Simulation Analysis of Value of Energy Storage Technologies in Existing Energy Systems

by

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Abstract

The desire to pursue decarbonisation of the energy sector has brought worldwide countries to face new challenges. The need of reducing CO_2 emissions has discouraged the intensive use of fossil-fuelled generators, and the increasing share of electricity from renewable sources has urged the investment in new energy technology able to balance the variability of the generation. Of various technologies, energy storage provides a potential solution to the balance of energy networks, supporting the low carbon energy development.

This work investigates the potential financial and environmental value of energy storage technologies when integrated into real energy systems. The results have been achieved through simulation analysis run on models that replicate the electricity dispatch of entire grid networks. Great Britain and Tenerife energy systems have been analysed as representative of two different electricity grid layouts, to assess the value of energy storage in different conditions.

The simulation analysis focuses on various roles of the energy storage with the purpose to assess the most convenient operation for the investor or the overall energy system perspectives. When simulating Tenerife grid, the energy storage plays three different roles: acting as load-shifter to facilitate the regulation provision and minimise the costs, working in synergy with a single OCGT to improve its energy performance, or increasing the penetration of renewable energy when large wind power plants will be installed. From the energy system point of view, the best results are achieved when the storage increases the penetration of renewables, because the presence of the storage allows reaching the minimum system costs and CO_2 emissions. In this case the operations of the energy storage device connected to the wind power plants save 0.5% of the total system costs, while the savings achieved with the similar device connected to the entire electric grid in absence of large renewable plants would be only 0.2%, and even less when directly linked to the single OCGT. It is interesting to notice that the case study that represents the most productive scenario for the entire energy system does not correspond to the most remunerative one for the energy storage owner. From the energy storage owner point of view, the best energy scenario is represented by the case where the storage acts as load-shifter, because it can maximise the number of discharge processes and profit from the fluctuation of the daily wholesale electricity price profile.

One aim of this work is to examine how energy storage technologies can be operated to optimise the penetration of renewable electricity in existing energy systems. An interesting case study looks at the potential adoption of thermal storage devices in GB for converting wind electricity excess into heat for residential applications. The benefits achievable with this solution would not be limited to the power sector but they would be extended to the domestic heat demand because of the link created by the thermal storage. The savings of gas heating consumptions are directly reflected in the reduction of fuel costs, due to the decrease of natural gas used for space heating purposes. After the installation of 1.1GW of thermal storage devices in Scotland, the reduction of the wind curtailment would be almost 60% and it would correspond to the savings of 30% of the total gas heating generation that is needed for household consumption in Scotland. The simulation results have shown that when replacing the thermal storage capacity with electric storage devices or transmission enlargement the wind curtailment reduction would be almost negligible.

Acknowledgement

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Thanks to the new friends I met in these 3 years, who always make me feel at home.

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Chapter 1

INTRODUCTION

1.1. BACKGROUND

The desire to develop sustainability in the global energy sector has brought worldwide nations to face the so-called “energy trilemma” (**Figure 1-1**), which defines the challenges to achieve three vital, and often competing, goals. The three dimensions of the energy trilemma are [1]:

- Energy security – effective management of energy supply and ability to ensure the energy provision in both short-term and long-term;
- Environmental sustainability – deployment of efficient energy consumption and low-carbon energy generation;
- Energy equity – accessibility and affordability of energy supply across the entire population.

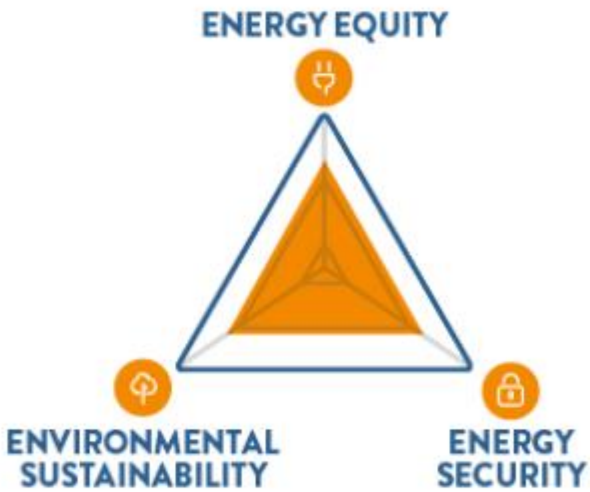


Figure 1-1 *Representation of the energy trilemma*

The concept of energy security concerns, on the one hand, maintaining the constant balance between electricity consumed and electricity generated, with regulation mechanisms that increase or reduce the power plants output to follow the exact demand (similar procedures have been developed also for managing the customers' demand); on the other hand, it refers to the need to forecast the future trend of the energy consumptions and ensure the supply of an increasing energy demand, by installing new energy capacity. Although, energy security should be achieved with respect to environmental sustainability. In other words, the energy demand should be supplied using low-carbon technologies that are not only able to supply the exact amount of energy demand, but that also minimise the production of greenhouse gases. In order to incentives this goal, strict targets have been imposed on a global level and the emission productions have been monitored since early 1990 with the Kyoto protocol [2]. The environmental sustainability targets should be obtained at minimum costs, to ensure the accessibility of the energy supply to the entire population. All these challenges summarise the difficulties represented by the energy trilemma.

When chasing these three energy goals, the installation of large-scale renewable plants, the improvement of energy efficiency of fossil-fuelled generators, and the enhanced management of the costumers' demand are the key points of the government strategies. However, the revolution of the current electricity grid concept does not come without severe consequences on electricity transmission and balancing mechanisms. In this energy scenario, it is necessary to introduce a new key player that could support the energy system to pursuit the sustainability target and to ensure the correct management of the network at the minimum costs. Energy storage technologies can perform this role.

1.2. SCOPE OF THE THESIS

This work **shows the benefits of real potential applications of energy storage technologies**. In the last decades, the energy storage technologies have been the object of a wide research investigation, which analysed different devices, materials and schedule optimisations. However, real implementations of large-scale energy storage technologies have yet to come. For this reason, it is fundamental to simulate the potential benefits that can be achieved with the use of such devices in real energy systems since these results might be used to support and encourage governments and policy-makers to invest in this energy technology.

A large focus has been addressed to both financial and environmental benefits that can be achievable with the use of different energy storage technologies in real systems. These benefits include increasing renewable penetration, reducing CO_2 emission generation, improving fossil-fuelled plants efficiency, and reducing of system costs for regulation or fuel consumptions. It is important to notice that all the benefits mentioned above, and investigated in this thesis, summarise the main concept of the energy trilemma (increasing the low-carbon energy generation at minimum costs). This underlines that this work is in line with the main topics faced by the global energy sector.

1.3. OBJECTIVES

The main objectives of this work have been:

- Conducting a comprehensive literature survey on assessing the energy storage value. “The energy storage value” refers to all the financial and environmental benefits achievable with the use of the energy storage and it can have different meanings according to the point of view from which the problem is observed (i.e. the whole energy system or the energy storage investor), the role performed by the storage, and the location of energy storage devices in the energy system. An exhaustive analysis of the work that has been done on this matter is fundamental to have all the information needed to assess the accurate value of the energy storage in the real case studies examined.

- Identifying the method that is most suitable to simulate the integration of energy storage technologies in national electricity networks. The chosen approach should be able to: simulate the mechanisms that regulate the unit commitment, following the variation of the electricity demand; adapt to different type of electricity grids, modelling isolated grids and, large and interconnected networks; optimise the schedule of the energy storage charging/discharging processes; integrate the heating demand, to simulate an “holistic” energy system that optimises the overall energy supply.

- Investigating the benefits of energy storage technologies in different energy systems, by analysing two main types of electric grid: small and isolated systems or large and interconnected energy networks. To achieve this aim, it has been decided to focus on two real electric grids chosen as representative of the two electric grid typologies mentioned above; the two energy systems selected are Tenerife, belonging to the Canary Islands archipelago, and Great Britain.

- Looking at the value of the energy storage devices when performing different roles. For Tenerife electric grid, it has been interesting to investigate how energy storage technologies could improve the energy efficiency of a single fossil-fuelled plant, increasing the penetration of renewables, and supporting the grid operator in the balancing mechanisms.

- Considering different energy storage technologies (i.e. thermal, electrical) and comparing their performance against other potential energy solutions. For the GB energy system, the installation of thermal energy storage, electric energy storage, and transmission line enlargement are potential solutions that could release the GB network by congestion problems. It is interesting to compare the financial and environmental outcomes reachable in the three different case studies and assess which energy technology is more suitable for the GB energy system.

1.4. APPROACH

Assessing the benefits of the use of grid-level energy storage technologies in real energy system has been carried out with the support of different approaches:

- **Real data analysis**, fundamental for the full understanding of the balancing mechanisms that regulated the electricity grid and highlighting the main issues that challenge the correct energy supply. This analysis has been focused, first, on collecting information regarding the power plants installed (i.e. capacity installed, energy source, plant factor, location of the generation units) in the real energy system considered; then, the attention has been drawn to the real energy demand, looking at the daily and yearly fluctuations, and to the technology mix used to supply this demand (i.e. renewable share, baseload plants, peak units). This in-depth analysis of the real energy systems has allowed pointing out the issues that might benefit by the use of grid-scale energy storage technologies.

- **Unit commitment model development**, that represents the basis for assessing the energy storage value. Being able to represent an accurate and trustable model of the real energy system is one of the main challenges faced in this work. The ability to simulate the real unit commitment following the variation of the electricity demand is based on the correct understanding of the balancing mechanisms implemented by the grid operator (that have been studied during the real data analysis). The lack of validation between the simulation results and the real generation data would compromise the reliability of the energy storage value assessed during the simulations.

- **Energy scenario simulations**, the real core of this work. Once the reliability of the unit commitment model is validated against the real data, it is possible to change the current energy scenario and considers several energy solutions that can be adopted to improve the overall system. It is during this step of the research approach that the real assessment of the energy storage value takes place. Several case studies have been investigated to provide a complete analysis of the potential benefits of energy storage technologies.

- **Real device investigation** follows the outcome of the simulation results. This work is not only focused on a simulation analysis; it examines the real operation of a thermal storage device for domestic applications. This part of the research work takes place in a demonstration house where the energy performance of the thermal device is tested and compared with the performance of the conventional heating systems.

1.5. CONTRIBUTIONS

The main contributions of this work are represented by:

- Developing simplified, but reliable, models of two different typologies of energy systems, the isolated network and the large and interconnected grid. The models have been built based on the real data collected about Tenerife and GB energy systems. However, they could be adapted to other countries affected by similar issues in the electricity grid. For instance, the issues related to the installation of large renewable plants in Tenerife are common to any other isolated grid, and the congestion problems in the transmission line in GB occur in any other large electric grid where the renewable plants are installed far from the electricity demand location. Thus, the two models could be implemented for the analysis of other case studies similar to Tenerife or GB energy systems.
- Assessing the value of electric energy storage in Tenerife, when considering the future installation of large wind power plants as planned by the Canarias government.
- Investigating an alternative energy technology for increasing the penetration of wind energy in Scotland. The thermal storage technology has interesting potentials not only for reducing energy curtailment but also for decarbonising part of the Scottish heating demand. With this solution, it would be possible to tackle two of the main GB energy issues at the same time.

1.6. STRUCTURE OF THESIS

Chapter 2 analyses the current global energy scenario, highlighting the main aims and challenges listed on the energy agenda. It summarizes the electricity market structure, describing the main participants, rules and regulation mechanism. Introducing new players into the energy market, like variable renewable generators, leads to increasing difficulties in the electricity management and encourages using different energy technologies to improve the network balancing, such as the use of energy storage devices.

Chapter 3 provides an overview of the energy storage technologies commercially available and their role in large energy systems. Energy storage devices play an essential role in balancing the variable renewable energy output. They could be a solution to speeding up the penetration of renewable energy into the electric grid, together with the use of very accurate power forecast and the enlargement of the transmission network. The primary classification of energy storage is based on the approach adopted for storing the energy, and it considers electrochemical, mechanical, chemical and thermal device. This chapter concludes with a careful review of the different procedures for assessing the value of energy storage when operating in large energy systems. The results achieved by various studies prove that the economic value of energy storage may widely differ according to the role or location of the storage considered and from which perspective the business case is analysed (the investor in the energy storage or the overall energy system).

Chapter 4 focuses on the method adopted to simulate two different energy systems and analyses the benefits achievable with installing grid-scale energy storage devices. The mixed integer linear programming is a mathematical theory implemented for the modelling of complex systems, such as the simulation of the unit commitment and economic dispatch of an electric network. This theory is the same used in the software modelling tool, PLEXOS Integrated Energy Model, chosen for this work. The Chapter goes through the main steps that have been followed to get a trustful model of the selected energy systems validated against real data. The modelling of the energy system status quo is the starting point for assessing the potential energy storage value: once the current issues of the electric network are highlighted it is possible to understand how the operation of the energy storage could improve the current network management.

Chapter 5 offers an analysis of the issues of large-scale wind plants installed in a small, isolated grid. The current and future energy scenario in Tenerife is analysed and model with PLEXOS. The operation of the energy storage technology is simulated in several energy scenarios (e.g. connected to the entire electric network, to a single gas plant, and to the wind power plant) in order to compare the different benefits of the energy storage technology.

Chapter 6 moves to a different case study that highlights the issues caused by large-scale wind power plants concentrated in Scotland (part of the GB energy system). First, the current energy system is described, defining the amount of traditional and renewable power capacity installed, the plant power factor, the national energy (electricity and heat) demand and the volume of wind energy curtailed. Then, the real properties of the energy system are introduced in the PLEXOS model that is characterised by two different regions to reproduce the congestion at the transmission line between Scotland and the England-Wales region: this is the main cause of wind energy curtailment in Scotland. The use of electric storage, thermal storage and the enlargement of the transmission line at the Scottish border are examined as potential energy solution for reducing wind energy curtailment.

Chapter 7 emphasises the potential adoption of thermal storage devices in Scotland, following the results achieved with the PLEXOS model and described in Chapter 5. It considers the large installation of thermal storage heaters for domestic applications. With the aid of a MATLAB model of the thermal storage heater, it is possible to analyse the operations of the device when is charged with excess wind energy. The Chapter presents an overview of the operating costs and the comparison with other common heating systems for domestic applications.

Chapter 2

CURRENT ENERGY SCENARIO

Researchers have proven the strict relation between the increase of greenhouse gases percentage in the atmosphere and global warming. If further actions are not undertaken, this phenomenon can lead to severe global catastrophes: temperature increase, extreme weather, the rise of sea level, growing desertification. The commitment of all countries to limit the effects of climate change has been officialised in the Paris Climate Agreement [3]. The document, signed by all 195 country members, asserts that the main aim is to maintain the global temperature rise "well below 2ºC over the pre-industrial temperature level". To achieve this target, each country must reduce the amount of greenhouse gas emitted by the energy sector. Electricity production, transportation, and domestic heat consumption are the primary cause for greenhouse gas emissions, whilst industrial and agricultural sources count for only 30% of total emissions.

The need to decarbonise the three energy sectors leads to severe changes in energy generation and management.

2.1. POWER SECTOR

In the power sector, the decarbonisation strategy has been adopted, and the use of coal for energy production has decreased, making new space for natural gas and low-carbon technologies. The International Energy Agency (IEA) [4] predicts that in 2040 renewable and gas generators will cover over 85% of the energy demand. Nowadays, the development of renewable power plants, in particular, solar panels and wind farms, has achieved a mature level. The growing adoption of these technologies has been allowed by the recent fall of their investment costs and by policies and financial incentives that aimed to promote the installation of low-carbon power plants. In the global power sector, renewable power plants generate 25% of the total amount of electricity [4]. Hydropower produces the most significant percentage (16%), followed by wind (4%), biomass (2%) and solar (1.5%). The leaders of the energy transition race are China, the United States, Brazil, and Germany which are the countries with the most substantial portion of installed renewable capacity [4].

These modifications of the power grids might cause various problems in the management and distribution of the electricity:

- first, the renewable output follows the variability of the natural source (i.e. wind speed, solar radiation) and cannot be controlled as the conventional fossil-fuelled power plants;
- then, the location of the renewable capacity is not decided based on the location of the electricity demand but on the availability of the natural source. This causes potential issues in the electricity's distribution from the generators to the customers.

To increase the penetration of renewables in the power sector and solve the energy management issues that might arise, it is necessary to introduce new players in the electricity grid, such as energy storage technologies.

2.2. HEAT AND TRANSPORT SECTORS

Although the power sector has been revolutionised by low-carbon policies, the commitment to reducing the energy-related gas emissions needs to happen across the whole energy sector (power, transport, and heating). Renewable energy is contributing to only 19.3% of the overall energy demand [5], meaning that oil and gas are still ruling the transport and heating sectors, because of their lower price compared to other alternatives sources.

The successful reduction of fossil-fuelled generation in the power sector raises the interests in the potential electrifications of the heat and transport demand. In this scenario, the use of energy storage devices, such as thermal storage and electric vehicles, might allow the interconnection of the three sectors, facilitate the management of the energy, and optimise the costs for the customers.

2.3. ENERGY MANAGEMENT

In the previous Section, it has been mentioned the importance of energy management and the new challenges brought by the decarbonisation. This topic is explained in the following paragraphs, where large attention is drawn on the complex balancing mechanisms that rule the electricity network. The description of the balancing strategies and management issues is a useful introduction to the simulation analysis conducted in this thesis.

2.3.1. ELECTRICITY MARKET

The electricity generation and distribution are organised in a network that spreads across the entire country, whose operation is based on the central principle that the electricity production needs to follow the demand required by the users. The electricity and its corresponding price are traded in a market, that follows similar rules across the world [6]. The supply of the electric demand occurs at any time of the day by a specific mix of power technology, which has been decided by the System Operators.

2.3.1.1. UNIT COMMITMENT AND ECONOMIC DISPATCH

The decision process that schedules the power plants operation is called unit commitment and is a complicated optimisation problem characterised by several variables [7]. The output of the unit commitment indicates whether a plant needs to be operating. Then it is necessary to specify the exact amount of electricity production (economic dispatch). Unit commitment and economic dispatch are based on a bid-offer energy market that chooses the most economic technologies compared to all the conventional units participating in the market. The electricity market is organised according to three different time scales [8] (Figure 2-1):

- *Day-ahead market*: for scheduling of the unit commitment and economic dispatch for the following day. Assessing the unit commitment in advance is necessary for traditional thermal plants that require long and expensive start-up processes.
- *Intraday market*: for scheduling the unit commitment and economic dispatch for the following hour. The electricity market is based on long-term load forecast, and the planning of the power plants operation can be improved by using more accurate predictions generated by one hour-ahead.
- *Real-time* or *Balancing market*: for assessing the final balancing mechanism of the system because of unpredictable faults in the operating plants or because of a mismatch between the predicted load and the effective one.

In the electricity market, a day is considered as divided into 48 half-hour periods, called settlement periods.

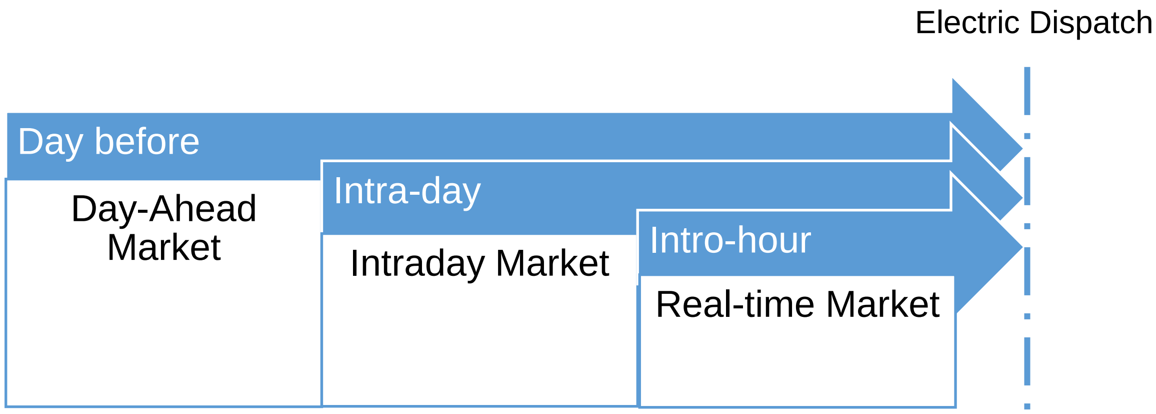


Figure 2-1 *Basic architecture of the electricity market*

2.3.1.2. RESERVE PROVISION

Once the unit commitment and the economic dispatch have been completed, it is necessary that the grid operator ensures the perfect balance between generation and demand by imposing real-time regulations. This means that a certain number of power plants need to be kept available for a rapid increase or decrease in demand. This action is required anytime there is an unforeseen variation of the electrical consumption, damage to the transmission line or outage of some conventional operating plants. The traditional power plants that operate this service are called *operating* or spinning reserve, and they are forced to work at a partial load because of the need to further change the output. This issue might last for a maximum of 15-30 seconds (*primary* *reserve*) [6], such as with a demand fluctuation that would lead to a minor regulation of the frequency, or several minutes, because of some severe outages (*secondary reserve*). In the latter case, the operating reserve could not provide an increased output for an extended period; thus, the intervention of further power plants that are not operating at that specific moment (*tertiary reserve*) might be required. These are called non-spinning reserve. **Figure 2-2** shows the time scale of the different regulation services.

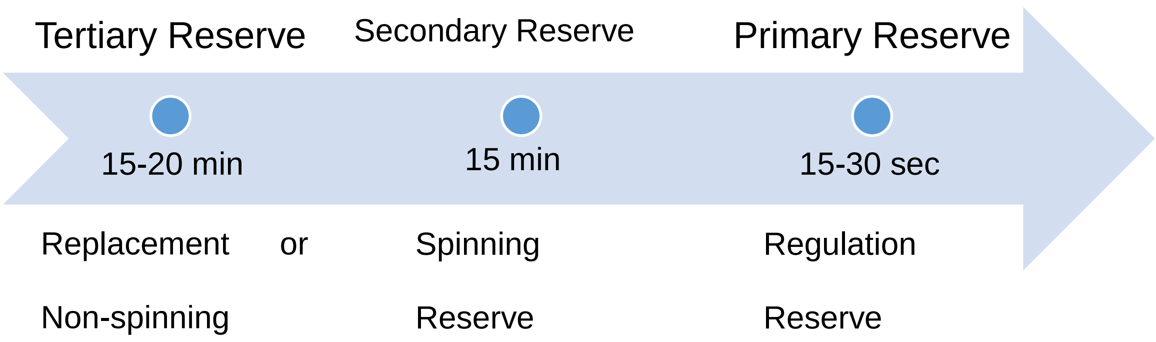


Figure 2-2 *Time scale of regulation services*

Reserve-down, and reserve-up, are classified as ancillary services that must be provided by all the power plants connected to the transmission lines. The provision of the reserve comes with a series of additional costs for the system that have a substantial impact on the overall costs of the electricity. First, having several plants operating in partial load condition forces the plant itself not to optimise its efficiency and thus face higher costs of generation. Second, this leads to the grid operator having more power plants operating at the same time increasing the overall capital costs. Finally, the units chosen as a spinning reserve are selected based on their quick response, and they might displace other more economical energy solutions.

2.3.1.3. TRADITIONAL AND RENEWABLE POWER PLANTS

The electricity is generated by various power plant technologies, classified as traditional or renewable generators.

Traditional power plants, like coal plants, diesel generators, open cycle gas turbines (OCGT), and combined cycle gas turbines (CCGT), burn fossil fuels in the electricity generation process (i.e. coal, gas, oil); their output is controllable by the system operator and is scheduled to supply the demand and provide reserve. They are characterised by elevated operations and start-up costs considered as constraints during the optimisation of the unit commitment, to supply the demand at minimum costs.

Renewable power plants, like photovoltaics (PV) panels, hydropower plants, and wind power plants, are fossil-free generators, characterised by a variable output. The renewable sources might be unlimited, unlike fossil fuels, but their availability is not constant in time. The electricity production from hydropower plants follows a season trend: abundant during the rainfall periods but poor in the dry seasons. Solar power plants depend on solar radiation, and thus their productions have a predictable profile that might change only during cloudy days (**Figure 2-3**). The variation of wind power output might be intense and not subjected to any pattern since it follows any change in wind speed (**Figure 2-3**). Sometimes, this variation could reflect the trend of energy consumptions; for instance, intense windy days could correspond to high-energy demand days because of the drop in the outside temperature. However, many days of high wind energy production and low energy demand have been registered. Studies of the wind output in UK have proven that the wide distribution of wind farm on a national level reduces the variability of the generation profile and allows a weak positive correlation with the electricity consumption [9]. However, it is not possible to define wind power plants as load following generators.

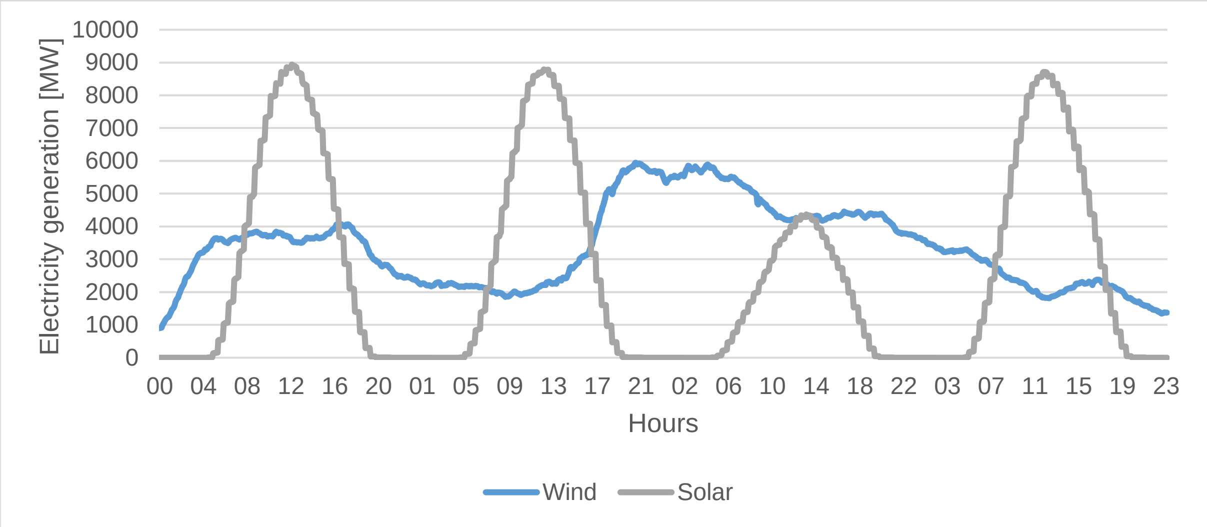


Figure 2-3 *Example of the variability of wind and solar generation (based on real UK data from 2018)*

The variability and uncontrollability of the electricity input into the electric grid by renewable power plants could have minor or essential consequences [10].

- Minute-to-minute fluctuations could have a negative impact on the quality of the power output, because of small modifications of the grid voltage. Being able to maintain a constant difference in voltage is fundamental to ensure the correct delivery of power into the transmission line. A small variation in the grid voltage, causing over or under voltage problems, could be repaired by changing the reactive power generation, that does not deliver active power to the load and is related to the voltage variation. The voltage control can be done by using power electronic converters. Renewable power plants can play this same role when equipped with this kind of device.

- Consequences that are more serious can occur when the modification of the power output from a renewable plant influences the frequency regulation. If there is a drop in electricity generation, the frequency will fall as well and vice versa. To overcome such issues, the generators need to adjust and change their output by providing ancillary service (as mentioned in the previous section).
- The extreme problem related to frequency unbalance could lead to an overloading of the grid. This happens when the actual production from renewable plants exceeds the forecasted value. An unexpected rise in the power output, if not controlled, could lead to inappropriate heating of power equipment, with a consequent increase of maintenance costs or an outage. One possibility for solving overloading problems is to disconnect the cause of this power increase. This means that with uncontrollable elevate power output, for instance, caused by a strong wind gust, the grid operator could curtail the excess of electricity that the grid cannot absorb.

2.3.2. HEAT MARKET

If the electricity market is regulated by complex mechanisms that need to ensure the constant balance between generation and demand, the heat market is based on a simpler structure. When referring to the heat demand, it is considered the final energy consumption of the industry sector, that requires high and medium temperatures heat demand for melting, evaporating, and drying processes, and the space heating and domestic hot water requirements that are supplied by low-temperature heat and appear in domestic, commercial, and industrial buildings [11]. The heat is generated from primary energy supply by the combustion of different fuels, like coal, fuel oil, natural gas, wood chips, and pellets. Alternative sources of heat are represented by the electricity, for instance through heat pumps or electric heaters, or by the recovery of waste heat from industrial processes and the distribution through a district heating network.

The various heat supply methods involve the use of fossil fuels (this might happen directly, by burning natural gas in boiler heaters, or indirectly, considering the fuel used in the industrial process that supplies the district heating) and contribute, in different measures, at the greenhouse gases emissions. The carbon emission limits are imposed on the entire energy sector (comprehensive of power, heat, and transport sectors). Although large effort has been addressed to reduce greenhouse gases emission from the electricity generation, the same cannot be said for the heat sector. An example of the trend of the industrialised countries is represented by Germany, where the percentage of renewable share in the power sector achieves 32%, whilst only 13% of the heat demand is covered by renewable [12].

2.3.2.1. DISTRICT HEATING

The district heating is a mature technology, well-established in many countries, although, in Europe, only 10% of the space heating and hot water demand is covered with district heating [13]. This heating system is based on the centralised production of heat, through large renewable plants (i.e. biomass, geothermic, solar), combined heat and power plants (CHP), or waste heat recovery from industrial processes, that is then distributed to the costumers through an underground pipe network.

Because of its centralised characteristic, the district heating encourages the use of renewable sources and waste heat for the heat generation, contributing to the CO_2 emission reduction in the heat sector. However, it is interesting to notice that, when looking at the main heat sources used for district heating in Europe (**Figure 2-4**), only a small portion is covered by renewables [14]. Surprising is also the small percentage of district heating penetration in Europe (only 10%), concentrated in the Scandinavian countries. One reason that might justify the modest spread of this technology, could be the lack of incentives and policy to promote it. According to Persson and Werner [15], this supporting mechanisms are present in countries where the district heating is already a popular technology while there is a lack of motivation to invest in this heating method in other countries, where the costs of district heating is less competitive to the fossil fuels price [16].

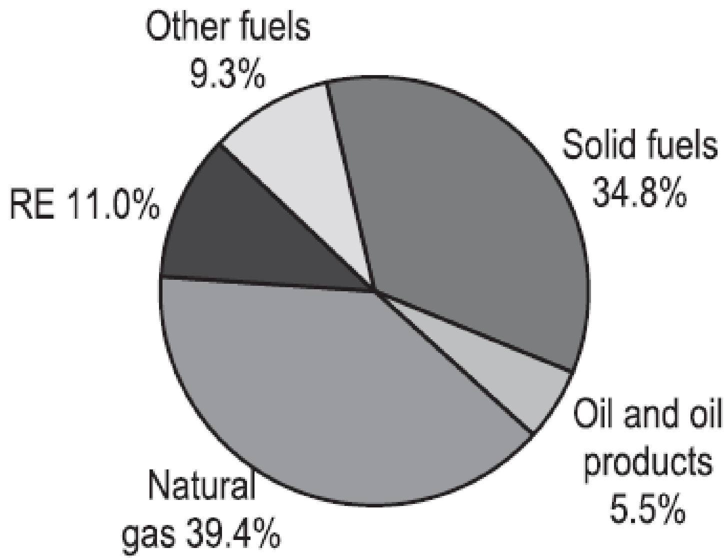


Figure 2-4 *District heating energy source*

2.3.2.2. POWER TO HEAT

Power-to-heat refers to the conversion of electricity into heat. Although in the previous years power-to-heat was not one of the preferred options for the heating generation, because of the main fossil-fuelled sources installed in the electricity network, it is now becoming a more popular solution [17]. This is also because power-to-heat could be employed to increase the flexibility of the grid by using electric boilers or heat pumps coupled with thermal storage devices. The power-to-heat approach can be defined as a demand response strategy that converts electricity to heat when the grid requires support in the balancing mechanisms. For instance, interesting works have been conducted in Germany and Sweden to investigate how power-to-heat could be combined with existing district heating networks [18], [19]. These studies analysed and compared the hourly profiles of the electricity demand, electricity generation and heat demand and assessed preliminary conclusions on the potential use of power-to-heat technologies for increasing the renewable penetrations in the national energy systems.

Part of this thesis focuses on power-to-heat as a solution for reducing wind energy curtailment in the GB energy system. This analysis has been performed by simulating the unit commitment of the entire energy system and it highlights how the use of thermal storage might have consequences on both the power and heat sectors by changing the original balancing mechanisms.

Chapter 3

ENERGY STORAGE

The previous chapter highlighted the necessity of increasing the electricity generated from renewable sources, to pursue the requirements of energy security and environmental sustainability. Although, it has been pointed out that renewable plants in the power grid have brought several challenges for the balancing mechanism operations, increasing the regulation costs and the thermal stresses for the conventional power plants.

This chapter, after a brief introduction of different techniques used for reducing the renewable energy output fluctuation, recommends the employment of energy storage technologies for buffering and balancing the renewable generation. The core of this chapter is an exhaustive summary of the methods for assessing the value of energy storage.

3.1. SOLUTIONS FOR RENEWABLE ENERGY PENETRATION

The variability of renewable power output is one of the leading causes that obstructs renewables to become a driver in the actual energy market. When the renewable share is around 15-20% of the total amount of electricity generated, the grid operator is able to balance the fluctuation of its output [20]. However, when this percentage reaches 25% and above, the grid perturbances and congestions caused by the variability of the renewable output are not easily offset [20]. Thus, it is essential to look at solutions capable of increasing the security of renewable supply, to pursue the low-carbon energy goal.

Using precise and accurate weather forecasts could allow renewables to be more competitive in the energy market [21]. Being able to rely on a reliable forecast for the renewable output could enable renewables to take part in the day-ahead spot market. Ummels et al. [22] investigated the impact of the growing wind power installations on the Dutch unit commitment. They analysed the wind speed forecast for the day ahead and the update of the energy dispatch every 15 minutes. According to their study, the correct prediction can reduce the operating cost, but, inaccurate estimation of the future wind power output could cause additional costs because of the penalty payments. The overestimation of the wind speed implicates the sudden start-up of a backup plant, whereas, in the opposite situation, the surplus of electricity produced must be sold at a lower price, decreased by the penalties. The more accurate the wind speed prediction is, the more optimised the distribution of energy will be. This is a benefit for the wind farm companies, who will get the highest profit from the wind turbines operation, avoiding curtailment and penalties, and for the grid operator, who will reduce the operational costs of its traditional power plants and provide the energy demand with a higher percentage of renewable power.

The installation of large renewable plants usually takes place in remote locations. This decision is driven by the necessity of natural source and space availability. To ensure the correct distribution of the renewable generation across the country, investment in the transmission line’s enlargement might be required. This would avoid the unpleasant occurrence of constraints in the lines because of the excessive energy flow. Although the analysis of different case studies has proven the competitiveness of the installation of further transmission lines as oppose to large-scale energy storage devices (such as compressed air energy storage) [23][24], governments are not enthusiastic about projects that involve the amplification of the transmission network. It is essential to consider other non-monetary factors, such as siting, line planning and permitting, that add further complexity to the transmission line development.

Moderate controllability of the renewable power output could be achieved given the availability of energy storage devices. The electricity generation from a hybrid system, characterised by the synergic operation of the renewable generator and an energy storage device in the same site, register much less fluctuation than the output from a single renewable plant. The energy storage may act as a buffer, and it could offset the strong variability of renewable production [25]. The control function performed by the storage device allows getting a power profile much closer to the one predicted by the forecast [26], filling the gap caused by poor forecast accuracy.

3.2. ROLE OF THE ENERGY STORAGE

The charging and discharging processes of the energy storage technology can be optimised to achieve different results. For instance, one of the possible services that can be provided by the storage is called energy arbitrage and involves the strategic purchasing and selling of electricity according to the wholesale electricity price variation [27][28][29]. The energy storage would acquire electricity from the grid during periods of excess of electricity or decrease of demand when the price is low, and then it would sell it during high demand. The electricity would be sold at a more expensive rate achieving an economic revenue.

This specific activity aims to maximise the revenue of the energy storage investors; however, there are many other operations that could increase the flexibility of the energy system, buffer the renewable power plants, maximise the efficiency of a traditional power plant. Table 3-1 summaries the main roles played by energy storage [30][31][32], which are described in the following sections.

Table 3-1 *Summary of the main roles of energy storage technology*

	Role energy storage
Balancing demand and supply	Seasonal / Weekly fluctuations Peak shaving Geographical unbalances Strong variability of wind power plants
Grid management	Voltage and frequency regulation Participate in balancing mechanism
Energy Efficiency	Improve efficiency of generation mix

3.2.1. BALANCING DEMAND AND SUPPLY

Energy storage technologies can play an important role in the increase of penetration of renewable energy in the electricity grid, because of their ability to store the energy when it is abundant and deliver it according to the demand profile [33]. The importance of energy storage application together with variable renewable energy could be understood by considering the typical solar PV panels electric output [34], [35]. The peak of production follows the solar radiation intensity and is concentrated in the middle of the day (Figure 3-1). However, the two daily peaks of electric consumptions take place during the morning and the evening. Here, the use of energy storage devices would allow collecting the excess electricity produced by the PV and spread its consumption during the peak demand. This adoption of the energy storage would take advantage of its capability of load shifting, by adapting the generation from a variable source to the energy demand. Similar considerations can be made for wind power plants, whose electrical outputs do not follow a typical daily profile but vary and fluctuate along the day following the wind speed variations.

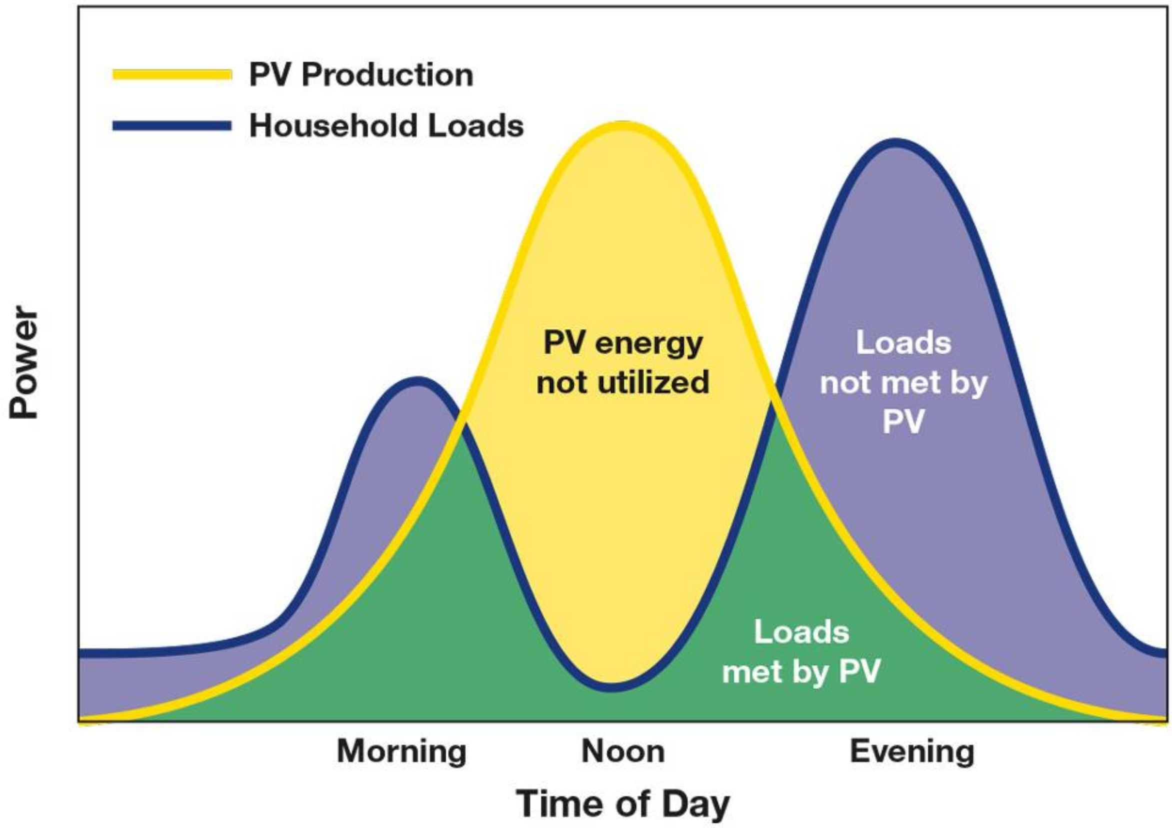


Figure 3-1 *Graphic representation of PV energy generation and demand profile*

This operation of the energy storage follows a daily frequency of charge and discharge within the single day. However, a similar balancing role could be played by different energy storage devices at a different time scale. For instance, run-of-river power plants have a season generation profile that variates according to the intensity of the raining period. Large hydro pump storage could be incorporated in the original power plant to accumulate water, and thus energy, for the future demand. Apart from this seasonal role, energy storage technologies (i.e. batteries) may assist the renewable generation by improving the quality of the electric output and smoothing the frequent fluctuation that occurs within the hour [36].

The strategic location of energy storage in the transmission network would allow the grid operator to manage the local unbalance of electricity with more flexibility [37]. Installing new power plants in remote areas might require the construction of additional transmission capacity, even if it is just to accommodate peak productions for a few hours per year. This investment might be expensive and difficult to implement, and thus alternative solutions should be investigated. The energy storage in the power plant’s proximity could collect and store the electricity in case the transmission lines are already saturated to avoid the curtailment of this surplus of electricity. This case is suitable for the installation of wind farms in the windy and remote area of the country.

Intense generation from wind power plant might cause the traditional power plants to drastically reduce their load. Sometimes, this operation cannot be done because of technical constraints of the plants (i.e. minimum capacity factor, maximum ramping rate). Thus, if this “excess” of renewable electricity produced cannot be absorbed by the demand, the grid operator is forced to curtail it. The intervention of energy storage devices could collect the surplus of electricity and dispatch it when the demand raises [38]. This operation of the energy storage would not just avoid the waste of clean energy but it would also save the grid operator by penalties costs due to curtailment.

3.2.2. GRID MANAGEMENT

The importance of the role of energy storage is recognised not only as a tool that supports the renewable generation but also as a technology that may improve the overall performance of energy generation and reduce the costs of electricity production.

The role of energy storage as an available reserve for the regulation and balance of the grid on the short and medium term (frequency control and secondary reserve) has already been mentioned above. Energy storage technologies could replace traditional fossil-fuelled power plant for the provision of the reserve [39], releasing them by the obligation to run partially loaded. The power plants operating in the unit commitment would then maximise their output and efficiency, and the number of units connected to the grid would be reduced since there would be a minor requirement of spinning reserve.

The ability of the energy storage to provide additional reserve and flexibility to the electric grid enables the overall energy system to achieve several goals:

- Increase the penetration of renewable energy, by adjusting the generation to the demand and improving the quality of the electricity produced [30];
- Reduce the CO_2 emission, not just by integrating more renewable energy in the system but also by improving the efficiency of the operation of conventional power plants [40];
- Decrease the overall wholesale electricity price, by reducing the operational costs from traditional fossil-fuelled power plants and by playing a leading role in the reserve provision [41].

3.2.3. ENERGY EFFICIENCY

Energy storage technologies working in combination with traditional power plants could improve the efficiency of the unit during electricity production. Considering a gas or oil-fuelled power plant used to provide the daily peaks of demand, it could not optimise its energy performance [42][40], because is required to follow the load. If the power plant would work with an energy storage device, then it could maximise its load and efficiency and to store the amount of electricity unnecessary at that moment. This approach would reduce the operating costs of the plant and have a positive impact on the reduction of CO_2 emission.

A similar method could be used in cooperation with a combined heat and power (CHP) plant [43][44][45]. The generation of electricity is related to the release of heat; thus, a moderate heat demand would force the plant to limit its output. In case the CHP is connected to a thermal storage device, then it would optimise its output and performance and store the unnecessary heat.

3.3. ENERGY STORAGE CLASSIFICATION

Electricity is difficult to store in its original form, and thus it is usually converted into another kind of energy. This new form of energy is stored and then converted back into electricity for being supplied to the power grid. Energy storage devices are classified according to the type of energy they can store [46][47][48]:

- *Electrochemical* energy storage involves batteries and supercapacitors
- *Mechanical* energy storage technology transforms the electricity into kinetic energy (e.g. flywheel), or potential energy (e.g. pumped hydro storage, compressed air energy storage);
- *Chemical* energy storage devices adopt electricity for operating chemical reactions. The new compounds obtained are stored and then used for regenerating the electricity;
- *Thermal* energy storage devices can store the energy as heat. According to the material used as a storage medium, the energy can be converted into sensible or latent heat.

A further classification of the energy storage devices can be done by looking at the primary function they can provide in the energy system [47]. Some large devices, such as pumped hydro storage (PHS) and compressed air energy storage (CAES), can supply energy to the grid for an extended period supporting the operations of balance between the supply and the load. Because of their moderate energy capacity, they can also provide arbitrage and load following services. Other more modest devices would be adopted for fast response power services, such as batteries, supercapacitors, flywheels. A clear example of the different roles of energy storage solutions could be seen in **Figure 3-2**.

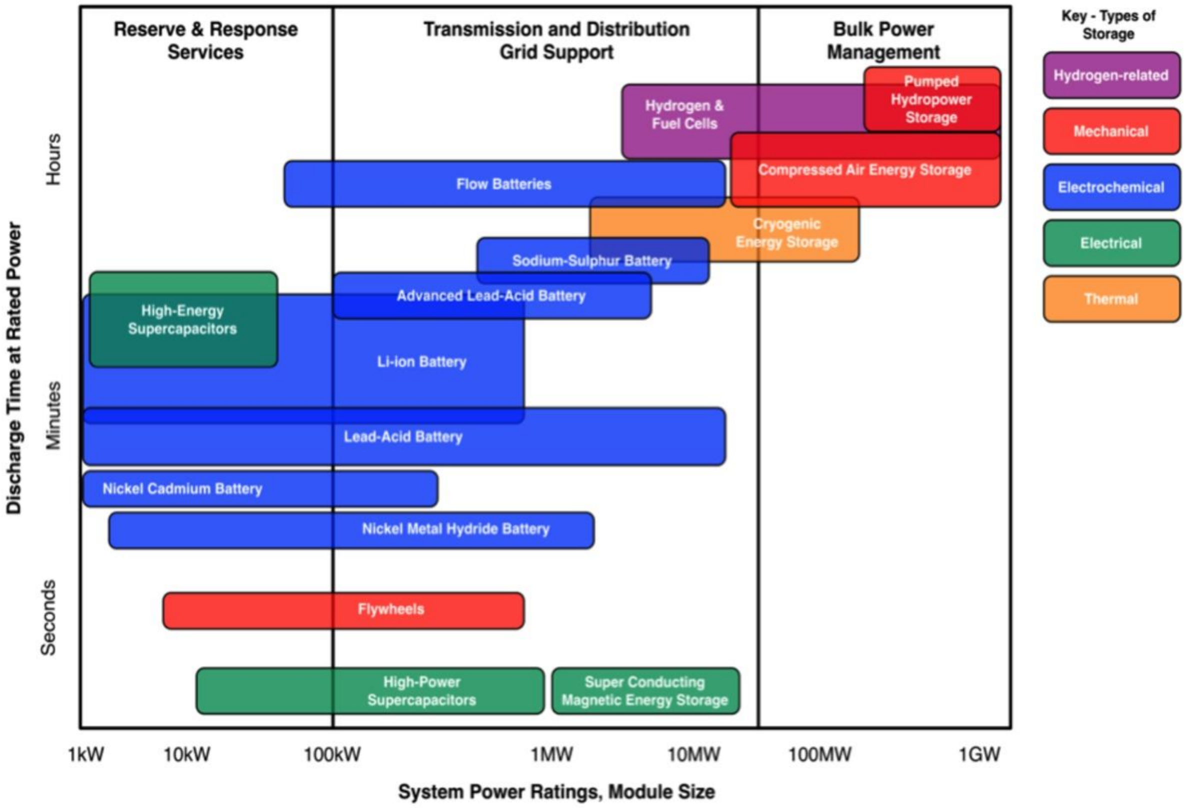


Figure 3-2 *Relationship between discharging time of energy storage technologies and their role in the energy system*

3.4. ENERGY STORAGE TECHNOLOGIES

The flywheel represents the oldest method adopted for storing the electricity. It is based on conservating the rotational kinetic energy by spinning a large mass. The rotation is activated by an electrical motor, which then works as a generator for discharging the storage device. Its efficiency is between 90-95%, and it has a long-life cycle compared to other storage devices. It is adopted for improving the quality of the power output, voltage regulation, but it cannot produce energy for a long time. Standalone wind turbine might be equipped with flywheel storage for compensating sudden power changes [49].

Pumped hydro storage converts the electricity into potential energy: it adopts the electricity for running the pumps that move the water to an elevated basin. When the grid operator requires operating the PHS, the water flows to the lower basin through a turbine that generates electricity again. The capacity of the storage is linked to the height of the water storage and to the amount of water that can be contained. The PHS technology is mature and widely adopted for large-scale application, because of its high roundtrip efficiency (around 70-80% considering evaporation and conversion losses). When looking at the different percentage of energy storage installations, PHS account for 99% of the worldwide storage capacity [50]. Taking advantage of its high ramp rate, it could provide arbitrage and ancillary service for the day-ahead and intraday energy market. The main drawback of this device is the large space requirements for the two reservoirs and the high investment costs. Moreover, the availability of a large volume of water might be an obstacle in a country subjected to long dry seasons.

A second large-scale technology that adopts the principle of converting the electricity into potential energy is the compressed air energy storage. This device is equipped with compressors and intercoolers that, powered by the electricity, compress the air efficiently; then, the compressed air is contained in a cavity before expanding in high and low-pressure turbines. Even though it has higher energy efficiency than PHS (70-90%) this storage plant is not commonly installed. The main barrier to the implementations of this technology is the necessity to use an underground cavity.

A standard way of storing electricity is the use of batteries. The process that leads to the conversion and storage of electricity is based on electrochemical reactions that take place at the electrodes. There are several various kinds of batteries available on the market, although most of them still require further development and research. The most common battery technology [49], adopted mainly with PV solar panels, are Nickel-Cadmium, Nickel-Zinc, and Lead acid. Batteries are not ideal for large grid-scale application due to their high maintenance costs, short life cycle, low energy density and power capacity.

Thermal storage devices include any processes of either cooling or heating a storage medium. The conversion of electricity into thermal energy might occur using electrical resistors or through cryogenic procedures. The range of temperature at which the energy storage take place could vary from -40°C to 400°C (industrial applications) [49]. Thermal storage devices are classified according to three different processes for storing the energy: sensible heat storage, latent heat storage, and thermo-chemical storage.

The energy stored in a sensible thermal storage device is proportional to the temperature reached by the material during the charging phase (heating or cooling). The most common material adopted for this technology is water, favourited for its availability, price, and safety. Also, ceramics, natural stones, and concrete are used as a sensible storage medium. The cost of sensible heat storage is very competitive on the energy market, and because of the simple system design, this technology is adopted for managing domestic heating consumptions (e.g. hot water tanks for gas boilers, solar panels, and co-generating systems).

When the material used is a phase change material (PCM), a higher amount of energy can be stored at an equal temperature. PCMs can increase their thermal capacity during the phase change process. This allows the materials to store more energy concerning sensible material with similar thermal properties [51][22]. The phase change takes place at a constant temperature permitting to store a large amount of thermal energy without exceeding high temperature. This could improve the safety concern in a domestic application, such as for the electric thermal storage. The category of PCM collects a large number of materials that present different thermal properties [52][53]. For each application, the most suitable PCM would be chosen according to the energy storage capacity needed and the temperature range of operation. Commercial organic PCMs, such as high-density polyethylene (HDPE) and paraffin wax [54], are adopted for their low costs and extensive range of melting temperature that makes them suitable for several purposes. They are chemically inert and stable material and have a good energy density. However, the adoption of additional metals or carbon composite is required for increasing the low thermal conductivity of the organic PCM. For space heating, fatty acid materials [55] can also be adopted as their melting temperature is around 60˚C and their considerable latent heat. When looking for a PCM with higher energy density and thermal conductivity, hydrated salts (inorganic PCM) represent a suitable choice for thermal storage application even though they are used for low-temperature operations.

Thermo-chemical storage can store thermal energy by using the heat for breaking chemical bonds between molecules. The reversible process, would release heat and discharge the storage. Since the elements in the device are stored at ambient temperature and are not supposed to heat up during the charging process, this storage system is characterised by very poor heat losses, and thus its application is preferred for long-term storage [56].

3.5. VALUE OF ENERGY STORAGE

One of the main objectives of this work is to provide a comprehensive review of the different approaches adopted to assess the value of energy storage technologies. Studies related to this topic differ one from the other; it is difficult to define a unique approach for calculating the benefits of energy storage. The economic benefits achievable with a single storage technology might depend on the role or location of the storage considered and on which perspective the business case is analysed (the owner of the energy storage or the overall energy system). When focusing on a specific business case, the return of the initial investment might occur at different moments according to the storage technology chosen and on its capital cost.

3.5.1. WHO RECEIVES THE ECONOMIC BENEFITS

It is necessary to specify who is the receiver of such economic revenue. The results of a single study could be different in case they are referred to the company that invests in the energy storage, or to the whole energy system that aims to minimise the overall operation costs.

3.5.1.1. INVESTORS

In the first case, a positive revenue could be achieved only with the trade of electricity. The owner of energy storage device could get a profit by selling the electricity to the market taking advantage of the feed-in tariffs, by performing arbitrage and ancillary services that include frequency response, short-term reserve, and other real-time balancing services. Thus the schedule of the storage needs to be optimised to maximise its economic revenue, as shown in the following equation [57]:

$$\sum C_{RT} * (P_s^d - P_s^c) + C_{Res} * P_s^{Res} + C_{STOR} * P_s^{STOR}$$

Where C_{RT}, C_{Res}, C_{STOR} represent respectively the price for real-time energy trading, for frequency response regulation and provision of short-term operating reserve (£/MWh); $P_s^{d/c}$ defines the power rate of charge and discharge of the storage device (MW), P_s^{Res}, and P_s^{STOR} refer to the scheduled response regulation or short-term operating reserve service of the storage unit.

Feed-in tariffs, arbitrage revenue and ancillary service price depend on the current energy market. Thus, if the study aims to analyse the value of the energy storage in a future energy system, then it will be necessary to consider the change of these prices. Feed-in tariffs, seen as an incentive for installing renewable plants, are meant to decrease with the increase of renewable penetration. However, the revenue that might be obtained by performing arbitrage is based on the daily variation of the wholesale electricity price, and this is considered to increase when more renewable energy is present in the market. When analysing the price paid by the grid operator for the provision of ancillary service, it is important also to consider the flexibility of the energy system and how large the requirements of balancing would be.
To conduct a complete analysis of the future value of the energy storage technology, it is necessary to look at the evolution of different future energy scenario. Those could be part of some government plans, and they could suggest different percentages of investment in renewable plants. Even considering a similar level of renewables in the energy system, there might be different policies managing the operation of the traditional power plants [58]:

- a *flexible system* would prioritise the maximum penetration of renewable energy and reduce the installed capacity of fossil-fuelled power plants, facilitate the operation of an open-cycle gas turbine (OCGT) as a backup for renewables output;
- an *inflexible system* would maintain a more conservative approach, scheduling the large fossil-fuelled plants to produce the daily base-load and reducing the share of renewable energy.

An inflexible system would highly remunerate the intervention of any technology able to provide balance to the energy system, a service that could not be easily supported by the operating power plants.

Furthermore, when assessing the economic benefit that could be achieved by adopting the energy storage technology for arbitrage services, it is fundamental to consider the electric market where this would take place. In this context, Zafirakis et al. [59] look at the adoption of PHS or CAES in different European markets. In accordance with several other studies, this paper concludes that, usually, the arbitrage service alone does not generate enough profit for justifying the investment in energy storage devices. This is true for stable and well-balanced power grids that do not suffer from significant variations in the wholesale electricity price. However, it has been highlighted that countries, which mostly rely on imported energy (such as Greece), might enjoy some financial relief with the use of energy storage technology. Also, the extensive presence of variable renewable power plants could increase the disparity in the daily wholesale electricity price and encourage the installation of energy storage for arbitrage service.

3.5.1.2. OVERALL ENERGY SYSTEM

However, when looking from the whole energy system perspective, further revenue could be obtained following the adoption of an energy storage device into the energy system. The energy system would receive direct or indirect economic benefits by:

Improving the renewable electricity share in the energy system. Child and Breyer [60] study the ambitious target of the Finnish government to achieve 100% of renewable production by 2050. According to the paper, as soon as the percentage of the renewable output in Finland overcomes 50%, it is necessary to support its variation with the operation of energy storage capacity. The authors suggest the adoption of a diversified mix of storage technology for tackling the strong daily and seasonal change of renewable production. The model of the Finnish power grid has been developed with EnergyPLAN, and it could be extended to any country at high latitude. The results have shown the necessity of introducing energy storage devices into the power system since over 50% of the renewable production of one year would have been stored and not directly used. Among all the technologies adopted, the electric vehicles appear as the devices that would be mostly exploited, questioning the real utility of stationary battery. Thermal storage devices cover only 4% of the heat demand; one reason for this poor exploitation could be the lack of spatial accuracy of the model that does not consider the small rural demand. The advantages that could be achieved by exploiting the time shifting properties of the energy storage system have been analysed by Careri et al. [61]. The authors developed a mixed integer linear programming (MILP) model able to optimise the unit commitment of a power grid equipped with wind power plants and energy storage systems. The model has been validated on the IEEE 24 bus test system, developed by the IEEE (Institute of Electrical and Electronics Engineers). The results show that the adoption of energy storage systems, with a charging efficiency of 80%, could reduce the wind energy curtailment from 16% to only 3.1% of wind energy. Future works are intended to look at expanding this model to real power systems and to considering real storage technologies.

Ensuring the maximisation of the generation efficiency and reducing fossil fuel consumption, in case the energy storage device would work in synergy with fossil-fuelled power plants. As mentioned in Section 1.1.2., the intense adoption of renewable power plants, not supported by additional measures intended to simplify the balancing operations of the power grid, could cause severe damage in thermal power plants. One of the first consequences is the reduction of efficiency of the plant, forced to operate at partial load condition to work as a backup for renewable energy production. Using energy storage systems in cooperation with traditional power plants could be suggested for improving their energy performance. Barelli et al. [62] looked at the energy efficiency reduction of a combined cycle gas turbine in Italy, due to the growing introduction or renewable plants into the energy system. This has been quantified as almost 4% of efficiency losses during four years of operation (2008-2012). The authors calculated the benefits that could be achieved in the year 2012 if energy storage capacity would be used for allowing the thermal plants to operate near nominal conditions and storing the excess of electricity not absorbed by the demand. A sensitivity analysis of the round-trip efficiency of the storage and on the rate of energy that could have been stored has been conducted. This shows that, with an energy storage device with 85% of energy efficiency and 30% rate of energy stored, it would have been possible to save 1.5% of the combined-cycle gas turbine (CCGT) fuel consumptions. Apart from the economic saving due to the reduction of fuel costs reduction, further benefits can be achieved by lowering the maintenance costs of the thermal power plants because of operations at the nominal condition.

Respecting strict CO_2 limits, since the energy storage device would allow larger exploitation of the renewable plant. A detailed analysis of future low carbon scenario for the Texas power grid has been presented by Sisternes et al. [63]. In this study, the value of two different storage technologies, pumped hydro storage and battery, has been assessed in case of strict CO_2 limits. According to the authors, the use of energy storage devices would allow larger exploitation of renewable power plants and, thus, reduce the electricity generation costs by 10-12%, based on the CO_2 limits imposed. However, the authors highlight that considering the actual installation costs of the energy storage the investment would not be covered by the revenues. The investment will be considered more convenient if the energy storage technology becomes more commercially available or it accomplishes different roles, like improving the distribution network. A different example of the positive effect of the use of energy storage technology on the CO_2 level is presented by Teng et al. [64]. Using electric vehicles (EVs) and heat pumps (HPs) can be seen as the implementation of distributed energy storage devices for achieving the electrification of the transport and heating sector. Here, the economic benefits related to the use of energy storage would account the savings in the investment in both further low-carbon technology, and additional balancing service for fluctuating renewable generations.

Avoiding additional enlargement of the transmission network, if the energy storage would be located at the renewable site and would avoid transmission constraints by storing the surplus produced. Fallahi et al. [24] looked at the value of the energy storage connected to a wind farm. This work investigates the best location of the energy system installation that includes a compressed air energy storage (CAES) and a wind power plant. The mathematical model has been tested on the IEEE 24-bus system. The value of the CAES is intensified in case the wind farm is installed in a remote area with weak transmission connections. Here, the economic revenue for the investment of the CAES is calculated according to the grid operator. Preliminary results show that the use of CAES looks feasible and remunerative compared to the investment in new transmission lines. The investment in energy storage devices or new transmission lines, for the connection of remote wind power plants, also has been analysed by Lamy et al. [23]. This paper looks at the installation of 200MW of wind power capacity in North Dakota for the supply of the demand in Illinois. The capital costs for energy storage device should be less than $ 100 /kWh to compete with the expansion costs of the transmission network. So far, the only energy storage system that could have similar costs are CAES and used Li-ion batteries.

Reducing the risk of blackout and ensuring a higher level of security of supply. Looking at the South Korean electric market [65], uncertainty in the electric supply is one of the main issues for the grid operator, which is trying to avoid blackout risks by considering the involvement of renewable power plants, demand response, and storage devices. However, according to Shcherbakova et al. [65] company owner of battery system would not find economic convenient to invest in this business case. If the battery systems do not decrease their capital costs and are used only for providing arbitrage services, the revenue cannot cover the investment. It is necessary to experiment different role of the energy storage into the power system, such as ancillary services or power regulation, to create a possible profitable business case.

3.5.2. ROLE ACCOMPLISHED

The results of the studies presented in the previous sections draw attention to the importance of the role of the storage when assessing the economic benefit of this technology in energy systems. As already discussed, the central roles played by energy storage can be classified as [66]:

- Ancillary Services and Arbitrage;
- Renewable integration, voltage support and peak shaving;
- Grid transmission and distribution support.

The value of battery energy storage systems (BESS) has been assessed by Oudalov et al. [67]. The authors analysed three different roles that could be covered by the BESS in a power system and looked for the most profitable one. BESS could be adopted for replacing the need of enlargement of the transmission and distribution network, for load shaving purposes and fast responding power control. According to the paper, only the latter two cases might represent an interesting investment for the BESS, even though the payback period would be longer than ten years in both scenarios.

3.5.3. CAPITAL COSTS

However, a different conclusion is achieved when considering different energy storage technologies: bulk and mature devices (e.g. PHS, CAES), or distributed and not commercially available technologies (e.g. battery). The capital costs of the investment have still a preponderant impact when assessing a business case for energy storage devices. The precise analysis of a business case for the investment in an energy storage technology is strongly dependant on the capital cost of the device itself.

However, the manufacturing companies consider there might be a drop in these costs soon, due to an increase of these products available in the market [68]. The capital costs of batteries are expensive also considering the adoption for load shifting and arbitrage service in connection to Greek industrial facilities [69]. This study reveals that a profitable investment for the industrial sector can be achieved if only the battery storage systems are more commercially available or in case the government would support a broad large-scale investment.

3.5.4. LOCATION

Pudjianto et al. [70] present a broad analysis of the effectiveness of energy storage technologies in the UK power system, and it focuses on the impact that the storage location might have on this value. In this work, when referring to the storage location, it is meant the distinction between the adoptions of several distributed storage or the agglomeration of all the storage capacity in a single bulk device. According to the simulation results, different storage locations lead to a different operating strategy of the storage device. The bulk storage would operate to balance the main renewable output so it would charge during peaks of the wind power generation and it would discharge when this value drops. Otherwise, the schedule of the distributed storage devices would ignore the trend of the renewable output profile, and it would focus on reducing the the daily peak load.

Another interesting study on the most valuable location for the energy storage device has been done by Denholm et al. [71] analysing three different cases in the US. According to this paper, the location of the storage device considering the wind farm influences the role that could be played by the storage in the power system. Installing the energy storage at the wind farm site means that the storage of energy would relive the transmission line from the peak of wind production and it would improve the quality of the wind output profile. Otherwise, when considering the energy storage device at the grid level, its function would be decoupled by the operation of the wind turbine and it would point at optimising the economic revenue with arbitrage and ancillary services. According to the authors, the most remunerative solution would be the second one. However, since this study is based on the adoption of CAES, locating the storage close to the user would not be possible and a more remote site would be preferred.

Chapter 4

MODELLING OF THE ELECTRIC GRID

To study the integration of energy storage device in an electric grid, it is necessary to start with modelling the electric grid itself. Several energy market parties benefit from the use of advanced models of the energy system [72]. The market operators can use this approach for planning purposes, the electricity generating companies can be able to provide valuable operational solutions, and government departments can develop future energy and climate policies on the simulation results of the future energy scenario.

4.1. UNIT COMMITMENT AND ECONOMIC DISPATCH

An electric grid is formed by several components, such as thermal power plants, renewable generators, and transmission lines. However, the feature that most characterises this complex system is the way how every single generator interacts to accomplish the daily demand. The contribution of each plant in the electricity market is decided by the grid operator by communicating a unit commitment and an economic dispatch. The former shows the status of operation of each plant (on/off), the latter chooses the amount of electricity that the generators should input into the grid. Because of the lengthy and expensive start-up procedure of most of the thermal power plants, the unit commitment is communicated days or months in advance, based on forecast on demand. The economic dispatch needs to decide the amount of electricity to produce to follow the exact demand. This critic decision is based on the latest forecasts of the demand, and it occurs minutes or hours before the settlement period.

The decision process that leads to determinating the unit commitment is a very complicated procedure. It looks not only at supplying the exact amount of demand required, but it also needs to do it by minimising the overall cost of the energy system. The grid operator needs to consider costs related to electricity generation, start-up of units, and penalty costs, such as the ones for reducing greenhouse gas emissions or renewable curtailment.

4.2. THE FORMULATION OF THE UNIT COMMITMENT PROBLEM

The section defines the equations that are used to model the unit commitment problem. Section 4.3 will focus on the methods adopted for solving these equations.

The objective function defines the system costs, and the aim of the model is minimising its value [7]. The cost function of an energy system can be defined as:

$$\sum_{i=1}^{N}\sum_{t=1}^{T} FC_{it}(P_{it}) + MC_{it}(P_{it}) + ST_{it}v_{it} + SD_{it}w_{it} \quad (1)$$

$FC_{it}(P_{it})$ is the fuel cost, normally defined as a quadrative function of P_{it}, with a, b, c are usually positive cost coefficients.

$$FC_{it}(P_{it}) = a * P_{it}^2 + b * P_{it} + c \quad (2)$$

$MC_{it}(P_{it})$ represents the maintenance cost, described by a linear function of P_{it};

ST_{it}, SD_{it} are the start-up and shutdown cost of the generation unit;

v_{it}, w_{it} refer to the start-up/shutdown decision [92].

Further costs might be included in the objective function, and they include [93]: transmission cost, load curtailment cost, renewable curtailment cost.

The constraints imposed to limit the system are several, and they concern technical limits on the operation of the power plants, safety issue related to the stability and balance of the grid, and some environmental constraints regarding the control of emission of greenhouses and other harmful gases.

- The balance of generation and demand

The first restriction that the grid operator must always guarantee is the power balance. This means that in any moment the overall demand for electricity must be covered and the generation cannot exceed this amount.

$$\sum_{i=1}^{N}(U_{it} * P_{it}) = D_t^f + losses \qquad (3)$$

U_{it} is the on/off status of unit i;

P_{it} is the power generation of unit i during the period t;

D_t^f represents the forecasted demand during the period t.

- Thermal power plant limitations

The unit commitment needs to respect technical boundaries of the thermal power plants [94]. First, every unit must produce a power output limited by the minimum and maximum power rate of the generator.

$$P_{it}min < P_{it} < P_{it}max \qquad (4)$$

The power output variation is limited by a maximum value that represents the maximum change of power output allowed per unit generator per hour.

$$RD_i < P_{it} - P_{it-1} < RU_i \qquad (5)$$

RD_i is the ramp-down rate of unit i;

RU_i is the ramp-up rate of unit i.

- Reserve service

To maintain the balance in the electric grid and being able to buffer sudden variation in the production, it is necessary to ensure a reserve service. This can be accomplished by charge or discharge of storage devices, ramp up or down power plants that can be part-loaded, operating fast response generators or curtail part of the renewable generation.

- Power flow constraints

The amount of electricity that can flow in each single transmission line is limited by the technical specifications of the line itself. In case the maximum value is achieved, the system is congested, and the excess of electricity that cannot be absorbed is curtailed.

$$MVAf_{ij} \leq MVAf_{ij}max \qquad (6)$$

$MVAf_{ij}$ is the magnitude of voltage rating of the transmission line connecting bus i and j.

- Emission constraints

This is a limit imposed on the total amount of greenhouse gases that could be produced in a specified period. This constraint, even though it is imposed on the overall system, is restrictive for fossil fuel plants such as coal and gas generators.

4.3. DIFFERENT METHODS FOR SOLVING THE UNIT COMMITMENT

The modelling of the electric grid and unit commitment decision process is achieved using mathematical algorithms. The increase of complexity of the mechanism behind the balancing of the energy system has brought to an evolution of the methods used for modelling.

4.3.1. PRIORITY LISTING

The priority listing (or priority list) approach is one of the simplest methods for modelling the unit commitment decision process. The critical point of this procedure is generating a rank that orders the power plants according to their average operating cost [73]. This value is calculated considering the fuel consumptions and start-up costs. Then, the lowest number of units selected for the electricity load supply is chosen from the top of the list. In this way, it is possible to operate the least-cost combination of power plants.

This simple method allows getting a fast response for the unit commitment and the solutions achieved are close to the optimal one [74]. However, the quality of the output generated by the priority list method suffers from some high heuristic properties and the negligence of some thermal power plants limitations. For instance, with this approach, it is not possible to consider the minimum up/down time of the units [75], defined as the minimum time a power plant needs to be continuously on/off due to the thermal stress caused by the start-up/shutdown processes.

4.3.2. DYNAMIC PROGRAMMING

The dynamic programming method is one of the oldest approach adopted for unit commitment problems [76]. It can analyse complex problems by dividing them into small optimisation subproblems. For each step, the model tests all the possible unit combinations and selects the most cost-effective solution for providing the demand requirements. If P is the total amount of power that needs to be covered by M number of power units, then $F_M(P)$ defines the minimum operating cost [77][76]. By applying the dynamic programming approach, the unit commitment problem would be solved by the recurring solutions of the following equation:

$$F_M(P) = \min[F_M(Q)+F_{M-1}(P-Q)]$$

Where Q is the portion of load covered by the M^{th} power unit, and $(P-Q)$ is the remaining load, supplied by the remaining $(M-1)$ power units. The optimisation of every single subproblem can bring to the optimisation of the overall unit commitment problem.

The main issue when adopting this technique is the strong dependence on the dimensionality of the problem. As soon as the size of the energy system by one power unit, the number of combinations to be analysed would increase [78]. To simplify this approach, some restriction can be imposed [79][80]: sequential dynamic programming (SDP) follows the priority listing order for selecting the units leading to a visible reduction of combinations from (2^M-1) to M, truncated dynamic programming (TDP) imposes a fixed number of power units that can take part at the unit commitment.

4.3.3. LAGRANGIAN RELAXATION

If the dynamic programming approach is not suitable for solving the unit commitment of large energy system, Lagrangian relaxation aims to “relax” the problem by temporarily neglecting some of the constraints [81]. The unit commitment problem can be seen as the sum of several small subproblems characterised by the optimisation of the operation of each power unit [82]. However, all these subproblems cannot be considered as independent, but they are bonded through the definitional of constraints such as power regulation (the generation must equal the demand) and spinning reserve provision [83].

The Lagrangian relaxation method allows ignoring the coupling constraints and looking separately at every unit. This step is managed by adopting dynamic programming. Then, once this first step is completed, a Lagrangian equation is maximised by tuning two non-negative Lagrangian variables [84].

4.3.4. GENETIC ALGORITHM

The genetic algorithm is an iterative procedure that takes inspiration by the natural selection and natural recombination [85], and it is based on the principle that the best individuals are the one that “survive” [86]. The solutions of the problem are presented as a binary variable, and for the unit commitment problem, the value represents the status of each power plant (ON/OFF). First step of this approach is selecting a fixed number of variables, and it tests the resulting value of the objective function, in this case, defined as the overall cost function that considers the operation costs, and several constraints in the form of cost penalties [87]. In this way, it is possible to include several limitations just considering the corresponding penalty function. Then, the value that minimises the cost function can be recombined (*crossover*), generating new candidate solution population.

4.3.5. MIXED INTEGER LINEAR PROGRAMMING

The electric grid operations are regulated by complex mechanism and complex will be the model that simulates it. A mathematical approach that has been adopted for the modelling of the electric grid is the mixed integer linear programming (MILP). This is an evolution of the linear programming (LP) method. The LP formulation considers a series of variables, whose values need to be assessed as an optimal solution of a function [88]. According to the different objective functions, the purpose of the model could be minimising it or maximising its value. This process is limited by several constraints imposed on the values of the variables. If a solution exists able to respect all the restrictions, then it is called a *feasible solution* [89]. In case these are also optimising the object function, it becomes an *optimised solution*. Otherwise, if the problem is limited by too many constraints, then the solutions will be defined *unfeasible* because they cannot respect all the restrictions. The unbounded solutions occur in case the objective function has an infinite number of solutions that could optimise it. The integer programming (IP) follows the same steps of an LP with the exception that all the variables must be integer number. This limitation is imposed by the nature of the problem and by the real meaning that the variables embody (some quantities, in reality, cannot be expressed by fractional number). The MILP is reasonably a combination of the LP and IP. This means that some of the variables are integer numbers.

Two main techniques are used for solving the MILP problem and they are called the branch-and-bound and the cutting planes [90]. They are similar approaches and both start by solving the LP problem since a feasible solution for the MILP is also respecting all the constraints of the correlated LP model. This means that the first step is removing the integer solution restriction. According to the branch-and-bound method [91] if the optimal solution of the LP is a fractional number, then the integer solution will be in the areas bounded by the two integer number that round-off the initial solution. Two new solutions are later found in the two areas, and the final comparison of them gives the overall optimal solution. In case it would still not be possible to identify an integer solution than the branching procedure is iterated, and the feasible area is again separated and bounded by other integer numbers until the process converts to an optimal integer solution.

The cutting planes techniques aim to already find an integer value as an optimal solution of the LP. This is achieved by introducing some inequalities to the LP to minimise the choice of fractional number and address the solution to an integer value. These additional limitations do not affect the final optimal decision since are imposed on fractional numbers that are not taken into account as feasible solutions of the MILP.

4.4. PLEXOS INTEGRATED ENERGY MODEL

When modelling an electric grid, one of the software that is adopted is PLEXOS Integrated Energy Model by Energy Exemplar. It simulates the decision process of the electric grid by optimising the cost function (equation (1) of Section 4.2) of the energy system and respecting the constraints as defined in Section 4.2. PLEXOS is an optimisation-based simulation tool that follows the principles of the MILP theory [93]. It is used for developing a simulation analysis of energy system for electricity or gas network. The choice of using PLEXOS can be justified for different purposes:

- It allows the optimisation of operation costs, by running optimal power flow or short-, medium- and long-term unit commitment;
- It can be used for simulating the future energy market evolution under various scenario; PLEXOS can support decision-making processes related to the needs for new investments, or to the size, location, and schedule of new power plants;
- It calculates the optimal trading strategy analysing generation and transmission constraints.

The model of the energy system can be simulated according to different time scales, based on the purpose of the analysis. Long-Term Plan performs simulations with long horizons, usually between 10 to 30 years. This simulation is used for expansion planning function. The software would optimise the operation costs of the energy system based on potential transmission upgrades, power plants installations or retirements. Medium-Term Schedule is run on a week-by-week or month-by-month basis. It generates a full representation of the generation and transmission system, and it is based on load duration curve analysis. Short-Term Schedule can have a time step of seconds, minutes or hours and it is used for generating the optimal power plants commitment [95].

These analyses could be run on a stand-alone application or they may also be used in an integrated way. PLEXOS provides automatic integration between the different layers so that the information can be fed from one time horizon to the other to ensure the integrity of the resulting solution. For instance, the medium-term model can be run as a stand-alone model for getting fast results for medium long-term studies or it could be used linked to the short-term schedule. In this second case, the medium-term model is run on a monthly horizon to determine the hydro resource targets for each day. Next, a daily short-term model computes an hourly unit commitment that optimises the arbitrage revenue of the energy storage devices.

PLEXOS is based on object-oriented programming design. This programming language focuses on objects, classes, and data. The concept of *class* is a crucial point for this kind of programming method. A class defines the data (properties) needed for identifying an object, and it specifies the behaviour that all the objects in this class need to follow. Examples of PLEXOS classes include System, Company, Region, Zone, Node, Line, Transformer, Contingency, Fuel, Emission, Generator, and Data File. Objects can belong only to one class; however, they might be connected to several collections. For instance, the generator object G is linked at the node N, uses the fuel F and produce emission E: node, fuel, and emission are defined as collections. The relationships between two objects are called membership. Considering the example as above, generator G is linked with node N through a membership where parent object is G and child object is N.

4.4.1. HOW TO DEFINE AN ENERGY SYSTEM

Any energy system is described in PLEXOS starting by creating a Region [96][97]. The region object can be considered as the transmission area. Then, it is possible to define one or more Zone objects that can be subsets or supersets of the region. Inside the region, it is possible to create several nodes, each of them linked to an object (e.g.

generators, energy storage). The transmission network is defined inside the region by connecting the nodes with lines object. The load can be described as an aggregated curve at the region/zone level, such that any generator belonging to the “transmission area” is contributing to the demand supply. Load data are read from text files and the time step of the files can be customised according to the user's needs.

Generator objects are created and enable (meaning they inject electricity in the grid and they contribute to the loaf) by specifying the number of units they are made of and the maximum capacity, so the size in terms of MW, for each unit. The unit heat rate is another fundamental information for the operation of the thermal generator since it defines the relationship between the amount of fuel intake and the electricity output (GJ/MWh). The definition of the unit heat rate is allowed in PLEXOS using four different formats: a constant value, an incremental heat rate, an average heat rate or a polynomial function. The latter methods are more accurate than the use of a single constant value because the unit heat rate varies across a unit’s operating range. Several other properties can be defined for each generator, and they can be chosen according to the user's information availability. They include [98]:

- Minimum Stable Level (MW): the minimum generation level when the unit is committed;
- Minimum Up/Down Time (h): the minimum number of hours that a unit must run for once it has been started/shutdown;
- Start Cost (€ or £): the cost of starting up a unit;
- Maximum Run Up/Down (MW/min): maximum change in the load per hour;

- Energy limits: minimum or maximum total amount of energy produced over any period (e.g. each day, week, month, or year).

Generator objects need to be associated with a fuel object. The fuel consumption is regulated by the unit heat rate function expressed in GJ/MWh. Knowing the cost of fuel (€/GJ or £/GJ), it is possible to calculate the cost of producing electricity. Then, this value might be increased taking into account further variable or fixed costs of maintenance related to the unit generator. The fuel object might be assigned to several different units so that the information available for one fuel type (e.g. fuel price, emission rate) are common to all the generators that consume such fuel.

The presence of the Reserve class of objects allows defining ancillary services for the optimisation of the energy dispatch. When creating a new reserve object, it is possible to decide the attribute it represents: spinning up/down reserve by units online, regulation raise/lower provided by units online separate to their spinning reserve provision, non-spinning reserve provided by units that are not online.

The definition of the renewable generation in PLEXOS could be achieved using two approaches: one considers a perfect foresight method [99], while the other follows a stochastic unit commitment modelling [100]. The perfect foresight modelling does not take into account any uncertainty due to errors in the power output forecast. To input the wind power profile, historical data can be used. When the times series is normalised, it can be implemented for simulating the generation from any wind power plant size by changing the number of units installed. Using this technique can result useful in case it is necessary to simulate several future scenarios for the same model, which may require the installations of different amount of renewable capacity.

Otherwise, if the model needs to consider the uncertainty related to renewable production forecasts the introduction of variables should be considered.

4.4.2. REAL APPLICATIONS OF PLEXOS SIMULATIONS

The simulation-based analysis executed on PLEXOS has been adopted as a decision-support tool by several energy authorities [101]. Energy-related industries benefit from the use of long-term PLEXOS results for evaluating significant investments or for predicting the future commercial competitiveness of some energy products in the market. Governments' energy and policy-maker departments are recommended on the deployment of new energy, or climate policies addressed to promote the adoption of specific products.

Long-term PLEXOS simulations analyse the future evolution of energy markets and, therefore, it can highlight the future key players that may appear. For instance, encouraging model results could attract industries in the investment in energy storage for grid-level integration or on electric vehicles for the reduction of CO_2 emission in the transport sector. In particular, the Commission for Energy Regulation (CER) developed and validated a PLEXOS model of the Irish single energy market (SEM), the wholesale energy market operating in Ireland and Northern Ireland. Since 2007, this specific model has been adopted in Ireland as a reliable starting point for several studies. Cleary et al. [102] show that a 270MW compressed air energy storage (CAES) could be able to displace a significant portion of the gas and coal production reducing by over 9% the CO_2 emission for the Irish market. The operation of the CAES in PLEXOS has been replicated by connecting a pumped storage plant with a gas turbine. The authors continued their work focused on the Irish SEM and CAES integration in [103].

This second paper is meant to support investors in the wind sectors and policy-makers that look at the evolution of the energy market once the compensation for curtailment will disappear.

By running long and medium-term simulations in PLEXOS, it is possible to define the best strategies for achieving renewable energy penetration targets in all energy sectors. Foley et al. [104] analysed the impact of a considerable number of electric vehicles (EVs) in the Irish SEM market. This work highlighted the ambitious plans for the renewable transport goal of the country and concluded that even 213,561 EVs could achieve only 1.45% of this target. The authors also studied the issues raised by integrating a significant amount of offshore wind power plants in the Irish-UK energy market [28]. The simulation analysed how improvements in offshore wind power output forecast positively affect the planning and management strategies.

Every country is subjected to CO_2 limit restrictions to fulfil, and PLEXOS model simulation might be a guide for policy-makers for understanding which the best approaches would be for achieving the aimed results. The simulation analysis of the future evolution of the Australian energy market and its impact on greenhouse gas emissions has been presented in [105]. The study has shown that substituting coal with gas-fired power plants will not be entirely beneficial for the $CO_{2\ reduction}$. Moreover, this would lead to an increase of the wholesale market price. Similar conclusions have been confirmed by Wagner et al. and by their work on the Australian market [106]. According to these two papers, PLEXOS results dissuade policy maker to incentivise gas generators over coal-fired power plants, because the modest emission savings would not be worth the considerable wholesale electricity price increase for the consumers due to the carbon price penalties addiction. However, an alternative solution to the CO_2 emission problem has been suggested by a different study carried out on the Australian energy system evolution [107]. This paper highlights the possible environmental benefits achievable with the extensive use of electric vehicles (EVs) connected to the grid. Following PLEXOS simulation results, the positive influence on the electricity industries, gasoline consumptions, and greenhouse gas emissions showed in the paper should motivate the deployment of policy addressed to the incentives and regulation of this interface between the electricity and the transport systems.

The analysis of various energy systems in PLEXOS highlights how the adoption of similar policies may have different effects on different markets. It has been mentioned above how several studies focused on the Australian energy market discourage the installation of gas power plants as a replacement of the more polluting coal stations. However, the same analysis carried out in Croatia [108] suggested that carbon price penalties could represent a powerful boost for the CO_2 emission reduction because they would make gas-fired plants1 more competitive than coal on the electricity market.

The investigation on transmission network enlargement can be run analysing the results of the model simulation in PLEXOS. The possibility to include transmission line description in the electric grid model allows studying the direction and behaviour of the electricity flows understanding when and where there might be congestions in the energy system. PLEXOS is popular in the United States, because the software offers a database of the Western Interchange (WECC). For instance, Diakov et al. [109] analysed the different level of wind and PV generation in the six large WECC regions and their influence on the net interchange in the Western United States. Studies, like the one presented in the paper mentioned above, are fundamental for understanding the requirement for future transmission network expansion. Another example is shown by the work carried on by Moazzen et al. [110] that analyses the planning of transmission network reinforcement for reducing renewable curtailment on Vancouver Island.

Simulation-based analysis of the energy market is often used for highlighting the existing barriers that obstacle the energy system evolution. This is shown in the work of Lytvyn and Hewitt [111] who investigate the reasons that limit efficient cross-border trading between the Irish SEM market and the GB market (e.g. market liquidity, mismatches between trading timeframe, market power). They suggested to policy-makers and governments the correct actions that should improve the benefits from the use of the interconnectors. The commitment of creating a European Single Electricity Market has risen the question about installing new lines connecting the neighbouring countries. This matter has been analysed in Reference [112], where the PLEXOS results urge installing more interconnectors at the European energy market level.

Energy-related industries might benefit from the use of long-term PLEXOS results for evaluating substantial investments [113][114][115], or for understanding future commercial competitiveness of some energy products (e.g. energy storage, renewable generators) in the market [116]. Brouwer et al. [117] aim to show the most cost-effective option for deploying a low-carbon power system. Nweke et al. [118] use PLEXOS as a decision-support tool for planning new investments. Ni et al. [119] compare the investment in a compressed air energy storage or a combined cycle gas turbine, concluding that the energy storage might have more expensive energy generation but higher revenue due to the ancillary service provision.

Chapter 5

TENERIFE ENERGY SYSTEM

This chapter analysis the value of energy storage technologies in isolated grids, such as Tenerife. It has been investigated the potential operations of energy storage for:

- Balancing demand supply – balance the variability of large wind power plants and reduce curtailment;
- Grid management – accomplish reserve and regulation tasks;
- Energy efficiency – increase the energy efficiency of a gas plant by time shifting the load from peak to off-peak periods.

The results have been assessed with simulation analysis on a model of the isolated grid, whose characteristics are described in the first sections of the chapter.

5.1. BACKGROUND

5.1.1. ISOLATED GRIDS

The exact definition of a small isolated grid, according to the European Directive 2009/72/EC [120], is “any system with consumption of less than 3000 GWh in the year 1996, where less than 5 % of annual consumption is obtained through interconnection with other systems”. This definition corresponds to remote areas, such as small communities or islands, that are not connected to a main electric network. Isolated grids are generally characterised by a radial distribution and few nodes where the main generators are connected [121]. The electricity generation is mainly based on small fossil-fuelled power plants, such as diesel or gas turbine, causing a dependence of isolated grids on imported fossil fuels.

The usual main objectives an isolated grid needs to fulfil are:

- The safe and secure supply of energy;
- The reduction of the electricity price;
- The increase of the efficiency and sustainability of the energy supply and the restriction of greenhouse gases emission;
- The pursuit of independence from fossil fuels transportation from the mainland.

The first three aims are common to any electric grid. However, achieving these objectives is more difficult in an isolated grid, because of the lack of interconnections with other networks. To ensure the safety and reliability of the energy system, it is important to rely on a large amount of reserve used in case of equipment failure or power plant malfunctioning. For this reason, fossil-fuelled power plants operate at partial load, restricting the efficiency of their operations. Due to these technical constraints, governments and companies involved are already investigating the possibility to use energy storage technologies for peak shaving and ancillary services [122]. These additional energy devices could be an economic alternative to reduce the number of start-ups and shut-downs of thermal units and release the power plants by these thermal stresses.

The electricity price is particularly high, compared to the average price of a large electric grid. For instance, for the Canary Islands archipelago, the average wholesale electricity price is above 0.20 €/KWh [123]. This is because of elevated costs for fossil fuel provision that, in case of islands, it is supplied by the mainland. Furthermore, the strong dependence on fossil fuels not only causes high electricity generation costs, but it is also the reason for a large amount of greenhouse gases emission.

The recent decrease in renewable installation costs has generated new opportunities for isolated grids. Remote areas, in particular islands, can have impressive amounts of natural resources available and the installation of hydro plants, wind turbines, solar panels or geothermal plants can be fruitful. The exploitation of local resources would allow the isolated grids to reduce the significant impact that fossil fuels have on their energy market. This would generate a reduction in the wholesale electricity price and decrease in greenhouse gases emissions.

5.1.2. INCREASE RENEWABLES PENETRATION IN ISOLATED GRIDS

The several benefits that could be achieved following the penetration of renewable plants are obstructed by the several problems that may arise in the grid management [124]. The balance of renewable output fluctuations afflicts any energy system and is even more stressed in small isolated grids with reduced flexibility. Thus, it is necessary to consider additional energy technologies to support the penetration of renewable plants in isolated grids.

Building new interconnections with neighbouring grids can allow the trade of electricity and abandon the condition of isolated grids. Example of this can be found in some of the Hawaiian Islands and in the interconnection between the North and South New Zealand [121]. Other projects investigate the possibility to link the islands with the mainland, as it happened in Italy as the outcome of the Insular Project [125] that aimed to connect the electric grid of Italian islands with the main network. A more ambitious project is looking at the possibility to create a connection between Iceland and the UK (Icelink Project) [126], allowing the large exploitation of the renewable energy sources present in Iceland.

However, this solution is not always achievable due to geographical constraints or prohibitive investment costs. This is the case of the Canary Island archipelago, where the distance with the mainland and the ocean depth prevent the realisation of interconnections within the islands of the archipelago or with the mainland.

The extensive use of electric vehicles (EVs) can facilitate the penetration of renewables in isolated grids, because of the additional flexibility added to the system. This solution can be particularly profitable in islands: the lack of space availability recommends the choice of small energy storage devices, to reduce the environmental impact, and the short road distance represents the perfect application for EVs that are not suitable for long trips [127]. Studies focused on the island of Guadalupe [128] show that introducing 20,000 EVs could increase the penetration of renewable energy by 69% and contribute to reducing greenhouse gases emission by 25%. However, the authors point out that these successful results could be achieved only in case the charging periods of the EVs were completely controlled and optimised to balance the variable energy resource. Otherwise, when considering an overnight charging period, typical of the users that intensively use the car during the day, the EVs would cause an increase in the demand and thus a negative impact on the carbon footprint with an increase of 50%. Furthermore, the ability to use vehicle-to-grid products, and thus to allow EVs to discharge into the grid, could increase the potential of this application. This concept has been investigated for the island of Sao Miguel in the Azores [129]. The paper presents the economic benefits that could be achieved by an EV's owner when exploiting different energy market: the contribution to the baseload generation, the provision of peak power energy supply or ancillary services to the grid, like spinning reserve and regulation. Finally, the large adoption of EVs in isolated grids would impact not only the energy management aspects but especially fossil fuel reduction. Reference [130] analyses the introduction of 50,000 EVs on the island of Tenerife and it concludes that the secondary benefits would impact on road transport, reducing the noise, fuel consumption, and emissions.

The geographical conformation of islands, in particular of volcanic islands, presents natural reservoirs and difference in altitude that encourage choosing pump hydro storage solutions. This idea has been examined for the Canary Island archipelago. Different studies have been focusing on the energy system of Gran Canaria and El Hierro, where a wind-powered pump hydro storage has already been realised [131][132]. The wind power plant in El Hierro is characterised by five wind turbines for a total of 11.5 MW of installed capacity. This renewable power plant can supply the electricity to 5,000 households, or in case of excess of generation, it can power the hydro pumps and store the energy [133]. The pumped hydro plant works as a backup system for the wind farm and generates electricity in case of lack of wind. This hybrid system can control the fluctuation of the wind power plant and contribute to the sustainable generation of electricity in the island: in August 2015 the isolated grid recorded four hours of 100% renewable energy supply.

5.1.3. TENERIFE (CANARY ISLANDS ARCHIPELAGO)

This work presents an overall assessment of the value of energy storage technologies in Tenerife. The electricity supply of the island is based on fossil-fuelled power plants and new government strategies are planning the installation of large renewable power plants in the isolated grid. In this scenario, the use of energy storage devices could implement the stability and reliability of the energy supply, the efficiency of thermal unit operations and the extensive penetration of renewables.

Tenerife belongs to the Canary Islands archipelago; it is regulated by the Spanish government and located in the northeast Atlantic, in front of the Western coast of Africa. Tenerife is the largest and most populated of the seven islands of the archipelago with an overall surface of 2034 km^2 and a total population of almost 900,000 inhabitants, with a further increase of over 10% of the population because of intensive tourist flow all over the year [134].

5.2. DATA REVIEW

The modest dimension of the considered isolated grid and the few numbers of units installed on the island allowed the in-depth investigation of the technical parameters of every unit. This approach differs with the one adopted for the analysis of the GB electric grid (Chapter 6), where the hundreds of electric units have been modelled as conglomerated in large generators, one for each power plant technology.

The examination of Tenerife electric grid has been facilitated by the large availability of real data and technical information published on the website of the Spanish transmission system operator (La Red Electrica) [135] and on the official government bulletin [136]. La Red Electrica distributes real-time and historical data related to the electric demand variation, the technology mix that supply the load, and the amount of CO_2 emission. The real data is collected and listed with the time step of 10 minutes. The information published in the government bulletin refers to important technical parameters for every single plant, like maximum and minimum capacity level, heat rate, variable and fixed costs of operation and fossil fuels costs.

5.2.1. INSTALLED CAPACITY

In Tenerife, the ring-shaped electric network connects the four main power plants of the island to the demand (**Figure 5-1**).

Figure 5-1 *Tenerife ring-shaped power grid*

The overall installed capacity corresponds to 1,266 MW and almost 90% is covered by fossil-fuelled power plants and the remaining is provided by solar panels and by a modest portion of wind power plants (**Figure 5-2**).

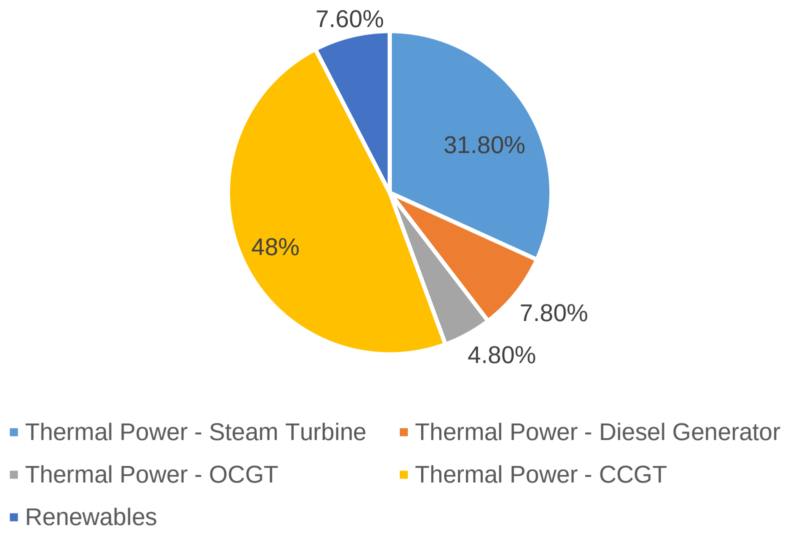


Figure 5-2 *Electricity demand by sources.*

The strong dependence of Tenerife on fossil fuels supply is common to many isolated grids. The thermal power plants include four open cycle gas turbine (OCGT) units, one oil-fuelled steam turbine, one diesel generator and one combined cycle (CCGT) plant. The size of these units rarely exceeds 100 MW of maximum capacity, except for the CCGT that achieves a total installed capacity of 432 MW (**Table 5-1**). The diesel generator is the unit with the highest heat rate and thus the best energy efficiency compared to the other technologies. Moreover, the oil fuel used in this plant is cheaper than natural gas, making the diesel generator the most competitive on Tenerife energy market. Thus, this unit operates at a constant rate generating a continuous base load for the demand supply. The OCGTs are the units with the most elevated operational costs, but fastest and cheapest start-ups: for these reasons the three gas units are used for providing only the demand peaks, with around 10% of the total capacity. The steam turbine and the CCGT are listed among the most efficient and competitive units, after the diesel generator. Moreover, they have strict technical constraints that require the plants to operate always at a minimum stable level around 35-37% of the installed capacity. This means that even during the valley periods the steam turbine and the combined cycle plant operate providing the minimum capacity level, while the diesel generator supplies the remaining part of the load.

Table 5-1 *Thermal power plants technical parameters.*

Thermal Power Plant	Max Capacity [MW]	Min Stable Capacity [MW]	Heat Rate [GJ/MWh]	Min Capacity Factor [%]
Arona OCGT	43.2	9.7	9.017	-
Candelaria Gas OCGT	79.38	20.37	9.313	-
Granadilla Diesel	41.02	28.18	5.78	68.7
Granadilla Gas OCGT	71.54	13.58	7.42	-
Granadilla Steam Turbine	148.48	55.68	9.04	37.5
Granadilla CCGT	432	149.5	8.05	34

5.2.2. DEMAND

The electric demand profile of Tenerife has an average daily peak of 460 MW that occurs during the evening (**Figure 5-3**), whilst the lowest demand can achieve the minimum value of 260 MW during the night. Figure 5-4 represents the average daily demand profile calculated over each month. Looking at Figure 5-4 it can be noticed that the electricity demand is not subjected to large variation along the year. The lack of season variation could be due to the mild temperature during the whole year and the temporary increase in population during the holiday periods.

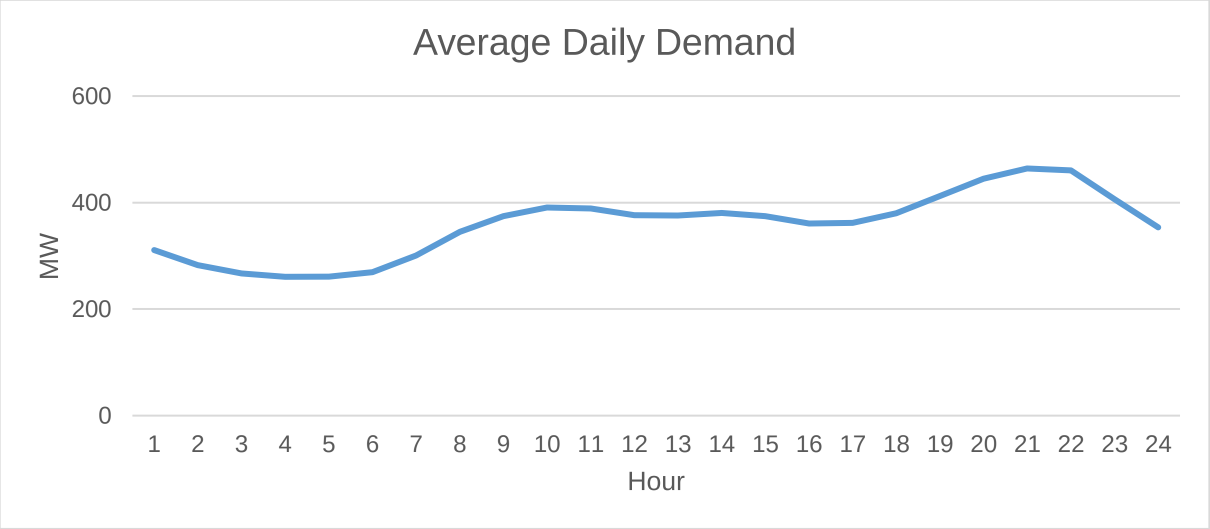


Figure 5-3 *Average daily demand (MW) - year 2015.*

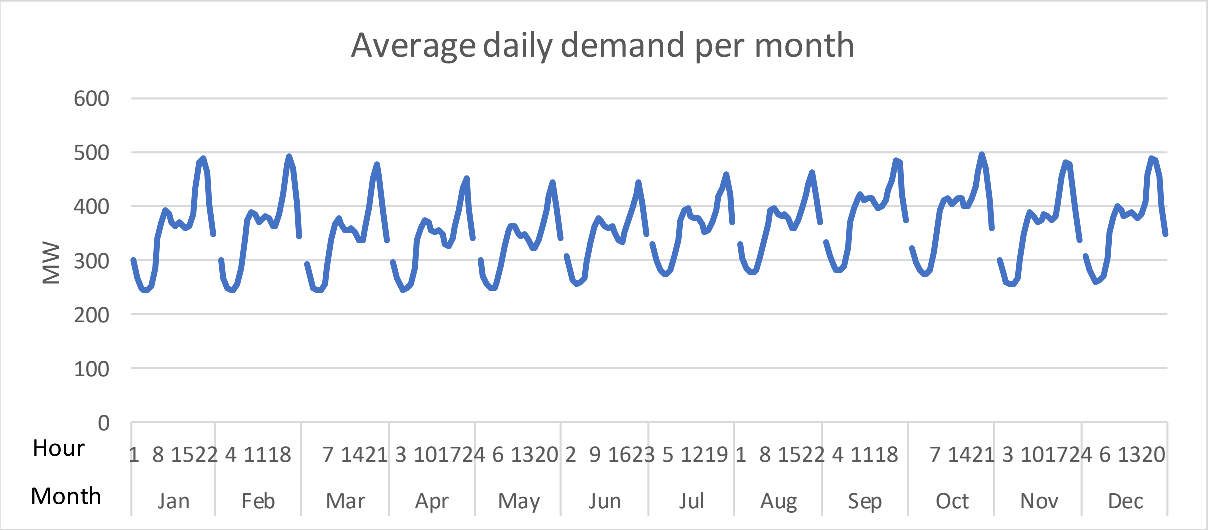


Figure 5-4: Average daily demand across the whole year

The trend of the total energy demand (**Figure 5-5**) is coherent with the yearly variation that affects the Canary Islands archipelago: the maximum total consumption has been achieved in 2008, after that year, the demand has been decreasing because of the economic crisis that influenced the whole Spanish energy market. In recent years, demand has risen again because of the economic growth and the increase of population [137]. However, this recent increase in the demand presents a slow growing rate because it has been mitigated by the progressive implementation of energy efficiency measures.

Predictions on the future trend on the population on the island show that this value is expected to rise, due to intense immigration flow to Tenerife, increasing by 18% compared to 2012 [137].

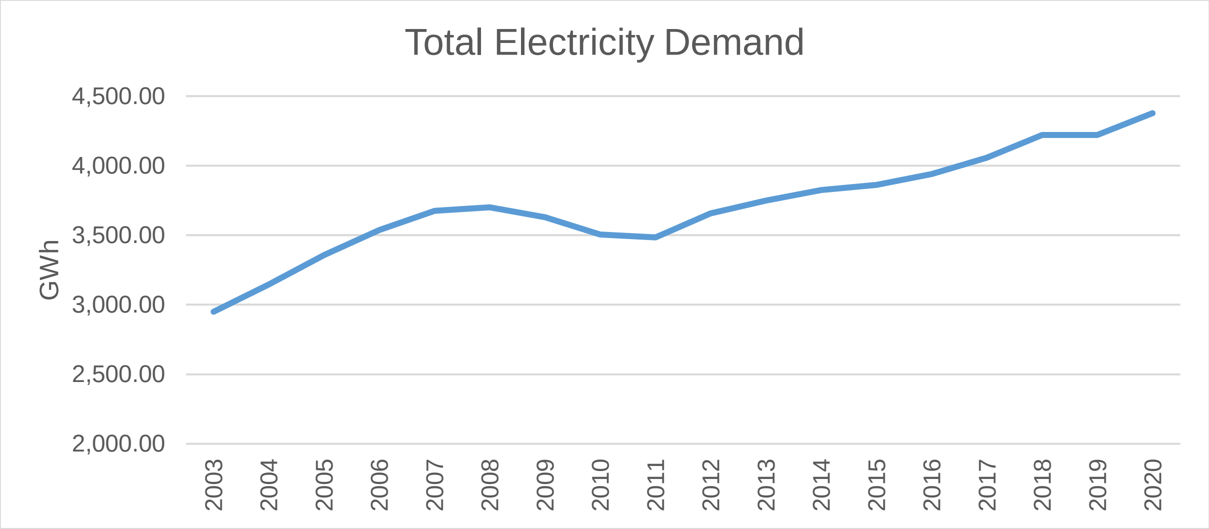


Figure 5-5 *Trend of annual electricity demand in Tenerife*

5.3. FUTURE SCENARIO

The government of the Canary Islands worked on three scenarios of the energy situation for the 2020s for the whole archipelago. This section focuses on the energy strategy suggested for the island of Tenerife. The necessity for new developments of the energy system layout has been driven by three factors:

- The need to increase the amount of power capacity, to cope with the future rise of the energy demand correlated to the local population increase;
- The desire to reduce the strong dependence on fossil fuels and do not rely anymore on fuel imports from the mainland. This aim would encourage the deployment of a more energy independent system and would reduce the energy costs, because of the avoidance of the fuel delivery and transport fees;
- The willingness to decrease the carbon footprint of Tenerife power sector, that is currently relying on 90% of fossil-fuelled energy production. This

achievement is planned to be reached by both improving the efficiency of energy consumption and increasing the renewable share on the island.

The three future energy scenarios for Tenerife energy system are presented hereafter and summarised in **Table 5-2**.

Table 5-2 *Summary of three future energy scenario*

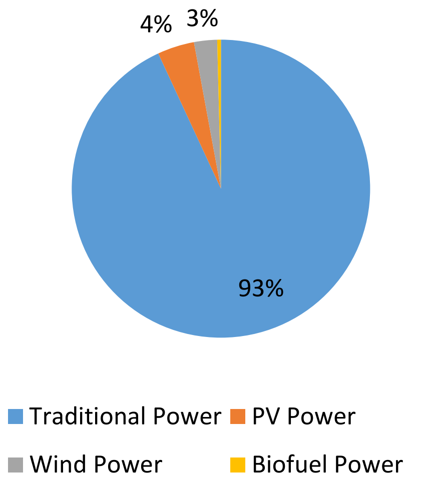
	Scenario 0	Scenario 1	Scenario 2
Demand [GWh/year]	4263.73	4189.3	4062.5
Traditional Power [MW]	1066	1066	1066
Wind Power [MW]	36.7	412	412
PV Power [MW]	97.3	218.5	218.5
Biofuel Power [MW]	1.6	12	12
Geo Power [MW]	-	10	10
Hydropower [MW]	-	90	-

Scenario 0: This is the most conservative of the future energy scenarios since it considers that the actual energy situation would be maintained with no alteration in the future (**Table 5-3**). The plan for the Ration Use of Energy (URE), which considers implementing efficiency measures to reduce consumptions, would not be applied; the natural gas would not be introduced and the infrastructures for the renewable energy

would be kept equal to the actual one. This means that this scenario presents the highest demand per year because no energy efficiency measure would be applied to reduce the energy consumption. The lack of any further addition to the power capacity installed would lead to more intense exploitation of the original thermal generators to cover a higher demand.

Table 5-3 *Projection of technology mix for power generation, Scenario 0.*

SCENARIO 0	**2020**
Demand [GWh/year]	4263.73
Traditional Power [MW]	1066
Wind Power [MW]	36.7
PV Power [MW]	97.3
Biofuel Power [MW]	1.6

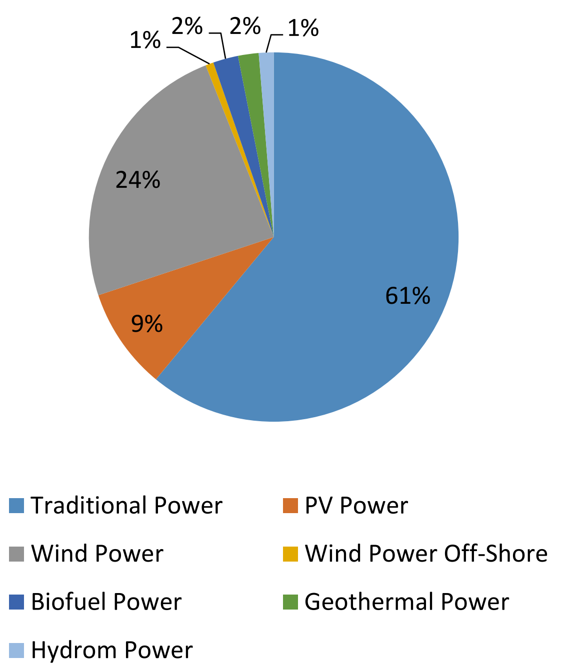


Scenario 1: This scenario is considered the most sustainable among the three different strategies suggested by the government. It considers applying the plan for the Ration Use of Energy (URE), the use of natural gas, improving the adoption of renewable energy sources and incrementing the penetration of the renewable energy production, using storage and energy demand control. The ambitious government future plan considers installing variable renewable energy for a total of 652.5 MW that corresponds to 61% of the total thermal power plants capacity. The largest renewable energy contribution would be provided by large-scale onshore wind power plants with a total of 402 MW installed, followed by almost 220 MW of PV. Minor energy provision

is expected from the offshore wind farm, geothermal, and biomass power plants, whose installed capacity is planned to be around 10 MW per generator. The expected large contribution of variable energy and the lack of interconnectors that might support the balancing mechanisms of the grid suggest the necessity of introducing further energy efficiency measures, like energy storage and demand control. Canary Islands government considers that for 2020 the most common storage technology adopted will be pumped hydro storage. In Scenario 1, to ensure the security of the energy supply and the flexibility of the electrical grid, the adoption of large hydro pumped storage will be preferred to the installation of combined cycle plants, diesel generators and small gas turbine, due to the storage's faster response and higher efficiency. In **Table 5-4**, the storage capacity installation is planned to be 90MW.

Table 5-4 *Projection of technology mix for power generation, Scenario 1.*

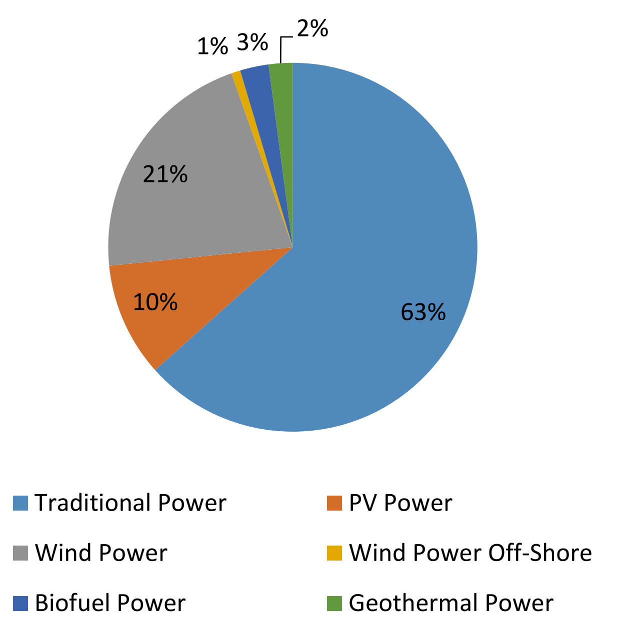
SCENARIO 1	**2020**
Demand [GWh/year]	4189.3
Traditional Power [MW]	1066
Wind Power [MW]	402
Wind Off-Shore [MW]	10
PV Power [MW]	218.5
Biofuel Power [MW]	12
Geo Power [MW]	10
Hydropower [MW]	90



Scenario 2: Similarly to Scenario 1, it considers applying the plan for the Ration Use of Energy (URE), the use of natural gas, adopting renewable energies, however, this scenario does not include the increment of the penetration of the renewable energy production, represented by the hydro pumped plant (**Table 5-5**). The absence of any storage technology would not allow the complete exploitation of renewable energy installed. Thus, the same installed capacity of renewable plants could provide a minor amount of electricity. According to the government expectation, renewable energies could cover 36.6% of energy demand in Scenario 2, while this percentage has been calculated equal to 39.6% in Scenario 1.

Table 5-5 *Projection of technology mix for power generation, Scenario 2.*

SCENARIO 2	**2020**
Demand [GWh/year]	4062.5
Traditional Power [MW]	1066
Wind Power [MW]	402
Wind Off-Shore [MW]	10
PV Power [MW]	218.5
Biofuel Power [MW]	12
Geo Power [MW]	10



The analysis of the future evolution of Tenerife energy system has been the object of this work. The aim is to draw attention to the potential implementation of energy storage technologies in an isolated grid with large-scale renewable power plants. Moreover, the simulations will analyse scenarios similar to the ones described in the government plans, drawing interesting conclusions on the environmental and economic optimizations. The energy scenarios have been modelled thanks to the use of the energy system modelling tool PLEXOS. The results are presented in the following sections.

5.4. DESCRIPTION TENERIFE ENERGY SYSTEM MODEL

PLEXOS, the optimisation tool for energy system, has been used for modelling Tenerife electric grid. The simulation of the unit commitment and economic dispatch of the isolated grid allows highlighting problematic situations that could be solved with the use of energy storage technologies. The focus has been drawn on:

- Reducing the system costs by increasing the balancing mechanisms flexibility
- Improving the efficiency of a single power plant;
- Increasing the penetration of renewable power plants considered in future energy scenario.

The case studies simulated in PLEXOS are the following:

- Case 0: the current status quo;
- Case 1: the installation of grid-scale energy storage, to improve the balance mechanisms;
- Case 2: the installation of an energy storage device directly connected to one gas plant, to improve its efficiency;

- Case 3: the introduction of wind power plants as planned in the government strategy that considers installing 400 MW of wind capacity without energy storage devices (following Scenario 2);
- Case 4: the installation of an energy storage device directly connected to the wind power plant, to improve the penetration of renewable energy and reduce curtailment (similarly to Scenario 1).

5.4.1. MODEL DESIGN

The power plants are connected to the demand, ideally agglomerated in one node, through the description of transmission lines. The load profile has been collected from the website of the Spanish transmission system operator and represents the demand request for the year 2017, sampled with a time step of one hour.

The model has been realised starting with defining the thermal power plants characteristics. Values of maximum installed capacity, heat rate, and variable and fixed costs have been collected from the official government bulletin and represented the first fundamental parameters to describe the operations of the thermal plants. Knowing the heat rate of the thermal plants and the fuel price (see Annex A) it is possible to calculate the total fuel costs for generating the electricity.

Based on these first inputs (demand profile and thermal plants techno-economical parameters) PLEXOS simulates the unit commitment of Tenerife's energy system by defining the unit commitment problem in mathematical terms (as described in Section 4.2). The cost function considers the sum of the fuel costs (FC) and operation costs (MC) for each power plant and each time step:

$$\sum_{i=1}^{N}\sum_{t=1}^{T} FC_{it}(P_{it}) + MC_{it}(P_{it})$$

By applying the MILP theory, PLEXOS optimises the cost function and defines the value of the power output (P_{it}) for each power plant and each time step, such that it minimises the costs for the energy system. The solution needs also to meet the following constraints:

- the demand constraint imposes that the sum of the power output for each power unit meets the demand for each time step:

$$\sum_{i=1}^{N}(U_{it} * P_{it}) = D_t^f$$

- the power plant technical constraint limits the power output of the power unit between the minimum and maximum values:

$$P_{it}min < P_{it} < P_{it}max$$

- the transmission line constraint limits the power flow through the transmission lines:

$$MVAf_{ij} \leq MVAf_{ij}max$$

  As the transmission constraints are not a focus of Tenerife case study, the maximum power flow has been set higher than the maximum peak demand, such that it would not affect the unit commitment result.

See Section 4.2 for more detailed information about the formulation of the mathematical model of the unit commitment.

5.4.2. MODEL VALIDATION

Based on this information it is possible to run the preliminary simulation. These first results are not aiming to present the validation of the model, but to show the (wrong) results that would be obtained if the modelling of the thermal plants would have been based just on the few fundamental parameters described so far (demand profile and thermal plants techno-economical parameters).

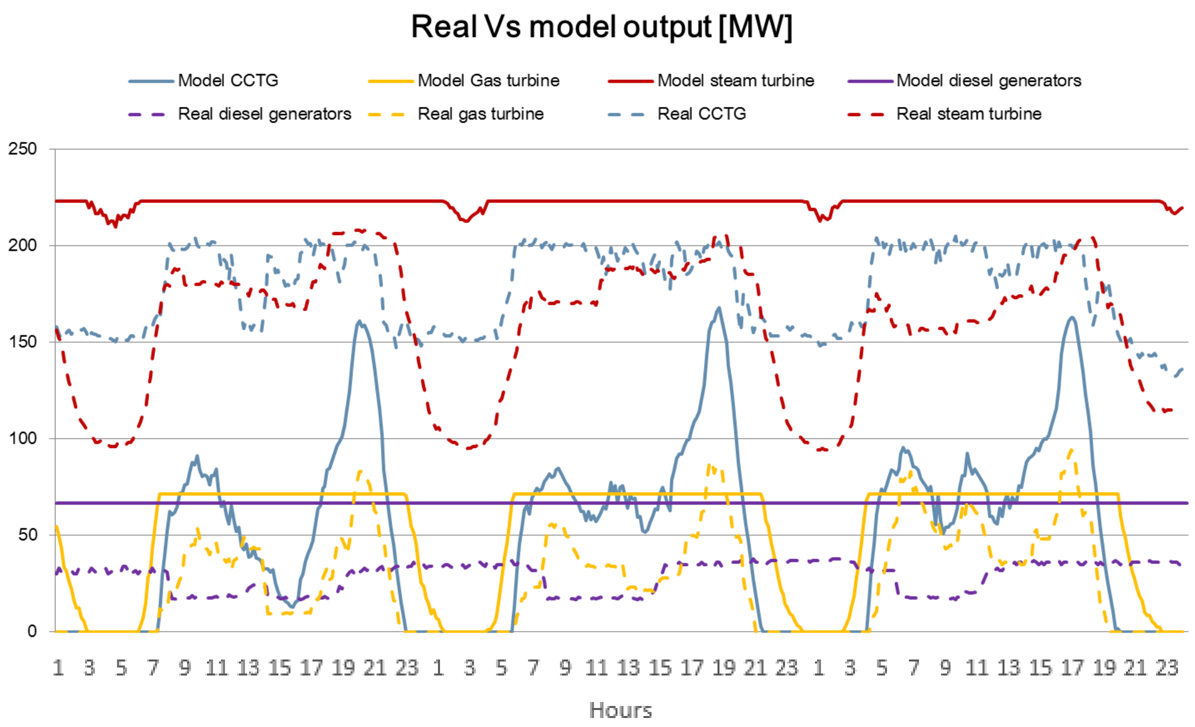


Figure 5-6 *Comparison of modelled thermal power plants generation and real data – Preliminary results*

PLEXOS simulates the optimal unit commitment such that it minimises the costs for the energy system and it respects the constraints imposed by the user, in this case the hourly demand and few technical parameters of the thermal plants. The initial results obtained are shown in Figure 5-6. Most of the demand is provided by the diesel generator and the steam turbine, which are the least expensive power plants and work at the maximum constant rate. The remaining part of the load, represented by the demand peak, is supplied by the CCGT and OCGTs.

As can be noticed in Figure 5-6, this optimal model solution (solid line) does not respect the technology mix that has been chosen by the grid operator for the demand supply (dotted line). The reason is that the transmission system operator needs to consider further technical constraints (**Table 5-6**) that force the final unit commitment to diverge from the optimal economic one:

- First, the start-up costs are considered in the cost function that defines the energy system (as described in Section 4.3) and this reduces the shutting down of the plants since the high start-up costs would increase the over costs for the energy system.
- Also, the minimum capacity factor forces the operator to run CCGT at a minimum of 34% of its total capacity.
- Then, the operations of the steam turbine and diesel generator have been limited by the minimum and maximum capacity factor.
- Finally, the schedule of the small gas turbines has been regulated by controlling the daily value of the capacity factor.

Table 5-6 *Technical constraints imposed on thermal power plants operations.*

Thermal Power Plant	Start-up Costs [€]	Maximum Capacity Factor [%]	Minimum Capacity Factor [%]	Average Daily Capacity Factor [%]
Arona OCGT	270	100	0	10

Candelaria Gas OCGT	270	70	0	10
Granadilla Diesel	1,000	87	50	-
Granadilla Gas OCGT	270	100	0	10
Granadilla Steam Turbine	72,000	100	37.5	-
Granadilla CCGT	11,000	100	34	38

Further improvements and better validation of the model results against the real data have been achieved by introducing the constraints of the reserve and regulation provision. The limits imposed, following the real grid code indications [138], require:

- The regulation up to cover the generation of the maximum generator, in this case, the CCGT;
- The regulation down to provide half of the amount of the regulation up.

Introducing the technical constraints of the thermal power plants and regulation provision allowed to achieve improvement in the modelled unit commitment, as can be noted looking at **Figure 5-7**, where the model output is compared with the real data across four days.

The complete list of data defined in the model is presented in Annex A.

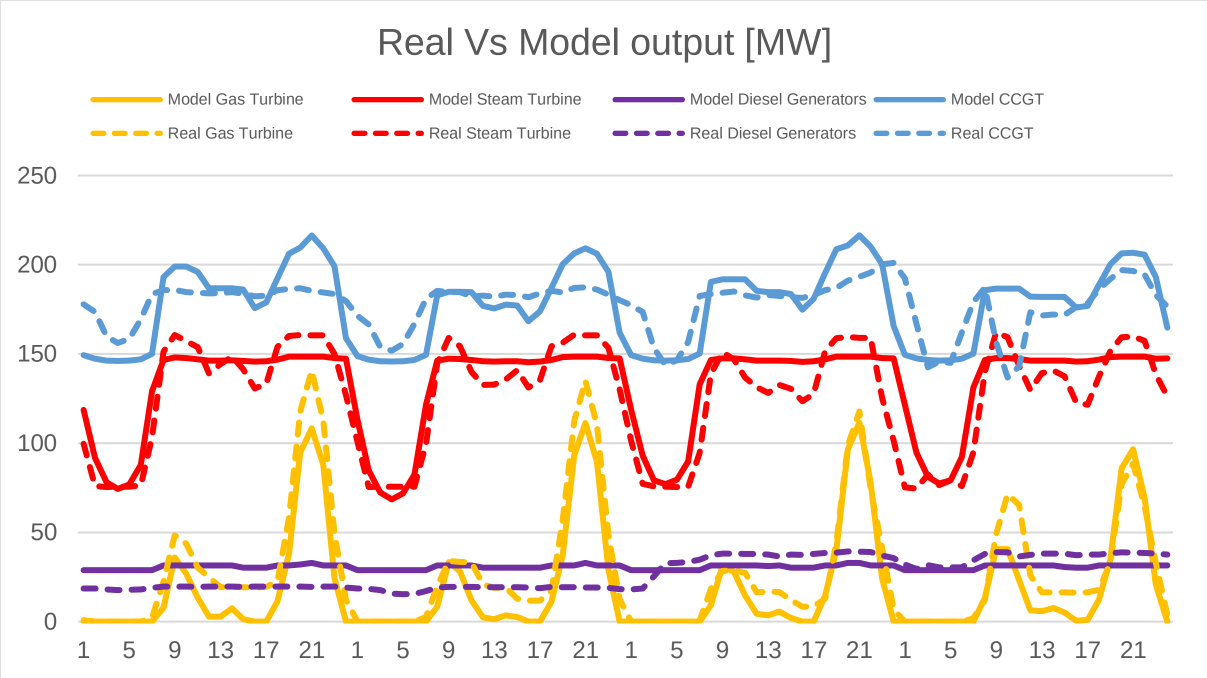


***Figure 5-7** Comparison of modelled thermal power plants generation and real data – Final results*

5.4.3. RENEWABLE POWER PLANTS

The current energy system layout in Tenerife is characterized by a modest portion of renewable capacity installed. The renewable energy generated by solar panels, wind turbines and biomass generators, covers less than 10% of the overall energy demand of the island. This modest percentage is the reason renewable generators have not been included in the model's realisation of the status quo of the energy system. Integrating these three technologies would add complexity to the model without bringing interesting contributions, in term of energy provision. However, integrating large-scale wind power plant is the core of the simulation of the case study that investigates the consequences of the future scenario suggested by the Canarias government. Even though the future energy scenarios (Scenario 1 and Scenario 2) consider installing any kind of renewable power plant (like wind farms, PV panels, biomass and geothermal plants), the model focuses only on the installation of wind power plants. This decision is justified by the very large percentage of wind power capacity compared to the other renewable sources and the intense variability of the output profile that makes it the most challenge renewable plant to balance into the electric system.

The lack of historical data from large-scale wind power plants installed in the Canary Island archipelago prevented the use of real data. To simulate the wind power plants generation, it has been decided to follow the deterministic approach, and rely on yearly wind speed profile for the island of Tenerife. The real information has been obtained from online sources that collect historical weather data from global reanalysis models and satellite observations [139]. The small dimension of the island has encouraged the use of a single wind profile, considering that the overall wind power plants output would not have been influenced by the exact location.

5.4.4. ENERGY STORAGE

Case 1, Case 2, and Case 4 consider the installation of large-scale energy storage. However, the role played by energy storage differs from case to case, investigating multiple benefits that could be achieved. Thus, the energy storage technology modelled changes according to the case study considered, in order to choose the most suitable energy storage device and maximize the revenue.

Liquid air and pumped hydro energy storage have been investigated for potential installation in Tenerife energy system. The liquid air energy storage (LAES) uses the air liquefaction process to store energy [140]. The electricity powers a liquefaction unit that refrigerates the air until it reaches the liquid state. This corresponds to the charging process, whilst the insulated tank of liquid air represents the storing component. Then, when the electricity is required to the energy system, the liquid air is pumped to high pressure, heated and expanded in a turbine to generate electricity. The advantages of this technology include the possibility to design independently each section of the device (charge, storing, and discharge process), and the lack of geographical restrictions like other grid-scale energy storage technologies, such as compressed air and pumped hydro energy storage. The LAES optimizes its energy performance when operating with a source of waste heat, like a thermal power plant. The waste heat would be used for heating the liquid air, avoiding the installation of an additional thermal unit for generating heat. All the reasons mentioned above encourage the use of LAES in Tenerife. In particular, this energy storage technology can be installed near thermal power plants for the recovery of the waste heat and the optimization of the process.

To simulate the LAES operation and not add an unnecessary level of complexity to the model, the layout of this device had to be simplified. The charging, storing, and discharging process of the LAES has been associated with the operation of a battery, whose performance improves when working in synergy with a thermal power plant. This detail aims to model the variation of the storage efficiency that improves when the device can recover waste heat from an external plant. This approach has been followed for Case 1 and Case 2, where the energy storage device is considered connected to the electric grid or to a OCGT plant. The technical characteristics of the modelled LAES are listed in Table 5-7.

Table 5-7 *LAES technical parameters defined in PLEXOS model* [140][141].

LAES Technical Parameters	
Round-trip Efficiency	70% (maximum efficiency occurs assuming that the OCGT would provide enough waste heat)
Power Output	25 MW
Energy Capacity	100 MWh
Charge/Discharge Duration	4 h

Investigating of the value of the energy storage in an isolated grid with large-scale renewable power plants (Case 3) has been done considering the installation of the pumped hydro storage (PHS) power plant. This decision is not only based on the government choice described in the energy Scenario 1 but has been achieved analysing several real cases where the PHS has been used for the balancing of large wind power plants in isolated grids [142][143][144][145][146]. The model of this energy storage technology is supported in PLEXOS by defining the characteristics of the two water basins (the lower and the upper ones), the water pump for the charging process and the turbine for generating the electricity (discharging process). **Table 5-8** summarizes the technical parameters that define the PHS power plant in the model. The size of the two storage devices modelled is identical in order to ease the comparison between the different case studies. However, the maximum power is smaller than the one suggested by the government in Scenario 1 (90MW). For this reason, it will only be possible to draw conclusions on the general application of energy storage connected to large wind power plants without analysing the details of the choices made for Scenario 1.

Table 5-8 *PHS technical parameters defined in PLEXOS model* [147].

PHS Technical Parameters	
Turbine Capacity	25 MW
Pump Load	25 MW
Pump Efficiency	70%
Head Reservoir Capacity	100 MWh
Tail Reservoir Capacity	100 MWh

5.5. RESULTS

For each of the five different models, the simulations are run for an entire year, following the historic electric demand of the year 2015. The outputs and the inputs are generated with a time step of one hour. The following sections explain the simulation results obtained for each case, highlighting the influence of the energy storage operations on the unit commitment, system costs and CO_2 emission profiles.

In Section 5.2.2, when analysing Tenerife electricity demand, it has been mentioned the lack of seasonal variation of the profile. Thus, the model results do not show interesting variations according to the different period of the year. For this reason, it has been decided to represent three days of data as a representative sample of the daily behaviour of the model results.

5.5.1. CASE 0: STATUS QUO

The detailed analysis of the simulation results of Case 0 is fundamental to understand the original balancing mechanism procedures that currently regulates Tenerife electric grid. The highlight of critical outcomes from the simulation will support the assessment of the energy storage potentials for the isolated grid.

5.5.1.1. UNIT COMMITMENT

The simulation results reproduce the unit commitment and economic dispatch for the supply of the demand required by the electric grid. The decisions made by the PLEXOS model follow the need to find the minimum system costs solution and to respect the technical constraints imposed by the correct operations of the thermal plants. Thus, according to these guidelines, it is possible to understand and critically analyse the generation profile for each power plant (**Figure 5-8**).

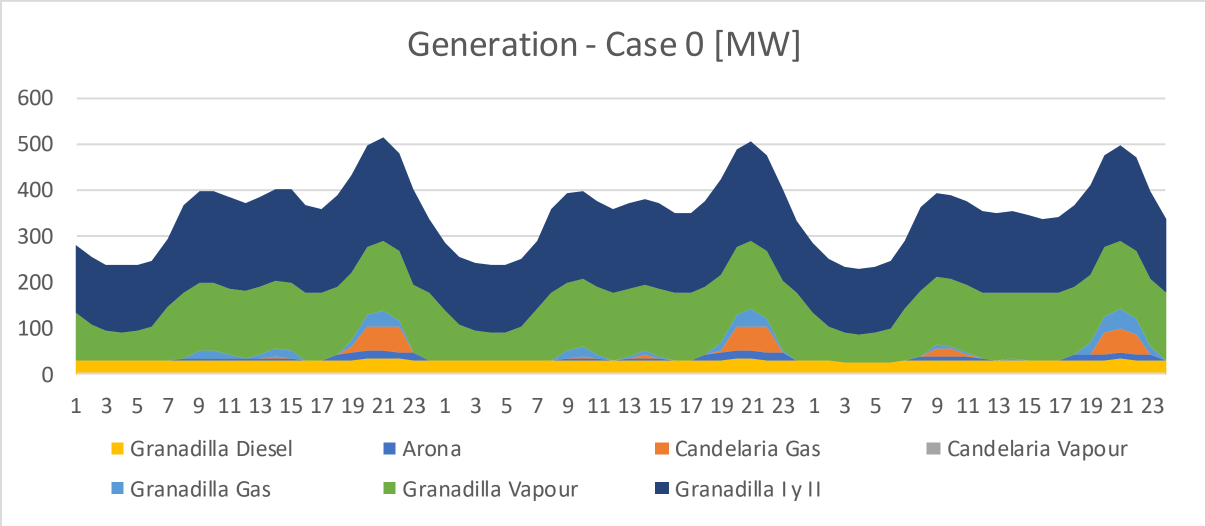


***Figure 5-8** Generation profile from each single thermal unit, according to simulation results.*

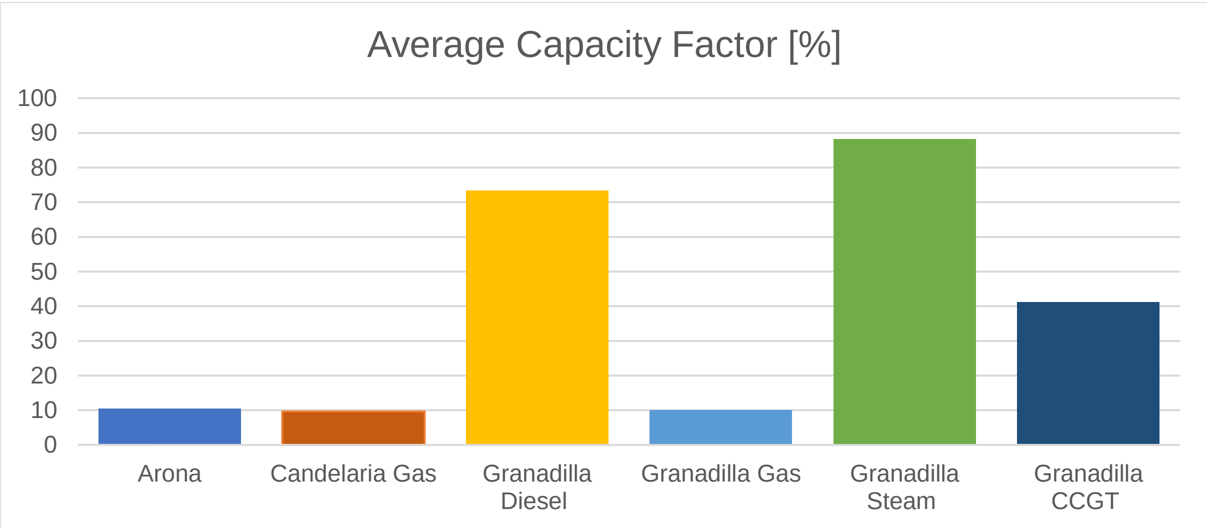


***Figure 5-9** Average capacity factor of each thermal unit across three days, according to simulation results.*

The graph in **Figure 5-8** represents an example of the technology mix designated by PLEXOS model to supply the demand across three days. As can be noticed looking at the graph, the CCGT is the plant that generates the largest portion of the demand, with production peaks that achieve 200-250 MW. However, the potential output of this plant could reach the maximum output of 400 MW, meaning that its capability is not completely exploited. Indeed, the average capacity factor for the CCGT is around 40% (**Figure 5-9**). The reasons for this limited percentage are due to the high operating costs of the plant. Nevertheless, the technical restrictions, like minimum capacity level and minimum daily capacity factor, forces the model to operate this plant instead of other more convenient options. The elevated start-up costs and the long time needed to start the plant suggest the continuous use of the combined cycle.

Looking at the average capacity factor for every single plant (**Figure 5-9**), it can be observed that the generators with the highest value are the diesel generator and the steam turbine. Both plants present the most competitive energy generation prices and for this reason, they are the most used ones for the demand provision. The average capacity factor of the diesel generator and steam turbine are 70% and 80%, meaning that none of the plants operates at the maximum capacity allowed (namely, 87% and 93%). This is because the energy system needs to respect several technical constraints at the same time and reaching a compromise for achieving an optimal solution for the entire system. For instance, the operation of the diesel generator is limited by the necessity to run both the steam turbine and the CCGT at the minimum capacity factor around 35-37%. Thus, during the demand valley periods, the diesel generator covers the remaining portion of the demand and cannot work at its maximum capacity factor, since this would impede the correct operation of the other two power plants. Similarly, when providing the demand peaks, the diesel generator needs to balance its generation with the output of the OCGTs that should work for at least 10% of their daily capacity to respect the minimum daily capacity factor imposed. Furthermore, the operation of the diesel generator or steam turbine at the maximum available capacity would not be recommended because otherwise these power plant could not provide regulation up services (as it will be explained in detail in the following paragraph focused on regulation results).

The OCGTs have elevated energy generation costs, however, the presence of competitive start-up costs and short starting time imply the scheduling of these plants for the peak demand provision. Among the OCGTs, the Granadilla Gas is the most cost-effective plant and for this reason it is the first plant that selected when the demand increases. Then, Arona and Candelaria Gas are turned on when the demand reaches the local peak values.

5.5.1.2. REGULATION RESERVE SERVICE

When analysing the regulation of reserve service in the energy grid, it is interesting to look at how the provision of this service alters the operation of the thermal plants and how the regulation costs affect the overall system costs. With a sudden increase of demand or an unexpected fault in an operating plant, the system operator requires to maintain the electricity balance by increasing the generation from the units, which need always to ensure the possibility to further increase their load. The regulation up represents the requirement to increase the spinning power plant generation, whilst the regulation down constraint stands for the need to decrease the output.

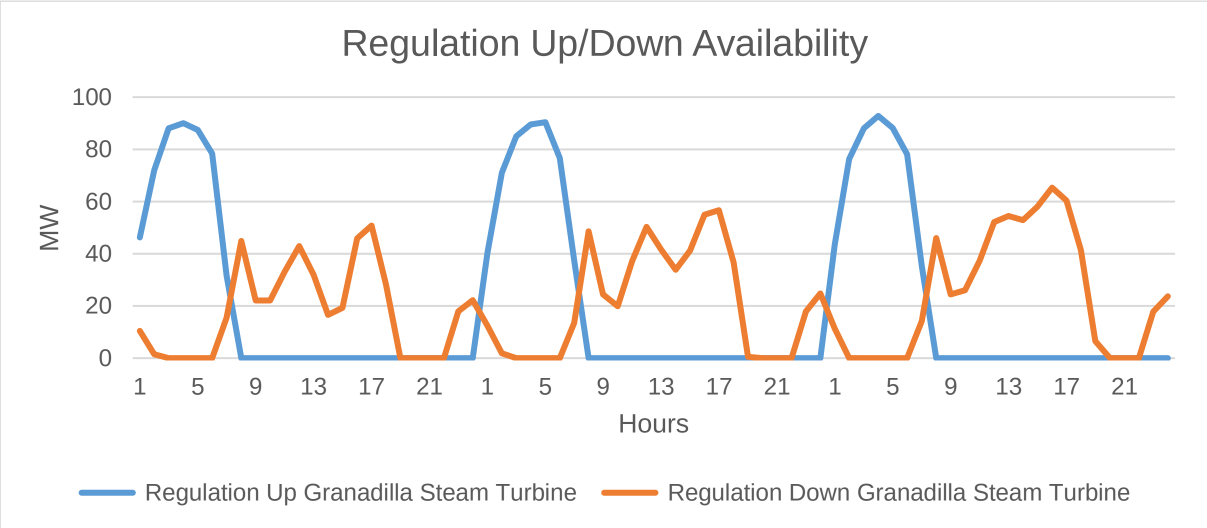


***Figure 5-10** Regulation up/down capacity availability for Granadilla steam turbine across three days, according to simulation results.*

The graph in **Figure 5-10** shows the rise and lower reserve available from the steam turbine. As expected, the reserve up is mostly available during the demand valley periods when the power plant operates at the minimum capacity level, whilst the reserve down reaches its minimum value because the plants would not be available to reduce their output. The necessity to provide regulation service limits the generation from some of the power plants impeding them the possibility to work at the maximum capacity available. For instance, this is the case of the diesel generator, whose flat profile is constrained by the necessity to supply around 10 MW of available reserve up.

The regulation price is calculated as the ratio between the cost to the system of providing reserve at the marginal cost of reserve provision and the total amount of reserve being provided. The prices paid to supply raise and lower reserve reflect the general availability of the power plants to provide the service. For instance, looking at the variation of the reserve up price (**Figure 5-11**), it can be noticed that the value is minimum during the night when the operating generators work at their minimum capacity and they all would be available to increase their output if needed. Instead, when the power plants increase their generation they would not be willing to accept a

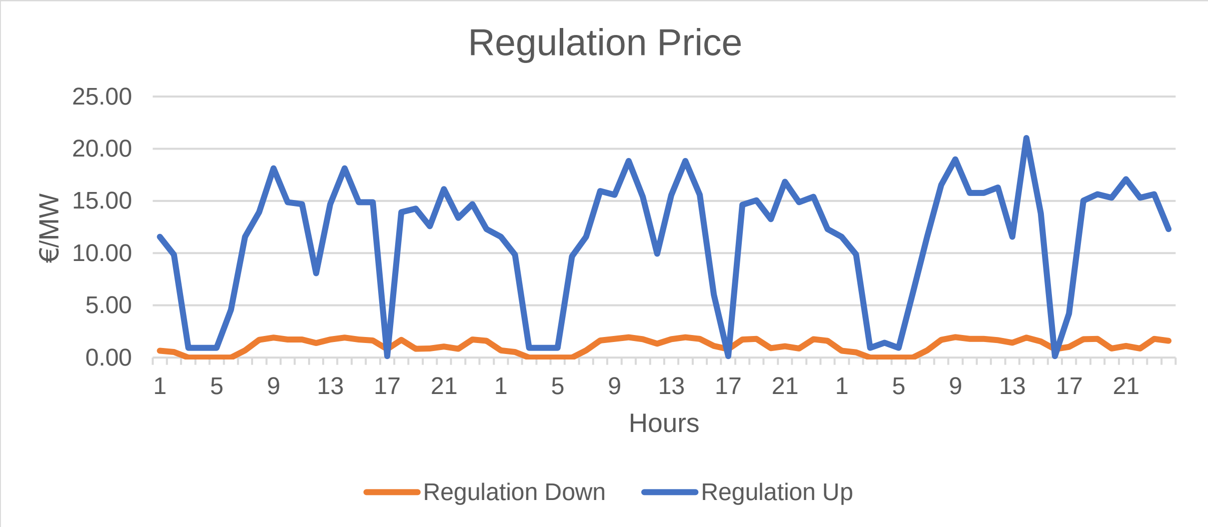


Figure 5-11 *Regulation up/down price across three days, according to simulation results.*

further increase in the load. For this reason, the reserve up price rises to incentive the provision of this service.

5.5.1.3. WHOLESALE ELECTRICITY PRICE

The wholesale electricity price corresponds to the price issued to the load for the consumption of energy and its value depend on the costs afforded to generate that amount of energy required. Thus, its value fluctuates during the day and follows the variation of the energy generation with peaks during the middle of the day and valleys during the night. Looking at **Figure 5-12**, it can be noticed that the average wholesale electricity price is above 200 €/MWh. Even if this value seems extremely elevated, it follows the real trend, as mentioned at the beginning of this chapter, when referring to the high wholesale electricity price of isolated grids.

The variation between the peaks and the valleys in the wholesale electricity price profile is less accentuated than the correspondence variation in the energy generation profile (**Figure 5-12**). The main reason that justifies this behaviour is that during the valley periods the principal power plants operating, the steam turbine and the CCGT, work at the minimum load. Thus, their operating point is far from being the optimum one. This operating condition forces the plants to work at low efficiency and the not optimized procedures lead to higher costs of energy generation. These costs are driven by the large amount of fossil fuels that need to be burnt due to the low efficiency.

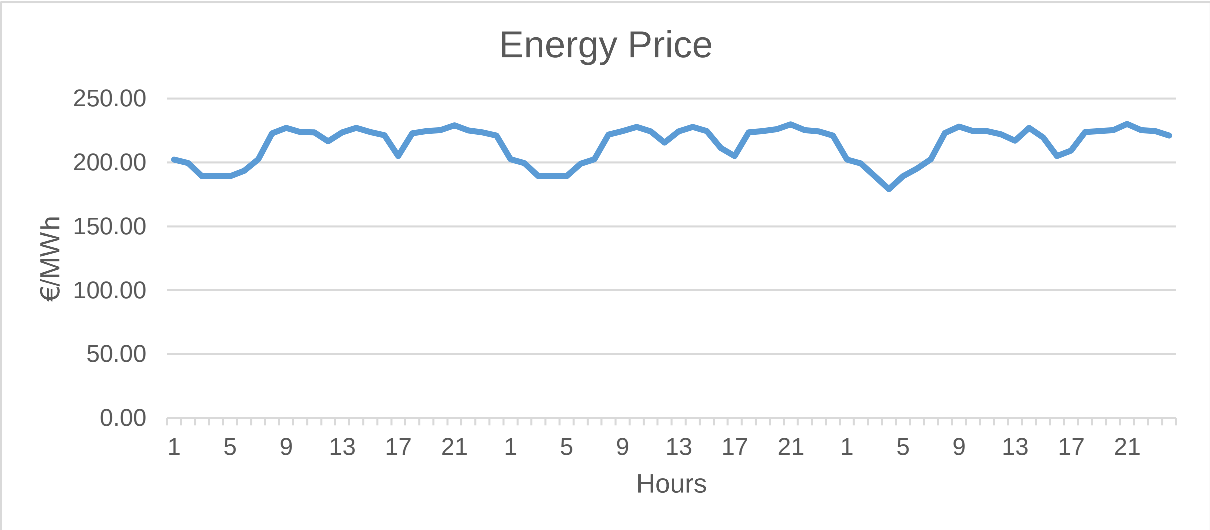


***Figure 5-12** Wholesale electricity price variation across three days, according to simulation results.*

5.5.1.4. CO_2 EMISSION

Figure 5-13 shows the CO_2 emission rate, defined as the total emission generated per unit of power output. The total emission production is calculated by knowing the relationship between the fuel usage of each thermal plant and the CO_2 emissions (see Annex A).

Looking at the graph, it can be noted that the emission curve is, first, subjected to a sharp increase corresponding to the instant when the OCGTs turn on to cover the demand rise. Then, the CO_2 emission rate profile stabiles as soon as the generators improve their operating efficiency. Finally, the curve shows a drastic fall in correspondence with the highest demand peak; the intensity of CO_2 production decreases because both the energy generation achieves its maximum local value, and the power plants reach their optimum operating point, maximizing the efficiency and, thus, reducing the amount of CO_2 emission rate.

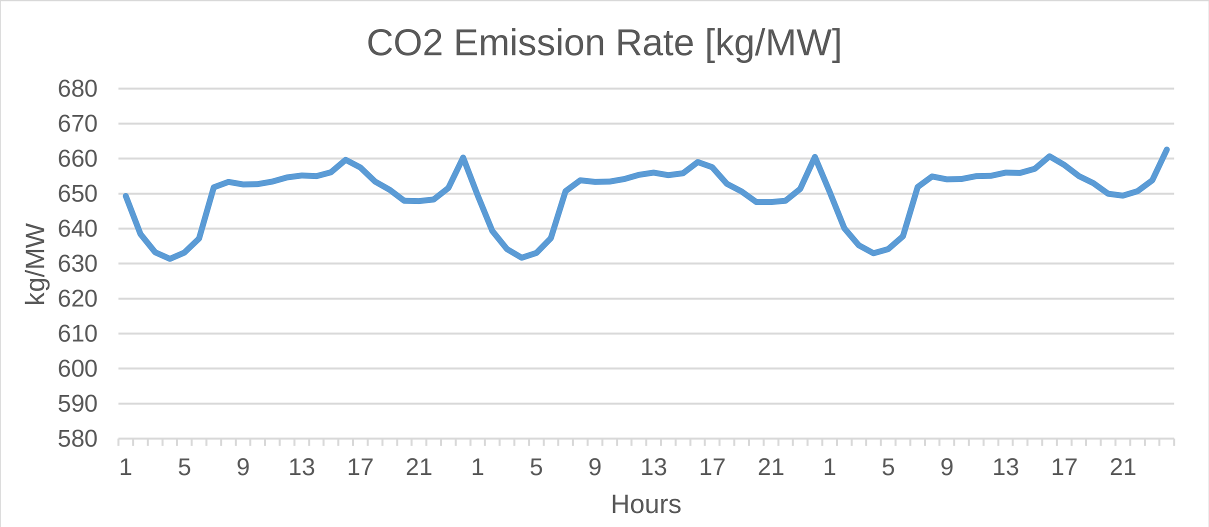


Figure 5-13 *CO_2 emission curve for Tenerife electric grid across three days, according to simulation results.*

5.5.2. CASE 1: ENERGY STORAGE CONNECTED TO GRID

The model presented in this paragraph analyses the potential influences energy storage technology can have on Tenerife energy system when connected to the entire electricity grid. The simulation results draw attention to the economic and environmental advantages that can be achieved and on the alteration of the balancing mechanism following the installation of grid-level energy storage devices.

The effects energy storage technologies have on Tenerife energy system are explained below. The value of the energy storage is investigated looking from the whole energy system perspective, and it is evaluated as the impact on unit commitment decisions, wholesale electricity price, and greenhouse gases emissions.

5.5.2.1. UNIT COMMITMENT

The presence of the energy storage device is seen by the system operator as an opportunity to reduce the overall system costs. For this reason, the role played by the storage can be summarised as load-shifter; the energy storage charges during the demand valley periods and discharge when the demand rises for covering the peaks (**Figure 5-14**). Therefore, the effect that the energy storage installation plays on the thermal power plants operation is increasing the generation during the valley periods and reducing it in correspondence to the peak periods. This means that the general generation curves gain a flatter profile compared to the output achieved in Case 0.

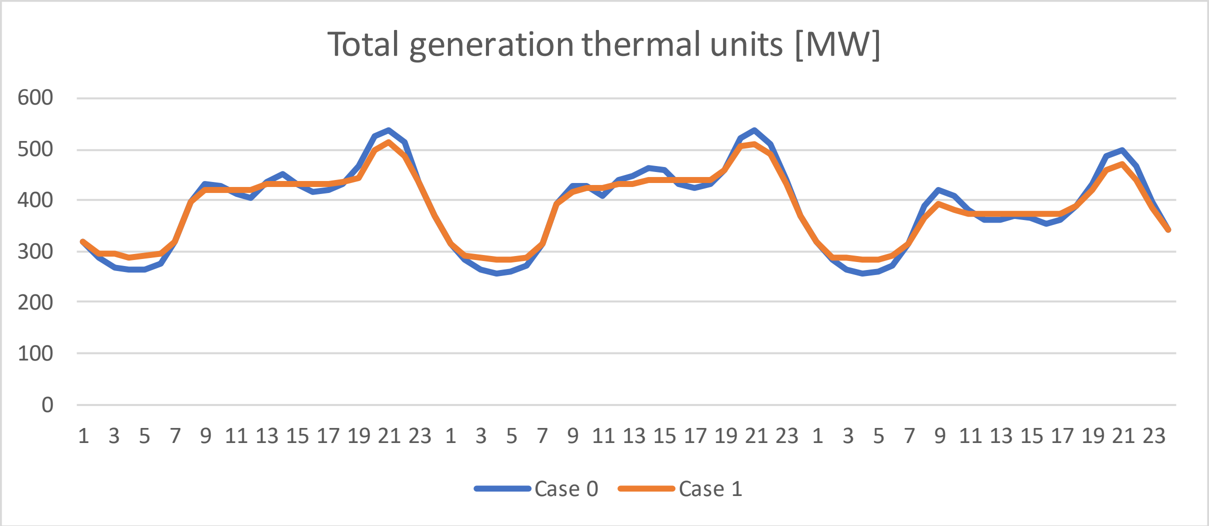


Figure 5-14 *Comparison of total generation of thermal power plants for Case 0 and Case 1, across three days.*

The consequences of introducing an energy storage device and the modifications of the generation profile are particularly visible for the steam turbine and the CCGT (**Figure 5-15**). Without the energy storage operation, the steam turbine generation curve shows a severe fall during the night with a rapid increase that follows the daily rise of the demand. The presence of the energy storage incentives the electricity production when the demand is minimum, reducing the variation in the steam turbine generation. The electricity that is stored during the night is then released during the day affecting the output of the CCGT that is the main provider of the demand peaks. The maximum value of generation achieved by the CCGT is reduced and the modest reduction disappears to supply more energy to the storage.

Similar, but less emphasised, consequences appear in the OCGTs output. The OCGTs, which generally operate to cover only the demand peaks, produce a more constant generation across a longer period. Looking at the graph, it can be noted that only Candelaria Gas and Granadilla Gas, are designated for the supply of the demand peaks.

The diesel generator shows modest variation in the generation profile. This curve already presents a constant behaviour, which incurs a slight reduction to follow the reduction of the demand and the resulting decrease of the steam turbine and CCGT output. It has already been shown how energy storage encourages a more intense electricity production from the steam turbine. Therefore, this means that also the diesel generator can increase its generation and achieve a constant operation across the entire working period.

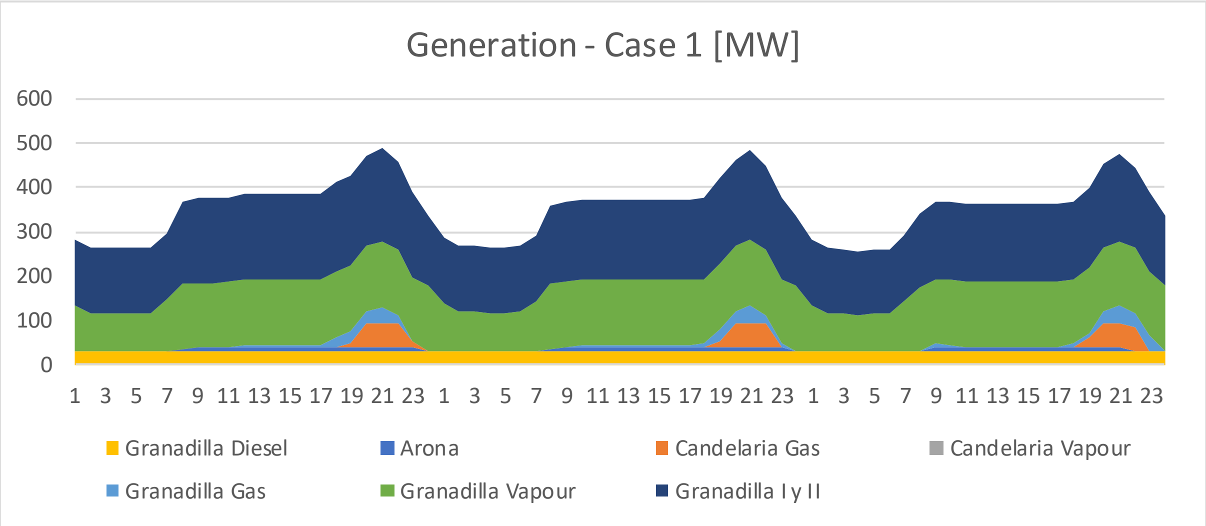


Figure 5-15 *Generation from each thermal unit across three days, according to Case 1 simulation results.*

5.5.2.2. SYSTEM COSTS

The detailed description of the influence of the energy storage technology on the unit commitment decisions facilitates understanding the system costs variation after installing the energy storage device. The system costs are calculated as the sum of the fuel cost, VO&M costs, and start-up/shut-down costs for each power plant and every time step. **Table 5-9** shows an overall decrease of the system costs between Case 0 and Case 1 following the use of grid-scale energy storage technology. This results as a combination of variating both wholesale electricity price and regulation costs.

Table 5-9 *Comparison of yearly system costs for Case 0 and Case 1.*

	Case 0	**Case 1**
System Costs [€000/year]	695,240	693,929

The daily wholesale electricity price fluctuation follows the general generation trend; this means that, regarding the results of Case 0, the wholesale electricity price slightly increases during the valley periods and decreases during the peak periods, due to the load shifting action of the energy storage (**Figure 5-16**).

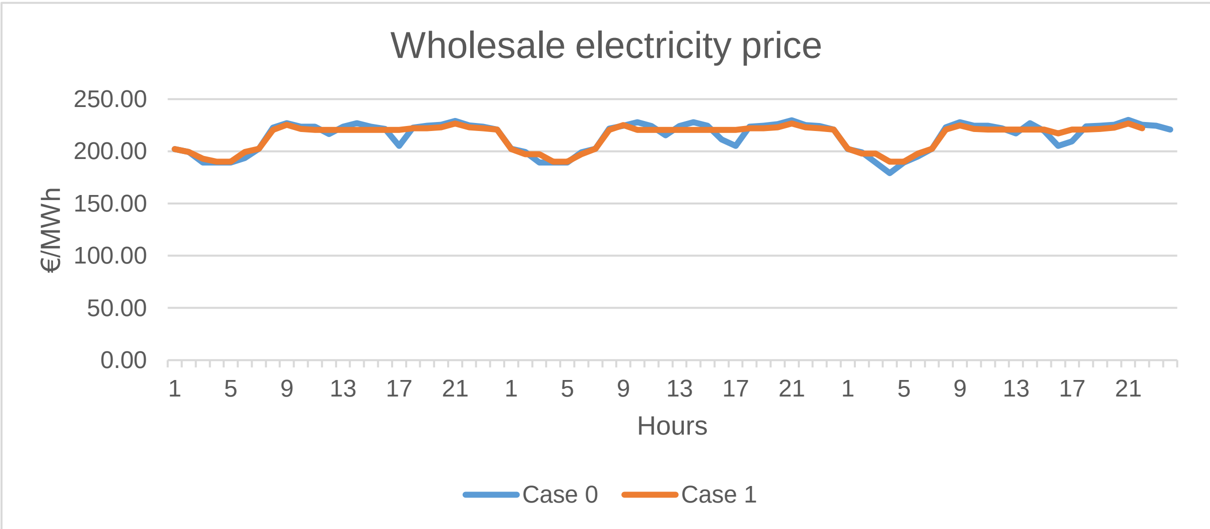


Figure 5-16 *Comparison wholesale electricity price variation in Case 0 and Case 1.*

Moreover, energy storage operation allows the system operator to optimize the schedule of the thermal power plants to minimize the generation costs. For this reason, the average wholesale electricity price is subject to a reduction because of the fossil fuel consumption savings. Indeed, the increased level of flexibility introduced by the energy storage encourages the generation from the diesel generator and steam turbine for charging the energy storage during the low demand periods. Thus, these two plants replace the operation of the gas turbines during the peak periods, and because of the fossil fuel costs differences, this is reflected in an overall wholesale electricity price reduction.

However, the variation of the wholesale electricity price profile has a slight effect on the overall system costs. Most of the reduction is due to the decrease of the regulation costs, compared to the values obtained for Case 0. As mentioned in the previous paragraphs, an energy storage device in an isolated grid can lead to interesting benefits for the management of the network. These benefits are then reflected in the reduction of the costs needed for the regulation services provision. The Regulation Down requires the spinning thermal power plants to reduce their output in case of an unbalance event in the network. The correspondence price for this service is usually elevated when the operating generators work at their minimum level, as shown for the Case 0 results. However, the necessity to charge the energy storage during the valley periods increases the operation rates of the power plants that could provide Regulation Down since they do not operate at the minimum level (**Figure 5-17**). Regulation up/down price variation across three days, according to Case 1 simulations results.

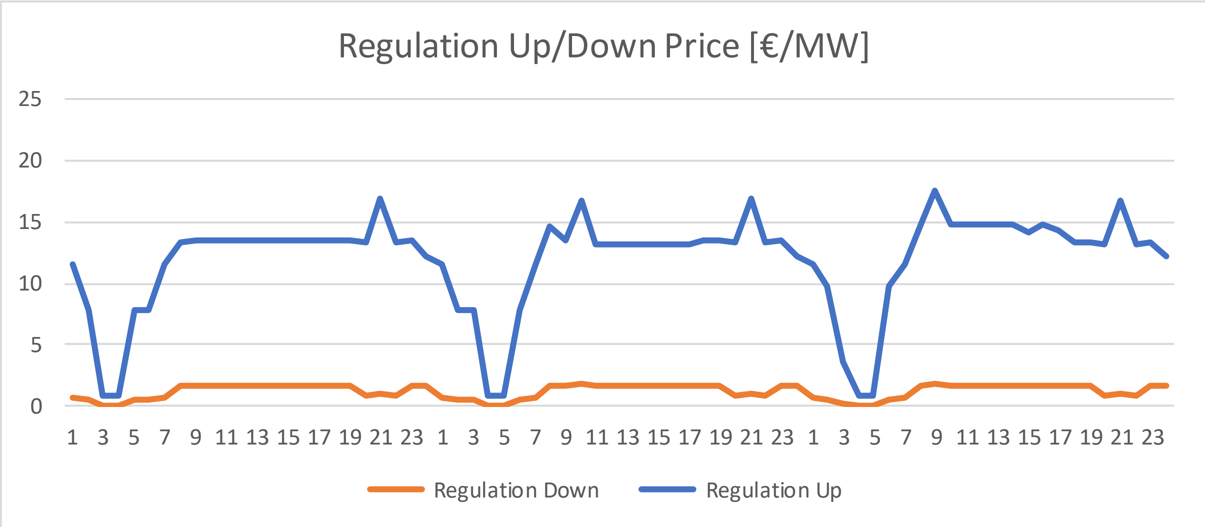


***Figure 5-17** Regulation up/down price variation across three days, according to Case 1 simulations results.*

Similarly, the Regulation Up price encourages the spinning power plants to suddenly increase their generation and it decreases when simulating the energy storage device in the grid. The energy storage discharging partially replaces the output from the peak plants (e.g. CCGT and OCGTs), which are more available to increase their generation (**Figure 5-17**).

5.5.2.3. CO_2 EMISSION

The main advantages achieved due to the use of energy storage technologies in isolated grids are mostly related to improving the network management and reducing the system costs. However, from an environmental point of view, energy storage devices do not seem to bring any benefit to the grid. According to the simulation results, the greenhouse gas emissions increase compared to the respective amount assessed in Case 0 (**Table 5-10**). Indeed, the energy storage operations have been optimized to minimize the overall system costs; the power plants prioritised have been the one with least operation costs considering no environmental constraints. Thus, the choice to minimise the system costs is detrimental to reducing CO_2 emission for the current Tenerife energy grid layout.

Table 5-10 *Comparison of yearly CO_2 emission for Case 0 and Case 1.*

	Case 0	**Case 1**
CO_2 generated [tonne/year]	2,031,647	2,037,801

It is important to notice that Case 1 does not take into account the installation of any renewable power plant. Thus, the only introduction of an energy storage device cannot contribute to the carbon footprint reduction, because it would be charged only by fossil-fuelled plants. Looking at the simulation results, it is also interesting to highlight that the strategy that minimises the CO_2 emission does not correspond to the one that optimises the overall costs. This means that the current Tenerife energy system needs to prioritise one objective over the other when defining the unit commitment. Further improvement will be shown when presenting the simulation results that consider installing large-scale wind power plants as planned in the government future scenario and modelled in Case 3 and Case 4.

5.5.2.4. ENERGY STORAGE REVENUE

The energy storage device can maximise its revenue by optimising the schedule of the charging and discharging periods. During the charge, the energy storage needs to purchase the electricity from the grid and pay it at the equivalent wholesale electricity price. Then, during the discharge, the electricity provided is sold again to the grid at the current wholesale electricity price. Thus, to maximise the revenue of the energy storage, the charge occurs when the wholesale electricity price is minimum, during the valley periods, and the discharge takes place during the peak periods when the energy storage can make the most out of the provision of electricity (**Figure 5-18**).

For this specific case study, the revenue of the energy storage device over the year has been calculated equal to 965,000 €/year, according to the model results. It will be interesting to compare this value with the financial revenue obtained for Case 2 and Case 4 that simulate different roles of the same energy storage capacity.

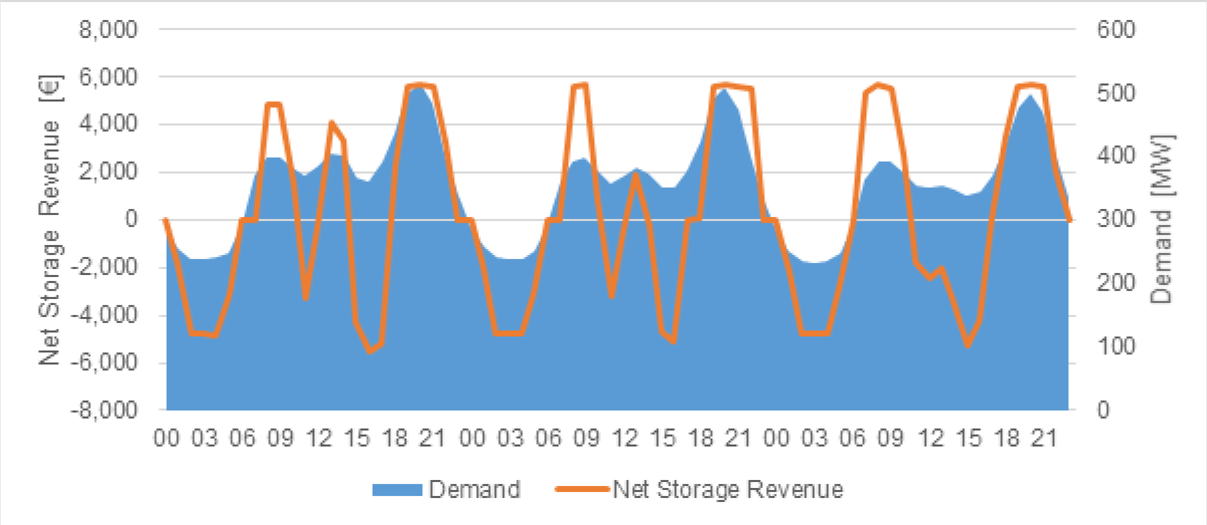


Figure 5-18 *Net storage revenue variation according to the demand profile, Case 1 simulation results.*

5.5.3. CASE 2: ENERGY STORAGE CONNECTED TO OCGT

This case study analyses the potential effects and benefits energy storage device would cause when connected only to a single generator. The thermal unit under consideration is an OCGT belonging to the Granadilla energy system (unit number 7 in **Figure 5-19**, the energy storage is represented by node number 12).

The restriction to interface with a single plant limits the energy storage operations and its beneficial influence on Tenerife energy system, as it will be highlighted when presenting the system costs and CO_2 emission variation.

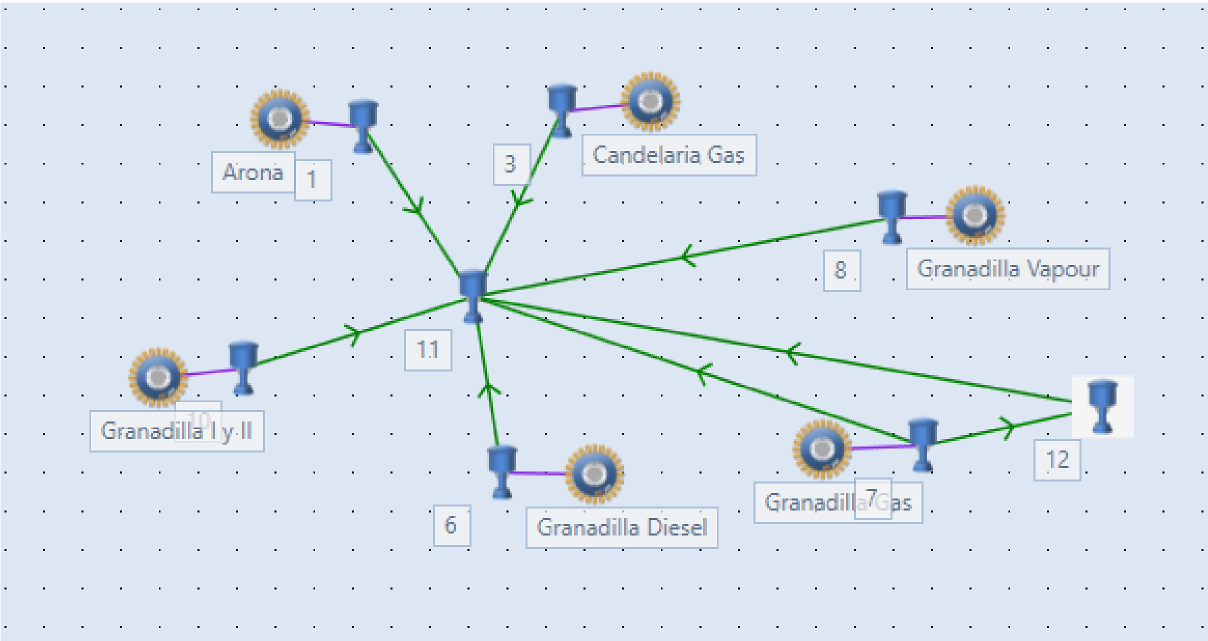


***Figure 5-19** Tenerife energy grid layout according to Case 2 model (figure taken from PLEXOS).*

5.5.3.1. UNIT COMMITMENT

The energy storage device connected to Granadilla Gas unit has large effects on this unit operations and, indirectly, also on some other plants schedule. The possibility to store the local excess of electricity produced incentivises Granadilla Gas to operate at a constant rate for the most part of the day. This strategy differs from the usual unit commitment of this OCGT, which is characterised by several daily start-ups and short-period operations that follow the demand peaks. The distribution of Granadilla Gas daily generation over a longer period means that the power output profile never achieves peak values but maintain a stable modest rate (**Figure 5-20**). This means that other competitive power plants may take advantage of reducing this output and increase their generation in case of peak demand; examples of this strategy are the operations of the diesel generator and steam turbine. In previous sections, the competitiveness of these plants has already been mentioned as well as their constrained operations by the several technical limitations. In this case, their output is not restricted anymore by Granadilla Gas peaks and it can slightly increase compared to Case 0.

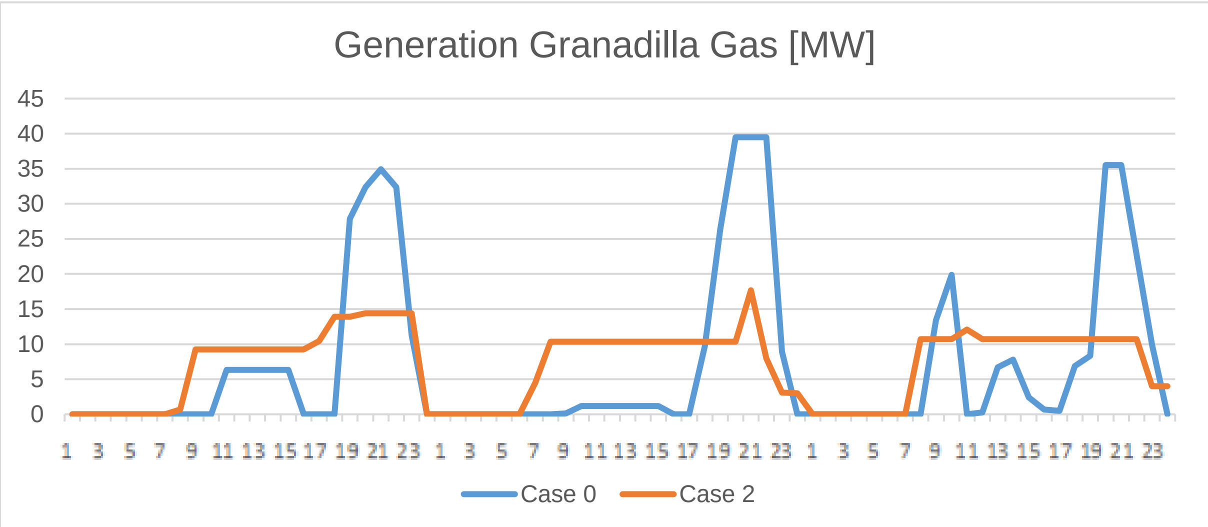


Figure 5-20 *Comparison of Granadilla Gas operations in Case 0 and Case 2, according to simulation results.*

It is interesting to notice that the energy storage device in the model does not increase the daily capacity of the OCGT, but it only affects its distribution. Further simulations run on the model have proven that this choice is bounded to the minimization of the system costs. When increasing the daily capacity factor of Granadilla Gas from 10% to 40%, PLEXOS is forced to run the unit more intensively increasing the productivity of both the OCGT and the energy storage. However, this cause extremely elevated system costs due to the high operative cost related to the large use of an expensive unit that does not allow minimizing the cost function.

5.5.3.2. SYSTEM COSTS

The slight decrease of the system costs with respect to Case 0 (**Table 5-11**) shows that the installation of an energy storage device in synergy with a single unit might bring economic advantage to the overall system. However, this improvement is not comparable to the cost reduction achieved when the same technology is assumed connected to the entire electric grid.

Table 5-11 *Comparison of yearly system costs for the three case studies, according to simulation results.*

	Case 0	Case 1	Case 2
System Costs [MEUR/year]	695.24	693.93	694.85

This result is partially influenced by the small reduction of fossil fuels costs. The slight increase of diesel generator and steam turbine operations leads to a consequent decrease in the gas consumption that represents the largest portion of the fossil fuels costs.

Most of the system costs savings are due to the reductions related to the regulation expenses. Even though the energy storage device is directly connected to a single unit, this approach brings benefits to the overall balancing mechanism. The reason is that Granadilla Gas conveniently operates at the constant flat rate for most of the 24-hour period and, thus, it is available to provide regulation down and up. Looking at the graph in **Figure 5-21**, it can be noted that, in absence of the energy storage, the regulation supply from the OCGT is restricted to short periods across the day, corresponding to the spinning periods. Extending these periods means that the flexibility of the OCGT increases across the day, reducing the need to force other operative power plants to provide regulation services.

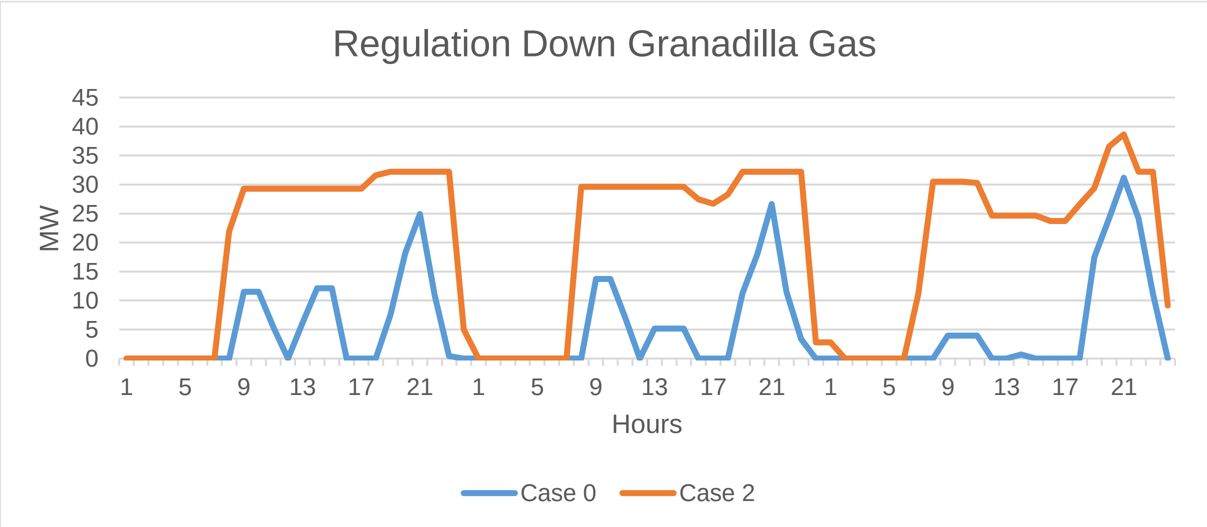


***Figure 5-21** Comparison of Granadilla Gas regulation down availability in Case 0 and Case 2.*

5.5.3.3. CO_2 EMISSIONS

The simulation results related to greenhouse gas emission show similar conclusions to the ones achieved for Case 1. The energy storage operation is planned by the model to minimise the overall costs function, and this choice leads to the increase of the CO_2

emissions since the least expensive solution does not correspond to the most environmentally friendly. As the system costs show a slight decrease with respect to Case 0 solutions, the CO_2 emission presents a minor increase (**Table 5-12**). Again, this can be explained considering the exploitation of oil fuel burnt in the diesel generator and steam turbine, which is cheaper and more pollutant than the natural gas used in the gas turbines.

Table 5-12 *Comparison of yearly CO_2 emission for the three case studies.*

	Case 0	**Case 1**	**Case 2**
CO_2 generated [tonne/year]	2,031,647	2,037,801	2,032,466

5.3.3.4. EFFECT OF ENERGY STORAGE ON OCGT PLANT

It is interesting to notice that the installation of the energy storage in cooperation with the OCGT is driven by the willingness to improve the performance of the unit.

The marginal heat rate and short-run margin costs values (**Figure 5-22**) indicate that the constant flat generation from the unit favours the potential increase of electricity production, making the OCGT flexible and suitable for regulation provision.

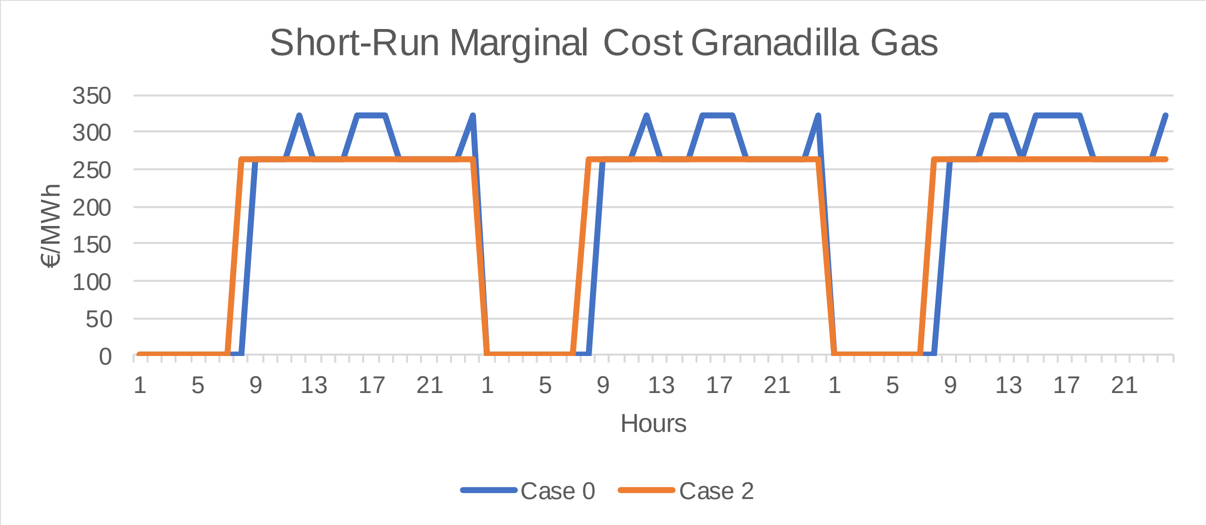


***Figure 5-22** Comparison of SRMC for Granadilla Gas in Case 0 and Case 2*

Although it has been proven how the energy storage can optimize the generation and regulation supplied by Granadilla Gas, there is no further evidence in the simulation results of the improvement of the unit efficiency. PLEXOS does not provide information about the amount of CO_2 emission from the single plant.

The correlation between the thermal efficiency of the OCGT and the power output (**Figure 5-23**) shows that the optimal performance is achieved when the plant operates at nominal power. Lower thermal efficiency leads to higher CO_2 generation because the gas combustion is not performed in optimal conditions (see Section 3.2.3). This information is provided in PLEXOS by defining the heat rate as a polynomial function, instead of a constant value (see Annex A).

However, the simulation results of Case 2 (**Figure 5-20**) suggest that the energy storage operation would not improve the energy efficiency of the OCGT plant since it would lead the plant to operate at a lower power output for a longer period. In Section 5.5.3.2, it has been explained that this operational choice is done by PLEXOS in order to minimise the overall costs of the energy system. Thus, the installation of the energy storage connected exclusively to the OCGT would be able to reduce the system costs by operating strategic arbitrage operation, but it would not bring benefits to the OCGT plant owner.

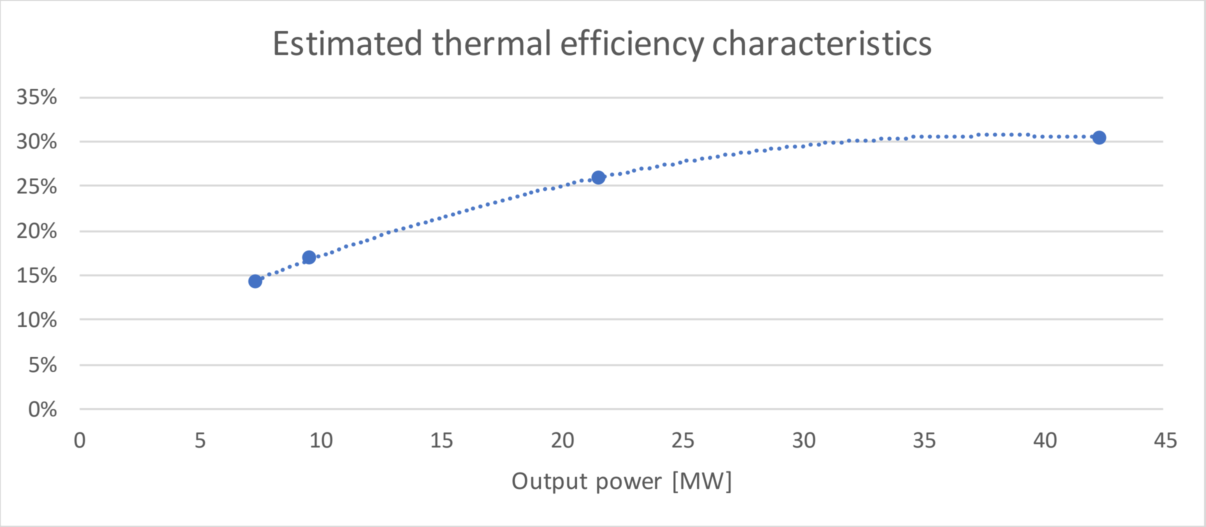


Figure 5-23 *Correlation between the thermal efficiency of the OCGT and the power output, based on official bulletin information*

5.5.3.5. ENERGY STORAGE REVENUE

The net generation revenue obtained by the energy storage device is only a small amount compared to the potential economic benefits achieved when connected to the entire grid (**Table 5-13**). First, this result can be explained considering that the restriction to be charged by a single unit limits the amount of energy stored by the device and, thus, the potential electricity generated. Secondly, the charging period of the energy storage is exclusively driven by the operations of one OCGT and, thus, the storage does not have the possibility to optimize its costs by charging during low wholesale electricity price periods. The variation of the charging period can be noticed in the graph in **Figure 5-24** that compares the schedule of the energy storage in the two different case studies.

Table 5-13 *Comparison of total energy storage net revenue in Case 1 and Case 2.*

	Case 1	**Case 2**
Energy Storage Net Generation Revenue [€/year]	969,000	113,000

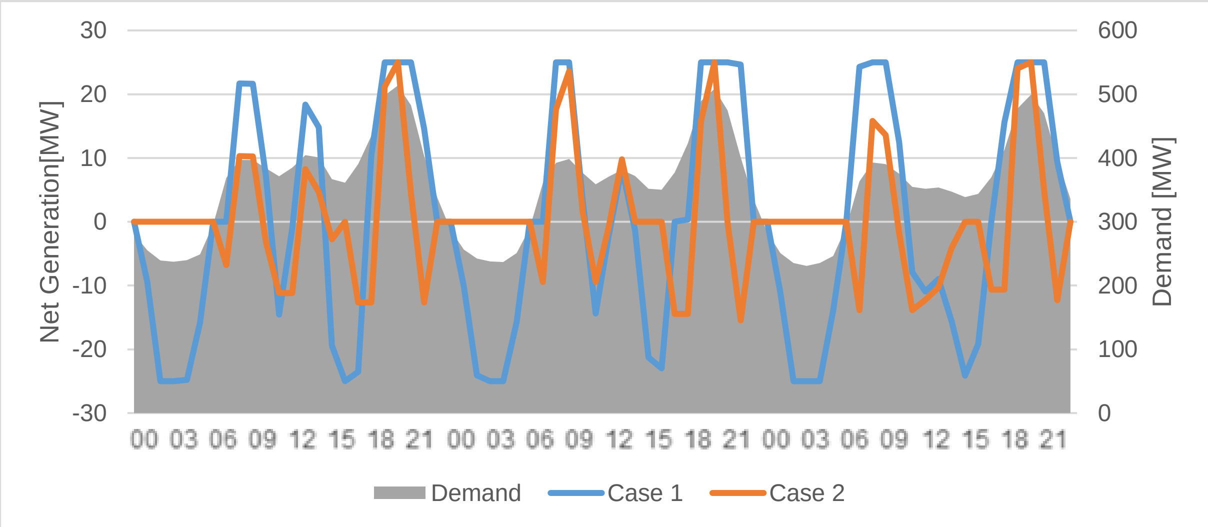


Figure 5-24 *Comparison of energy storage charging/discharging periods in Case 1 and Case 2 according to the demand profile.*

5.5.4. CASE 3 AND CASE 4: ENERGY STORAGE CONNECTED TO WIND POWER PLANT

Adding large-scale wind power plants in Tenerife grid completely distorts the original electricity dispatch strategy. The simulation results of Case 0 show that each power plant generation has a periodic profile that recurs across the days following the variation of the demand and all the technical constraints. Installing large-scale wind power plants forces the model to change balancing mechanism strategy: the main priority becomes the maximization of the wind energy that represents the cheapest electricity source and the other power plants generation needs to adapt to this variable profile and supply the remaining portion of the demand. This largely affects the daily capacity factor of every single plant reducing visibly the fossil fuel consumptions.

As expected, the main benefits of this new energy system layout are the costs and CO_2 emission reduction, due to the supply of clean and cheap energy from the wind farms. The price that needs to be paid to achieve these economic and environmental advantages is the variability and fluctuation of the wind energy output that increases the need for regulation services. The amount of wind power capacity planned to be installed in Tenerife is high and the small isolated grid will be challenged to absorb the intense flow of variable energy. **Figure 5-25** shows the total volume that would be curtailed according to the size of wind power plant installed in Tenerife, (based on PLEXOS simulations run for a time period of two months). Already 100 MW of wind power capacity installed would require the curtailment of renewable electricity excess (equal to 11% of the total volume generated in two months). Then, the volume of energy curtailed would increase with the rise of wind capacity installed reaching almost 50% of the total wind energy produced across the simulated period. This first result suggests that the installation of large wind power plants without considering the presence of an energy storage device (as considered in Scenario 2) would require consistent balancing costs for the management of the wind curtailment.

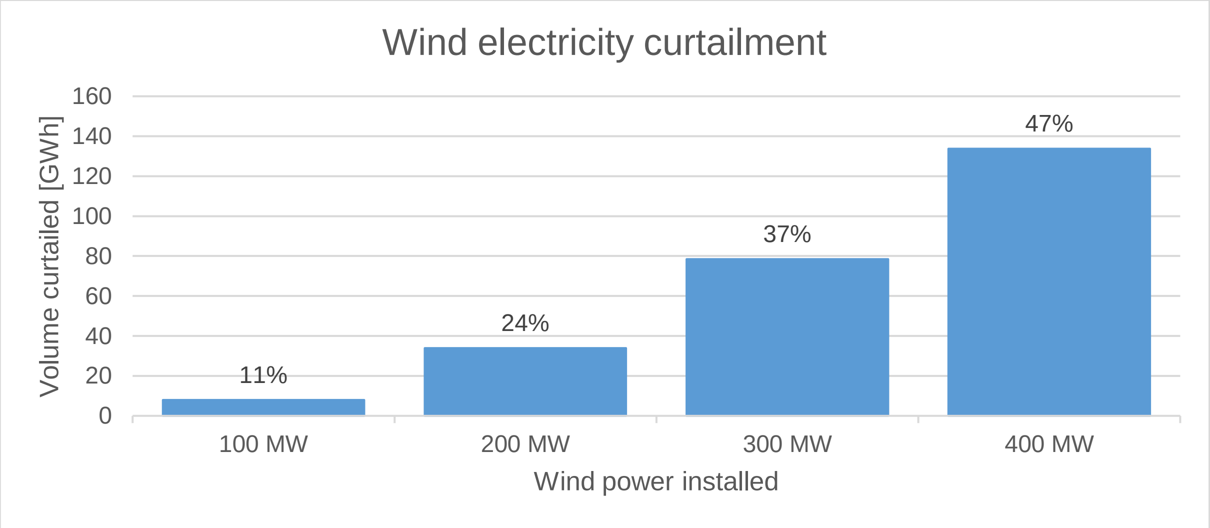


Figure 5-25 *Wind curtailment volume for increasing amount of wind capacity installed, according to simulation results across two months*

This problematic situation encourages the adoption of energy storage technologies for supporting the balancing mechanism of the electric grid. To be able to compare the different case studies that involve the presence of an energy storage device (Case 1, Case 2, and Case 4), it has been decided to size the energy storage as in the previous case analysed (100 MWh of energy capacity, and 25 MW of power capacity). However, this choice brings modest results for this specific case study, because it appears undersized compared to the large capacity of wind power plant installed.

5.5.4.1. UNIT COMMITMENT

As mentioned above, the unit commitment simulation supports the large consumption of renewable energy and, thus, prioritizes the wind output over the conventional power plants generation. The wind energy generation has a fluctuating profile and the presence of the fossil-fuelled generators is necessary as backups to cover the remaining portion of the demand (**Figure 5-26**). The diesel generator produces a constant baseload, while the gas turbines oscillate between a minimum and maximum value of electricity production following the peak and valley alternations. The thermal unit that covers the largest portion of the demand is the CCGT, due to its strict technical operating constraints. Moreover, this generator provides the demand peaks in case of lack of wind generation; on some occasions, this is done together with the steam turbine or some gas turbine.

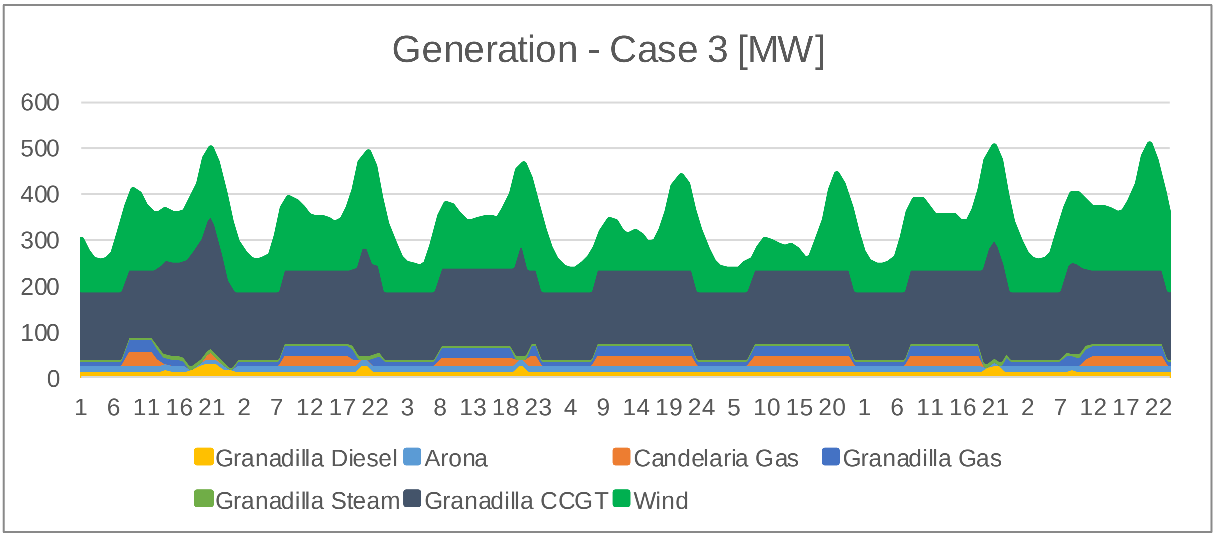


Figure 5-26 *Generation profile for each renewable and thermal unit across seven days, according to Case 3 simulation results.*

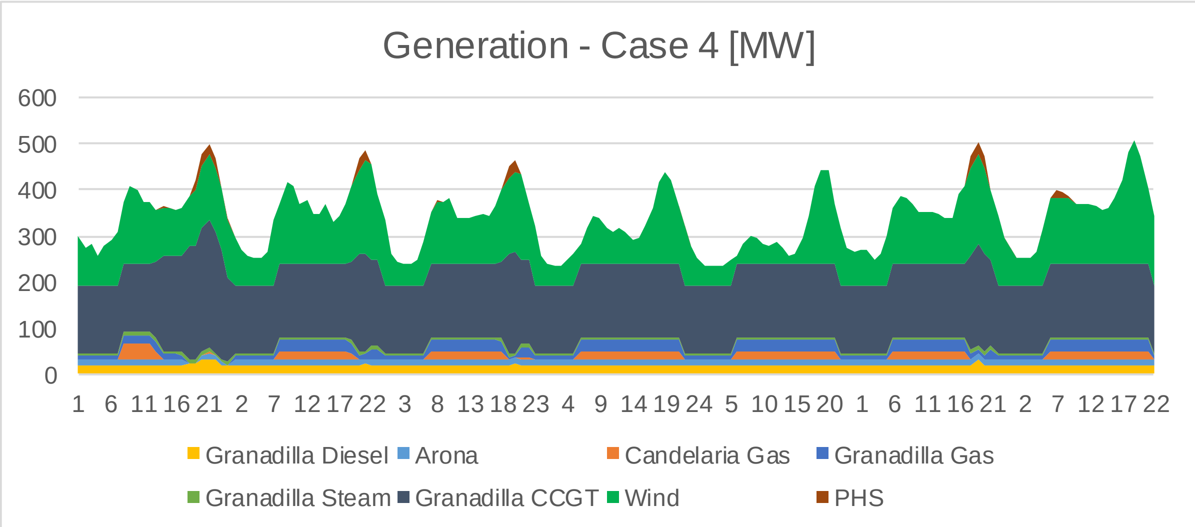


Figure 5-27 *Generation profile for each renewable, thermal and storage unit across seven days according to Case 4 simulation results.*

The addition of the energy storage device slightly affects the unit commitment as shown in **Figure 5-26**, due to its limited power output compared to the predominance of the wind power capacity. The energy storage discharge usually occurs during demand peak periods and it partially replaces the CCGT output, whilst the charging periods exclusively intensify the wind energy profile, due to the direct synergy between the energy storage device and the wind turbines.

The detailed analysis of the simulation results highlights that the energy storage device does not maximise its output and does not discharge its energy stored for several days in a row. Even though this strategy may appear counterproductive for the energy storage revenue, it is coherent with the current wholesale electricity price profile. The large availability of wind energy generation drives the electric market and drops the overall wholesale electricity price. To optimise its revenue, the energy storage needs to ensure to sell the electricity to the grid when the wholesale electricity price overcomes the value it paid during the charging period. For this reason, it may happen that the system operator prefers not to run the energy storage and wait for the increase in the wholesale electricity price.

5.5.4.2. SYSTEM COSTS

The overall system costs decrease because of the installation of large-scale wind power plants and, following, of the energy storage device (**Table 5-14**). It is interesting to notice that this general decreasing trend is consistent with the large reduction of fossil fuel consumption and average wholesale electricity price, but it is in contradiction of the extreme increase of the regulation service costs. The necessity to balance the variable wind power output causes a significant rise of the regulation price, in particular for the provision of regulation down; indeed, most of the power plants operate at their minimum stable capacity level and a further reduction of the output could cause severe technical damages. Also, the regulation up service requires high costs, due to the fact that the wind power plants produce one of the largest portions of electricity generation, and a sudden drop in this profile need to be immediately balanced by the increase o generation from the spinning thermal plants.

Table 5-14 *Comparison of yearly system costs in Case 0, Case 3 and Case 4.*

	Case 0	Case 3	Case 4
System Costs [MEUR/year]	695.24	549.76	547.14

The addition of energy storage technologies allows decreasing these regulation service prices. In the graph in **Figure 5-28**, it can be noticed that the discharging periods of the energy storage device correspond to drastic drops in the regulation price, due to the increase of flexibility of the energy system. This influence, together with the minimisation of the fossil fuel costs, explain why the latest case study is the one with the minimum system costs.

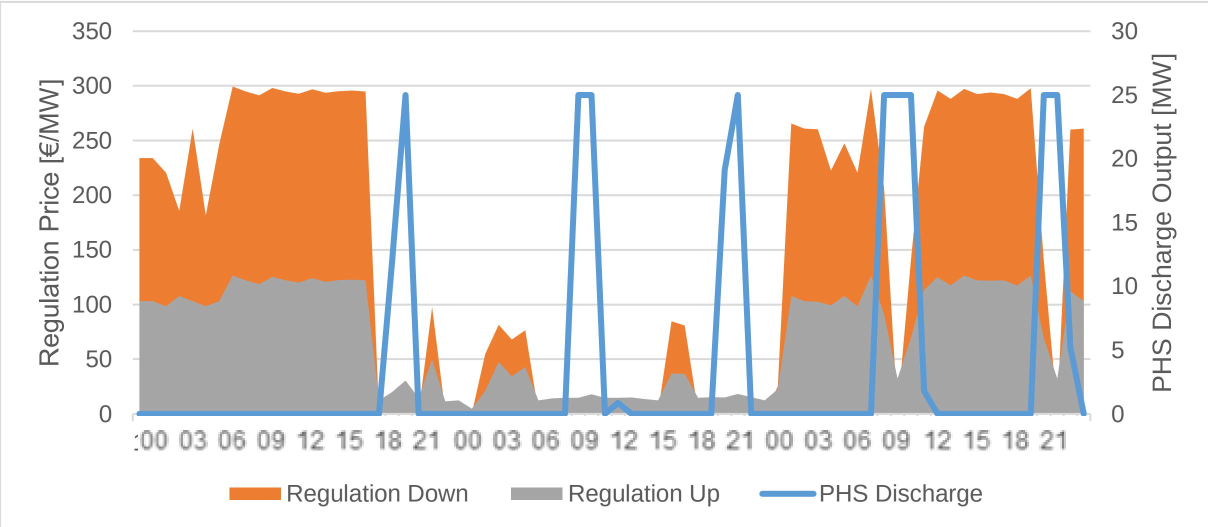


Figure 5-28 *Comparison of regulation price variation and PHS discharge power across three days, according to Case 4 simulation results.*

5.5.4.3. CO_2 EMISSIONS

The CO_2 emission profile follows the fossil fuel consumption curve and, thus, it drops due to the large renewable generation that displaces the output of the thermal unit (**Table 5-15**). The minimum total value of CO_2 generated per year of simulation is achieved for the case study that considers the cooperation of the energy storage device with the wind power plants and that maximises the total renewable generation.

Table 5-15 *Comparison of yearly CO_2 emission in Case 0, Case 3 and Case 4.*

	Case 0	**Case 3**	**Case 4**
CO_2 emission [tonne/year]	2,031,647	1,425,772	1,419,801

5.5.4.4. ENERGY STORAGE REVENUE

The previous paragraphs have highlighted the economic and environmental benefits the energy storage can add to an isolated electric grid with large-scale wind power plants. However, from the energy storage owner perspective, this latter case study represents the less profitable among the different energy scenario investigated. **Table 5-16** collects the yearly energy generation produced by the energy storage device according to the three model simulations. It can be noticed that Case 4 is characterized by the smallest value of total generation per year. While the modest amount of Case 2 is justified by the limited availability of energy due to the synergy with a single OCGT operation, in Case 4 the wind power plants generate abundant energy for storing purposes. Thus, the reason for the modest energy storage contribution is not due to the lack of excess of energy for charging the storage device, but to the limited wholesale electricity price variation. As it has already been mentioned, the number of discharging processes of the energy storage in Case 4 is not maximised because of the lack of wholesale electricity price peaks. The flat wholesale electricity price profile driven by the large wind energy production does not encourage the energy storage to sell back the electricity to the grid because it would not be profitable.

Table 5-16 *Comparison of yearly energy storage net generation in Case 0, Case 3 and Case 4.*

	Case 1	**Case 2**	**Case 4**
Energy Storage Net Generation [GWh/year]	64.30	33.84	16.16

Although the energy storage device reaches the smallest amount of total generation, its contribution to the whole energy system is still remarkable, making Case 4 the least expensive and pollutant energy scenario. The size of the wind power plants and the excess of renewable energy generated in the isolated grid implicitly promote the installation of large energy storage devices. The model has been simulated with a 100 MWh of storage capacity, for the sake of comparison with the previous case studies. However, as shown in **Table 5-17**, a larger energy storage device would improve the penetration of renewable in the isolated grid and, thus, increase its revenue and its positive effects on the entire system. This suggests that the choice to install 90MW of PHS, as proposed in Scenario 1, might be appropriate for the optimisation of the wind generation in Tenerife.

Table 5-17 *Increase of wind energy output for different energy storage capacity*

Energy Storage Capacity	**100 MWh**	**200 MWh**
Wind Energy Output (compared to Case 3)	+ 2.54%	+ 4%

5.6. DISCUSSION AND CONCLUSION

The simulation of Tenerife electric grid operations has stressed potentially problematic management issues for the current and the future energy scenario layout. First, the strict dependency on fossil fuels leads to elevated greenhouse gases emission and the expensive transportation fees cause high wholesale electricity prices for the current energy system. Then, the lack of interconnections and flexibility in the balancing mechanisms force the thermal units to operate at partial load for regulation and reserve provision, causing thermal stresses and poor energy performance. Finally, the future installation of large-scale wind power plants, planned with the aim to solve most of the current energy issues of the island, would achieve significant savings in fossil fuel consumptions but it would completely distort the original unit commitment forcing the thermal unit to operate as a backup at the minimum capacity. Whilst the previous statements have been verified against real data, this latter conclusion has been based exclusively on simulation results since it concerns future energy scenario. In this case, the simulation has been run considering the rules and constraints existing for the current electric grid (e.g. minimum capacity factor, minimum daily capacity). However, the installation of large-scale renewable plants could suggest modifying the traditional plant operations, like reducing the number of spinning units. The shutdown of some of the thermal plants could improve the energy performance of the remaining operating ones. Moreover, the simulation has been based on the principle to prioritise the renewable generation, leading to the predominance of wind generation and the drop in the wholesale electricity price. It has already been noticed that this strategy would bring interesting system costs savings, but it would minimise the revenue of other components of the system, like the energy storage. Thus, further measures could be introduced to benefit from renewable energy but do not obstruct the deployment and the correct operations of other energy technologies.

These conclusions show that if the government would choose either Scenario 0 or Scenario 2 as future development of the power sector, it needs to consider:

- In the first case, high electricity price and CO_2 emission due to the exploitation of imported fossil fuel;
- In the second case, intensive wind energy curtailment (almost 50% of the total wind generation) and potential thermal stress for the thermal plants that need to constantly operate at partial load.

For these reasons, the adoption of energy storage technologies would be recommended in both the scenarios.

5.6.1. ENERGY STORAGE POTENTIALS

This work has investigated three different roles that could be played by the energy storage device in Tenerife grid: acting as load-shifter to facilitate the regulation provision and minimise the costs, working in synergy with a single OCGT to improve its energy performance or increasing the penetration of renewable energy when large wind power plants will be installed. It is interesting to notice that the case study that represents the most productive scenario for the entire energy system does not correspond to the most remunerative one for the energy storage owner. From the energy system point of view, the best results are achieved in Case 4, where the presence of the storage allows reaching the minimum system costs and CO_2 emissions. In Case 4 the operations of the energy storage device connected to the wind power plants save 0.5% of the total system costs compared to Case 3, while the savings achieved with the similar device connected to the entire electric grid would be only 0.2%, and even less when directly linked to the single OCGT. However, from the energy storage owner point of view, the best energy scenario is represented by Case 1, where the storage can maximise the number of discharge processes and profit from the fluctuation of the daily wholesale electricity price profile.

In conclusion, this simulation analysis suggests the existence of interesting potential applications for the energy storage technologies in Tenerife isolated grid, assessing the value of the storage according to different case studies, roles and perspectives.

5.6.2. MAIN ASSUMPTIONS AND LIMITATIONS OF THE MODEL

It is important to notice that these conclusions are based purely on the results from a simulation analysis where the benefits of the energy storage operations are expressed in terms of differences compared to the simulation results of the current energy system. The model of Tenerife energy system is quite accurate due to the small dimension of the grid. This has been proven in Section 5.4.2 where the validation of the unit commitment results is shown.

However, in order to simplify the simulation model, it has been decided to neglect the current renewable capacity installed, since this covered only 10% of the overall energy demand in 2017 (chosen as reference year for the simulations).

This choice might have resulted in slightly higher wholesale electricity prices because the modest portion of demand covered by renewable capacity is replaced by thermal generation in the simulation results. In terms of energy storage revenues, the decision of neglecting the renewable generation might have negatively affected the results since the generation from variable renewable source increase the revenue from arbitrage and regulation. This means that the revenue of the energy storage when charged with the electricity from the grid or from the OCGT plant could be slightly higher in the real application.

Chapter 6

GB ENERGY SYSTEM

The software PLEXOS has been used for modelling Great Britain national grid to be able to assess the value of the energy storage technologies when installed at grid level. The potential benefits that are considered involve the increase of penetration of renewable, the reduction of overall system and regulation costs and the decrease of CO_2 emissions. The geographical unbalance between the generation and demand has drawn the attention to the innovative adoption of thermal storage devices, that would tackle the renewable integration and heat decarbonisation issues.

6.1. BACKGROUND

Great Britain energy scenario has been selected as the target of this study because it represents a clear example of the renewable curtailment issues that may happen due to lack of sufficient transmission lines. The rapid installation of large-scale wind power plants in Scotland has not been followed by an enlargement of the transmission network, creating congestion issues in the line [148]. This problem is common to several other countries (e.g. China, Brazil, Germany) since the most suitable locations for the installation of large-scale wind power plants are remote, windy areas far from the most populated cities. Thus, in these energy systems, the constrained transmission network acts as a bottleneck and limits the amount of renewable power that can meet the demand.

Wind power development in China grew rapidly between the 2000 and the 2012 and it took place mainly in the Three North region (Northeast, Northwest and North China) due to resource availability and wind farm constructions requirements. Wind power curtailment became a major problem starting from the year 2010 and according to Luo G. L. et al [149], the lack of proper planning and network management were the main reasons that led to poor integration of the renewable. The authors blame the lack of a national energy deployment planning, which would have been beneficial when authorizing the local installation of wind power plants. Moreover, the slow progression of the grid enlargement construction created further obstacles to the penetration of the large-scale wind power plants into the national grid.

Similarly, in Germany, the transmission lines prevent the correct dispatch of the wind-generated electricity [150]. The most suitable location for the installation of new power plants is in the northern area, not convenient for the grid distribution that is mostly addressed to the central and southern regions.

The Brazilian energy system has been investigated through a simulation analysis run on PLEXOS [151]. This work contributes to an article previously published [152] that analysed the increase of wind integration in the Northeast of Brazil without considering transmission lines and congestion issues. The paper concludes that wind curtailment would occur only in case the renewable output overcome the overall demand. The second work questioned that it would have been possible to achieve 65% of wind integration in the Northeast of Brazil almost without curtailment. Indeed, the simulation results presented in the second paper showed that several events of curtailment could be registered. The reason for this curtailment has been investigated with the power flow analysis, which highlighted congestion issues in the transmission lines connecting the wind farm sites with the rest of the electric network.

In the case of GB energy system, the bottleneck in the network is located exactly at the border between Scotland and England. Looking at the map of the network grid across GB in **Figure 6-1**, most of the congestions take place between zone B6 and B7, corresponding to the Scottish border. This area is crossed by only two transmission lines. The purpose of the simulation-based analysis is to quantify the savings that could be achieved if energy storage devices would be used in Scotland for collecting the excess of renewable energy produced. To stress the attention on the congestions that obstruct the power flow from Scotland to England, the grid model is represented by a two-region network connected by a single transmission line. The first region embodies the wind power location while the second aggregates most of the demand. This approach could be easily extended to other national grid characterized by a similar structure, such as China, Brazil and Germany.

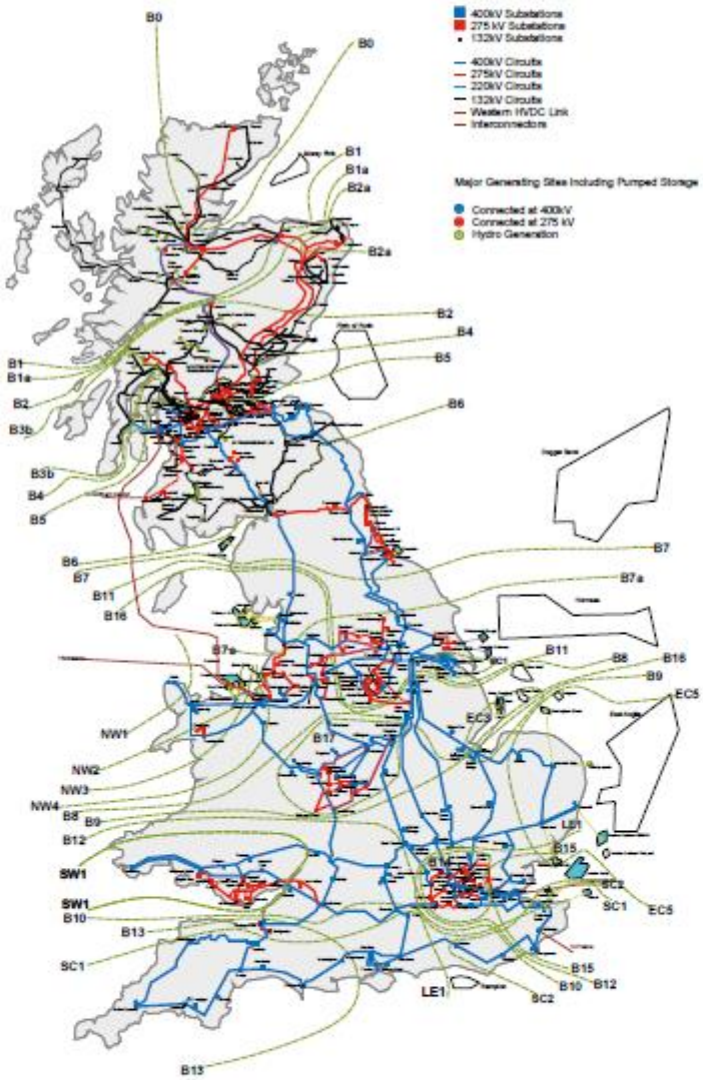


Figure 6-1 *Map of transmission lines in Great Britain*

The following paragraphs present an overview of the current energy situation in GB highlighting the distribution of installed capacity across the country and the different energy mix that provides the daily demand. An accurate analysis of the electric and heat demand in England and Scotland is presented, suggesting possible interesting power-to-heat solutions for handling the wind curtailment.

Section 6.3 introduces some further comments for the development of the model of the grid, applying to a specific case the methodology defined in Chapter 3. The chapter concludes with a detailed analysis of the results achieved with the simulations and some discussion on the potential deployment of energy storage technologies in Scotland.

6.2. DATA REVIEW

6.2.1. INSTALLED CAPACITY

The overall electricity system in GB is constituted by almost 81.3 GW of power installed in 2017 [153]. This value is calculated based on the power plants (renewable and fossil-fuelled) connected to the transmission line. Smaller generation units (in total 32.4 GW [154]), such as diesel generators, solar panels, and wind turbines connected to distribution networks, are not included in this amount.

64% of this capacity is fossil-fuelled power plants. Combined cycle gas turbines (CCGTs) cover the largest portion of this percentage with over 30 GW of capacity installed (**Figure 6-2**). The remaining fraction is then shared between open cycle gas turbines (OCGTs), diesel and coal power plants. The latter counts eight remaining units, all placed in England and Wales since the last coal-fired power plant in Scotland (Longanett) has been closed in 2016 [155].

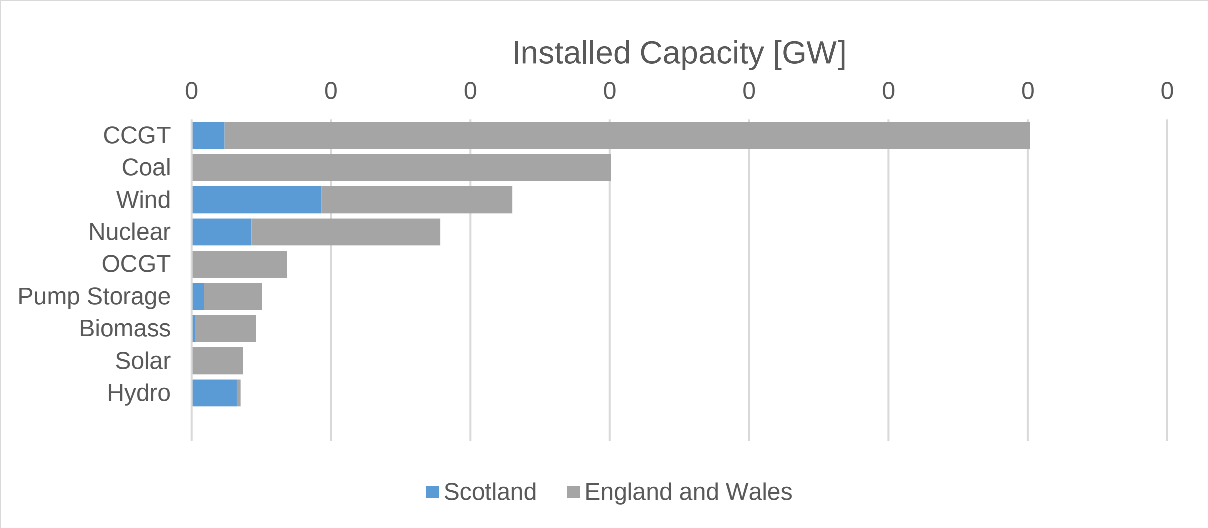


Figure 6-2 *Installed capacity according to plant type*

The largest installation of renewable power in GB is represented by wind farms, 15% of the overall installed capacity (**Figure 6-2**). 40% of this total amount is concentrated in Scotland, representing the most intense installed capacity in the region as shown in **Figure 6-2**. Nuclear power plants are an established technology in GB with 8 GW of capacity installed (11% of the national installed capacity) and they provide baseload for the daily demand. Biomass, solar and hydropower plants represent a similar share around 2-3% of the overall installed capacity.

From **Figure 6-2**, it can be noted that a considerable amount of the renewable plants is located in Scotland, where the main contribution to the fossil-fuelled generation is given by only the single CCGT of 1.1 GW capacity. The total installed capacity in Scotland is abundant for the local electric demand and a large portion of the electricity produced in Scotland is exported to England (in 2017 this amount corresponded to 27% of the total electricity produced, according to official government figures [156][157]). The modest Scottish electric demand is mostly covered by renewable energy (60% of the total), and the ambitious government plans for this region consider the achievement of 140% of renewable electricity by 2030 [158]. This is aligned with the target to reach full decarbonisation of the energy sector by 2050. The future energy scenario considers almost doubling the current amount of renewable capacity in Scotland (reaching a total of 17 GW) and implementing further policies and energy technologies for facilitating renewable penetration into the grid.

6.2.2. PLANT CAPACITY FACTOR

The plant capacity factor is defined as the ratio between the real output that has been generated by the unit during a certain amount of time and the maximum capacity that could be generated for the same amount of time. This parameter is an indicator of how intensively each technology has been exploited and it could give interesting information about the energy mix that provides electricity in GB. The plant capacity factor is mainly driven by the actual demand and by the balancing mechanism decisions that govern the energy system, but a reduction of this value could also be caused by technical issues of the unit, such as planned or unplanned outages. The plant capacity factor of nuclear power plants represents the highest capacity factor in GB (**Figure 6-3**) at 77.4% in 2017 [159]. In other words, nuclear technology is the type of plant which is mostly exploited in the GB, covering almost 26% of the electric demand. The CCGT capacity factor has grown to reach almost 50% in 2016 [153], due to the closure of coal-fired plants. CCGT cover the highest portion of electric demand by following the peak trends. The decrease (-4.3 percentage point) of CCGT capacity factor in 2017 is due to the decrease of supply as renewable share increased. As mentioned before, the coal-fired power plants are drastically decreasing their operation and in 2016 the plant capacity factor reached the lowest value ever registered (16.5%). This value is expected to further decrease due to the government decision of limiting the generation from coal-fired power plants. The plant capacity factor of renewable plants is mostly affected by weather conditions that influence the natural water flow for the hydropower system as well as the wind intensity or number of sun hours. For this reason, the plant capacity factor of wind power plants, solar panels and hydropower have all seen a slight reduction in 2016 compared to the previous years due to unfavourable weather conditions [159]. In 2017, high wind speed allowed wind power achieving 31.7% of capacity factor. The increase of hydro capacity factor is not related to weather conditions but to the addition of small-scale hydro plant capacity. The operations of pumped hydro storage plants are controlled and driven by the decision of storing excess electricity then provided it during the peak time demand. The pump storage capacity factor has kept the almost constant value of 12% over the last five years (**Figure 6-3**).

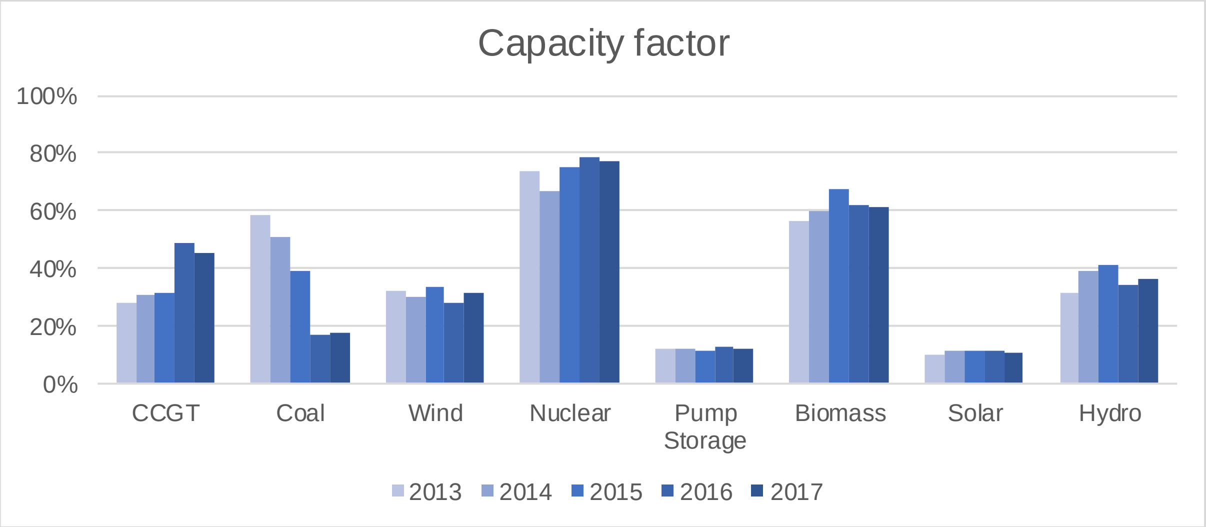


Figure 6-3 *Plant capacity factor for main power plant technologies in GB [%]*

6.2.3. GENERATION DATA

The electricity generation in Great Britain has been keeping a constant value for the past years, since 2014. However, the amount of fossil fuels burnt has decreased, due to the gradual shift from coal-fired power plants to more energy efficient gas turbines, as can be noted in **Figure 6-4**. The reason for this change is due to the increase in the carbon tax in 2015, from £9 to £18 per tonne of CO_2 emitted [153]. Since the coal-fired plants produce more greenhouse gas emission than other technologies, this decision weighed heavily on their production and it favoured other power plant types, like CCGT. The renewable capacity has largely increased in 2017 and the renewable generation (that includes wind, solar, natural flow hydro, tidal, waste and biofuel) has increased by 19.5% in 2017 compared to the previous year [154].

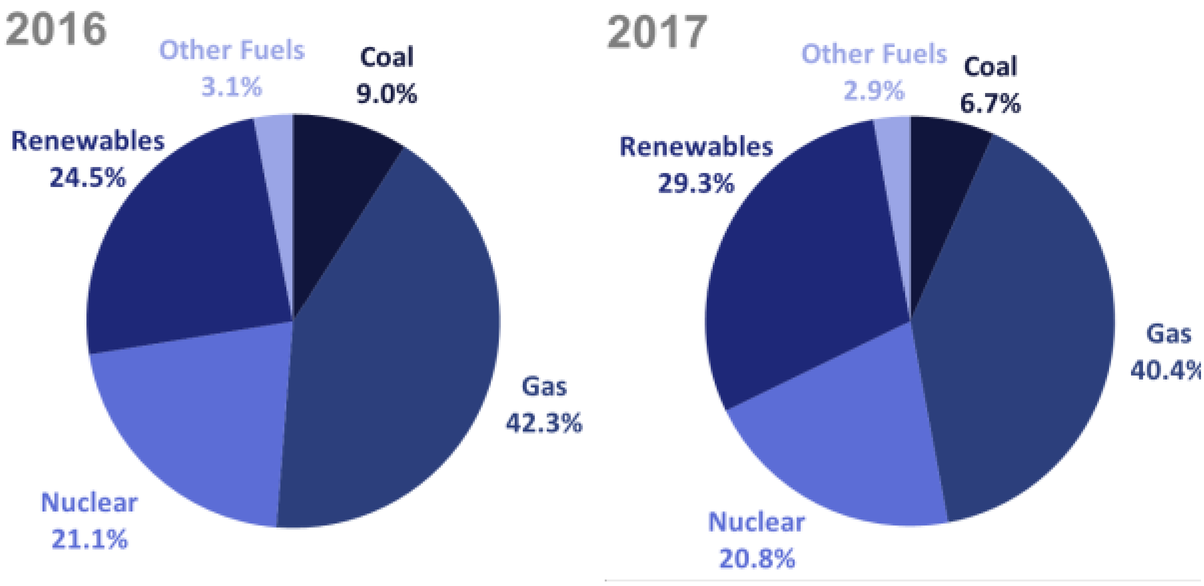


Figure 6-4 *Shares of electricity generation, by fuel*

6.2.3.1. TRADITIONAL POWER PLANTS

The real profile of the electricity generation is available through the online platform managed by Elexon. Elexon is the company that administers the Balancing and

Settlement Code for GB and provide the services needed to implement it [160]. The data accessible on this website is gathered through National Grid, the owner and operator of the transmission lines in England. The electric output from each power plant is collected according to the different technology and updated each settlement period (30 minutes) that corresponds to the moment in which actions are taken in the energy market.

Each power plant unit, both fossil-fuelled and renewable, is identified by an ID number, whose prefix provides information about the role of the unit in the energy system. The main classification recognises when a unit is directly connected to the transmission line (using the prefix T), it is a small size power plant and it is embedded in the distribution network (prefix E), or is one of the four interconnectors, France, Netherlands, Northern Ireland, Republic of Ireland (prefix I). Knowing the unit ID number gives access to the generation recorded for each unit. Due to the large number of units installed in the energy system in GB, this work does not go through the specifics of each unit but analyses the electricity output according to the different technologies that gather all the operating units together. The study of the generation profile from every single unit could be useful when only a few units of a specific type of plants are installed (like for the Tenerife case study). This is the case of the fossil fuel power plants installed in Scotland that count one single CCGT unit and eight diesel generators. Creating a model of GB energy system divided into two regions allowed the analysis of the few traditional power plants in Scotland. This analysis has shown that contrary to the CCGT operation in the rest of GB, the CCGT plant installed in Scotland (Peterhead) does not follow the demand trend but alternate long periods of shutting down with periods of constant and flat generation (**Figure 6-5**).

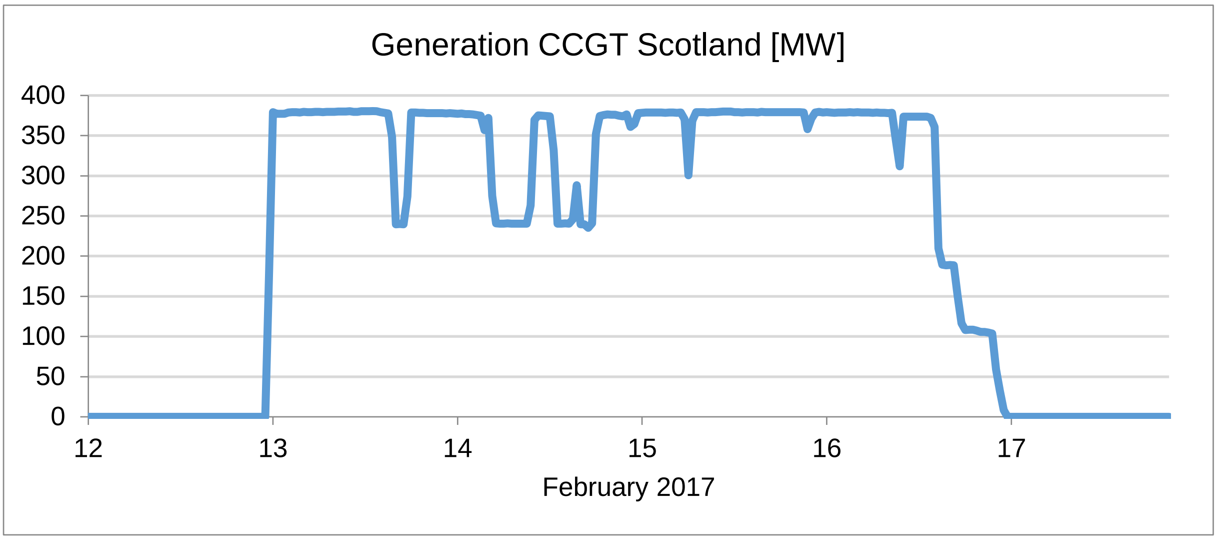


Figure 6-5 *Generation profile of the CCGT in Scotland across six days in February 2017*

6.2.3.2. RENEWABLE POWER PLANTS

The data related to the generation from renewable power plants could also be collected from Elexon website. Together with the real electric generation input in the transmission line, it is possible to access to the forecasted generation for the following weeks or days. Due to the variability of the sun and wind generation, the balancing mechanism decisions are initially based on the information generated by the weather forecast. The uncertainty of the predicted values leads to several changes and adjustments of the original unit commitment until the final decision is taken half an hour before the beginning of the settlement period. To simplify the mathematical model of the energy system, it has been decided not to consider the forecasted value of the wind power output but the actual generation and to input it in the model as a perfect foresight. The use of historical wind output profile for the realization of the model allows obtaining a trustable representation of the real wind curtailment profile, which is one of the main objectives of the simulation.

6.2.4. DEMAND DATA

This work investigates different energy solutions to reduce the wind curtailment between Scotland and England and to improve the penetration of renewable at the national level. It focuses on the possible adoption of electric and thermal energy storage devices for the absorption of the excess of wind energy. For this reason, it is interesting to analyses both the electric and domestic heat demand to identify potentials for the installation of energy storage technologies.

6.2.4.1. ELECTRICITY DEMAND

Being able to balance and follow the electric demand is one of the constraints of the mathematical model of the electric grid. Thus, the demand profile is defined as input in the model. In this case, the assumption is that the model takes the unit commitment decision based on perfect forecasted demand. In other words, as for the renewable generation, the model does not consider any uncertainties in the forecasted demand. The time series adopted is the real demand measured by the grid operator. Moreover, using a historical profile it is possible to validate the performance of the model against real generators output.

The UK electric demand is collected by the Elexon website. The curve is updated every 30 minutes and agglomerates all the demands from England, Wales, Scotland, and Northern Ireland.

The total annual electricity consumption in the UK in 2017 is 353.8 TWh [154]. Of this, consumption in Scotland roughly corresponds to 10% of the overall electricity demand (**Figure 6-6**) [156][161]. The value of the total consumption has been gradually decreasing since 2010 because of the implementation of energy efficiency measures employed in the industrial and residential sectors (**Figure 6-7**). Moreover, the slight increase in the outside temperature has also contributed to the reduction of consumption [154]. The value recorded in 2017 has been the minimum since 1995. However, the last three years present a similar demand due to the increase of electrification in the heat and transport sectors that compensate the savings achieved in the domestic consumptions.

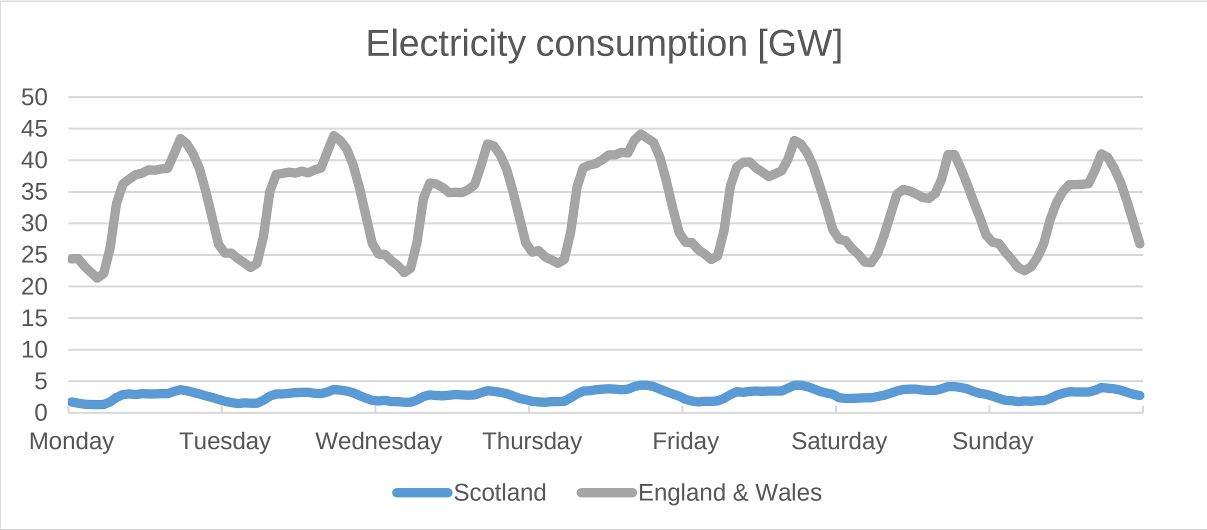


Figure 6-6 *Average weekly demand profile, by region*

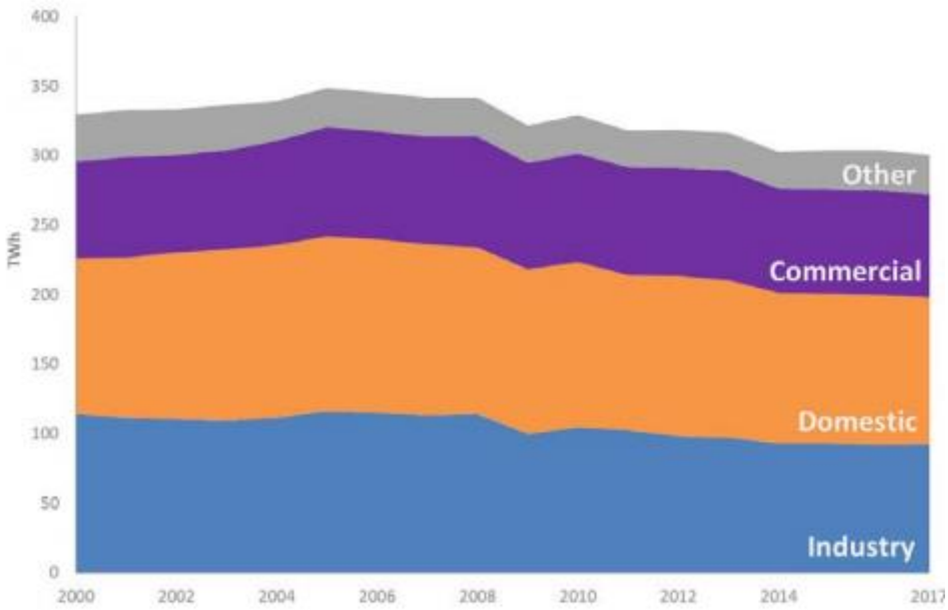


Figure 6-7 *Electricity consumption yearly trend, by sector*

6.2.4.2. HEAT DEMAND

Contrary to electricity consumption, domestic heat demand cannot be precisely monitored.

The heating demand can be supplied by different sources. Natural gas, used in boilers, is the most common fossil fuel adopted across GB. The natural gas is provided across the country through a network comparable to the electricity grid. It is first transported in a transmission network characterised by high pressure and then it is delivered to the single consumer by a forked distribution system.

Almost 2.2 mln households in GB [162] are not connected to the gas distribution network. The highest percentage of “off-gas” households is in Scotland (22%), followed by Wales (21%), and 15% in England [163]. Where a natural gas connection is not available, different sources for heat can be used: electricity, solid fuel (including biomass), heating oil. In particular, the use of electric heaters is most common in Scotland, while several households in Wales have been using heating oil as a replacement for natural gas [164]. The main space heating fuels used in GB are listed in **Table 6-1**, along with the proportion of households that use it.

Table 6-1 *Percentage of GB household by main space heating fuel [%]*

	England	Scotland	Wales	GB
Main gas	85	78	79	84.2
Communal & DH	2	1	0	1.6
LPG	1	1	2	0.7
Heating oil	4	6	11	4.2
Solid fuel	1	1	3	0.8
Electricity	8	13	5	8.5

Among all the primary heating fuel, natural gas consumption is the only one that can be monitored. The electricity demand for space heating purpose is obviously included as part of the overall electricity consumption and it is not possible to extract the exact amount necessary for covering the electrified heat demand. Annual figures can be calculated on the base of national surveys, but no information is available for daily domestic consumption. The same consideration can be extended to the heating oil or petrol product used in households as an alternative to natural gas.

National Grid collects and publishes the daily gas consumption for the whole GB [163]. In particular, it is possible to access non-daily metered natural gas demand (NDM) that reflects the gas demand for all the cosumers that are not monitored by a daily meter [165], [166]. Those include households, small industrial units and small commercial units. This information is collected at region level and, thus, it is possible to separate the NDM gas consumption of Scotland from England and Wales. The variation of the NDM value in Scotland across the year is shown in **Figure 6-8**. There is no possibility to understand the portion of natural gas that is actually adopted for space heating or for other domestic purposes. According to a statistical study run by the UK Government [167], 23% of the overall domestic gas consumption is deployed for hot water, 3% is used for cooking purpose, and 74% of the natural gas demand is used for space heating. These percentages can help drawing assumptions on the portion of daily gas consumption that is employed for the domestic space heating in Scotland.

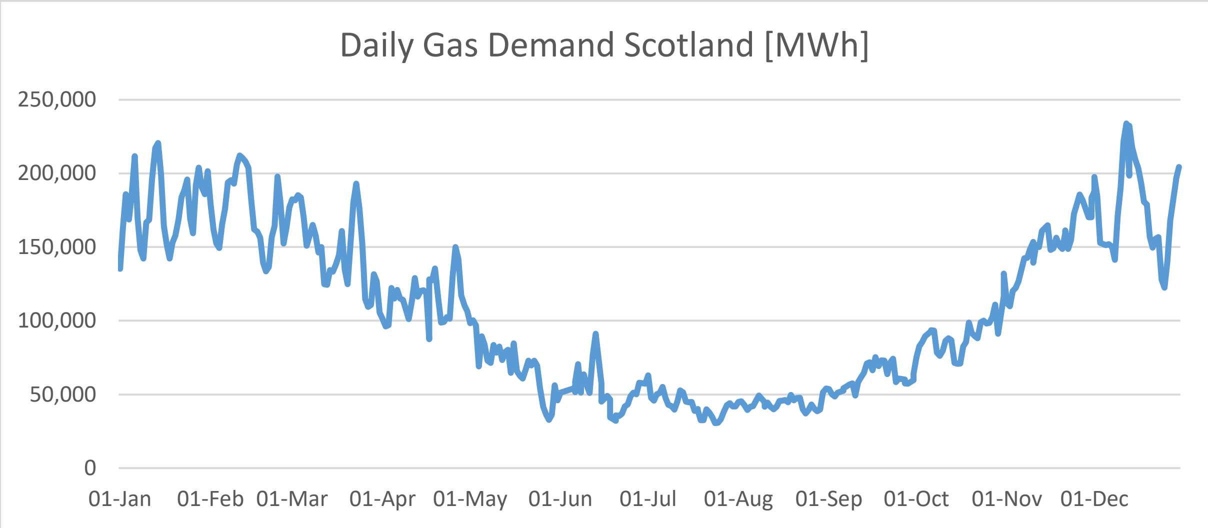


Figure 6-8 *Daily NDM total gas consumption in Scotland across the year 2017*

The domestic heat demand, and thus the gas consumption, is related to the outside temperature. It is not unusual that the highest mean gas consumption per household is recorded in Scotland, where the high latitude causes more severe temperatures. In 2017, the mean domestic gas consumption in England for 2015 was 13,210 kWh, while in Scotland was 13,657 kWh [163]. This latter value has fallen by approximately 32% since 2005, due to the energy efficiency measures that have been introduced in households and due to the increase in temperature [154].

6.2.5. WIND CURTAILMENT DATA

The main objective of this simulation analysis is the reproduction of the wind curtailment at the Scottish border to assess the benefits of energy storage technology when tackling this issue. Thus, attention has been drawn to the analysis of the wind output and wind curtailment profile. This data analysis has been fundamental for the identification of the causes of the curtailment and the understanding of this problem, delimited at the border between Scotland and England.

The collection of real and precise data of wind curtailment is fundamental for understanding the seriousness of the issue and for the validation of the model. Having access to this data is a complex and long process. The curtailment strategy affects any power plant technology and it is not limited exclusively to the renewable output. In case of severe transmission constraints, the network operator can force the reduction of the generation from any type of power plant to restore the balance in the grid. Information about the monthly curtailment volumes is accessible through the Monthly Balancing Mechanism Report [168]. These documents do not specify the exact amount of energy that is curtailed from wind power plants, but they gather together all the information that concerns the balancing mechanisms due to constraints in the transmission lines and the prices that have been paid for sorting out the problem. To understand which is the exact wind energy curtailment, it is necessary to analyse the half-hourly bid-offer data and identify the one flagged with “SO”; this particular information means that the bid flagged has been made as a consequence of congestion in the transmission line. As already mentioned, this balancing mechanism does not involve exclusively wind power plants but also fossil-fuelled stations. Thus, it has been necessary to analyse the source of each bid action to exclude the one related to traditional power plants that are not considered meaningful for this study. The format of the data analysed is presented in **Figure 6-9**. For this study the attention has been drawn on: the ID column for the identification of the power unit involved in the curtailment, SO-Flag column that specifies if the balancing action has been caused by congestion in the transmission network, the Bid Price (£/MWh) and Bid Volume (MWh) columns that collect information about the amount of power the station is willing to curtail and the price it ask for this service.

Buy Stack | **Sell Stack**

Index	Id	Acc ID	BOP ID	CADL Flag	SO-Flag	STOR-Flag	Re-Priced	RSP	Bid Price	Bid Volume	DMAT Adjusted Volume	Arbitrage Adjusted Volume
10	T_DIDCB6	122925	-1	F	F	F	F	NULL	43.60000	-21.067	-21.067	-21.067
11	T_STAY-1	57952	-1	F	F	F	F	NULL	38.15000	-3.722	-3.722	-3.722
12	T_STAY-1	57953	-1	F	F	F	F	NULL	38.15000	-5.384	-5.384	-5.384
13	T_SEAB-2	75145	-1	F	F	F	F	NULL	6.00000	-0.158	0.000	0.000
14	1	NULL	NULL	F	T	F	F	NULL	37.00000	-50.000	-50.000	-50.000
15	T_PEMB-11	56631	-1	F	T	F	F	NULL	36.00000	-11.183	-11.183	-11.183
16	T_PEMB-51	48021	-1	F	T	F	F	NULL	36.00000	-18.367	-18.367	-18.367
17	T_PEMB-51	48020	-1	F	T	F	F	NULL	36.00000	-10.633	-10.633	-10.633
18	T_PEMB-41	46426	-1	F	T	F	F	NULL	36.00000	-16.575	-16.575	-16.575
19	T_PEMB-41	46425	-1	F	T	F	F	NULL	36.00000	-8.925	-8.925	-8.925
20	T_PEMB-31	47815	-1	F	T	F	F	NULL	36.00000	-17.417	-17.417	-17.417

Figure 6-9 *Detailed system price, published by ELEXON*

The trend and the magnitude of the volume curtailed in GB for the month of January 2017 could be analysed in **Figure 6-10**. This curve is compared with the GB wind production and the electricity flow across the transmission line between Scotland and England. The real-time data related to the electricity export from Scotland to England is published on National Grid live status website. The website does not contain any historical data. Thus, the generation of a profile has been possible via a MATLAB code that queries the website each half-hour and saves the data in a separated file. The information on the Scotland-England export flow in the first 11 days of the year is missing due to a lack of real data. The analysis of this graph allows understanding the strict relations between these three profiles.

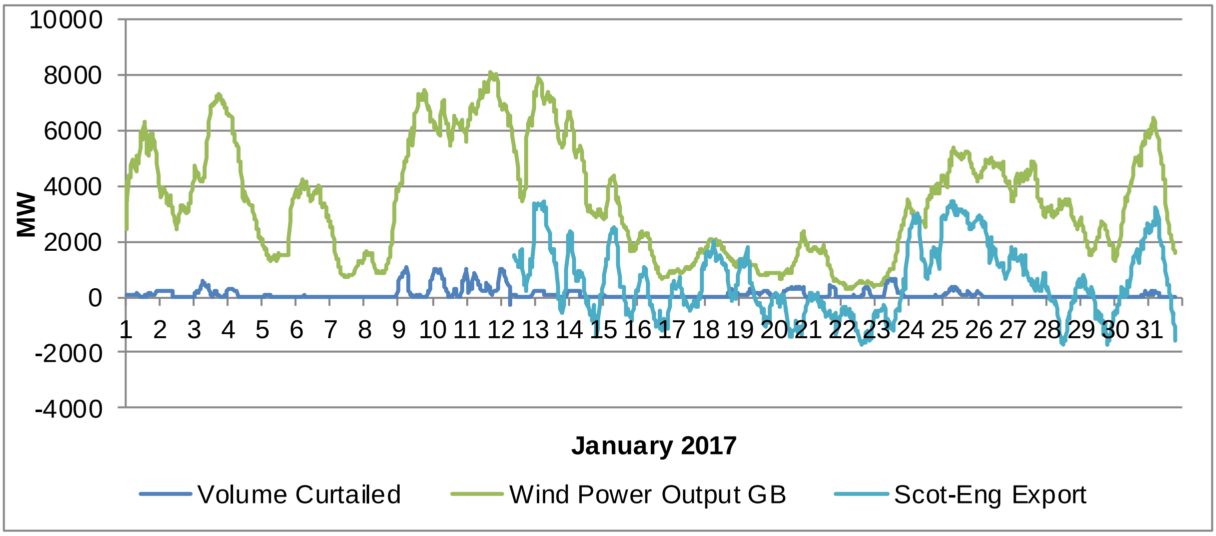


***Figure 6-10** Analysis of wind power output, power curtailed and electricity export flow from Scotland to England for the month of January 2017*

January 2017 has been characterised by five curtailment periods with different durations. Information on the five curtailment periods are listed in the table below:

***Table 6-2** Identification of the five curtailment periods*

Period	Duration [day]	Start date	End date
A	5	01/01/2017	05/01/2017
B	6	09/01/2017	14/01/2017
C	5	19/01/2017	23/01/2017
D	1	25/01/2017	25/01/2017
E	1	31/01/2017	31/01/2017

Looking at the three curves in the chart a quite straightforward relation could be seen: the curtailments occur when the total wind production and the electricity flow from Scotland to England achieve very intense value. This can be confirmed checking the identity of the power stations involved in the curtailment (information collected in the

ID column of the Detailed System Price page, **Figure 6-9**). It is proved that all those power stations are wind plants located in Scotland. However, the curtailment period C corresponds to a period of low wind output and, so, it is not due to an excess of wind. The analysis of the power stations curtailed at that moment shows that those are exclusively coal and gas plants located in England and Wales. Indeed, looking at the graph, it can be noticed that this curtailment period corresponds to a small wind power production and a negative value of the electricity flow through the Scotland-England transmission line. This means that electricity was imported in Scotland to cover the lack of wind production. It can be concluded that the sudden drop in the wind output forces the fossil-fuelled plants to increase their production to cover the demand. This rapid rise of the electricity must have caused congestions in other parts of the transmission networks, leading to the dispatch-down of the power plants that caused the congestion itself.

The volume of energy curtailed from gas and coal-fired power plants is not considered during the simulation-based analysis of the Great Britain energy system. This is because this work focuses on the reduction of curtailment related to renewable energy.

6.2.5.1. WHY DO WE WANT TO AVOID CURTAILMENT?

The curtailment of renewable energy is the result of congestions in the grid due to the lack of adequate transmission lines. Being forced to curtail part of the renewable output means that a portion of the clean electricity available is wasted. Thus, the first negative consequence of renewable energy curtailment is the lack of optimization of the renewable generation and reduction of CO_2 gas emissions. However, one of the effects that is most relevant for the grid operator is the significant cost that is paid for the management of the transmission constraint. This value includes two main terms: on one hand, the penalties costs for the forced power shut down and on the other hand the costs for rebalancing the system. The payment related to the energy curtailment has been increasing for the past years achieving the peak in 2017, where the total constraint costs count for £m 446.34 (**Figure 6-11**) and the wind energy curtailment contribution corresponds to 88% of the total amount [168]. According to the Balancing Service Reports [169], published every month by National Grid, between 2015 and 2017, the constraint costs were 29-33% of the total costs related to balancing services for the grid.

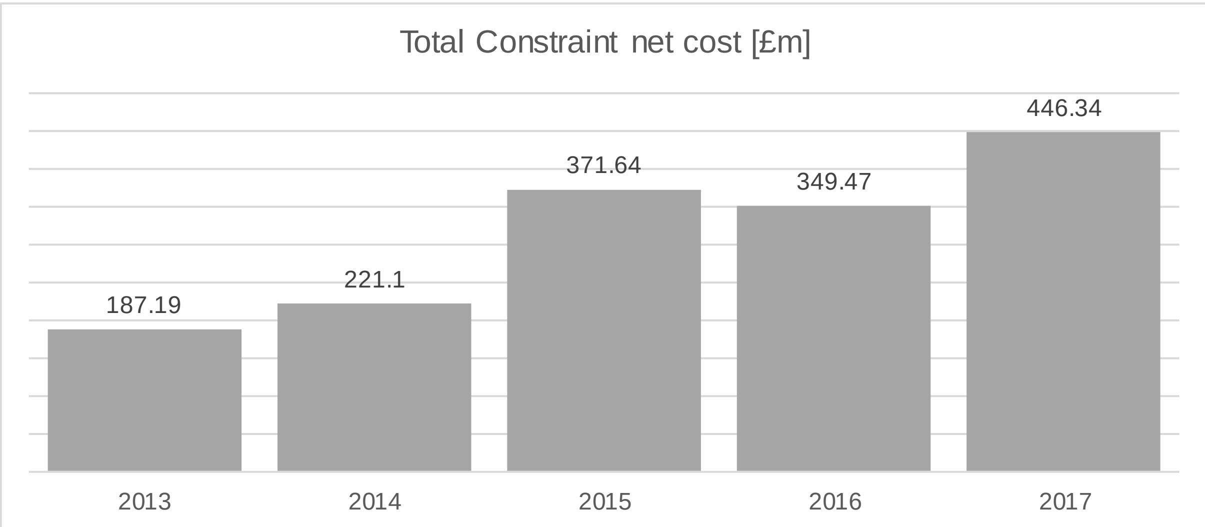


Figure 6-11 *Variation of the total constrained costs per year, 2013-2017*

6.2.5.2. MEASURES FOR AVOIDING WIND CURTAILMENT IN GB

Curtailment is a straightforward procedure for solving congestion issues in the transmission line, however, it comes with a significant cost and with negative effects on the low-carbon electricity generation. The most suitable solution to reduce curtailment depends on the energy system characteristics.

Particularly, in the case of GB energy system, the renewable energy curtailment is due to a local excess of renewable energy generation that cannot be absorbed by the local demand and cannot be distributed to the rest of the network either. The first solution that can be considered is the strengthening of the transmission network, particularly focusing on the line across the Scotland-England border. However, as mention in Section 0 analysing previous works on assessing the value of the energy storage, it has been found that the enlargements of the transmission line cause not only large investment costs but also problems related to the siting and construction. Secondly, the installation of storage capacity could relieve the transmission network by the congestion issues caused by the excess of wind generation. Although, it should be noted that, to avoid the transmission bottleneck at the Scottish border, it is important to concentrate the energy storage capacity in Scotland. If the reserve capacity was added in England, then the congestion and curtailment would still occur.

It is important to remember that the population living in Scotland corresponds to only 8% of the overall British population. With a density population of 67 inhabitants per square kilometre, Scotland represents the perfect remote location for the installation of large-scale wind power plant. This number also explains the very modest electric demand registered in Scotland. For this reason, the choice of investing in electric energy storage may be a risk, the electric demand may be insufficient for absorbing the energy stored.

An innovative solution, which could be implemented to reduce curtailment in Scotland, investigates the power-to-heat conversion of the excess of wind power output and the following storage of thermal energy. In this work, the heat stored would then be supplied for space heating purpose.

In other words, by increasing the amount of electric heating demand it could be possible to absorb a higher percentage of renewable energy in Scotland. Moreover, the presence of storage would allow the decoupling of generation from demand, collecting all the excess energy and distributing it according to the heating requests.

This approach could achieve two main objectives:

- The avoidance of transmission congestions and wind energy curtailment, by increasing the local consumption of renewable energy in Scotland;
- The contribution to the decarbonisation of the heating sector, by replacing part of the domestic gas boiler consumption with the excess generated from the wind power plants.

All the three solutions mentioned above (transmission enlargement, electric energy storage, and thermal energy storage) have been investigated with PLEXOS model and the results will be presented in the following sections.

6.3. DESCRIPTION PLEXOS MODEL

The purpose of the simulation-based analysis of the GB energy system is to assess the potential value of thermal energy storage technology. These benefits will be compared with the advantages achievable with the adoption of different energy solutions, such as transmission lines enlargement and electric energy storage. Thus, the main requirements for the energy model are:

- To represent the dualism of the British energy system, in two regions Scotland-England;
- To be able to replicate the wind energy curtailment at the Scottish border;

- To incorporate the Scottish domestic heating demand, to simulate the benefits achieved with the power-to-heat approach.

The case studies simulated in PLEXOS are the following:

- Case 0: the current status quo;
- Case 1: the installation of thermal energy storage devices in Scotland, to reduce the wind curtailment and use the excess wind energy for domestic space heating consumption.
- Case 2: the potential enlargement of the transmission line at the Scottish border, to increase the penetration of wind energy at the national level;
- Case 3: the installation of electric energy storage devices in Scotland, to reduce wind curtailment.

See Annex A for detailed information of the simulation model.

6.3.1. TWO-REGION MODEL

The first step for the definition of the GB energy system has been defining two regions: one for Scotland and the other for England and Wales. The two energy regions are

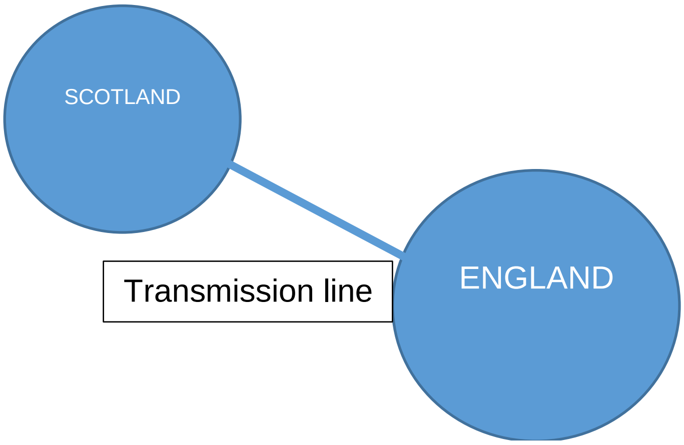


Figure 6-12 *Simplified layout of the PLEXOS model of GB electric system*

connected by a transmission line (**Figure 6-12**), whose power rating has been defined according to the real power flow limitation. The actual dimension of the transmission line is 3.5 GW, according to a report on the British transmission network [168]. **Figure 6-13** shows an example of the electricity flow from Scotland to England in February 2017. Looking at the graph, it can be confirmed that the electricity flow profile never overcomes a maximum value that corresponds at 3.5 GW.

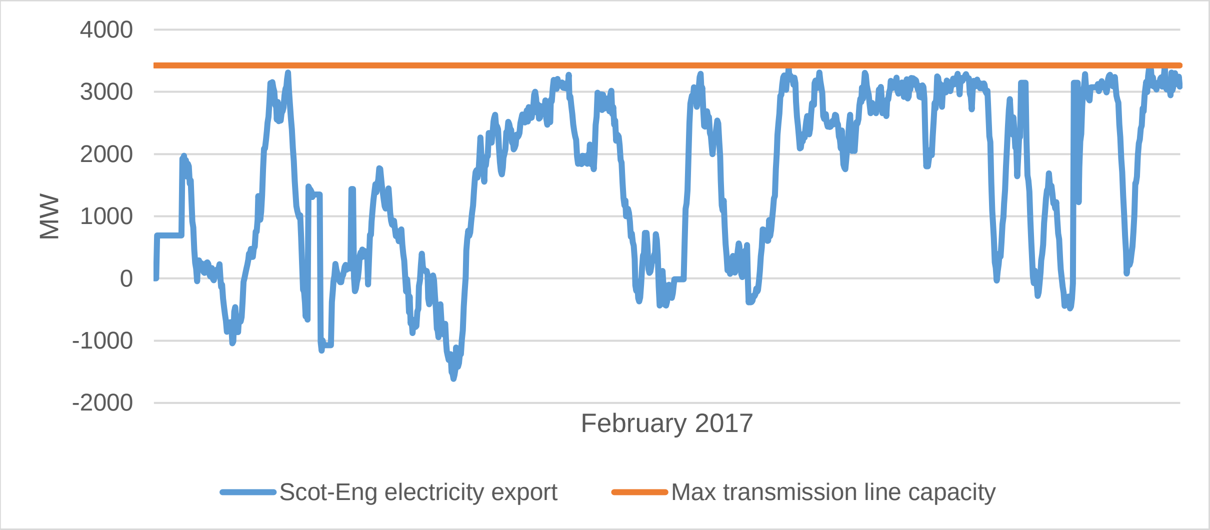


***Figure 6-13** Electricity flow from Scotland to England for the month of February 2017*

Each region is characterized by a local electric demand the can be supplied by the power plants located in the region itself or by the power generated in the other region, which needs to flow through the transmission line that connects Scotland and England.

6.3.2. CONGLOMERATED GENERATION

The GB electricity system includes almost 900 power plants connected to the transmission and distribution network [153]. Due to the large number of generators involved it has been decided not to describe every single unit, but rather conglomerate the power plants according to the type of technology they belong to. This decision has helped to drastically reduce the number of objects that define the model and to simplify the computational optimization problem.

The energy model is characterized by the existence of two main regions: Scotland and England, which include also the generation and demand from Wales. Each region contains the correspondence capacity installed and connected to the transmission line of:

- Combined cycle gas turbine (CCGT)
- Coal power plants
- Open cycle gas turbine (OCGT)
- Nuclear power plants
- Hydropower plants (run-of-river and pump hydro plants)
- Wind power plants

Each generator object is characterized by the number of units that correspond to the overall number of power plants that belong to the energy technology and it can produce a maximum output equal to the maximum cumulative power generation achieved when considering all the power plants (**Table 6-3**). See Annex A for more information.

Table 6-3 *Number of units and maximum capacity of generators defined in PLEXOS model*

Generator	Region	Units	Max Capacity Single unit [MW]
CCTG _S	Scotland	1	1180
Hydro river_S	Scotland	100	13.16
Nuclear_S	Scotland	1	1075
Pumped storage_S	Scotland	1	740
CCTG	England&Wales	30	963.67
Coal	England&Wales	16	940.81
Hydro river	England&Wales	1	141.70
Nuclear	England&Wales	8	846
OCGT	England&Wales	1	32.30
Pumped storage	England&Wales	3	700

6.3.3. DEFINITION OF WIND POWER OUTPUT

It has been decided to follow a deterministic approach for simulating the renewable generation in the PLEXOS model. Thus, the information needed consists of the total amount of renewable capacity installed and the normalized generation profile. The amount of wind power capacity installed has been added to the model by distinguishing the percentages present in Scotland and in the England-Wales area, respectively 4667 MW and 6840 MW, following the data published by the government energy department [159]. The normalized generation profile has been created by using the historical profile available on the Elexon online portal. The historical profile collects the generation on a national basis and it is not possible to separate the contribution from the Scottish wind farms. One of the possible approaches would have been collecting the real output for every single renewable unit installed in the interested region for the entire time period considered (one year). This solution has been considered long and unproductive, not adding concrete advantages to the simulation. For these reasons, it has been preferred to look at the whole wind production and split it out in the two regions according to the share of participation. To generate two separated wind power profiles, it has been decided to divide the total value according to the percentage of capacity presents in each region. Scotland hosts 40% of the overall wind power capacity, thus it has been assigned with 40% of the overall wind generation. The remaining portion of wind power generation has been allocated in the England-Wales region.

The lack of accurate available data can be a limitation for the model development and could cause some discrepancies between the model results and the real data. However, the results have confirmed that this assumption on the wind power generation profile has not severely affected the overall validation of the model, as it will be shown in the following sections.

To simulate wind energy curtailment at the Scotland-England border, it is necessary to modify the original historical profile of the wind power plants installed in Scotland. When only considering the power output registered by National Grid, this takes into account exclusively the amount of power that is input into the grid. This profile differs from the real power output generated from the wind farms and the difference between the two curves corresponds exactly to the amount curtailed (**Figure 6-14**). Therefore, it is necessary to modify the wind power profile and add the amount of energy volume curtailed to register constraints in the transmission line and force the software to interrupt the generation from the wind power plants. This is one of the reasons why the curtailment data collection and analysis has been fundamental for the correct modelling of the renewable integration issues in Scotland.

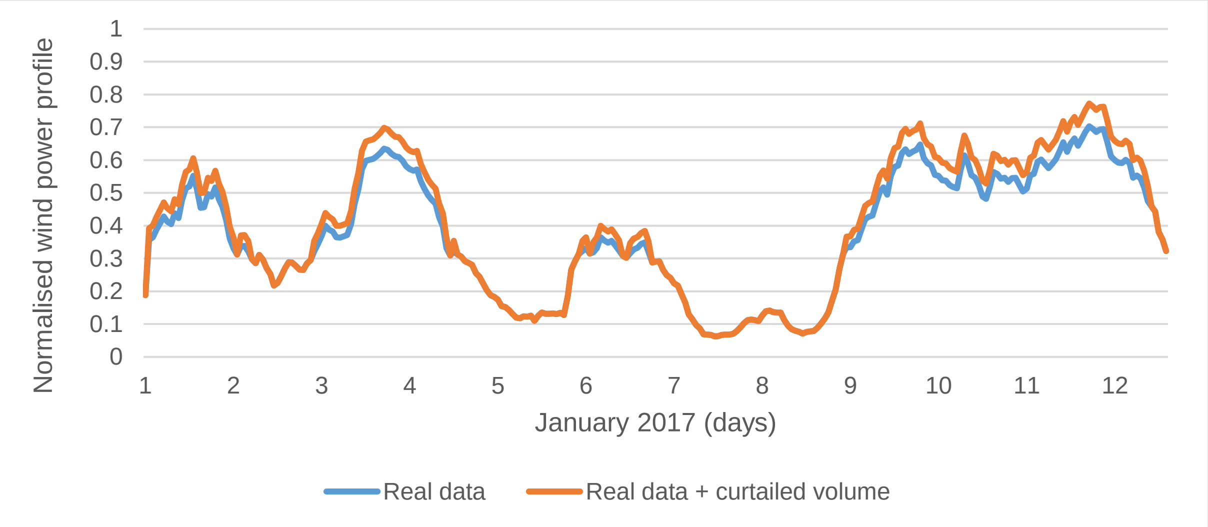


Figure 6-14 *Difference between real normalised wind power profile and normalised wind power profile with the addition of power curtailed*

6.3.4. DEFINITION OF ELECTRIC DEMAND

The electric demand has been input into the model as a constraint to the simulation, such that the unit commitment and economic dispatch are optimized to supply the exact consumptions. To validate the model against the real data, it is necessary to run the simulation using the historical demand profile. For this case study, it has been decided to focus on the most recent data available and run the model using the demand data of the year 2017. The data is collected from National Grid website with a time step of one hour, for a total of 8760 data per year. The information related to the national electric demand is classified into different categories according to the origin of the demand, national level or England-Wales regions only, with the possibility to include the interconnectors demand. From this data, it has been possible to extrapolate the yearly profile for the Scottish and England-Wales regions to input in the PLEXOS model.

6.3.5. DEFINITION OF HEAT DEMAND

The willingness to investigate a power-to-heat solution, among the different energy solutions simulated for the absorption of wind energy excess, has required the integration of the heating demand in the model. As mention in Section 6.2.4.2 it is not possible to access the exact amount of heating consumption for domestic applications. However, a quite accurate estimation can be achieved analysing the natural gas consumptions for non-daily metered users. The value registered by National Grid is the overall daily consumption that considers all the contributions from any kind of domestic service that requires natural gas consumption (like cooking, space heating, and hot water). The value needs to be scaled down in order to consider the only impact of the space heating, correspondent to 74% of the total consumption [167], and it needs to be distributed according to a daily profile in order to be coherent with the electric demand profile added to the energy system model.

No information is available concerning the distribution of natural gas consumption across the day. Thus, the definition of the heating profile needs to be based on some assumptions. The analysis of real heating profile carried out in several studies [165], [170]–[173] has highlighted that the heat consumption is usually concentrated in two different moments of the day: during morning and evening. Moreover, the space heating is usually required for a total of seven or eight hours per day, according to an accurate survey on the energy consumption for GB households [162]. Based on this information the daily heating profile has been created by distributing the total gas consumption per day across eight hours, four in the morning and four in the evening, as can be seen in **Figure 6-15**.

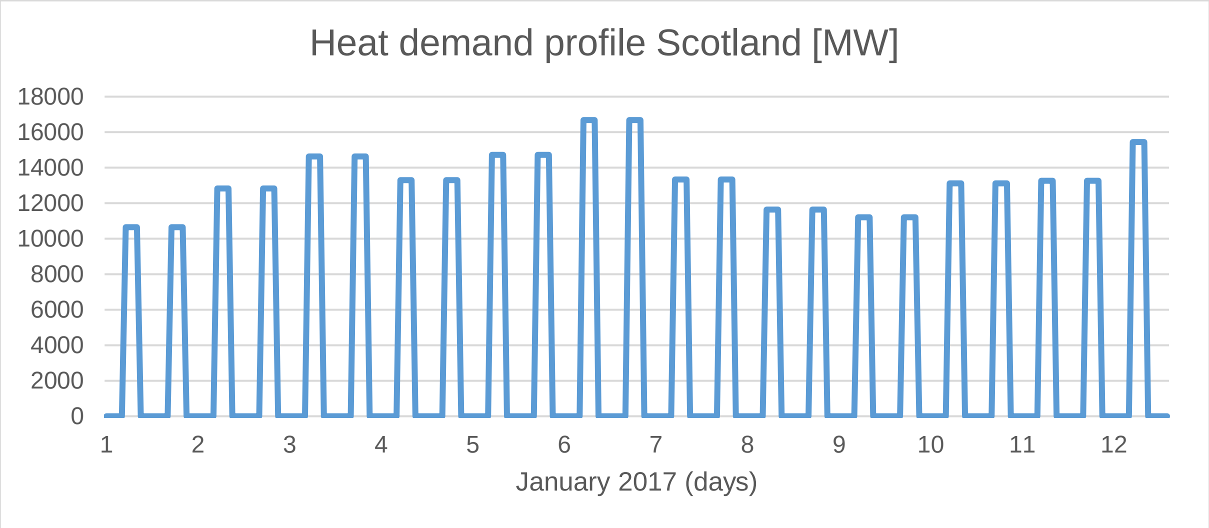


Figure 6-15 *Heat demand profile for Scotland region, based on daily distribution assumptions extrapolated from literature*

6.3.5.1. HOW TO DEFINE HEAT NETWORK IN PLEXOS

One of the peculiarities of this work is the interconnection between the electric and heating network. Using the excess of electricity for displacing part of the gas consumption for space heating application requires to link the electric generation with the domestic heating demand. It has been necessary to find the best method for including the balance of the heating generation and demand with a software tool focused on the optimization of the unit commitment and economic dispatch. Three different approaches have been identified to accomplish this task. **Table 6-4** summarises the advantage and disadvantage of each approach.

The first idea considered the possibility to represent a gas network. PLEXOS allows analysing the optimal distribution of the natural gas fuel across the gas generators

[174] [101]. The gas network includes: a gas field that represents the gas availability, several nodes and pipelines that define the distribution network, gas storage devices, and gas demand. The gas and electric models integrate at the gas nodes, where the gas generators are connected. Defining both these memberships instructs the simulator that the generator is physically supplied with fuel from the gas node and it will demand gas according to its heat rate and generation. The adoption of this method would allow a clear and simple definition of the demand: the gas demand would correspond to the exact gas consumption data collected from National Grid and that corresponds to the heat demand. In other words, the natural gas demand would simulate the request of energy for space heating. However, problems could arise when looking at how to connect this demand with excess wind production. As mentioned above, the electric generators and the gas network are linked through the presence of gas node, but this relation needs the definition of the heat rate and generation. For this reason, this approach has been rejected.

The second option considered looks at the possibility to define a proper heat demand by using the combined heat and power (CHP) plant modelling scheme [175]. PLEXOS recognises the operation of a CHP plant, which produces electricity and provides heating demand using the recovering heat. Moreover, tuning specific parameters of the CHP model allows the simulation of a thermal storage device or electric boiler. This solution would have allowed the definition of the heating demand and the connection between the electric and heating network using the electric boiler. The key point of the modelling of this device is defying it as an “anti-generator”, a generator that acts as a load and absorbs electricity from the grid. Although, the simulation of the heat demand and electric boiler is possible only if they coexist with the CHP electric generator. Thus, it is not feasible to represent a stand-alone electric boiler connected to the heat network. For this reason, this approach has been considered not viable.

Table 6-4 *Summary of approaches identified to represent heat demand in PLEXOS*

	Advantage	**Disadvantage**
Gas network	Allow input gas demand	Difficulties of connecting gas network and excess wind electricity
CHP modelling	Allow input heat load	Impossibility of decoupling heat and electricity generation
Heat-electricity analogy	Allow direct connection between excess wind electricity and heat demand	Heat demand needs to be converted in electricity consumption

The third approach considers the creation of a heat-electricity analogy (**Figure 6-16**). This idea looks at the heat demand as the equivalent electric consumption that would be needed to provide the same amount of space heating using electric boilers. The conversion is done by considering the real efficiency of a gas and electric boiler. Following this analogy, the heat demand can be replaced by electricity demand, the gas boiler can be simulated with an electric generator.

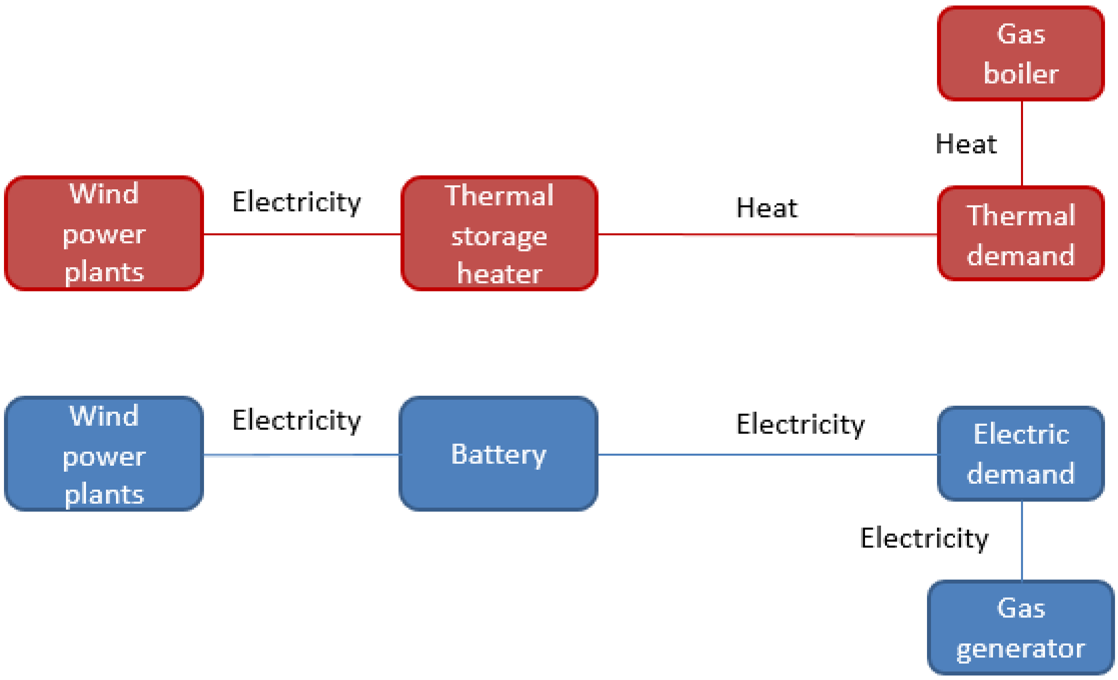


Figure 6-16 *Representation of heat-electricity analogy*

The electric network and the "heat network" are defined as two separated grids inside the Scotland region: the operation of each of them is optimized to provide each separate demand profile. As in reality, the connection between the two networks happens at the thermal storage level (**Figure 6-17**). In a real application, the thermal storage converts the electricity into heat, usually using electric resistance immersed in the storage medium. Then, it stores the energy in form of thermal energy and it delivers it following the space heating demand. In the energy model, the operation of the thermal storage is simulated by a battery to be coherent with the heat-electricity analogy.

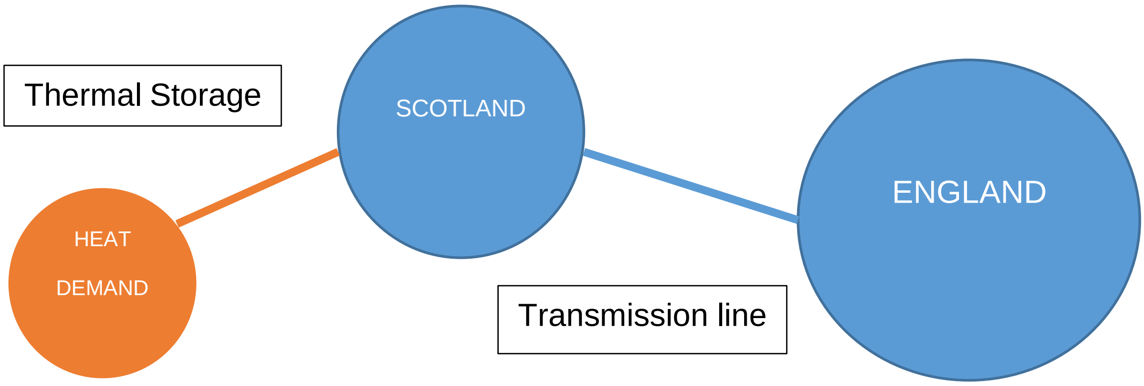


Figure 6-17 *Representation of the integration between heating network and electricity network*

This method allows connecting the heating and electric network in a software tool focused on the optimization of the unit commitment. In case of excess of generation from the Scottish wind power plants, the software schedules the charge of the electric storage. The electricity stored is delivered according to the “heating network” demand profile input in the model.

6.3.6. INTERCONNECTORS

The British energy system is interconnected with four European countries; a total amount of 4GW of capacity is shared among the interconnectors, providing almost 5% of the national demand [176]. The interconnections represent the physical link that enables the power flow across the borders. Currently, the existing British interconnectors include:

- 2GW to France (IFA)
- 1GW to the Netherlands (BritNed)
- 500MW to Northern Ireland (Moyle)

- 500MW to the Republic of Ireland (East-West).

The mechanism behind the exchange of electricity across interconnectors is controlled by different regulatory models. In some cases, the electricity is traded as a result of the market arbitrage model, whilst in other cases can be a combination between the market arbitrage model and regulated transmission asset models [177].

The complicated balancing mechanisms that regulate the net electricity interchange across the national borders is not the focus of this work. The existence of long-term contracts and agreement between the European countries complicates the simulation and optimization of the national electric dispatch. Moreover, it has been assumed that the congestion issues that take place between Scotland and England are not influenced by the balancing mechanisms that involve international interconnectors. Thus, when modelling the British energy system, it has been decided to neglect the modelling of the interconnectors.

6.3.7. ENERGY STORAGE

Energy storage can be modelled in PLEXOS as pumped hydro systems or batteries. The GB model includes both typologies since PHS are already present in the real electric grid layout and batteries are introduced as potential solutions for wind curtailment avoidance. To include a pumped hydropower plant is necessary to define the characteristics of the upper and lower water basins, in terms of maximum energy stored, the electric pump and the generator. This information input in the model is summarised in **Table 6-5** and is referred to the real PHS plant installed in GB [178].

Table 6-5 *Technical parameters PHS installed in GB*

PHS station	Region	Max capacity (GW)	Head basin (m)	Volume basin (million m^3)	Energy capacity (GWh)
Ffestiniog	Wales	0.36	320–295	1.7	1.3
Cruachan	Scotland	0.40	365–334	11.3	10
Foyers	Scotland	0.30	178–172	13.6	6.3
Dinorwig	Wales	1.80	542–494	6.7	9.1

Case 1 and Case 3 respectively simulate the operations of thermal and electrical energy storage devices in synergy with the wind power plants in Scotland and both technologies have been simulated as battery objects. While for Case 3 the use of a battery model does not represent an issue, in Case 1 it might seem unusual to adopt the same approach for the simulation of a thermal storage system. However, in accordance with the power-heat analogy used for this simulation analysis, the thermal storage can be modelled as a battery system. To simulate the effect of the use of excess wind energy for partially replace the use of gas boiler for space heating application, the thermal storage model is connected to the Scottish wind power generators, for the charging process, and to the Scottish heat demand, for the discharging process.

The battery object can be implemented by specifying the power rating, energy capacity and charging or discharging efficiency. The main parameters that define the battery system model are tuned and modified during the simulation in order to run sensitivity analysis and assess their influence on the overall value of the thermal storage.

The operation of the energy storage devices is scheduled by PLEXOS to optimize the economic revenue of the plant. Following energy arbitrage basic concepts, the storage buys energy during off-peak periods and discharge during peak periods to maximize the income by selling the electricity at the highest price. The energy storage is seen as a consumer of electricity because it has charge efficiency lower than 1. Thanks to the optimized operation and the disparity between peak and off-peak prices, it is still able to generate economic revenue.

The optimum schedule of the energy storage can be achieved only running a Short-Term simulation. The Medium-Term simulation would not be able to identify the arbitrage opportunities for the storage device because it would not capture the daily price variation. For this reason, it is necessary to use a small time step (e.g. one hour) in order to assess the optimum schedule of the storage and maximise its economic revenue.

6.4. RESULTS

6.4.1. CASE 0: STATUS QUO

The simulation is run with the time step of one hour and the time horizon of one year. The demand profile adopted for the simulation corresponds to the real electric consumption measured in the year 2017. This choice allows comparing and validating the model against the real output of the power plants, generated in the same year.

6.4.1.1. UNIT COMMITMENT AND ECONOMIC DISPATCH

The following graphs (**Figure 6-18**, and **Figure 6-19**) show the economic dispatch of the generating units installed in GB according to the different periods of the year, at the beginning and at the middle of the year 2017. The solid lines represent the model results while the coloured areas show the corresponding real generation. Looking at both figures, it can be noticed that the nuclear power plants contribute to the national load with a constant baseload; the wind output is characterised by a fluctuating profile due to the variation of the wind speed; the hydropower plants (both run-river and pumped hydro) have a small contribution to the demand, while a quite large portion of electricity is supplied by fossil-fuelled units, such as coal and CCGT plants. The output of these power plants is regulated to compensate the renewables generation and supply the electricity demand, as can be observed by looking at the two daily peaks, typical of the demand profile.

The two periods have been selected to show the differences in the unit commitment following the seasonality of the electricity load, characterised by high value during the winter and low demand during the summer. For instance, in June (**Figure 6-19**), the electricity generation of the coal and CCGT power plants is visibly reduced due to the reduction of the electricity requirements. Moreover, the variation of the electricity generation can be driven by other factors, such as the seasonality of the renewable source. **Figure 6-20** shows the variation of the run-river units generation that decreases during the summer periods due to shortages of water to supply the power stations.

The graphs below present both the simulation results and the real data collected in the year 2017. This similarity of the several profiles according to the different generator fuel types, the moment of the day, and the seasonality of the electricity demand allows validating the model against the real data. When comparing the simulation results with the real data, it is important to take into account that the model considers several assumptions, such as the division in two regions (Scotland and England-Wales) connected by a single transmission line, the agglomeration of the generation and demand, and the lack of interconnectors, that might cause some gaps between the simulated and real profiles.

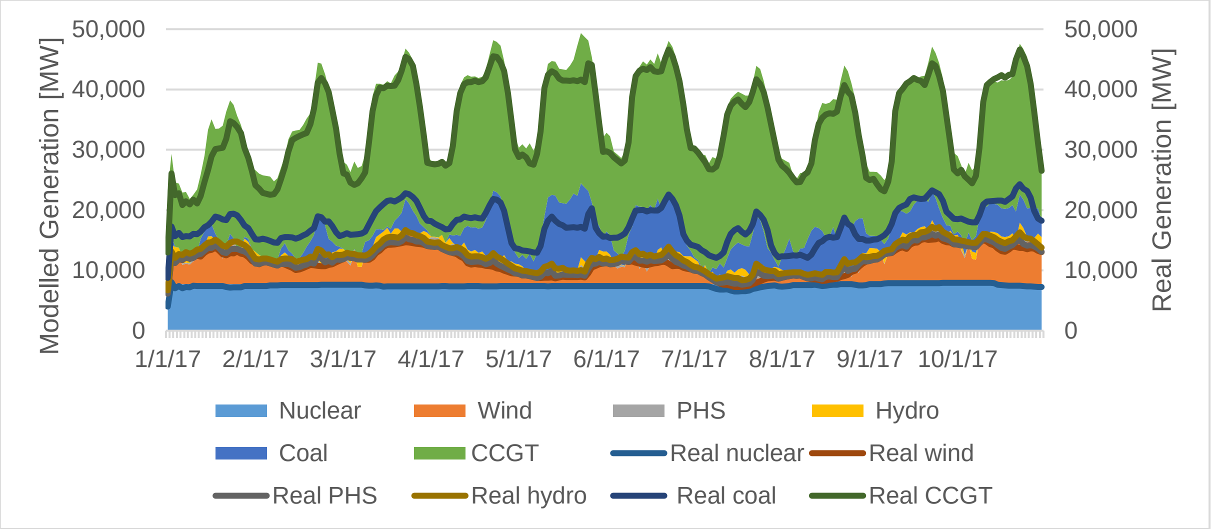


Figure 6-18 *Unit commitment and economic dispatch of generation units in GB across 10 days at the beginning of the year 2017. The simulation results are compared with the real generation data for each fuel type.*

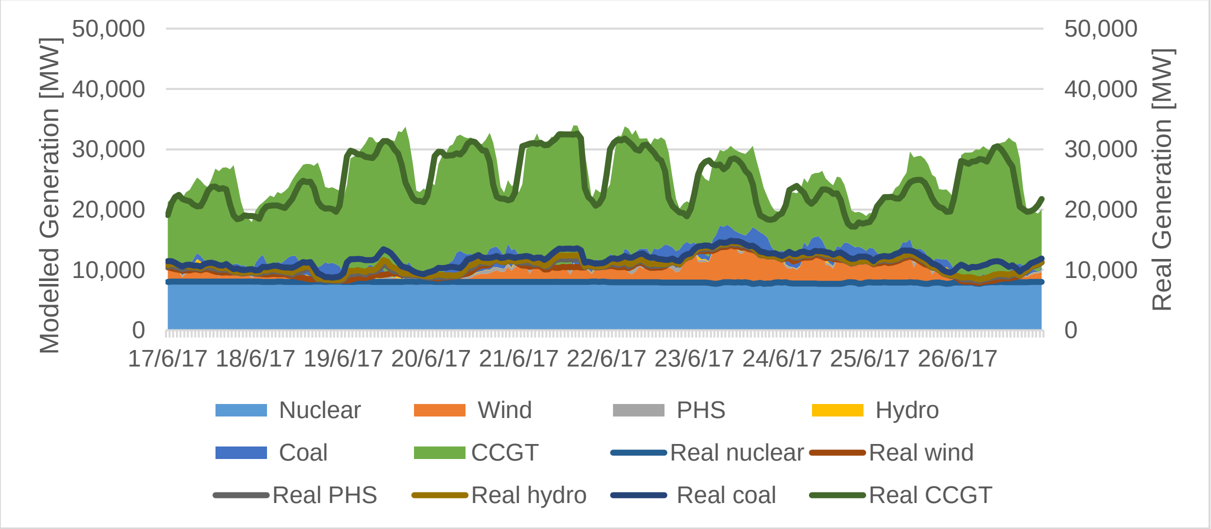


Figure 6-19 *Unit commitment and economic dispatch of generation units in GB across 10 days at the mid of the year 2017. The simulation results are compared with the real generation data for each fuel type.*

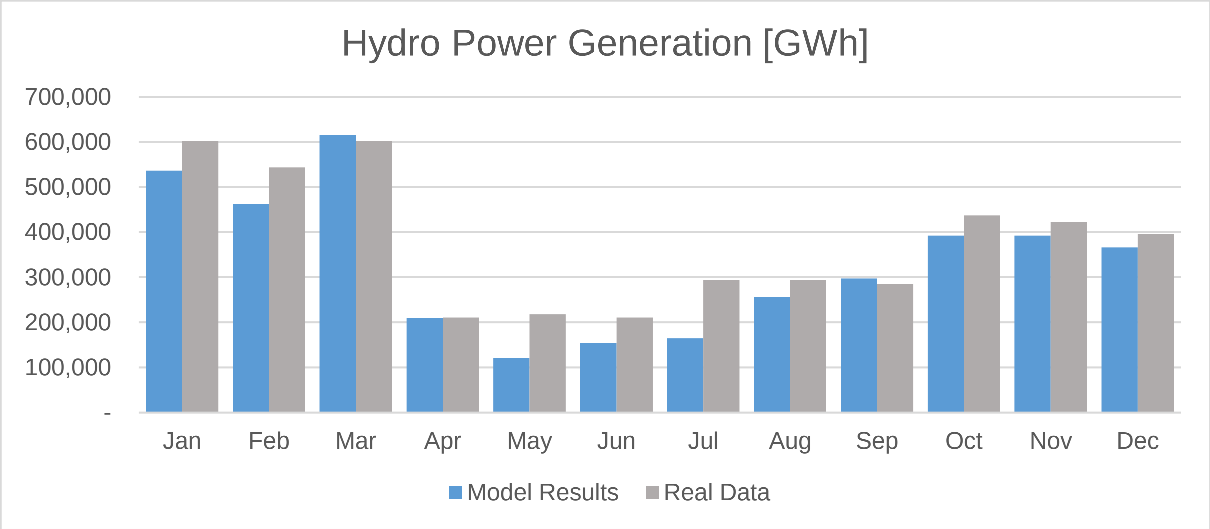


Figure 6-20 *Example of electricity generation seasonality following the availability of renewable source. The monthly generation of the hydro power plants simulated with PLEXOS is compared with the real data.*

6.4.1.2. ELECTRICITY EXPORT AND WIND ENERGY CURTAILMENT

Another important result achieved with the simplified model of the GB electricity network is shown in **Figure 6-21**. The graph presents the similarity between the electricity export flow between Scotland and England simulated by the PLEXOS model and the corresponding real data. The reproduction of this information has been possible by separating the modelled electric network in two regions (Scotland and England-Wales), connected by one single transmission line, as it happens in reality.

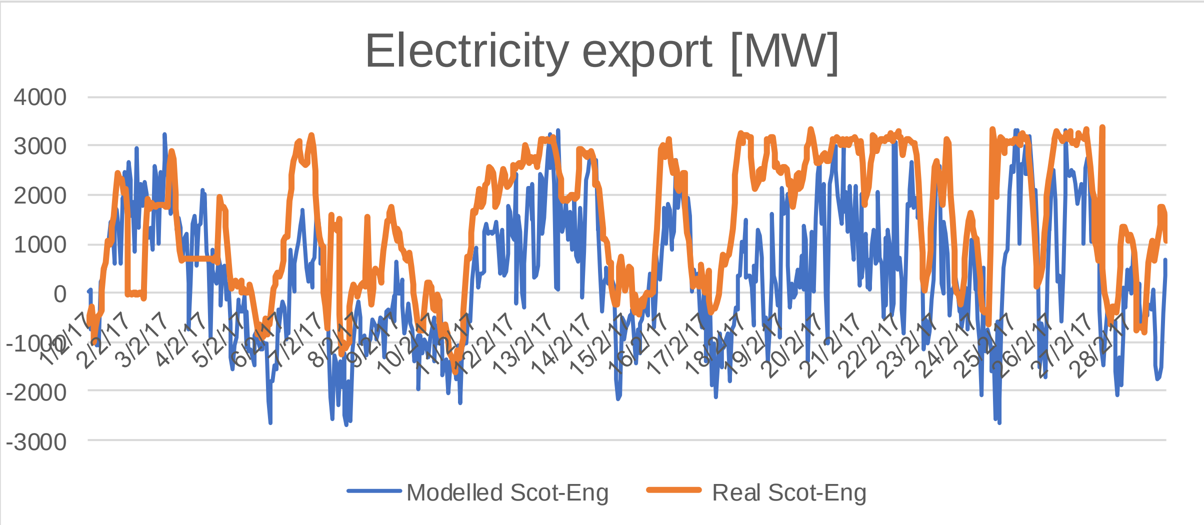


Figure 6-21 *Comparison between the electricity export at the Scotland-England border simulated by the model and the real data.*

Being able to validate the accuracy of the modelled export flow with the measured data is fundamental for the aims of this work. This means that the model can simulate the congestions in the transmission lines at the border between Scotland and England that cause the curtailment of the excess wind output. Indeed, wind energy curtailment has been detected by the model and an example of the volume curtailed profile is shown in **Figure 6-22**. The simulation results reproduce the intermittent behaviour of the wind power curtailment that is clustered in periods when the transmission line is obstructed by congestion, or absent for several days in a row (as it appears between the 5th and the 12th of February 2017, according to the simulation).

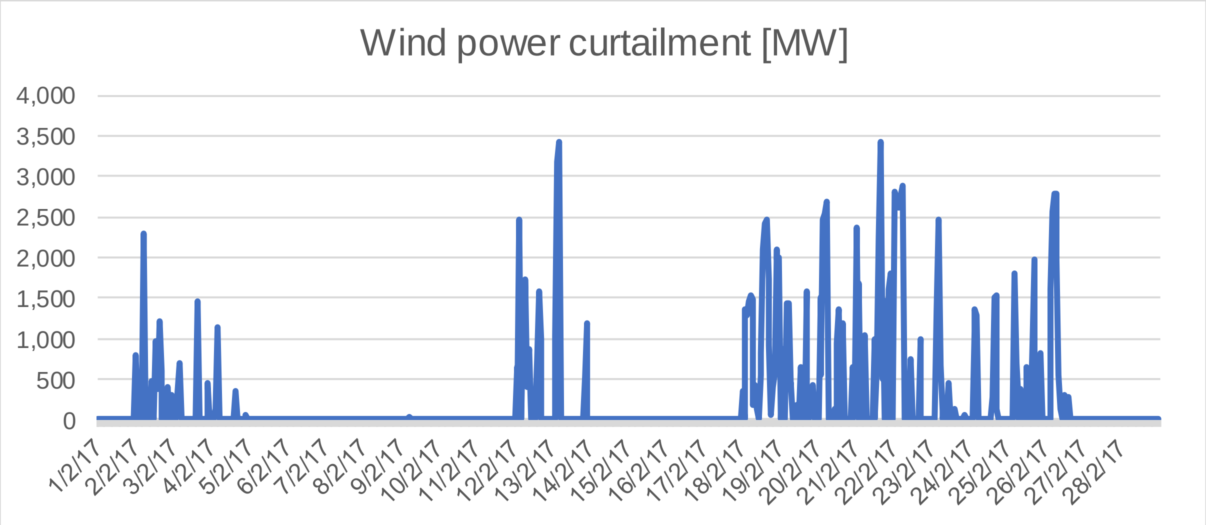


Figure 6-22 *Example of wind power curtailment, occurred in Scotland in February 2017, according to the simulation results*

The analysis of the simulated wind energy curtailment across the year has not shown any visible pattern or seasonality (**Figure 6-23**). The volume of renewable energy curtailed per month is a function of the wind speed intensity and the electricity demand; since both values are subjected to different level of variation over the year and are not correlated one to each other, it is reasonable that the total amount of wind energy curtailed per month changes over the year without following a clear pattern.

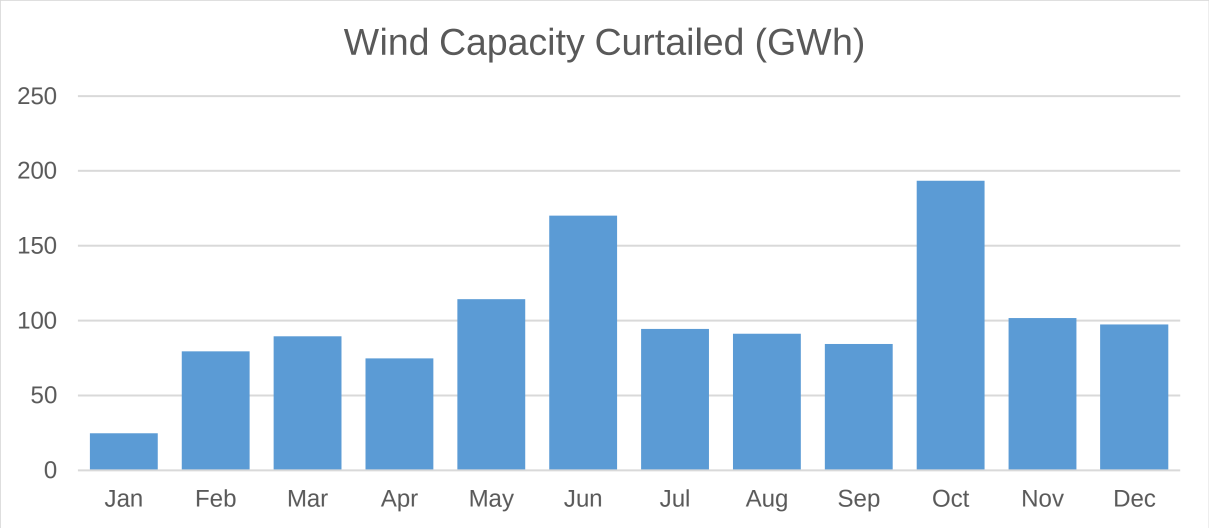


Figure 6-23 *Total wind energy curtailed per month due to congestion in the transmission line between Scotland and England, according to the PLEXOS model*

6.4.2. CASE 1: THERMAL STORAGE

The assessment of the benefits that can be achieved with the installation of grid-scale thermal energy storage in Scotland is the key point of this section and the main direct and indirect effects are the central topics of this paragraph. The thermal storage technology has been modelled considering a maximum power rate in the range of 1.1-2.2 GW and an energy capacity corresponding to 8 hours of charge at the maximum power. For this technology, suitable for domestic space heating, it has been considered the maximum value of energy efficiency. This assumption is justified thinking that the coefficient of conversion from electricity into heat is equal to 1.0, according to the Joule effect theory [179], and that any thermal losses of the device into the surrounding area can be seen as heat gain for the space that needs to be heated.

6.4.2.1. OPERATING STRATEGY

One of the peculiarities of this solution is that the charging and discharging processes of the thermal storage are decoupled and driven by two different markets: the charging process aims to maximise the amount of renewable energy stored, while the discharging is driven by the space heating requirements. For this reason, the operating strategy of the thermal storage devices does not follow the variation of the electricity price, that is usually employed to optimise the economic revenue of the storage itself. **Figure 6-24** shows the charging strategy of the thermal storage compared to the Scottish wind power output profile. It can be noticed that the grid scale thermal storage device aims to maximise the charge. This is because the wind wholesale electricity price is convenient compared to the price of the gas heating system, used in the model for the heating provision. Thus, when possible, the thermal storage operates at maximum charging load, otherwise, in case of low wind speed, it achieves the maximum wind power output. Moreover, since the charge and discharge process cannot happen simultaneously, it can be observed that the charging process is regularly interrupted by the discharge that follows the space heating requirements assumed for this model. This charging strategy is coherent with the optimisation approach adopted by PLEXOS, whose aim is to minimize the costs of the entire energy system that in this case is seen as the combination of the electricity and heating network.

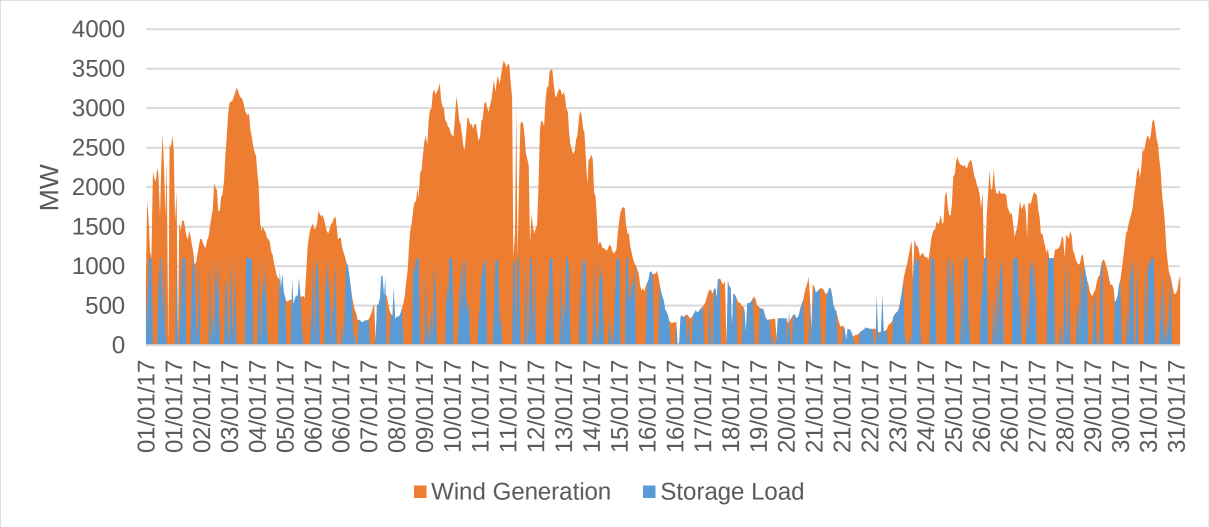


Figure 6-24 *Charging strategy for thermal storage, assumed connected to the wind power plants in Scotland*

It is important to highlight that the use of thermal storage devices, rather than direct electric heating systems, ensures the avoidance of peak electricity price. Indeed, the heating periods are usually set during the peak hours (this is because they correspond to the moments when people are at home and, thus, generate the highest consumptions) and use of direct electricity for the space heating would cause high costs. The use of thermal storage devices would overcome this issue by charging in periods of off-peak and, thus, low prices. **Figure 6-25** and **Figure 6-26** show an example of the wholesale electricity price profile according to the simulation results for the GB energy system. This curve is compared to the space heating demand, as assumed for the model and based on national surveys reports. Looking at **Figure 6-25** and **Figure 6-26** it is confirmed that the wholesale electricity price peaks correspond to the space heating periods.

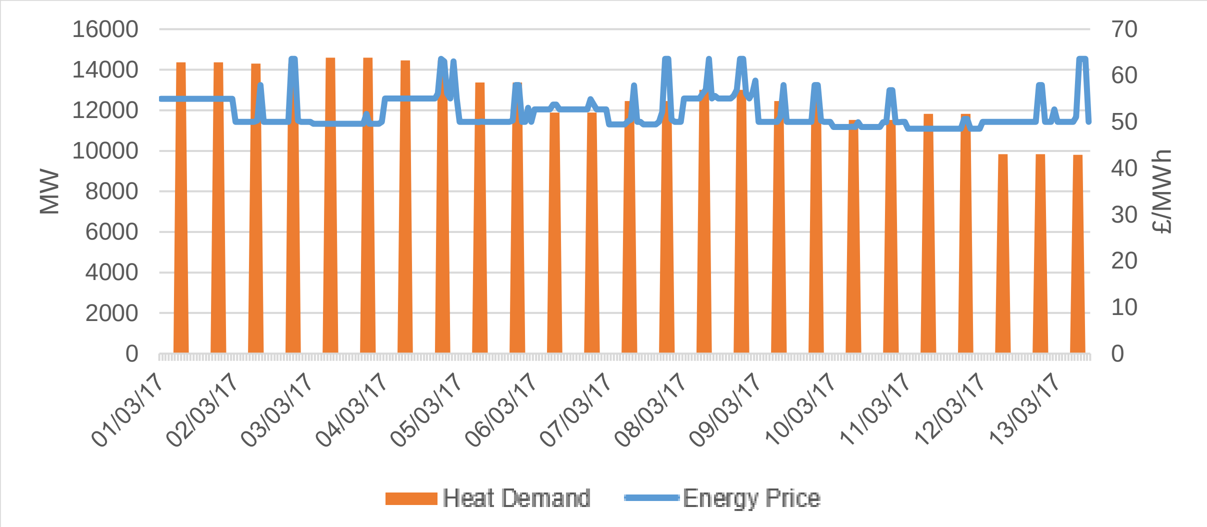


Figure 6-25 *Evolution of wholesale electricity price variation compared to heating profile in March, according to simulation results*

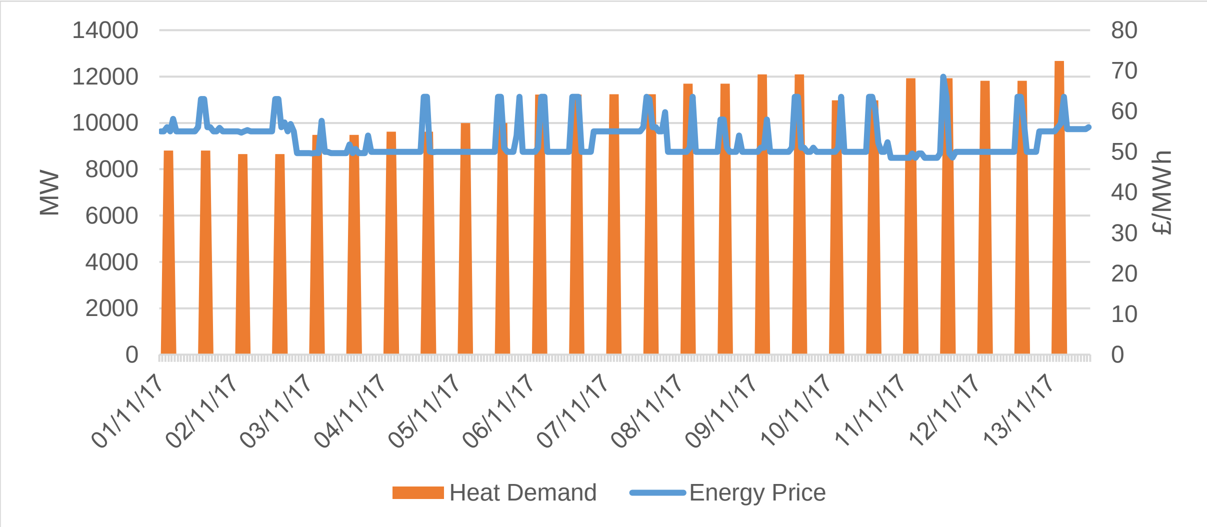


Figure 6-26 *Evolution of wholesale electricity price variation compared to heating profile in November, according to simulation results*

6.4.2.2. VALUE OF THE THERMAL STORAGE TECHNOLOGY

System point of view. The first outcome directly dependent on the use of thermal energy storage in synergy with wind power plants is the reduction of wind energy curtailment across the year. Different simulations and energy scenario have been run according to different sizes of the storage capacity. The larger the size of the overall energy storage capacity installed, the larger the reduction of wind energy curtailment across the years, since the thermal storage devices store the excess of wind electricity (**Figure 6-28**). The installation of 1.1 GW and 8.8 GWh of energy storage can already achieve almost 60% of reduction of wind energy curtailment across the year, as can be read in **Table 6-6**. When increasing the storing energy capacity, the reduction of wind curtailment per year follows a non-linear trend (**Figure 6-28**). The reason is that the addition of further capacity would have a significant effect only in case of peaks of energy curtailments or for curtailment periods that last for a long time. The amount of volume curtailed is not homogenously distributed across the month but is usually concentrated in short periods that may present also relevant peaks. For this reason, the installation of large thermal storage capacity able to completely avoid curtailment can be not convenient, since the entire capacity would be exploited just on a few occasions per year. Sizing the energy storage to avoid curtailment can be not economically convenient and the revenues will not be able to cover the capital invested.

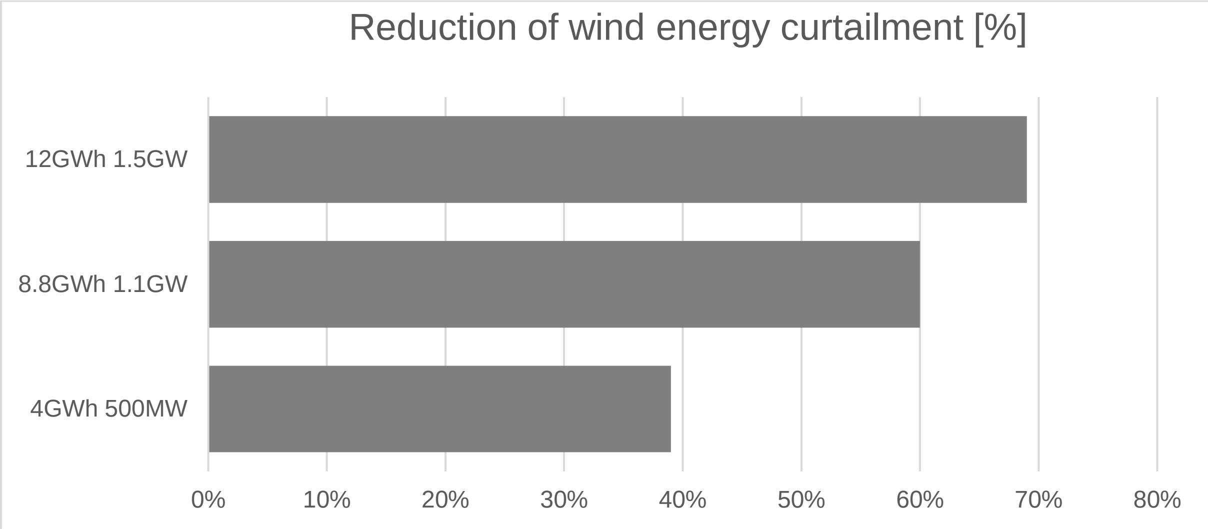


Figure 6-27 *Comparison of wind energy curtailment reduction according to different thermal storage size*

Table 6-6 *Reduction of wind energy curtailment per year according to simulation analysis based on thermal storage with different energy capacity*

	Wind generation Scotland [GWh]	**Wind energy curtailed Scotland [GWh]**	**Reduction of wind energy curtailment**
Case 0: Status Quo	10,686.90	2,913.11	-
Case 1: Thermal Storage 1.1GW 8.8GWh	12,383.81	1,216.20	58.25%

Apart from the reduction of wind energy curtailment, the use of thermal energy storage can generate secondary but not less important benefits. By addressing the wind energy excess to the heat sector, thermal storage devices contribute to the electrification and decarbonization of the space heating generation. The savings of gas heating consumptions are directly reflected in the reduction of fuel costs, due to the decrease of natural gas used for space heating purposes. The reduction of almost 60% of the wind curtailment would correspond to the savings of 30% of the total gas heating generation that is needed for household consumption in Scotland.

Table 6-7 *Comparison of generation, costs and emission for the heating system in Scotland, according to simulation results*

	Gas heating consumption [GWh]	**Heating costs [£m]**	**CO_2 emission [Mt]**
Case 0: Status Quo	24,547.64	1,562.49	5.13
Case 1: Thermal Storage 1.1GW 8.8GWh	17,393.34	1,107.21	3.63

The reduction of gas boiler consumption means a visible decrease in the CO_2 emission per year. The potential reduction achievable could reach almost 30% of the current emission quantity. It is important to notice that this decrease in CO_2 emission is calculated according to the real heating consumption in Scotland (and not to the total GB heating demand) and it is coherent with the interventions suggested by the Committee on Climate Change (CCC) [180] that stresses the necessity to increase the percentage of electric heating system. Moreover, according to the 4th Carbon Budget published by the CCC, a reduction of emission related to the domestic heat sector of approximately 30% by 2030 should allow the achievement of the CO_2 target by 2050 [181]. This means that the simulation results obtained by using large scale thermal storage devices connected to wind power plants agree with the CCC's projections.

It is interesting to notice that the exploitation of the wind energy and the partial use of this energy for heating purposes could cause modifications in the unit commitment of the Scotland region. Part of the wind energy that is addressed to the heat sector is no more available to cover the electricity demand; thus, another power technology needs to supply this demand. As can be noted looking at **Figure 6-28** the generation of hydropower, nuclear and PHS plant is limited by maximum energy constraints, due to technical limitation or natural source availability. Thus, the difference in energy needed is covered by the CCGT, whose energy production is normally restricted to only 3% of the total capacity, due to the presence of large alternative power available.

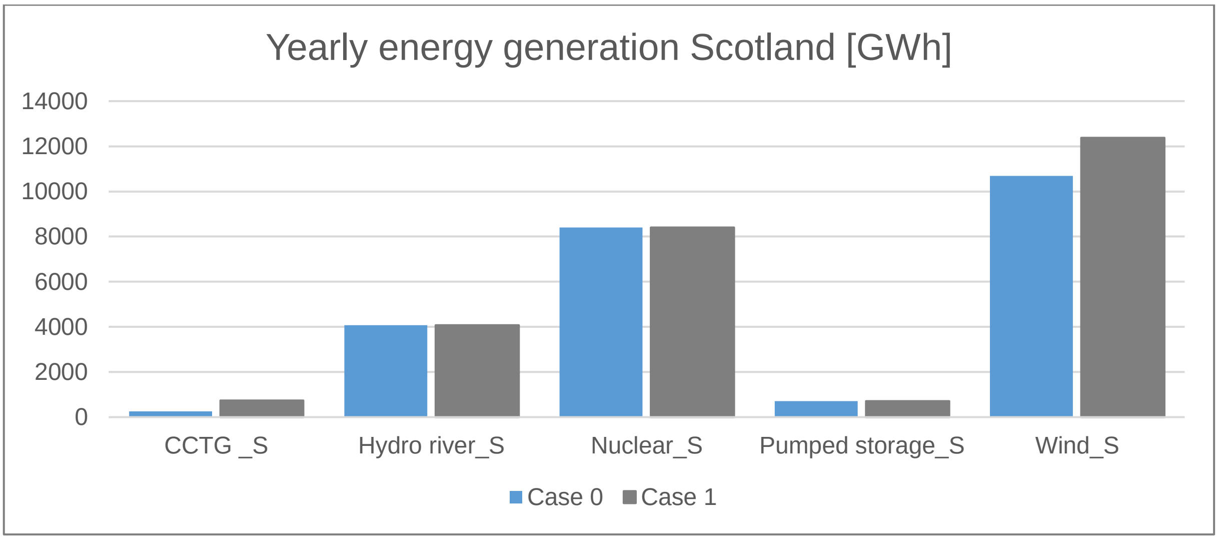


Figure 6-28 *Comparison of yearly energy generation from power plants in Scotland, according to simulation results*

Investor point of view. The previous paragraph showed the environmental and financial benefits of the use of thermal storage technology regarding the entire energy system (i.e. savings of natural gas consumptions and CO_2 emissions). However, as it has been mentioned in the literature review in Chapter 3, the value of the storage can be assessed also in relation to the investor's point of view that looks at the economic revenue of the storage technology itself. In this case, the benefit of the storage is represented by the possibility to buy wind electricity and thus to generate the same amount of heat at a cheaper price than with the use of gas boilers. The energy storage value can be calculated as the total revenue of the energy storage over its lifetime divided the energy capacity (kWh) [57]. According to the simulation results, when considering the installation of 8.8 GWh of thermal storage capacity the value of the storage could be approximately £35/kWh. This quantity is smaller compared to results presented in other works [57] and the reason is due to the fact that in this case the value of the thermal storage is only based on arbitrage activity and it does not consider ancillary services. One of the devices that could be adopted as thermal storage technology is the thermal storage heater (whose characteristics are the object of the discussion section of this chapter and Chapter 7). In this case, the current price of the product on the market is in the range of £20-40/kWh (based on real quotations), which is of the same order of magnitude of the value calculated in the present system.

6.4.2.3. SENSITIVITY ANALYSIS

The potential effects of the thermal storage system when connected to the Scottish wind power plants have been analysed according to the variation of the storage capacity and power rate.

Storage capacity. The first results have been obtained assuming the installation of the thermal device with large storage capacity, able to charge at maximum power for 8 hours. This choice has been based on the average daily heating demand (that is approximately 8 hours/day). However, the simulations results have shown that the storage is not able to benefit from the full charge since the heating profile is characterised by two heating periods per day of 4 hours each (**Figure 6-30**). This means that the storage would not be able to optimise the charge and thus maximise the amount of wind power to store during the charging period.

When simulating the installation of thermal storage heaters with 4 hours of reserve, the storage would be able to completely discharge during the heating periods (**Figure 6-30**). However, with a limited storage capacity, it is not able to maximise the amount of wind power stored during the 8 hours of charging period and it achieves worse results than in the previous case (**Figure 6-30**).

In other words, not only the storage capacity but also the heating demand profile would influence the schedule and optimisation of the thermal storage strategy. For instance, concentrating all the heating hours in a single period would allow the employment of storage with large capacity. Another strategy would be dividing the heating demand into several short periods per day, this heating pattern might fit the requirements of people who spend most of the daily time at home.

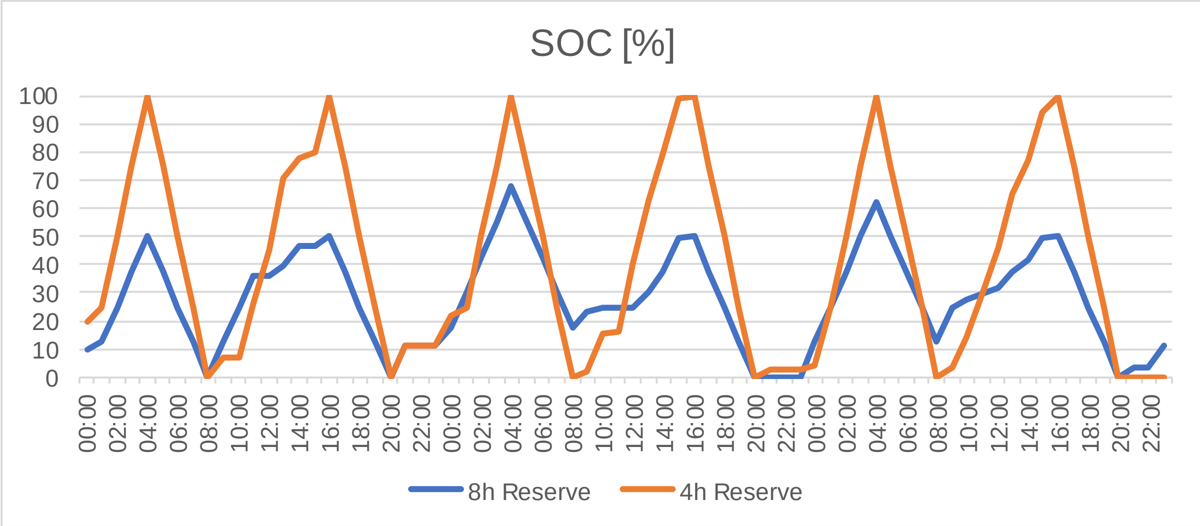


Figure 6-29 *Comparison of state of charge of thermal storage systems according to different storage capacity*

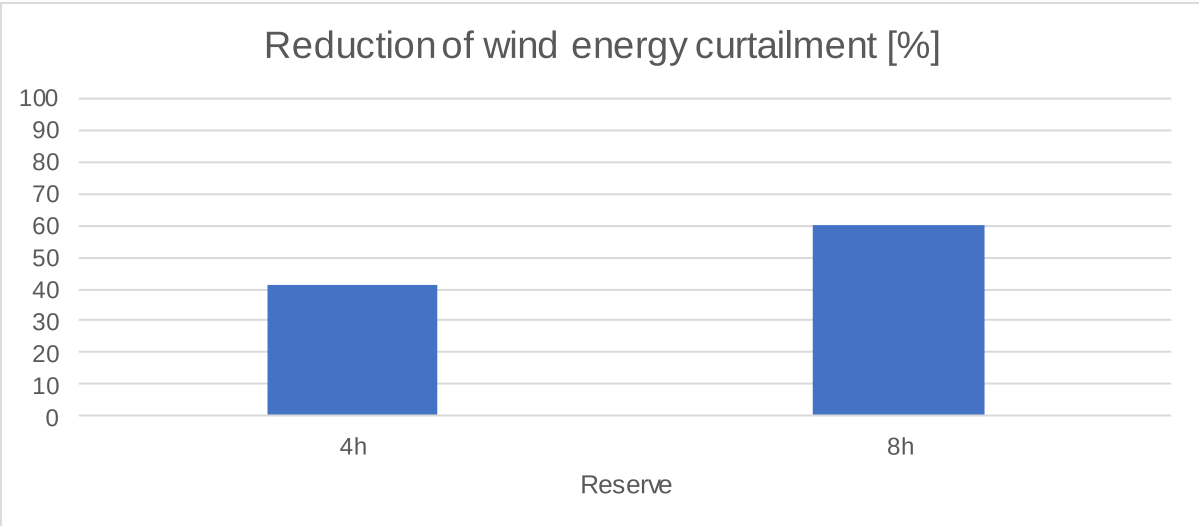


Figure 6-30 *Comparison of reduction of wind energy curtailment according to different storage capacity of the thermal storage system*

Storage power rate. Simulation results have been obtained also modifying the power rate of the storage technology, maintaining constant the reserve capacity to 8 hours. As expect, doubling the power rate allows achieving better reduction of the wind energy curtailment (**Figure 6-31**). This is because in the same amount of time, it is possible to store a larger amount of energy. Although, it is interesting to notice that, by doubling the power rate, the percentage of curtailment reduced is not doubled. As mentioned above, this is due to the wind curtailment profile, which is usually clustered in short periods with high peaks and discourage the installation of oversized storage system.

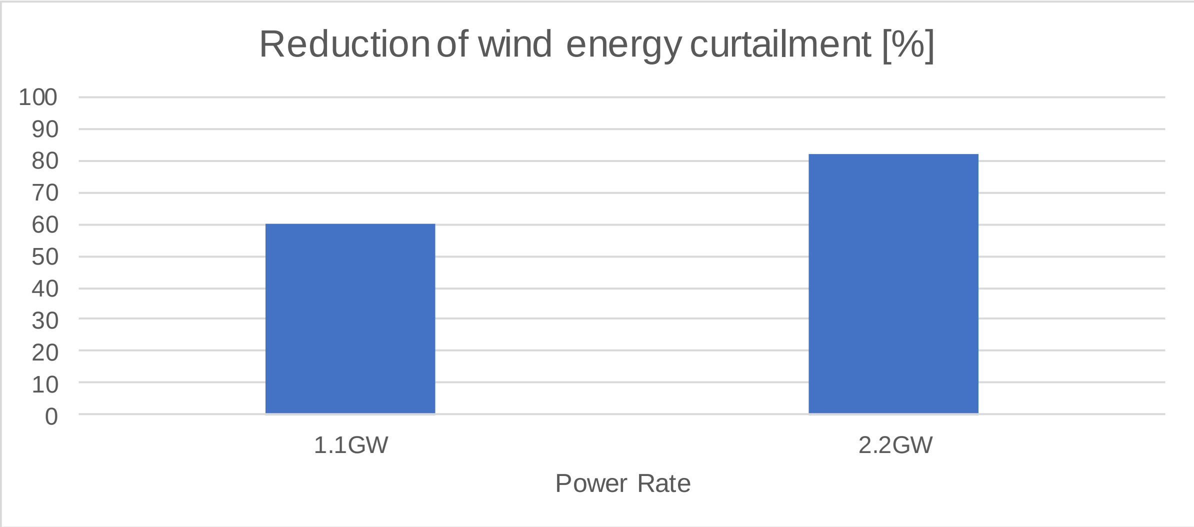


Figure 6-31 *Comparison of reduction of wind energy curtailment according to different power rate value of the thermal storage system*

6.4.3. CASE 2: TRANSMISSION LINE ENLARGEMENT

The adoption of thermal storage looks a promising solution for the reduction of wind energy curtailment. Different energy solutions have been investigated and their performance and simulation results have been compared with the ones reported in the previous paragraph. An alternative to the installation of thermal storage devices can be the enlargement of the transmission line that connects the Scottish electric grid with England. Some of the government projections for future energy scenario are considering the enlargement of this specific transmission line to reduce congestion issues at the border between Scotland and England [182]. It has been decided to simulate the effect of transmission enlargement on the GB energy system and for doing that the maximum capacity of the transmission line has been incremented by 1.1 GW (according to government future scenario). The simulation results obtained for this scenario have been compared with the ones simulated in Case 1 considering large thermal storage installation. The over thermal storage power rating has been set equal to 1.1 GW, to simulate two scenarios with similar technical conditions.

Compared to the installation of energy storage devices connected to the wind power plants, the enlargement of the transmission line that links the Scottish and English electric grid has only an indirect effect of the wind power output. This energy solution allows the increase of electricity flow between the two regions bringing relief to the network affected by congestions at the border, which lead to the wind energy curtailment. However, it is important to notice that the modification of the transmission line power limits influences the balance mechanism of the entire GB electricity grid and the cost optimisation problem run on the unit commitment modify the output of different power plants technology, not only the Scottish wind power profile.

The simulation results show that the enlargement of the transmission line at the border between Scotland and England would reduce the overall CO_2 emission and system costs of the entire energy system (**Table 6-8**).

Table 6-8 *Comparison of the main results of Case 0 and Case 2, according to simulation results*

	System Costs [£m]	**CO_2 emission [Mt]**	**Wind Energy Curtailment [GWh]**
Case 0: Status Quo	1,431.83	78.93	2,913.11
Case 2: Transmission Line Enlargement	1,427.25	78.68	2,842.64

Table 6-8 shows that even though this solution might gain overall economic and environmental benefits, the reduction of wind energy curtailment is not remarkable (2.43%). This result could be explained thinking that the aim of the unit commitment is the achievement of the most optimised solution for the whole system. The enlargement of the transmission line at the border between Scotland and England allows the model to get an overall reduction of the CO_2 emission and system costs by increasing the renewable generation in the whole network. Thus, this choice might still prevent wind power plants in Scotland to maximises their output and avoid curtailment.

6.4.4. CASE 3: ELECTRIC STORAGE

A third energy solution simulated for the GB energy system model includes the installation of electric storage systems in the Scottish electric grid. The electric storage devices collect and store the excess of electricity generated by the wind power plants and dispatch it later in time during intense electric demand. Comparing this approach with the adoption of thermal storage devices, the main difference is the kind of demand they address their generation. Electric storage would optimize the discharge period according to the variation of the electric demand of Scotland, whilst the generation from thermal storage devices would be driven by the space heating requirements. This difference is also the main reason why thermal storage technology would be preferable for this case study.

Indeed, the simulation results obtained for the electric storage discourage the use of this kind of technology in Scotland. Whilst the thermal storage would achieve the extensive reduction of energy curtailment per year (60% of reduction of volume curtailed), the same energy capacity expressed in electric storage would have negligible effects on the wind energy curtailment. The reason should be sought in the modest local electric demand that does not allow flexibility in the operation of the electric storage. Moreover, the electric storage devices have been modelled considering an average round trip efficiency of 75%. Thus, according to the model the storage of wind energy in the electric device would be convenient only in extreme circumstances, otherwise, it would be preferred to lose the surplus of wind energy generated rather than dissipate it as energy losses from the electric storage.

Figure 6-32 shows an example of the state of charge of the electrical energy storage system. It can be noted that the percentage of charge is particularly low, proving that the optimisation model does not consider convenient the charge of the electricity storage with wind energy; moreover, the discharge processes are not frequent, due to the fact that the Scottish electric consumption is saturated and not able to absorb wind electricity peak generations neither when they occur or later in time after being stored.

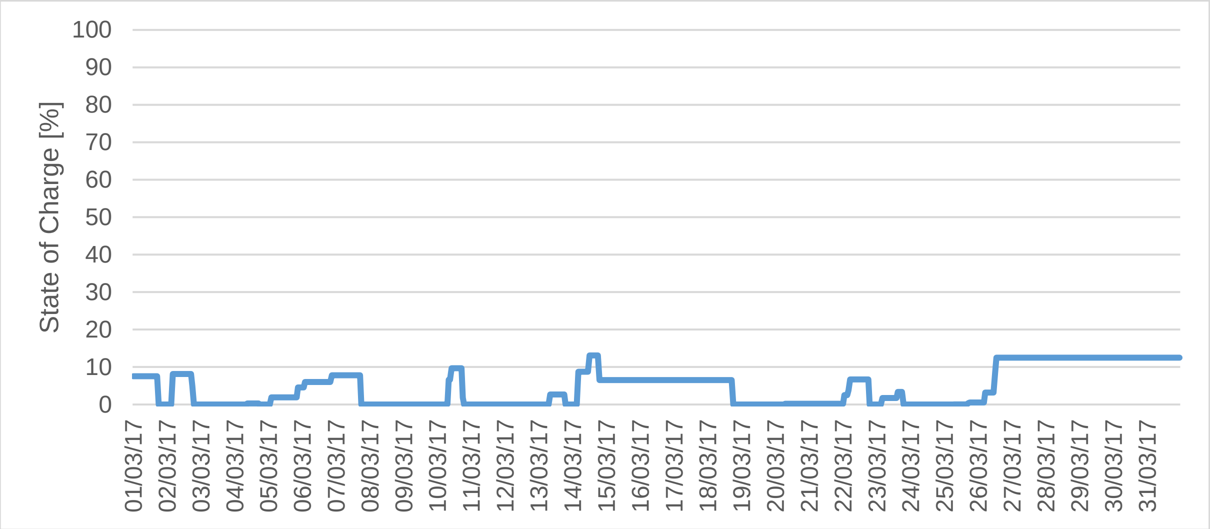


Figure 6-32 *Example of State of Charge (SOC) profile of electric storage device across March 2017, according to simulation results*

Therefore, for the reasons mentioned above, it should be concluded that large electric storage systems are not suitable for increasing the penetration of wind energy in the Scotland electric grid.

6.4.4.1. REGULATION COSTS

Even though the electric storage system would not positively influence the wind power curtailment, it could lead to some reduction in the overall system costs (**Table 6-9**). The installation of electric storage capacity in Scotland would represent an increase of flexibility in the grid balancing mechanism. Thus, the presence of this further source of energy capacity causes a reduction of the reserve prices and thus a decrease in the costs due to the yearly reserve provision. A similar conclusion cannot be drawn for the thermal storage capacity. The reason is because this latter system is not exclusively connected to the electricity network, but it links the electricity grid to the heating demand. Thus, in case of need of a rapid increase of generation to balance a peak in the electricity demand, the thermal storage would not be able to contribute to the balancing mechanism since its discharge is connected to the heating sector.

Table 6-9 *Comparison of regulation costs according to different simulation results*

	Total Costs for Balancing Mechanism [£m/year]
Case 0: Status Quo	4.347
Case 1: Thermal Storage	4.357
Case 3: Electric Storage	4.281

6.5. DISCUSSION AND CONCLUSION

This chapter has presented a detailed analysis of the GB electric grid highlighting the congestion issues that affect the transmission lines and cause the curtailment of a portion of the wind power generated in Scotland. The analysis has been carried out following different approaches:

- firstly, the real data published by the GB grid operation has been the object of in-depth investigation, focusing on the installed generation mix, the renewable share and the electricity flow from Scotland to England. This research has emphasised the duality of the GB electricity network, that can be schematised as two regions (Scotland and England-Wales) connected by a single transmission line with limited flow capacity. A large portion of the total renewable capacity is installed in Scotland and, due to the modest local demand, most of this energy is exported to England. The analysis of the export flow allowed to understand that the several congestion issues in the transmission line are the reason for wind energy curtailment concentrated in Scotland.

- Then, based on the main outcome of the real data analysis, it has been possible to realise a unit commitment model of the real GB system. The definition of two separated regions, the conglomeration of the power stations in few large power plants and the avoidance of interconnectors allowed to achieve a simplified version of a complex system without losing the accuracy of the results.

- The optimisation model has been the core part of this work focused on identify future system development options for the GB electricity network. The technical potentials and implications of the installation of grid-scale energy storage (thermal or electric) and enlargement of the transmission line have been described based on the several simulation results.

The choice of a power-to-heat approach together with the installation of large thermal storage devices has resulted the most suitable and promising solution for the current energy scenario in Scotland. Indeed, this approach would tackle two major problems, wind energy curtailment and intense carbon emission from the heating sector. Compared to the use of electric storage technology or the enlargement of the transmission line, thermal storage devices would achieve remarkable results in terms of reduction of volume curtailed and CO_2 emission per year.

6.5.1. MAIN ASSUMPTIONS AND LIMITATIONS OF THE MODEL

It is important to notice that these conclusions are based purely on the results from a simulation analysis where the benefits of the energy storage operations are expressed in terms of differences compared to the simulation results of the current energy system. For GB energy system it has been decided to represent a simplified model of a complex reality in order to achieve shorter computational time (even though, the simulation of the unit commitment across an entire year with a time step of 1 hour takes more than 12 hours) and the possibility to adapt this model to different electricity grid with similar features and issues (like Germany, China or Brazil all characterised by the clear identification of two regions and congestions in the transmission line that connects them). Although the simulated unit commitment shows accurate results compared to real data, the conglomeration of the power stations and the lack of interconnectors might cause some small discrepancy it the total amount of the electricity generated, as shown in previous graphs. The model error can also be assessed by comparing the wholesale electricity price of the simulation model with the real data (**Figure 6-33**). According to the model, the average annual wholesale electricity price is equal to £51.4/MWh while in 2017 the average annual wholesale electricity price was £46.3/MWh. This leads to an average annual difference of £5.1/MWh that correspond to the 11% of the average annual wholesale electricity price in 2017. Based on that, it could be concluded that the accuracy of the value of the energy storage calculated through the simulation analysis fall in a range of 11% of error.

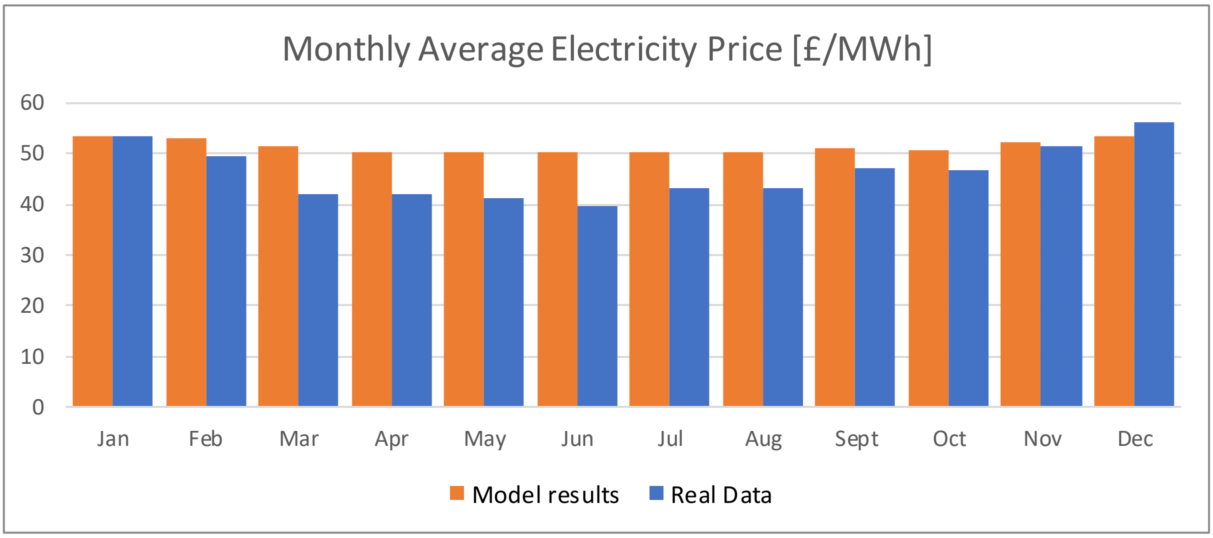


Figure 6-33 *Validation of monthly average electricity price (Source real data: Ofgem)*

When considering the limitations of the software, it is important to mention that although it is particularly suitable for the simulation of the unit commitment and economic dispatch of a complex electricity grid, it does not consider the possibility to easily define a heating network. One of the reasons could be that the electricity, heating (and transport) sectors have usually been identified as separate entities with their own demand, generation and control. Thus, so far, it has not been considered important the modelling of a “holistic” network that considers different demand profiles (such as electricity and space heating) and analyses how to optimise the supply of both together. However, the necessity to increase the electrification of all the energy demand will require, in an early future, the ability to model the interactions between the different sectors. During the development of the GB energy system model, this challenge has been faced by generating an electricity-heat analogy able to include the Scottish heating demand in the model and to quantify the benefits of introducing large scale thermal storage devices in the system.

6.5.2. REAL IMPLEMENTATION

One of the most interesting results achieved with the GB energy system model is the understanding of the interesting economic and environmental potential of the use of thermal storage devices to connect the wind power output to the space heating demand. This solution is particularly suitable for remote and cold areas (such as the Scotland region) that host large wind power plants and, at the same time, are characterised by intense space heating demand due to the low temperatures. The simulation analysis run on the GB energy system is based on a technical-agnostic approach, and it considers storage power and capacity without defining the characteristic of a specific device. In this Section, two different thermal storage technologies are suggested as potential devices for achieving the results simulated in the model.

When thinking about large-scale thermal storage technologies connected to the domestic heating demand, one of the potential candidates are heat pumps or electric boilers connect to large water storage as part of the district heating system. A similar idea has been realised in Denmark and Sweden [183], [184] where this kind of thermal storage technology is already in operation in the district heating system and is considered as a valid alternative for the balancing of the electricity grid. A quite ramified district heating network is already present in Scotland and it connects the most populated cities on the coasts, as it is shown in **Figure 6-34** that represents the Scotland Heat Map [185]. According to the Scottish Government [186], this network is supposed to be considerably enlarged, as can be noticed in **Figure 6-34**, and to cover 1.5 TWh of heating demand corresponding to almost 40,000 dwellings connected by 2020.

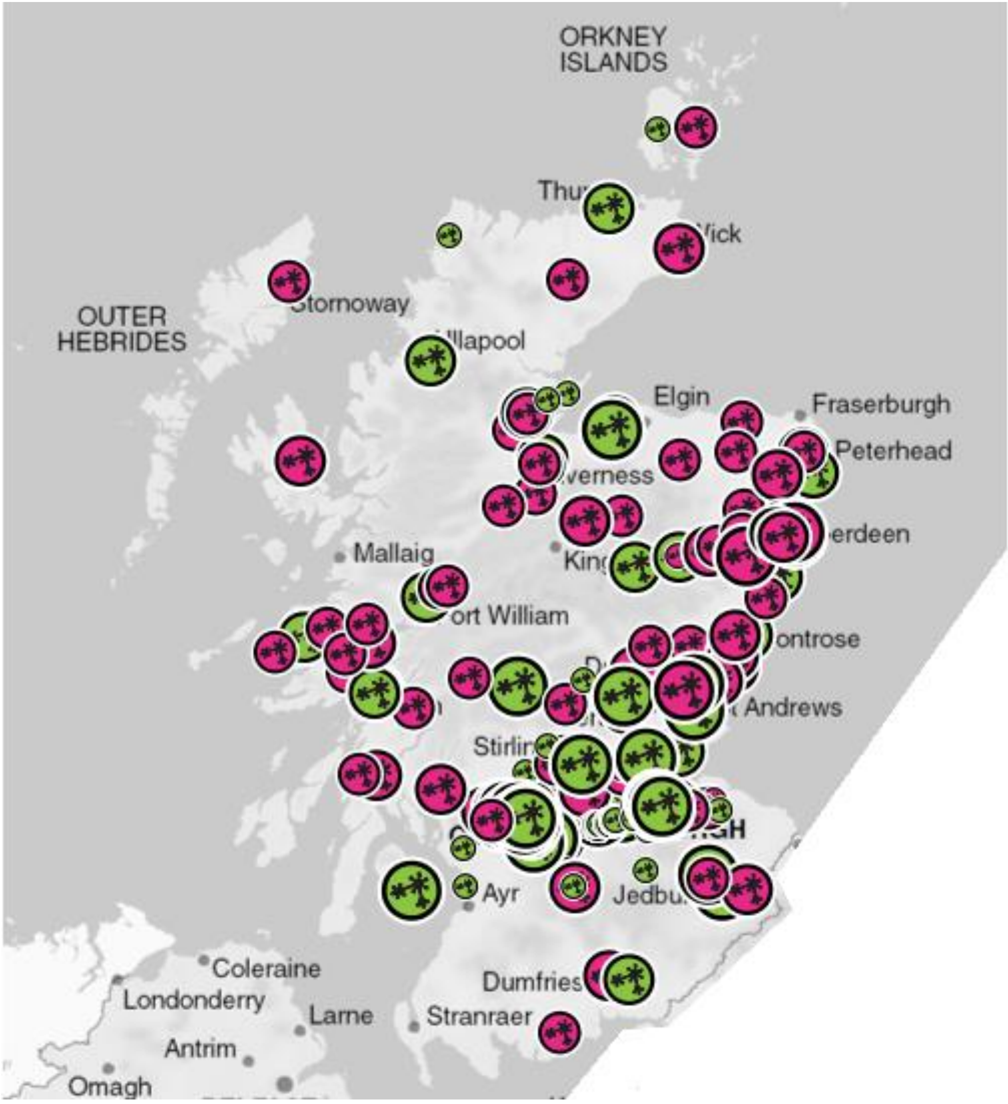


***Figure 6-34** District heating map in Scotland. The pink marks represent the operational plants, the green marks show the plants in development.*

Alternatively, instead of large thermal storage devices connected to the district heating network, it can be considered the option of installing several thermal storage heaters for domestic applications. This device uses electricity to heat a storage medium and release the energy according to the user's requirements and it is usually designed for the space heating of a room [187]. The potential “smart” control of the charging periods of the devices, following the variation of the wholesale electricity price or the energy available, is under investigation in Ireland, Germany, and the Shetland Islands in the north of Scotland [188]. The investigation of the specific use of smart thermal storage heaters for increasing the penetration of wind energy and the electrification of the heating sector in Scotland is the object of the following chapter. The chapter describes a detailed analysis of the schedule of a domestic thermal storage heater, following the real wind power curtailment profile. These results have been obtained using a MATLAB model of the storage device based on real data collected in a demonstration house.

6.5.3. ENERGY POLICY IMPLICATIONS

This work considers the combined use of electrification of heat and thermal storage technologies for increasing the penetration of wind energy in Scotland and the partial decarbonisation of the heat demand. The UK government encourages a low carbon energy deployment with the introduction of several supporting mechanisms that give economic incentives to justifies investment in new energy project. Nevertheless, neither electric heaters or storage devices are included in the products incentive by the current policies.

These energy policies include the Renewables Obligation Certificates, now substituted by the Contract for Difference, that economically supports the construction and operations large low carbon power plants, or the Feed-in Tariffs that is addressed to small-scale renewable plants, like solar panels and biomass [188]. Most of the attention of the UK government is addressed to the decarbonisation of the electricity sector achieving impressive results: the renewable share has risen from about 2% in the early 1990s to approximately 25% in 2016 [189]. Also, the decarbonisation of heat sector is supported by economic incentives: Renewable Heat Incentives (RHI) provides the financial support to industrial and domestic users that switch their heating system to renewable sources, such as heat pumps, solar thermal and biomass.

Among the list of products eligible for the RHI direct or off-peak electric heaters are not included [190]. In the last year, the average CO_2 emission from the electricity grid decrease to 292 g/kWh (according to real-time measurements [191]) being still higher than the emission rate from a domestic gas boiler (202 g/kWh). However, during off-peak periods the CO_2 generation rate falls to minimum value being competitive with the low-carbon heating system. For this reason, it might be interesting to provide financial support to the installation of electric heaters that uses off-peak electricity, as investigated in this work.

Moreover, the installation and use of energy storage technology have not been included in the supported mechanisms yet. Currently, the UK government is still working on the correct definition and on the specific actions to be accomplished by energy storage [190]. The introduction of new regulations and support for energy storage devices is one of the priorities of the UK energy agenda.

Chapter 7

THERMAL STORAGE HEATER

Following the results achieved with the simulation model run in PLEXOS, it is interesting to study the feasibility of this application of the thermal storage for domestic heating purposes.

The main contribution of this work is to investigate a combination of physical demonstration, laboratory performance tests and modelling. The physical demonstration analyses the thermal comfort achieved by the thermal storage heater in an existing dwelling and how the consumptions compare with a gas boiler heating system. this investigation allows to critically analyse the data showed by the manufacturer and to test the feasibility of the storage schedule assumed for the simulation model. The laboratory tests are fundamental to study the internal temperature evolution of the thermal storage device. These results are used as reference data for the validation of the mathematical model of the thermal storage device implemented in MATLAB. The contribution of the simulation model is to investigate the feasibility of charging the thermal storage heater with excess generation from the Scotland wind plants as assumed in the PLEXOS model.

7.1. ELECTRIC HEATING

The growing electrification of heat demand offers an alternative to the heavy fossil fuel consumption for the heating purpose (e.g. natural gas, heating oil) and will affect the electricity demand. Currently, heat pumps and resistive heating represent the most valid options for domestic space heating [192]. Heat pumps are a mature and efficient technology, whose consumptions can compete with a classic natural gas boiler system [193]. However, the dimension of the device and the elevated investment costs obstruct heat pumps adoption on large scale. Direct electric heating systems, on the contrary, are simple to install, being the size comparable to a radiator, and thus are suitable for flats and maisonettes. To confirm that, 2.2m households in GB are equipped with resistive heating technologies while less than 100.000 dwellings own a heat pump device [194]. Although more widely adopted than heat pumps, direct electric heating systems require a considerable amount of electricity, even more, if installed in inefficient, high-consuming buildings. Moreover, a recent national survey run by Ofgem highlighted that households that adopt electric heating tend to have a lower income [164]; this, combined with the elevated operating costs of heating, could cause an increase of fuel poverty.

Therefore, resistive heating devices are usually equipped with thermal storage to advantage on off-peak electricity prices and reduce the impact on the user utility bills. Almost 80% of the total number of dwellings heated by electric radiators preferred the installation of heating systems with the capability to store heat [194], rather than direct-acting heating systems without storage functionality. Traditional night thermal storage heaters heat the medium during the night and release the energy stored during the day.

This work investigates a more flexible schedule of the storage heater, able to charge at any time following the electricity grid conditions. Due to the possibility to decouple the charging and discharging process, the modification of the charging schedule does not affect the thermal comfort of the user, who has full control over the release of the heat.

7.2. WHAT IS A THERMAL STORAGE HEATER?

The thermal storage heater is a decentralized heating system that provides space heating for domestic applications. The device dimensions, comparable to the ones of a radiator, suit the heating demand of a single room, and thus, the heating of an entire dwelling requires the installation of several devices, at least one for each room. An example of thermal storage heater is the Quantum Dimplex device, shown in **Figure 7-1**.

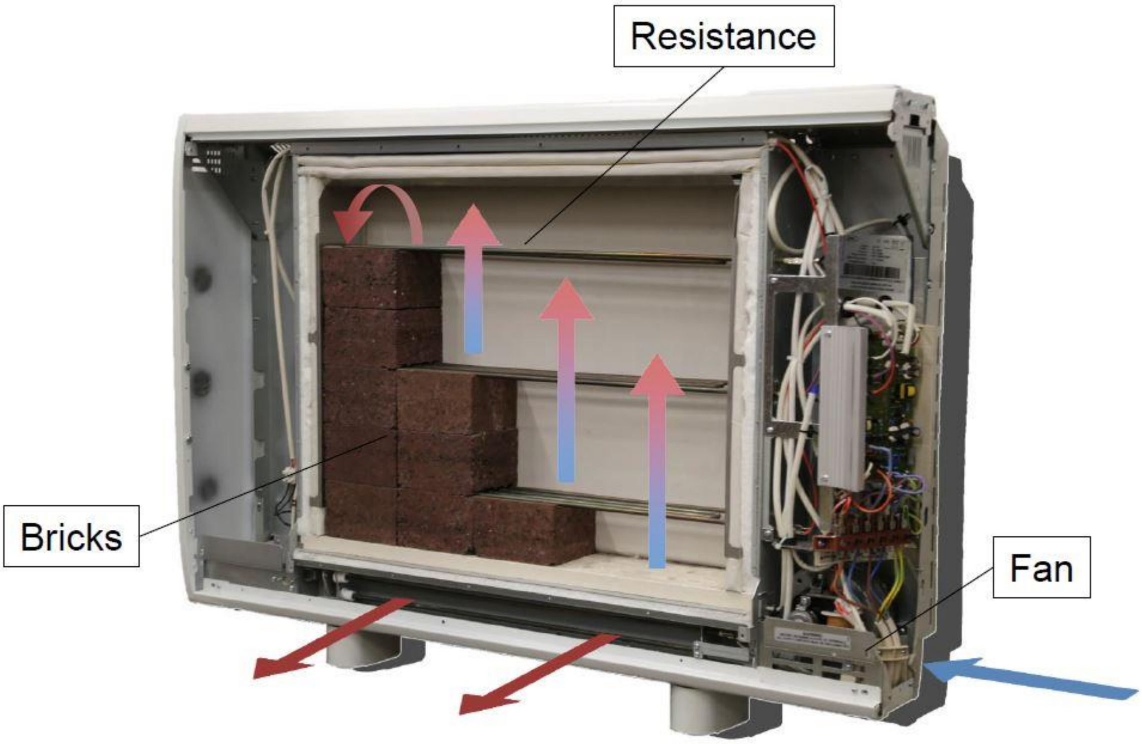


Figure 7-1 *Thermal storage heater operation principles*

As shown in **Figure 7-1**, the electro-thermal system consists of three electric heating elements that are embedded between high-density masonry material, such as red bricks. During the charge period, the bricks are heated, through thermal conduction, by the contact with resistances that convert the electricity flow into heat. The temperature of the bricks is measured by thermocouples, which are used to control and monitor the charging operation of the heater. The close-packed medium accumulates and stores the thermal energy, then the heat can be released into the room with the use of a fan that blows air inside the conducts carved into the bricks. The operation of the fan is controlled by the user who decides the period and the temperature of the heating release. During the discharging period, the heat is transferred through convection by forcing air over the solid matrix with a thermostatically controlled fan. Moreover, the presence of a thermostat allows maintaining the room temperature within ±0.3˚C depending on the user's heating requirements and the weather conditions. The energy difference between the amount of heat input in the system, through the heating elements, and the quantity that is released during the forced discharge is due to the heat losses to the surrounding environment. The heater is also equipped with a boost resistance, whose operations can be compared to the ones of a direct-electric heater; the boost is activated in case the thermal energy stored in the device is not enough to cover the heat demand of the room. Since the boost resistance is based on direct electricity consumptions, the activation of this extra heating element during the day causes a drastic increase in the electricity bill. Thus, the optimal schedule of the thermal storage device should charge the storage with the right amount of energy for the daily space heating requirements and avoid the use of the boost. According to the manufacturer [187], approximately 90% of the energy requirement is expected to be off-peak electrical heating energy, due to the sophisticated algorithm that regulates the charging process.

The core medium characteristics are critical to the effective storage of thermal energy. Ceramic bricks are widely used for thermal energy storage because they constitute an inexpensive option, with valid thermal properties. Indeed, masonry material represents a suitable medium for thermal energy storage due to the relatively high energy storage density and heat retention characteristic. However, the ceramic material might need to achieve elevated temperature (e.g. 700°C) to store the required amount of heat, causing intense heat losses through the heater surface due to the high difference of temperature. Therefore, the research interest is focused on formulating alternative material fabrication for more effective thermal energy storage. For instance, the use of phase change materials (PCMs) might allow achieving similar performance at a lower temperature, being able to reduce the heat losses to the environment. To be competitive with the ceramic material, the PCM should have high heat storage capacity, no phase segregation and high thermal conductivity [195]. Previous experiments focused on the performance of paraffin wax in thermal storage heater [196] showed that this solution could drastically reduce the overall weight of the heating device, however, it could negatively impact on the costs of the device. The thermal property of the PCM can be improved by using a specific composite. For example, Zhang et al. [197] have shown that phase change carbon nanofiber with paraffin wax composites disposes five times higher thermal storage capacity and enhanced electrical conductivity in comparison to conventional bricks.

7.2.1. STORAGE SCHEDULE

The optimal schedule of the thermal storage heater operations is based on demand-response principles. The electricity demand profile can change due to the active involvement of the consumers [198] that reduce their consumptions [199] or, like in the case of the thermal storage heater, act as load-shifter and move their consumptions to off-peak periods. The load shifting is convenient for both customers and electric system; the former benefits using cheap electricity, such as with the use of the Economy 7 tariff, and the latter takes advantage on the reduction of peak demand during the day.

The traditional operation of the night thermal storage heater described above can be improved and adapted to the new requirements of the electric grid. The need for balancing the excess of renewable energy might encourage the charge of the thermal storage heater also during the day [200], in contrast with the conventional schedule of the device. This might be the case of the potential wide installation of thermal storage heaters in Scotland, whose benefits and influence on the electric grid have been presented in the previous chapter. This approach assumes the deployment of smart devices able to be remotely controlled to charge in case of excess of wind generation. Moreover, to encourage the customers to charge their storage devices during the day it is necessary to consider profitable electricity tariff, which might follow the intensity of the renewable generation. Following this idea, charging the storage with wind energy excess could improve the system flexibility and saving the extra charge due to the balancing management; thus, the demand-response of the customers should be “awarded” with convenient tariffs to encourage the extra charge out of night off-peak hours.

The following paragraphs investigate the potential adoption of smart thermal storage heater for the absorption of wind energy excess in Scotland. This analysis has been completed using a combination of physical demonstration, laboratory performance tests and modelling.

7.3. DEMONSTRATION PROJECTS

The thermal storage heater performance has been widely analysed in different domestic contexts as an object of several European projects. The main interests of these works are to assess the potential use of this technology for ancillary service provision and, at the same time, to ensure the constant thermal comfort of the consumers.

7.3.1. EUROPEAN TRIAL PROJECTS

The largest European demonstration project that experiments the potential of small scale energy storage for ancillary service provision is Real Value [201]. It is a €15.5m Europe Horizon 2020 energy storage project that involves the installation, control and monitor of smart thermal storage systems in a total of 1,250 houses in Ireland, Germany and Latvia [202]. The technologies adopted include thermal storage heater for space heating purpose, like Quantum Dimplex, and smart hot water tank for the domestic hot water dispatch. The choice of these thermal technologies is due to their affordable costs, compared to other electro-chemical systems available on the market, and their ability to decouple the energy production and energy consumption without altering the user thermal comfort [203]. The potential aggregation of several smart thermal storage systems is investigated to assess the value of these devices for the provision of different grid services (e.g. load shifting, frequency response, ramping duty).

Quantum Dimplex technology has been adopted in other interesting European projects, such as Shetland-based Northern Isles New Energy Solutions (NINES) project [204][205]. This trail project demonstrated that smart thermal storage technologies can play a key role in the decarbonisation of the isolated grid, because of their ability to reduce peak demand and increment renewable penetration.

7.3.2. DEMONSTRATION HOUSE

This work had the possibility to investigate the real operation of a thermal storage heater device in a domestic application. The demonstration house object of this work is a terraced property located in Harbourne (Birmingham, UK), whose room temperature and energy consumption have been carefully monitored for 24 months. A single thermal storage heater has been installed in one of the three bedrooms to compare the performance of this technology with the operation of a gas or electric heating system. The internal temperature variation of the bedroom has been observed during the operation of the thermal storage heater; **Figure 7-2** shows an example of the room temperature daily profile of the double bedroom when heated with central gas heating system or thermal storage heater. Comparing the daily temperature variation of the same room presents some challenging due to the strong influence of the external temperature and weather conditions, for instance, the sun radiation usually causes a drastic increase of the temperature in the middle of the day due to the south exposition of the room. For this reason, the two curves have been monitored in two days of the same month (February 2018) presenting similar weather (mostly cloudy) conditions. The first temperature profile visibly presents two daily peaks due to the operation of the gas heating, scheduled for the morning (6-9 am) and the evening (7-11 pm) following the user heat requirements. Even though the thermal storage heater is controlled to release the heat in the same time periods, the two temperature peaks are not visible in the curve monitored during the thermal storage operation and the room temperature presents a flat profile. This behaviour is due to the heat losses of the thermal storage that can be considered as heat gain for the room. The storage device can maintain a constant room temperature around the comfort value set by the user. If this behaviour can be considered as an advantage for the user, it reveals insulation issue of the storage device contrary to what is claimed by the manufacturer, who declare “exceptional level of insulation” [187].

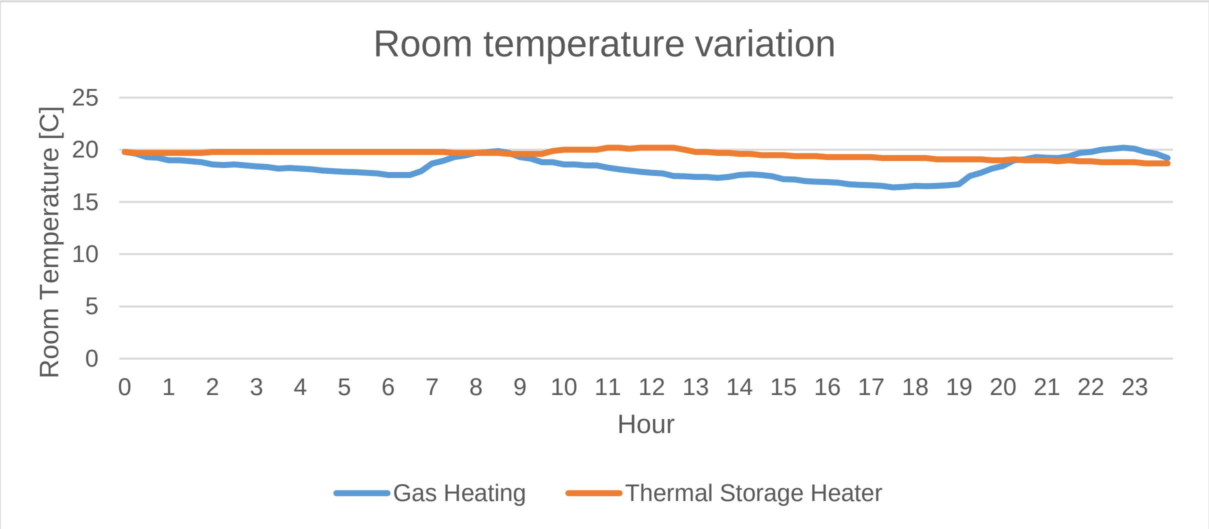


Figure 7-2 *Double bedroom temperature profile when heated with gas central heating system or thermal storage heater (Quantum QM125)*

However, it is also interesting to point out that, despite the constant heat losses to the room, the energy stored in the device is enough to ensure the thermal comfort for the entire days without the use of the extra boost resistance. This can be noticed also looking at the electricity consumption during the night (**Figure 7-3**) that correspond to the charging period of the thermal storage heater. The graph in **Figure 7-3** shows the night electricity consumption for the whole house across five consecutive days. The storage constantly charged from midnight to 6 am on the night of 31st of January and, apparently, the amount of energy stored is enough for covering the heating demand of two days since the following night (1st of February) there is no evidence of extra consumption during night due to the charge of the storage. Similarly, also during the nights of the 3rd and 4th of February the charge periods present different durations and do not last the whole night. This means that the algorithm that controls the charge period is optimized to store the amount of energy considering the potential heating demand for the following day and the current state of charge of the device, to avoid unnecessary consumption of energy. Thus, although the device can charge for a total of seven hours per night (corresponding to the off-peak electricity tariff), it does not follow a constant charge schedule every night, but it optimises the charge period in order to minimise the energy consumption.

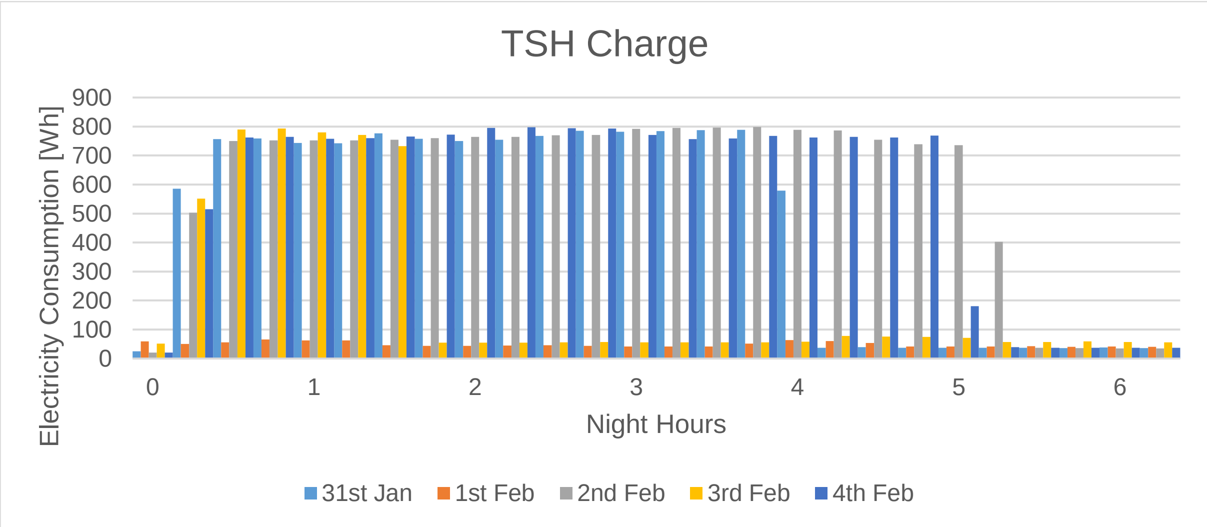


Figure 7-3 *Night electricity consumption recorded with a smart meter across five consecutive days (heating period 2018)*

The Quantum Dimplex installed in the demonstration house represents the state-of-art in term of thermal storage heater technology, due to its sophisticated charging strategy and to the possibility to schedule the discharge based on the user requirements. These improvements, together with the increase of insulation layers compared with previous technologies, minimise the energy consumption of the device and reduces the consumer costs. Although, when considering more mature and efficient technology, such as gas/oil central heating, the yearly operating costs of the thermal storage heater do not look promising. Analysing the results presented in **Table 7-1**, it can be noticed that, with the current energy tariffs, the use of gas/oil heating system is still convenient compared to any electric system even when equipped of thermal storage. Moreover, the installation of thermal storage systems requires the use of the Economy 7 tariff, due to its cheap off-peak price, and this cause a further increase of the electricity bill due to the elevated peak price (around £85 per year). These costs have been calculated considering the yearly heating consumption of the demonstration house, the efficiency of each heating system and the energy tariffs based on the six major suppliers in GB.

Table 7-1 *Yearly costs comparison of different heating systems, based on yearly heating consumption of the demonstration house, the current thermal efficiency of the different heating system, and energy tariff according to six major suppliers*

	Operating costs without TSH [£/year]
Natural Gas	331.54
Heating Oil	440.54
Direct Electricity (no storage)	977.90
Thermal Storage Heater	513.304 + (~85)

The analysis of these results suggests that the potential use of renewable energy excess at a convenient price could increase the cost-efficiency of the thermal storage heater compared to more traditional heating systems.

7.4. LABORATORY PERFORMANCE TESTS

The Quantum Dimplex thermal storage heater QM125 has been monitored also in the laboratory, where its core temperature variation has been carefully measured to assess the thermal performance of the device. Moreover, the real data collected during the performance tests have been fundamental for the deployment of a mathematical model of the device.

The storage core consists of thirty high density (3,780 kg/m^3) magnetite energy cells that are heated by three embedded heating elements. The specific heat capacity of the energy cells is 0.948 kJ/kg K and the total mass of the core is 97.56 kg, which has been derived by the volume and the density of the energy elements. The input rating of the heater is 2.76 kW and the maximum storage capacity is 19.3 kWh. Finally, the core is covered by insulation which enables energy storage during low demand periods and about 24 hours supply when its required [187].

Figure 7-5 shows some of the results that have been obtained during the experiments run on the device. The thermal storage heater has been equipped with several thermocouples (**Figure 7-4**), to monitor the temperature variation during the different operative mode of the device. The curves reflect the temperature variation during the periods of charging, natural discharging, due to natural heat losses, and forced discharge. This latest mode corresponds to the heating release period that is controlled with the use of an air fan and it can be observed following the evolution of the outlet air temperature (dotted line).

During the experiment, the desired temperature set by the user is 20°C. Looking at the temperature values, it could be noticed that, once the average core temperature reaches a value around 30°C, the slope of the curves suddenly changes. This point has been identified as the moment when the forced discharging automatically stops. For this reason, in the following model, it has been considered that the heater is able to provide heating into the room until it reaches this minimum internal temperature.

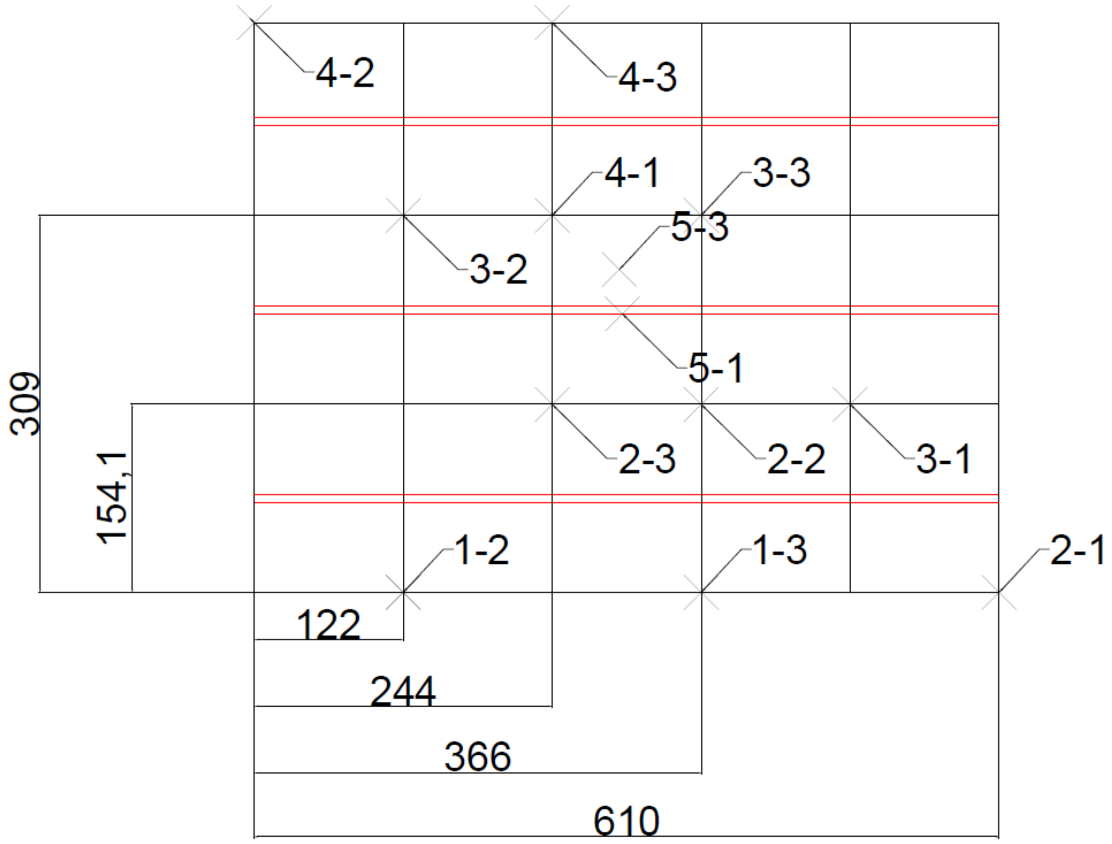


Figure 7-4 *Location thermocouples in storage core and dimensions (mm)*

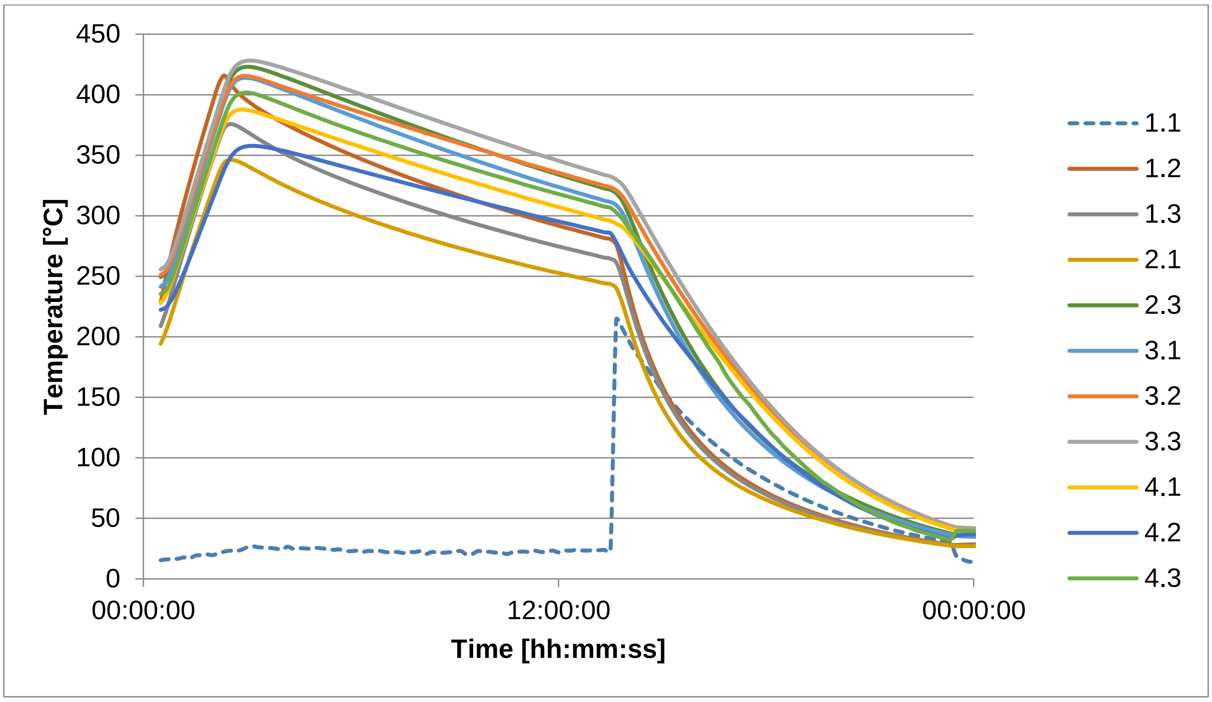


***Figure 7-5** Experiment results during charging, natural discharging, and forced discharging*

During the charging process, all the heat generated by the electric resistance is transferred to the surrounding storage medium and the average temperature increases based on the ability of the material to store energy [206]. Thus, this first thermal process is described by the following equation:

$$Q_{in} = m_{storage}cp_{storage}(T - T_0) = m_{storage}cp_{storage}\frac{dT}{dt}$$

Where Q_{in} is the constant amount of heat generated by the resistances, $m_{storage}$ is the mass of the storage medium and $cp_{storage}$ is its specific heat capacity. Since the characteristics of the sensible heat material do not change in time, then the increase of the internal temperature results as a linear curve, directly proportioned to the duration time of the process.

The natural discharge is a direct consequence of the heat losses of the device to the environment. This is a function of the temperature difference between the storage surface and the room and of the thermal properties of the storage medium and insulation. The heat is first transferred from the core of the device to the surface through conduction and then released to the room through natural convection.

$$Q_{losses} = UA\left(T - T_{surface}\right) + h_{natural}A_{surface}(T_{surface} - T_{room})$$

Where U is the overall heat transfer coefficient that considers the thermal properties of both the storage material and the surrounding insulation, A is the internal surface through which the heat is transferred, $h_{natural}$ is the air natural convection coefficient, $A_{surface}$ is the external surface of the heater, and $T, T_{surface}, and\ T_{room}$ are respectively the average temperature of the core material, the external surface, and the room.

The controlled heat release takes place through forced air convection and, thus, assuming a constant air flow through the internal channels, it depends on the difference between the output temperature of the heater and the room temperature: smaller the temperature difference, smaller the heat released.

$$Q_{released} = h_{forced}A_{channels}(T - T_{room})$$

These three equations together with empirical relations obtained from the experiment data analysis have been adopted for the deployment of a mathematical model in MATLAB that represents the thermal behaviour of the thermal storage device.

7.5. MODELLING

The model investigates the potential operation of the thermal storage heater when coupled with the wind energy excess in Scotland. It is interesting to analyse whether the device could rely exclusively on the renewable generation excess or if it is necessary to consider some conventional backup for ensuring the constant heat demand provision.

The model has been tested with a space heating pattern like the daily schedule defined in the PLEXOS model, that considers two heating periods, for a total of 8 hours per day. To simulate the wind energy excess, it has been decided to use the wind curtailment volume measured at the Scottish border, already implemented in the PLEXOS model.

The algorithm developed in the model considers the following steps:

- The thermal storage heater covers the heat demand as scheduled by the user;
- If there is wind energy excess available, and the state of charge of the device is not equal to 100%, the electricity is used to charge the storage;
- When the thermal storage heater is in a state of idle (meaning that is not charging/discharging) it is subject to natural discharge due to heat losses;
- [Further addition to the original model] When the device achieves the minimum level of state of charge and there is no wind energy excess available, then the thermal storage heater charges using off-peak electricity during the night, like a normal night storage heater.

7.5.1. MODEL RESULTS

The following results are based on the curtailment data collected for the month of January 2017 and on the thermal properties of the thermal storage heater tested in the laboratory. The information that is used as input for controlling the charging schedule of the storage is a signal that communicates when the wind curtailment occurs. If the signal is equal to 1, it means that the grid operator registers curtailment and the thermal storage heaters can be charged to realise the network by the renewable excess; otherwise if the signal is equal to 0, there is no surplus of electricity in the transmission line. **Figure 7-6** shows the signal that has been created analysing the data from January 2017.

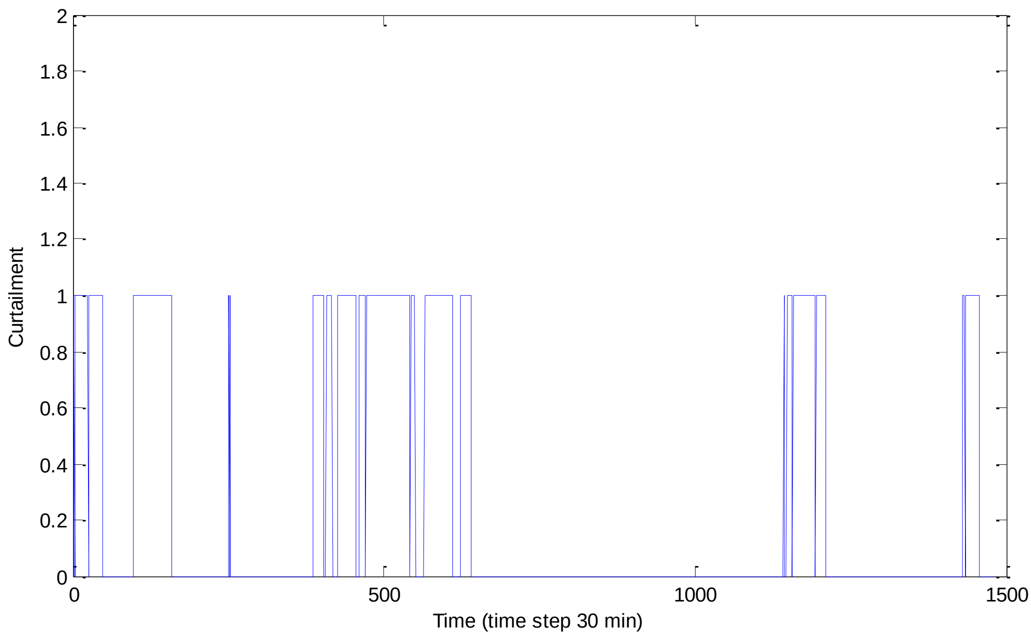


Figure 7-6 *Duration of each curtailment period due to excess of wind production for January 2017*

Figure 7-7 reports the inside temperature variation of the thermal storage heater in case this would be charged exclusively according to the signal of the wind energy excess. In the figure, the three operative modes of the thermal storage heater are visible; the sudden increase of temperature represents the charging, the slow decrease of the curve show the natural discharging of the device and, finally, the fast decrease of temperature means that the heater is warming up the surrounding environment.

Figure 7-7 shows a quite long period, between two curtailments, where the thermal storage heater stays at the minimum state of charge (corresponding to the minimum internal temperature). This means that the thermal heater storage has no more heat stored inside and, thus, it is not able to operate as a heater and supply the heating demand. This period lasts more than three days. To be operative and to provide thermal comfort continuously for the whole month, it is necessary to modify the control of the storage simulated in the model.

The further modification of the model has included additional charging process during the periods when the curtailment is not registered. The results of this second approach are presented in **Figure 7-8**.

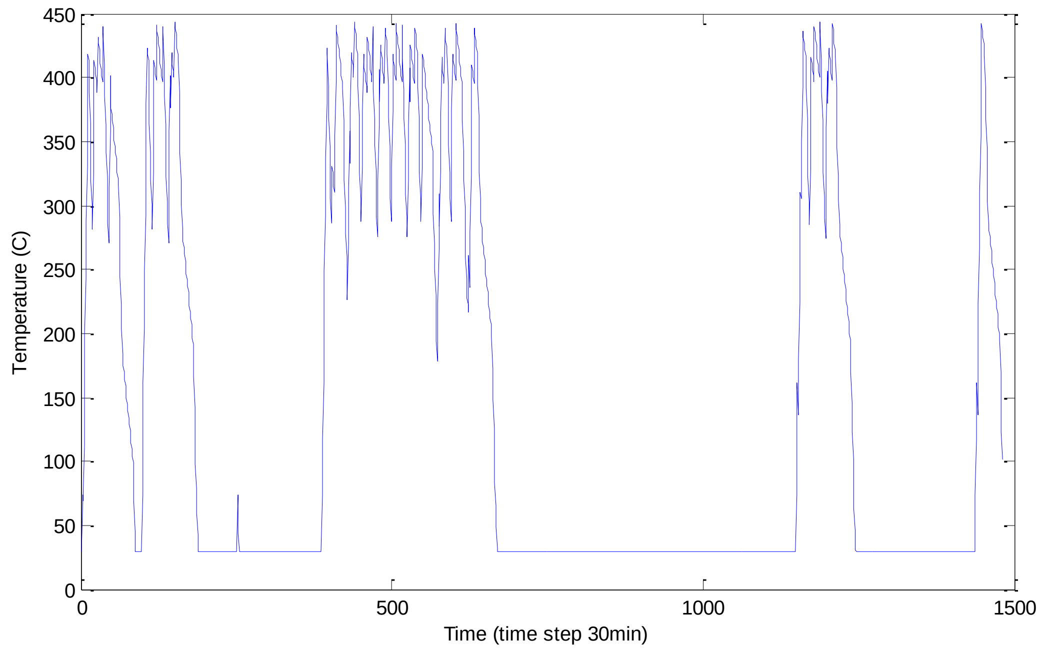


Figure 7-7 *Average temperature evolution of storage medium when charged exclusively with wind energy excess*

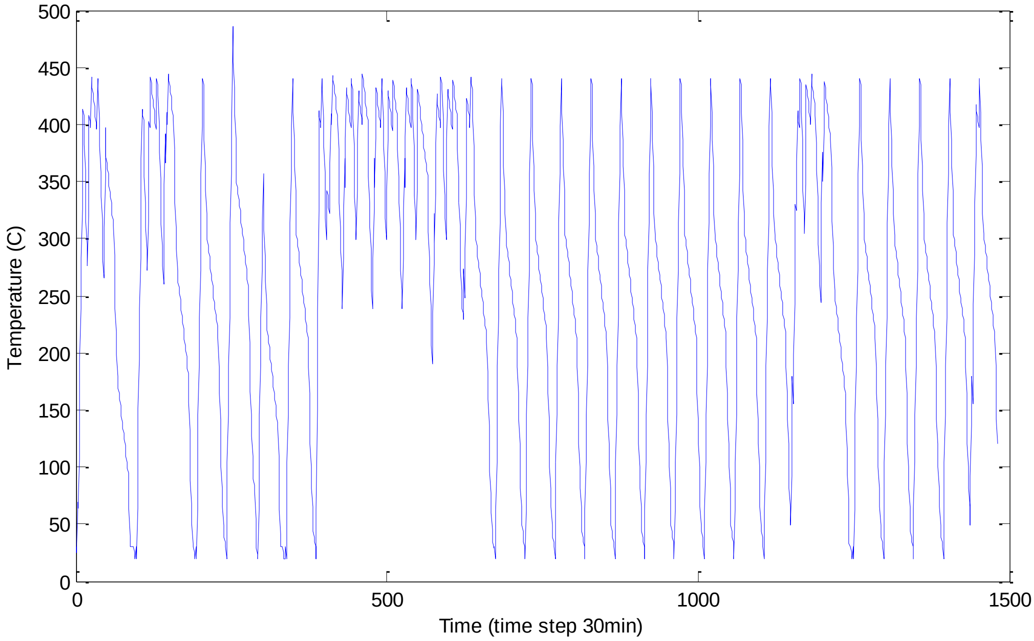


Figure 7-8 *Average temperature evolution of storage medium when charged with wind energy excess and off-peak electricity*

Although the maximum temperature achieved after the night charge of the thermal storage is around 400 °C, the actual maximum temperature achievable by the ceramic material employed in the specific device tested (Quantum Dimplex QM125) is around 700 °C. Thus, it has been possible to simulate the thermal performance of the same device in case the wind energy excess could be exploited until the storage medium achieves 700 °C. As expected, the results (**Figure 7-9**) show that the possibility to achieve a higher temperature and, thus, to store a larger amount of energy, would reduce the necessity of charging the storage during the night using off-peak electricity.

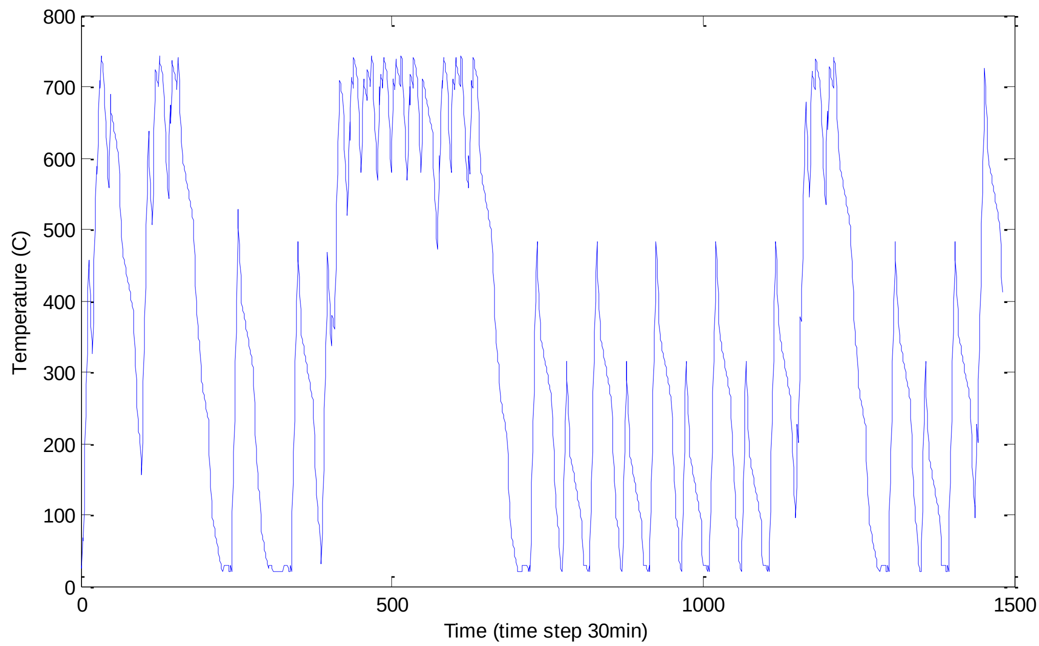


Figure 7-9 *Average temperature evolution of storage medium if maximum temperature achievable is 700°C*

Looking at the results it is possible to notice that the stochastic nature of the wind curtailment, clustered across few days of the month, does not allow the possibility to rely the space heating exclusively on the excess of wind energy. Thus, it is necessary to consider an extra backup for ensuring the correct and regular operation of the heating device. This means that the large installation of thermal storage heater for the absorption of wind energy excess could cause a drastic increase in the electric demand. Thus, when understanding the amount of storage capacity to install in Scotland, it is necessary also to consider this secondary effect on the electric demand that might even cause more problem on the balancing management, when the aim of the installation of the storage technology was to solve this problem in the first place. Although, it is also possible to consider the smart thermal storage heater as a secondary heating system to add in the households already heated by a gas/oil heating system. In this case, the storage technology would operate exclusively during wind energy excess periods replacing fossil fuel consumption with renewable energy generation.

7.6. COSTS

The elevated operating costs of the resistive heating system represent a barrier to consider this technology as a real alternative to a gas boiler. It has already been mentioned that the use of a storage medium reduces visibly the costs compared to a tradition direct resistive heating system. However, these costs are still not competitive to the mature and cheap gas heating system. Thus, the introduction of smart storage heater technology could be a solution for reducing the operating costs and it could represent a valid alternative to the fossil fuel heating systems.

It can be assumed that the national grid operator would incentives the consumption of excess wind energy by offering cheap tariff or accessing this electricity for free since otherwise it would have been curtailed, causing extra costs to the grid operator. This means that the use of smart storage heater would be economically beneficial to the users (**Figure 7-10**). However, it is necessary to point out that this economic advantage is directly related to the amount of excess wind energy available. The increasing number of dwelling equipped with smart thermal storage systems will improve the penetration of renewable and thus the costs for the total heating of the dwellings is convenient compared to the case where they are heated with gas heating system. Although, once the optimum number is achieved (**Figure 7-11**), then the benefits would decrease since the amount of excess wind energy would not be enough to cover the total heat demand and more electric backup would be needed.

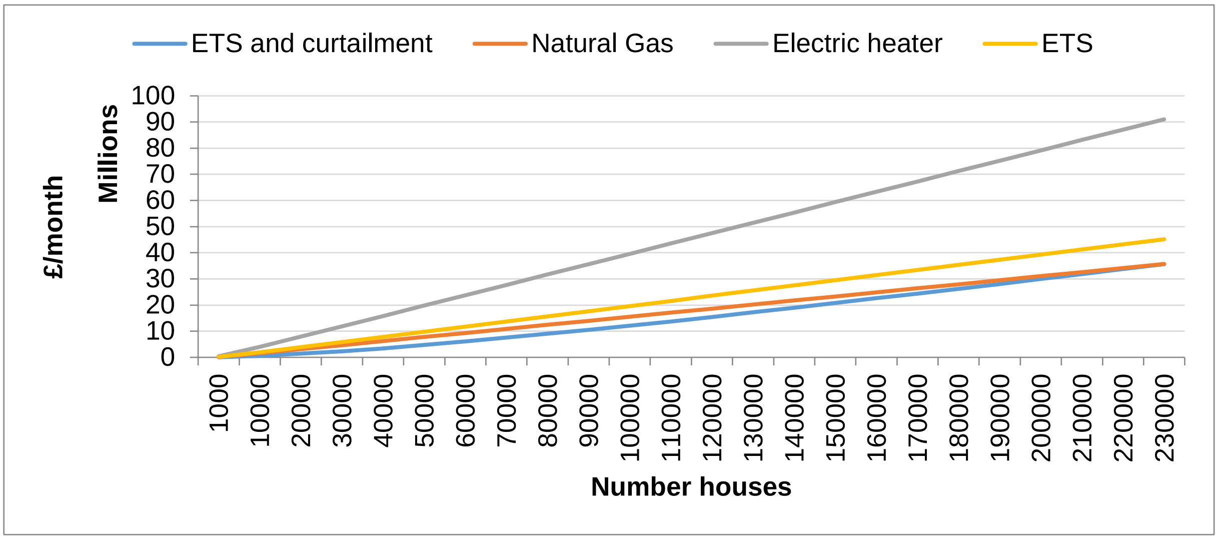


Figure 7-10 *Comparison of monthly costs by the heating system according to the number of dwellings considered*

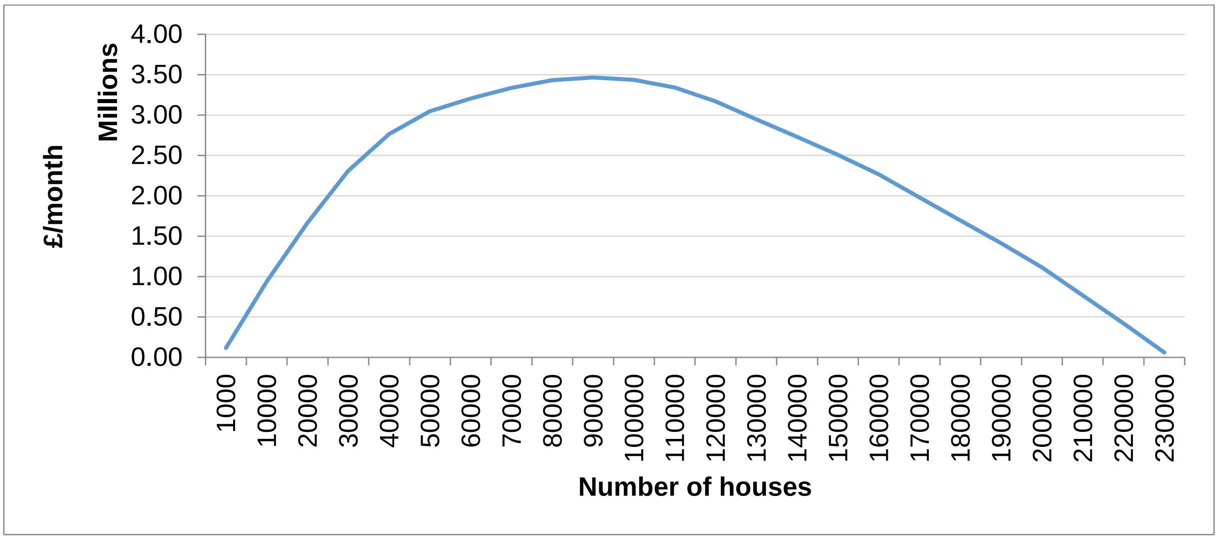


Figure 7-11 *Difference operating costs between gas central heating and smart thermal storage heater charged with wind energy excess*

7.7. WIND CURTAILMENT REDUCTION

By considering an average of seven thermal storage heaters (7*2.75kW) installed per house to cover the total domestic heating demand, it is possible to calculate the correspondent amount of storage capacity per number of houses. Thus, it is possible to express the simulation results discussed in Section 6.4.2.1 in terms of number of houses as shown in **Figure 7-12**, where 55,000 houses correspond to around 1.1GW of thermal storage, while 80,000 and 25,000 houses represent respectively 1.5GW and 500MW of thermal storage.

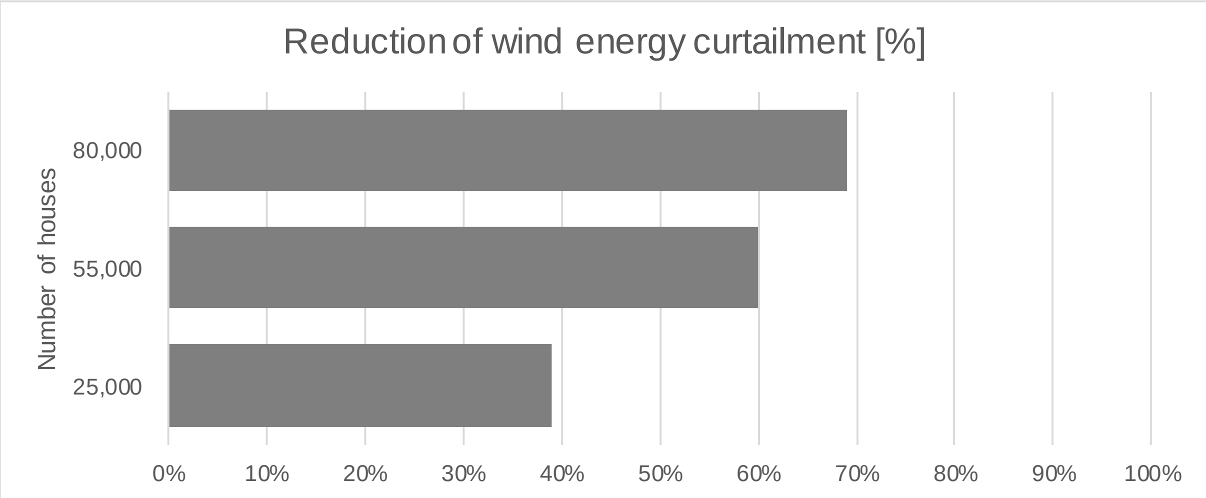


Figure 7-12 *Wind curtailment reduction achieved according to number of houses heated with thermal storage heaters (charged with onshore wind electricity) – results based on PLEXOS simulations*

7.8. DISCUSSION AND CONCLUSION

This work analyses the performance and operations of the thermal storage heater technology, to assess the feasibility of using these smart devices for the absorption of excess renewable in cold country (e.g. Scotland). This means that the charging process of the thermal storage heater would be scheduled based on an alternative method to the usual night program. The simulations results have shown that the combination of thermal storage heaters and excess wind energy could be employed for the partial provision of the heat demand in Scotland. The storage heating devices could support the electric network for balancing the renewable generation surplus and displace part of the fossil fuel heating systems, because of the flexibility of the storage to adapt its charging periods to surplus wind generation periods. However, the limited capacity of the thermal storage heater for domestic applications might not be able to store enough renewable energy to cover long periods of lack of wind curtailment. Thus, this would force the consumers to find alternative energy sources for the heat supply in those periods (e.g. conventional gas/oil heating system, buying off-peak electricity for charging the storage). The simulation results have also highlighted that the increase of storage capacity of the thermal device could provide a valid solution to “bridge” the long period with insufficient wind energy generation. In the model two maximum temperatures have been tested; however, the adoption of different material, like PCM, could also be investigated for replacing the original ceramic bricks.

The wide installation of thermal storage heater systems could provide balancing services to the grid in countries with intense renewable generation. The resolution of congestion issues with the use of thermal storage capacity could bring relief to the overall electric network. Thus, this service provided by the thermal storage heater should be rewarded by the grid operator with convenient electricity prices. The introduction of new policies is necessary to incentivise the purchase and installation of thermal storage systems and their charge out of the usual off-peak periods. The lack of such measures would not allow the potential adoption of excess renewable for space heating purposes.

7.8.1. MAIN ASSUMPTIONS AND LIMITATIONS OF THE MODEL

It is important to notice that these conclusions are purely based on the results of a MATLAB model. The mathematical model of the thermal storage heater is quite accurate since its results have been compared with the temperature evolution observed in the laboratory during the charge and natural/forced discharge phases. However, in order to simplify the model, it has been decided to use a single thermal storage heater operation based on an “out-all-day” timer profile, with eight hours of heating per day, has been selected; this choice has been based on the GB national survey report [162] and the heating requirement of the participants of the demonstration house. The “out-all-day” pattern is suitable for users who work out of home all day and come back in the late afternoon. Different occupants could rather choose different programs that suit more their lifestyle. For instance, users who work or study from home might enjoy having the heater on for few hours also during the middle of the day, increasing in this way the overall heating demand for the thermal heater storage. Future work could focus on the model of the thermal storage heater operations according to the variation of the outside temperature rather than using a fixed charging/discharging schedule. Although, it is expected that this change would not largely compromise the model results because colder days could be easily offset by sunnier and warmer periods without affecting the overall results.

Chapter 8

DISCUSSION AND CONCLUSION

The main purpose of this thesis is to assess the value of energy storage technologies in existing energy systems. An exhaustive review focused on the different approaches adopted so far for analysing the benefits of the energy storage showed that the results might change according to the technologies, roles, and perspectives considered. This literature survey confirmed the importance of running simulations on real energy system models, since it is not possible to generalise the value of the energy storage for any circumstance.

The choice of PLEXOS as software to simulate the electricity dispatch of real energy systems has been driven by the necessity of:

- Achieving reliable and accurate unit commitment simulations for small and isolated grids, as well as, for large and interconnected networks. This requirement has been fulfilled, on one hand, with a detailed model of each of the few elements of the electricity system, and, on the other hand, with a simplified model that maintained the features of the real system.

- Analysing the electricity flow in the transmission lines and simulate the congestion issues that obstruct the electricity export from Scotland to England.

- Simulating wind power curtailment in case of surplus electricity that cannot be absorbed by the demand and jeopardise the stability of the grid. This point was fundamental for this work since it was one of the reasons that support the use of energy storage technologies at the grid level.

- Modelling and optimising the operation of the energy storage devices both when connected to a single power plant or to the entire network.

The flexibility, accuracy, and details of the simulations run are the reasons why PLEXOS has been selected as the most suitable software for this work. However, when analysing the GB case study, it has been highlighted the difficulties faced to integrate a heat network in the model of the electricity grid. The reason is that the focus of PLEXOS is the representation of the electricity network without considering possible interactions with other sectors (heat or transport). This approach is coherent with the current vision of the energy sector, which is usually considered as divided into three different and separated areas.

Nevertheless, this way of representing the energy sector is expected to change soon following the latest evolutions in the energy field and the necessity to pursue the "energy trilemma". Indeed, as shown through the simulation analysis of the GB energy system, the use of thermal storage technology for linking the power generation with the heat demand could allow the country to achieve interesting results regarding the reduction of wind power curtailment (up to 60%) and the decarbonisation of the heat sector (30% of the Scottish heat consumption). These results have been compared with the operations of a different energy storage technology, the electric storage, following one of the objectives of this thesis. The comparison of these two case studies has proven that different technologies installed in the same energy system might obtain different values. In this specific case, the electric storage showed good potentials for the reduction of the regulation costs, due to the increased level of flexibility of the electricity grid, while it had negligible influences on the wind power curtailment. In contrast with these results, the same amount of storage capacity expressed in terms of thermal energy might allow minimising wind power curtailment, but it would not be able to participate to the balancing market since its discharge process is not linked to the electricity grid.

Another objective of this thesis was to look at the value of the same energy storage technology playing different roles. This aspect has been investigated with simulations on the Tenerife energy system model that looked at the use of energy storage devices in the current and future energy scenario. Currently, the energy system lacks large renewable share and the energy storage would work, together with the traditional power plants, to shift part of the load from peak to off-peak hours. This strategy would maximise the revenue of the energy storage investor, due to the large variation of the wholesale electricity price during the day. However, the maximum benefits for the entire energy system, in terms of system costs and CO_2 emissions, would be achieved when the energy storage is coupled with large wind power plants since the storage device would maximise the penetration of renewables in the electricity grid.

This thesis aimed to show the various benefits of energy storage technology in existing energy systems and how its adoption on large scale can address specific issues according to the operation strategy used. However, due to the complexity of the so-called “energy trilemma”, the energy storage cannot represent the unique solution able to solve all the problems. The deployment of the energy trilemma might need a radical revolution of the entire energy system, and the energy storage can play a key role together with decentralised renewable generation, demand management, district heating, and reduction of energy consumption.

8.1. MAIN OUTCOMES

8.1.1. TENERIFE ENERGY SYSTEM

This work presents a full evaluation of the value that an energy storage installation would have on Tenerife through power flow modelling of the island system under different energy scenarios to determine the value of the energy storage. The analysis focused on a storage device of 25MW of power and 100MWh of capacity. This choice was driven by the willingness to compare the value of the storage assuming the latter is charged with electricity from three sources (i.e. the grid, OCGT plant, onshore wind). Thus, it has been necessary to choose a size that could fit all the scenarios.

The integration of an energy storage device with Tenerife energy system offers an enhanced peaking solution that not only responds to peaks in grid demand but also absorbs energy during times of excess production – allowing greater renewable penetration and reduced cycling of baseload thermal plant.

It is possible to see that when charged with onshore wind electricity emissions from the combined system are the lowest – leading to a potential reduction of 30% compared to the current emission level. In contrast, when electricity from the grid is used to charge the energy storage device, emissions from the overall energy system are the highest. This is due to a combination of carbon intense plants generating the electricity used to charge the storage and the losses during the storage of electricity that reduce the amount of electricity that can be discharged. For the same reasons, it is possible to see that also emissions from the hybrid system OCGT+ES are also higher compared to the current level.

From a whole system perspective, it has been simulated that the operations of the energy storage are more beneficial when coupled with the integration of a greater renewable capacity, reducing the costs associated with curtailment and reducing the carbon intensity and cost of peaking power required to allow the integration of these renewables. This highlights the importance of taking into account projections for renewable deployment. Larger energy storage device could be considered in case the government committed to a fast deployment of renewable sources.

From the energy storage owner perspective, it would be more profitable to operate the energy storage device in an energy system based on thermal capacity (i.e. carbon intense grid, OCGT plant). In these scenarios, the high variation of wholesale electricity price during the day encourages the arbitrage operation of the storage device and maximises the revenue for the energy storage owner. The choice of a LAES could be beneficial because it would allow to recover part of the heat waste from the electricity generation process and increase the efficiency of the storage device.

8.1.2. GB ENERGY SYSTEM

The focus of this work is the assessment of the reduction of the wind curtailment due to transmission constraints between at the Scotland-England border in different scenarios (i.e. thermal storage devices, enlargement of transmission lines, batteries).

The installation of thermal storage devices charged with wind energy and discharged to provide residential heating it has been proven to be the most interesting solution. The simulation results show that this scenario can obtain the reduction of almost 60% of the wind curtailment would correspond to the savings of 30% of the total gas heating generation that is needed for household consumption in Scotland. If the installation of

1.1 GW and 8.8 GWh of energy storage can already achieve almost 60% of reduction of wind energy curtailment across the year, when increasing the storing energy capacity (to 1.5GW), the reduction of wind curtailment per year does not follow a linear trend. The reason is that the addition of further capacity would have a significant effect only in case of peaks of energy curtailments or for curtailment periods that last for a long time. The amount of volume curtailed is not homogenously distributed across the month but is usually concentrated in short periods that may present also relevant peaks. For this reason, the installation of larger thermal storage capacity able to completely avoid curtailment can be not convenient, since the entire capacity would be exploited just on a few occasions per year. Sizing the energy storage to completely avoid curtailment can be not economically convenient and the revenues will not be able to cover the capital invested.

The simulation of the scenario based on the enlargement of the transmission lines shows that even though this solution might gain overall economic and environmental benefits, the reduction of wind energy curtailment is not remarkable (2.43%). This result could be explained thinking that the aim of the unit commitment is the achievement of the most optimised solution for the whole system. The enlargement of the transmission line at the border between Scotland and England allows the model to get an overall reduction of the CO_2 emission and system costs by increasing the renewable generation in the whole network. Thus, this choice might still prevent wind power plants in Scotland to maximises their output and avoid curtailment.

The installation of large battery systems does not seem particularly interesting for this case study, as proven by the simulation results. The percentage of charge is particularly low, proving that the optimisation model does not consider convenient the charge of the electricity storage with wind energy; moreover, the discharge processes are not frequent, due to the fact that the Scottish electric consumption is saturated and not able to absorb wind electricity peak generations neither when they occur or later in time after being stored. Therefore, for the reasons mentioned above, it should be concluded that large electric storage systems are not suitable for increasing the penetration of wind energy in the Scotland electric grid. The low state of charge achieved by the large battery systems suggests that smaller electric storage devices could be used instead. However, it is important to notice that their operations would still achieve negligible results in terms of wind curtailment reduction, as showed by the simulation results.

8.2. FUTURE WORKS

The simulation analysis of GB energy system performed in this work focuses only on the current energy scenario. The value of the energy storage technologies has been calculated considering the actual level of renewable penetration and thermal power capacity. However, GB energy system will go through a consistent modification of the current status quo to achieve the decarbonisation targets. The achievement of these goals will require the increase of renewable penetration and the reduction of coal plant capacity [207]. Thus, it would be interesting to run simulations on this future scenario and understand how the value of the storage will be affected. On one hand, the increase of fluctuating and unpredictable renewable generation will increase the requirements for energy solutions to balance the energy grid, like the energy storage technologies. On the other hand, the future wholesale electricity prices might fall due to the reduction of thermal power plant generation and the flattened wholesale electricity price might not be profitable for the energy storage devices that take advantage from the variation of the daily wholesale electricity price.

The choice of analysing Tenerife and Great Britain electricity networks has been justified by the willingness to study two countries representative of two different energy system types. Several other countries are affected by network balancing issues and it would be interesting to extend the simulation analysis done for Tenerife and GB also to those countries. It has already been mentioned that German electricity grid is characterised by large volume of wind curtailment due to transmission congestions. Siemens Gamesa is currently investigating the potential of including electric thermal energy storage (ETES) for repowering closed coal power plants [208]. This idea suggests that German energy players have large interest in energy storage technologies and in pursuing novel energy solutions, like the power-to-heat application as it has been investigated in this work for GB energy system.

Due to its central position in Europe, the exchange flows with the neighbouring countries play a key role in the German electricity network. Poland and Czech Republic complain that German grid operators use the interconnectors for moving the renewable electricity from the northern part of the country to the southern regions when the national transmission lines are congested (loop flows [209]). The presence of these loop flows would bring new challenges to the modelling of the electricity network in PLEXOS because for the study of Germany energy system it would not be possible to ignore the interconnector flows, as it has been done for GB energy system.

Annex A

MODEL INPUTS

Table A-1 *Techno-economical parameters of generators in Tenerife simulation model*

Generator	Max Capacity (MW)	Min Stable Level (MW)	Heat Rate Base (GJ/hr)	Heat Rate Increment (GJ/MWh)	Heat Rate Increment (GJ/MWh²)	VO&M Charge (€/MWh)	Running Cost (€/hr)	Start Cost (€)	Start Cost Time (h)	Max Capacity Factor (%)	Min Capacity Factor (%)	Fuel	Nodes
Arona	43.20	9.70	38.38	9.02	0.07	18.60	130	270	0.10	-	-	Gasoleo	1
Candelaria Diesel	25.53	13.74	31.88	5.78	0.06	10.50	360	470	0.10	56	25	Fueloil BIA 0.73%	2
Candelaria Gas	79.38	20.37	122.94	9.31	0.01	24.40	130	270	0.10	70	-	Gasoleo	3
Candelaria Vapour	74.56	27.16	35.12	11.97	0.00	8.33	320	72,000	3.50	100	-	Fueloil BIA 0.73%	4
Cotesa	38.00	23.00	39.00	9.09	0.07	21.17	130	270	0.10	-	-	Gasoleo	5
Granadilla Diesel	41.02	28.18	31.88	5.78	0.06	11.43	360	1,000	0.10	87	50	Fueloil BIA 1%	6
Granadilla Gas	71.54	13.58	131.43	7.42	0.05	20.53	130	270	0.10	100	-	Gasoleo	7
Granadilla Vapour	148.48	55.68	88.99	9.04	0.00	5.21	320	72,000	3.50	100	-	Fueloil BIA 1%	8
Guia Isora	43.00	20.00	40.00	9.94	0.07	21.17	130	270	0.10	100	-	Gasoleo	9
Granadilla I y II	432.00	149.50	253.04	8.05	0.00	18.69	2,550	11,000	1.50	-	34	Gasoleo	10
Wind	400.00	-	-	-	-	13.00	-	-	-	-	-	Wind	13

***Table A-2** Technical specifications for the three scenarios in Tenerife model*

Scenario	Storage capacity (MWh)	Storage Power (MW)	Node	Storage Charge Efficiency (%)	Storage Discharge Efficiency (%)	Timeslice	Pattern
Storage (LAES)	100.0	25.0	12	100	50	offpeak	H1-7,H24
					70	peak	H8-23
Storage and OCGT	100.0	25.0	12	100	70	-	-
Storage and wind	100.0	25.0	12	100	70	-	-

***Table A-3** Fuel costs in Tenerife model*

Fuel	Price (€/GJ)	Delivery Charge (€/GJ)
Fueloil BIA 0.73%	18.0	0.50
Fueloil BIA 1%	20.0	0.77
Gasoleo	21.0	0.47
Wind	-	-

***Table A-4** Reserve specifications in Tenerife model*

Reserve	Type	Value (MW)	Timeslice	Pattern
Regulation down	Lower	75.0	offpeak	H1-7,H24
		100.0	peak	H8-23
Regulation up	Raise	150.0	offpeak	H1-7,H24
		200.0	peak	H8-23

Table A-5 *Techno-economical specifications of generators in GB simulation model – region England&Wales*

Generator	Units	Max Capacity (MW)	Min Stable Level (MW)	Heat Rate (GJ/MWh)	VO&M Charge (£/MWh)	Running Cost (£/hr)	Start Cost (£m)	Start Cost Time (h)	Min Up Time (h)	Max Ramp Up (MW/min)	Max Ramp Down (MW/min)	Fixed Charge (£/kW/year)	Fuel	Nodes
CCTG	30	963.7	96.0	7.5	3.0	8,357.0	20.5	4.0	4.0	25.0	25.0	110.0	Gas	6
Coal	16	940.8	-	10.1	5.0	1,000.0	107.0	4.0	4.0	5.0	5.0	250.0	Coal	7
Hydro river	1	141.7	10.0	1.0	18.0	20.0	-	-	5.0	-	-	-	Hydro	8
Nuclear	8	846.0	427.5	9.2	1.0	320.0	4,000.0	96.0	-	5.0	5.0	470.0	Uranium	9
OCGT	10	32.3	-	10.0	50.0	4,200.0	0.3	1.0	1.0	-	-	72.0	Gas	10
Wind	6,840	1.0	-	-	-	-	-	-	-	-	-	-	Wind	11
Pumped storage	1	2,060.0	-	-	10.0	-	-	0.5	20.0	20.0	20.0	-	Hydro	12

Table A-6 *Techno-economical specifications of generators in GB simulation model – region Scotland*

Generator	Units	Max Capacity (MW)	Min Stable Level (MW)	Heat Rate (GJ/MWh)	VO&M Charge (£/MWh)	Running Cost (£/hr)	Start Cost (£m)	Start Cost Time (h)	Min Up Time (h)	Max Ramp Up (MW/min)	Max Ramp Down (MW/min)	Fixed Charge (£/kW/year)	Fuel	Nodes
CCTG _S	1	1,180.0	120.0	7.5	3.0	8,357.0	390.4	4.0	4.0	25.0	25.0	110.0	Gas	1
Hydro river_S	1	1,315.6	-	1.0	10.0	-	-	0.5	20.0	-	-	-	Hydro	2
Nuclear_S	1	1,075.0	540.0	9.2	1.0	320.0	4,000.0	96.0	-	5.0	5.0	470.0	Uranium	3
Wind_S	4,667	1.0	-	1.0	-	-	-	-	-	-	-	-	Wind	4
Pumped storage_S	1	700.0	-	-	10.0	-	-	0.5	20.0	20.0	20.0	-	Hydro	5
Boiler Scotland	10	3,000.0	-	4.8	60.0	130.0	0.3	0.1	-	-	-	-	Gas boiler	13

Table A-7 *Technical specifications for the three scenarios in GB model*

Scenario	Units	Storage capacity (MWh)	Max Power (MW)	Node	Storage Charge Efficiency (%)	Storage Discharge Efficiency (%)
Thermal electricity storage	11	400.0	200.0	14	100	100
Battery	11	400.0	200.0	14	100	75
Transmission enlargement	-	-	4,500.0	-	-	-

Table A-8 *Fuel costs in GB model*

Fuel	Price (£/GJ)
Coal	4.69
Gas	6.07
Gas boiler	0.75
Hydro	3.00
Uranium	0.34
Wind	-

Table A-9 *Carbon price and emission limits in GB model*

Emission	Price (£/kg)	Property	Value (mtonne)	Timeslice	Pattern
CO2	18.00	Max Production Month	21.00	Q1	M1-3
CO2	18.00	Max Production Month	15.55	Q2	M4-6
CO2	18.00	Max Production Month	15.13	Q3	M7-9
CO2	18.00	Max Production Month	20.48	Q4	M10-12

Table A-10 *Reserve specifications in GB model*

Reserve	Type	Value (MW)	Timeframe (s)	Duration (s)
Frequency down	Lower	200.0	10.0	900.0
Frequency up	Raise	200.0	10.0	900.0
STOR down	Regulation Lower	1,800.0	1,200.0	14,400.0
STOR up	Regulation Raise	1,800.0	1,200.0	14,400.0

List of References

[1] “World Energy Trilemma Index | 2017 MONITORING THE SUSTAINABILITY OF NATIONAL ENERGY SYSTEMS In Partnership with OLIVER WYMAN,” 2017.

[2] “Kyoto Protocol Introduction | UNFCCC.” [Online]. Available: https://unfccc.int/process/the-kyoto-protocol. [Accessed: 31-Aug-2018].

[3] UNFCCC, “Paris Agreement,” *Conf. Parties its twenty-first Sess.*, vol. 21932, no. December, p. 32, 2015.

[4] IEA, “World Energy Outlook 2017 - Executive summary,” *Int. Energy Agancy*, 2017.

[5] REN21, *Renewables 2017: global status report*, vol. 72, no. October 2016. 2017.

[6] Q. Wang, C. Zhang, Y. Ding, G. Xydis, J. Wang, and J. Østergaard, “Review of real-time electricity markets for integrating Distributed Energy Resources and Demand Response,” *Appl. Energy*, vol. 138, pp. 695–706, 2015.

[7] A. Bhardwaj, B. Singh, and P. Khurana, “Unit commitment in electrical power system-a literature review,” *2012 IEEE Int. Power Eng. Optim. Conf.*, no. June, pp. 275–280, 2012.

[8] K. Imran and I. Kockar, “A technical comparison of wholesale electricity markets in North America and Europe,” *Electr. Power Syst. Res.*, vol. 108, pp. 59–67, 2014.

[9] G. Sinden, “Characteristics of the UK wind resource: Long-term patterns and relationship to electricity demand,” *Energy Policy*, vol. 35, no. 1, pp. 112–127,

2007.

[10] D. Liang, “Renewable Integration – The Impact to the Grid,” pp. 1–66, 2014.

[11] Euroheat & Power, “ECOHEATCOOL Work package 1 - The European Heat Market.”

[12] K. Bauermann, “German Energiewende and the heating market – Impact and limits of policy,” *Energy Policy*, vol. 94, pp. 235–246, Jul. 2016.

[13] U. Persson and S. Werner, “Heat distribution and the future competitiveness of district heating,” *Appl. Energy*, vol. 88, no. 3, pp. 568–576, 2011.

[14] M. A. Sayegh *et al.*, “Trends of European research and development in district heating technologies,” *Renew. Sustain. Energy Rev.*, vol. 68, pp. 1183–1192, 2017.

[15] U. Persson and S. Werner, “District heating in sequential energy supply,” *Appl. Energy*, vol. 95, pp. 123–131, 2012.

[16] S. Werner, “International review of district heating and cooling,” *Energy*, vol. 137, pp. 617–631, 2017.

[17] A. Bloess, W. P. Schill, and A. Zerrahn, “Power-to-heat for renewable energy integration: A review of technologies, modeling approaches, and flexibility potentials,” *Appl. Energy*, vol. 212, no. August 2017, pp. 1611–1626, 2018.

[18] D. Böttger, M. Götz, N. Lehr, H. Kondziella, and T. Bruckner, “Potential of the Power-to-Heat technology in district heating grids in Germany,” *Energy Procedia*, vol. 46, pp. 246–253, 2014.

[19] G. Schweiger, J. Rantzer, K. Ericsson, and P. Lauenburg, “The potential of power-to-heat in Swedish district heating systems,” *Energy*, vol. 137, pp. 661–669, 2017.

[20] European Commission, “DG ENER Working Paper: ‘The future role and challenges of Energy Storage,’” 2012.

[21] R. J. Barthelmie, F. Murray, and S. C. Pryor, “The economic benefit of short-term forecasting for wind energy in the UK electricity market,” *Energy Policy*, vol. 36, no. 5, pp. 1687–1696, 2008.

[22] B. C. Ummels, M. Gibescu, E. Pelgrum, W. L. Kling, and A. J. Brand, “Impacts of wind power on thermal generation unit commitment and dispatch,” *IEEE Trans. Energy Convers.*, vol. 22, no. 1, pp. 44–51, 2007.

[23] J. Lamy, I. L. Azevedo, and P. Jaramillo, “The role of energy storage in accessing remote wind resources in the Midwest,” *Energy Policy*, vol. 68, pp. 123–131, 2014.

[24] F. Fallahi, M. Nick, G. H. Riahy, S. H. Hosseinian, and A. Doroudi, “The value of energy storage in optimal non-firm wind capacity connection to power systems,” *Renew. Energy*, vol. 64, pp. 34–42, 2014.

[25] P. Zhao, J. Wang, and Y. Dai, “Capacity allocation of a hybrid energy storage system for power system peak shaving at high wind power penetration level,” *Renew. Energy*, vol. 75, pp. 541–549, 2015.

[26] T. K. a Brekken, A. Yokochi, A. Von Jouanne, Z. Z. Yen, H. M. Hapke, and D. a Halamay, “Optimal energy storage sizing and control for wind power

applications," *IEEE Trans. Sustain. Energy*, vol. 2, no. 1, pp. 69–77, 2011.

[27] I. Staffell and M. Rustomji, "Maximising the value of electricity storage," *J. Energy Storage*, vol. 8, pp. 212–225, 2016.

[28] P. R. Thimmapuram, A. Botterud, C. Uckun, D. Krishnamurthy, and Z. Zhou, "Energy Storage Arbitrage Under Day-Ahead and Real-Time Price Uncertainty," *IEEE Trans. Power Syst.*, vol. 33, no. 1, pp. 84–93, 2017.

[29] M. B. C. Salles, "Potential Arbitrage Revenue of Energy Storage Systems in PJM," 2017.

[30] A. D. Bank, "Energy Storage in Grids With High Penetration of Variable Generation," 2017.

[31] N. Günter and A. Marinopoulos, "Energy storage for grid services and applications: Classification, market review, metrics, and methodology for evaluation of deployment cases," *J. Energy Storage*, vol. 8, pp. 226–234, 2016.

[32] M. Katsanevakis, R. A. Stewart, and J. Lu, "Aggregated applications and benefits of energy storage systems with application-specific control methods: A review," *Renew. Sustain. Energy Rev.*, vol. 75, no. November 2015, pp. 719–741, 2017.

[33] A. A. Jamali, N. M. Nor, and T. Ibrahim, "Energy storage systems and their sizing techniques in power system - A review," *2015 IEEE Conf. Energy Conversion, CENCON 2015*, pp. 215–220, 2016.

[34] A. Nottrott, J. Kleissl, and B. Washom, "Energy dispatch schedule optimization and cost benefit analysis for grid-connected, photovoltaic-battery storage systems," *Renew. Energy*, vol. 55, pp. 230–240, Jul. 2013.

[35] M. Z. Daud, A. Mohamed, and M. A. Hannan, "An improved control method of battery energy storage system for hourly dispatch of photovoltaic power sources," *Energy Convers. Manag.*, vol. 73, pp. 256–270, Sep. 2013.

[36] J. Marcos, I. de La Parra, M. García, and L. Marroyo, "Control strategies to smooth short-term power fluctuations in large photovoltaic plants using battery storage systems," *Energies*, vol. 7, no. 10, pp. 6593–6619, 2014.

[37] R. Moreno, R. Moreira, and G. Strbac, "Value of corrective network security for distributed energy storage applications," *IET Gener. Transm. Distrib.*, vol. 10, no. 7, pp. 1758–1767, 2016.

[38] P. Denholm, E. Ela, B. Kirby, and M. Milligan, "The Role of Energy Storage with Renewable Electricity Generation," 2010.

[39] D. M. Greenwood, K. Y. Lim, C. Patsios, P. F. Lyons, Y. S. Lim, and P. C. Taylor, "Frequency response services designed for energy storage," *Appl. Energy*, vol. 203, pp. 115–127, 2017.

[40] Agora Energiewende, "Flexibility in thermal power plants with a focus on existing coal-fired power plants," 2017.

[41] Energy Storage Association, "Grid Operations Benefits | Energy Storage Association." [Online]. Available: http://energystorage.org/energy-storage/energy-storage-benefits/benefit-categories/grid-operations-benefits. [Accessed: 21-Mar-2019].

[42] N. K. Gupta, "Changing Role of Coal-Fired Power Plants : From Base Load Operation to Flexible Operation," *Int. Res. J. Eng. Technol.*, vol. 4, no. 3, pp. 3–

6, 2017.

[43] E. S. Barbieri, F. Melino, and M. Morini, "Influence of the thermal energy storage on the profitability of micro-CHP systems for residential building applications," *Appl. Energy*, vol. 97, pp. 714–722, 2012.

[44] G. Pagliarini and S. Rainieri, "Modeling of a thermal energy storage system coupled with combined heat and power generation for the heating requirements of a University Campus," *Appl. Therm. Eng.*, vol. 30, no. 10, pp. 1255–1261, 2010.

[45] A. D. Smith, P. J. Mago, and N. Fumo, "Benefits of thermal energy storage option combined with CHP system for different commercial building types," *Sustain. Energy Technol. Assessments*, vol. 1, no. 1, pp. 3–12, 2013.

[46] M. Sevket Guney and Y. Tepe, "Classification and assessment of energy storage systems," *Renew. Sustain. Energy Rev.*, vol. 75, pp. 1187–1197, 2017.

[47] O. Palizban and K. Kauhaniemi, "Energy storage systems in modern grids—Matrix of technologies and applications," *J. Energy Storage*, vol. 6, pp. 248–259, 2016.

[48] X. Luo, J. Wang, M. Dooner, and J. Clarke, "Overview of current development in electrical energy storage technologies and the application potential in power system operation," *Appl. Energy*, 2015.

[49] S. Ould Amrouche, D. Rekioua, T. Rekioua, and S. Bacha, "Overview of energy storage in renewable energy systems," *Int. J. Hydrogen Energy*, vol. 41, no. 45, pp. 20914–20927, 2016.

[50] B. Dunn, B. Dunn, H. Kamath, and J. Tarascon, “Electrical energy storage for the gridfor the Grid : A Battery of choices,” *Sci. Mag.*, vol. 334, no. 6058, pp. 928–936, 2011.

[51] M. M. Farid, A. M. Khudhair, S. A. K. Razack, and S. Al-Hallaj, “A review on phase change energy storage: Materials and applications,” *Energy Convers. Manag.*, vol. 45, no. 9–10, pp. 1597–1615, 2004.

[52] A. Sharma, V. V. Tyagi, C. R. Chen, and D. Buddhi, “Review on thermal energy storage with phase change materials and applications,” *Renew. Sustain. Energy Rev.*, vol. 13, no. 2, pp. 318–345, 2009.

[53] B. Zalba, “Review on thermal energy storage with phase change: materials, heat transfer analysis and applications,” *Appl. Therm. Eng.*, vol. 23, no. 3, pp. 251–283, 2003.

[54] K. Kaygusuz and a. Sari, “High Density Polyethylene/Paraffin Composites as Form-stable Phase Change Material for Thermal Energy Storage,” *Energy Sources, Part A Recover. Util. Environ. Eff.*, vol. 29, no. 3, pp. 261–270, 2007.

[55] T. G. Chuah, D. Rozanna, a. Salmiah, S. Y. Thomas Choong, and M. Sa’ari, “Fatty acids used as phase change materials (PCMs) for thermal energy storage in building material applications,” *Appl. Energy*, no. July, pp. 123–137, 2006.

[56] T. M. I. Mahlia, T. J. Saktisahdan, A. Jannifar, M. H. Hasan, and H. S. C. Matseelar, “A review of available methods and development on energy storage; technology update,” *Renew. Sustain. Energy Rev.*, vol. 33, pp. 532–545, 2014.

[57] F. Teng, J. Miles, A. Thomson, G. Strbac, N. Brandon, and D. Pudjianto, “Potential value of energy storage in the UK electricity system,” *Proc. ICE - Energy*, vol. 168, no. 2, pp. 107–117, 2015.

[58] M. Black and G. Strbac, “Value of storage in providing balancing services for electricity generation systems with high wind penetration,” *J. Power Sources*, vol. 162, no. 2 SPEC. ISS., pp. 949–953, 2006.

[59] D. Zafirakis, K. J. Chalvatzis, G. Baiocchi, and G. Daskalakis, “The value of arbitrage for energy storage: Evidence from European electricity markets,” *Appl. Energy*, vol. 184, pp. 971–986, 2016.

[60] M. Child and C. Breyer, “The Role of Energy Storage Solutions in a 100% Renewable Finnish Energy System,” *Energy Procedia*, vol. 99, no. March, pp. 25–34, 2016.

[61] F. Careri, C. Genesi, M. Montagna, and S. Rossi, “The role of energy storage systems to manage RES volatility in day-ahead scheduling,” *2012 IEEE Int. Energy Conf. Exhib. ENERGYCON 2012*, pp. 680–686, 2012.

[62] L. Barelli, U. Desideri, and A. Ottaviano, “Challenges in load balance due to renewable energy sources penetration: The possible role of energy storage technologies relative to the Italian case,” *Energy*, vol. 93, pp. 393–405, 2015.

[63] F. J. de Sisternes, J. D. Jenkins, and A. Botterud, “The value of energy storage in decarbonizing the electricity sector,” *Appl. Energy*, vol. 175, pp. 368–379, 2016.

[64] F. Teng, M. Aunedi, and G. Strbac, “Benefits of flexibility from smart electrified

transportation and heating in the future UK electricity system," *Appl. Energy*, vol. 167, pp. 420–431, 2016.

[65] A. Shcherbakova, A. Kleit, and J. Cho, "The value of energy storage in South Korea's electricity market: A Hotelling approach," *Appl. Energy*, vol. 125, pp. 93–102, 2014.

[66] D. Rastler, "Energy storage markets, application and value analysis," *IEEE PES Gen. Meet.*, pp. 1–3, 2010.

[67] A. Oudalov, D. Chartouni, C. Ohler, and G. Linhofer, "Value Analysis of Battery Energy Storage Applications in Power Systems," *2006 IEEE PES Power Syst. Conf. Expo.*, pp. 2206–2211, 2006.

[68] K. Anderson and A. El Gamal, "Co-optimizing the value of storage in energy and regulation service markets," *Energy Syst.*, vol. 8, no. 2, pp. 369–387, 2017.

[69] D. Zafirakis *et al.*, "The multiple role of energy storage in the industrial sector: Evidence from a Greek industrial facility," *Energy Procedia*, vol. 46, no. 0, pp. 178–185, 2014.

[70] D. Pudjianto, M. Aunedi, P. Djapic, and G. Strbac, "Whole-systems assessment of the value of energy storage in low-carbon electricity systems," *IEEE Trans. Smart Grid*, vol. 5, no. 2, pp. 1098–1109, 2014.

[71] P. Denholm and R. Sioshansi, "The value of compressed air energy storage with wind in transmission-constrained electric power systems," *Energy Policy*, vol. 37, no. 8, pp. 3149–3158, 2009.

[72] E. Delarue, D. Cattrysse, and W. D'haeseleer, "Enhanced priority list unit

commitment method for power systems with a high share of renewables," *Electr. Power Syst. Res.*, vol. 105, pp. 115–123, 2013.

[73] M. Govardhan, "Solution to Unit Commitment with Priority," pp. 5114–5121, 2016.

[74] T. Senjyu, K. Shimabukuro, K. Uezato, and T. Funabashi, "A fast technique for unit commitment problem by extended priority list," *IEEE Trans. Power Syst.*, vol. 18, no. 2, pp. 882–888, 2003.

[75] K. K. Bawa and A. Kaur, "Unit Commitment by an Improved Priority List Method," vol. 5, no. 5, pp. 2015–2017, 2016.

[76] N. P. Padhy, "Unit Commitment—A Bibliographical Survey," *IEEE Trans. Power Syst.*, vol. 19, no. 2, pp. 1196–1205, 2004.

[77] N. Thakur and L. S. Titare, "Determination of Unit Commitment Problem Using Dynamic Programming," *Int. J. Nov. Res. Electr. Mech. Eng.*, vol. 3, no. 1, pp. 24–28, 2016.

[78] K. K. Mon, T. Z. Htwe, S. Soe, and E. Aung, "Dynamic Programming Method Approach to Unit Commitment for Electricity Generation Schedule in Yangon Division," pp. 215–222, 2016.

[79] P. K. Singhal and R. N. Sharma, "Dynamic programming approach for solving power generating unit commitment problem," *2011 2nd Int. Conf. Comput. Commun. Technol. ICCCT-2011*, no. September 2011, pp. 298–303, 2011.

[80] a. K. Ayoub and a. D. Patton, "Optimal thermal generating unit commitment," *IEEE Trans. Power Appar. Syst.*, vol. PAS-90, no. 4, pp. 1752–1756, 1971.

[81] C. Cheng, C. Liu, and C. Liu, "Unit commitment by Lagrangian relaxation and genetic algorithms," *IEEE Trans. Power Syst.*, vol. 15, no. 2, pp. 707–714, 2000.

[82] S. Mukherjee and E. C. Adrian, "Implementation of a lagrangian relaxation based unit commitment problem," *IEEE Trans. Power Syst.*, vol. 4, no. 4, pp. 1373–1380, 1989.

[83] L. R. Srinivas, S. T. Kalyani, and M. Ramu, "Unit commitment by Lagrangian relaxation incorporating Differential Evolution," *J. Electr. Eng.*, vol. 15, no. 3, pp. 49–54, 2015.

[84] X. Yu and X. Zhang, "Unit commitment using Lagrangian relaxation and particle swarm optimization," *Int. J. Electr. Power Energy Syst.*, vol. 61, pp. 510–522, 2014.

[85] A. Ademovic, S. Bisanovic, and M. Hajro, "A Genetic Algorithm solution to the Unit Commitment problem based on real-coded chromosomes and Fuzzy Optimization," *MELECON 2010 - 2010 15th IEEE Mediterr. Electrotech. Conf.*, pp. 1476–1481, 2010.

[86] K. S. Swarup and S. Yamashiro, "Unit commitment solution methodology using genetic algorithm," *IEEE Trans. Power Syst.*, vol. 17, no. 1, pp. 87–91, 2002.

[87] K. K. Swankar, "A Genetic Algorithm Approach to Solve Unit Commitment Problem," vol. 7, no. 3, pp. 60–64, 2013.

[88] E. Delarue and W. D'haeseleer, "Adaptive mixed-integer programming unit commitment strategy for determining the value of forecasting," *Appl. Energy*, vol. 85, no. 4, pp. 171–181, 2008.

[89] M. Reza Norouzi, A. Ahmadi, A. Esmaeel Nezhad, and A. Ghaedi, “Mixed integer programming of multi-objective security-constrained hydro/thermal unit commitment,” *Renew. Sustain. Energy Rev.*, vol. 29, pp. 911–923, 2014.

[90] J. Smith and Z. Taskin, “A Tutorial Guide to Mixed Integer Programming Models and Solution Techniques,” *Optim. Med. Biol.*, pp. 1–23, 2008.

[91] E. Engineering, “A Two-Stage Method with Mixed Integer Quadratic Programming,” pp. 374–378, 2008.

[92] Y. Huang, P. M. Pardalos, and Q. P. Zheng, *Electrical Power Unit Commitment*. 2017.

[93] K. Van Den Bergh, K. Bruninx, E. Delarue, and D. William, “LUSYM : a Unit Commitment Model formulated as a Mixed-Integer Linear Program (internal version),” no. June, pp. 1–23, 2015.

[94] M. Carri??n and J. M. Arroyo, “A computationally efficient mixed-integer linear formulation for the thermal unit commitment problem,” *IEEE Trans. Power Syst.*, vol. 21, no. 3, pp. 1371–1378, 2006.

[95] J. P. Deane, G. Drayton, and B. P. Ó. Gallachóir, “The impact of sub-hourly modelling in power systems with significant levels of renewable generation,” *Appl. Energy*, vol. 113, pp. 152–158, 2014.

[96] Energy Exemplar, “PLEXOS Wiki | Article / ConciseModellingGuide.” [Online]. Available: https://wiki.energyexemplar.com/index.php?n=Article.ConciseModellingGuide?action=print. [Accessed: 11-Mar-2019].

[97] Energy Exemplar, “PLEXOS Integrated Energy Model - Tutorial ‘ 3 - Nodes ,’” 2010.

[98] Energy Exemplar, “Unit Commitment Modelling and Stochastic Optimization,” 2013.

[99] Energy Exemplar, “PLEXOS Wiki | Article / Renewable Energy Sources.” [Online]. Available: https://wiki.energyexemplar.com/index.php?n=Article.RES?action=print. [Accessed: 13-Mar-2019].

[100] Energy Exemplar, “Wind Modeling - How to model wind generation in the PLEXOS software,” 2019.

[101] Energy Exemplar, “PLEXOS Integrated Energy Model - Applications,” 2016.

[102] B. Cleary, M. Conlon, A. Duffy, V. Fthenakis, and A. O’Connor, “Assessing the benefits of compressed air energy storage on the 2020 Irish power system,” *Proc. Univ. Power Eng. Conf.*, 2013.

[103] B. Cleary, a Duffy, a O’Connor, M. Conlon, and V. Fthenakis, “Assessing the Economic Benefits of Compressed Air Energy Storage for Mitigating Wind Curtailment,” *Sustain. Energy, IEEE Trans.*, vol. 6, no. 3, pp. 1021–1028, 2015.

[104] A. Foley, B. Tyther, P. Calnan, and B. Ó Gallachóir, “Impacts of Electric Vehicle charging under electricity market operations,” *Appl. Energy*, vol. 101, pp. 93–102, 2013.

[105] L. Molyneaux, C. Froome, L. Wagner, and J. Foster, “Australian power: Can renewable technologies change the dominant industry view?,” *Renew. Energy*,

vol. 60, pp. 215–221, 2013.

[106] L. Wagner, L. Molyneaux, and J. Foster, “The magnitude of the impact of a shift from coal to gas under a Carbon Price,” *Energy Policy*, vol. 66, pp. 280–291, 2014.

[107] G. Mills and I. F. MacGill, “Assessing the generation capacity, energy, and GHG emission reduction value of public electric vehicle recharging infrastructure in the Australian National Electricity Market,” *2014 IEEE Int. Electr. Veh. Conf. IEVC 2014*, 2015.

[108] R. Pašičko, S. Robić, and Ž. Tomšić, “Modelling CO2 emissions impacts on Croatian power system,” *Therm. Sci.*, vol. 14, no. 3, pp. 655–669, 2010.

[109] V. Diakov, G. Brinkman, P. Denholm, T. Jenkin, and R. Margolis, “Renewable generation effect on net regional energy interchange,” *IEEE Power Energy Soc. Gen. Meet.*, vol. 2015–Septe, pp. 0–3, 2015.

[110] I. Moazzen, B. Robertson, P. Wild, A. Rowe, and B. Buckham, “Impacts of large-scale wave integration into a transmission-constrained grid,” *Renew. Energy*, vol. 88, pp. 408–417, 2016.

[111] I. V. Lytvyn and N. Hewitt, “Barriers to increased electricity interconnection between neighboring markets,” *Int. Conf. Eur. Energy Mark. EEM*, 2013.

[112] V. Di Cosmo, V. Bertsch, and P. Deane, “Impact of new interconnection lines on the EU electricity market,” *Int. Conf. Eur. Energy Mark. EEM*, vol. 2016–July, 2016.

[113] R. Edmunds, L. Davies, P. Deane, and M. Pourkashanian, “Thermal power plant

operating regimes in future British power systems with increasing variable renewable penetration," *Energy Convers. Manag.*, vol. 105, pp. 977–985, 2015.

[114] J. P. Deane, F. Gracceva, A. Chiodi, M. Gargiulo, and B. P. Ó. Gallachóir, "Assessing power system security. A framework and a multi model approach," *Int. J. Electr. Power Energy Syst.*, vol. 73, pp. 283–297, 2015.

[115] E. P. Ahern, P. Deane, T. Persson, B. Ó Gallachóir, and J. D. Murphy, "A perspective on the potential role of renewable gas in a smart energy island system," *Renew. Energy*, vol. 78, pp. 648–656, 2015.

[116] M. Senatla and C. Mushwana, "A mini-integrated resource plan for a commercial entity in Gauteng Province: Planning for energy autonomous businesses," *Proc. Conf. Ind. Commer. Use Energy, ICUE*, 2017.

[117] A. S. Brouwer, M. van den Broek, W. Zappa, W. C. Turkenburg, and A. Faaij, "Least-cost options for integrating intermittent renewables in low-carbon power systems," *Appl. Energy*, vol. 161, pp. 48–74, 2016.

[118] C. I. Nweke, F. Leanez, G. R. Drayton, and M. Kolhe, "Benefits of chronological optimization in capacity planning for electricity markets," *2012 IEEE Int. Conf. Power Syst. Technol. POWERCON 2012*, pp. 1–6, 2012.

[119] M. Ni, Z. Zhou, and D. Osborn, "Economic and operation benefits of energy storage A case study at MISO," *IEEE Power Energy Soc. Gen. Meet.*, pp. 1–7, 2012.

[120] "DIRECTIVE 2009/72/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 13 July 2009 concerning common rules for the internal market in

electricity and repealing Directive 2003/54/EC," 2009. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009L0072&from=EN. [Accessed: 01-Jun-2018].

[121] J. Merino, P. Mendoza-Araya, and C. Veganzones, "State of the art and future trends in grid codes applicable to isolated electrical systems," *Energies*, vol. 7, no. 12, pp. 7936–7954, 2014.

[122] E. Lobato, L. Sigrist, and L. Rouco, "Use of energy storage systems for peak shaving in the Spanish Canary Islands," *IEEE Power Energy Soc. Gen. Meet.*, 2013.

[123] S. de Otto, M. Bevacqua, and F. Ferrán, "Energy [R]evolution for the Canary Islands," pp. 1–31, 2015.

[124] G. Notton, "Importance of islands in renewable energy production and storage: The situation of the French islands," *Renew. Sustain. Energy Rev.*, vol. 47, pp. 260–269, 2015.

[125] R. Calabria, "' Insula Project ': a grid to join Italy with its islands," 2010.

[126] National Grid, "UK Interconnector Development," no. January, 2015.

[127] M. F. and M. C. A. Linares, B. González-Díaz, J. Gómez-González, L. López-Manzanares, C. Montes, S. González-Pérez, R. Guerrero-Lemus, J. Rodriguez, "Electric Cars in Small Grid: a Possible Solution To Accomplish the Demand Curves in Tenerife Island," *Igarss 2014*, no. 1, pp. 1–5, 2014.

[128] G. M. L. Guerin and P. R. W. G. Bucknall, "High penetration of electric vehicles

in an isolated grid: A study in Guadeloupe," *EEEIC 2016 - Int. Conf. Environ. Electr. Eng.*, 2016.

[129] P. Kadurek, C. Loakimidis, and P. Ferräo, "Electric vehicles and their impact to the electric grid in isolated systems," *POWERENG 2009 - 2nd Int. Conf. Power Eng. Energy Electr. Drives Proc.*, pp. 49–54, 2009.

[130] A. R. Diaz, F. J. Ramos-Real, G. a. Marrero, and Y. Perez, "Impact of electric vehicles as distributed energy storage in isolated systems: The case of tenerife," *Sustain.*, vol. 7, no. 11, pp. 15152–15178, 2015.

[131] J. Merino, C. Veganzones, J. a. Sanchez, S. Martinez, and C. a. Platero, "Power system stability of a small sized isolated network supplied by a combined wind-pumped storage generation system: A case study in the canary islands," *Energies*, vol. 5, no. 7, pp. 2351–2369, 2012.

[132] S. Padrón, J. F. Medina, and a. Rodríguez, "Analysis of a pumped storage system to increase the penetration level of renewable energy in isolated power systems. Gran Canaria: A case study," *Energy*, vol. 36, no. 12, pp. 6753–6762, 2011.

[133] C. Bueno and J. a. Carta, "Technical-economic analysis of wind-powered pumped hydrostorage systems. Part II: Model application to the island of El Hierro," *Sol. Energy*, vol. 78, no. 3, pp. 396–405, 2005.

[134] J. Schallenberg-Rodriguez, "Photovoltaic techno-economical potential on roofs in the Canary Islands," *J. Sustain. Dev. Energy, Water Environ. Syst.*, vol. 2, no. 1, pp. 68–87, 2014.

[135] "Demanda canaria en tiempo real | Red Eléctrica de España." [Online]. Available: http://www.ree.es/es/actividades/sistema-electrico-canario/demanda-de-energia-en-tiempo-real. [Accessed: 01-Jun-2018].

[136] Gobierno de España. Ministerio de Industria Energía y Turismo, "Real Decreto 738/2015, de 31 de julio, por el que se regula la actividad de producción de energía eléctrica y el procedimiento de despacho en los sistemas eléctricos de los territorios no peninsulares.," *Boletín Of. del Estado*, vol. 183, no. Sec. I, pp. 66752–66903, 2015.

[137] M. Ortiz, "Estudio Exploratorio del Potencial de Generación de Energía E ólic a y Fotovoltaica en el Distrito Metropolitano de Quito," pp. 19–24, 2014.

[138] "ECONOMIC ASSESSMENT OF PROVIDING PRIMARY RESERVE SERVICE WITH ENERGY STORAGE SYSTEMS IN ISOLATED SYSTEMS E . Lobato , L . Rouco and L . Sigrist SPAIN M . Cruz , P . Fontela , J . Magriñá and E . Moreda," 2012.

[139] "Renewables.ninja." [Online]. Available: https://www.renewables.ninja/. [Accessed: 03-Sep-2018].

[140] A. Sciacovelli, D. Smith, H. Navarro, Y. Li, and Y. Ding, "Liquid air energy storage – Operation and performance of the first pilot plant in the world," *Ecos 2016*, no. June, 2016.

[141] ENEL, "Feasibility Study: Liquid Air Energy Storage – Technical integration and market analysis," 2016.

[142] P. Tsamaslis, G. Karagiorgis, and A. Katsanevakis, "Hybridization of

photovoltaics with pumped storage hydroelectricity . An approach to increase RES penetration and achieve grid benefits . Application in the island of Cyprus," vol. 4, no. 97, pp. 336–341, 2017.

[143] G. Frydrychowicz-Jastrzębska, "El Hierro renewable energy hybrid system: A tough compromise," *Energies*, vol. 11, no. 10, 2018.

[144] G. Caralis, K. Rados, and A. Zervos, "On the market of wind with hydro-pumped storage systems in autonomous Greek islands," *Renew. Sustain. Energy Rev.*, vol. 14, no. 8, pp. 2221–2226, 2010.

[145] G. Notton, D. Mistrushi, L. Stoyanov, and P. Berberi, "Operation of a photovoltaic-wind plant with a hydro pumping-storage for electricity peak-shaving in an island context," *Sol. Energy*, vol. 157, pp. 20–34, 2017.

[146] T. Ma, H. Yang, L. Lu, and J. Peng, "Technical feasibility study on a standalone hybrid solar-wind system with pumped hydro storage for a remote island in Hong Kong," *Renew. Energy*, vol. 69, pp. 7–15, 2014.

[147] International Electrotechnical Commission IEC, "Electrical Energy Storage," 2012.

[148] National Grid Electricity Transmission, "Electricity Ten Year Statement," 2017.

[149] G. Luo, Y. Li, W. Tang, and X. Wei, "Wind curtailment of China′s wind power operation: Evolution, causes and solutions," *Renew. Sustain. Energy Rev.*, vol. 53, no. 2, pp. 1190–1201, 2016.

[150] F. Böing, "Reliving the German Transmission Grid with Regulated Wind Power Development," pp. 1–15.

[151] R. Miranda, R. Soria, R. Schaeffer, A. Szklo, and L. Saporta, “Contributions to the analysis of ‘Integrating large scale wind power into the electricity grid in the Northeast of Brazil’ [Energy 100 (2016) 401–415],” *Energy*, vol. 118, pp. 1198–1209, 2017.

[152] P. De Jong, A. Kiperstok, A. Santos S Anchez, R. Dargaville, and A. Torres, “Integrating large scale wind power into the electricity grid in the Northeast of Brazil,” *Energy*, vol. 100, pp. 401–415, 2016.

[153] BEIS, “Dukes 2017,” *Dig. UK Energy Stat.*, pp. 111–151, 2017.

[154] E. and I. S. Digest of UK Energy Statistics (DUKES), Department of Business, “Chapter 5 Electricity,” 2018.

[155] “Longannet Closure marks end of Coal-Fired Generation - ScottishPower.” [Online]. Available: https://www.scottishpower.com/news/pages/longannet_closure_marks_the_end_of_coal_fired_electricity_generation_in_scotland.aspx. [Accessed: 05-Jun-2018].

[156] E. and I. S. Digest of UK Energy Statistics (DUKES), Department of Business, “Total generation by country (all generating companies) 2013-2016,” 2017.

[157] The Scottish Government, “Energy in Scotland 2016,” 2017.

[158] “Scottish Energy Strategy: The future of energy in Scotland,” 2017.

[159] DUKES, “Digest of UK Energy Statistics (DUKES): renewable sources of energy,” *Dig. United Kingdom Stat.*, pp. 153–191, 2017.

[160] “Electricity Data Summary | BMRS.” [Online]. Available:

https://www.bmreports.com/bmrs/?q=eds/main. [Accessed: 06-Jun-2018].

[161] The Scottish Government, “Energy in Scotland 2017,” 2017.

[162] The Scottish Government, “Scottish House Condition Survey - Energy Use in the Home, Measuring & Analysing Domestic Energy Use & Energy Efficiency in Scotland,” p. 105, 2012.

[163] “SUB-NATIONAL ELECTRICITY AND GAS CONSUMPTION STATISTICS Regional and Local Authority,” 2018.

[164] Ofgem, “Insights paper on households with electric and other non-gas heating.”

[165] I. A. G. Wilson, A. J. R. Rennie, Y. Ding, P. C. Eames, P. J. Hall, and N. J. Kelly, “Historical daily gas and electrical energy flows through Great Britain’s transmission networks and the decarbonisation of domestic heat,” *Energy Policy*, vol. 61, pp. 301–305, 2013.

[166] I. A. Grant Wilson, “Energy Data Visualization Requires Additional Approaches to Continue to be Relevant in a World with Greater Low-Carbon Generation,” *Front. Energy Res.*, vol. 4, no. August, pp. 1–10, 2016.

[167] E. & I. S. Department of Business, “Energy Consumption in the UK,” 2018.

[168] National Grid Electricity Transmission, “February 2017 Monthly Balancing Services Summary,” no. February, 2017.

[169] National Grid, “Monthly Balancing Services Summary 2018/2018, December 2017,” 2017.

[170] T. Kane, S. Firth, D. Allinson, K. Irvine, and K. Lomas, “Understanding occupant

heating practices in UK dwellings," *World Renew. Energy Congr. 2011*, no. May, pp. 8–11, 2011.

[171] R. A. Buswell, D. Marini, L. H. Webb, and M. Thomson, "Determining Heat Use in Residential Buildings Using High Resolution Gas and Domestic Hot Water Monitoring," *Unknown*, 2013.

[172] N. Kelly, P. Tuohy, and M. Thomson, "Future Energy Demand in the Domestic Sector," no. October, p. 33, 2012.

[173] I. Knight, N. Kreutzer, M. Manning, M. Swinton, and H. Ribberink, "European and Canadian non-HVAC electric and DHW load profiles for use in simulating the performance of residential cogeneration systems," *Energy Conserv. Build. community Syst. Program. IEA Annex 42*, vol. 6, p. 84, 2007.

[174] Energy Exemplar, "PLEXOS Wiki | Article / Gas Modelling." [Online]. Available: https://wiki.energyexemplar.com/index.php?n=Article.GasModelling?action=print. [Accessed: 13-Mar-2019].

[175] Energy Exemplar, "Generator Resources Modelling - CHP & Distric Heating," 2013.

[176] "Electricity interconnectors | Ofgem." [Online]. Available: https://www.ofgem.gov.uk/electricity/transmission-networks/electricity-interconnectors. [Accessed: 14-Jun-2018].

[177] "House of Lords - The Resilience of the Electricity System - Science and Technology Committee." [Online]. Available: https://publications.parliament.uk/pa/ld201415/ldselect/ldsctech/121/12109.htm

. [Accessed: 14-Jun-2018].

[178] "Ch 26 Page 191: Sustainable Energy - without the hot air | David MacKay." [Online]. Available: https://www.withouthotair.com/c26/page_191.shtml. [Accessed: 14-Jun-2018].

[179] Department of Energy, "Electric Resistance Heating." [Online]. Available: https://www.energy.gov/energysaver/home-heating-systems/electric-resistance-heating. [Accessed: 03-Mar-2019].

[180] "Home - Committee on Climate Change." [Online]. Available: https://www.theccc.org.uk/. [Accessed: 20-Aug-2018].

[181] M. Chaudry, M. Abeysekera, S. H. R. Hosseini, N. Jenkins, and J. Wu, "Uncertainties in decarbonising heat in the UK," *Energy Policy*, vol. 87, pp. 623–640, 2015.

[182] ENSG, "Our Electricity Transmission Network: A Vision for 2020," no. February 2012, p. 148, 2012.

[183] O. Odgaard and S. Advisor, "District Heating in Denmark-2 questions and 5 answers on how to promote cost-effective DH nationwide," 2016.

[184] M. Harris, P. Peck, and M. Backman, "Thermal Energy Storage in Sweden and Denmark Potentials for Technology Transfer," 2011.

[185] "Scotland Heat Mapping." [Online]. Available: http://heatmap.scotland.gov.uk/. [Accessed: 24-Aug-2018].

[186] "Scottish Government - Heat." [Online]. Available: https://www.gov.scot/Topics/Business-Industry/Energy/Energy-

sources/19185/Heat. [Accessed: 24-Aug-2018].

[187] QUANTUM Heating System, “Introducing the Quantum heating system - The heater that adapts to its environment,” 2014.

[188] S. J. Darby, “BALANCING THE SYSTEM COMFORTABLY? ELECTRIC STORAGE HEATING AND RESIDENTIAL DEMAND RESPONSE.”

[189] E. & I. S. Department of Business, “Digest of United Kingdom Energy Statistics,” 2016.

[190] BEIS, Ofgem, and National Grid, “Policy Analysis-Energy Storage in UK,” 2017.

[191] “Real Time British Electricity Fuel Mix.” [Online]. Available: http://electricityinfo.org/real-time-british-electricity-supply/. [Accessed: 25-Aug-2018].

[192] K. MacLean, R. Sansom, T. Watson, and R. Gross, “Managing Heat System Decarbonisation Comparing the impacts and costs of transitions in heat infrastructure,” no. Final Report – Annexes and literature review, p. 42, 2016.

[193] S. J. Darby, “Smart electric storage heating and potential for residential demand response,” *Energy Effic.*, vol. 11, no. 1, pp. 67–77, 2018.

[194] Ofgem, “Insights paper on households with electric and other non-gas heating,” no. December, pp. 1–84, 2015.

[195] X. Wang, J. Liu, Y. Zhang, H. Di, and Y. Jiang, “Experimental research on a kind of novel high temperature phase change storage heater,” *Energy Convers. Manag.*, vol. 47, no. 15–16, pp. 2211–2222, 2006.

[196] M. Farid and R. Husian, “An electrical storage heater using phase change method of heat storage,” *Energy Convers. Manag.*, vol. 30, no. 30, pp. 219–230, 1990.

[197] K. Zhang, B. Han, and X. Yu, “Electrically conductive carbon nanofiber/paraffin wax composites for electric thermal storage,” *Energy Convers. Manag.*, vol. 64, pp. 62–67, 2012.

[198] W. A. Qureshi, N. K. C. Nair, and M. M. Farid, “Impact of energy storage in buildings on electricity demand side management,” *Energy Convers. Manag.*, vol. 52, no. 5, pp. 2110–2120, 2011.

[199] J. Ward and S. Darcy, “The household electricity demand-side and participation in the GB electricity markets,” no. July, p. 161, 2014.

[200] L. Hughes, “Meeting residential space heating demand with wind-generated electricity,” *Renew. Energy*, vol. 35, no. 8, pp. 1765–1772, 2010.

[201] “RealValue Project Horizon 2020.” [Online]. Available: http://www.realvalueproject.com/. [Accessed: 02-Jul-2018].

[202] “Periodic Reporting for period 1 - RealValue (Realising Value from Electricity Markets with Local Smart Electric Thermal Storage Technology) | Report Summary | RealValue | H2020 | CORDIS | European Commission.” [Online]. Available: https://cordis.europa.eu/result/rcn/198181_en.html. [Accessed: 02-Jul-2018].

[203] R. Mccappin, “HORIZON 2020 CALL FOR COMPETITIVE LOW CARBON ENERGY REALISING VALUE FROM ELECTRICITY MARKETS WITH LOCAL

SMART ELECTRIC THERMAL STORAGE TECHNOLOGY," 2015.

[204] "Northern Isles New Energy Solutions project." [Online]. Available: http://news.ssen.co.uk/news/all-articles/2017/06/northern-isles-new-energy-solutions-project/. [Accessed: 02-Jul-2018].

[205] J. Clarke, J. Hand, J.-M. Kim, A. Samuel, and K. Svehla, "Electricity storage within the domestic sector as a means to enable renewable energy integration within existing electricity networks," *Proc. BS 2013 13th Conf. Int. Build. Perform. Simul. Assoc.*, pp. 2733–2740, 2013.

[206] M. Iustinian and M. Andreea, "The Modeling of the Heating Resistors in Transient Regime," no. 4, pp. 201–206, 2010.

[207] National Grid Electricity Transmission, "Future Energy Scenarios System Operator," 2018.

[208] Siemens Gamesa Renewable Energy, "Introducing Electric Thermal Energy Storage (ETES)-putting gigawatt hours of energy at your command," 2018.

[209] THEMA Consulting Group, A. Von Schemde, B. Tennbakk, G. Gravdehaug, and R. Grøndahl, "Loop flows-Final advice Prepared for The European Commission," 2013.