, a cadmium hydroxide cathode and an alkaline electrolyte. The main disadvantages are the highly toxicity of heavy metals and its memory effect [81]. However, the main advantages are related with the good performance under low temperatures, the low maintenance requirements and high reliability [82].

Sodium-sulphur consists of molten sulfur at the positive electrode and molten sodium at the negative electrode separated by a solid ß-alumina ceramic electrolyte. In order to take advantage of the increasing conductivity of the electrolyte the operating temperatures are between 300ºC and 350º [82]. Consequently, a heat source is required which reduces the battery performance. However, this technology has high efficiency (90% including heat losses), high power and energy densities and low-cost maintenance [80].

The lithium-ion batteries family have, typically, the anode made of graphitic carbon with a layer structure, the cathode is made of a lithiated metal and the electrolyte is made up of lithium salts dissolved in organic carbonates [44]. When the battery is being charged, the lithium ions move from the cathode to anode and the process is reversed during discharge. The main advantages of this type of solution are the high energy density and the relatively low self-discharge rate. Moreover, due to the high nominal voltage cell, the number of cells in series can be lower to achieve the target voltage. However, there are some drawbacks, such as the reduced depth of discharge and the requirement of a protection circuit. The fact that the battery's lifetime is affected by temperatures above 40ºC also represents a disadvantage [81].

Chapter 3

Key Performance Indicators regarding the integration of Hybrid Off-grid Systems with BESS

In order to understand whether a company or project is on track to achieve its goals, companies employs Key Performance Indicators to assess their success at reaching defined targets. A KPI is the industry term used for a measure or metric whose performance is evaluated regarding some objectives [83].

Currently, KPIs continue to be more used in the business and process areas in order to choose projects between the various alternatives or to assess the progress of a specific project. For corporate reporting to remain critical and transparent, KPIs should [84]:

- Provide a balanced and comprehensive analysis;
- Provide a fair review of the business;
- Provide information to the extent necessary for an understanding of the development, performance or position of the business.

In R&D, the use of KPIs can serve as the background for an analytic evaluation of a technology solution by being in position to technically and economically valorize the various proposed solutions and specific needs of each case that they were designed to serve [85].

Due to the resulting benefits of using KPIs in the different industry sectors, this concept has been extended to other sectors such as the energy industry. For example, due to the smart grid concept having multidisciplinary character, since it involves a stack of technologies, it is very difficult to assess the overall project success. The work in [86] proposes a new approach of business intelligence to bring about a new set of KPIs for its rating.

Due to the complexity of some systems such as Urban Rail systems, it is very complex to assess the impact of each component, if the system is considered as a whole. In [87] the complex system is divided into subsystems and proposes the implementation of KPIs that make the assessment of the potential improvement for each subsystem. Such as Urban Rail systems, microgrid are very complex and the improvement of some parameters can become difficult, so there is a need to divide the microgrid into subsystems in order to assess the potential for improvement.

In [88] a 7-step method is developed to production-tailored and energy-related KPIs and these KPIs supports the identification of weaknesses and areas for energy efficiency improvements related to the management of productions and operations;

In [89], the authors defined KPIs to assess the reliability of a coal-fired power plant. Also, the authors developed an alternative approach that employs approximation methods for the deterministic prediction of KPIs. Moreover, the authors claimed that high reliability indices allow reducing powerplant equipment oversizing, which should result in lower capital and operating cost.

3.1. Identification and Description of KPIs for the assessment of Hybrid Off-grid Systems with BESS

In the process of creating KPIs several considerations need to be taken into consideration. Namely [90]:

- number of KPIs to be formulated;
- frequency of measuring KPIs;
- targets to be set for the identified KPIs;
- KPIs observability and controllability;
- infrastructure to support the formulated KPIs;
- identifying the purpose of establishing each KPI;

So that there is no replicated information in multiple KPIs, the maker of KPIs should opt for the minimum possible number of KPIs. Having too many KPIs can be time- and resource-consuming.

The Data collection must be made as simple as possible and every KPI created should be meaningful. The systematic use of these KPIs can be essential to the process because the trend of the evolution of the values of KPIs can help anticipate a failure and, thus, help to improve the process.

When adding BESSs into an off-grid, utilities, planners, investors and consumers want to know:

- What is the operational impact on the generation system?
- What is the reduction of the environmental impact of electricity generation?
- What is the technical and economic benefit in the integration of BESS?

Therefore, the KPIs formulated in this chapter aim at answering these questions.

3.1.1. Operational KPIs

Operational KPIs aim to participate in the operation strategy of the microgrid system. These KPIs perform as monitored variables and determine whether the system is working as expected relative to its mandate or whether it should adapt its behaviour.

3.1.1.1. Renewable Curtailment Avoidance (RCA)

In a microgrid scenario, one of the applications of the BESS is to minimize the renewable curtailment, there is an intention to enlarge the integration of renewable energy. In this context it is considered the RCA indicator, whose task is to evaluate how many MWh are stored for each MWh in excess of renewable energy. In other words, this indicator evaluates the amount of renewable integration in the microgrid with the BESS. (Eq. 3.1) proposes

$$RCA = \sum_{t=1}^{T} \frac{(Curtail^{w/oBESS}(t) - Curtail^{w/BESS}(t)) * \Delta t}{Curtail^{w/oBESS}(t) * \Delta t} \quad [MWh_{stored}/MWh_{excess}] \qquad \text{(Eq. 3.1)}$$

In which:

- $Curtail^{w/oBESS}$- Renewable Curtailment without BESS in period t (MWh);
- $Curtail^{w/BESS}$ - Renewable Curtailment with BESS in period t (MWh);
- Δt - time interval;
- T - number of periods.

3.1.1.2. Average Cost Reduction (ACR)

In order to compare the improvement of the microgrid with and without the BESS it is adopted the ACR KPI. This KPI studies the correlation of the value of the average operational cost of energy between the two scenarios, (Eq. 3.2).

The microgrid in which the energy storage system is included is expected to admit a lower operation cost as a result of the further integration of energy from renewable sources. The storage system must also be able to compensate the forecast error related to the different renewable generation resources, as well as the electric demand. For this reason, this indicator can likewise evaluate the performance of the energy storage system for this application.

$$ACR = \frac{\sum_{t=1}^{T}(C_{system}^{w/o\,BESS}(t) - C_{system}^{w/BESS}(t))}{T} \quad [€/\Delta t] \qquad \text{(Eq. 3.2)}$$

In which:

- $C_{system}^{w/0BESS}$ – Cost of the system without BESS in the period t (€);
- $C_{system}^{w/BESS}$ – Cost of the system with BESS in the period t (€);
- T – Number of periods.

3.1.1.3. Emissions Cost Reduction (ECR)

One of the main purposes of the introduction of energy storage systems and RES is the reduction of fuel and, consequently, the reduction of CO_2 emissions.

Some countries have already been implemented some incentives to reduce CO_2 emissions. For instance, the European Commission launched the EU ETS in 2005. This system works on the 'cap and trade' principle. The EU sets a cap and, within this cap, companies receive or buy emission allowances which they can trade [91]. Therefore, these CO_2 emissions can be monetized and the reduction of CO_2 emissions when comparing a microgrid with and without energy storage should be considered, (Eq. 3.3). To that end, it is defined a KPI that evaluates the reduction of CO_2 emission costs called ECR.

$$ECR = \sum_{t=1}^{T} \alpha * (Q_{CO_2}^{w/oBESS}(t) - Q_{CO_2}^{w/BESS}(t)) \quad [€] \qquad \text{(Eq. 3.3)}$$

In which:

- α - CO_2 emissions cost factor (€/ton);
- $Q_{CO_2}^{w/oBESS}$ - quantity of CO_2 released without BESS in the period t (ton);
- $Q_{CO_2}^{w/BESS}$- quantity of CO_2 released with BESS in the period t (ton).

3.1.1.4. Microgrid Autonomy (MA)

The microgrid autonomy is the KPI that evaluates the resilience of the microgrid in isolated mode in terms of reserves. The inclusion of energy storage systems in a microgrid improves this KPI, as one of the objectives of the system can be the guarantee of spinning reserve in case of loss of a producing unit during a certain period. This period corresponds to the time to place a thermal group in service on the grid. If the microgrid autonomy does not meet the KPI requirements, the spinning reserve guaranteed by the BESS needs to be increased [92].

The Energy Not Supplied (ENS) over a scheduling period T is

$$ENS = \sum_{t=1}^{T} L(t) \quad [MWh] \qquad \text{(Eq. 3.4)}$$

The Expected Energy Not Supplied (EENS) is a probabilistic index for the reliability analysis of the microgrid and is expressed as:

$$EENS = \frac{\sum_{n=1}^{N} ENS_n}{N} \quad [MWh] \qquad \text{(Eq. 3.5)}$$

Therefore, the KPI used to assess the autonomy of the microgrid is the Microgrid Autonomy (MA) as follows:

$$MA = 1 - \frac{EENS}{EE} \qquad \text{(Eq. 3.6)}$$

In which:

- L – energy not supplied in the period t (MWh);
- T – scheduling period;
- N – number of scheduling periods;
- EE – expected energy demand of the microgrid (MWh).

3.1.1.5. Cycle Benefits (CB)

The purpose of this KPI is to verify if the discharge and charge the battery is performed only when it is profitable. In this KPI, 4 possible economic benefits scenarios can be considered:

- In a market scenario, it is considered the energy sold;
- In a services provider scenario, it is considered the benefits from the provision of services to ISO;
- In a renewable promotor scenario, it is considered the increase in the revenues;
- In a microgrid scenario, it is considered the savings in the microgrid.

Therefore, in the microgrid scenario, it is considered the cost of each BESS cycle and the savings in the electricity generation, (Eq. 3.7).

$$CB = ACR - EC * C_{cycle} \ [€] \qquad \text{(Eq. 3.7)}$$

In which:

- EC – equivalent cycle [cycle];
- C_{cycle} – cost per cycle [€/cycle].

3.1.1.6. State of Health (SoH)

When the scheduling of charging and discharging periods ends, there is a need to assess the SoH of the BESS. The indicator SoH has the function of acknowledging the health status of the system and to predict when the End of Life will be reached.

The SoH of the cell is defined as the cell capacity after a certain time of operation normalized with its initial one, with the number of equivalent cycles and with different current rates [93]. So, the mathematical formulation for SoH is presented in (Eq. 3.8).

$$SoH(N) = \frac{SoH_0 - m * \sum_{n=1}^{N} EC(n)}{SoH_0} * 100\% \ [\%] \quad \text{(Eq. 3.8)}$$

In which:

- SoH_0 – initial state of health;
- N – number of scheduling periods;
- EC – equivalent cycles in the scheduling period n;
- m – is the rate of decrease of the SoH in function of the C_{rate} at which cycles are performed.

3.1.2. Planning KPIs

Planning KPIs aim to assess the impact of the system at the BESS's End of Life. The improvement in operating KPIs have an impact on planning KPIs, providing planning KPIs an overview of the system. These KPIs are the ones that allow us to decide whether integrating BESS into the microgrid is a viable decision or not.

3.1.2.1. Levelized Cost (LC)

The Levelized Cost is defined as the cost of an investor assuming the certainty of production costs and the stability of electricity prices. Thus, the LC corresponds to the sum of all costs incurred over the lifetime of a given generating technology divided by the delivered energy [94].

Furthermore, the LC represents a life cycle cost per kilowatt hour (kWh). It can be interpreted as the minimum price per kWh that an electricity generating plant would have to obtain in order to break-even on its investment over the entire life cycle of the facility [95].

For instance, the energy from renewable sources has high capital costs, low operational costs and significantly low capacity factors due to their variability. On the contrary, fossil-fuel power plants are associated to lower capital costs, higher operational costs and higher capacity factors. Therefore, LC takes these differences into account and allows investors to make better decisions on investments in electricity generation as it can be used to assess different options and determine the most cost-effective energy source [96,99].

The projected LC for different technologies in the US by 2023 is presented in the Figure 3.1.

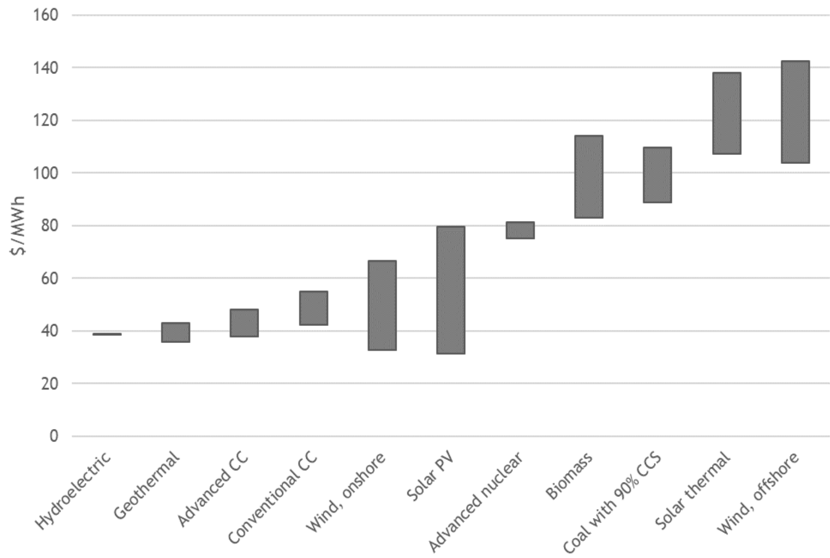

Figure 3.1 - Projected LC for different technologies in the US by 2023 [98].

Therefore, it is identified a first type of LC, **Levelized Cost Of Energy (LCOE)**, in which are considered the costs of the entire system producer. (Eq. 3.9) and (Eq. 3.10) presents the LCOE formulation.

$$LCOE = \frac{\sum_{y=0}^{EoL} \frac{I(y)+O\&M(y)+\tau * F(y)+\alpha * CO_2(y)}{(1+k)^y}}{\sum_{d=0}^{EoL} \frac{E^{consumed}(y)}{(1+k)^y}} \quad [€] \qquad \text{(Eq. 3.9)}$$

$$(1+k) = (1+d) * (1+i) \qquad \text{(Eq. 3.10)}$$

In which:

- I – Investment in year y (€);
- $O\&M$ – Operations and maintenance in year y (€);
- F – Fuel consumption in year y (kg);
- CO_2 - CO_2 emissions in year y (ton_{CO2});
- τ – fuel costs (€/kg);
- α – CO2 emissions allowances (€/ton_{CO2});
- $E^{consumed}$ – Energy consumed in year y (MWh);
- k - nominal discount rate;
- d - real discount rate (e.g. 8%);
- i - inflation rate (e.g. 2%).

Moreover, it is also identified a second LC type, the **Levelized Cost Of Storage (LCOS)** which are only considered the costs of BESS in the microgrid scenario. The LCOS is formulated by the (Eq. 3.11).

$$LCOS = \frac{\sum_{y=0}^{EoL} \frac{I(y)+O\&M(y)}{(1+k)^y}}{\sum_{y=0}^{EoL} \frac{E^{discharged}(y)}{(1+k)^y}} \quad [€] \qquad \text{(Eq. 3.11)}$$

In which:

- I – Investment in year y (€);
- $O\&M$ – Operations and maintenance in year y (€);
- $E^{discharged}$ – Energy discharged in year y (MWh);
- k - nominal discount rate;

3.1.2.2. Levelized Benefits of Storage (LBOS)

The LBOS consider the sources of income of the BESS. The source of earnings is the same as in the KPI CB. LBOS is expressed by the (Eq. 3.12). The LBOS and LCOS can be applied together and determine if the project is profitable (LBOS>LCOS), which has a considerable importance to policy makers and investors. Both KPIs are directly influenced by the system operation, since it is only their operation that determines them.

$$LBOS = \frac{\sum_{y=0}^{EoL} \frac{\sum_{n=0}^{N} ACR(n)}{(1+k)^y}}{\sum_{y=0}^{EoL} \frac{E^{discharged}(y)}{(1+k)^y}} \quad [€] \qquad \text{(Eq. 3.12)}$$

In which:

- $E^{discharged}$ - Energy discharged by the BESS (MWh);
- N - number of scheduling periods in the year y;
- EoL – BESS end of life;
- k - nominal discount rate;
- d - real discount rate (e.g. 8%);
- i - inflation rate (e.g. 2%).

3.1.2.3. Net Present Value (NPV)

The idea of NPV is based on the concept of the time value of money and takes into consideration that money spent and obtained in future periods has a different value than money spent or obtained in the present. The NPV is widely adopted in different applications as a measure of the economic feasibility of a project.

The NPV is chosen as a KPI over other indicators, i.e. Internal Rate of Return, because it considers different discount rates for the same project and takes into account the cost of capital, which is indispensable for long-term investments such as a microgrid and BESS.

The calculation formula for NPV is presented in (Eq. 3.13) and (Eq 3.14).

$$NPV = \sum_{t=0}^{T} \frac{CF(t)}{(1+k)^t} \quad [€] \qquad \text{(Eq. 3.13)}$$

$$(1 + k) = (1 + d) * (1 + i) \qquad \text{(Eq. 3.14)}$$

In which:

- CF - Cash Flow in the period t (€);
- k - nominal discount rate;
- d - real discount rate (e.g. 8%);
- i - inflation rate (e.g. 2%);
- T - BESS's lifetime.

3.1.2.4. Payback Time (PT)

The payback period is the length of time required to recover the cost of an investment or is the length of time an investment reaches a break-even point. Payback focuses at the cumulative cash flow of the investment up to the point at which the original investment has been recouped from the investment cash flows. Therefore, this KPI is a criteria of risk assessment, being more attractive a project that allows a recovery of the capital invested in less time.

The payback time indicates the number of years required to achieve a zero or positive NPV as in (Eq. 3.15).

$$PT = T, when \sum_{t=0}^{T} CF_t = I_0 \quad [years] \quad \text{(Eq. 3.15)}$$

In which:

- CF - Cash Flow (€);
- I_0 - Initial investment (€).

3.2. Final Remarks

In this chapter eleven KPIs are identified and described, and are divided in two categories, Operational KPIs and Planning KPIs.

The Operational KPIs aim to assess the operational strategy of the off-grid generator system and to monitor the energy storage system. Through the division into subsystems, such as CO_2 emissions and operating costs, it allows to identify the potential for improvement in the off-grid system.

The Planning KPIs aim to assess the performance of the system when the BESS reaches EoL and thus assess the viability of integrating the storage system into the off-grid system. These KPIs are strongly influenced by the Operational KPIs, so if during the optimisation of the operational strategy the Operational KPIs are improved, better Planning KPIs are obtained.

Chapter 4

DIOPHOS Methodology

The developed DIOPHOS (Day-ahead and Intra-day Operational Planning for Hybrid Off-grid Systems) methodology aims to perform the day-ahead planning of operation for the generating and energy storage resources in the microgrid. Additional stages of optimisation are also performed on an hourly intra-day basis in order to address the uncertainty associated with RES as well as electric demand. The objectives are achieved through a technical-economic analysis based on the Operational KPIs, identified in the Section 3.1, in order to define the optimal strategy for the functioning of the controllable resources, which operation may be adapted according to the resulting evaluation of the these KPIs. Moreover, the evaluation performed through the Planning KPIs allows to give insights on which battery energy storage technology and which sizing is most appropriate, after recognizing the technological options and sizing to be applied.

The Section 4.1 contains a literature review on operating strategies for energy storage systems and microgrids. The Section 4.2, firstly, introduces the methodology in general and then it is presented a detailed description of the methodology. This section is divided into 7 subsections that explain in detail the modeling of the system, the various stages of the methodology and the way the technical-economic analysis is performed.

4.1. Operational Methodologies for Energy Storage and Microgrids

Several methodologies have been proposed in the literature either for the operation of a complex electric system with multiple energy resources (i.e. microgrid) or for the operation of a single controllable energy resource, namely energy storage systems. Nonetheless, the underlying operation strategies are based on deterministic rules or in dynamic strategies with deterministic rules, [99] evaluates different charging strategies for stand-alone supercapacitors, lithium-ion, and lead-acid batteries. Optimal charging strategies are formulated, and the corresponding charging currents are obtained. These strategies are Constant Current, Constant Voltage, Constant Power. Considering the systems dynamics, [100] presents a model-based controller design approach to control energy storage devices for residential PV applications. The model-based approach assumes that an energy storage device is equipped with a set of predetermined real-time control modes, and the control objective consists in choosing the best operation mode of the Energy Storage Device to achieve an improved performance at the lowest cost. An Economic MPC algorithm is used.

Depending on the modelling of the BESS and other grid resources, the problem can be defined as a LP problem, as a MILP problem, or as a NLP problem for a given time horizon. In a microgrid context, nonlinearities are present in all characteristics of the system such as the thermal generators cost function, primary reserve requirements and the BESS's dynamic characteristics (i.e. Efficiency, SoH, charge and discharge rates). These nonlinearities are often linearized through techniques such as piecewise linearization. In [101] it is presented the modelling and design of a modular energy management system and its integration to a grid-connected battery-based microgrid. The scheduling model is defined as MILP problem and conclude that the EMS allows to reduce cost in the microgrid and manage the storage devices in a proper way. In [102], it is studied the economic performance gains achievable by using a nonlinear, electrochemical battery model, including a more representative model of its dynamics and degradation, in an economic optimisation for a grid application. From the simplest to the most complex model the total simulated profit increased by 175%.

Due to the maturity, versatility and possibility of combining several types of algorithms, the use of MPC for optimal BESS scheduling has been proposed for the adequate integration of BESS in a microgrid context. Through a sliding time window, MPC is capable of solving a multi-temporal optimisation problem. Due to the challenges associated with forecasting electrical energy production by renewable sources as well as electric demand, MPC presents itself as an adequate method to address the need to compensate the deviations of actual realizations from these forecasts at each time step, thus obtaining a result closer to the global optimum. Work in [103] presents a two-stage centralized model predictive control scheme for distributed battery storage that consists of a scheduling entity and a real-time control entity.

For problems of temporal operational planning under uncertainty, such as scheduling in microgrid, there are methods that try to provide optimal sequential stochastic decisions rules. In [104] it is proposed an optimal scheduling mode for minimizing the operating costs of an isolated microgrid by using chance-constrained programming. The spinning reserve provided by energy storage was modelled with probabilistic constraints to consider the uncertainty. This design enables the microgrid operation to achieve a balanced trade-off between reliability and cost-effectiveness by setting a proper confidence level.

Other techniques for solving BESS optimal scheduling are based on dynamic programming, either deterministic or stochastic dynamic programming. Furthermore, several studies have been conducted using RL. This method has the advantage of learning through the interactions with the system to be optimised, however does not require knowledge of an explicit model of the system. [105] based on the idea of ADP, a self-learning algorithm is constructed to obtain the interactive control law sequence for the BESS. The optimal performance index function aims to minimize the total electricity cost and, simultaneously, extends the battery's lifetime and it was proven that the iterative value function converges to the corresponding optimal performance index as the iterative index increases to infinity.

In order to compare the two real time control perspectives, work in [106] compared RL with MPC. The results obtained showed that the MPC is slightly less robust than the fitted Q-iteration based RL from the numerical point of view but presents an advantage in terms of accuracy. In summary, they suggest that the proper way is to combine model-based techniques such as MPC in online mode and learning-based techniques such as RL in offline model together with samples generated by Monte Carlo Simulation in order to circumvent limitations of MPC such as convergence problems or the risk of being trapped in a local optimum.

4.2. Description of the DIOPHOS Methodology

Given the applications that the energy storage systems are capable of providing to off-grid systems, the methodology presents the capability of maximizing the integration of RES and, consequently, further offset the use of diesel-fired generating units with the integration of BESS. As a consequence of the various challenges associated with off-grid systems, the methodology adapts the dispatch of the production sources according to the evaluation performed through the results of the Operational KPIs. Thus, the methodology aims to:

- Higher integration shares of RES by storing the energy in excess and by providing spinning reserve;
- Optimisation of the thermal units' operating point through the possibility of increasing the operating point by charging the energy storage device or to reduce the operating point by discharging the energy storage device and, consequently, reducing fuel consumption;
- Reducing the operating time of thermal units and improving reliability rates due to the provision of primary reserve by the energy storage device.

The Figure 4.1 presents an overview of the methodology developed. The methodology requires inputs that will model the generating system, the BESS and the demand as well as operational requirements. The methodology incorporates a multi-stage operational algorithm that consists in two optimisations framed in different time horizons in relation to real-time operation.

The outputs of the methodology are the dispatch of BESS and thermal units, the RES curtailment for each hour and the result of each KPI that allow the technical-economic evaluation of the system. The resulting evaluation of the Operational KPIs intends to adapt the behaviour of the system and, consequently, improve the result of the Planning KPIs.

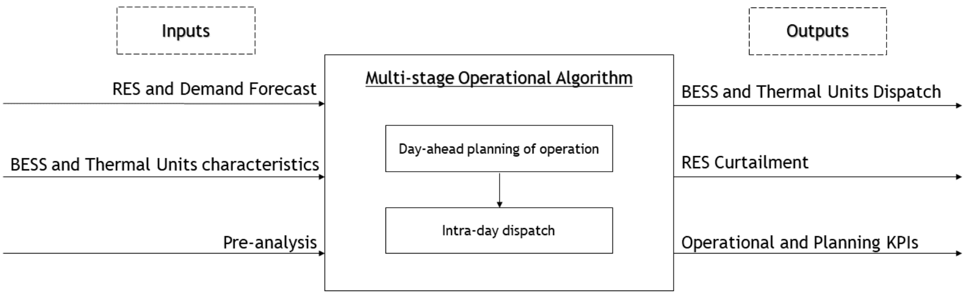

Figure 4.1 - Overview of the Operational Algorithm for the Energy Resources in Off-grid Systems.

4.2.1. Description of the Methodology

The Figure 4.2 summarizes the methodological steps to achieve the optimal dispatch of the generation system with the introduction of the BESS in order to improve the management of the off-grid resources and to reduce the OPEX of the global system.

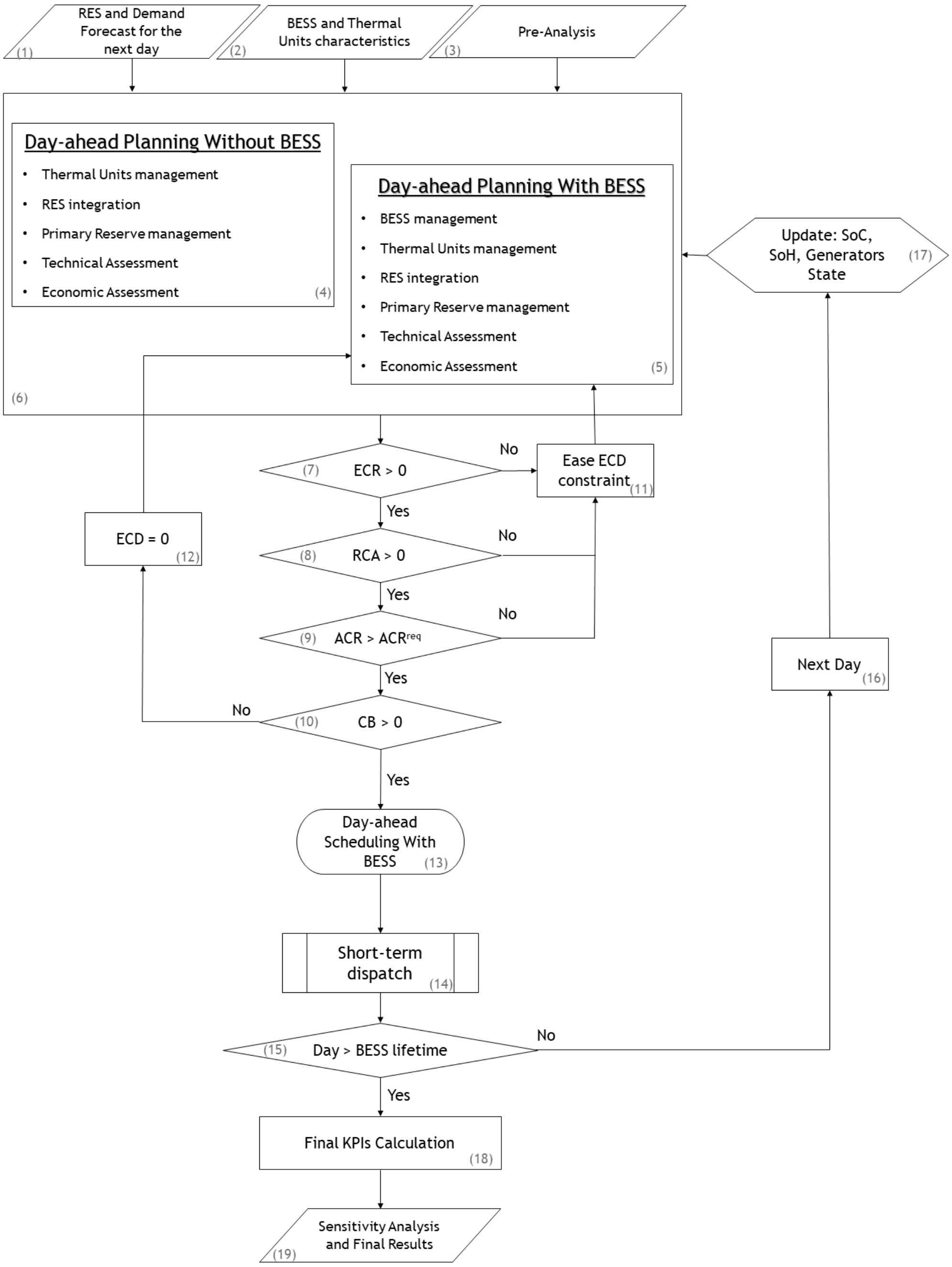

Figure 4.2 - DIOPHOS Methodology's Flowchart.

To initialize the process, several inputs are required which are divided in three categories (Step (1), Step (2) and Step (3) in Figure 4.2). Thus, Step (1) is the introduction of forecasts of RES production profiles and consumption profiles for the next day. Step (2) is the introduction of BESS and thermal units data characteristics, so that the generating system can be modeled (described in detail in Subsection 4.2.2). Step (3) is the introduction of parameters that will influence the optimisation, such as the hour of the day-ahead planning beginning, the maximum Equivalent Cycles per Day and the minimum ACR required. These parameters are obtained through a study performed a priori, i.e. before the start of the operational algorithm in order to feed such parameters as constraints to the optimisation problem. This is performed considering the average behaviour in terms of generation and electric demand of the microgrid in each season of the year (summer, winter and spring/autumn).

In Step (4), the day-ahead planning of operation for the off-grid system is performed without considering the battery energy storage system. In Step (5), the day-ahead planning for the off-grid system is performed considering the battery energy storage system. In Step (6) the calculations of the Operational KPIs are realized with the information obtained from the two scenarios. The calculated KPIs are subsequently assessed and the BESS adapts its operation according to the result of this assessment. The day-ahead planning is performed 12 hours before the hour resulting from the pre-analysis for each season with the main purpose of performing the Thermal Unit Commitment for that day.

In Steps (7), (8), (9) and (10) are performed the assessment of the obtained KPIs. These KPIs are technical-economic and have a direct impact on the reduction of the Off-grid system's OPEX. In Step (7) are compared the CO_2 emissions between the two schedules by KPI ECR. In this methodology it is considered that only the emission reduction has to be accomplished but it is possible to change this value according to the environmental restrictions imposed in each system. In Step (8) the RES curtailment between the two plans is compared using the KPI RCA. Due to the BESS ability to store excess energy produced from renewable sources and to provide primary reserve, RES curtailment must be smaller in the day-ahead planning with BESS than in the day-ahead planning without BESS and, thus, increase the share of renewable energy in the system. In Step (9) the average cost per hour of the two schedules is compared through the KPI ACR. Due to the BESS behaviour from the viewpoint of the system operator, the economic benefits of the integration of the BESS in the system are in the logic of avoided costs. Therefore, through the results obtained in Step (3), the system must ensure a certain average cost reduction per hour for each day so that at the end of its lifetime it has a Net Present Value at least equal to zero. In Step (10) the economic benefits in relation to battery degradation are evaluated through the KPI CB. With this evaluation, the BESS only discharges if the equivalent cycles performed presents an economic value higher than the equivalent cost of its degradation.

In Steps (11) and (12), the BESS operation is adapted by evaluating the results of the Operational KPIs. If the assessment is positive for all Operational KPIs, then the BESS doesn't need to adapt, therefore no change is made in relation to the initial inputs and the day-ahead planning of operation with BESS is obtained in Step (13). If the BESS fails in Steps (7), (8) and (9), an easing of the restriction of the maximum equivalent cycles per day is implemented so that the energy storage system has more freedom of operation and, thus, may achieve improvements in the operation and the defined KPIs. This easing of the maximum equivalent cycles per day is based on the concept that the maximum equivalent cycles per day are not used every day and, therefore, use the difference between the maximum equivalent cycles per day and the equivalent cycles used per day. If the system fails in Step (10), the BESS does not enter in the dispatch to inject power into the grid but only enters as a primary reserve resource. Therefore, the restriction of the maximum equivalent cycles per day is set to 0 and a new day-ahead planning is carried out with BESS.

After the assessment of the KPI results, the final day-ahead planning is obtained with the BESS, in Step (13).

In Step (14) the intra-day dispatch of the system is conducted in order to eliminate errors in the forecasts of the RES production and the Demand profiles and thus obtain a more optimised scheduling but following the UC of the previous day. The intra-day dispatch is performed hourly with the time horizon at the end of the day and is based on the same modelling used in the day-ahead planning.

If the lifetime of the BESS has not yet been reached, Step (15), the methodology continues for the next day, in Step (16), and some BESS parameters are updated, Step (17). In the Step (17), the SoC of the energy storage system and its SoH are updated considering the equivalent cycles performed on the previous day. Also, the thermal units' status of the last hour of the previous day is updated in such a way that their minimum operating times are respected.

Having reached the lifetime of the BESS, the KPIs are calculated, in Step (18), allowing a careful and reasoned technical-economic analysis to be carried out by them, Step (19).

4.2.2. Off-grid System Modelling

The modeling of the system aims to reflect the behaviour of the system components and the method used to reproduce these behaviours is the Mixed Integer Linear Programming, as presented in (Eq. 4.1).

$$min_x f^T x \text{ subject to } \begin{cases} x(int) \text{ are integers} \\ A.x \leq b \\ Aeq.x = beq \\ lb \leq x \leq ub \end{cases} \quad \text{(Eq. 4.1)}$$

The nomenclature for the mathematical formulation of the addressed problem is:

- Sets:
  - I – Set of indices of the Thermal Units;
  - T – Set of indices of the hourly time periods;
  - J – Set of indices of the piecewise linear cost function blocks;
  - K – Set of indices of the piecewise linear BESS degradation function blocks;
- Parameters:
  - λ_{i0} - Fixed cost of the Thermal Unit i;
  - λ_{ij} - Slope of cost block j of the Thermal Unit i;
  - $m_{emissions_{i0}}$ - Fixed emissions cost of the Thermal Unit i;
  - $m_{emissions_{ij}}$ - Slope of emissions cost block j of the Thermal Unit i;
  - α_{start}^{i} , α_{shut}^{i} - Start and shutdown costs, respectively;
  - m_{RC} - Penalty for RES curtailment;
  - P_{max}^{d} - Maximum discharge power of the BESS;
  - P_{max}^{c} - Maximum charge power of the BESS;
  - SoC_0 - Initial state of charge of the BESS;
  - SoC_{min} - Minimum state of charge of the BESS;
  - SoC_{max} - Maximum state of charge of the BESS;
  - η_c , η_d - Charge and discharge efficiency of the BESS;
  - E^{BESS} - Storage capacity of the BESS;
  - P_{min}^{i} - Minimum power output of the Thermal Unit i;
  - P_{max}^{i} - Maximum power output of the Thermal Unit I;
  - M - Large positive penalty constant;
  - P_{dk}^{max} - Maximum discharge power of the block k;
  - ECD - Limit of equivalent cycles per day;
  - b_k - Fixed degradation of the block k;
  - m_k - Slope of block k of the piecewise linear BESS degradation function;
  - T_{min}^{fun} - Minimum operation time of the Thermal Unit;

  - Δt - Time step;
  - π_{Load} - Percentage of Load reserve;
  - π_{RES} - Percentage of RES reserve;
  - T^{start} - Time to start Thermal Unit;
- Variables:
  - $c_{gen}^{i}(t)$ - Generation cost Thermal Unit i in period t;
  - $c_{start}^{i}(t)$ - Starting cost of Thermal Unit i in period t;
  - $c_{shut}^{i}(t)$ - Shutdown cost of Thermal Unit i in period t;
  - $c_{RC}(t)$ - Renewable curtailment cost in period t;
  - $\mu_i(t)$ - Binary variable that is equal to 1 if Thermal Unit k is online in period t and 0 otherwise;
  - $\mu_d(t)$ - Binary variable that is equal to 1 if the BESS is discharging in period t and 0 otherwise;
  - $\mu_c(t)$ - Binary variable that is equal to 1 if the BESS is charging in period t and 0 otherwise;
  - $P_g^i(t)$ - Power output of thermal unit i in period t;
  - $P_c(t)$ - Charging power of the BESS in period t;
  - $P_d(t)$ - Discharging power of the BESS in period t;
  - $P_{BESS}(t)$ - Power exchange of the BESS in period t;
  - $P_{Wind}(t)$ - Power output of the Wind farm in period t;
  - $P_{PV}(t)$ - Power output of the PV power plant in period t;
  - $P_{Load}(t)$ - Electrical Demand in period t;
  - $P_{RC}(t)$ - RES power curtailed in period t;
  - $G_{ij}(t)$ - Power produced in block j of the piecewise linear cost function of thermal unit k in period t;
  - $EC(t)$ - Equivalent cycles performed in period t;

The equations of the mathematical formulation are valid for every set defined in the nomenclature (i.e., ∀i ∈ I, ∀t ∈ T, ∀j ∈ J, ∀k ∈ K).

4.2.2.1. Objective Function

Since environmental concerns have emerged, the introduction of RES into electrical grids has become a necessity although typically such implementation only occurs in case there is economic rationale. Although RES present very low operating costs, their investment costs are still very high. So, one of the ways to increase their economic benefits is to include penalties for the use of non-renewable sources, such as penalties to the CO_2 emissions of the thermal units and penalties to RES curtailment. Therefore, the objective function used in the methodology follows the principles of the Planning KPI LCOE but for only a certain interval of time (i.e. a day). Then, the objective function is defined by (Eq. 4.2):

$$min \sum_{t=1}^{T} \left(\sum_{i=1}^{I} \left(c_{gen}^{i}(t) + c_{start}^{i}(t) + c_{shut}^{i}(t) \right) + c_{RC}(t) \right) \quad \text{(Eq. 4. 2)}$$

The production costs of the generators in (Eq. 4.3) result from an approximation through linearization in segments of the real cost function curve of the thermal units. λ_{i0} is the exact cost incurred by thermal generator i to produce at its minimum operating point if the generator is online ($\mu_i(t) = 1$). λ_{ij} is the rate of the operational cost for the block G_{ij} (defined in the (Eq.

4.3)). $m_{emissions0}$ and $m_{emissionsj}$ have the same meaning as λ_{i0} and λ_{ij} but in relation to the costs of CO_2 emissions released into the atmosphere.

$$c_{gen}^{i}(t) = (\lambda_{i0} + m_{emissions_{i0}}) * \mu_i(t) + \sum_{j=1}^{J} \left(\lambda_{ij} + m_{emissions_j}\right) * G_{ij}(t) \quad \text{(Eq. 4.3)}$$

The thermal generator's starting and shutdown costs, modelled in (Eq. 4.4) (Eq. 4.5), respectively, reflect their need to consume more fuel when operating at low operation point.

$$c_{start}^{i}(t) \geq \alpha_{start}^{i} * \left(\mu_i(t) - \mu_i(t-1)\right) \land c_{start}^{i}(t) \geq 0 \quad \text{(Eq. 4.4)}$$

$$c_{shut}^{i}(t) \geq \alpha_{shut}^{i} * \left(\mu_i(t-1) - \mu_i(t)\right) \land c_{shut}^{i}(t) \geq 0 \quad \text{(Eq. 4.5)}$$

The formulation of the curtailing renewable energy cost in (Eq. 4.6) reflects the compensation RES owners may receive for the necessity to curtail that same energy.

$$c_{RC}(t) = m_{RC} * P_{RC}(t) \quad \text{(Eq. 4.6)}$$

4.2.2.2. Balance Equation

(Eq. 4.7) models the balance between the power consumed and the generated power so that the system maintains its safety.

$$P_{BESS}(t) + \sum_{i=1}^{I} P_g^i(t) + P_{Wind}(t) + P_{PV}(t) = P_{Load}(t) - P_{RC}(t) \quad \text{(Eq. 4.7)}$$

4.2.2.3. Battery Energy Storage System

The exchange power of the BESS is given by the difference between the discharge and charge of the storage system in (Eq. 4.8). It is considered that the battery is discharging with the positive value (Eq. 4.9) as the production of the generators and the charging is considered with the negative value (Eq. 4.10) such as loads.

$$P_{BESS}(t) = P_{BESS}^{d}(t) - P_{BESS}^{c}(t) \quad \text{(Eq. 4.8)}$$

$$P_{BESS}^{d}(t) \geq 0 \quad \text{(Eq. 4. 9)}$$

$$P_{BESS}^{c}(t) \geq 0 \quad \text{(Eq. 4. 10)}$$

The discharging and charging must have to satisfy the maximum technical requirements (Eq. 4.11), (Eq. 4.12). Also, the discharging and charging cannot coincide in the same time interval (Eq. 4.13).

$$P_{BESS}^{d}(t) \leq P_{max}^{d} * \mu_d(t) \quad \text{(Eq. 4.11)}$$

$$P_{BESS}^{c}(t) \leq P_{max}^{c} * \mu_c(t) \quad \text{(Eq. 4.12)}$$

$$\mu_d(t) + \mu_c(t) \leq 1 \quad \text{(Eq. 4.13)}$$

Like its power capacity, the energy capacity in the BESS must also respect the technical limits of the battery as formulated in (Eq. 4.14) and (Eq. 4.15). These two equations are not only useful to model the technical limits but also to know how energy is available in the battery device.

$$SoC_0 + \left[\sum_{n=1}^{t} \frac{P_{BESS}^{c}(n) * \eta_c * \Delta t}{E^{BESS}} - \sum_{n=1}^{t} \frac{P_{BESS}^{d}(n) * \Delta t}{E^{BESS} * \eta_d}\right] \leq SoC^{max} \quad \text{(Eq. 4.14)}$$

$$SoC_0 + \left[\sum_{n=1}^{t} \frac{P_{BESS}^{c}(n) * \eta_c * \Delta t}{E^{BESS}} - \sum_{n=1}^{t} \frac{P_{BESS}^{d}(n) * \Delta t}{E^{BESS} * \eta_d}\right] \geq SoC^{min} \quad \text{(Eq. 4.15)}$$

The consideration of the battery capacity decay through time must be considered in the mathematical models for an adequate quantification of the impacts of its integration in microgrids, once it influences the operation of BESS and their economic assessment. Several analytical approaches have been proposed for estimating the useful life of battery storage such as the “rainflow” method that considers that the number of cycles that a battery can perform is a function of the depth of discharge of those cycles [107]. So, this method relies on two steps, the first step is to identify the parameters of a battery lifespan and the second step consists on using the aging curve of the storage component [108].

The method considered in this methodology takes into account the current rate effect through a weighted energy throughput [93]. The energy exchanged during its operation can be defined as in:

$$E_{exch} = \sum_{k=1}^{N} w(k) * E_{BESS}^{d}(k) \quad \text{(Eq. 4.16)}$$

Where $w(k)$ is the degradation weight of the cell for a specific C-rate and E_{BESS}^{d} is the energy discharge by the BESS. The ratio between E_{exch} and E_{rated}, rated energy capacity of the cell, defines the number of equivalent cycles that the battery cell performed in the period k.

$$N_c = \frac{E_{exch}(k)}{E_{rated}} \quad \text{(Eq. 4.17)}$$

The weights are calculated from cycling data provided by a cell manufacturer on their cell datasheet, as shown in the example in Figure 4.3. The weights are the slopes in the cycling ageing curves, which means that higher rates for charging or discharging causes faster degradation of the cell.

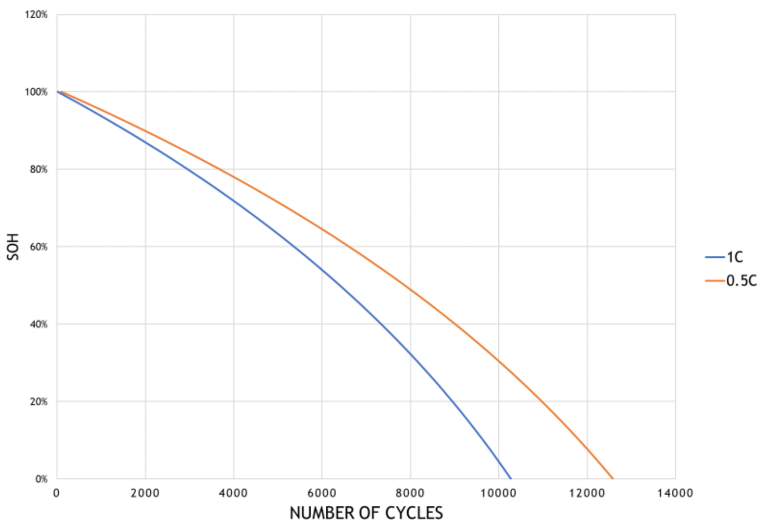

Figure 4.3 - Example of Battery Cycling ageing at 1C and 0.5C.

To implement this method in the mathematical formulation, it is necessary to linearize the ageing curves. Due to the need to identify the location in each segment, the Big M method is implemented, as shown in (Eq. 4.18) – (Eq. 4.24).

$$P_{BESS}^{d}(t) - P_{dk}^{max} \leq M * \xi_k(t) \quad \text{(Eq. 4.18)}$$

$$P_{dk}^{max} - P_{BESS}^{d}(t) \leq M * \left(1 - \xi_k(t)\right) \quad \text{(Eq. 4.19)}$$

$$\rho_k(t) = \xi_k(t) - \xi_{k+1}(t) \quad \text{(Eq. 4.20)}$$

$$P_{dk}(t) \leq P_{BESS}^{d\_max} * \rho_k(t) \quad \text{(Eq. 4.21)}$$

$$P_{dk}(t) \leq P_{BESS}^{d}(t) \quad \text{(Eq. 4.22)}$$

$$P_{BESS}^{d}(t) - P_{dk}(t) + P_{BESS}^{d\_max} * \rho_k(t) \leq 0 \quad \text{(Eq. 4.23)}$$

$$EC(t) = \frac{\sum_{k=1}^{K}\left(b_k * \rho_k(t) + m_k * P_{dk}(t)\right)}{E^{BESS}} \leq ECD \quad \text{(Eq. 4.24)}$$

4.2.2.4. Thermal Units

The thermal units must respect the maximum (Eq. 4.25) and minimum (Eq. 4.26) technical generating limits.

$$P_{gen}^{i}(t) \leq P_{min}^{i} * \mu_i(t) \quad \text{(Eq. 4.25)}$$

$$P_{gen}^{i}(t) \geq P_{max}^{i} * \mu_i(t) \quad \text{(Eq. 4.26)}$$

In order to deal with a linear problem, the quadratic cost function of generators is approximated by linearization in j segments with the same power interval as in (Eq. 4.27) – (Eq. 4.30).

$$P_{gen}^{i}(t) = P_{min}^{i} * \mu_i(t) + \sum_{j=1}^{J} G_{ij}(t) \quad \text{(Eq. 4.27)}$$

$$G_{ij}(t) \geq 0 \quad \text{(Eq. 4.28)}$$

$$G_{ij}(t) \geq G_{i,j+1}(t) \quad \text{(Eq. 4.29)}$$

$$G_{ij}(t) \leq \frac{P_{max}^{i} - P_{min}^{i}}{j} \quad \text{(Eq. 4.30)}$$

Due to thermal constraints, the thermal units have to remain online once they are brought online during a certain amount of time. Therefore, the minimum operating time of the thermal units is modelled with the Big M method as follows (Eq. 4.31) – (Eq. 4.37):

$$\sigma_i(t-1) + 1 - \left(1 - \mu_i(t)\right) * M \leq \sigma_i(t) \leq \sigma_i(t-1) + 1 + \left(1 - \mu_i(t)\right) * M \quad \text{(Eq. 4.31)}$$

$$0 \leq \sigma_i(t) \leq \mu_i(t) * M \quad \text{(Eq. 4.32)}$$

$$\sigma_i(t-1) - \mu_i(t) * M - \left(1 - \mu_i(t-1)\right) * M \leq \phi_i(t) \quad \text{(Eq. 4.33)}$$

$$\phi_i(t) \leq \sigma_i(t-1) + \mu_i(t) * M + \left(1 - \mu_i(t-1)\right) * M \quad \text{(Eq. 4.34)}$$

$$0 \leq \phi_i(t) \leq \mu_i(t-1) * M \quad \text{(Eq. 4.35)}$$

$$\phi_i(t) \leq \left(1 - \mu_i(t)\right) * M \quad \text{(Eq. 4.36)}$$

$$\phi_i(t) \geq T_{min}^{fun}\left(\mu_i(t-1) - \mu_i(t)\right) \quad \text{(Eq. 4.37)}$$

4.2.2.5. Spinning Reserve Management

In order to ensure the security, efficiency and flexibility of operation of an off-grid system, the primary reserve management is one of the key factors to be taken into consideration. The generation system must ensure a minimum spinning reserve level for the electrical system in case of increase in demand (Eq. 4.38), loss of a certain percentage of the existing intermittent renewable sources (Eq 4.39) and failure of the largest thermal unit (Eq. 4.40), provided by the BESS.

$$(SoC_0 - SoC_{min}) * E_{nom} + \left[\sum_{n=1}^{t} P_{BESS}^{c}(n) * \eta_c * \Delta t - \sum_{n=1}^{t} \frac{P_{BESS}^{d}(n) * \Delta t}{\eta_d}\right] + \sum_{i=1}^{I} \mu_i(t) * \left(P_{gen}^{i\_max} - P_{gi}(t)\right) \geq T^{start} * \pi_{Load} * P_{Load}(t) \quad \text{(Eq. 4.38)}$$

$$(SoC_0 - SoC_{min}) * E_{nom} + \left[\sum_{n=1}^{t} P_{BESS}^{c}(n) * \eta_c * \Delta t - \sum_{n=1}^{t} \frac{P_{BESS}^{d}(n) * \Delta t}{\eta_d}\right] + \sum_{i=1}^{I} \mu_i(t) * \left(P_{gen}^{i\_max} - P_{gi}(t)\right) \geq T^{start} * \pi_{RES} * (P_{PV}(t) + P_{Wind}(t)) \quad \text{(Eq. 4.39)}$$

$$(SoC_0 - SoC_{min}) * E_{nom} + \left[\sum_{n=1}^{t} P_{BESS}^{c}(n) * \eta_c * \Delta t - \sum_{n=1}^{t} \frac{P_{BESS}^{d}(n) * \Delta t}{\eta_d}\right] \geq T^{start} * P_{gen}^{i\_max} \quad \text{(Eq. 4.40)}$$

Furthermore, to maintain the N-1 security criteria, at least 2 thermal units must be connected, in the case without BESS, as in (Eq. 4.41), or at least 1 thermal unit, in the case with BESS, as in (Eq. 4.42), in case the BESS is sized to provide sufficient spinning reserve ensure the backup of the largest thermal unit.

$$\sum_{i=1}^{I} \mu_i(t) \geq 2 \quad \text{(Eq. 4.41)}$$

$$\sum_{i=1}^{I} \mu_i(t) \geq 1 \quad \text{(Eq. 4.42)}$$

It is also considered that the amount of reserve to be guaranteed is equal to the required power multiplied by the time required to connect another thermal unit.

4.2.2.6. Forecast

To simulate the behaviour of the micro-grid with historical time-series, it is necessary to model the uncertainties in the renewable generation and electric demand forecasts. For this modelling it is used the EWMA method of seventh order [109].

$$\hat{X}(t) = \sigma * X(t) + \sigma * \sum_{j=1}^{7} (1-\sigma)^j * X(t-j) \quad \text{(Eq. 4. 43)}$$

Where $X(t)$ is the real electrical quantity, $\hat{X}(t)$ is the forecast in period t, and σ is the weighting factor (0≤σ≤1). With different σ values, it is obtained different forecasts with larger errors as the weighting factor decreases. For example, a value of 1 means a perfect forecast. Forecast errors are calculated using Root Mean Square Error (RMSE):

$$f_{RMSE} = \frac{1}{X_{rated}} * \sqrt{\frac{1}{t} \sum_{t=1}^{T} [X(t) - \hat{X}(t)]^2} \quad \text{(Eq. 4. 44)}$$

Where X_{rated} is the rated value of the electrical quantity $X(t)$, and T is the size of the time series. Currently, the consumption forecast has fewer errors in relation to the RES forecast. Also, the forecast error increases with the time horizon of the forecast.

4.2.3. Step (3) - Pre-analysis

In order to set parameters to improve the off-grid system optimisation, a preliminary study is carried out to get these parameters. Typically, when network planning studies are performed, there are historical time-series of consumption and production of RES. Then, with the aggregation of these time-series in seasons it is possible to determine typical days for each season. The aggregation mode chosen for this methodology considered three levels of consumption demand: Low Demand, Medium Demand and High Demand.

The pre-analysis focuses on defining the time of the day when the BESS may reach the minimum SoC, the maximum equivalents cycle per day and average cost reduction required for each season.

4.2.3.1. Pre-analysis – hour with minimum SoC

Due to the defined target function, the energy storage device ends the day with the minimum state of charge, as the charge of the energy storage device may incur costs and the discharge provides economic benefits. Also, in an off-grid system, the optimisation of the management of the thermal units' state is one of the fundamental aspects for the system to be efficient.

Thus, so that the system does not end the day with a fixed state of charge, i.e. typically 50%, or with the minimum state of charge in the last hour of the day, a pre-analysis is conducted to the performance of the microgrid for the different hours of the day with the typical time-series of each season.

The methodology implemented for this study is presented in Figure 4.4 and has as main criteria the evaluation of the Operational KPI ACR result for each hour. The final result of this methodology is to obtain the time of day when the day-ahead planning should take place.

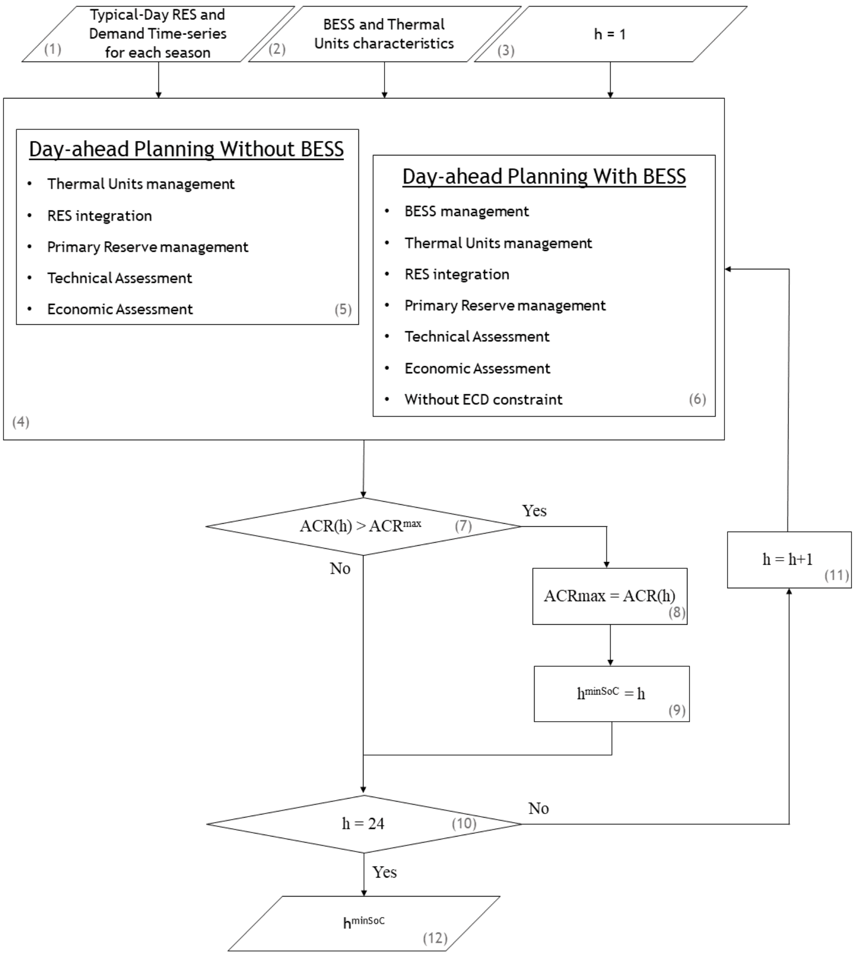

Figure 4.4 - Methodology to find the best hour with minimum SoC.

4.2.3.2. Pre-analysis – maximum Equivalent Cycles per Day and minimum Average Cost Reduction Required

In order to assess the charging and discharging cycles of the energy storage system, it is considered that the system should have limited Equivalent Cycles per Day (ECD) to guarantee the lifetime of the BESS.

The reasons why it is important to consider a limit are:

- If the equivalent cycles are much greater than the limit, the useful life reduces and this can affect the return on investment;
- If the equivalent cycles are much smaller than the limit, the capabilities of the system are not being fully exploited.

In this analysis, the most profitable seasons are identified, which gives the storage system more freedom to degrade more in these seasons. The methodology implemented is shown in the Figure 4.5.

Having already defined the hour at which the minimum state of charge is obtained, the day-ahead planning is made for the typical days of each season. The maximum amount of equivalent cycles per day is the output of the Step (12) in Figure 4.5.

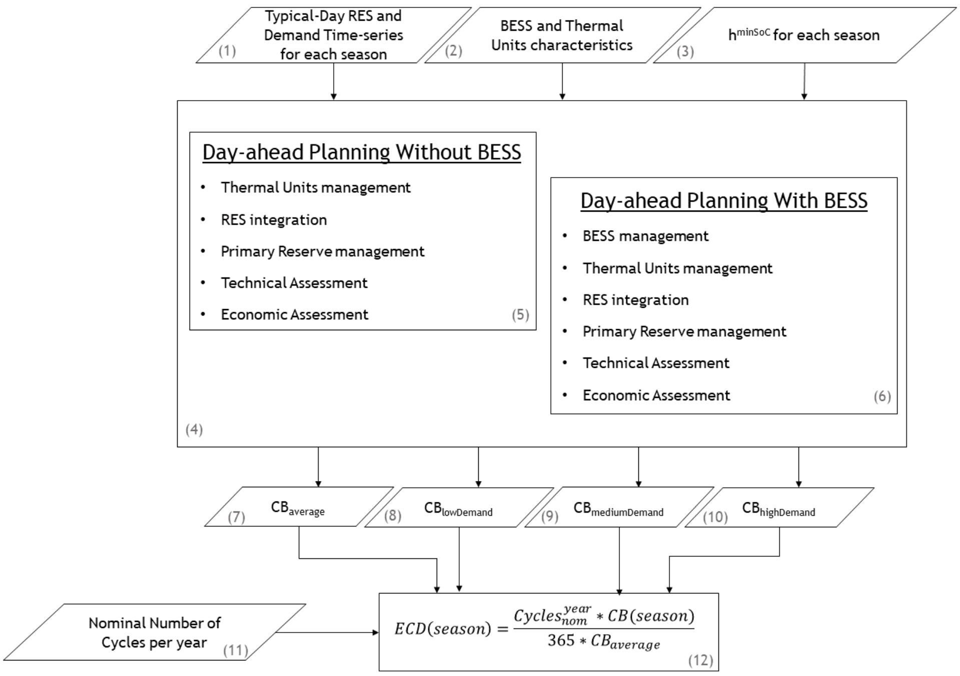

Figure 4.5 - Methodology to find de ECD and ACR^{req}.

With the maximum equivalent cycles per day, the minimum average cost reduction for each day of each season, given by (Eq. 4.45), is obtained to ensure that the Net Present Value of the BESS is greater than or equal to zero at the end of the BESS lifetime.

$$ACR^{req}{}_{season} = \frac{\frac{Rent}{Cycles_{per\ year}} * ECD_{season}}{24} \quad \text{(Eq. 4.45)}$$

The minimum rent per year is the minimum value of economic benefits that the BESS needs to achieve taking into account the investment and operational costs, the number of years considered in the investment project and the inflation rate. The minimum rent per year is the considered the same for the years considered in the investment project.

4.2.4. Step(6) - Day-Ahead Planning for Operation

The day-ahead planning of operation performs the unit commitment and the forecast of RES curtailment for the following day according to the objectives and subject to constraints defined in Section 4.2.2.

Therefore, at least two MILP problems are solved for each day, at hourly steps, considering forecasted electric demand and renewable power and the available power. Initially, a day-ahead planning of operation is solved without the existence of BESS and then another is solved with BESS. It may be necessary to resolve more schedules with the BESS if the results of the KPIs are not accepted and there is the need to change the use of the off-grid system resources.

The planning of operation occurs 12 hours before the start of the planned operation. According to the result of the pre-analysis (see Section 4.2.3), the operation starts in the hour after the hour that achieves the greatest reduction of the average cost per hour.

Due to the planning being performed with forecasts, the production of each thermal unit resulting from the planning of operation is not corresponding to the actual production but allows the determination of which generators will be connected and the chronologic sequence of starts and shutdowns of the thermal units i.e. allows the optimisation of the unit commitment.

In the Figure 4.6 it is exemplified the chronologic sequence of the day-ahead planning of operation. For example, if, in the pre-analysis, it is obtained that the most suitable time at which the BESS reaches the minimum SoC is at 4h, then, the start of the day is considered at 5h. Therefore, the day-ahead planning takes place 12 hours before, at 17h.

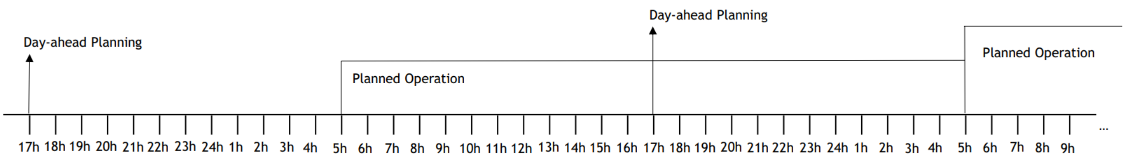

Figure 4.6 – Chronologic sequence of the Day-Ahead Planning.

4.2.5. Step (14) - Intra-day Dispatch

The intra-day dispatch relies on the result obtained in the day-ahead planning of operation. Therefore, in order to address potential forecast errors, the system operator performs dispatches at each hour of the day. This concept is based on the MPC method. This control method is constructed by solving a finite horizon optimal control problem at each time step based on the present [110].

The Model Predictive Control implemented has as fixed time horizon i.e. the end of the day. Thus, as the time advances, the time span decreases as shown in Figure 4.7. It is not considered a moving window with a moving time horizon due to the restriction of the maximum equivalent cycles per day. During the intra-day dispatch, it may be necessary to start or shutdown more thermal units than those planned in the previous day, as well as to change the scheduling of the BESS's charge and discharge.

Due to the day-ahead planning taking place in the day before, it is necessary to guarantee the state of charge considered in the day-ahead planning in the last hour of the day so that the planning of operation stays valid. As defined in the MPC method, only the result of the dispatch for the hour when the dispatch is made is executed.

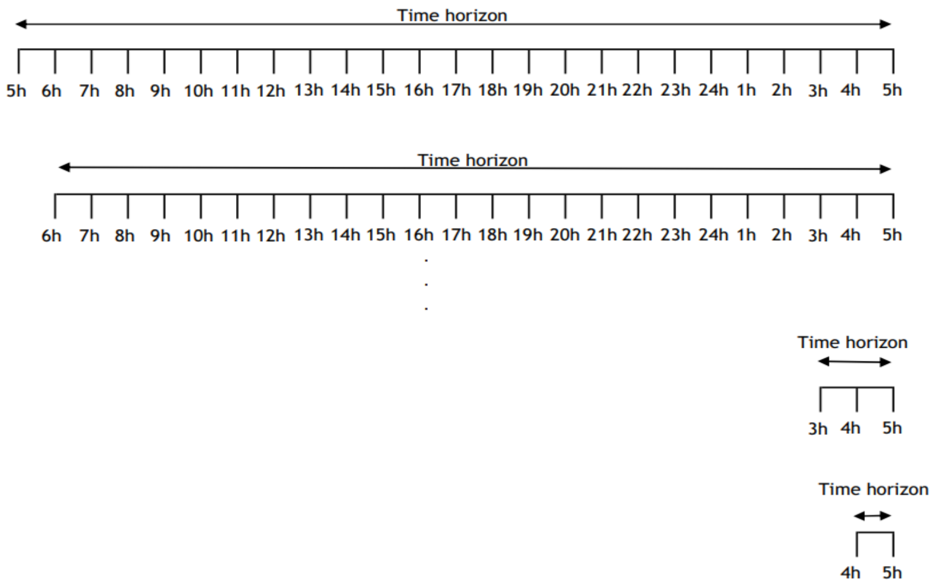

Figure 4.7 - Intra-Day Dispatch Horizon along the day.

For simulation purposes, as the time horizon is shortened, the σ in the EWMA function increases so that the errors in the forecasts are smaller when it is closer to the end of the day than at the beginning of the day. This assumes that new forecasts are available closer to the time of delivery and, as a consequence, present small forecasting errors.

4.2.6. Step (19) – Technical-Economic Analysis

The technical-economic analysis is carried out using the KPIs identified in Chapter 3 and this analysis is performed using the results obtained with and without BESS, namely comparing the off-grid system performance in the two distinct scenarios. The Operational KPIs are included in the technical analysis and their results are evaluated during the methodology. It is through these KPIs that the technical improvements are evaluated, such as the RES share in the off-grid system (e.g. KPI RCA) and the optimisation of the thermal units operating point (e.g. KPI ECR and ACR). This technical evaluation also allows the evaluation of the state of health of the battery storage system (e.g. KPI SoH). Some of the KPIs have been monetized so that their impact is analysed in a more straightforward way, and economic conclusions can be derived (e.g. KPI ECR and KPI CB). Due to the time interval considered in the methodology, i.e. one-hour time-step, and the lack of consideration of maintenance actions or failures of the generation sources, it is not possible to analyze the KPI MA.

After the aggregation of the data obtained through the methodology for the calculation of the Planning KPIs, the economic viability of the project is verified. Due to the monetization of some Operational KPIs and the technical impact that the improvement of the Operational KPIs infer in the off-grid system, the improvement of the technical performance is reflected in a positive impact on the economic viability of the system. In the analysis of the investment made for the integration of battery storage, it is interesting for the investor to know in how much time this investment is paid (i.e. KPI PT) and its value at the end of the project (i.e. KPI NPV). In order to understand the benefits that the integration of the energy storage system has in the system, the use of the KPIs LC makes it possible to assess the economic viability of the system. The KPIs used for the economic analysis of the system, Planning KPIs, can be used not only for the economic analysis of the integration of a storage system into the off-grid system but, moreover, can also be used for the economic analysis of any investment in the off-grid system, e.g. investments in renewable generation.

4.2.7. Step (19) – Sensitivity Analysis

The sensitivity analysis is performed in Step (19) of the DIOPHOS methodology and, using the optimal schedules and dispatches, analyses the sensitivity of each KPI to the variation of the most relevant technical and economic parameters. The analysis is performed for each of the parameters considered individually. This analysis is also divided into three groups: variation of inputs, stages analysis and variation of requirements.

In the variation of inputs, it is analysed the variation of the investment cost, the change in the technology, the change in the size of the storage system and the variation in the installed RES capacity.

The investment cost has an impact on planning KPIs but also on operational KPIs. The lower the investment cost, the greater the number of cycles performed as the cost of each cycle is consequentially lower. On the other hand, from a sufficiently large value, the BESS only provides primary reserve.

The change in the technology is directly linked to the degradation performance of the system. The evaluation among the various technologies is conducted through the LBOS and with the NPV. Due to the time interval considered to be one hour, the dynamic characteristics of each technology are not assessed.

Changing the size, i.e. power and energy capacity, of the battery has a direct impact on the operation of the BESS. The larger its sizing, the greater the capacity to provide reserve and/or store excess renewable energy and, thus, to reduce the operating time of the thermal units and increase the share of RES in the off-grid system. It also has an impact on the Planning KPIs because the larger the size, the higher the investment cost and, therefore, this increase can make the storage system unfeasible economically.

The amount of RES in the system has an impact on the operation of the storage system and on the economic indexes of the off-grid system. It is obvious that the greater the production of renewable energy the better, i.e. fewer CO_2 emissions and lower operational costs, but this is only true if the system has the capacity and flexibility to integrate such production. For this reason, this characteristic is related with the size of the BESS and the technical limits of the thermal units.

In the analysis of the two steps of the methodology, the results obtained between day-ahead planning and intra-day dispatch are compared. In this analysis, one of the factors that most influences the differences between the two methods is the magnitude of the forecast errors in day-ahead planning of operation. The magnitude of the error in the forecasts has influence on the analysis of the daily performance but, in the long term, these differences may not be significant.

If during the day there are reductions in the production of renewable energy or an increase in consumption in relation to forecasts, it may be necessary to connect more thermal units. Otherwise, if the consumption is lower and there is more renewable energy than expected, the schedule is changed, and thermal units may be shutdown.

The elimination of Steps (9) and (10), which correspond to constraints that regarding the operation economic benefits and BESS's capital cost, has a global impact on the system. At the operation level, more equivalent cycles are performed, equivalent cycles that may not bring economic benefits taking into account the degradation of the system. When more equivalent cycles are performed, the cells degrade more quickly, the lifetime decreases, and the BESS can become economically unfeasible.

4.3. Final Remarks

In this chapter is developed the DIOPHOS, Day-ahead and Intra-day Operational Planning for Hybrid Off-grid Systems, multi-stage methodology. The methodology needs inputs, such as RES and Demand forecasts, BESS and thermal units characteristics and Pre-analysis, performs a multi-stage operational algorithm and the outputs are the BESS and thermal units dispatch, RES curtailment and the Operational and Planning KPIs.

The DIOPHOS methodology aims to higher integration shares of RES, optimisation of the thermal unit's operating point, reducing the operating time of thermal units and improving reliability rates.

The multi-stage methodology consists in two optimisations framed in different time horizons in relation to real-time operation. These optimisations are influenced by the result of each Operational KPI and, if some Operational KPI is rejected, the methodology adapts his behaviour. The assessment performed by the Operational KPIs ensure that the investment executed in the BESS has a NPV at least equal to zero when the BESS reaches the EoL. The two optimisations are necessary due to the uncertainty in the RES and Demand forecasts.

Chapter 5

Case Study on the integration of BESS in a Hybrid Off-grid system

Following the presentation of the multi-stage methodology in Chapter 4, Chapter 5 arises with the purpose of validating the proposed methodology for the integration of BESSs in hybrid off-grid power systems.

The methodology is assessed and validated on a case study of an island electric grid with RES, considering a planning horizon of 10 years, with the objective of minimizing operational costs. The study is performed in the perspective of the islanded system operator, i.e., considering the typically vertically integrated structure of these systems. The assessment of the case study enables the quantification of the potential technical and economic impacts of the BESS during the planning horizon. The case study is described in detail in Section 5.1.

5.1. Presentation of the Case Study

System Operators work to ensure the reliability of electrical systems, as well as minimize the impact of its activity on the environment, in an environmentally sustainable policy logic. This is achieved namely by improving the energy efficiency of its systems and maximizing the use of renewable energy sources for the generation of electricity, which allows both the reduction of energy dependence on fossil fuels and the reduction of the costs associated with the electricity system.

The generating system of the island under study can be synthesized as in Figure 5.1.

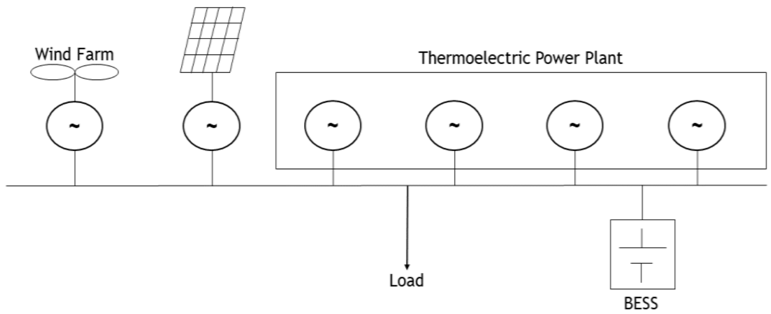

Figure 5.1 – Overview of the generating system.

5.1.1. Thermal Power Plant

The thermal power plant is composed by 4 active generators with a total capacity of 16 MW, all having their neutral point grounded. Table 5.1 presents the main characteristics of the installed generators.

Table 5.1 -Thermoelectric Power Plant – characteristics.

Characteristics of the Thermoelectric Power Plant	
Motor type	Internal Combustion
Number	4
Fuel type	Diesel
Rated power (kW)	4 000
Power factor (cosφ)	0,8
Minimum power (kW)	800
Nominal voltage (V)	6 600
Frequency (Hz)	50
Minimum Operating Time (h)	2
Diesel Cost (€/kg)	0,86

The fuel specific consumption and the power output cost for each thermal unit is given in Figure 5.2.

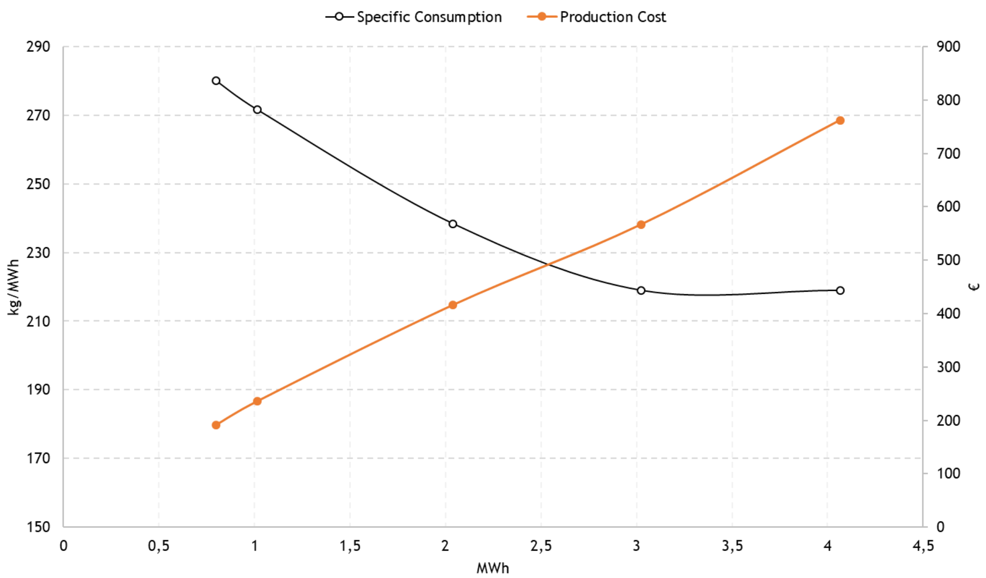

Figure 5.2 – Fuel Specific Consumption (kg/MWh) and Power Output Cost (€).

Through the analysis of the Figure 5.2, thermal units have a higher consumption per MWh of diesel when they are operating at a low operating point. The optimal value is when it is producing at about 3 MW.

Due to the need to linearize the cost function, the function was linearized in 3 equal segments, each having different slopes. The middle segment is the one with the best performance because it is the one with the lowest slope.

According to [111], typically thermal units emit around 2,7kg of CO_2 per liter of diesel consumed. In the European Emissions Allowances market for CO_2 allowances trading, the cost is 26,81[1] €/tonCO_2.

5.1.2. Renewable Energy Sources

The isolated system currently has around 3,1 MW of installed power in RES, divided into a 2 MWp photovoltaic farm (peak MW) (i.e. 1 MW + 1 MW), and a wind farm with three turbines (i.e. 2x225 kW + 1x 660 kW=1,1 MW).

Due to low demand values and the N-1 safety criteria, renewable production may have to be limited so that the power of thermal units does not fall below 1 600 kW (i.e. 2x800 kW), which corresponds to the minimum technical limit of such generating units.

5.1.3. Battery Energy Storage System

The energy storage system is connected to the same voltage level as the thermal power plant. The BESS main goals are the provision of spinning reserve, the optimisation of the thermal units operating point and the adequate integration of RES. The BESS characteristics are presented in the Table 5.2.

Table 5.2 – Characteristics of the BESS considered in the case study

BESS Characteristics	
Technology	Li-ion
Charge (kW)	4 000
Discharge (kW)	4 000
Storage capacity (kWh)	4 000
Useful SoC	80%
Discharge efficiency	95%
Charge efficiency	96%
Investment cost (€/kWh)	400
Maintenance costs (% of CAPEX/year)	2%

The EoL of the battery system is considered to be reached when their storage capacity is equal to 80% of their initial capacity. In the economic assessment of the BESS, the financial indices of the real discount rate and the inflation rate are assumed to be 8% and 2% [113], respectively, and the investment project is considered to 10 years. The degradation curve is as shown in Figure 4.3 of Chapter 4.

[1] Market Value at 10 May 2019 [112].

5.1.4. Time-series

The consumption data under study consists of a time-series of electric demand for one year. In this year the total energy consumption is 32,3 GWh, the peak power is 7,7 MW, the minimum power is 1,9 MW and has an average load of 3,7 MW. The typical time-series for the three seasons of the year are thus obtained in relation to energy consumption. Due to the methodology taking into account the distinction between seasons for energy demand, the typical series for the three seasons of the year are obtained. The three seasons are Low Season, Medium Season and High Season, and the time-series have the following duration: one quarter of the year, one half of the year and one quarter of the year, respectively. Due to the very seasonal behaviour of electric demand in the islanded system, the High season has almost twice the total demand than the Low season.

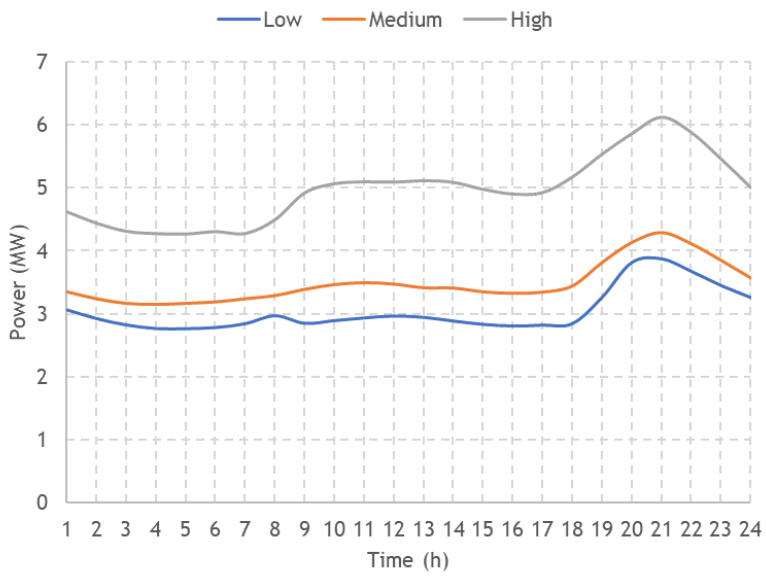

Figure 5.3 – Typical time-series for the demand for each season.

Following the same seasons obtained for demand, it is also necessary to define the typical time series for renewables, thus obtaining the Figure 5.4 for PV generation and Figure 5.5 for wind generation.

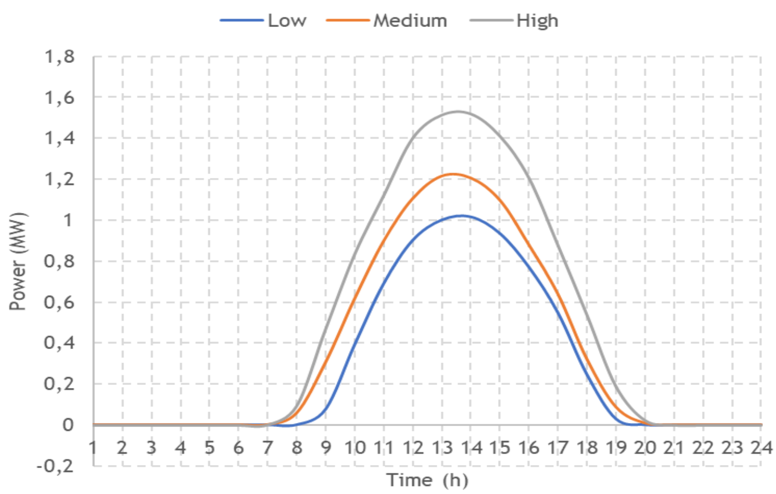

Figure 5.4 – Typical time-series for the PV production for each season.

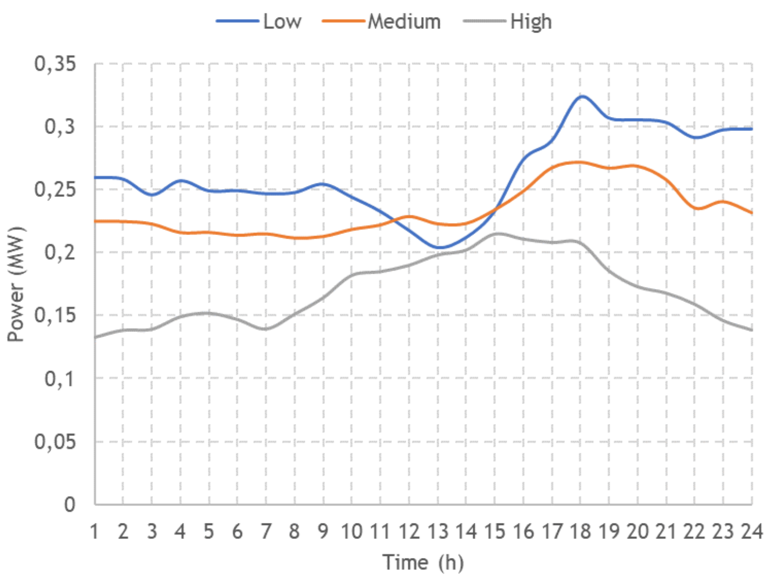

Figure 5.5 – Typical time-series for the Wind production for each season.

Because Low Season (categorized in terms of electric consumption) is in the early months of the year and High Season is in the summer months, PV production is lower in Low Season and higher in High Season. In what concerns wind production, the behaviour is the opposite of PV production i.e. is higher in Low and Medium Seasons and lower in High Season.

5.1.5. Simulation of the off-grid operation

The implementation of the developed methodology in this case study requires the analysis of a 10-year planning period of the off-grid system where the operational stage of the integration problem is modelled consisting of a multi-stage operational approach. It is assumed that no new investments are made in production capacity and the consumption remains stable during these 10 years.

For the different stages of the methodology, the error of the consumption forecast and the RES production forecast is different and decreases linearly up to the moment of actual power delivery. Currently, the forecast of consumption has a smaller error than the forecast of the RES production. In order to simulate the error in the forecasts, the exponential weighted moving average described in Section 4.2.2.6 is implemented. Therefore, the error, RMSE accounted annually, decreases linearly from 10% in the day-ahead planning to 2% in the last hour of the intra-day dispatch for the consumption forecast and from 15% in the day-ahead planning to 3% in the last hour of the intra-day dispatch for the RES production forecast.

5.2. The Day-ahead optimisation performance

The first stage of the methodology is the realization of the day-ahead planning of operation for the off-grid system. In order to carry out the technical-economic assessment of the off-grid system, the performance of the off-grid system is compared with and without the BESS.

5.2.1. Pre-analysis

Before starting the methodology, it is necessary to pre-analyze the system through the typical series of each season. The purpose of the pre-analysis is to define parameters that aim to improve the performance of the system.

The first parameter to set is the time of day in which the day-ahead planning of operation starts. A study is then conducted to find the time when the highest average cost reduction is achieved. Then, there is no restriction that defines which should be the load state at the end of the day. The results for the 3 seasons are presented in Table 5.3.

Table 5.3 – Results of the pre-analysis to the best hour to start the day.

Maximum Average Cost Reduction			
	Low Season	**Medium Season**	**High Season**
ACR (€/h)	65,90	55,38	12,00
Starting Hour (h)	6	1	8

Considering the obtained results, the planning of operation for the next day starts at 18h for Low Season, 13h for Medium Season and 20h for High Season. Although these are not the optimal results, they are sustained by the typical time-series of each Season. At Low Season and High Season, the best results are obtained for the early morning because that's when the need to charge the battery begins due to the higher RES production, namely wind production. Therefore, with the planning of operation starting at that time, the battery is at the lowest possible state of charge which provides the most storage capacity range.

The next parameters to be defined are the maximum equivalent cycles per day and the average cost reduction required.

Figure 4.3 shows that, with discharges at 1C, the 80% health status is reached with 3 000 cycles. Therefore, in order for the storage system to reach 80% by the end of 10 years, the system is limited to perform 300 cycles per year.

With the investment of the energy storage system to be paid in 7 years with an interest rate of 7%, the payment per year is 296 885€. Therefore, in order to reach the net present value of 0€, the system must have economic benefits of 214 853€ in the first year (and in the following years equal but considering the economic indices considered above).

The cost per cycle is 716,18€ and, on average, the system is limited to perform approximately 0,82 cycles per day (i.e. the equivalent to 3,1 MWh of energy throughput). Then, applying the methodology in Figure 4.5, the results are presented in Table 5.4.

Table 5.4 – Results of the pre-analysis to ensure the BESS lifetime and BESS NPV.

Maximum Equivalent Cycles per Day and Average Cost Reduction required			
	Low Season	**Medium Season**	**High Season**
CB (€)	65,90	55,38	12,00
ECD	1,14	1,00	0,15
Cycles per season	103,80	182,78	13,41
ACR^{req} (€/h)	33,95	29,89	4,38

5.2.2. Off-grid system operation without BESS

To verify the behaviour of the system in a situation where there is an excess of RES production, it is selected a Low Season day in which there is a large curtailment of renewable energy. The day-ahead planning of operation obtained is represented in Figure 5.6.

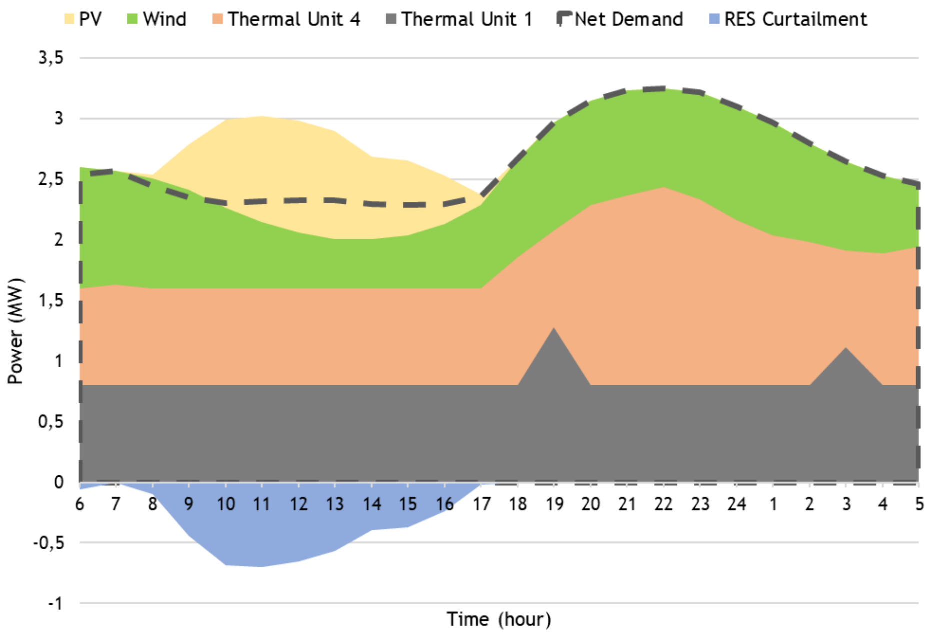

Figure 5.6 – Day-ahead planning of the generating system without BESS for a day at Low Season.

Through da Figure 5.6, it is observed that it is a day with a reduced consumption, of about 63,4 MWh, but with high production through renewable energies, of about 23,1 MWh, which represents 36,4% of the total consumption. The wind production is high during the whole day and the PV production is also high during the hours of greater solar radiation. With this type of scenario, the generators are working at the minimum technical limit for a significant portion of the day (i.e. 73% of time). This type of operation is not recommended due to the high losses at this point of operation that cause faster ageing.

On this day it is necessary to curtail 4,3 MWh of renewable energy. In this exercise, no distinction is made in which of the renewable plants the curtailment is performed but, in the islands, the first to be cut would be the newest plants due to the higher controllability and lower investment.

In this case, which is representative of the typical behaviour, due to the linearization of the cost function, only one thermal unit follows the load. When this thermal unit reaches the limit of the segment with the highest performance, the load following starts to be performed by another thermal unit.

In order to compare a low consumption scenario with a high consumption scenario, the Figure 5.7 is obtained.

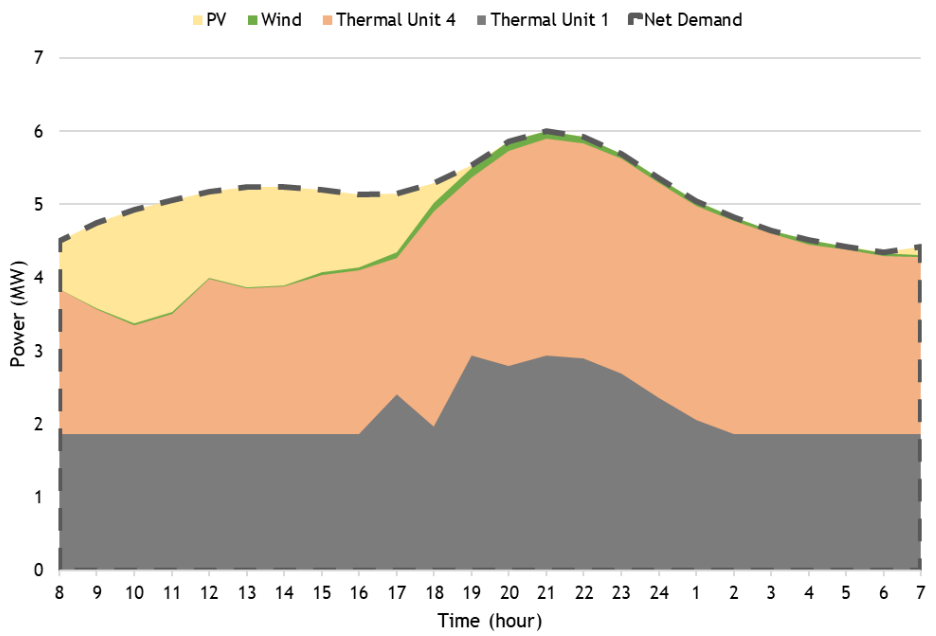

Figure 5.7 - Day-ahead planning of operation of the generating system without BESS for a day at High Season.

Figure 5.7 corresponds to a day in High Season. The energy consumption is almost double that obtained in Figure 5.6, of about 122,2 MWh. Unlike the scenario in Figure 5.6, this day has a very low Wind production but high PV production. In spite of the high component of PV, the system manages to integrate the renewable energy due to the high demand.

Although the consumption is high, the two thermal units can provide enough reserve for the system because they have very large maximum production limits, i.e. 4 MW each generator, in comparison to the consumption.

5.2.3. Off-grid system operation with BESS

For the day with the largest renewable curtailment without BESS, the Figure 5.8 is presented. With the BESS integrated in the system, there is no renewable curtailment because the BESS performs the RES energy time-shift and, with only one thermal unit connected, the thermoelectric power plant presents the lowest minimum production limits. Thus, through the BESS, some of this energy is stored and discharged during the periods in which consumption is higher and the remaining renewable energy is integrated directly into the system because only a thermal unit is on.

The reason for having only one thermal unit connected is because the BESS performs reserve and guarantees the N-1 safety criteria. With only one thermal unit on, the off-grid system becomes more flexible and its point of operation is at a higher point, which is more advantageous for its management and efficiency.

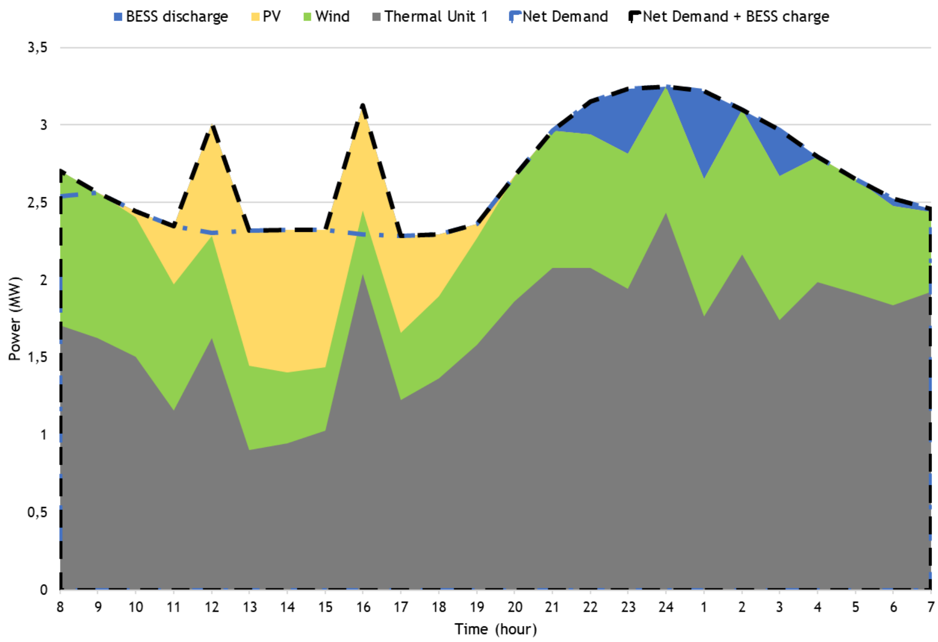

Figure 5.8 - Day-ahead planning of the generating system with BESS for a day at Low Season.

The charging and discharging profile and the evolution of the BESS' state of charge during the day are shown in Figure 5.9.

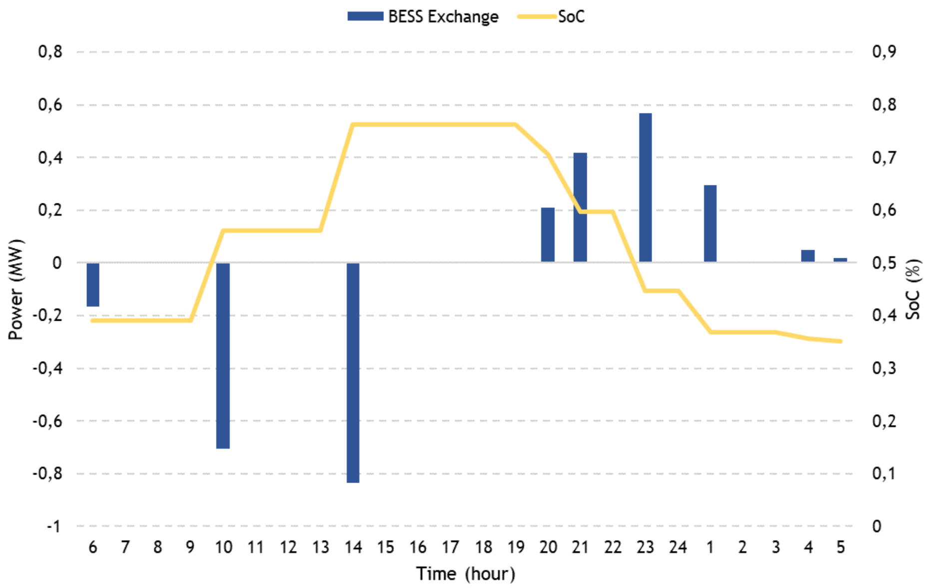

Figure 5.9 – Scheduling of the BESS operation and the SoC evolution.

In Figure 5.9 it is observed that the BESS begins and ends with the minimum allowed SoC, i.e. battery limits plus required reserve. The reason for the BESS to end the planning of operation horizon with the minimum SoC is due to the optimisation having its time horizon of one day. In order to support the need of the pre-analysis, if the system had as beginning of the day hour 1, the system would not discharge in the hours 1, 4 and 5 because it would not have enough energy capacity to execute those required discharges.

For the day with high consumption, the result of the planning is equal to the one obtained without BESS, presented in Figure 5.7. Although the BESS provides backup, the system still needs one more thermal unit because of the high consumption. So, on this day the BESS does not provide any economic benefits.

The equivalent cycles performed by the BESS and the state of health evolution of the BESS are presented in Figure 5.10.

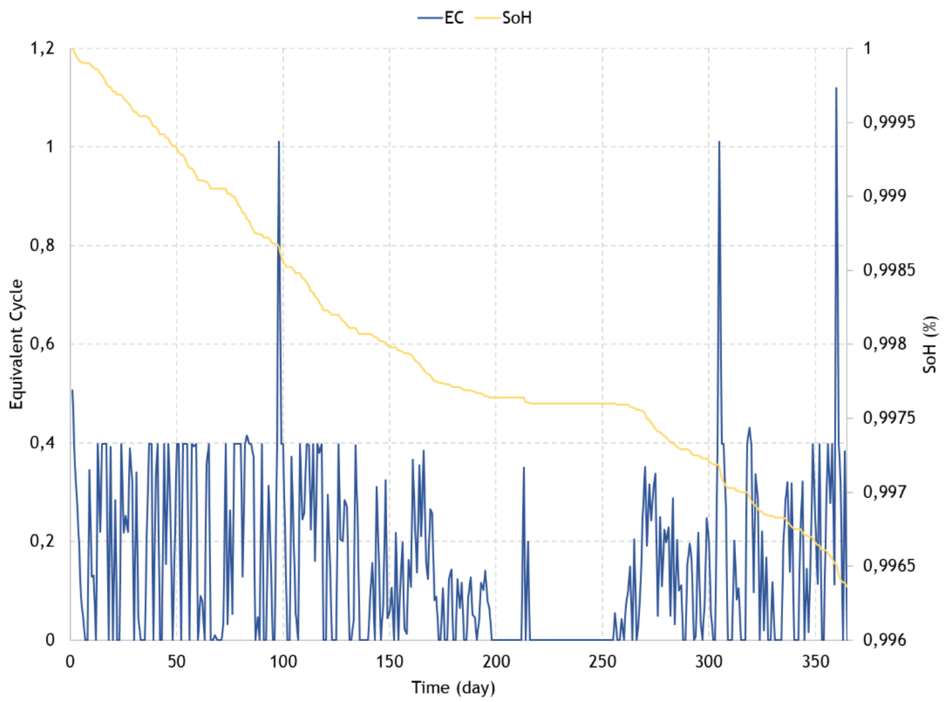

Figure 5.10 – The equivalent cycles performed by the BESS and the SoH evolution.

By the analysis of Figure 5.10, it is realized that during the High Season (day 171 to day 265), the system performs few or no equivalent cycles per day. Due to the fact that the consumption is much higher than the production of renewable energy during this season and because the thermal units are in high operating points, the time-shift of renewable energy by the BESS is not cost effective. Thus, the vast majority of equivalent cycles are performed in the remaining seasons of the year because the potential to obtain economic benefits is higher.

As a consequence of the described behaviour, the SoH of the BESS decreases almost linearly during Low Season and Medium Season and stabilizes during High Season.

The evolution of the BESS degradation can have errors in comparison with the real value because in the modelling the unavailability of the generating sources is not considered, therefore, the cycles made during the provision of the spinning reserve are not considered. Also, neither the degradation by calendar nor the impact of the temperature of the battery cells is modelled.

In order to check the distribution of equivalent cycles by ranges, it is presented the Figure 5.11.

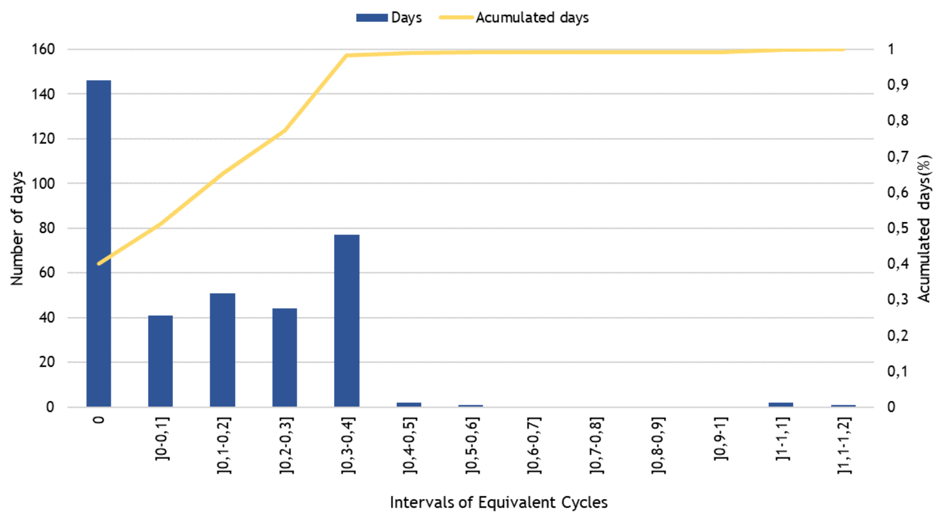

Figure 5.11 – Histogram of the number and equivalent cycles performed by the BESS.

From the histogram it is verified that during 146 days the storage system does not inject energy into the grid, which corresponds to 40% of the year. From the analysis of Figure 5.10, it is concluded that most of these days are in High Season.

Only in 6 days of the year, the equivalent cycles performed were greater than 0,4 equivalent cycles. Thus, the final result of the optimisation is rarely close to the frontier of the maximum equivalent cycles per day. This is due to the low installed capacity of RES and also to the fact that the energy storage system has a high energy capacity.

When the system discharges, most of the equivalent cycles are in the range]0,3;0,4].

5.2.4. BESS impact

The impact of the BESS on the off-grid system through the KPIS RCA and ECR throughout the year is shown in the following figures.

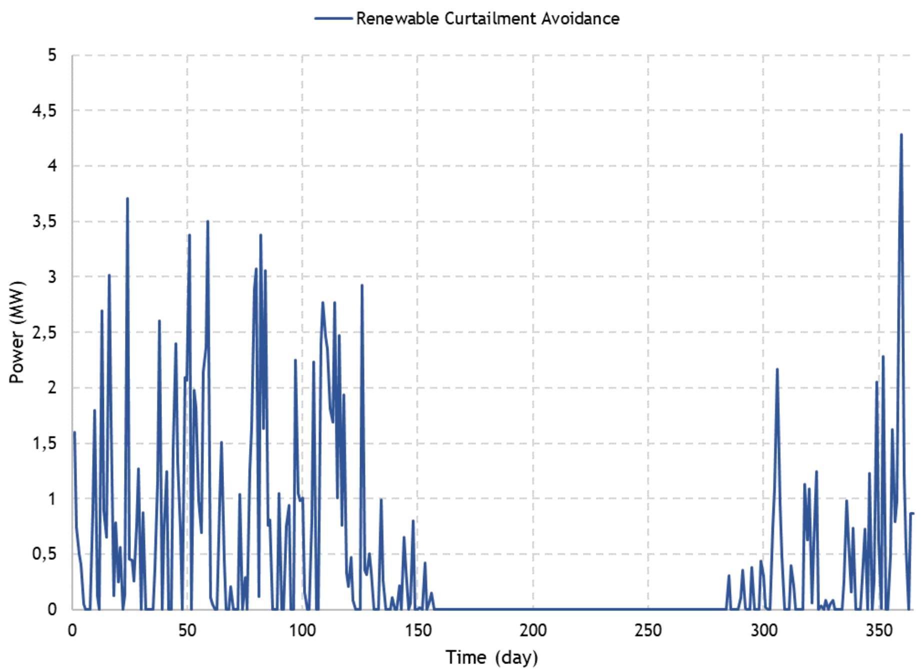

Figure 5.12 – Renewable Curtailment Avoidance by the off-grid system with BESS.

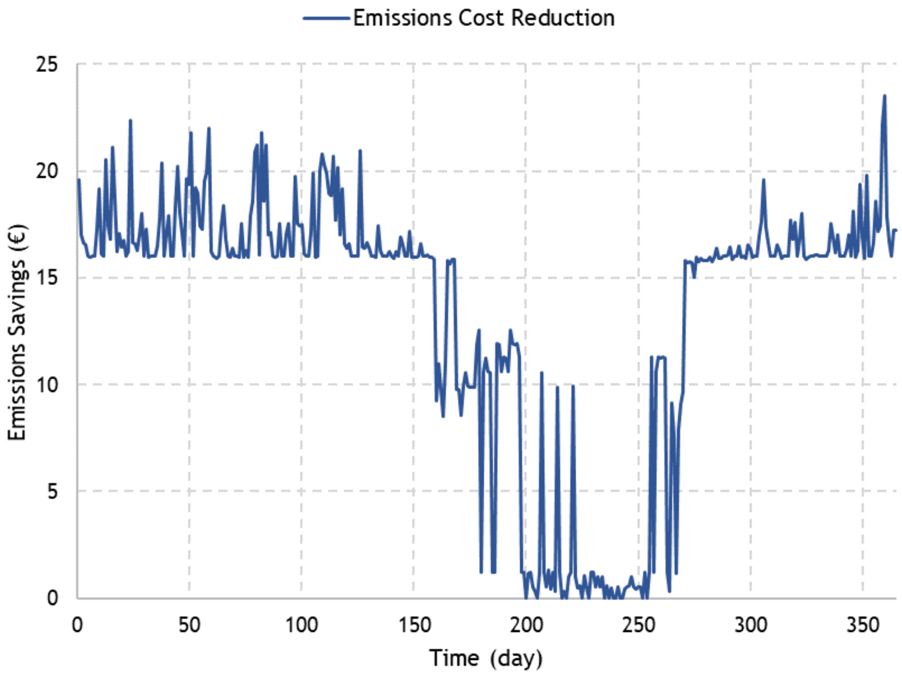

Figure 5.13 – Emissions Cost Reduction by the off-grid system with BESS.

The trends between Figure 5.12 and Figure 5.13 are identical. In High Season, there are no major improvements in these KPIs, but in the others, the integration of the BESS provides evident improvements i.e. avoiding renewable curtailment and, thus, CO2 emissions.

During Low Season and Medium Season, the off-grid system saves at least 16€ per day in relation to the costs associated with emissions. The main reason is the operation without an additional thermal unit. During High Season there are certain periods of the day when it is possible to remove a thermal unit from service and this improves the KPI ECR.

The KPIs RCA and ECR are related to each other in Low Season and Medium Season because the behaviour of the two KPIs is the same. Since the ECR has a typical value for these seasons (i.e. 16€/day), the improvement of this KPI is main achieved through RES curtailment avoidance.

Table 5.5 provides a comparison of the performance of the off-grid system with and without BESS.

Table 5.5 – Comparison of the RES and thermal units operation in 2 different scenarios.

	Without BESS	With BESS
Potential RES production (MWh/year)	5 001	5 001
RES production (MWh/year)	4 839	5 001
Curtailed RES (MWh/year)	162	0
RES curtail reduction (MWh/year)	-	162
Thermal Units operating hours (hours/year)	17 520	10 643
Thermal Unit average operating point (%)	38,43	62,90
Operation Expenditure (€/year)	5 449 000	5 121 300
Operation Expenditure reduction (€/year)	-	327 700

The data analysis shows that the off-grid system with the BESS integrates all the energy from renewable sources and this represents an improvement of 162 MWh/year over the system without the BESS.

In Table 5.5, the off-grid system sees a reduction of about 40% in the operating time of the thermal units with the BESS. This is because the off-grid system only requires one thermal unit in the majority of the time and this also has a positive impact on the operating point of the thermal units. With the increase in the operating point of the thermal units, the off-grid system went from an average specific diesel consumption of 253 kg/MWh to 227 kg/MWh.

With these system improvements, the off-grid system with BESS reduces its OPEX by 6%.

After having an overview of the problem, a more objective analysis of the system is now carried out taking into account the KPIs identified in Chapter 3.

Table 5.6 – Operational KPIs for the day-ahead optimisation.

Operational KPIs	
RCA ($MWh_{stored}/MWh_{excess}$)	1
ACR (€/hour)	37,4
ECR (€/day)	13,4
CB (€/day)	1 143,4
SoH (%)	96,2

The KPI RCA has the maximum possible value because all of the renewable energy excess in the off-grid system is stored, which means that there is no loss of clean renewable energy. This is mainly a consequence of the fact that the BESS increases the flexibility of the off-grid system and because the BESS always has available capacity to store the excess.

Even if a few equivalent cycles are carried out per year, around 18% of the limit of the equivalent cycles per year, these cycles are very profitable economically, which makes KPI CB a positive value. Another positive aspect has to do with the fact that the system can have economic benefits without degrading itself through the supply of primary reserve.

One of the requirements of the BESS investment is to have SoH higher than 80% at the end of the project. This requirement is largely overcome due to the low installed power in RES and because most of the benefits associated with this case study are related to primary reserve supply.

Table 5.7 – Planning KPIs for the day-ahead optimisation.

Planning KPIs	
LCOE (€/kWh)	0,169
LCOS (€/kWh)	0,988
LBOS (€/kWh)	1,21
NPV (€)	371 587
PT	8 year

The LCOE of the off-grid system without BESS is 0,172 €/kWh. Table 5.7 shows that a lower LCOE value is obtained with the integration of BESS. The improvement of this KPI may represent a reduction in the cost to be paid by end consumers.

The effective economic benefit of the BESS is the difference between the LBOS and the LCOS. The difference is 0,222€ for each kWh injected into the grid by the BESS. This is represented by the positive value of the NPV and a PT lower than the time of the investment project.

5.3. The Multi-stage optimisation performance

The technical and economic assessment of the BESS integration in the off-grid results from the performance of the overall off-grid system. In this section a study is conducted on the performance of the system with and without BESS, the impact of the intra-day and the impact of the BESS.

5.3.1. Multi-stage operation without BESS

Figure 5.14 shows the same day shown in section 5.2.2 so that comparisons can be made between the two operation modes.

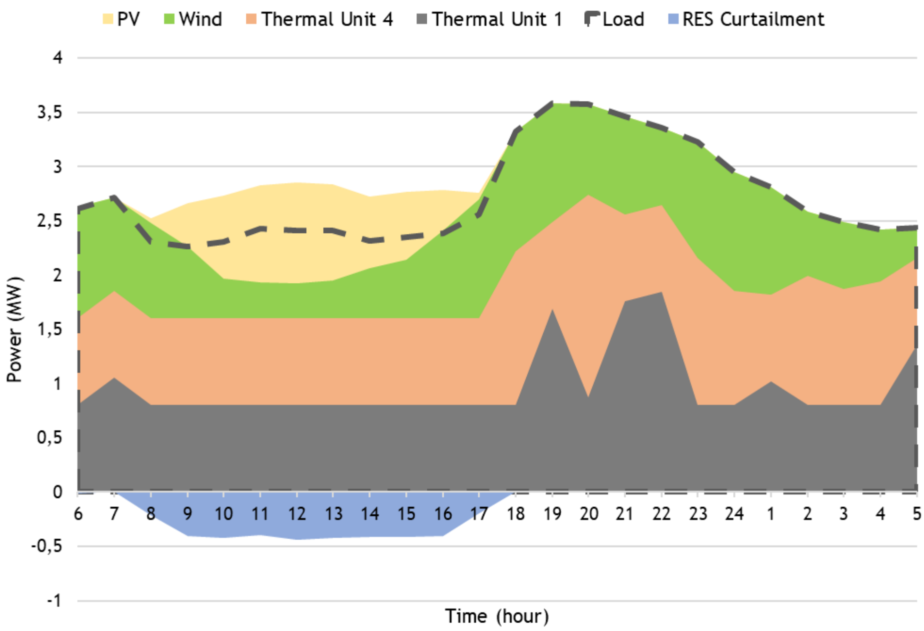

Figure 5.14 – Multi-stage operation of the generating system without BESS for a day at Low Season.

On this day, the production of wind and PV is high for the existing low consumption. That said, the integration of this high amount of RES is constrained by the technical limits of thermal units. With the N-1 criteria, the system must necessarily work with two connected thermal units. During off-peak hours (8h to 17h) the thermal units are forced to operate at their lowest point of operation and cause an increase in fuel consumption per unit of energy.

During the peak hours (18h to 23h) the system works without the PV production and can integrate all the wind production. Thus, for a large part of the time, the system cannot integrate more renewable energy, which makes it not interesting from an economic point of view to invest in more RES capacity.

Compared to the day-ahead planning of operation optimisation, the forecasts had predictions that consumption would be higher but that there would also be more renewable production. Thus, the renewable energy curtailment is lower than in day-ahead planning of operation.

As in section 5.2.2, the operating strategy of the system for the day with the highest consumption of the year is presented in Figure 5.15. Because it is the High Season, the system has little wind energy but a lot of PV production. Contrary to what happens at Low Season, there is no RES curtailment and the two thermal units have flexibility in their operation because they are not close to the minimum technical limits.

Contrary to what happens in the result presented for Low Season, the forecast for the next day has an error of 1 MW at the peak of the day in electricity consumption.

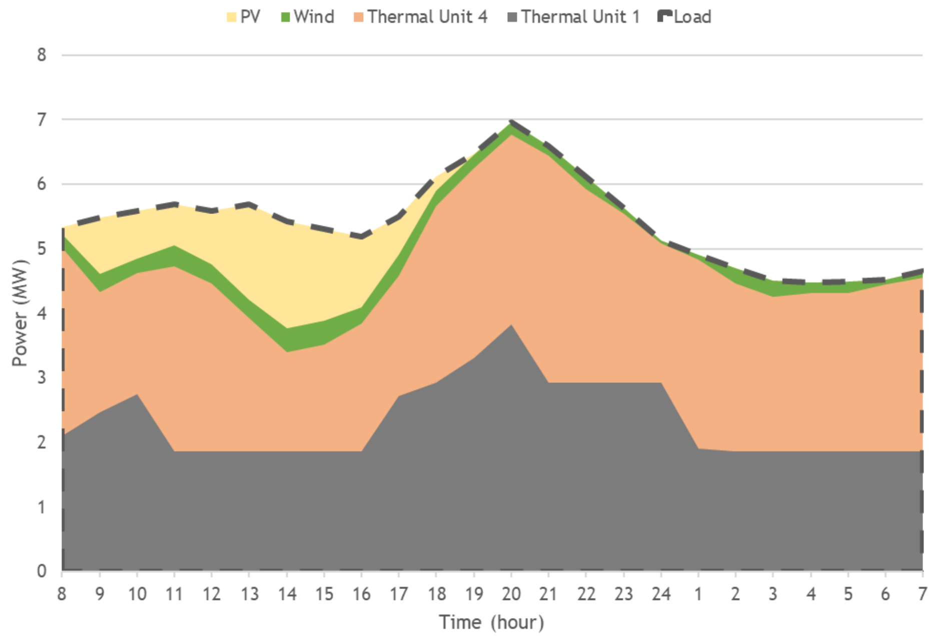

Figure 5.15 - Multi-stage operation of the generating system without BESS for a day at High Season.

5.3.2. Multi-stage operation with BESS

Figure 5.16 presents the operation of the generating system for the day with greater renewable curtailment in the operation without BESS and Figure 5.17 presents the charge and discharge periods of the BESS and evolution throughout the day of SoC.

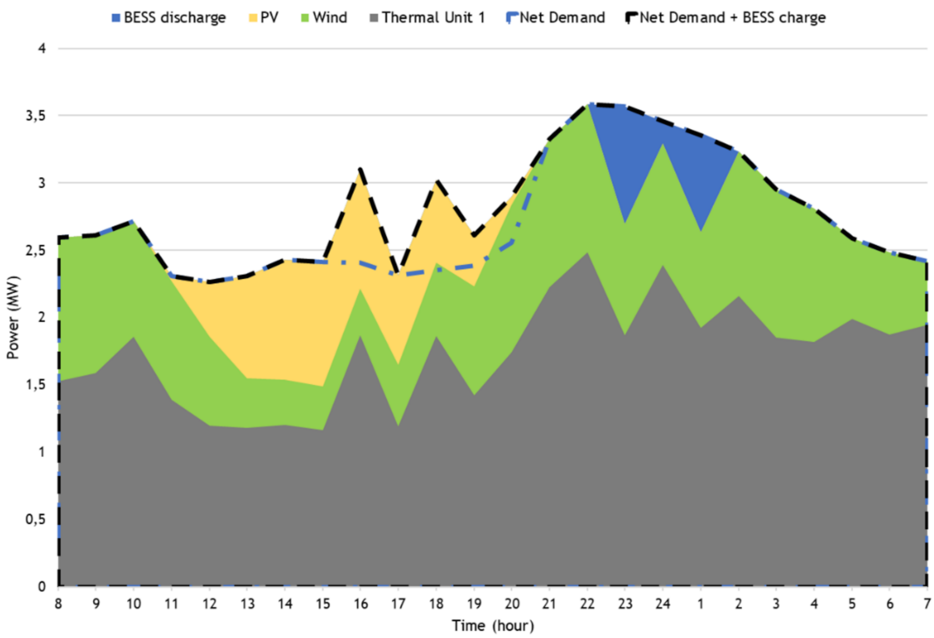

Figure 5.16 - Multi-stage operation of the generating system with BESS for a day at Low Season.

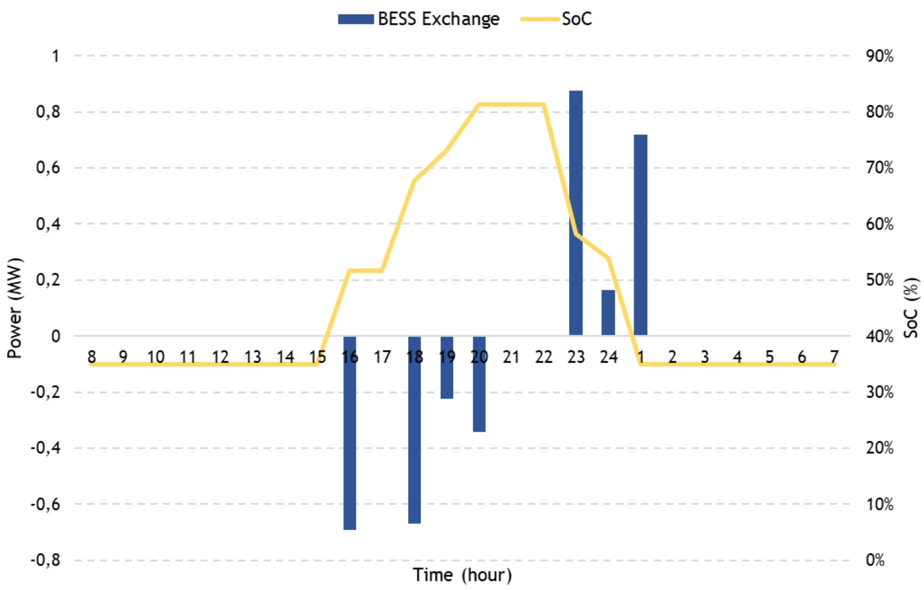

Figure 5.17 - BESS operation and the SoC evolution.

As in the day-ahead planning, the off-grid system with BESS only needed to have one thermal unit running despite the forecast errors. Although it is a day of low demand and high RES production, only for three hours the thermal unit operates close to the minimum production limit.

Although this is a critical day for the system when there is no BESS, there is no loss of RES energy. Therefore, with the consideration of forecasting errors, the system is able to integrate all energy from renewable sources.

Compared to the day-ahead, the charging and discharging of the BESS periods have changed. With this dynamic dispatch, the result of the system's operation is more optimised, managing to mitigate the forecast errors.

The battery operation is carried out in the most critical periods, valley hours (close to the minimum limits of thermal units) and peak hours (higher fuel consumption).

Considering the same day with higher consumption, the result with multi-stage optimisation is the same as that presented in multi-stage operation without BESS and the conclusions drawn are the same as in Section 5.2.3.

During data analysis, it is detected that some generators are disconnected from service for short periods of the day, two hours to four hours, but this disconnection is not foreseen in the planning of the next day. The removal of the thermal unit is possible because the production from the PV park could be higher than forecasted. This result makes more relevant the need for an intra-day hourly dispatch of the off-grid system resources.

Also, in some days it is verified that the realization of cycles is not beneficial in the day-ahead planning but during the intra-day dispatch it is verified that, in spite of being slight, the energy storage device performs the optimisation of the thermal unit operating point.

5.3.3. Impact of the intra-day dispatch

In order to understand the impact that the intra-day dispatch has on the off-grid system and on the BESS, some graphs are presented in which the results are presented both in the methodology only with the day-ahead optimisation and those obtained with the day-ahead planning and intra-day optimisation.

The first comparisons to be made are through the number of equivalent cycles in each day and the evolution of SoH.

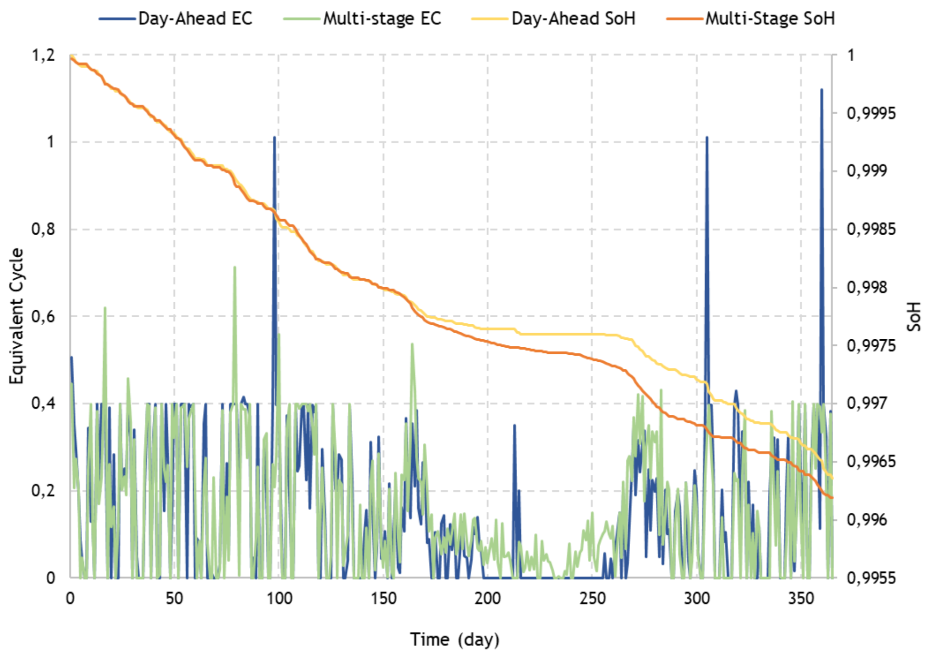

Figure 5.18 – Comparison of the equivalent cycles and SoH evolution between the two optimisations.

The realization of equivalent cycles in Low Season and Medium Season are very identical between the two dispatches, as shown with the overlap of SoH during the first two seasons of the year in Figure 5.18, which no longer happens during High Season. The reason why storage performs more equivalent cycles at High Season is because from midday the methodology recognizes benefits in performing the optimisation of the thermal units operating point. Therefore, during High Season a gap is created between day-ahead planning SoH and multi-stage SoH and this gap is maintained during the following seasons until another High Season is reached.

Another graph that compares the operation of the BESS is the Figure 5.19. From this figure it is obtained that the intra-day dispatch has more impact on the High Season due to the passage of days in which there is no cycle to the interval of]0;0,1] equivalent cycles.

Moreover, despite some differences related to forecast errors, the performance of equivalent cycles related to day-ahead optimisation and multi-stage optimisation are very similar.

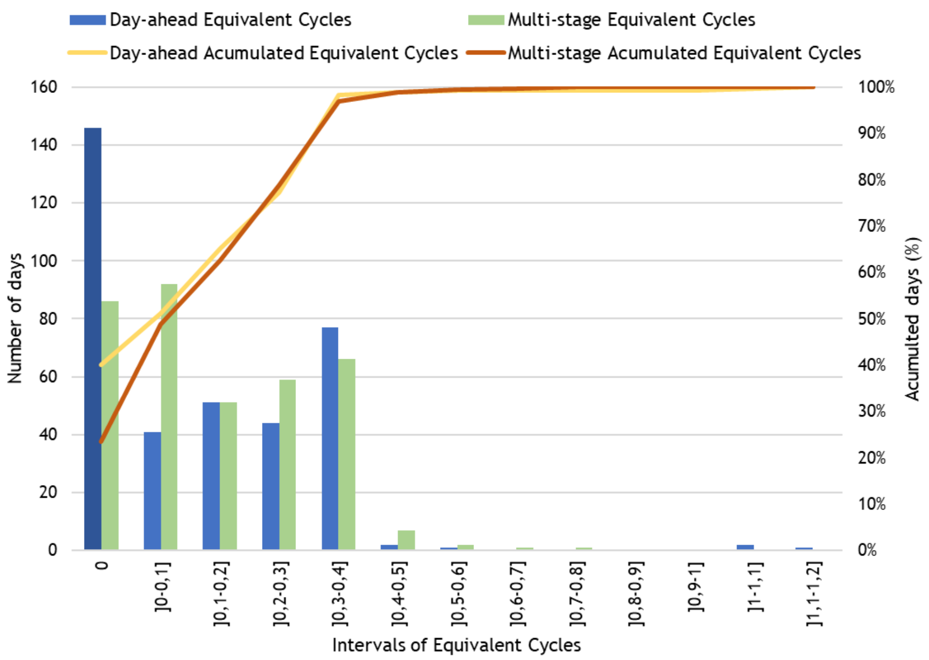

Figure 5.19 – Histogram of the number of equivalent cycles for both optimisations.

The comparison between the two dispatches relative to the renewable curtailment avoidance is presented in the Figure 5.20.

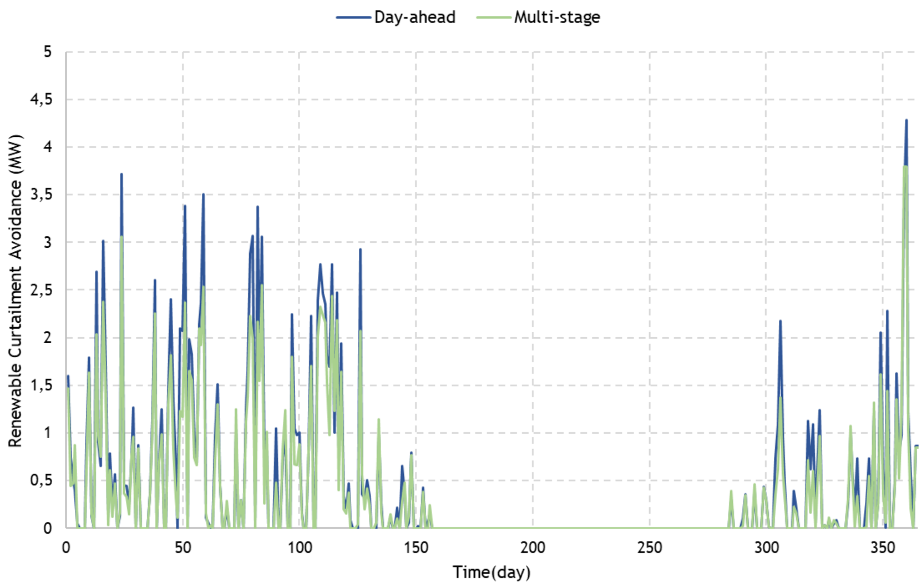

Figure 5.20 – Comparison of the Renewable Curtailment Avoidance between the two optimisations.

As all excess energy in both dispatches is integrated, the analysis of Figure 5.20 cannot be analysed as an improvement in the performance of the system using intra-day dispatch. The reason for the difference between these scenarios is related with the error of the forecasts. And, as can be seen in Figure 5.20, the method used to model the uncertainty in the forecasts has impact on the system, in the sense that it provides a pessimistic forecast for the renewable curtailment.

The comparison between the reduction in the CO_2 emissions cost is analysed in Figure 5.21.

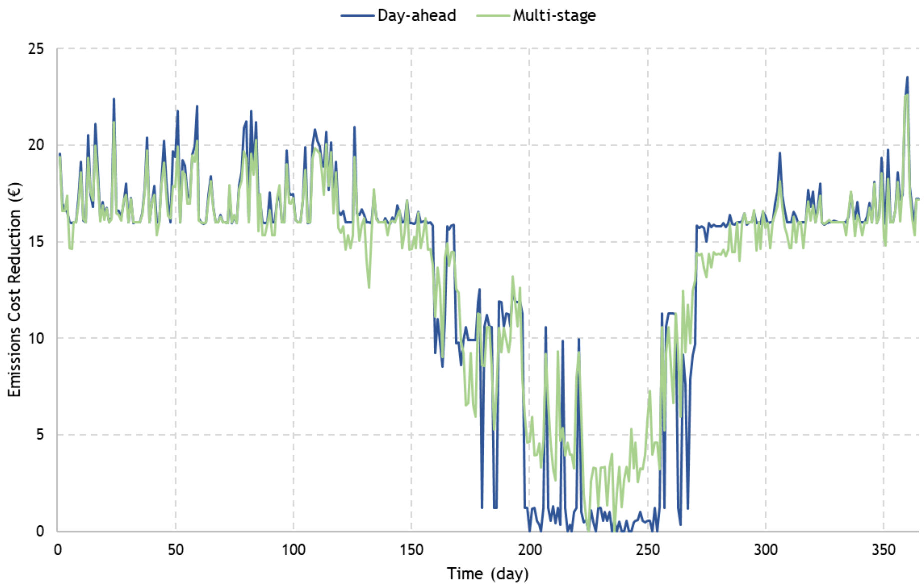

Figure 5.21 - Comparison of the Emissions Cost Reduction between the two optimisations.

For the Multi-stage operation, the analysis follows the same conclusions as for the Day-ahead operation, section 5.2.4. One of the main conclusions obtained in section 5.2.4 is the impact that the renewable curtailment avoidance has on emissions reduction. Since it is observed that in Figure 5.20 the renewable curtailment is lower at Multi-stage, during the seasons where there is renewable curtailment (Low Season and Medium Season) the reduction in emissions is slightly lower. Through the analysis of Figure 5.18 it is observed that more equivalent cycles are performed during High Season and this performance of equivalent cycles has impact on emissions cost reduction.

Due to the change in the operating mode of the system, the following table performs the comparison to assess the impact of the intra-day dispatch in the thermoelectric power plant.

Table 5.8 - Summary of the operation of the thermal units in the two optimisations stages.

	Day-ahead optimisation	**Multi-stage optimisation**
Thermal Units operating hours (hours/year)	10 643	10 370
Thermal Units average operating point (%)	62,90	66,68
Operation Expenditure (€/year)	5 121 300	5 258 154
Operation Expenditure reduction (€/year)	327 700	335 246

There are differences in the operation time of the thermal units because the actual demand RES production diagrams are different from the forecasts of these same diagrams. It is observed that there is a reduction in the operation time of the thermal units, therefore, as only in the High Season it is necessary to work with two generators, the intra-day dispatch can remove a thermal unit from service in some hours of the day.

Due to the removal of the generators from service, the average operating point increased to 66,68%, which is equivalent to a specific average consumption of 224,2 kg/MWh and a reduction of 2,85 kg/MWh.

Other aspects to be highlighted in the table are the increase in OPEX and the increase in OPEX reduction.

The presentation of the Operational KPIs for the two optimisations is made in Table 5.9.

Table 5.9 – Operational KPIs for the two optimisations.

Operational KPIs	Day-ahead optimisation	Multi-stage optimisation
RCA ($MWh_{stored}/MWh_{excess}$)	1	1
ACR (€/hour)	37,42	38,27
ECR (€/day)	13,40	13,54
CB (€/day)	1 143,43	1 076,61
SoH (%)	96,2	95,9

Due to the increased reduction of OPEX, the KPI ACR has increased. With the increase in equivalents cycles during the summer, the costs of CO_2 emissions have been reduced but the SoH is lower. In spite of having degraded more, the value is still much higher than required by the project.

The presentation of the Planning KPIs for the two optimisations is made in Table 5.10.

Table 5.10 Planning KPIs for the two optimisations.

Planning KPIs	Day-ahead optimisation	Multi-stage optimisation
LCOE (€/kWh)	0,1691	0,1689
LCOS (€/kWh)	0,988	0,918
LBOS (€/kWh)	1,21	1,152
NPV (€)	371 587	417 954
PT	8 year	8 year

With the realization of more equivalent cycles, the energy injected into the grid is higher, which causes the decrease of LCOS and LBOS but increases the difference between them, 0,233 €/kWh, which is positive for the system. Also, with the increase in the OPEX reduction, the NPV of the investment increases.

5.3.4. Impact of the BESS

Finally, in order to perform the technical-economic assessment of the BESS impact on the off-grid system through the full implementation of the DIOPHOS methodology, the summary tables of the integration of RES production and the operation of thermal units in Table 5.11, the Operational KPIs in Table 5.12 and the Planning KPIs in Table 5.13 are analysed.

Table 5.11 – Comparison of the generation system in 2 scenarios with multi-stage optimisation

	Without BESS	With BESS
Potential RES production (MWh/year)	5 112	5 112
RES production (MWh/year)	4 980	5 112
Curtailed RES (MWh/year)	132	0
RES curtail reduction (MWh/year)	-	132
Thermal Units operating hours (hours/year)	17 472	10 370
Thermal Unit average operating point (%)	39,70	66,68
Operation Expenditure (€/year)	5 593 400	5 258 154
Operation Expenditure reduction (€/year)	-	335 246

With the integration of BESS into the off-grid system, all renewable energy is integrated into the grid either by direct integration due to the increased flexibility of the system or by storing excess energy in the BESS. This observation has a direct impact on the reduction of RES curtail and, through the average operating point of the BESS scenario, a reduction of 29 594 kg of diesel consumed per year.

The increased flexibility imposed by BESS results in a reduction of 7 102 operating hours per year and a reduction in specific consumption of 27,6 kg/MWh. The main reason is that it is only necessary to have one thermal unit for much of the year, about 81% of the year.

Therefore, the improvements mentioned above are reflected in the reduction of operating costs, resulting in a 6% reduction in the OPEX of the off-grid system.

Table 5.12 – Operational KPIs for the multi-stage optimisation.

Operational KPIs	
RCA ($MWh_{stored}/MWh_{excess}$)	1
ACR (€/hour)	38,27
ECR (€/day)	13,54
CB (€/day)	1 035,25
SoH (%)	95,9

As observed in Table 5.11, the KPI RCA has a value of 1 because the off-grid system can integrate all RES production.

By fully integrating RES production and optimising the operation of the thermoelectric power plant, the KPIs ACR and ECR have a positive value. Also, the KPI ACR has the value above the required so that, at the end of the project (year 10), the investment has the NPV above 0.

As in the DIOPHOS methodology, the BESS only performs equivalent cycles if these equivalent cycles offset its degradation, the CB KPI has a positive value.

One of the project requirements is that the battery system does not reach the SoH of 80% before the end of the project. Thus, as the installed RES capacity is reduced, the realization of cycles is also reduced, and the project ends with SoH well above 80%.

Table 5.13 – Planning KPIs for the multi-stage optimisation.

Planning KPIs	
LCOE (€/kWh)	0,1689
LCOS (€/kWh)	0,918
LBOS (€/kWh)	1,152
NPV (€)	417 954
PT	8 year

The LCOE of the off-grid system without BESS has the LCOE of 0,1710 €/kWh. Therefore, the LCOE of the off-grid system with BESS is lower, but the reduction is only 1,23%. The difference may be greater because, as the investment is already payed off and the SoH is still well above the final value, the time of the investment project can be extended. Then, the cost per cycle can be reviewed in order to give more freedom to BESS and increasing the economic benefits.

As there is a reduction in LCOE, the difference between LBOS and LCOS is positive, 0,234 €/kWh. One of the parameters that most influence this analysis is the capital cost of the BESS and the result of the DIOPHOS methodology is also influenced by the variation of this parameter, so it is not possible to make a direct sensitivity analysis to evaluate the variation of this parameter but through a new simulation.

Chapter 6

Conclusions and Future Work

6.1. Conclusions

This dissertation presents a set of Key Performance Indicators to assess the integration of BESS in hybrid off-grid systems. Regarding these KPIs, the DIOPHOS (Day-ahead and Intra-day Operational Planning for Hybrid Off-grid Systems) methodology is developed and provides a tool to perform the day-ahead planning of operation and intra-day dispatches of an off-grid system with battery energy storage system, in order to maximize the technical and economic benefits of its integration.

The implementation of the proposed methodology in a case study demonstrates that BESS addresses the variability and limited predictability of RES enabling a reduction of RES curtailment that is reflected in avoided operational costs and CO_2 emissions of the off-grid system. Furthermore, assessment results reveal that, albeit the currently high investment costs of battery systems, BESS presents technical and, consequently, economic benefits that can surpass its cycle-life costs.

Moreover, the integration of BESS in the off-grid system provides technical improvements in conventional thermal power plants by reducing their operating time and optimising their operating point. These improvements lead to a lower specific fuel consumption and consequent reduction of CO_2 emissions.

Through the analysis of the case study, it is verified that, in off-grid systems with relatively low installed capacity of RES, the performance of cycles is quite reduced. Even with only a few cycles, the storage system is able to obtain economic benefits due to the provision of primary spinning reserve. This provision allows an increase in the flexibility of the off-grid system because it allows less many thermal units need to be online during a significant proportion of time and, thus, the minimum technical limits of production of thermal units are lower.

The implementation of intra-day dispatches proved to be fundamental for an adequate quantification of the technical and economic impacts of BESSs during the planning horizon. This is mainly due to the fact that the forecasts contain errors, leading to the need to start up or shut down thermal units during the operation that were not foreseen in the day-ahead planning of operation. Thus, with the realization of intra-day dispatches, the error decreases throughout the day, obtaining a more optimised result. It has also been demonstrated that with multi-stage optimisation, the BESS realizes more cycles because from midday the methodology recognizes benefits in performing the optimisation of the thermal units operating point.

6.2. DIOPHOS Methodology limitations

The methodology presents limitations related to the modelling of thermal units from the point of view of non-consideration of the maintenance, which influences the performance of the Unit Commitment and can lead to less efficient machines having to operate and, thus, result in higher operational costs. Also, the non-consideration of minimum shutdown time and failures has an impact on the operation of the system and leads to an underestimation of operating costs. In the system with BESS, the system performs more cycles because of the spinning reserve provisioning.

The evolution of energy consumption and the introduction of new generation sources are not considered in the methodology. If were to be considered, the pre-analysis had /needed to be modified to consider the various seasons and the various years, so it would become a more complex problem.

The price of fuels and the cost of CO_2 emissions allowances are considered fixed over time but they fluctuate as they are subject to their markets. Regarding the cost of CO_2 emissions allowances, it is expected that this price will continue to increase as environmental restrictions are tightened, then, the operation costs will rise.

The degradation models of battery energy storage systems are quite complex and the linearizations required to integrate into the optimisation model impose errors that over time can have a considerable impact. Also, the non-consideration of degradation by ageing has an effect on long projects such as the one presented in the case study, 10 years.

Because the time interval is one hour, production fluctuations through RES and consumption are not considered. If shorter time intervals were considered, it would be necessary to model the thermal units and BESS ramping characteristic. Also, with shorter time intervals, the energy storage system can provide other types of benefits and thus increase its value but also present a greater degradation.

The methodology does not consider the representation of the microgrid. Although it is a small network, the electric losses must be considered. Moreover, in these systems, the short-circuit currents are high and the inertia is very low, so there are some voltage problems. Thus, the dispatches resulting from the methodology must be validated through the execution of an AC power flow or even incorporate the technical constraints of the system in the optimisation and turn the optimisation problem into an Optimal Power Flow (OPF).

In a system with several renewable energy sources, the methodology does not differentiate which is the renewable energy source curtailed between the various sources. During optimisation, the control variable of RES curtailment is a continuous variable but, in reality, this variable is discrete across scales. For this reason, there is an underestimation of the curtailment performed, which leads to lower operational costs in relation to reality.

6.3. Future Work

The work developed over this thesis contributes to perform planning of operation for the generating and energy storage resources in off-grid systems.

However, there are still new contributions to be made into the model presented to have a better performance. Some suggestions will be presented to further develop this work:

- Perform a deeper sensitivity analysis to verify the impacts of each parameter in the case study (i.e. BESS capital cost);
- In the modelling of the production system, consider maintenance and failures so that the Unit Commitment takes into account the maintenance periods and allows the assessment of the KPI MA;
- In the modelling of thermal units, consider the consumption of two types of fuel because most thermal units in off-grid systems operates with two types of fuel (i.e. diesel to start-up and fuel-oil to operate);
- In the BESS modelling, consider a battery degradation model that considers the impact of more parameters so that the degradation obtained has lower error in relation to the actual degradation;
- In order to validate the dispatch from the methodology, the integration of an OPF makes sense. Regarding the integration of the OPF, the incorporation of one more step in the methodology, closer to the moment of the energy delivery, to address more challenges of the integration of RES (i.e. voltage profile, power quality, protection schemes and stability) and, thus, increase the economic benefits of the integration of BESS in the off-grid system;
- To avoid the pre-analysis being performed through deterministic rules, the use of Machine Learning to obtain the pre-analysis parameters would result in a more optimised methodology.

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