Department of Mechanical and Aerospace Engineering

Dispatchability of Renewable Energy Systems through an Electrical Energy Storage System to supply a non-residential demand connected to a Microgrid

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Abstract

The increasing use of Renewable Energy Systems (RES) with its intermittent nature due to the weather conditions has boosted substantially the development of energy storage technologies. Accordingly, this project aims to size appropriately an Electrical Energy Storage System (EESS) for two different applications through the implementation of two replicable algorithms created in MatLab software into a model study case: The first one is for dimensioning an EESS relying on the load shifting application with energy market prices constraint and the second one for maximising the RES penetration.

The algorithms aid to assess the minimum EESS to cover a diversified non-residential load in an island located in the western Scotland named Islay, as the study case. The location has the potential for RES generation, which it was produced by MERIT software with Wind Turbine (WT) and Photovoltaic (PV) panels' arrangement. The demand side was created by 2 distilleries and an office building in Islay. Furthermore, the model was validated by HOMER, where the demand data and energy market prices were loaded. The energy market prices 2016 were taken from (Nord pool AB et al., n.d.). All the data were analysed by hourly slots and it was considered the daily energy management and the EESS State of Charge (SOC) for dimensioning a suitable EESS by the worst day scenario throughout the year. Parameters such as energy price reference and the initial EESS size were changed sequentially as main parameters to do the simulations and obtaining the diverse results. The outcomes were gathered by tables and it was calculated RES penetration rate, the yearly energy rate managed by EESS, saving and payback time in each run.

The energy system performance was depicted in both simulations, where it was quite interesting to see EESS operation in each application. Clearly, both algorithms demonstrate that are applicable to dimensioning small and medium EESS. The best result during the first application was an EESS (130KWh, 20KW), which just it was involved 6% of the total energy managed through the year, and while in the second code the EESS (6400KWh, 300KW) was over 67%. Consequently, RES penetration is greater in the second case. Moreover, EESS is still an expensive solution (minimum payback achieved around 34 years). However, exhaustive benefits are discussed.

Acknowledgements

It has been an intensive and exciting experience at the University of Strathclyde, where I have laid the foundation and learned the novel tendencies related to the sustainable energy sector.

Regarding the dissertation project, I would like to thank my supervisor Dr Nicolas Kelly for his support.

In addition, I am very grateful to all MAE Staff for their guidance and support throughout the year.

This achievement would not have been possible without them.

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List of Abbreviations

BES: Battery Energy Storage.

DOD: Depth of discharge in the battery.

EESS: Electrical Energy Storage Systems.

EESS_nom: EESS used as a parameter in MatLab to evaluate the BES SOC.

ESS: Energy Storage Systems.

FBES: Flow battery energy system.

GBP: Great Britain Pound.

GWh: Gigawatts-hour.

HESS: Hybrid Energy Storage Systems.

KW: Kilowatts.

KWh: Kilowatts-hour.

LDC: Load Duration Curve.

MAE: Mechanical and Aerospace Engineering Department of the University of Strathclyde.

MG: Main grid.

MW: Megawatts.

MWh: Megawatts-hour.

NPV: Net Present Value.

PV: Photovoltaic solar panels system.

Pnet: Net power. It is the numerical difference between the RES supply and demand.

RES: Renewable Energy Systems.

RESE: Sustainable Engineering: Renewable Energy Systems and Environment.

SOC: State of Charge of the battery.

TOU: Time of use.

WT: Wind turbine system.

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1. Introduction

Despite the fact that international agreements have been established to confront the climate change and achieving the target of reducing CO_2 emissions and other pollutants, the worldwide energy consumption has increased exponentially over the last decades. As a promise solution, the growing use of RES as clean energy generation has been progressing with diminishing reliance on fossil fuels. Thus, the developing and implementation of concepts such as Microgrid and consequently Smartgrid are now a reality.

A Microgrid is at small scale a smart and dynamic electrical power system that incorporates generation, transmission, and distribution, with a good performance in power balance and optimal energy allocation of the power supply such as RES and loads for instance as industrial, commercial, educational and residential buildings, which is commonly called 'the electrical demand' in the distribution network. The benefits and reliability of RES depend on the weather conditions, which is characterised to be stochastic or intermittent in its nature, especially with the actual climate change.

In order to ensure power network stability and reliability, and to overcome the uncertainty drawbacks to the demand, a wide range of EESS technologies and control energy systems have been developing, meantime it is contributing to pollutant emission reduction.

1.1. Background

There are a considerable number of articles which have been released with details about the contribution of novel EESS into Microgrids. Undoubtedly, EESS has been recognised from researchers as one of the most promising approaches. Moreover, there are several energy storage topologies that adequate its use for one or more purposes and more in researching has been emerging.

As it would be expected, some forecast has been created to measure the energy market expectation. As an example, (Kairies, 2017) shows an economic estimation of the electrical energy storage technologies as a part of the analysis market price by 2030 compared to prices nowadays. At the first glance, Figure 1 displays that EESS will be more affordable in the near future, it means that the penetration of those technologies will increase substantially and through new other daily applications.

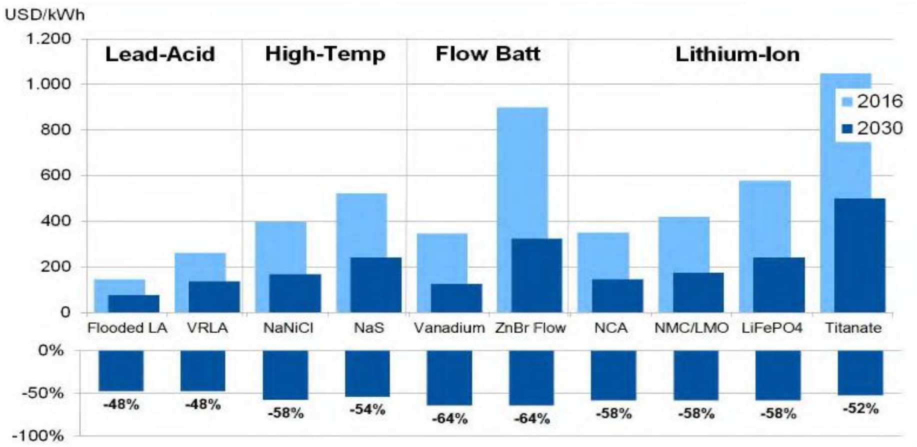


Figure 1: Cost development of different storage technologies (Kairies, 2017)

Dimensioning an EESS involves economic constraints and operational challenges. Oversizing it increases the capital cost to the total system, whereas undersized the EESS capacity can carry dispatchability problems to cover the energy demand.

Storage systems have been used for multiple purposes. One of them is to increase or manage the availability of RES when the primary resource is not accessible for multiple reasons. Accordingly, the author proposes an algorithm for dimensioning the minimum EESS from two diverse applications related to RES: The first one from the demand side, where is constraining the hourly peak cost and is increased the RES penetration to the electrical load. The second one, from the supply side, related to just maximise the RES penetration to the electrical load. Furthermore, an electrical energy system scenario is created to assess the algorithms capabilities.

Nowadays, some of the software programmes that are mentioned in Table 1: Software Appraisal for Dissertation has been developed to simulate the optimal techno-economical EESS appraisal through the traditional optimization methods. However, these software programmes have some limitations to apply the load shifting concept. In this scenario, creating an open code without restrictions allow obtaining more substantial results for this piece of research.

On the other hand, regarding the structure of this Thesis, the author shows how the chapters are related to each other as it is seen in Figure 2, also the content refers to the topics which are going to be discussed in each chapter.

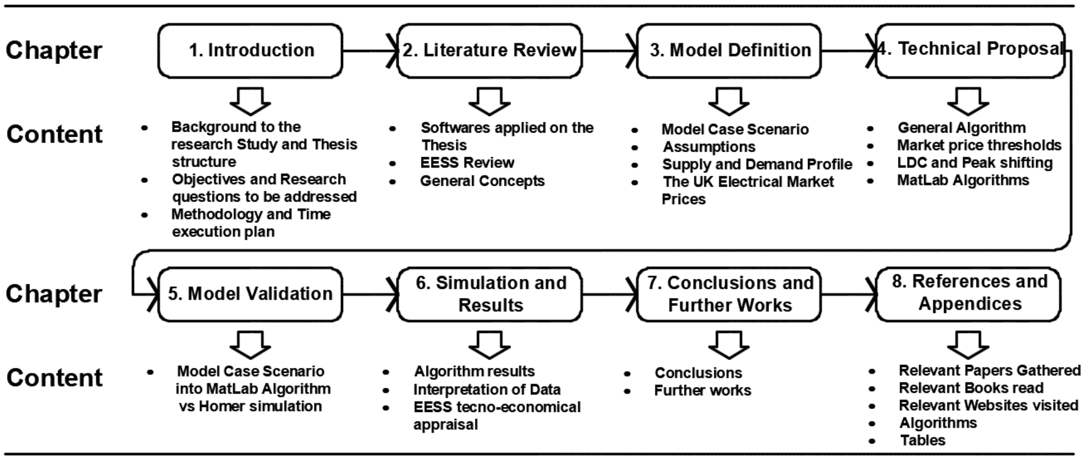


Figure 2: Thesis Road Map

Subsequently, the purpose of this project is outlined as follow:

1.2. Aim

The dissertation project aims to obtain two algorithms developed for dimensioning the minimum EESS required considering two diverse application: the load shifting application (demand side) constrained by the hourly peak cost, and the maximisation of RES penetration (supply side) to the electrical load.

1.3. Objectives

As a part of the contribution, it is intended to create and apply an electrical energy management decision process by hourly slots for a year period, where the energy market price and the existing electrical consumption conditions change continuously by hours, in order to meet the minimum electrical energy storage requirement and consequently, supplying effectively the electrical energy to the loads.

The main objectives are emphasised as follow:

- Proposing a power management general algorithm used for sizing through a MatLab code an EESS from the demand and supply side.
- Quantifying the RES penetration through the EESS calculated for each application and measuring the EESS contribution to the electrical load.
- Assessing the feasibility of the results obtained from the simulation.
- Elaborating an EESS techno-economical appraisal to validate the technical characteristics used as parameters into the MatLab code, the NPV and payback time to be calculated.

On the other hand, the questions to be addressed through the code construction process are:

- In order to capture the greatest amount of energy supplied by RES to cover the electricity demand: How to size the minimum EESS required and diminishing the grid supply?
- What are the variables and constraints to take into consideration to choose the most appropriate EESS size?
- Which selection criteria could be applied in order to choose the most appropriate EESS to reduce the higher energy cost from the demand side?

Successively, the overall thesis approach is given below:

1.4. Overview

In chapter 2 is given the Literature Review content in the thesis, with the aim to clarify any concept related with the knowledge reflected in the entire document. It is seen briefly the software evaluated to develop the dissertation project, the electrical energy storage review and general concepts applied in the technical proposal.

Chapter 3, called Model (Study case), describes the study case, where is explained integrally each part of the scenario assessed. It is outlined the assumptions considered for the problem addressed. It is displayed the demand profile, the supply profile, and the UK electrical market prices involved into the main scenario.

Chapter 4, Model (Algorithms), is the technical proposal for each application to be developed, where the general algorithm is shown and described by steps. Even more, the operational selectivity process of the MatLab code is detailed graphically by an event tree, and the energy market price as a parameter is justified graphically by an energy price duration curve. The LDC is used to illustrate the EESS nominal power as another parameter with its limits criteria, to apply the load shifting concept in the first algorithm proposed. The MatLab algorithms are displayed as a logic flow diagram for each application aforementioned and explained by steps.

After the explanation, the code was created into MatLab and tested several times. Firstly, it was run each code step by step, after the trial was successful, it was applied to the study case Islay by one month period in four different episodes through the year, and the results were graphically observed and logically confirmed with the flow diagram. The MatLab coding is printed in the Appendixes section.

Chapter 5, is the Model Validation, where is displayed the results obtained after coding the algorithms developed in chapter 4, with the entire data shown in chapter 3 and run it into MatLab software vs HOMER simulation, with the demand profile loaded and creating a previous similar RES model to compare both results.

Chapter 6, is the Simulation Results stage, where the MatLab simulation was done, and the outcomes from both codings were gathered by Excel tables. These tables are printed in the Appendixes section. From this tables are created the graphs shown and the final energy system performance achieved by both codings, which is plotted directly from MatLab software.

Chapter 7, is the Conclusions and Recommendations stage, where the general and particular discussion are addressed and suggestions for further works are given. Consecutively, the overall methodology is explained below:

1.5. Methodology

Due to the nature of this Thesis, the development of the total strategy for carrying out the scientific investigation, suggests a type of quantitative research, with an undoubtedly inductive evaluation and explanatory purposes (Dresh et al., 2015).
In order to address the aforementioned objectives and achieve the desired results in the previous section, an appropriate methodology was established in order to define the necessary stages and limits of this thesis.

The applied methodology was formulated graphically by phases in Figure 3 and it is subsequently explained. The effective application of this project management process allowed the author to develop the dissertation work smoothly.

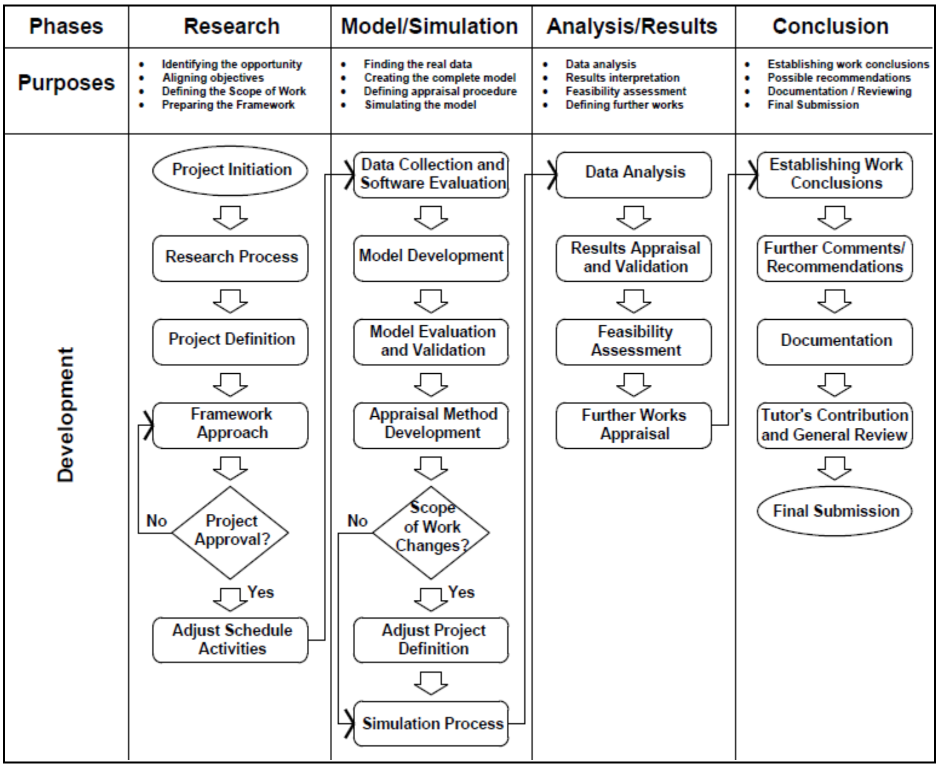


Figure 3: Methodology Process

As an overview, each phase shown in Figure 3 is briefly described as follow:

Researching phase

The dissertation project starts with the identification of the study theme into the wide range of technical papers developed in the international investigation field. Once the topic is chosen, the research process allows recognising the study gap where it would be developed the author's investigation. Consequently, the project definition is created and the author's technical contribution framework is obtained.

Model/Simulation phase

After the project is approved by the MAE Direction of the Master in RESE, specialised software in the field is evaluated regarding the project definition. Meantime, the real data is acquired from different resources and collated conveniently to model the scenario which would be the study case to be analysed deeply through the simulation process. Appropriately, while the technical proposal is created through an algorithm, it is possible to recognise that it is needed to change the scope of work due to any reason. Some examples would be such as the study gap decided during the last phase might be inadequate, or the time for learning a new programme package is scarce, or the model scenario could not be fully obtained with the data collected, or other no exclusive. Thus, if the scope of work needs to be changed, the project definition is customised and consequently, the simulation process can be initiated. The simulation process has been defined in this document as the code routines programme execution established to determine the results of the dissertation project.

Analysis/Results

After modelling, validation and simulation process, the data obtained in each test case is analysed and validated. The aim to achieve a suitable solution is acquired through the analysis and compared to the given results. At this stage, conveniently can be identified further works for the topic investigated which are achievable to obtain a deeper understanding.

Conclusion

Finally, the author's position or opinion reached after the analysis and results stage is written. The general and particular results, the suggested further works and recommendations are taken into consideration to extend the research contribution.

Once the document is written completely, it is sent to the supervisor with the main purpose to be reviewed and opportunely it is received with the correspondent feedback. Consistently, the improvement is completed and the final submission was done.

Timetable Proposed

The main activities related to the methodological process explained before and illustrated in Figure 3 were taken into consideration to propose a general Gantt chart which is illustrated in Figure 4. The timetable guides the author to reach the aforementioned objectives.

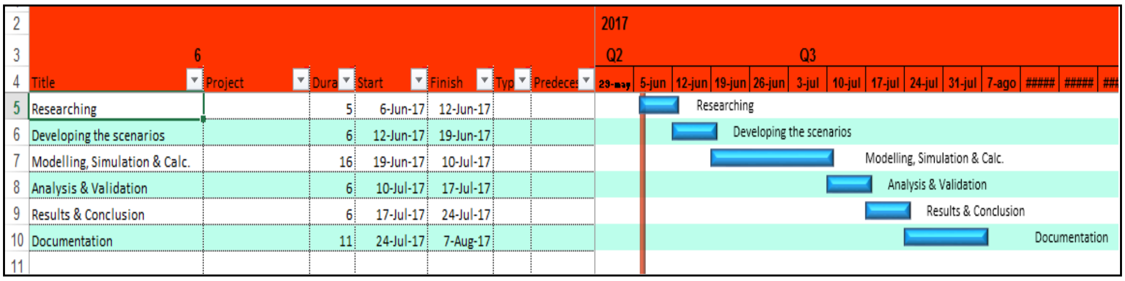


Figure 4: Dissertation Timetable

2. Literature Review

This section clarifies the concepts related with the knowledge reflected in the entire document. It is seen briefly the applicability, some observations and the author's decision on the suitability of each software evaluated to develop the dissertation project. It is conceded the electrical energy storage review, where is identified, selected and explained each storage technology relying on its functionality into the main grid. Lastly, general concepts applied in the technical proposal are elucidated.

2.1. Software assessment

A few software programmes were used to develop the dissertation project. However, in Table 1: Software Appraisal for Dissertation it will be roughly described and compared those which were considered suitable at the beginning of the research and it will be seen that little changes were done through the process due to the software restrictions or functionalities.

Software	Applicability	Observation	Author's Decision
EnergyPlan	Simulating the national or regional energy systems, including heating, power, industry and transportation (Aalborg University, n.d.)	It is required the possibility to analyse systems at smaller scale, rather than the global integration of RES.	No suitable for the analysis required.
EnergyPro	Simulating both, techno-economic and diverse of heating and cooling process plants. Mixing fossil fuels and renewable energy system technologies (International, 2017)	It is more suitable for a project such as tri-generation plant, rather than demand energy consumption and RES dispatchability analysis.	No attractive for the analysis required.
HOMER	Evaluating, optimizing the technical and economic performance of small systems for	Attractive software for Microgrids. However, the load shifting module is	It was taken into consideration to validate the modelling data

	electrical and thermal loads (Homerenergy, n.d.)	missing and it is not possible working with energy market prices as a variable or parameter.	and the MatLab algorithm results with the model proposed.
MERIT	Evaluating technical performance of small systems for electrical, thermal, and water loads (Strathclyde, n.d.)	Attractive software for Renewables. However, it has restrictions regarding RES models, storage alternatives and economic analysis.	It was taken to create the Islay demand and supply profile to export to Excel software.
MATLAB	Powerful software used as a tool for simulation and optimisation of suited systems (MathWorks, n.d.)	Ideal software for simulations, creating algorithms and optimising linear and nonlinear solutions.	It was taken for creating the algorithm. Other option for coding: Mathcad.
ES-Select	Software used for selecting EESS, considering technical and economic constraints (DNV-KEMA, n.d.)	Attractive and easy software for measuring feasibility on energy storages by cost and also technologically. Useful to compare the potential of EESS dimensioned.	It was taken as a reliable market reference to facilitate the technological EESS options, including cost analysis and actual feasibility.
AutoCAD	Powerful software for drawing in 2D, 3D, create renders, and other. See (AutoDesk, n.d.)	Ideal software to create schematics adapted to the Author's necessity.	It was taken to create schematics through the entire document.

Table 1: Software Appraisal for Dissertation

2.2. Electrical Energy Storage for Grids

There are plenty of information globally related to electrical energy storage. However, the significant characteristics will be mentioned to review the basic theories according to with the dissertation project. Sizing the EESS also involves the Microgrid bus efficiency, the inverter efficiency and BES technology efficiency, in order to assure the demand requirement. For example, if the Microgrid has an efficiency of 0.90, the inverter 0.95, and the BES technology is 0.80, then the EESS should be dimensioned considering all values: 0.90x0.95x0.80=0.68 as a divisor of the final power and energy (capacity) estimated.

Classification of EESS

As it is shown in the literature, EESS can be classified according to the Microgrid needs, according to the supply time, according to the storage purpose, according to the storage position in the Grid and service offers, and other. Thus, agreeing with (Uwe Sauer, 2015), the same technology might be categorised in different positions.

Regarding EESS types and technologies involved, Figure 5 offers a good and easy understanding about the physical options of stored energy nowadays.

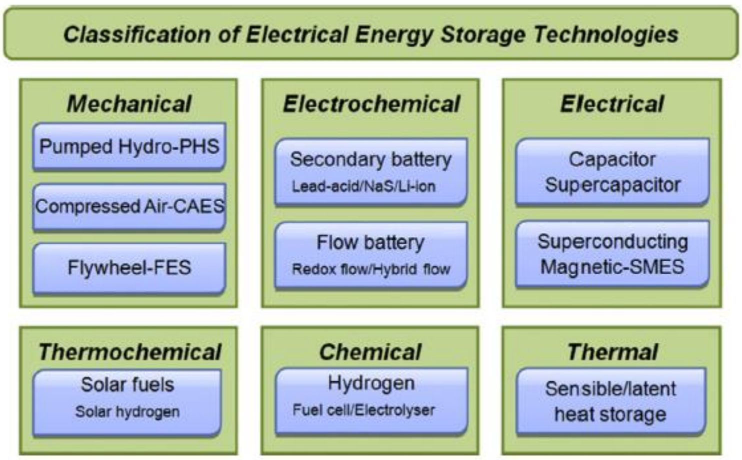


Figure 5: Classification of EESS by the form of stored energy (Luo et al., 2015)

On the other hand, the technologies aforementioned could be located in one or more places on the Grid as it is displayed in Figure 6, where basically, the electrical system is divided into five main groups. For this particular study, is relevant to know the model scenario position in the grid, which is represented by a red colour square. Accordingly, the EESS is supporting a Microgrid for non-residential loads.

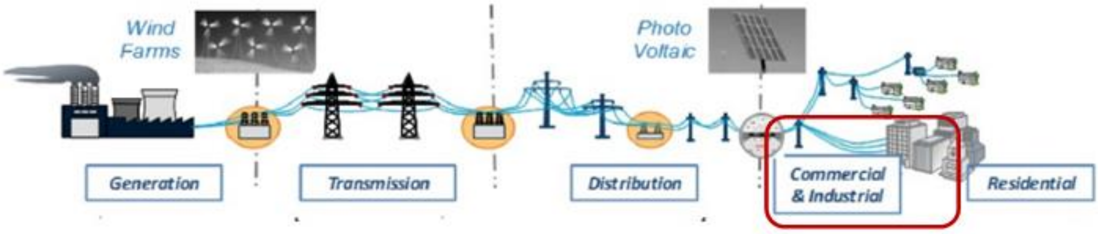


Figure 6: Possible locations for Grid-Connected EESS (KEMA, 2012)

Uwe Sauer (2015) explains logically and by operational reasons, how the diverse EESS technological options might be distributed at different levels on the Grid including the RES penetration (especially WT and PV). Thus, *Figure 7* illustrates the EESS options at different Grid levels.

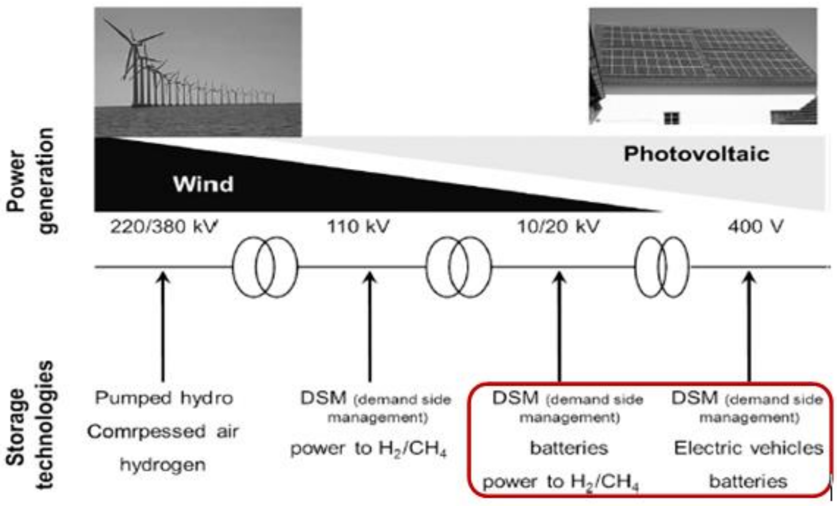


Figure 7: Feeding points for PV / WT Generation and different EESS and flexibility options at different Grid levels (Uwe Sauer, 2015)

Moreover, considering the study case location seen by the red colour square in *Figure 6*, it is easy to draw the red colour square in *Figure 7* to allocate the general technological alternatives on the Grid to be used in this Thesis.

Considering the EESS application, the energy storage options are functionally distinguished by its frequency of use and its charge and discharge performance.

Hence, *Figure 8* displays the main applications by sectors concerning both characteristics.

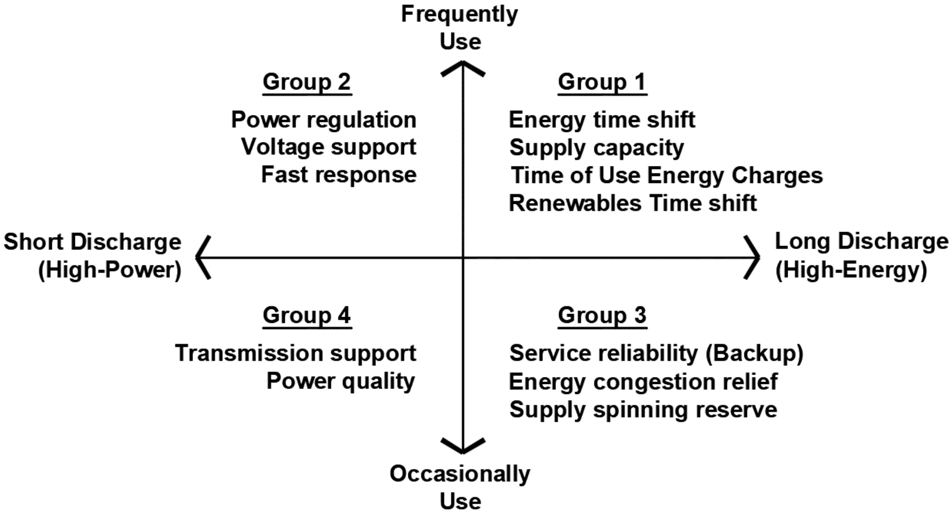


Figure 8: Four Groups of Grid Applications for EESS (KEMA, 2012)

It is clearly seen in *Figure 8* that the EESS applications in this project are categorised in group 1. Thus, it is possible to classify the suitability of EESS technologies relying on its performance and physical characteristics as it is structured in *Figure 9*. Moreover, following the selection procedure applied before for the study case developed in this Thesis, it is possible to precise even more the EESS options market in the red colour square.

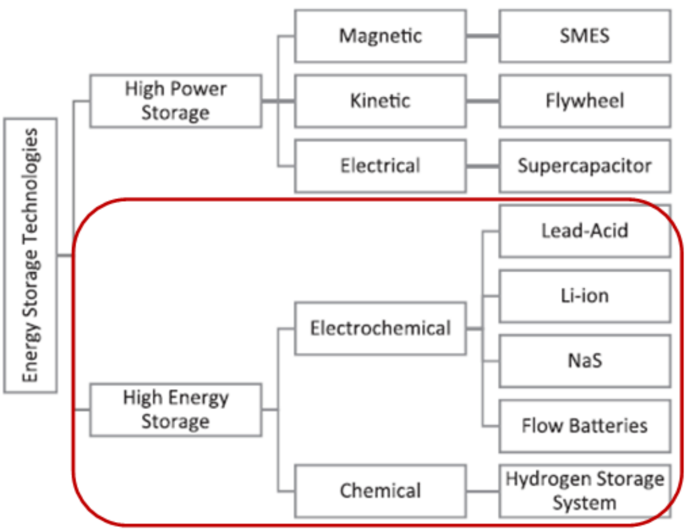


Figure 9: Classification of EESS by its suitability and form of storage (Wai Chong et al., 2016)

Overview of current High Energy Storage applied on Microgrids

After narrowing the storage options to be used in the study scenario from the wide range of energy storage market solutions, it will be described briefly each EESS technology shown into the red colour square in *Figure 9*. A deeper understanding is available in the reference cited in the text.

Electrochemical Energy Storage (Battery Energy Storage)

Figure 10 shows the simplified operational principle of a typical rechargeable battery energy storage (BES) system. "A BES system consists of a number of electrochemical cells connected in series or parallel, which produce electricity with a desired voltage from an electrochemical reaction. Each cell contains two electrodes (one anode and one cathode) with an electrolyte which can be a solid, liquid or ropy/viscose states. A cell can bi-directionally convert energy between electrical and chemical energy.

During discharging, the electrochemical reactions occur at the anodes and the cathodes simultaneously. To the external circuit, electrons are provided from the anodes and are collected at the cathodes. During charging, the reverse reactions happen and the battery is recharged by applying an external voltage to the two electrodes" (*Luo et al., 2015).*

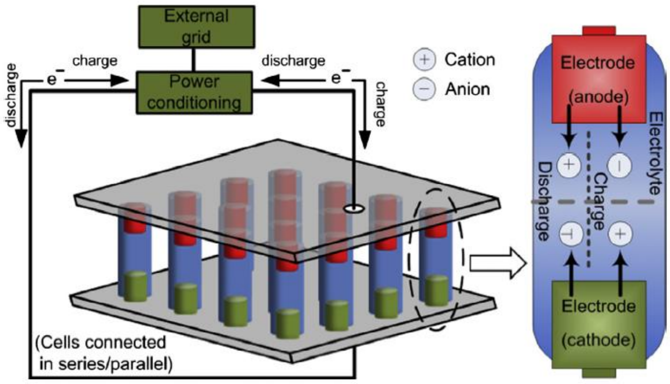


Figure 10: Schematic diagram of a battery energy storage system operation (Luo et al., 2015)

Depends on the chemical reaction in each cell connected, the voltage unit is different. *Figure 11* illustrates the chemical reaction and the voltage unit cell produced in each type of BES. Through unit voltage, cells can be connected in series or parallel to obtain the design voltage, in order to adapt the battery arrangement to the electrical system which would be interconnected.

Battery type	Chemical reactions at anodes and cathodes	Unit voltage
Lead–acid	$Pb + SO_4^{2-} \Longleftrightarrow PbSO_4 + 2e^-$	2.0 V
	$PbO_2 + SO_4^{2-} + 4H^+ + 2e^- \Longleftrightarrow PbSO_4 + 2H_2O$	
Lithium-ion	$C + nLi^+ + ne^- \Longleftrightarrow Li_nC$	3.7 V
	$LiXXO_2 \Longleftrightarrow Li_{1-n}XXO_2 + nLi^+ + ne^-$	
Sodium–sulfur	$2Na \Longleftrightarrow 2Na^+ + 2e^-$	~2.08 V
	$\chi S + 2e^- \Longleftrightarrow \chi S^{2-}$	
Nickel–cadmium	$Cd + 2OH^- \Longleftrightarrow Cd(OH)_2 + 2e^-$	1.0–
	$2NiOOH + 2H_2O + 2e^- \Longleftrightarrow 2Ni(OH)_2 + 2OH^-$	1.3 V
Nickel–metal hydride	$H_2O + e^- \Longleftrightarrow 1/2H_2 + OH^-$	1.0–
	$Ni(OH)_2 + OH^- \Longleftrightarrow NiOOH + H_2O + e^-$	1.3 V
Sodium nickel chloride	$2Na \Longleftrightarrow 2Na^+ + 2e^-$	~2.58 V
	$NiCl_2 + 2e^- \Longleftrightarrow Ni + 2Cl^-$	

Figure 11: Chemical reactions and single unit voltages of main BES available nowadays (Luo et al., 2015)

Those chemical reactions allow BES to charge or discharge energy. As a general and idealistic charge/discharge, BES curve is given in *Figure 12*, where MPV (mid-point voltage) is the nominal voltage of the cell during charge or discharge. A "flatter" curve means a reduced amount of voltage variation. "When peak charged, the actual cell voltage will be higher than the MPV. When nearing the EODV (end of discharge voltage) point, the cell voltage will be less than the MPV. The EODV is sometimes referred to as the EOL (end of life) voltage by manufacturers" *(Simpson, 2011)*.

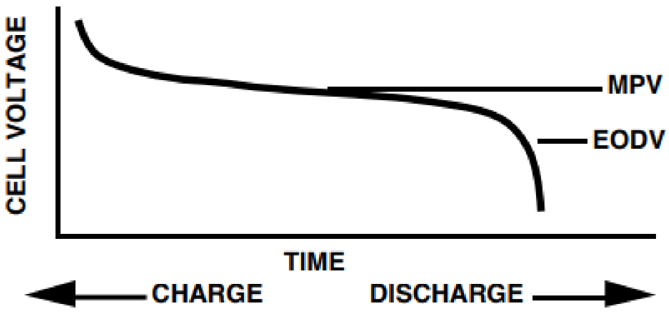


Figure 12: BES typical idealistic charge/discharge curve (Simpson, 2011)

Consequently, an important concept related to batteries is the state of charge (SOC), which is defined as "the ratio of its current capacity ($Q\ (t)$) to the nominal capacity

(Qn). The nominal capacity is given by the manufacturer and represents the maximum amount of charge that can be stored in the battery" (*Chang, 2013)*.

In order to avoid operational problems which can be seen on the reference, some recommendations can be translated into the operating range of the SOC shown in *Figure 13*. The SOC working range will be used to build the algorithm proposed in this dissertation project.

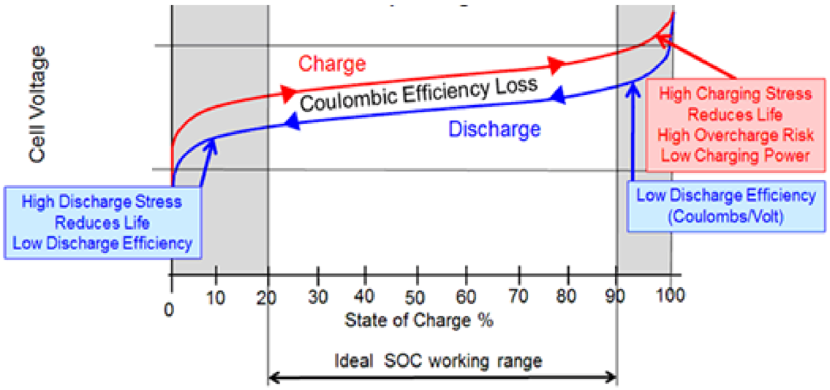


Figure 13: SOC operating window in BES (Woodbank Communications Ltd, 2005)

As it can be illustrated, it is suggested to keep a healthy SOC value between 20% and 90%. Moreover, the charging rate to reach 90% of SOC is greater than the equivalent to complete the extra 10% to achieve 100% of SOC. Thus, the time required for the BES to be ready is less compared to achieve an extra final 10% of SOC.

Similarly, another important concept is the battery depth of discharge (DOD), which is the portion of energy discharged from a BES respective to the amount extractable stored energy (*Akhil, et al., 2013)*. Hence, the maximum DOD determine the available storage capacity.

Conclusively, both concepts SOC and DOD vary with the chemical reaction or battery technology. It means that each technology has its efficiency for charging and discharging energy. The efficiency effect is clearly seen in *Figure 13*, where the charge curve is represented in red colour and the discharge curve is drawn in blue colour, both have different paths. If the efficiency were ideally one, the curves for charging and discharging would be the same. It would be something equivalent to *Figure 12*.

Electrochemical Energy Storage (Flow Battery Energy System)

Another type of electrochemical energy storage system is the flow battery energy system (FBES). FBES "stores in two soluble redox couples contained in external liquid electrolyte tanks. These electrolytes can be pumped from the tanks to the cell stack which consists of two electrolyte flow compartments separated by ion selective membranes" *(Luo et al., 2015)*.

FBES "are classified into the categories of redox flow batteries and hybrid flow batteries, depending on whether all electroactive components can be dissolved in the electrolyte" *(Luo et al., 2015)*. *Figure 14* displays a schematic diagram of a Vanadium Redox FBES.

A relevant benefit of FBES is that the power is independent of its storage capability. Due to its power is determined by the magnitude of the electrodes and the number of cells in the stack; whereas the storage capacity is determined by the concentration and the amount of electrolyte *(Luo et al., 2015)*.

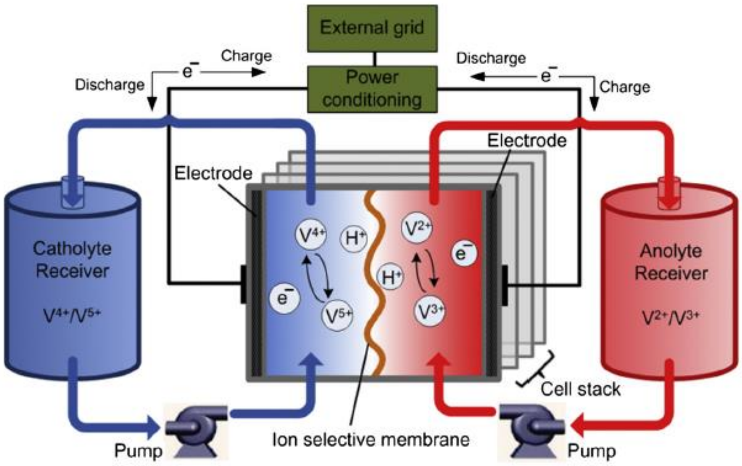


Figure 14: Schematic diagram of a Vanadium Redox FBES (Luo et al., 2015)

Chemical Energy Storage (Solar energy storage)

Solar fuel is a relatively new thermochemical technology at the development stage. The strategy to produce solar fuel includes the natural photosynthesis, the artificial photosynthesis and thermochemical approaches.

For the natural and artificial photosynthesis to produce solar fuels, "solar energy is captured via photosynthesis and then stored in chemical bonds, i.e., the sunlight is used to convert water and/or carbon dioxide into oxygen and other materials" *(Luo et al., 2015). Figure 15* shows a comparison between both, natural and artificial process.

"The artificial system for water-splitting catalysts generally relies on scarce elements, e.g., Ruthenium (Ru), Palladium (Pd) and Rhenium (Re). For example, sunlight can be captured by Ruthenium (Ru) as a catalyst, and electrons move from the donor (marked as ''D'') to the acceptor" *(Luo et al., 2015).*

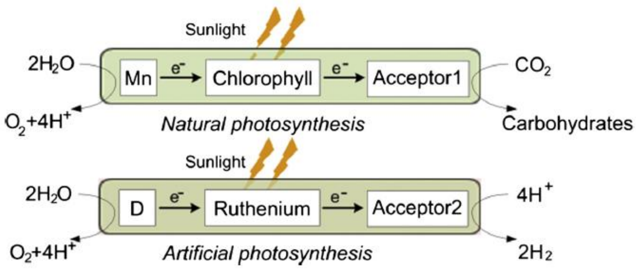


Figure 15: Comparison of natural and artificial photosynthesis (Luo et al., 2015)

The thermochemical approach takes advantage of thermal processes for solar fuel production, which include the generation of very high temperatures in a sealed environment to split water into its essential parts. Hence, this technique is more reliant on strong sunlight compared to the other two aforementioned. "After the solar radiant energy is concentrated by heliostats, an endothermic chemical transformation is carried out in a reaction vessel. The reaction produces hydrogen and/or carbon monoxide and/or other materials" *(Luo et al., 2015).*

Main characteristics of EESS

As it is shown in Table 2, it was collated in a general board the main operational characteristics of EESS aforementioned. Electrical, mechanical, chemical and thermal energy storage technologies are available with reasonably different technical parameters. The advantages are highlighted in yellow and a general cost reference was given by 2016. Table 2, is helpful for selecting an EESS technology that might be more suitable for a particular application (*Bocklisch, 2016)*.

	super-cap	SMES	flywheel	pumped hydro	CAES	lead acid battery	lithium-ion battery	NaS battery	VRFB	H2	power-to-CH4
storage duration	seconds to minutes			hours to weeks						weeks to month	
typical capacity	Wh to kWh			MWh to GWh		kWh to GWh (modular)				MWh to TWh	
energy density (Wh/l)	2-20	0.5-10	20-200	0.27-1.5	3-6	50-100	200-350	150-250	20-70	500-2500	1500-4000
power density (W/l)	15000-50000	1000-5000	5000-15000	0.5-1.5	0.5-2	10-500	10-350	140-180	<2	-	-
cycle effiency (%)	77-83	80-90	80-95	75-82	60-70	70-75	80-85	68-75	70-80	34-40	30-35
self-discharge rate (%/day)	≈10-20	10-15	70-100	0.005-0.02	0.5-1	0.1-0.4	0.1-0.3	≈10	0.1-0.4	0.003-0.03	0.003-0.03
response time (ms)	<10	1-10	>10	>3min	3-10min	3-5	3-5	3-5	>1s	≈10min	≈10min
lifetime (years)	15	20	15	≈80	≈25	5-15	5-20	10-15	10-15	5-15	5-15
cycle lifetime (full cycles)	up to 1mill.	>1mill.	>1mill.	10000-30000	8000-12000	500-2000	2000-7000	5000-10000	>10000	1000-10000	1000-10000
costs (€/kWh)	10000-20000	1000-10000	≈1000	5-20	40-80	100-250	300-800	500-700	300-500	0.3-0.6	0.3-0.6
costs (€/kW)	150-200	200-300	≈300	500-1000	700-1000	150-200	150-200	150-200	1000-1500	1500-2000	1000-2000

Table 2: Comparison of different energy storage technologies advantages highlighted (Bocklisch, 2016)

Furthermore, Figure 16, shows between the X and Y axes a more technical comparison related to the power and energy capacity among different storage technologies aforementioned.

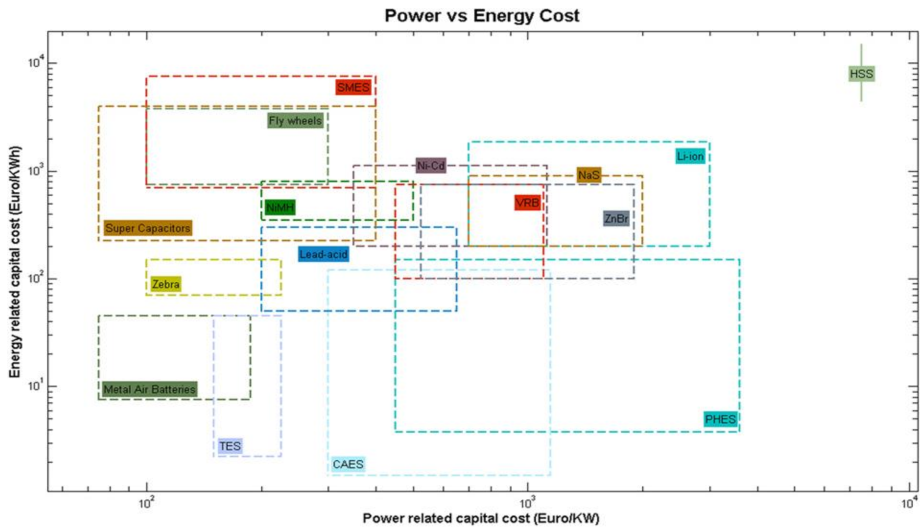


Figure 16: Comparison of power density and energy density costs among diverse technologies (Lopes Ferreira et al., 2013)

2.3. General Concepts

Load Levelling and Peak Shifting

As it has been mentioned from researchers, the value of EESS for managing energy and improving the stability and economy of a Microgrid is immeasurable. The main energy management purposes involve load levelling and peak shifting. Both of them work levelling the demand for the grid through the EESS. However, the load levelling is more focused on short-term fluctuation, while peak shifting is more for the long-term (24 h) variation *(Wenzhong Gao, 2015)*.

Figure 17 displays an example of load levelling (straight lines highlighted in colour), which can be used to smooth the demand (black colour lines).

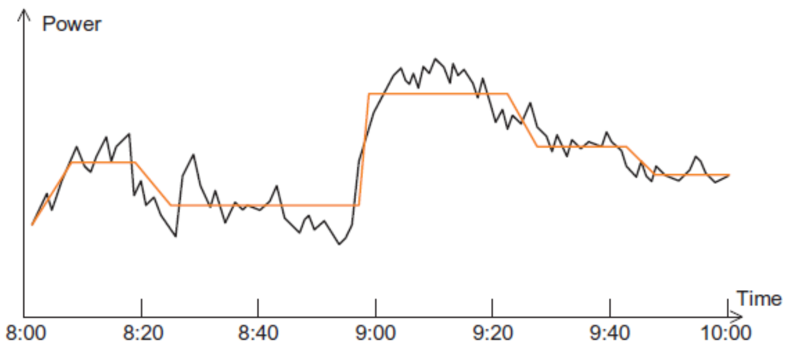


Figure 17: Example of Load Levelling (Wenzhong Gao, 2015)

On the other hand, *Figure 18* represents a simple example of peak shifting, where is shown how the demand varies a lot during a day. The peak demand happens in the evening, but in the early morning, the load is very light. So it is possible with the EESS to accumulate energy in the early morning and output the energy to supply the Microgrid in the early evening. As a result of both operational activities, the efficiency and power quality of the Microgrid would be improved.

For this research, the peak shifting concept is applied considering the energy market price, in order to avoid higher energy prices compared with a price reference.

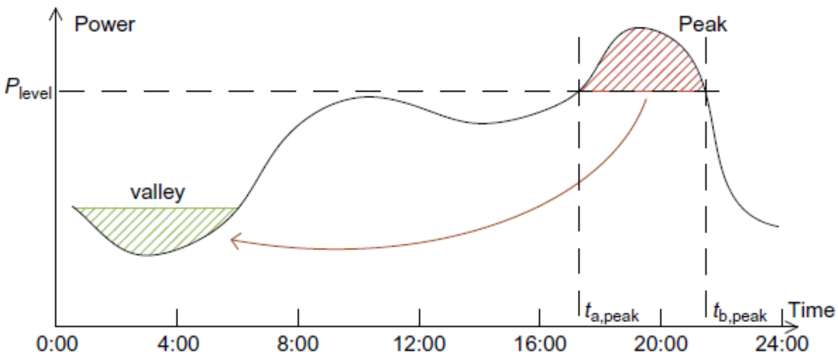


Figure 18: Example of Peak Shifting (Wenzhong Gao, 2015)

In the energy market industry, peak shifting is based on load forecasting technology. From the demand prediction results, the Microgrid is provided with the data of how much power is required throughout peak times. Consistently, the ESS stores the required energy during Valley period and provide power to the system in peak time. “Nowadays, load forecasting is very precise. For some regions, the prediction errors can be as low as 1% to 3%” *(Wenzhong Gao, 2015)*.

Load Duration Curve (LDC)

An LDC is an arrangement of the power consumed by a certain load in a downward form, where the greatest value on the Y-axis is displayed on the left side. On the X-axis is the time, where is represented the duration of each load continues during the time-slot. Thus, the area under the curve quantifies the energy consumed in the total time period by the energy system.

Furthermore, LDC is widely used in economic dispatching, in system planning is used to illustrate the relationship between generating capacity requirements and capacity utilization, and reliability evaluation *(Masters, 2004).*

Figure 19 shows an example of LDC and how to understand the information plotted.

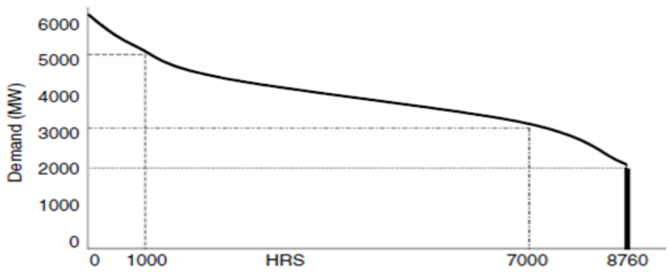


Figure 19: Example for interpreting an LDC (Masters, 2004)

It is clear to see in *Figure 19* that the load is given between 2000MW and 6000MW, also for 1000hrs is greater than 5000MW, similarly the load is greater than 3000MW for 7000hrs, and likewise, the load is enclosed by 3000MW and 5000MW for 6000hrs.

Net Present Value (NPV)

Is the difference between the present value of cash inflows and the present value of cash outflows. NPV is used in capital budgeting to analyse the profitability of a projected investment or project (Investopedia, 2017). In this project, the author used the concept to calculate the BES technology NPV considering the operation and maintenance for 10 or 15 years depending on the BES technology.

The equation used is:

$$\text{NPV}= \sum_{t=0}^{n} \frac{C_t}{(1+i)^t}$$

Equation 1: Net Present Value (NPV) formula

Where:

t: Time of the cash flow (10 years applied to VRLA and 15 years to NaS and Li-Ion).

i: Discount rate assumed to be 6% annually for operational and maintenance costs.

Ct: Cost of the benefit in that time “t”.

3. Model: Study case

This section explains integrally the study case applied to appraise the potential of the algorithms proposed in the next chapter 4, in order to measure its replicability as a helpful tool for other electrical systems.

In general, is created a Microgrid in Islay (an island located in western Scotland), which has the potential for RES generation due to its climate conditions. The demand side is depicted by two distilleries located on the island, mixed with a typical office building load to recreate a mixed non-residential demand. The RES supply side is produced by a hybrid system between WT and PV arrangement, in order to take advantage of the local natural weather resources. It is outlined the assumptions considered for the problem addressed. It is displayed graphically the Microgrid, the demand profile, the supply profile, and the 2016 UK electrical market prices involved into the main scenario.

3.1. General Description

As it was stated before, it is intended to focus the study by dimensioning accordingly an EESS creating an algorithm which can be used for: Firstly, minimising the EESS size applying the load shifting concept considering avoiding the higher tariff. Secondly, minimising the EESS size for maximising the RES penetration to the electrical load.

In order to accomplish the aim, the supply and demand profile was available from the MERIT software data base, which contains some real technical characteristics from various RES models, such as different WT and PV panels, some tested local demand data and climate conditions.

MERIT uses algorithms that model RES and low carbon energy systems (such as PV components, WT, and other systems) based on manufacturers' specifications, locational parameters and weather data to simulate its power production (Energy System Research Unit, n.d.). However, the technical characteristics of WT and PV models used were found on the manufacturer website and validated against MERIT

data base. Consequently, for the WT (NORDEX, 2005) and PV (SHARP, n.d.). Moreover, the weather conditions were validated through the request to UK Met Office (Office, 2017), who sent kindly the complete year 1972 climate data.
In this context, with a model based on real data from the supply and the demand side, and the UK 2016 electrical market price data downloaded from (Nord pool AB et al., n.d.), the model for one year period with hourly slots was exported to Excel files with the aim to be an input easily manageable by MatLab software.

Using MatLab, a code routine was created from the algorithms proposed, where is exposed the author's criteria for the power management analysis to meet the requirements of the suitable EESS selection. In each hourly slot, the different parameters involved was taken and managed accordingly, to dimension operationally an appropriate EESS to cover the uncertainties from RES, and shifting the electrical energy supply relying on the electricity market price.

As part of the MatLab code testing process, the electrical load was chosen as fluctuant as possible, in order to avoid the standard and practically stable behaviour from a typical residential demand. Successively, the author tests his algorithm against to an available non-residential demand, which is more intermittent and unpredictable than a residential demand. The Microgrid system model schematic is represented in Figure 20, where the EESS to be dimensioned is also shown.

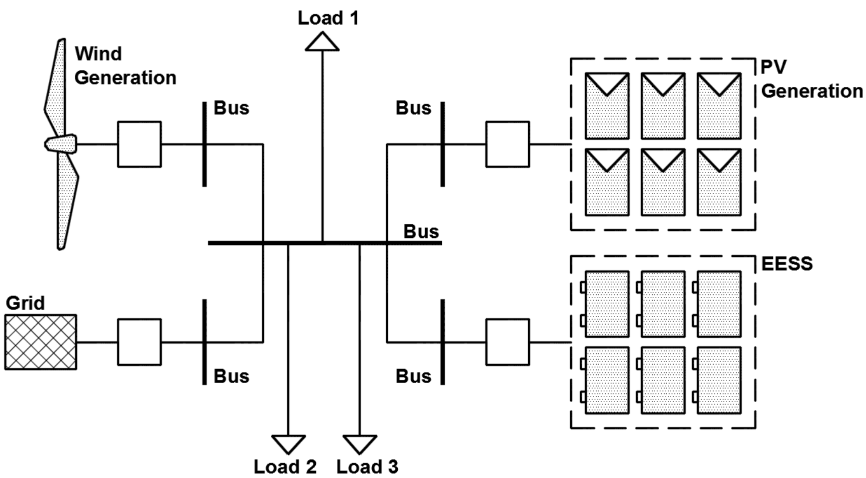


Figure 20: Microgrid System Model Schematic

Operationally, the power flow of the Microgrid system model is illustrated by red colour as following in *Figure 21*, where is remarkable the charging and discharging process of the EESS by the power flow dual direction.

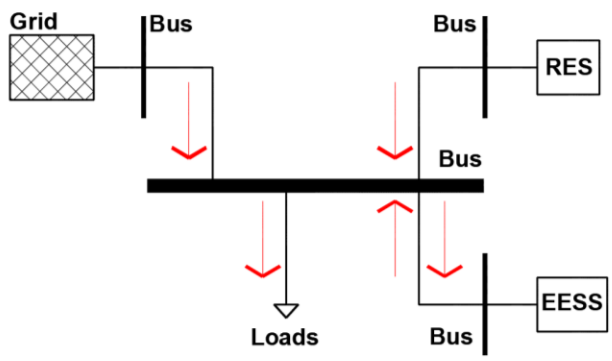


Figure 21: Microgrid System Model Schematic Power Flow

Thus, the main grid and RES are supplying energy to the Microgrid and the electrical demand (loads) are receiving such energy.

Regarding the operational conditions and limitations, some bullet points were considered as follow:

3.2. Assumptions

In order to narrow the spectrum of the operational possibilities, and testing measurably the algorithm competencies, some assumptions were given and outlined below:

- The Microgrid Control System and possible constraints which could have a typical smart electrical distribution system were not considered.
- Parameters appraised by hourly slots were assumed quasi-static or invariable within each time-slot. But, it could have changed from one slot to another.
- Selling energy to the grid was not a part of the analysis.
- Frequency stabilization analysis and any kind of charging station for the electrical energy storage system proposed was discarded.

- Current and temperature limitations analysis in BES was considered, but just through the proposal of SOC range values to ensure its proper operation.
- The real operational BES charge-discharge model could not be recreated by hour slots. However, it was added a charge factor control, to allow the BES to be useful with at least 50% of its total capacity. Moreover, in order to minimise the cost impact, it was assumed in 1.10 when SOC < 0.25.
- Charge and discharge efficiency were considered identical and equivalent to 0.70 due to the BES technology, Microgrid and electronic devices that are involved in the entire system. The value is applied at the end of the MatLab code to determine the final EESS size by energy (capacity) and power required.

The operational constraints mentioned above aid to consider the reasonable application of the energy management process built with MatLab. The algorithms are explained in detail in the Model (Algorithms) section (chapter 4).

3.3. Demand Profile

As it was aforementioned in the general description, as part of the MatLab code testing process, the real non-residential demand from MERIT data base as fluctuant as possible is depicted by the two distilleries located in Islay, mixed with a typical office building load. The real data were Lagavulin and Laphroaig Distilleries, and Office_A_.

The amount of energy among the electrical demand profiles is given in *Figure 22* for the entire year by hourly slots (8760 hours). It is clear to see that the maximum power in some points of the year is roughly 140KW. Moreover, it is also seen that during the summer period (June to August) and at the end of the year (November to January), the energy consumption is sharply reduced (around 50KW and 25KW respectively). The x-axis shows the time by hours for one complete year and Y-axis represents the power consumption in KW.

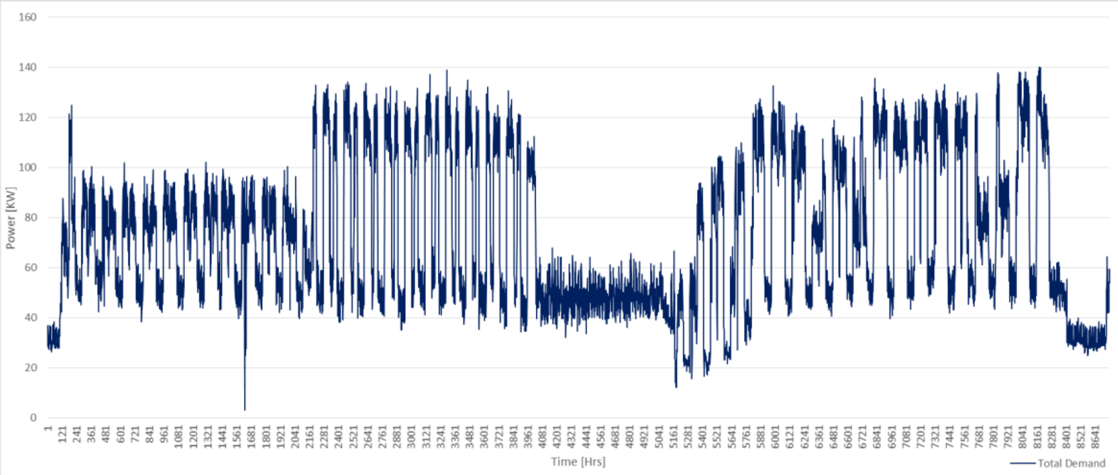


Figure 22: Non-Residential Electrical Demand Profile in Islay

3.4. Supply Profiles

The demand displayed before was fed by the supply system aforementioned in the general description. The WT Farm and PV Panels arrangement as the RES generation. Figure 23, shows the WT generation created by MERIT into western Scotland climate conditions, where X-axis shows the time by hours for one complete year and Y-axis represents the power consumption in KW.

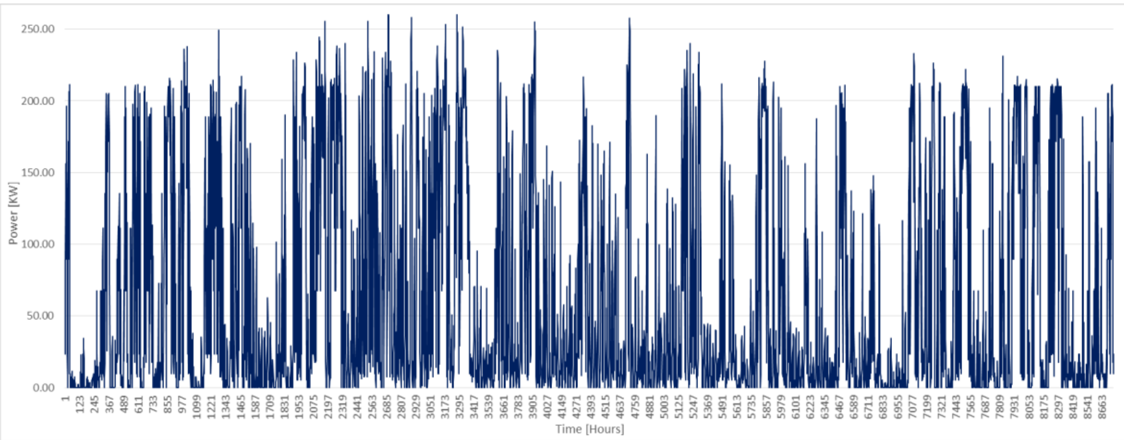


Figure 23: Wind Turbine Farm Generation in Islay

Moreover, Figure 24 shows the power of the PV panels arrangement produced through the year to cover part of the aforementioned electrical demand in Islay, where

X-axis shows the time by hours for one complete year and Y-axis represents the power consumption in KW.

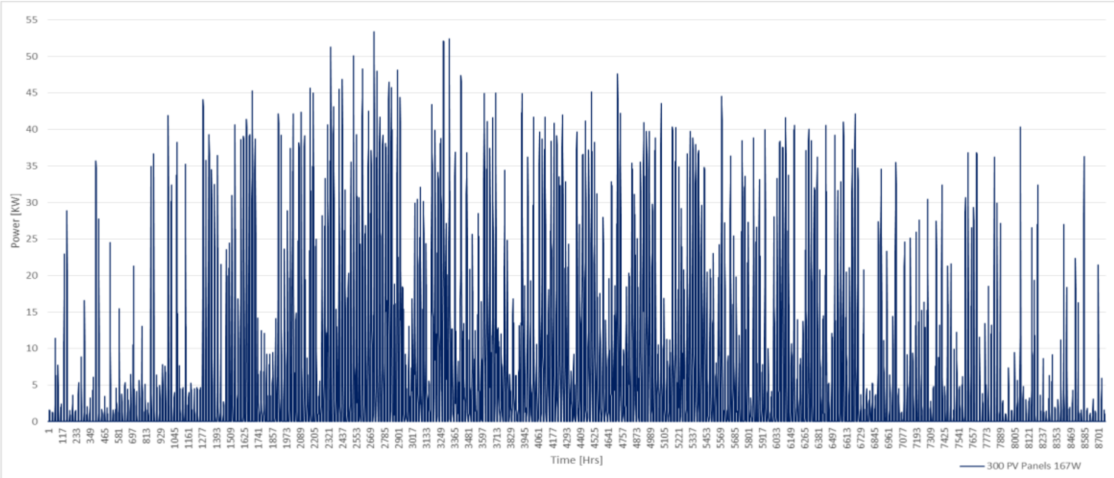


Figure 24: PV Panels Generation in Islay

3.5. The UK Electrical Market Prices

The UK electrical market price (Nord pool AB et al., n.d.) is very variable compared with other markets. Prices constantly change through the day the entire year. Thus, despite the graph scale, is not a surprise to see the hourly variability in Figure 25, where the 2016 electricity market price is given as the price reference for the Microgrid developed in this Thesis. The x-axis shows the time by hours for one complete year and Y-axis represents the electricity cost per KWh in GBP.

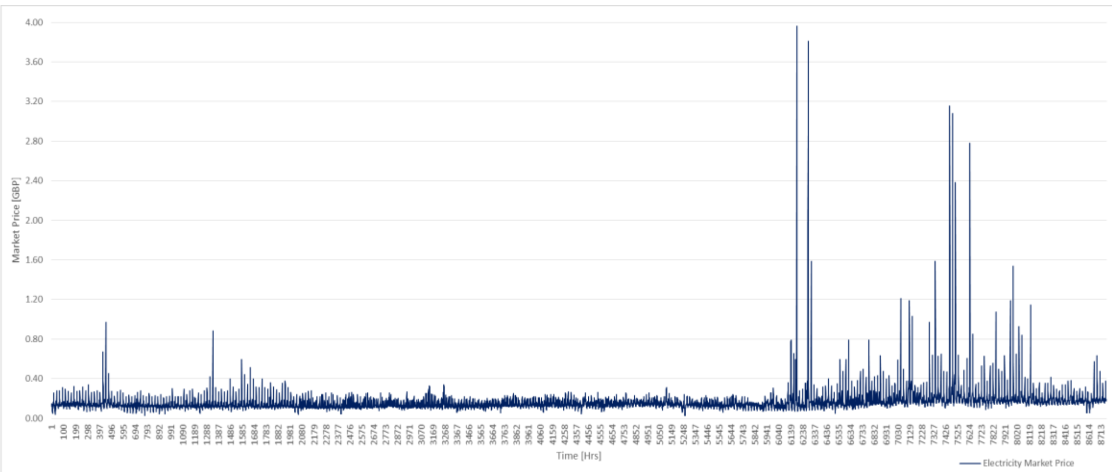


Figure 25: Electricity Market Price 2016(Nord pool AB et al., n.d.)

Conclusively, it was created a model scenario considering the aforementioned assumptions. Afterward, having shaped the model definition, the technical proposal is outlined as follow:

4. Model: Algorithms

In this section is explained the algorithm design criteria to estimate the minimum EESS in two totally diverse BES applications. The first one from the demand side, and the second one from the supply side. The first application aims to size a minimum daily EESS to operate when the energy market price is higher than a price reference given (demand side application). Conversely, the purpose of the second application is to dimension the minimum BES to maximise the RES penetration into the Microgrid (supply side application). The outcome from both proposals is compared and analysed to measure the algorithm applicability and generate the general conclusions.

4.1. General algorithms

The proposed power management general algorithm is given in Figure 26, where it is identified the main steps coded in MatLab.

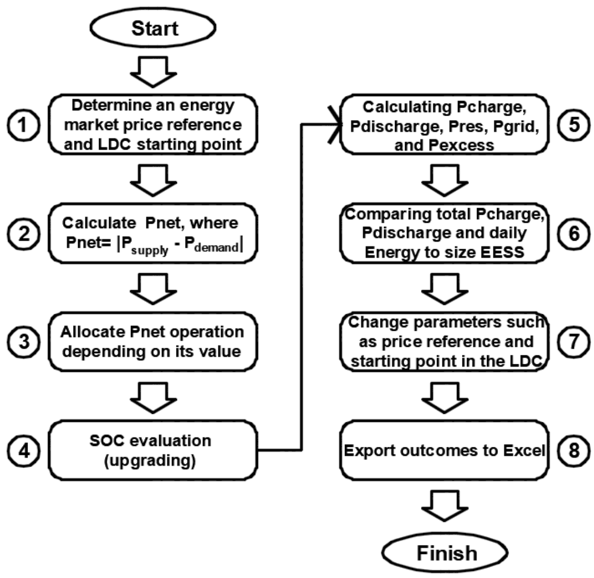


Figure 26: Proposed power management general algorithm

Each square has a purpose and it was described as steps of the power management process:

Step 1: It is considered as the initialization stage, where is set up the parameters such as energy price reference (running the first application, if the energy price is lower than the price reference, the grid feed the demand, otherwise EESS feed the demand), EESS nominal size (Using the LDC as a tool in the first application, it is necessary to size the EESS as the starting point to quantify the power available in BES at any hourly slot throughout the year, which is monitored by the SOC assessment), and other. Also, it is taken the power produced by RES and the power required from the demand side.

Step 2: From RES (as green energy supply side) and the demand (Islay electrical non-residential loads) is calculated the power difference between both values which is called net power (or Pnet). If Pnet>0, there is an excess power from RES, otherwise, the demand is higher than RES supply.

Step 3: Pnet value is compared to the amount of power preserved in EESS at each time slot. Generally, the amount of power available is calculated by EESS nominal times SOC. But, diverse situations are given and there will be explained later. Moreover, appendix A.1 and A.4 show each case where Pnet is allocated.

Step 4: After the Pnet allocation is given, it is required upgrade the SOC of BES for next appraisal (next time slot). Thus, step 3 and step 4 are closely related to prepare the future BES power conditions.

Step 5: Once steps 2, 3, and 4 depict the current conditions, it is clear how the power will be distributed to the electrical system variables regarding its functionalities (as example: for charging BES, for discharging power from BES or Grid to the electrical loads, or if the power is just in excess).

Step 6: Steps 1 to 5 is analysed by hourly slots the entire year. Now, for the capacity dimensioning, the total daily energy charged and discharged by BES is summarised individually and compared day by day throughout the year. The bigger value is stated as the minimum EESS size required. Subsequently, for the power required from EESS is identified hour by hour the greatest power necessary for charging or discharging the BES.

Step 7: With the aim to run several test cases, the parameters mentioned in step 1 are changed. As an example, for the same EESS nominal (EESSnom), the routine was run with the parameter energy price reference (Pref) changed sequentially from 0.10GBP to 0.25GBP, meanwhile, EESSnom was changed from 10KW to 100KW.

Step 8: The outcomes are exporting to Excel, to gather the results by manageable tables displayed in the appendixes and creating the graphs shown in the simulation results section (chapter 6).

However, the power management general algorithm in Figure 26 is general for both applications mentioned, which are: Firstly, minimising the EESS size applying the load shifting concept considering avoiding the higher tariff. Secondly, minimising the EESS size for maximising the RES penetration to the electrical load.

For the first application, the energy operation is explained graphically taken into account the step 1 to step 5 from Figure 26 through the event tree analysis in Figure 27. It is displayed from the left to the right the different Microgrid operational situations and it is prioritised the segments involved, such as energy market price (first column), Pnet by time slots (second column), EESS operational conditions through its SOC (third column), and the decision to be taken (fourth column), with the purpose of each stage in the second row (under each title).

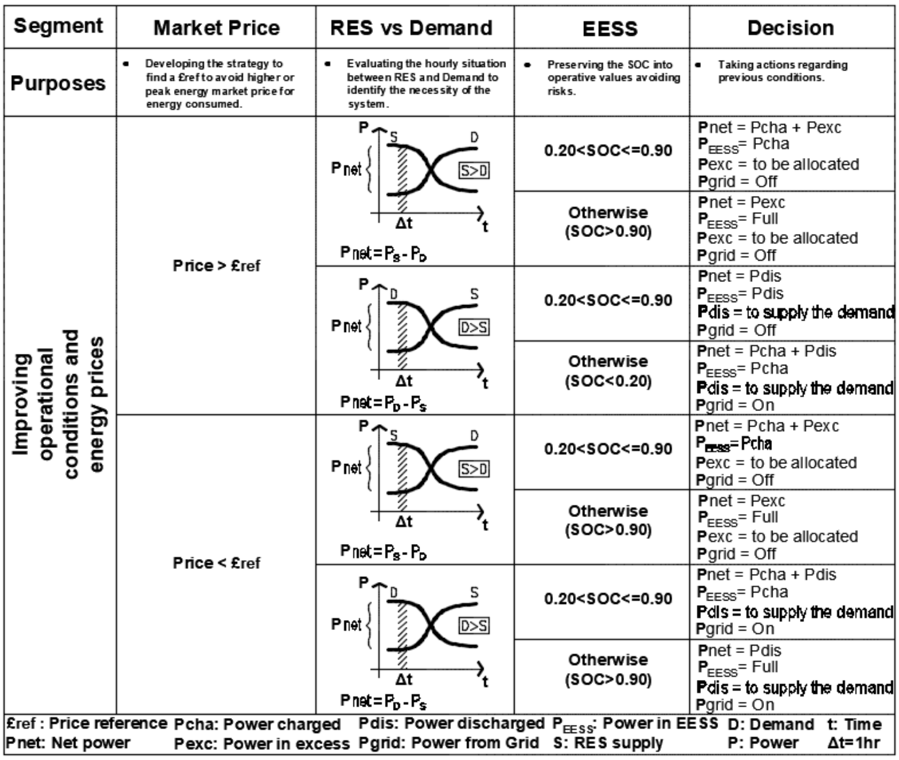


Figure 27: General operational selectivity process on first application (demand side)

Figure 27 also highlights the line graphs for each particular situation. The SOC threshold values mentioned in chapter 3.2, now is shown in each scenario. Successively, the decision equivalent to step 5 is taken as it is described in the last column. Moreover, in the last row is written a small list of abbreviations describing the diverse symbols used.

For the second application, the market price column is just a parameter used to compare diverse results when the proportion of the demand is reduced, with the aim to measure the algorithm response. However, the parameter EESS nominal is completely omitted. Thus, just 4 cases are taken into consideration for the EESS. Additionally, the excess energy is added entirely into BES to maximise the RES penetration.

Successively, the algorithms for both applications are explained by a logic flow diagram as follow:

4.2. Load shifting application algorithm with energy price constraints

Figure 28, shows the general logic flow diagram created to determine the minimum operational EESS to avoid high energy market prices, while is intended to increase the RES penetration applying the load shifting concept (analysis from the demand side).

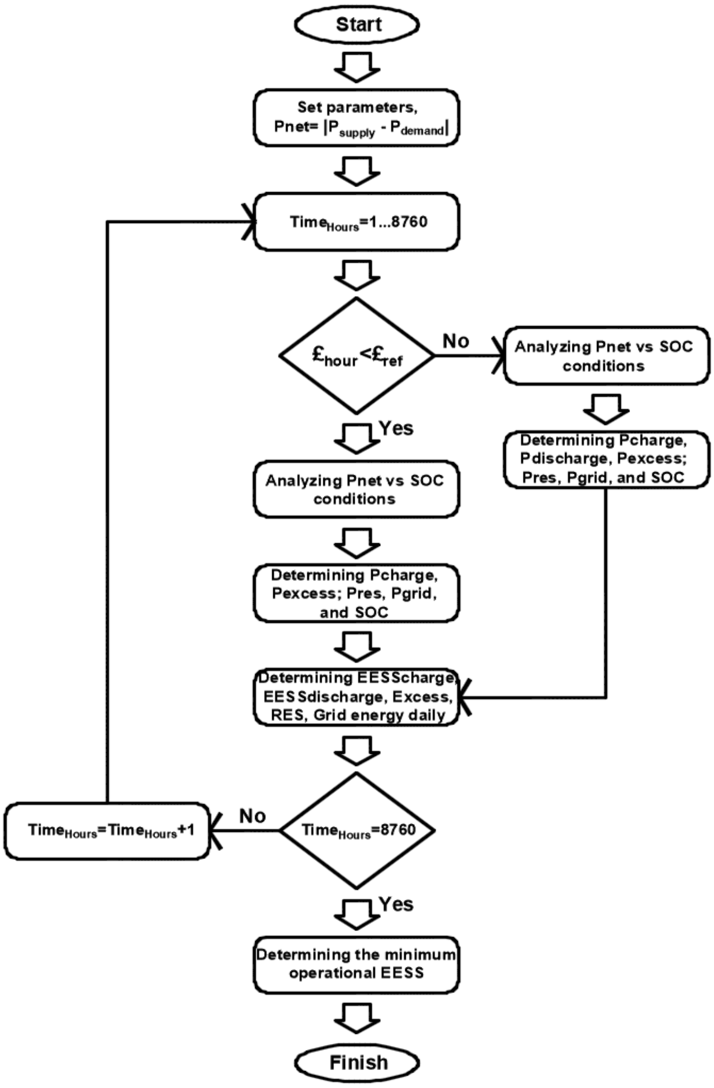


Figure 28: General logic flow diagram designed to determine the minimum operational EESS through load shifting application with energy price constraints

Parameters such as the energy market price reference and the nominal EESS were changed to develop the sensitivity analysis and measuring the algorithm robustness.

The general modular algorithm was coded into 6 sub-algorithms and results were exported to an excel file. Each MatLab code is depicted in the appendix A.1 and the purpose of each module is described as follows:

- Power_Analysis.m: As the general file to be called from the MatLab command window, it contains the other 5 sub-algorithms.
- Parameters.m: Is the initialization file and set up all the parameters involved in the program code. Also, it prepares the memory for the future matrix arrangements to improve the running time.
- Hourly_Net_Power_Analysis.m: Contains the algorithm where is evaluated Pnet vs SOC, restricted to an energy market price lower than the price reference.
- High_Hourly_Net_Power_Analysis.m: Contains the algorithm where is evaluated Pnet vs SOC, restricted to an energy market price higher than the price reference.
- EESS_Daily_Analysis.m: Contains the total daily amount of energy of parameters such as EESScharge, EESSdischarge, Excess, RES, and Grid.
- EESS_Size.m: Contains the code to calculate the final EESS in KW and KWh considering the BES efficiency for charging/discharging energy.
- Data_Microgrid.xlsx: Excel file which contains the data from the study case and the results from the MatLab test case.

4.3. Algorithm to maximise RES penetration into the Microgrid

Figure 29, shows the general logic flow diagram to determine the minimum operational EESS through the maximisation of RES penetration into the Microgrid (analysis from the supply side).

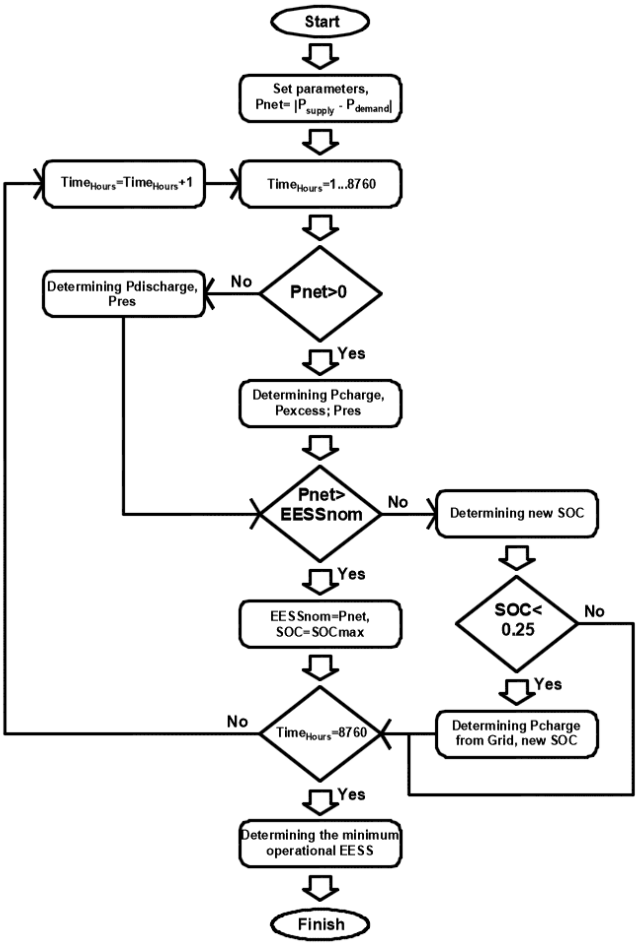


Figure 29: General logic flow diagram to determine the minimum operational EESS through the maximisation of RES penetration into the Microgrid

Similarly, than in the first algorithm, the modular MatLab code has analogous sub-algorithms that are depicted in the Appendix A.4. But with the exception of 2 of them which were replaced by just 1 new code. Each MatLab code is described as follow:

- Power_Analysis.m: As the general file to be called from the MatLab command window, it contains the other 5 sub-algorithms.
- Parameters.m: Is the initialization file and set up all the parameters involved in the program code. Also, it prepares the memory for the future matrix arrangements to improve the running time.
- Maximise_EESS_Net_Power_Analysis.m: Contains the algorithm where is evaluated Pnet vs SOC, to maximise the EESS dimension.

- EESS_Daily_Analysis.m: Contains the total daily amount of energy of parameters such as EESScharge, EESSdischarge, Excess, RES, and Grid.
- EESS_Size.m: Contains the code to calculate the final EESS in KW and KWh considering the BES efficiency for charging/discharging energy.
- Data_Microgrid.xlsx: Excel file which contains the data from the study case and the results from the MatLab test case.

Subsequently, the range of values to determine the starting point and the parameters set up in the MatLab code initialization stage for the load shifting application algorithm, are given in the next 2 sections:

4.4. Energy market price thresholds

With the aim to define the range of values regarding the energy market price, it was depicted an annual electricity market price duration curve in Figure 30, from the energy market price graph in chapter 3.5, which is the same concept given for LDC in chapter 2.3 but applied to the energy market prices.

Figure 30 shows a simpler way to display the frequency of the energy market prices throughout the year in blue colour, and also the curve allows to visualise its proportion of data on the demand side reading a number of hours that could be avoided when the restriction for energy prices is applied.

The first aspect is the calculation of the yearly average price, with the aim to have the mean value as the main reference. The second important factor is avoiding the over average prices, and a good reference from Figure 30 is to have a look the concavity in the left hand addressed to the highest prices.

Consequently, in red colour is represented the energy price mean value (0.16 £/KWh). Over this red line, prices are higher just 30% of the year (2700hrs). Moreover, close to the Y-axis, the lower energy price before the incremental concavity is 0.25 £/KWh with just under 500hrs, which represents less than 6% of the year. In green line, colour is highlighted both umbral.

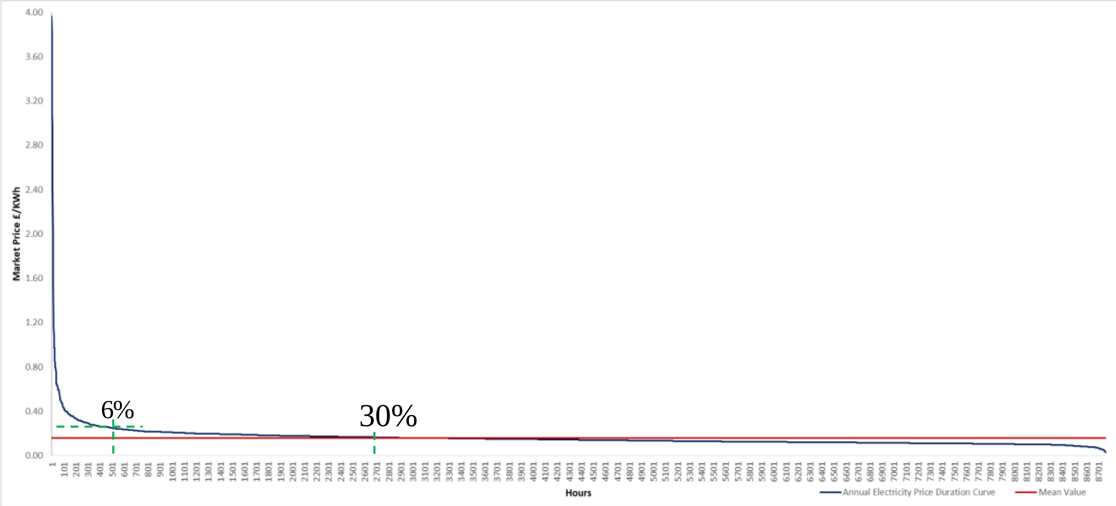


Figure 30: Annual electricity market price duration curve its mean value

However, Table 3, shows the highest prices from the data illustrated in chapter 3.5 and its consumption related from chapter 3.3 at the same time. Also, RES generation is added to the table to appreciate the relationship with the supply side simultaneously. In Table 3 was highlighted the electrical demand in red and blue colours to compare it with the mean consumption through the year and displaying its prices respectively. Thus, it can be seen that the highest energy price is not correlated with the highest demand and vice versa. Additionally, it is appreciated that some of those values were supplied by RES partially or totally.

Power consumed with highest energy market prices					
Price (GBP)	Load (KW)	Time (Hrs)	Day of the year	WT (KW)	PV (KW)
3.96	**96.59**	**6189**	**Sep. 13 - 4.00am**	**127.98**	**0.00**
3.81	47.13	6285	Sep. 17 - 9.00pm	14.03	0.00
3.17	**97.67**	**6190**	**Sep. 13 - 5.00am**	**127.98**	**0.00**
3.16	51.18	7459	Nov. 5 - 7.00pm	10.78	0.00
3.08	52.53	7483	Nov. 6 - 7.00pm	127.98	0.00
2.98	53.27	6284	Sep. 17 - 8.00pm	14.03	0.00
2.96	44.41	6286	Sep. 17 - 10.00pm	14.03	0.00
2.78	59.01	7627	Nov. 12 - 7.00pm	0.00	0.00
2.38	**114.43**	**7507**	**Nov. 6 - 11.00pm**	**300.24**	**0.00**
1.98	50.76	6283	Sep. 17 - 7.00pm	127.98	2.43
1.59	**69.68**	**6309**	**Sep. 18 - 4.00am**	**0.00**	**0.00**
1.59	**122.84**	**7339**	**Oct. 30 - 11.00pm**	**10.78**	**0.00**
	Demand (KW) over the yearly mean value				
	Demand (KW) around the yearly mean value				
Note:	Other demand values are under the mean value				

Table 3: Examples of power consumed vs highest energy market prices

Nevertheless, generally, the UK energy market price applies higher prices during the peak hours. Hence, it is considered this fact as criteria to apply the energy price parameterization from 0.10GBP to 0.25GBP. The under from 0.10GBP until 0.16GBP is for analysed the simulation results in a wider spectrum of results, from a greater amount of demand data (from 92% of the total data).

Successively, the criteria to obtain the range of values for the EESS nominal as initial set up is described in the next section:

4.5. Load duration curve and load shifting application

With the same criteria as it was done for the energy prices, the first step is the calculation of the yearly mean load with the aim to have the main reference. In Figure 31, is depicted in blue colour the LDC and its mean value in red colour are located in around 72KW. The power demand over the mean value is required by the load 3890hrs during the entire year, which is slightly over 44% of the total period.

The second important characteristic is avoiding the peak demands which usually operates at scarce hours through the entire year, and those electrical demands usually are paid at a very expensive price per KWh, due to the extra generation cost from the supply side. The highest values are located on the first roughly 150 hours, where the slope of the curve is sharply greater compared with its line graph extension depicted in Figure 31, and it represents 1.7% of the total yearly operation from the supply side.

Hence, the range of values for the EESS nominal has an operation window between 10KW and 70KW, which is the difference between the maximum power demand (140KW) and both references aforementioned (Y-axis values for 1.7% and the mean value drawn in red colour).

Furthermore, it should be taken into consideration the aforementioned references for the energy market prices, which is 6% of the total yearly operation, and the mean value which represents 30% of the year time. Both references are marked in Figure 31 and are located in the same range of values mentioned for EESS nominal.

Conclusively, regarding the power to be set up for EESS nominal, is estimated as a starting point in 10KW and could be extended for analytical reasons until 70KW.

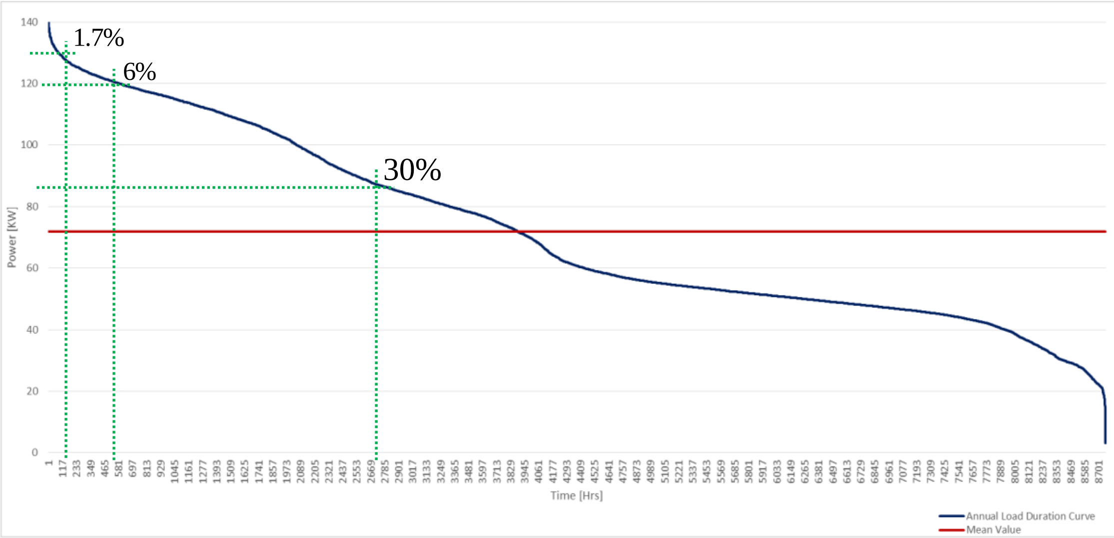


Figure 31: Annual load duration curve and its mean value

Consequently, after having modelled the study case and the algorithms, the next step is validating the model completely. For that purpose, it was employed HOMER software and it is described the procedure as following in the subsequent section.

5. Validation

This section intends to use HOMER software as an integral tool which provided a modest, and natural instinct interface. The program package allows hourly annual analysis with both options contained in a Microgrid system: islanded and grid-connected, and it has remarkable characteristics content compared to this dissertation project.

However, HOMER uses the optimisation method with a cost analysis to calculate its results and has two diverse controller functions: load following and cycle charging (as dispatch strategies operation). Moreover, it incorporates the efficiency of each element (such as WT, PV, BES, the controller, the rectifiers, and other) into the Microgrid.

Furthermore, optimisation is not contained in this report. This project contains the appraisal of two algorithms to be used for sizing a minimum EESS applying two diverse operations: the load shifting application and RES maximisation. But, the software package is useful to compare the data obtained by MERIT, which is related to RES, climate local conditions and its operational performance with the demand profile. Thus, is expected to see some differences associated with the energy allocation in the main electrical system components.

Each software package investigated has its limitations and diverse objectives. This has needed for some calculations to be used during the coding process to achieved reasonable results at the simulation stage.

Successively, it is described the simulation process of the model proposed by MERIT and the algorithms coded in MatLab into HOMER, and the procedures to assess it to certify its validation for the future application and qualify its results.

5.1. Model from MERIT and MatLab into HOMER

Applying HOMER software, similar WT's and PV's were chosen, selecting Islay as the location. Also, the demand profile was imported and the schematic is depicted in

Figure 32. From this data, a demand proportion was defined as deferrable load and the another one as a base load, with the aim to recreate operationally a kind of load shifting operation, due to the gap of this functionality in the software package. The proportion reference was taken from the LDC set up criteria in order to create a fixed base demand portion (70%) and a variable portion to be managed by the storage (30%) through the deferrable load function.

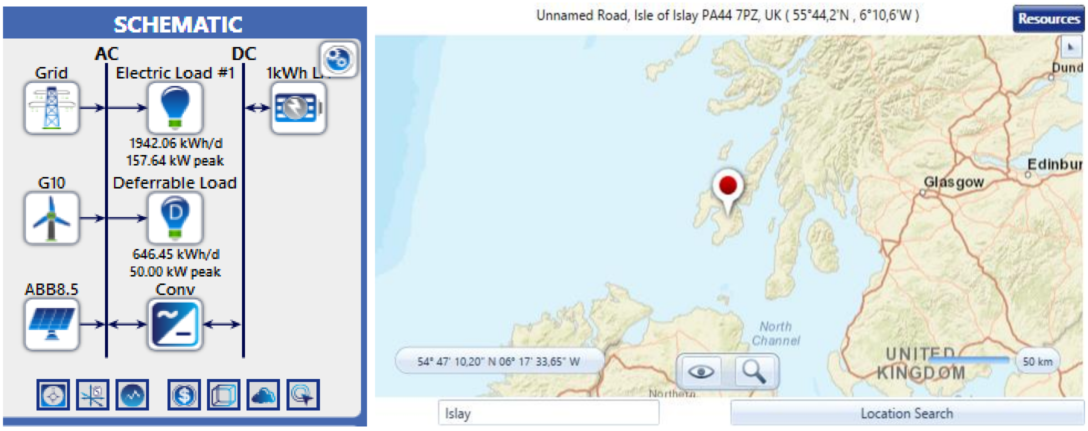
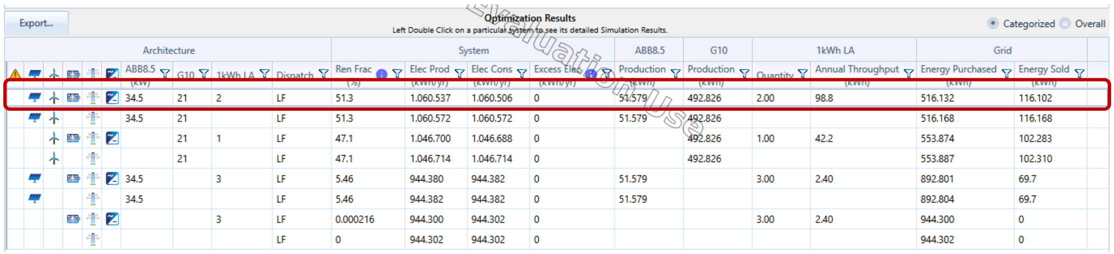


Figure 32: HOMER electrical system modelled and its location (Islay)

Consequently, having adapted RES supply into the software package, and splitting the demand profile into deferrable and non-deferrable loads, is running the optimisation process, which is displayed in Figure 33.

In a red colour square, is highlighted the results including all RES defined in the modelling chapter. In the architecture column on the left-hand side is appreciated that RES values are quite similar to MERIT model. In the system, the column is seen that the total energy produced is over 1GWh/year which 51.3% comes from RES. Moreover, each RES systems on the next 3 columns to the right side refer to the energy produced individually, the first one is the PV arrange which produced over 51 MWh, WT with over 492 MWh and BES 98 KWh, which was calculated by the software. Regarding the grid in the next column, it produced over 516 MWh, and the energy sold in the last column refers to the excess energy from RES which accounted over 116 MWh.



Optimization Results
Left Double Click on a particular system to see its detailed Simulation Results.

ABB8.5 (kW)	G10	1kWh LA	Dispatch	Ren Frac (%)	Elec Prod (kWh/yr)	Elec Cons (kWh/yr)	Excess Elec (kWh/yr)	ABB8.5 Production (kWh)	G10 Production (kWh)	1kWh LA Quantity	1kWh LA Annual Throughput (kWh)	Grid Energy Purchased (kWh)	Grid Energy Sold (kWh)
34.5	21	2	LF	51.3	1.060.537	1.060.506	0	51.579	492.826	2.00	98.8	516.132	116.102
34.5	21		LF	51.3	1.060.572	1.060.572	0	51.579	492.826			516.168	116.168
	21	1	LF	47.1	1.046.700	1.046.688	0		492.826	1.00	42.2	553.874	102.283
	21		LF	47.1	1.046.714	1.046.714	0		492.826			553.887	102.310
34.5		3	LF	5.46	944.380	944.382	0	51.579		3.00	2.40	892.801	69.7
34.5			LF	5.46	944.382	944.382	0	51.579				892.804	69.7
		3	LF	0.000216	944.300	944.302	0			3.00	2.40	944.300	0
			LF	0	944.302	944.302	0					944.302	0

Figure 33: HOMER Optimization results

Comparing with the algorithm for load shifting applications run in MatLab, Table 4, displays the MatLab code results for diverse energy prices. The lowest one (0.10GBP) represents the simulation for 92% of the complete demand comparable with HOMER. As a result, it is seen in the table that the proportion of RES (48.92%) is slightly lower compared with 51.3% from HOMER. The difference is just under 5% due to the efficiency of each Microgrid device, technical operational differences between models chosen in each software and the proportion of the demand involved in the calculation. However, the EESS efficiency was considered just at the last stage into the MatLab code to size the suitable EESS, but it is out of this purpose.

Energy Price[GBP]	Excess[MWh]	RES[MWh]	Grid[MWh]	%RES
0.10	146.77	387.44	557.70	48.92
0.13	147.24	386.96	558.17	48.92
0.14	147.49	386.71	558.42	48.92
0.15	147.59	386.61	558.53	48.92
0.16	147.91	386.29	558.84	48.92
0.17	148.06	386.14	559.00	48.92
0.18	148.26	385.95	559.18	48.92
0.19	148.42	385.79	559.36	48.92
0.20	148.70	385.50	559.64	48.92

Table 4: MatLab example results varying the energy price reference

On the other hand, the total energy generated in the entire year run from the MatLab code is gathered in the same Table 4, with the variables Excess (RES energy over the demand requirement), RES (energy to supply the demand or charging BES), and Grid (energy from the grid) values. Successively, the total energy produced with the demand over 0.10GBP is calculated accounting the 3 values, which is 1,092,091KWh/year compared with 1,060,537KWh/year from HOMER. In this context, the difference for the entire year is under 2.8%.

Conclusively, the operation of each component such as the supply devices (WT and PV), the demand profile, and weather conditions (Islay climate conditions) were validated independently to ratify MERIT database, and the operation of the algorithms proposed coded in MatLab with results at a satisfactory level compared with HOMER.

6. Simulation Results

The developed algorithms for each aforementioned applications were run and the parameters identified in chapter 3 and 4 (Modelling sections) were sequentially changed to obtain a range of values that will be analyzed in this chapter.

In the first application (load shifting concept with energy price constraints), the parameter price was varied between 0.10GBP and 0.25GBP, and the parameter EESS nominal was changed between 10KW and 100KW. From those changes, the energy management process proposed estimates in each test case the minimum suitable operative EESS by energy capacity and power, which will be analyzed and compared with all the results. Moreover, the energy allocated in RES and the Grid is gathered for further analysis.

In the second application (maximisation of RES penetration into the Microgrid), the EESS nominal parameter is omitted and any RES generation is saved into EESS. The energy price reference act as a calibrator of the demand proportion into the electrical system with the aim to evaluate the algorithm performance.

Both algorithms considered to obtain the minimum EESS suitable for its application through matrix operations of 8760 and 365 rows or columns several times due to the hourly slot evaluation. The data input and output for both MatLab code are briefly displayed in Figure 34.

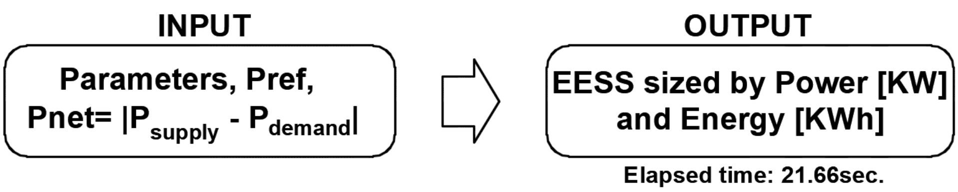


Figure 34: Input/Output of MatLab algorithms created

Finally, even though is out of scope in this dissertation project, it is applied a BES techno-economical appraisal through ES-Select software described in section 2.1 in the literature review, with the aim to justify the electrical storage technology involved in the solution achieved from the proposed algorithm in each application.

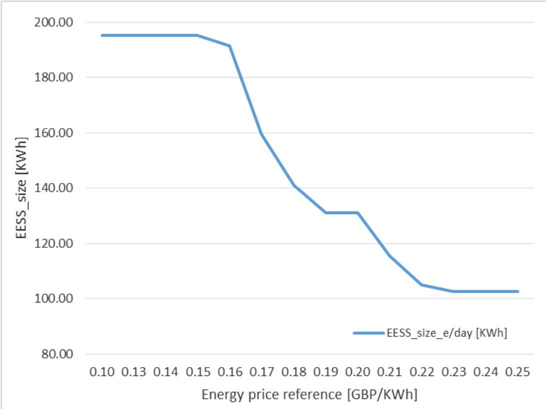
Finally, even though is out of scope in this dissertation project, it is applied a BES techno-economical appraisal through ES-Select software described in section 2.1 in the literature review, with the aim to justify the electrical storage technology involved in the solution achieved from the proposed algorithm in each application.

6.1. Load shifting application algorithm with energy price constraints

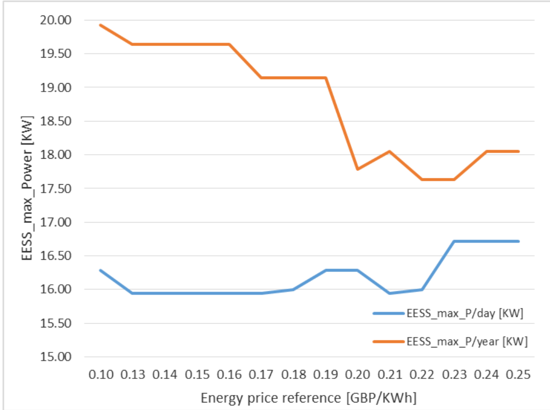
In this section, it is shown the graphs for the test cases. However, one of the parameters is fixed as analysis example. The total test case tables are given in the appendix A.2.

Running the MatLab algorithm for a nominal initial capacity of 20KW (parameter fixed, see Table 9 in the appendix A.2.), Figure 35 shows the results at successive price references (parameter sequentially altered). As it can be seen in Figure 35.a, the maximum energy capacity is required when the initial energy price reference (£ref) is low.

Figure 35.b, illustrates the maximum power required for the EESS. In blue colour is represented by the same day than Figure 35.a., while in orange colour is the maximum power found through the year, which is at different day compared with the blue line. Hence, Figure 35 demonstrates that the maximum energy capacity is not demanded in the same day than the maximum power is needed. The original collated data for both graphs with its respective days for each energy price reference is gathered on Table 7 in the appendix A.2. In this case (EESSnom=20KW), the minimum EESS capacity required to supply the demand through the year is a BES with 195.15KWh and 19.93KW. Or in rounded numbers: 200KWh and 20KW, including the efficiency value mentioned in the assumptions section 3.2.



a. Maximum energy/day [KWh]



b. Maximum power/day [KW]

Figure 35: Maximum energy capacity and power required by EESS at EESSnom=20KW (BES efficiency included)

Furthermore, *Figure 36* depicts the amount of energy from RES and the Grid into the study case and the energy surplus which can be preserved in a thermal storage or sell it. In this scenario, the EESS size is not considering the BES oversize to store the excess. As it can be seen in the bar graph, the energy proportion is quite similar and independently of the price reference parameter, where RES (blue colour) is generated in 35.5% and the total renewables rate is over 48% (including the energy excess). Otherwise, the energy used by the Grid to charge the BES and supply the demand is under 52% (orange colour).

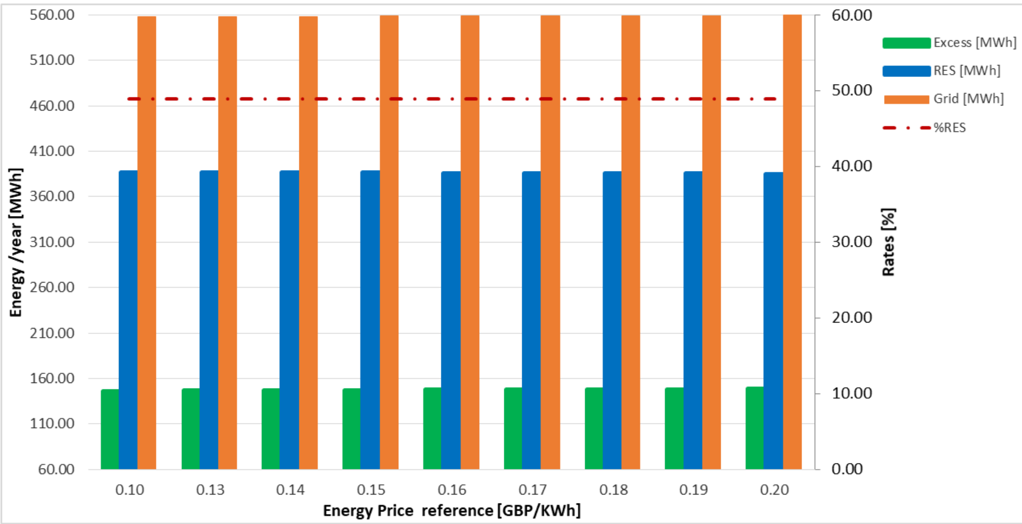


Figure 36: Penetration of RES and the Grid for EESSnom=20KW

Figure 37, displays the results of the MatLab code with an EESS nominal size of 100KW (parameter fixed with the highest value). Basically, the energy values are higher than before because the nominal initial size of the electrical storage is 5 times bigger, however, the energy rates between the Grid and RES are almost identical and independently of the price reference variation (over 48%).

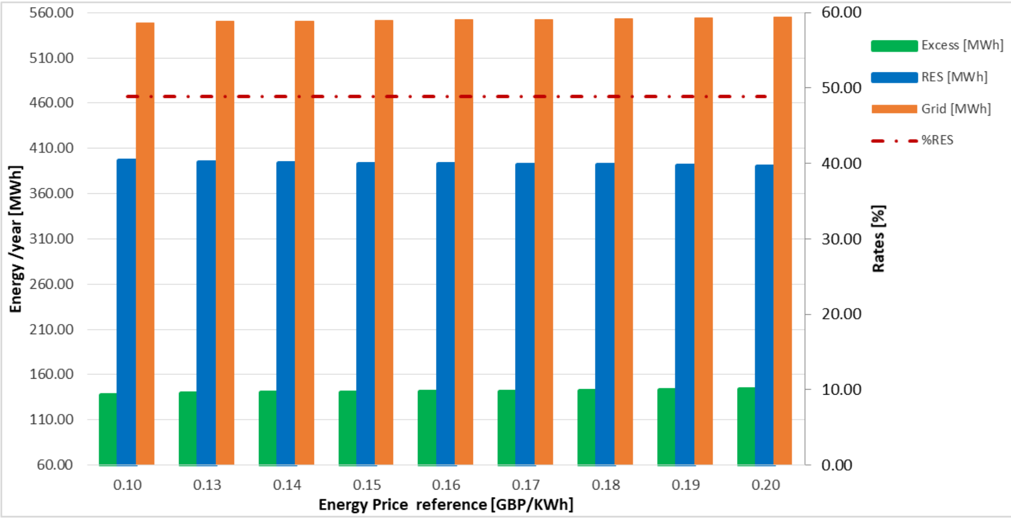


Figure 37: Penetration of RES and the Grid for EESSnom=100KW

Nevertheless, *Figure 38*, represents the operational energy cost managed by the BES at EESS nominal size of 20KW (parameter fixed). In blue colour, P_discharge represents the energy sold at higher price than the price reference (when the storage system is used), and in orange colour is P_charge, which illustrates the energy sold at lower price than the price reference. Also, a portion of P_charge comes from RES energy surplus to charge the BES. The difference between both is the saving value and it is depicted in green colour. As it is clearly seen, the mayor storage contribution is when the price reference is low. But even in that condition, the storage penetration into the system just achieved a roughly 6% at 0.10GBP (black hidden line) out of 35.5% aforementioned from RES, and it is decreased notably through the escalation of the price reference. Meanwhile, the saving varies slightly compared with the EESS rate penetration curve.

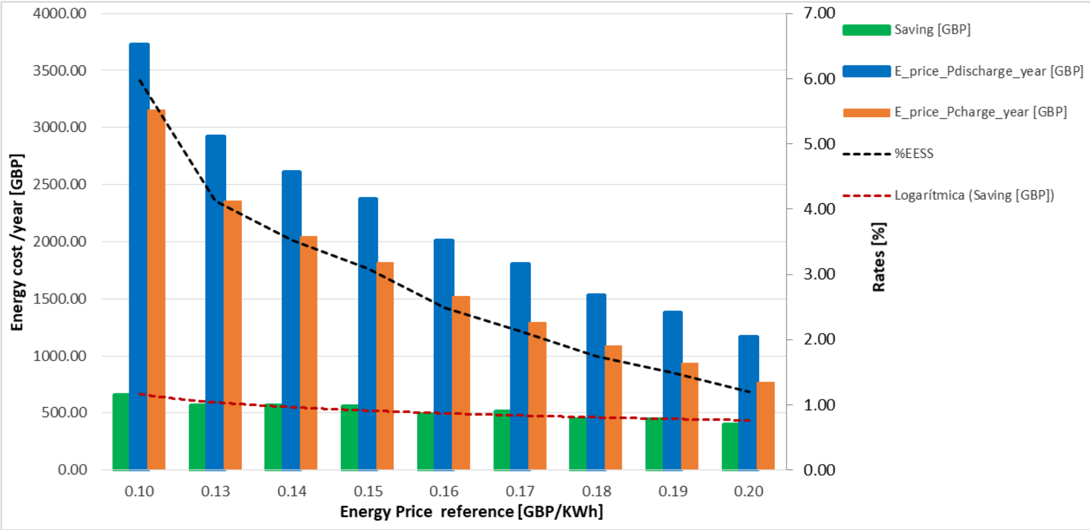


Figure 38: EESS insertion and benefits with EESSnom=20KW

Similarly, changing the EESS nominal size parameter to 100KW, *Figure 39* shows the results of the operational BES contribution. It is perceptible that both, energy cost and EESS rate have increased almost 5 times compared with the last graph, which is proportional to the storage size (parameter changed). Thus, the participation of the storage into the study case is under 28% at 0.10GBP (black hidden line) out of 35.5% from RES. However, the difference between the similarities between the energy paid for charging and discharging EESS are closer than is around 4 times, which is smaller than in *Figure 38*.

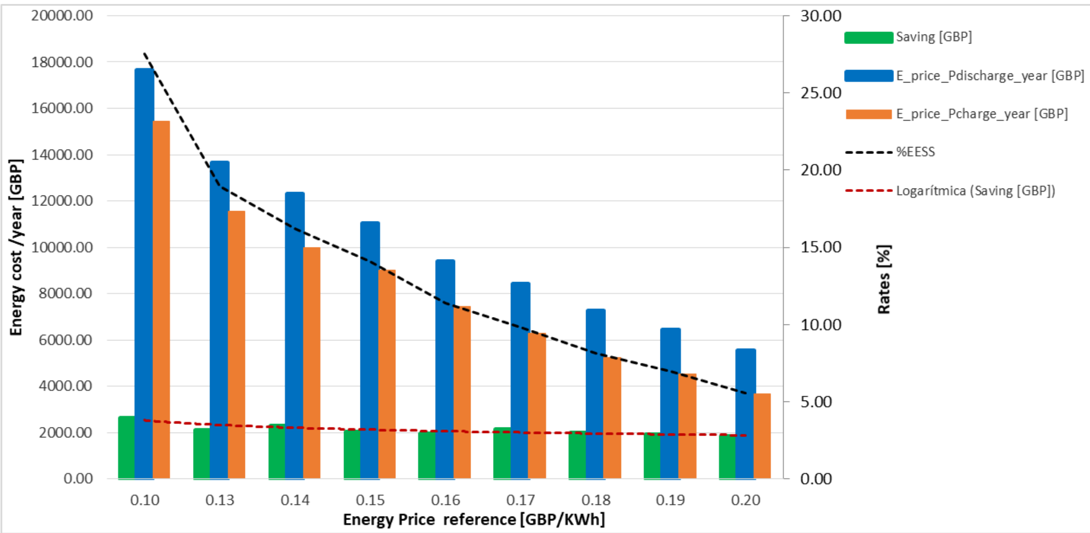


Figure 39: EESS insertion and benefits with EESSnom=100KW

Moreover, the total simulation results converge in Table 5, where the parameter EESS_nom (now, as the variable parameter) is in the first column from 10KW until 100KW, and each one was run in MatLab with the energy price reference at 0.10GBP (parameter fixed), which represents the 92% of the total demand.

While the BES energy capacity is increased, EESS penetration rate rises almost proportionally (from 3.80% to 27.51%). Nonetheless, the saving grows unperceivable compared with the potential investment on a storage system for the energy required. Hence, the payback time reaches around 4 times the BES lifespan for the cheapest technology. The NPV to assess the payback time gathers the capital cost, replacement cost, and operational and maintenance cost. Table 14 in the appendix A.3. displays the NPV and cost values data assumed for each BES technology.

EESS_nom [KW]	EESS capacity [KWh]	EESS power [KW]	%EESS	Saving [GBP]	Payback
10.00	79.16	9.45	3.80	310.89	62.92
20.00	126.96	19.93	5.98	659.01	47.61
40.00	253.92	39.72	11.65	1255.98	49.96
60.00	395.04	59.44	17.12	1698.89	57.46
80.00	507.89	78.88	22.42	2339.57	53.65
100.00	636.52	99.61	27.51	2652.69	59.30

Table 5: EESS insertion and benefits results with its payback

Graphically, the energy system performance results is obtained and shown in Figure 40, where the supply and demand are clearly identified, Pres is the RES portion that is feeding the load, Pgrid is the energy supplied by the Grid to feed the load and charging the BES when SOC is under 0.25, Pdischarge is the EESS energy to feed the demand, and Pcharge is the energy to charge the BES. The algorithm was run with an EESSnom=80KW and energy price=0.13GBP.

It is seen in the line graph that while RES is higher than the load, RES feed the demand. However, while RES is lower than the load, if the energy price is over 0.13GBP, the demand is fed by EESS, or it is fed by the grid if the price is under the energy price reference.

At first glance, Figure 40 validates that the load shifting application with energy price constraints does not allow RES to have a strong penetration into the microgrid. Moreover, reducing the value of the energy price reference to increase RES participation, just increase the payback time of the BES system to be installed, the EESS rate does not rise proportionally and either RES dispatchability.

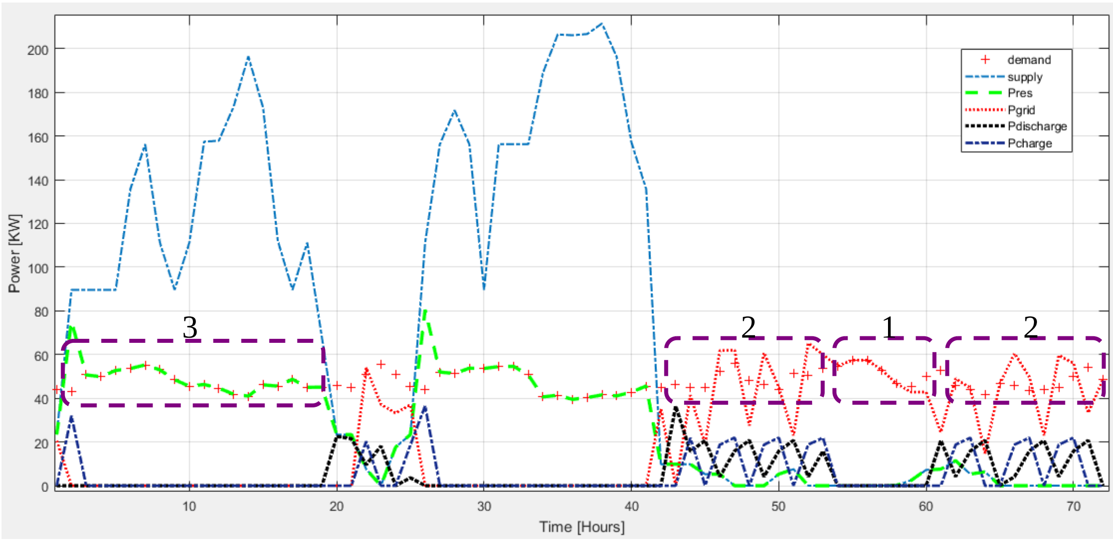


Figure 40: Energy systems performance achieved with the MatLab algorithm where EESSnom=80KW and energy price reference=0.13GBP

1. *Energy price reference under 0.13GBP (Grid supplies the demand).*
2. *Energy price reference over 0.13GBP (EESS supplies the demand as much as possible).*
3. *Demand fed by RES while BES is off.*

From another perspective, the application aforementioned could be evaluated as part of the scenario in a techno-economical analysis, comparing it to the installation of distributed generation systems. Accordingly, the saving value could be increased and the payback time would be reduced.

In another way, measuring the RES dispatchability without an EESS is useful to compare the storage benefits on RES operations. Thus, Figure 41 displays the demand dispatched by RES, which is almost 16% without a BES.

RES dispatchability without EESS			
Pnet>0 [KWh]	Pnet<0 [KWh]	% RES dispatchable	% Grid
150143.89	561075.70	15.89	84.11

Figure 41: RES dispatchability without EESS

Irrefutably, load shifting applications to avoid higher energy prices can be designed at any BES size, managing a particular criteria through the LDC to identify and select the time of use through the year, and governing the BES penetration into the Microgrid relying mainly on RES.

As it is clearly depicted in Figure 41, the algorithm proposed include the natural RES generation and an extra RES supply which depends on the EESS dimension seen in Table 5. However, the load shifting application usually accounts for a few hours through the year because is for covering the peak energy prices. Consequently, it is expected a small BES size, which should be into the values range shown in Figure 31, where the LDC illustrates the BES operation time through the year. Thus, the lowest payback achieved was for an EESS sized by 20KW and energy capacity of 126.96KWh (or 130KWh in rounded numbers) displayed in Table 5, where the EESS operation would be for just 6% and the payback time is equivalent to roughly 3 times more than the BES lifespan. However, the final benefit should be measured it compared to a distributed generation system investment from the generation side, but that evaluation is out of this dissertation project.

Conclusively, the algorithm proposed for the demand side of a Microgrid offers reasonable results with a clear applicability demonstrated in the study case. Now, in order to run the algorithm with the applicability to the supply side, in the following section is described the MatLab code evaluation through the study case with its results.

6.2. Maximisation of RES penetration application algorithm

Maximising the RES penetration imply to store the greatest amount of RES energy to supply the electrical system. Consequently, the parameter energy price reference is considered from 0.02GBP to run the MatLab code with 100% of the electrical demand.

From the algorithm proposed, it is expected to achieve results with substantial reductions of energy served by the grid, due to storing of the RES energy excess which help to feed the demand when Pnet <0 (case when the demand is greater than the supply). Moreover, it is expected that the total amount of RES and energy excess variables achieve the same rate than in the first algorithm (is the same study case).

Figure 42, illustrates in blue and green colour the RES and Excess energy produced respectively, where RES represents the energy required by the load and Excess is the stored energy by EESS. Contrarely, in orange colour is the BES energy required to keep the SOC over 0.20 solely. Moreover, as it seen in red dashdot colour, the RES rate is increased notably over 84% compared to almost 49% in the first simulation (load shaving application) out of the total energy supply from the microgrid, due to the huge energy reduction from the grid.

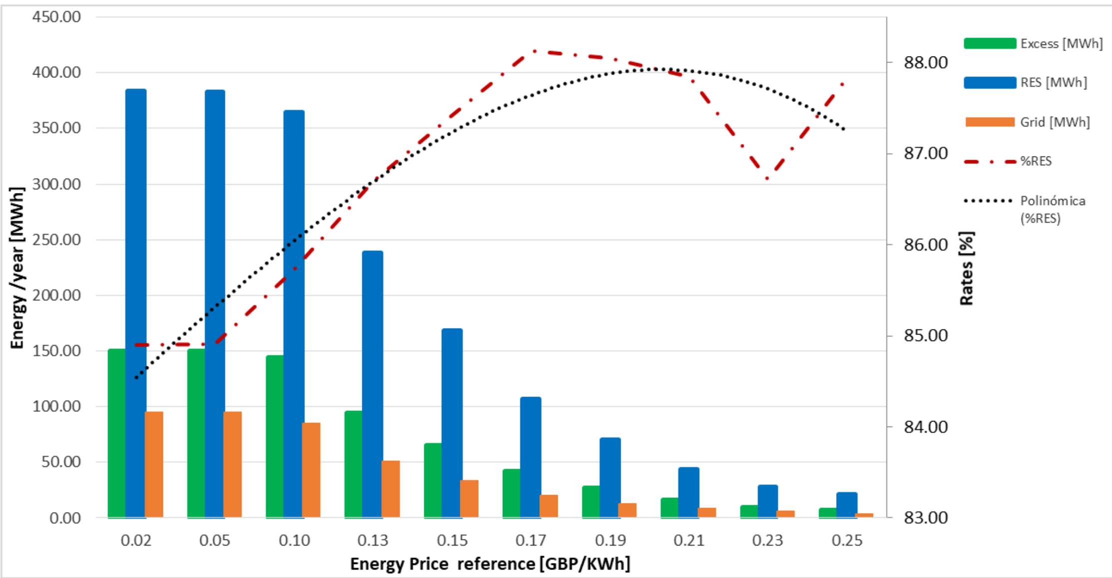


Figure 42: Maximization of RES penetration parameterized by energy prices

Figure 43, displays the operational energy cost managed by BES without restriction of EESSnom size, because differing with the first simulation, the main goal is to take the maximum energy from RES to dispatch it into the microgrid. Hence, in blue colour is P_discharge which represents the energy supplied by BES at free energy market price in each time slot (when the storage system is used). In orange colour is P_charge, which illustrates the energy from the grid to charge BES when is required (to keep the SOC over 0.20) at the energy market price. The difference between both is the saving value and it is depicted in green colour.

As it is clearly seen, the mayor EESS penetration and the maximum saving is at lowest price reference (when the total demand is managed by the system). In that condition, the electrical storage contribution in the system achieved over 67%, which it was calculated as the total energy managed by BES over the total demand, and it is decreased notably through the successive escalation of the price reference due to the reduction of the total amount of energy managed. Meanwhile, the saving varies correspondingly with the EESS rate penetration.

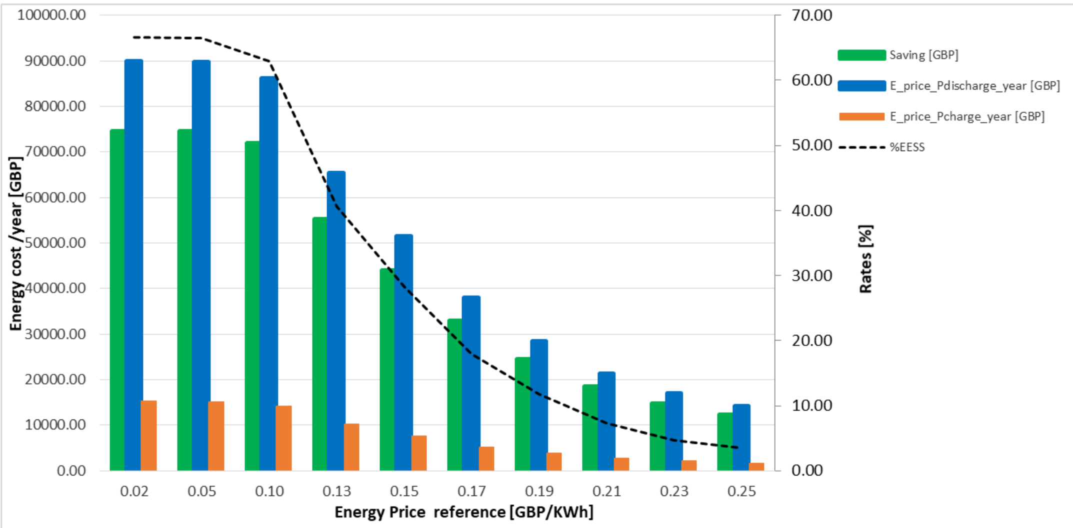


Figure 43:EESS insertion and benefits through energy prices

Regarding the energy contribution among the main components of the Microgrid to the loads, Figure 44 shows that the greatest proportion is given by RES independently of the energy market price reference with more than 85%. By contrast, a remarkable small proportion is required by the grid (under 17%), to supply the energy demand and charging the EESS when it is required. Moreover, while the EESS energy capacity and saving value are increased, the EESS penetration rate rises correspondingly. Nevertheless, the payback time reaches in the best scenario around 2 times the BES lifespan for the cheapest technology. Hence, the solution to increase RES dispatchability through EESS is still expensive, but is notably cheaper compared to the first algorithm. However, the application is totally different.

As it was abovementioned, Table 14 in the appendix A.3. displays the NPV to assess the payback time and cost values assumed for each BES technology.

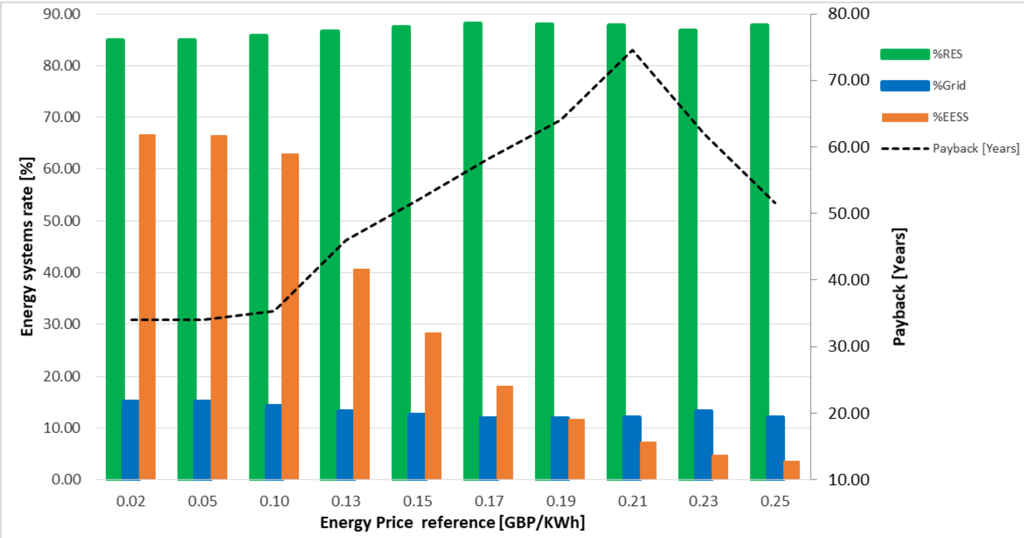


Figure 44: Energy systems penetration and EESS payback through energy prices

Graphically, the energy system performance results is presented in Figure 45, where the supply and demand are clearly identified, Pres is the RES portion that is feeding the load, Pgrid is the energy supplied by the Grid to feed the BES (rising the SOC), Pdischarge is the EESS energy to feed the demand, and Pcharge is the energy from RES to charge the BES. The algorithm was run with the energy price=0.02GBP (100% of the demand).

It can be seen in the line graph that, the green colour is identified as Pcharge and it represents the energy excess from RES which is stored by BES. In this situation, RES is consequently feeding the demand. However, while RES is lower than the load, BES has accumulated enough energy to supply the demand for some hours. The grid, represented by red colour, is just supplying energy when the SOC is under 0.25.

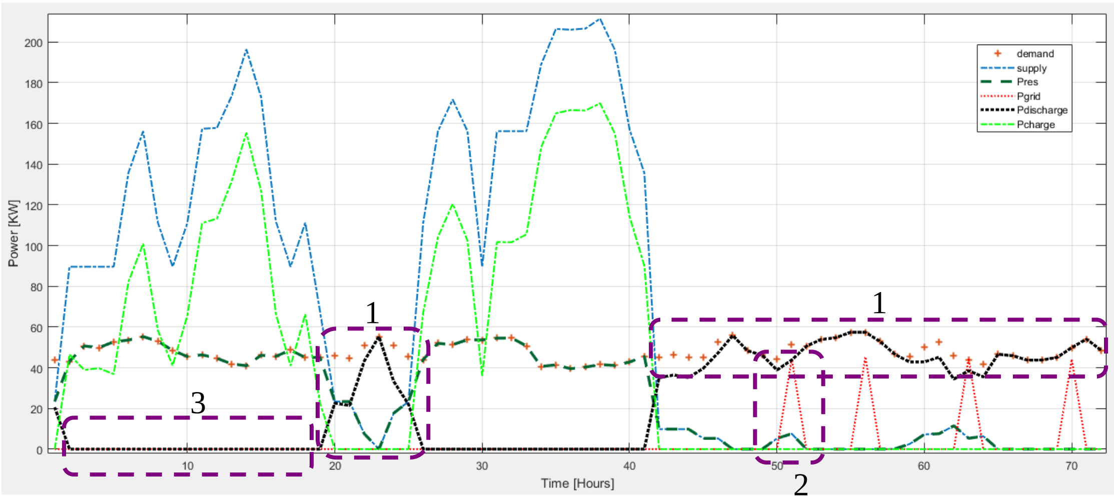


Figure 45:Energy systems performance achieved with the modified algorithm

1. *BES on, feeding the demand totally or partially when a few RES energy is supplied.*
2. *Grid charging BES to increase the SOC.*
3. *BES off, charging from RES.*

Table 6 gathers some results reached through both simulations, especially with the greatest RES penetration in each case. Even when each algorithm was created for a different purpose, the aim is to illustrate in which scenario is achieved the best results in terms of RES penetration and feasibility. Thus, the EESS capacity and power achieved with the second simulation were 10 times 3 times higher respectively than in the first simulation. Also, in the second simulation, the results have been better in term of RES penetration (1.75 times higher), EESS operation management (over 2.4 times higher) and payback time (almost one-third earlier). The total simulation results are given in the appendix A.5., Table 15.

EESS_size=100KW		First simulation				
Energy Price[GBP]	EESS_size_e/ day [KWh]	EESS_max_P /year [KW]	%RES	%EESS	Saving [GBP]	Payback [Years]
0.10	636.52	99.61	48.92	27.51	2652.69	95.29
		Second simulation				
Energy Price[GBP]	EESS_size_e/ day [KWh]	EESS_max_P /year [KW]	%RES	%EESS	Saving [GBP]	Payback [Years]
0.02	6398.22	300.27	84.90	66.58	74679.13	34.02
0.05	6398.22	300.27	84.91	66.47	74670.36	34.03
0.10	6398.22	300.27	85.72	62.92	71981.59	35.30

Table 6: Examples of simulation results

6.3. EESS techno-economic appraisal

From chapter 2.1 and chapter 2.2 was given the technical support and criteria to choose a BES as a feasible solution. Nevertheless, with ES-Select software, is added the cost and feasibility variables as part of the EESS technology study. Hence, is included the feasible cost-technological appraisal to complete the selection of the most appropriate EESS technology nowadays.

Figure 46, shows the location of the study case on the Grid system, in order to determine the most suitable EESS technology solution.

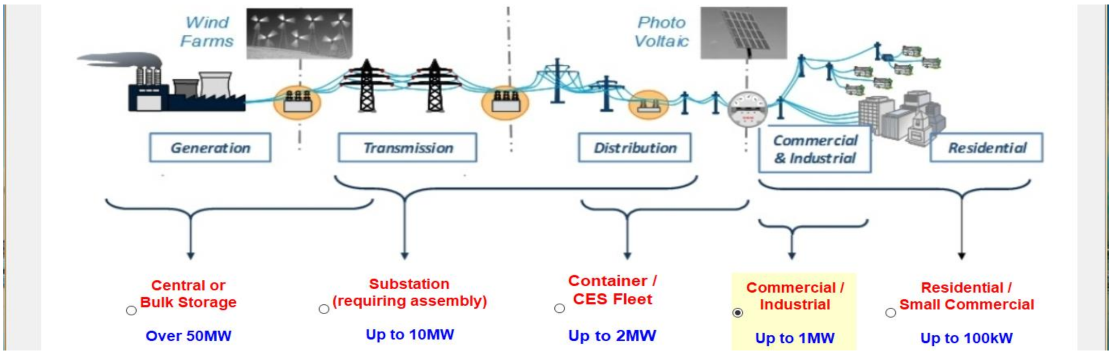


Figure 46: ES-Select software - Study case location on the Grid

Figure 47, shows the ES-Select software main screen. On the left hand is seen the input of the software, where is easily chosen the more important applications of the system to be studied, and the right side is displayed all energy storage technologies (options) considered as better options listed. Consequently, in red colour squares are highlighted the main applications (inputs) of the study case, and in a blue colour square, is highlighted the more suitable and feasible technology options applicable to the study case (output).

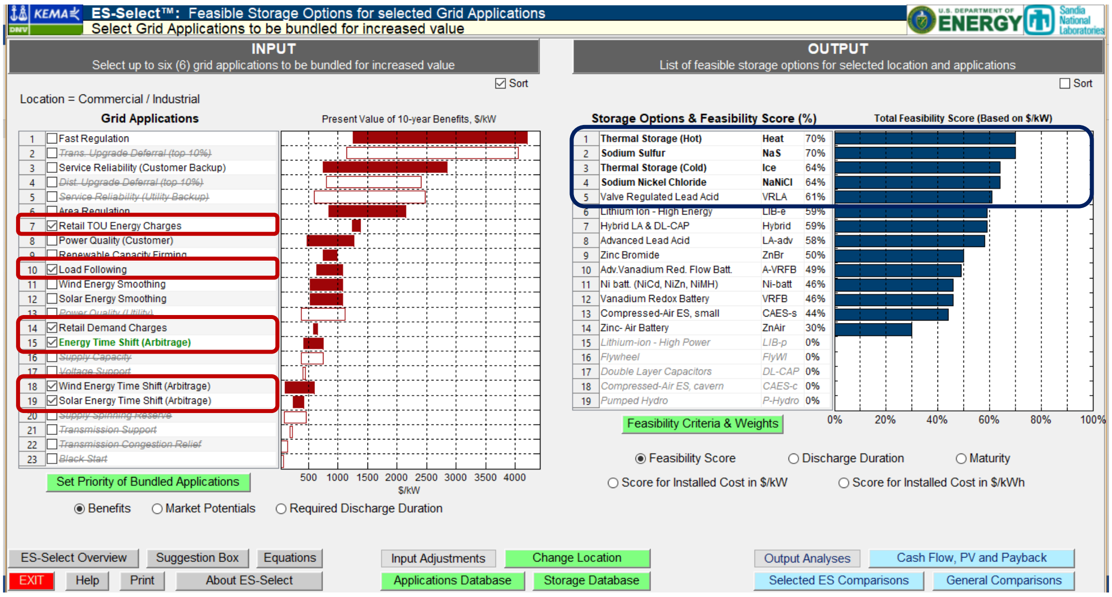


Figure 47: ES-Select software - Input/Output main-screen for up to 1MW EESS

On the input side, it was selected the options relatives to the applications aforementioned in this document, which are: Increasing the RES penetration, load shifting, demand charges, and time of use of the demand side (retail TOU). As a result, on the output side is revealed the sodium sulfur (NaS) technology as the most suitable and feasible solution for the application considered with 70% of feasibility score (in $/KW), secondly the sodium nickel chloride (NaNiCl) technology with 64%, and thirdly the valve regulated lead acid (VRLA) technology with 61%. Moreover, if there is excess power from RES, thermal storage (hot) is highly recommended (70%).

On the other hand, ES-Select offers more details about the feasible technologies appraisal. As an example, Figure 48 depicts for the best EESS option (NaS) which has a discharge duration between 6 and 7 hours, and the highest level of commercial maturity (90%). Those parameters help to measure the reliability of the system to be implemented.

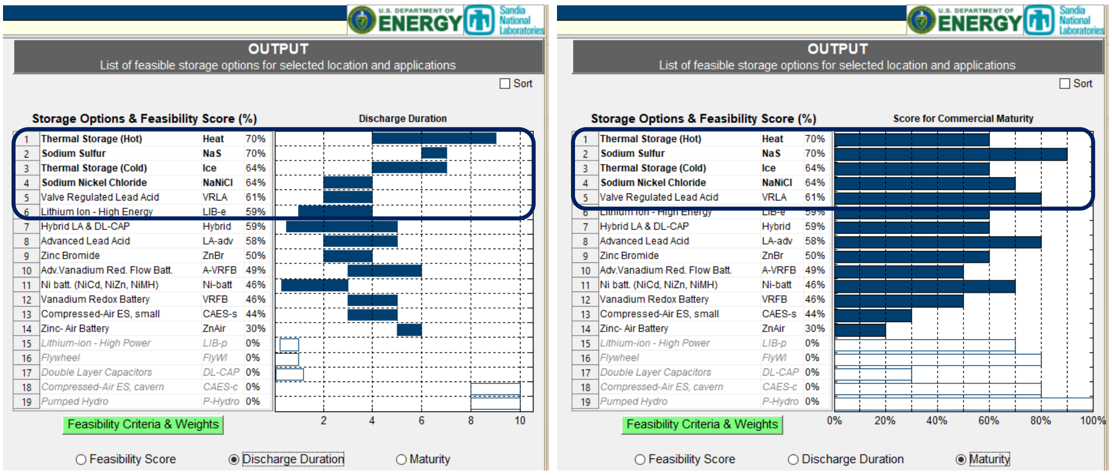


Figure 48: ES-Select software - Discharge duration and Maturity of feasible EESS technologies solutions

Regarding economic constraints, Figure 49, Figure 50, and Figure 51 display graphically diverse comparisons among the best technological options aforementioned. Those characteristics and other related concluded in favor of the sodium sulfur (NaS) technology as the best feasible solution.

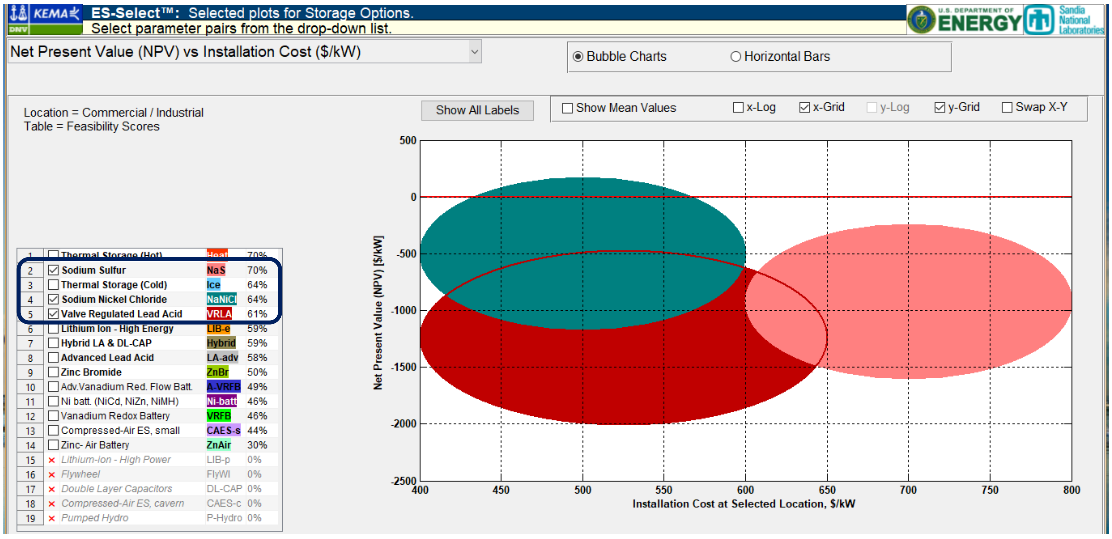


Figure 49:ES-Select software - NPV vs Installation cost ($/KW) comparison

Figure 49, illustrates negative net present value (NPV) for the three better options in the study case related to the installation cost. These values represent the typical economic losses at 15 years lifespan for the BES technology investment costs, without social, environmental or technological considerations, which are always associated with other factors not considered in the graph. As a validation test, in the appendix A.3 is shown the NPV for each BES technology calculated in Excel with the economic values data base from HOMER and Table 2. The results look quite analogous and into each ellipse displayed in the graph.

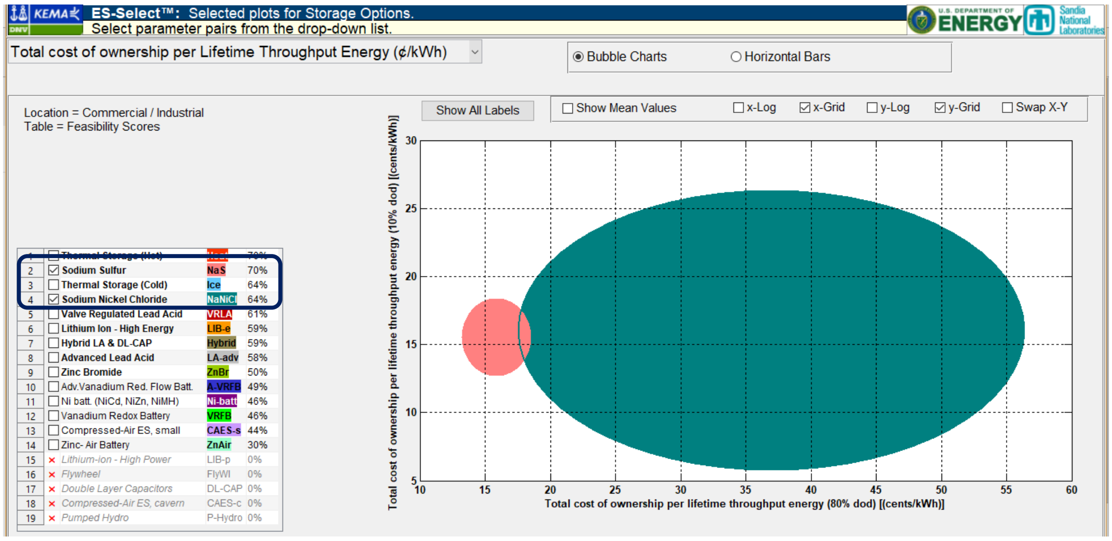


Figure 50: ES-Select software - Total cost of ownership per lifetime throughout energy (c/KWh)

Figure 50, displays the life cycle cost of both best BES technologies in the study case. The values represent the cost of the system including capital cost, operation, and maintenance cost, long-term costs (upgrading, decommissioning and replacement) and other associated costs. The graph helps to determine if the cost-benefit of the EESS (as an asset) could be profitable or not, excluding social, environmental or technological benefits.

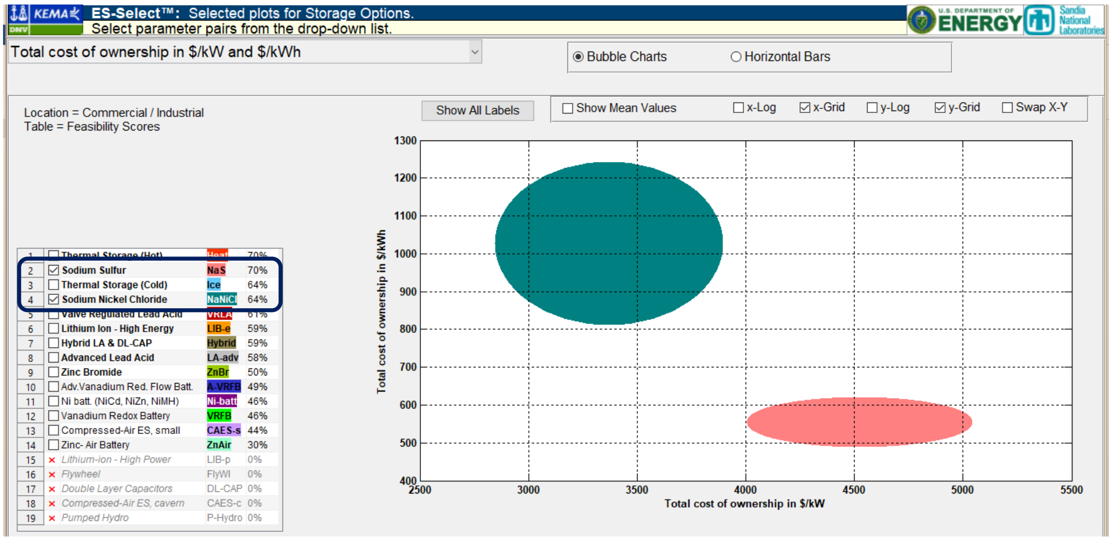


Figure 51: ES-Select software - Total cost of ownership in $/KW and $/KWh

Figure 51, shows the similar concept than Figure 50, but is related to the power cost installed vs the energy cost consumed, with the aim to identify the best operational position of the asset. The graph exclude social, environmental or technological benefits.

Nevertheless, assuming that the final EESS were smaller than 100KW (see Figure 46), the best feasible solution would be given by Figure 52, where is highlighted the Valve Regulated Lead Acid (VRLA) technology as the best EESS technology with 61% of feasibility score, and the Lithium-Ion High Energy (LIB-e) technology as the second best solution with 60%. Accordingly, independently of the solution given, the thermal storage is highly recommended with 76%, in the case of to be required a thermal storage due to excess of energy from RES.

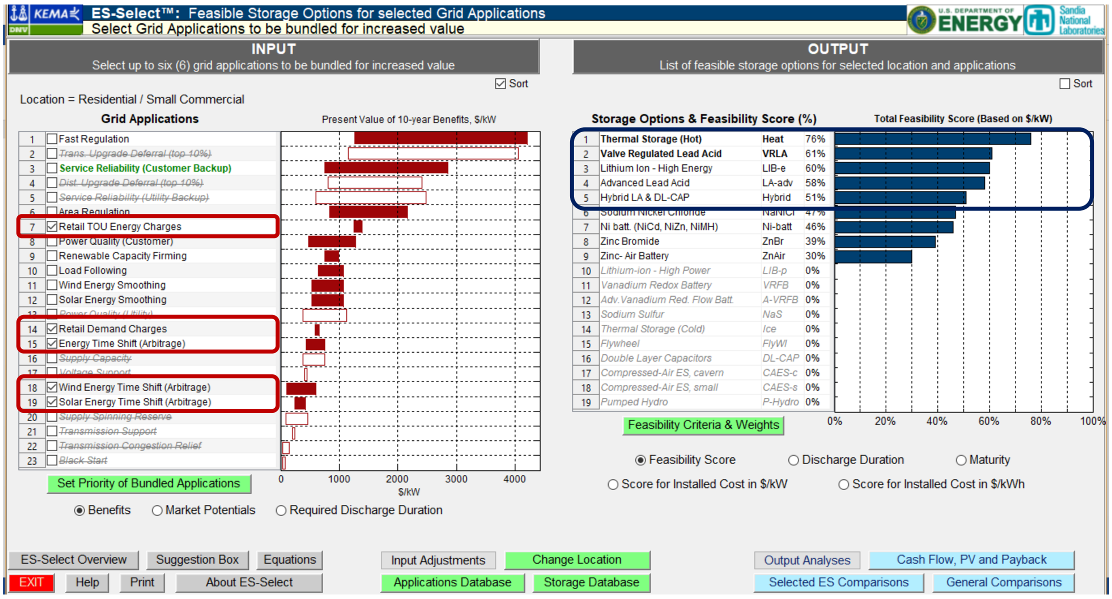


Figure 52: ES-Select software - Input/Output main screen for up to 100KW EESS

Conclusively, regarding the techno-economic appraisal from ES-Select side, the most suitable BES technology for an EESS up to 1MW is the sodium sulfur (NaS) technology, and for a smaller system (up to 100KW) is the Valve Regulated Lead Acid (VRLA) technology. Both scenarios suggest to include a thermal storage (hot) to keep any excess of energy coming from RES.

The author considers that due to the last tendencies on research, it should not exclude predictable improvements and reduced costs on BES technologies in the near future. As an example, the development of Li-Ion BES technology, which is actually widely used in other applications but, with the high potential to incease its uses as energy storage solution on RES and in electrical vehicles.

The comparative costs illustrated in Table 2 and Figure 16 demonstrate that cost per KW of NaS and Li-Ion technologies are actually almost equivalent. Operationally, Li-Ion offer a better power and energy density performance, remarkable lower degradation rate and lower storage volume. However, NaS has double duration on the discharge operation and more commercial maturity, especially in USA and Japan.

Another imperative aspect for RES penetration applications is the cycle lifetime and its efficiency. Comparing both technologies aforementioned, Li-Ion is slightly more efficient nowadays, but NaS looks quite generous related to its cycle lifetime.
Despite the cost and technical qualities, a third aspect is the implementation facility. According to (Wai Chong et al., 2016), NaS batteries are excessively flammable and considerable care must be taken during its operation. Thus, Li-Ion could be advantageous if the installation area requires meeting some demanding operational safe conditions.

Regarding the environmental impact, due to the current natural chemical composition of Li-Ion and NaS technologies, the last one is shown as more environmentally friendly and easier to recycle. Li-Ion is not totally recyclable yet. Nevertheless, agreeing with (Oliveira et al., 2015), using high efficiency storage units, such as Li-ion, NaNiCl and NaS can reduce the climate change impacts.

Concerning to human toxicity, reasonable efficiency and high volume systems, such as pumped hydro storage, NaS batteries and CAES are more supportive. Hence, regarding RES, the technologies aforementioned perform with low impacts to the ecosystem throughout all the categories addressed when the load is fed by WT.

Nowadays, batteries are everywhere and it is predictable to see it massively used as EESS in novel purposes, such as electric vehicles, network storage and surely new applications. On the other hand, researchers have been developing new EESS advances and reasonably each technology will improve its performance, intrinsical characteristics, its impact on the ecosystem, and prices will be reduced consistently, in order to act as a main contributor to the climate change through the incremental participation of RES on Microgrids.

Conclusively, the author opinion is that the final technology chosen in this chapter will depend on not just cost-technological analysis, it should also include the environmental assessment, recyclability and circular economy, safety considerations, the installation conditions with its possible expansion, the predictable growth rate and research tendencies, the location, and other potential factors. Thus, due to the dynamism on researching nowadays, it might be considered NaS, Li-Ion, and Lead Acid as feasible technologies to the particular context given.

7. Conclusions and Recommendations

The dissertation project aims to obtain two algorithms developed for dimensioning the minimum EESS required considering two diverse application: the load shifting application (demand side) constrained by the hourly peak cost, and the maximisation of RES penetration (supply side) to the electrical load. As a part of this section, it is intended to summarise the assessment of the results of the algorithms, its applicability, and suggestions of further works that could be done for this purpose.

7.1. General Discussion

The algorithms aid to assess the minimum EESS to cover a diversified non-residential load in Islay, an island located in the western Scotland as the study case. It was chosen because the location has the potential for RES generation, a Microgrid can be installed and the algorithms applicability is measurable. Thus, it is a suitable good small example to test the algorithms proposed.

For the algorithms testing process, the electrical load was chosen as fluctuant and demanding as possible, in order to avoid the standard and practically stable behaviour from a typical residential demand. Successively, the algorithms tests aided to elaborate the calculation refinement.

As part of the results, the energy system performance was depicted in both simulations, where it was quite interesting to see EESS operation on each application. It was clear how the storage operated against the RES power availability by hourly slots. Hence, the MatLab code operation was accurate. Moreover, the algorithms outcomes were gathered by tables and it was calculated the RES penetration rate, the yearly energy rate managed by EESS, saving and payback time in each test case. Clearly, both algorithms demonstrate that are applicable for sizing small and medium EESS. The best result during the first application was an EESS (130KWh, 20KW), which just it was involved 6% of the total energy managed through the year, and while in the second code the EESS (6400KWh, 300KW) was over 67%. Undoubtedly, the second application for RES penetration purposes has better results.

Sizing a minimum suitable EESS for each application coded, required the SOC calculation continuously. The BES performance was simulated and considered prudently, however a more accurate BES model could be elaborated to improve the final EESS estimation.

Regarding the dispatchability improvement for the study case, the total difference between the yearly supply and demand (calculation of yearly Pnet) is negative. It is mean that on the best scenario, it would never be achieved a 100% of RES dispatchability on the second application algorithm. Thus, the outcomes from the MatLab code calculation process are potentially reliable.

On the first application algorithm (demand side), usually the final benefit appraisal is calculated with a techno-economic analysis of the potential distributed generation system installation, which would cover the peak demand for a few hours through the year. Accordingly, the total saving value and payback time estimation in the algorithm proposed could be improved if it is added the cost/KWh of a typical generation plant installation into the calculation process.

On the second application algorithm (supply side), the final benefit appraisal could be improved if it is considered the BES price/KWh for a medium size installations or potentially a massive application, which usually is cheaper than the smaller size devices. Thus, the total saving value and payback time estimation in the algorithm proposed could be more realistic.

Conclusively, the algorithm results for each application have been logically reasonable. Its modular structure facilitate the expansion for future applications. Improvements related to BES modelling into the code can help to improve the SOC estimation through the hourly slot calculation process. Techno-economic benefits could be improved considering the application appraise in each algorithm.

Subsequently, further works could be done to improve the algorithm proposed.

7.2. Further works

A number of subjects for further research could be extended to this project and some are listed below.

A ponderation factor could be measured and implemented into the algorithm calculation process. In the modular code, after sizing the final EESS, could be added another module refered to the integral assessment, which consider not just cost-technological analysis, it should also include the environmental assessment, recyclability, safety considerations, easy implementation, and other potential factors.

Applying the optimization methods and improving the BES SOC calculation accurately, involving a general SOC curve and validation by a software to analyse the study case.

HESS (EESS-Power and EESS-Energy) model appraisal into the algorithm with shorter slots periods data to analyse the frequency response and regulation applications.

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Appendices

A.1. MatLab coding: Load shifting application

Parameters script

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```
% Defining parameters to be used in the Algorithm

clear; close all;

EESSnom=60;                       % Initial EESS capacity (from LDC)
EESSsize_maxE=0;                  % EESS size by energy [KWh](initial value)
EESSsize_maxP=0;                  % EESS size by power [KW](initial value)
BES_factor=1.10;                  % EESS minimum charge in high prices (<3)
EESScharge=zeros(365,1);          % Total energy charged in EESS/day
EESSdischarge=zeros(365,1);       % Total energy discharged in EESS/day
EESS_acum_maxE_day=zeros(365,1);  % Max energy used (cha or dis) in EESS/day
Excess=zeros(365,1);              % Total excess from RES/day
Grid=zeros(365,1);                % Total energy from the grid/day
RES=zeros(365,1);                 % Total energy from RES/day
Pcharge=zeros(8760,1);            % Power charged in EESS/slot
Pdischarge=zeros(8760,1);         % Power discharged in EESS/slot
Pexcess=zeros(8760,1);            % Power in excess from RES
Pres=zeros(8760,1);               % Power to the load fed by RES
Price_Pcharge_E=zeros(365,1);     % Total energy price charged in EESS/day
Price_Pdischarge_E=zeros(365,1);  % Total energy price discharged in EESS/day
Price_Pcharge_E_hour=zeros(8760,1);     % Total energy price charged in EESS/year
Price_Pdischarge_E_hour=zeros(8760,1); % Total energy price discharged in EESS/year
Pgrid=zeros(8760,1);              % Power from the Grid
Pnet=zeros(8760,1);               % RES - Demand net power
SOC=0.5*ones(8760,1);             % EESS assumes starting load
SOCmin=0.20;                      % EESS assumes minimum load
SOCmax=0.90;                      % EESS assumes maximum load
PriceReference=0.05;              % Energy price reference for analysis
EESSefficiency=0.70;              % Charging/Discharging efficiency
```

Power analysis script

16/08/17 11:13 PM C:\Users\fausto\Documents\M...\Power Analysis.m 1 of 1

```
% Power analysis between supply and demand by hourly slots


supply=xlsread('Data_Microgrid.xls',1,'1:8760');    % Read RES from .xls
demand=xlsread('Data_Microgrid.xls',2,'1:8760');    % Read demand from .xls
Pnet=supply-demand;                                 % Net power available
Prices=xlsread('Data_Microgrid.xls',3,'1:8760');    % UK energy prices 2016



for i=1:8760

    if Prices(i)<PriceReference                    % Energy price constraint

        Hourly_Net_Power_Analysis;                 % Hourly Pnet analysis
                                                   % under price reference
    else

        High_Hourly_Net_Power_Analysis;            % Hourly Pnet analysis
                                                   % over price reference
    end

    EESS_Daily_Analysis;                           % Gather energy and prices
                                                   % by days

end

EESS_Size;                                         % Size of the EESS

Export_Excel;                                      % Export Variables

```

Hourly Net Power analysis script

16/08/17 11:16 PM C:\Users\fausto\...\Hourly Net Power Analysis.m 1 of 1

```
% Algorithm to analyse the Hourly net power between supply and demand

if Pnet(i)>=EESSnom*(SOCmax-SOC(i)) && Pnet(i)>0     % Pnet >= EESS capacity
                                                     % S>D
    Pcharge(i)=EESSnom*(SOCmax-SOC(i));
    Pres(i)=demand(i)+Pcharge(i);
    Pexcess(i)=Pnet(i)-Pcharge(i);
    SOC(i+1)=SOCmax;

elseif Pnet(i)<EESSnom*(SOCmax-SOC(i)) && Pnet(i)>0 % Pnet < EESS capacity
                                                     % S>D
    Pcharge(i)=Pnet(i);
    Pres(i)=demand(i)+Pcharge(i);
    SOC(i+1)=SOC(i)+Pcharge(i)/EESSnom;

elseif (-1)*(Pnet(i))>=EESSnom*(SOC(i)-SOCmin) && Pnet(i)<0  % Pnet >= EESS capacity
                                                              % D>S
    Pres(i)=supply(i);
    Pgrid(i)=(-1)*Pnet(i);
    SOC(i+1)=SOC(i);

    if SOC(i+1)<0.25

        Pgrid(i)=Pgrid(i)+BES_factor*EESSnom*SOC(i+1);
        Pcharge(i)=BES_factor*EESSnom*SOC(i+1);
        SOC(i+1)=SOC(i+1)*(1+BES_factor);
        Price_Pcharge_E_hour(i)=Prices(i)'*Pcharge(i);

    end

elseif (-1)*(Pnet(i))<EESSnom*(SOC(i)-SOCmin) && Pnet(i)<0  % Pnet < EESS capacity
                                                             % D>S
    Pres(i)=supply(i);
    Pgrid(i)=(-1)*Pnet(i);
    SOC(i+1)=SOC(i);

    if SOC(i+1)<0.25

        Pgrid(i)=Pgrid(i)+BES_factor*EESSnom*SOC(i+1);
        Pcharge(i)=BES_factor*EESSnom*SOC(i+1);
        SOC(i+1)=SOC(i+1)*(1+BES_factor);
        Price_Pcharge_E_hour(i)=Prices(i)'*Pcharge(i);

    end

end
```

High Hourly Net Power analysis script


```
% Algorithm to analyse the Hourly net power between supply and demand
% at higher energy prices than the price reference

if Pnet(i)>=EESSnom*(SOCmax-SOC(i)) && Pnet(i)>0     % Pnet >= EESS capacity
                                                     % S>D
    Pcharge(i)=EESSnom*(SOCmax-SOC(i));
    Pres(i)=demand(i)+Pcharge(i);
    Pexcess(i)=Pnet(i)-Pcharge(i);
    SOC(i+1)=SOCmax;

elseif Pnet(i)<EESSnom*(SOCmax-SOC(i)) && Pnet(i)>0 % Pnet < EESS capacity
                                                     % S>D
    Pcharge(i)=Pnet(i);
    Pres(i)=demand(i)+Pcharge(i);
    SOC(i+1)=SOC(i)+Pcharge(i)/EESSnom;

elseif (-1)*(Pnet(i))>=EESSnom*(SOC(i)-SOCmin) && Pnet(i)<0  % Pnet >= EESS capacity
                                                              % D>S
    Pdischarge(i)=0.8*EESSnom*(SOC(i)-SOCmin);
    Pgrid(i)=(-1)*Pnet(i)-Pdischarge(i);
    Pres(i)=supply(i);
    SOC(i+1)=SOCmin+0.2*(SOC(i)-SOCmin);
    Price_Pdischarge_E_hour(i)=Prices(i)'*Pdischarge(i);

    if SOC(i+1)<0.25

        Pgrid(i)=Pgrid(i)+BES_factor*EESSnom*SOC(i+1);
        Pcharge(i)=BES_factor*EESSnom*SOC(i+1);
        SOC(i+1)=SOC(i+1)*(1+BES_factor);
        Price_Pcharge_E_hour(i)=Prices(i)'*Pcharge(i);

    end

elseif (-1)*(Pnet(i))<EESSnom*(SOC(i)-SOCmin) && Pnet(i)<0  % Pnet < EESS capacity
                                                             % D>S
    Pdischarge(i)=(-1)*(Pnet(i));
    Pres(i)=supply(i);
    SOC(i+1)=SOC(i)-Pdischarge(i)/EESSnom;
    Price_Pdischarge_E_hour(i)=Prices(i)'*Pdischarge(i);

    if SOC(i+1)<0.25

        Pgrid(i)=Pgrid(i)+BES_factor*EESSnom*SOC(i+1);
        Pcharge(i)=BES_factor*EESSnom*SOC(i+1);
        SOC(i+1)=SOC(i+1)*(1+BES_factor);
        Price_Pcharge_E_hour(i)=Prices(i)'*Pcharge(i);

    end

end
```

EESS Daily analysis script


```
% Algorithm to gather energy on daily basis


    day=365-(8760-i)/24;

    if mod(day,1)==0 && 1<=day && day<=365

        Pcharge_day=Pcharge((day-1)*24+1:(day-1)*24+24);

        Price_Pcharge_E_day=Price_Pcharge_E_hour((day-1)*24+1:(day-1)*24+24);

        Pdischarge_day=Pdischarge((day-1)*24+1:(day-1)*24+24);

        Price_Pdischarge_E_day=Price_Pdischarge_E_hour((day-1)*24+1:(day-1)*24+24);

        Pexcess_day=Pexcess((day-1)*24+1:(day-1)*24+24);

        Pres_day=Pres((day-1)*24+1:(day-1)*24+24);

        Pgrid_day=Pgrid((day-1)*24+1:(day-1)*24+24);

        EESScharge(day)=sum(Pcharge_day);

        Price_Pcharge_E(day)=sum(Price_Pcharge_E_day);

        EESSdischarge(day)=sum(Pdischarge_day);

        Price_Pdischarge_E(day)=sum(Price_Pdischarge_E_day);

        Excess(day)=sum(Pexcess_day);

        RES(day)=sum(Pres_day);

        Grid(day)=sum(Pgrid_day);

        % Determining max Energy/day by EESS

        if EESScharge(day)> EESSdischarge(day)

            EESS_acum_maxE_day(day)= EESScharge(day);

        else

            EESS_acum_maxE_day(day)= EESSdischarge(day);

        end

    end

```

EESS size script

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```
% Algorithm to determine the size of the EESS by Energy and Power

if max(EESScharge)>max(EESSdischarge)          % Determining max Energy

    EESSsize_maxE=max(EESScharge)/EESSefficiency;

else

    EESSsize_maxE=max(EESSdischarge)/EESSefficiency;

end

if max(Pcharge)>max(Pdischarge)                % Determining max Power

    EESSsize_maxP=max(Pcharge)/EESSefficiency;

else

    EESSsize_maxP=max(Pdischarge)/EESSefficiency;

end

EESS_acum_maxE_year=sum(EESS_acum_maxE_day);  % Max contribution of EESS
                                              % through the year
```

Export Excel script


```
% Export to Excel the variables gathered

% Export to Excel file "Data_Microgrid", EESScharge on sheet 4, range B

Expo_EESScharge_B=xlswrite('Data_Microgrid.xls',EESScharge,4,'B3');

% Export to Excel file "Data_Microgrid", EESSdischarge on sheet 4, range C

Expo_EESSdischarge_C=xlswrite('Data_Microgrid.xls',EESSdischarge,4,'C3');

% Export to Excel file "Data_Microgrid", Excess on sheet 4, range D

Expo_Excess_D=xlswrite('Data_Microgrid.xls',Excess,4,'D3');

% Export to Excel file "Data_Microgrid", RES on sheet 4, range E

Expo_RES_E=xlswrite('Data_Microgrid.xls',RES,4,'E3');

% Export to Excel file "Data_Microgrid", Grid on sheet 4, range F

Expo_GRID_F=xlswrite('Data_Microgrid.xls',Grid,4,'F3');

% Export to Excel file "Data_Microgrid", SOC on sheet 4, range G

Expo_SOC_G=xlswrite('Data_Microgrid.xls',SOC,4,'G3');

% Export to Excel file "Data_Microgrid", EESSsize_maxE on sheet 4, range G

Expo_EESSsize_maxE=xlswrite('Data_Microgrid.xls',EESSsize_maxE,4,'G1');

% Export to Excel file "Data_Microgrid", EESSsize_maxP on sheet 4, range E

Expo_EESSsize_maxP=xlswrite('Data_Microgrid.xls',EESSsize_maxP,4,'E1');

% Export to Excel file "Data_Microgrid", EESS_acum_maxE_year on sheet 4,
% range J

Expo_EESS_acum_maxE_year=xlswrite('Data_Microgrid.xls',EESS_acum_maxE_year,4,'J1');

% Export to Excel file "Data_Microgrid", Price_Pcharge_E_year on sheet 4,
% range J3

Expo_Price_Pcharge_E_year=xlswrite('Data_Microgrid.xls',Price_Pcharge_E,4,'J3');

% Export to Excel file "Data_Microgrid", Price_Pdischarge_E_year on sheet 4,
% range L3

Expo_Price_Pdischarge_E_year=xlswrite('Data_Microgrid.xls',Price_Pdischarge_E,4,'L3');
```

A.2. Simulation results: Load shifting application

EESS_size=20KW

Energy Price [GBP]	EESS_size_e/day [KWh]	EESS_max_P/day [KW]	Day	Date	EESS_max_P/year [KW]	Day	Date
0.10	195.15	16.29	14	Jan. 14 / 2016	19.93	128	May 07 / 2016
0.13	195.15	15.94	336	Dec. 01 / 2016	19.64	51	Feb. 20 / 2016
0.14	195.14	15.94	336	Dec. 01 / 2016	19.64	51	Feb. 20 / 2016
0.15	195.14	15.94	336	Dec. 01 / 2016	19.64	51	Feb. 20 / 2016
0.16	191.36	15.94	308	Nov. 03 / 2016	19.64	51	Feb. 20 / 2016
0.17	159.47	15.94	308	Nov. 03 / 2016	19.14	24	Jan. 24 / 2016
0.18	140.94	16.00	306	Nov. 01 / 2016	19.14	24	Jan. 24 / 2016
0.19	130.97	16.29	306	Nov. 01 / 2016	19.14	24	Jan. 24 / 2016
0.20	130.97	16.29	306	Nov. 01 / 2016	17.79	225	Oct. 12 / 2016
0.21	115.41	15.94	336	Dec. 01 / 2016	18.05	321	Nov. 16 / 2016
0.22	105.12	16.00	297	Nov. 23 / 2016	17.63	311	Nov. 06 / 2016
0.23	102.49	16.71	297	Nov. 23 / 2016	17.63	311	Nov. 06 / 2016
0.24	102.49	16.71	297	Nov. 23 / 2016	18.05	321	Nov. 16 / 2016
0.25	102.49	16.71	297	Nov. 23 / 2016	18.05	321	Nov. 16 / 2016
EESS_size_P/day [KW]:		16.71	EESS_size_P/year [KW]:		19.93	Note: Efficiency included	

Table 7: EESS energy and power capacity at EESSnom=20KW with dates

EESS_size=10KW

Energy Price[GBP]	EESS_size_e/day [KWh]	EESS_max_P/year [KW]	Excess [MWh]	RES [MWh]	Grid [MWh]	%RES	EESS_max_E_year [MWh]	%EESS	E_price_Pcharge_year [GBP]	E_price_Pdischarge_year [GBP]	Saving [GBP]	Payback [Years]
0.10	79.16	9.45	148.60	385.61	559.53	48.92	14.66	3.80	2118.03	2376.68	258.65	75.63
0.13	79.16	9.84	148.81	385.40	559.74	48.92	10.05	2.61	1593.23	1849.99	256.75	76.19
0.14	78.63	9.45	148.92	385.28	559.85	48.92	8.50	2.21	1400.33	1644.56	244.24	79.56
0.15	78.63	9.45	148.99	385.22	559.92	48.92	7.39	1.92	1243.26	1488.97	245.71	79.08
0.16	74.81	8.92	149.14	385.06	560.08	48.92	5.93	1.54	1033.22	1268.48	235.25	78.58
0.17	62.34	9.07	149.22	384.98	560.16	48.92	5.02	1.30	901.44	1127.49	226.05	68.15
0.18	56.43	8.72	149.32	384.89	560.25	48.92	4.06	1.05	751.90	952.95	201.05	69.36
0.19	53.38	8.70	149.39	384.81	560.33	48.92	3.49	0.91	637.35	853.24	215.88	61.11
0.20	53.38	8.71	149.48	384.73	560.41	48.92	2.73	0.71	538.53	707.59	169.05	78.03
	Note: Efficiency included											

Table 8: Simulation for EESSnom=10KW

EESS_size=20KW

Energy Price[GBP]	EESS_size_e/day [KWh]	EESS_max_P/year [KW]	Excess [MWh]	RES [MWh]	Grid [MWh]	%RES	EESS_max_E_year [MWh]	%EESS	E_price_Pcharge_year [GBP]	E_price_Pdischarge_year [GBP]	Saving [GBP]	Payback [Years]
0.10	126.96	19.93	146.77	387.44	557.70	48.92	23.15	5.98	3154.45	3729.67	575.22	54.54
0.13	126.96	19.64	147.24	386.96	558.17	48.92	15.97	4.13	2353.03	2920.33	567.30	55.30
0.14	126.96	19.64	147.49	386.71	558.42	48.92	13.61	3.52	2048.54	2614.55	566.01	55.43
0.15	126.96	19.64	147.59	386.61	558.53	48.92	11.92	3.08	1816.77	2378.61	561.84	55.84
0.16	112.43	19.64	147.91	386.29	558.84	48.92	9.61	2.49	1520.88	2013.77	492.88	56.37
0.17	100.25	19.14	148.06	386.14	559.00	48.92	8.23	2.13	1294.06	1808.02	513.96	48.20
0.18	87.03	19.14	148.26	385.95	559.18	48.92	6.73	1.74	1085.85	1531.90	446.06	48.21
0.19	87.03	19.14	148.42	385.79	559.36	48.92	5.78	1.50	932.80	1378.83	446.03	48.22
0.20	87.03	18.52	148.70	385.50	559.64	48.92	4.63	1.20	767.09	1168.87	401.79	53.53
	Note: Efficiency included											

Table 9: Simulation for EESSnom=20KW

EESS_size=40KW

Energy Price[GBP]	EESS_size_e/day [KWh]	EESS_max_P/year [KW]	Excess [MWh]	RES [MWh]	Grid [MWh]	%RES	EESS_max_E_year [MWh]	%EESS	E_price_Pcharge_year [GBP]	E_price_Pdischarge_year [GBP]	Saving [GBP]	Payback [Years]
0.10	253.92	39.72	144.01	390.20	554.94	48.92	45.45	11.65	6259.03	7347.43	1088.39	57.65
0.13	253.92	39.72	144.81	389.39	555.74	48.92	31.34	8.05	4638.64	5745.52	1106.88	56.69
0.14	253.92	39.72	145.18	389.03	556.11	48.92	26.64	6.85	4058.96	5129.87	1070.91	58.59
0.15	253.92	39.72	145.42	388.79	556.35	48.92	23.31	5.99	3615.22	4662.18	1046.96	59.93
0.16	224.85	39.72	145.97	388.24	556.90	48.92	18.79	4.84	2970.21	3960.34	990.13	56.12
0.17	200.49	39.72	146.21	388.00	557.14	48.92	16.09	4.15	2561.37	3535.23	973.86	50.88
0.18	180.93	39.69	146.64	387.56	557.56	48.92	13.22	3.41	2152.94	3014.63	861.70	51.89
0.19	165.26	37.80	146.89	387.32	557.83	48.92	11.37	2.94	1832.85	2723.91	891.06	45.83
0.20	165.26	37.80	147.39	386.81	558.34	48.92	9.09	2.35	1505.26	2312.33	807.07	50.60

Note: Efficiency included

Table 10: Simulation for EESSnom=40KW

EESS_size=60KW

Energy Price[GBP]	EESS_size_e/day [KWh]	EESS_max_P/year [KW]	Excess [MWh]	RES [MWh]	Grid [MWh]	%RES	EESS_max_E_year [MWh]	%EESS	E_price_Pcharge_year [GBP]	E_price_Pdischarge_year [GBP]	Saving [GBP]	Payback [Years]
0.10	395.04	59.44	141.73	392.47	552.66	48.92	67.21	17.12	9393.79	10831.95	1438.16	67.88
0.13	380.88	59.48	142.63	391.57	553.56	48.92	46.34	11.83	6987.69	8513.98	1526.29	61.67
0.14	380.88	59.48	143.16	391.04	554.09	48.92	39.54	10.11	6153.43	7573.19	1419.76	66.29
0.15	380.88	59.48	143.68	390.52	554.61	48.92	34.31	8.78	5445.63	6874.34	1428.72	65.88
0.16	337.28	59.48	144.32	389.89	555.25	48.92	27.79	7.13	4437.67	5868.66	1430.99	58.25
0.17	305.18	59.48	144.65	389.56	555.58	48.92	23.70	6.08	3903.92	5185.35	1281.43	58.85
0.18	244.61	59.39	145.12	389.09	556.04	48.92	19.49	5.01	3191.86	4475.27	1283.42	47.10
0.19	241.50	55.22	145.43	388.78	556.38	48.92	16.75	4.31	2742.60	4035.33	1292.73	46.17
0.20	240.02	55.22	146.24	387.97	557.19	48.92	13.32	3.43	2269.21	3406.34	1137.13	52.16

Note: Efficiency included

Table 11:Simulation for EESSnom=60KW

EESS_size=80KW

Energy Price[GBP]	EESS_size_e/day [KWh]	EESS_max_P/year [KW]	Excess [MWh]	RES [MWh]	Grid [MWh]	%RES	EESS_max_E_year [MWh]	%EESS	E_price_Pcharge_year [GBP]	E_price_Pdischarge_year [GBP]	Saving [GBP]	Payback [Years]
0.10	507.89	78.88	139.61	394.60	550.53	48.92	88.46	22.42	12340.67	14345.02	2004.36	62.62
0.13	507.89	79.79	140.94	393.26	551.87	48.92	60.74	15.45	9352.27	11085.56	1733.29	72.41
0.14	507.89	79.48	141.52	392.68	552.45	48.92	51.83	13.20	8216.30	9957.18	1740.88	72.10
0.15	507.89	79.48	141.93	392.27	552.86	48.92	45.06	11.49	7264.40	8962.98	1698.59	73.89
0.16	449.76	79.48	142.70	391.51	553.63	48.92	36.41	9.30	6012.93	7652.12	1639.20	67.81
0.17	400.98	79.48	143.17	391.04	554.09	48.92	30.99	7.93	5053.15	6864.30	1811.15	54.71
0.18	354.80	79.48	143.77	390.44	554.68	48.92	25.63	6.56	4227.44	5900.80	1673.35	52.40
0.19	323.44	78.64	144.19	390.01	555.16	48.92	22.01	5.64	3713.76	5202.80	1489.04	53.68
0.20	323.44	78.64	145.07	389.13	556.04	48.92	17.58	4.52	3005.53	4407.52	1401.98	57.01

Note: Efficiency included

Table 12: Simulation for EESSnom=80KW

EESS_size=100KW

Energy Price[GBP]	EESS_size_e/day [KWh]	EESS_max_P/year [KW]	Excess [MWh]	RES [MWh]	Grid [MWh]	%RES	EESS_max_E_year [MWh]	%EESS	E_price_Pcharge_year [GBP]	E_price_Pdischarge_year [GBP]	Saving [GBP]	Payback [Years]
0.10	636.52	99.61	137.81	396.40	548.73	48.92	109.07	27.51	15442.15	17674.74	2232.59	70.46
0.13	636.52	99.61	139.31	394.89	550.24	48.92	74.90	18.97	11551.18	13667.72	2116.53	74.32
0.14	636.52	99.79	139.97	394.24	550.89	48.92	63.95	16.22	9997.63	12319.52	2321.89	67.75
0.15	636.52	99.79	140.84	393.36	551.77	48.92	55.37	14.08	9018.37	11051.99	2033.62	77.35
0.16	581.29	99.79	141.32	392.88	552.25	48.92	44.82	11.41	7428.39	9413.41	1985.02	72.37
0.17	501.23	99.79	141.72	392.48	552.65	48.92	38.48	9.81	6298.99	8440.95	2141.96	57.83
0.18	441.91	99.79	142.54	391.67	553.44	48.92	31.84	8.13	5257.42	7275.06	2017.64	54.13
0.19	402.71	99.79	143.18	391.02	554.15	48.92	27.20	6.96	4543.40	6463.57	1920.17	51.83
0.20	402.71	99.79	144.24	389.97	555.21	48.92	21.69	5.56	3677.52	5547.89	1870.37	53.21

Note: Efficiency included

Table 13: Simulation for EESSnom=100KW

A.3. Net Present Value (NPV) for each BES technology

Prices from HOMER software and Table 2			
Technology:	**VRLA**	**NaS**	**Li-Ion**
LifeSpam[years]:	10.00	15.00	15.00
Capital Cost [GBP/KWh]:	150.00	500.00	300.00
Replacement[GBP/KWh]:	150.00	500.00	300.00
Op. & Mnt.[GBP/year]:	10.00	10.00	10.00
NPV O&M [GBP/Lifespan]:	83.60	97.12	97.12
NPV O&M [GBP/5years]:	52.12		
NPV @15years [GBP/KWh]:	**435.72**	**597.12**	**397.12**
Lifespan post 20years[years]:	**5.00**	**0.00**	**0.00**

Table 14: NPV for each BES technology

A.4. MatLab coding: Maximise RES penetration application

Power Analysis to maximise EESS script

17/08/17 06:56 PM C:\Users\faus...\Power Analysis Maximise EESS.m 1 of 1

```
% Analysis of hourly power between supply and demand


supply=xlsread('Data_Microgrid.xls',1,'1:8760');    % Read RES from .xls
demand=xlsread('Data_Microgrid.xls',2,'1:8760');    % Read demand from .xls
Pnet=supply-demand;                                 % Net power available
Prices=xlsread('Data_Microgrid.xls',3,'1:8760');    % UK energy prices 2016



for i=1:8760

    if Prices(i)>PriceReference                     % Energy price constraint

        Maximise_EESS_Net_Power_Analysis;           % Hourly Pnet analysis
                                                    % over price reference
    end

    EESS_Daily_Analysis;                            % Gather energy and prices
                                                    % by days

end

EESS_Size;                                          % Size of the EESS

Export_Excel;                                       % Export Variables
```

Maximise EESS Net Power analysis script


```
% Algorithm to maximise EESS through the Hourly net power
if Pnet(i)>0 && Pnet(i)>0                               % S>D
    Pcharge(i)=Pnet(i);                                 % Accounting the BES portion
    Pres(i)=demand(i);                                  % RES feeding the load
    Pexcess(i)=Pnet(i);                                 % S-D = Pnet
    if Pnet(i)>EESSnom  && Pnet(i)>0                    % Pnet > EESS capacity
                                                        % S>D
        EESSnom=Pnet(i);                                % New BES size
        SOC(i+1)=SOCmax;
    else
        SOC(i+1)=SOC(i)+(Pnet(i)/EESSnom)*(SOCmax-SOC(i));
    end
else
                                                        % D>S
    Pdischarge(i)=(-1)*(Pnet(i));                       % Accounting the BES portion
    Pres(i)=supply(i);                                  % RES feeding the load
    Price_Pdischarge_E_hour(i)=Prices(i)'*Pdischarge(i);
    if (-1)*(Pnet(i))>EESSnom && Pnet(i)<0              % Pnet > EESS capacity
        EESSnom=(-1)*(Pnet(i));                         % New BES size
        SOC(i+1)=SOCmax;
    else
        SOC(i+1)=SOC(i)-((-1)*(Pnet(i))/EESSnom)*(SOC(i)-SOCmin);
        if SOC(i+1)<0.25
            Pgrid(i)=BES_factor*EESSnom*SOC(i+1);
            Pcharge2(i)=Pgrid(i);
            SOC(i+1)=SOC(i+1)*(1+BES_factor);
            Price_Pcharge_E_hour(i)=Prices(i)'*Pcharge2(i);
        end
    end
end
```

A.5. Simulation results: Maximise RES penetration application

Simulation results from Matlab algorithm modified												
Energy Price[GBP]	EESS_size_e/day [KWh]	EESS_max_P/year [KW]	Excess [MWh]	RES [MWh]	Grid [MWh]	%RES	EESS_max_E_year [MWh]	%EESS	E_price_Pcharge_year [GBP]	E_price_Pdischarge _year [GBP]	Saving [GBP]	Payback [Years]
0.02	6398.22	300.27	150.14	384.06	95.03	84.90	645.81	66.58	15253.98	89933.11	74679.13	34.02
0.05	6398.22	300.27	150.05	383.42	94.78	84.91	645.18	66.47	15232.69	89903.06	74670.36	34.03
0.10	6398.22	300.27	144.83	364.93	84.89	85.72	602.97	62.92	14248.01	86229.60	71981.59	35.30
0.13	6398.22	300.27	94.91	238.18	51.12	86.69	400.91	40.65	10277.24	65527.62	55250.38	45.99
0.15	5764.84	300.27	65.73	168.68	33.74	87.42	285.10	28.37	7649.28	51658.22	44008.94	52.02
0.17	4853.60	300.27	42.36	107.55	20.18	88.14	187.76	18.00	5140.59	38175.12	33034.53	58.35
0.19	3982.50	300.27	27.21	70.47	13.26	88.05	123.89	11.74	3906.28	28600.65	24694.37	64.04
0.21	3497.94	293.99	16.68	43.74	8.36	87.85	79.82	7.28	2766.41	21398.97	18632.56	74.55
0.23	2311.05	293.99	10.05	28.61	5.92	86.72	54.82	4.72	2301.53	17106.71	14805.18	61.99
0.25	1625.46	293.99	7.46	21.59	4.03	87.83	40.58	3.50	1699.68	14215.69	12516.01	51.57
	Note: Efficiency included											

Table 15: Simulation results (algorithm modified)