CRANFIELD UNIVERSITY

Albert Sancho Balsells

Management of the Electricity Supply in Alderney

School of Energy, Environment and Agrifood
MSc in Offshore and Ocean Technology with Offshore Renewable Energy

MSc Thesis
Academic Year: 2014 -2015

Supervisor: Dr. J.V. Sharp
Industrial Supervisor: James Lancaster
Sep 2015

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This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science

ABSTRACT

The energy system in islands usually relies upon the fossil fuel importation and, consequently has low security of supply as well as high and fluctuated costs. An alternative to address these problems is the development of a Renewable Energy (RE) system which can provide the whole electricity demand and can be funded through community owned investment. This master thesis aims to assess the feasibility of supplying the electricity demand of the Channel Island of Alderney by a combination of RE with energy storage.

The island of Alderney is the most northerly of all the Channel Island and its location is perfect to harness onshore and offshore renewable resources. After assessing the different renewable resources and current energy storage technologies, this report proposes an energy system of 1.5MW anaerobic digester plant and a 475 kW solar PV park with NaS batteries to reduce the dependency on diesel and generate the Alderney electricity supply of 1.5MW. The feasibility of supplying the Alderney's electricity demand by the proposed energy scheme is assessed and it is concluded that the RE system is technically feasible. However, the main roadblock to its implementation is the socioeconomic constraint. This could be solved through community owned renewable energy system or with more community involvement in the Alderney's energy decisions such as the funding mechanism for the necessary grid upgrades to allow the safely operation and the connection of the RE system.

The report concludes, after analysing different energy fuels such as diesel, hydrogen and other RE resources, that there are multiple options to supply the electricity demand in Alderney with important advantages in terms of cost, reliability and environmental impact. The proposed RE system could be one of the best alternatives to supply the island electricity with low-carbon fuel, high security of supply and stable prices.

Keywords:

Renewable energy; Electrical energy storage; Alderney; Anaerobic digester; Solar PV energy; Hydrogen.

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LIST OF ACRONYMS

Alderney Commission Renewable Energy (ACRE)

Alderney Electricity Limited (AEL)

Alderney Renewable Energy (ARE)

Alderney Wildlife Trust (AWT)

Alternative Current (AC)

Anaerobic Digestion or Anaerobic Digester (AD)

Battery Energy Storage System (BESS)

Capital Expenditure (CAPEX)

Combined Heat and Power (CHP)

Community Owned Renewable Energy (CORE)

Direct Current (DC)

Electrical Energy Storage (EES)

European Union (EU)

France-Alderney-Britain (FAB)

Global Horizontal Irradiation (GHI)

Great Britain Pound (GBP)

Green House Gas (GHG)

Horizontal Axis Wind Turbine (HAWT)

Levelised Cost Of Energy (LCOE)

Operation and Maintenance (O&M)

Operational Expenditure (OPEX)

Photovoltaic (PV)

Pumped Hydrogen Energy Storage (PHES)

Renewable Energy (RE)

Round Trip Efficiency (RTE)

States of Alderney (SoA)

Tidal Stream Turbine (TST)

United Kingdom (UK)

United States (US)

United States Dollar (USD)

Vertical Axis Wind Turbine (VAWT)

Wind Turbine (WT)

1 INTRODUCTION

During the last decades, Renewable Energy (RE) technologies have improved their performance and reliability. Consequently, their share in the electrical market has been increased. Specially, they are emerging as an alternative in isolated systems like an island where the electricity generation was based on fossil fuels as diesel. As a result, several examples of electrical isolated system with an important RE integration can be found. Furthermore, there are some cases as the Island of Samso [1] in Denmark as well as the Isle of Eigg [2] in Scotland where the whole electricity demand is generated through RE. Another example is the Island of Hierro in Spain which became the first isolated system in the World to supply the whole electricity demand during 4 hours through RE [3]. This thesis assesses the potential of Alderney to become one of the first in the World with 100% RE integration into the electrical system.

Usually these kind of developments is highly linked to community owned systems where the community owns the RE system. Apart from funding the investment, the community actively participates in the development and receive several advantages of it as saving the money of the electricity bills, getting some grants from the governments, the creation of new jobs for the community and the increase of the local economy.

Firstly, this master thesis introduces the island of Alderney and its characteristics as the location, the current electricity situation and the electrical grid. Then, it is generally presented the different RE and available Electrical Energy Storage (EES). After assessing these, a RE energy systems with EES is proposed and its feasibility is analysed in two different scenarios. Finally, the thesis concludes by introducing the different funding strategies as well as comparing the proposed system based on RE fuels against other energy fuels such as diesel, hydrogen and other RE.

2 INTRODUCTION TO ALDERNEY

Alderney is the third largest and most northerly Channel Island. Despite it is part of Europe, it is independent from the European Union (EU) as well as the United Kingdom (UK). However, the Alderney inhabitants are considered British citizens and there are other influences as in the language and the official currency that is the Pound Stirling [4]. The government of Alderney is ruled by the State of Alderney (SoA) but since 1948, when Alderney became part of the Bailiwick of Guernsey, the States of Guernsey has financial and administrative responsibility for some public service such as the airport, the breakwater, police, social service, health and education [5]. As a result, Alderney pays to Guernsey for that service as well as it requires approval from Guernsey for large financial expenditure.

Alderney has a population around the 2000 residents which the majority of them live in the capital of the island, St. Anne. Nowadays, this population can be divided in two groups where approximately 2/3 of the inhabitants are normal demographic families and the other 1/3 are people at the last stage of their career [6]. As a result of this third, the population in Alderney has been decreasing along the recent years. In addition to those residents, the population in Alderney peaks at 3000 people during the summer period, especially during the Alderney Week in August, due to touristic attractions as ecotourism, war history and sailing. Apart from the tourism, the economy of the island is mainly based on e-gambling as well as on small businesses [7]. Below, it can be seen a map of Alderney with the airport in the southwest, the main harbour, Braye Harbour, and the capital of St Anne.

Figure 2-A: Map of Alderney [4]

2.1 Geographical location

As explained before as well as displayed in the Figure 2-B, Alderney is the most northerly of all the Channel Island located at 60 miles from the south coast of England as well as at 20 miles northeast away from the island of Guernsey. In addition, the Alderney Race separates the island from the closest French mainland, the Cherbourg Peninsula, which is located 8 miles west of Alderney.

However, the nearest British port, Poole, and French port, Cherbourg, are situated at 110 km and 30 km from the island respectively.

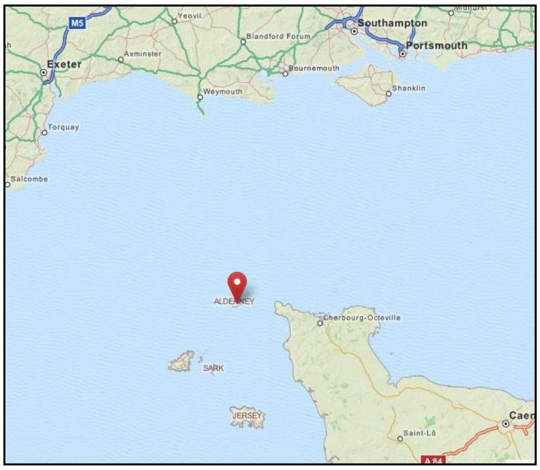
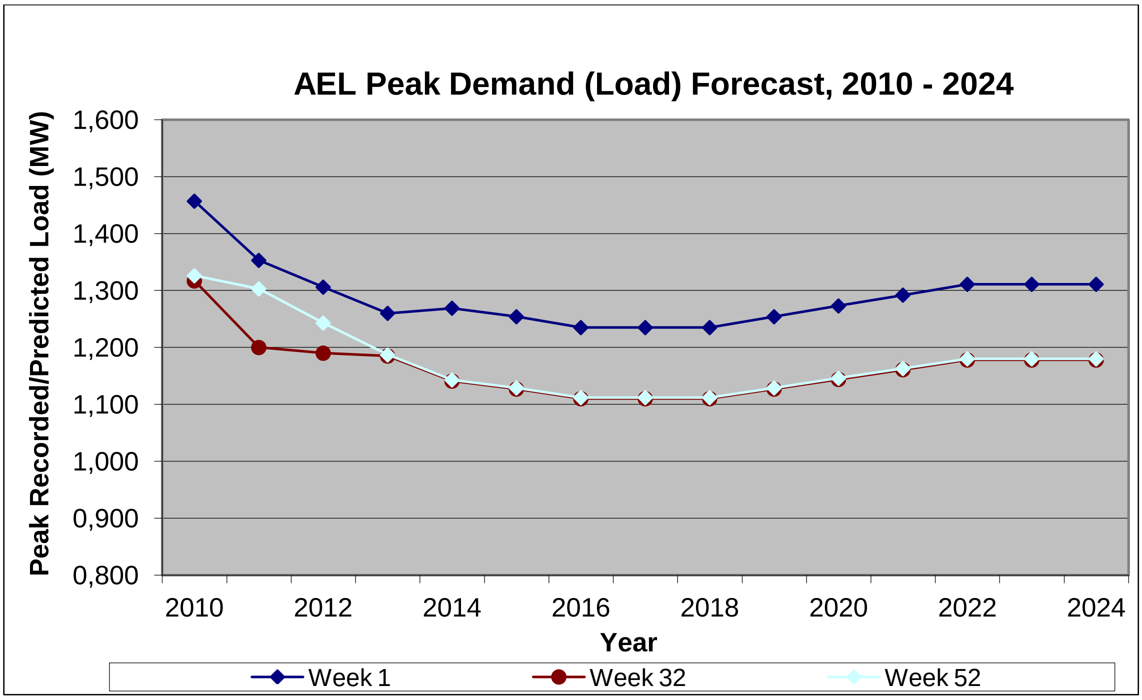


Figure 2-B: Geographical location of Alderney [8]

The island itself is 3.5 miles long and 1.5 miles wide, having a total area of 3 square miles. Moreover, Alderney's territorial waters extends 90 nm^2 around the island and due to the third United Nations Convention of the Law of the Sea it has the right to claim for a total of 500 nm^2. In spite of the benefit of having more territorial waters to harness RE resources, the SoA is not planning to claim that right due to the higher legal responsibilities such as ship transport and buried munitions of the World War II [9]. Despite the small territory, the island of Alderney and its surroundings have a huge diversity in flora and fauna, especially in birds that use the island for reproduction and during the migration routes. As a result, there are three conservation reserves that differ dramatically between them, two conservation reserves and one Ramsar site, which are managed by the Alderney Wildlife Trust (AWT) in order to protect these zones in a long term [10].

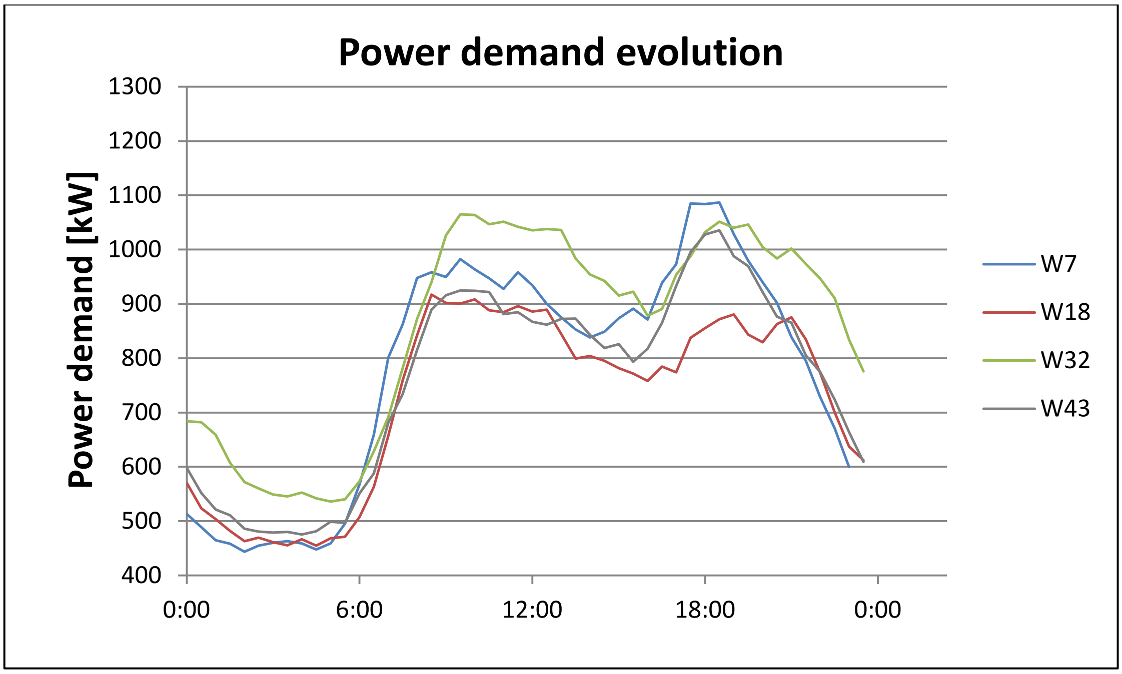
2.2 Current electricity situation

Currently, the electricity demand in Alderney varies between 1.1 MW and 0.4MW with the peaks of demand during the Alderney week and August (weeks 31 to 33) and winter periods (weeks 50 to 52 and 1 to 4) [11]. The electricity peak demand it has been decreasing along the last 7 years and it is forecasted to continue decreasing in the following years as displayed in the graph.

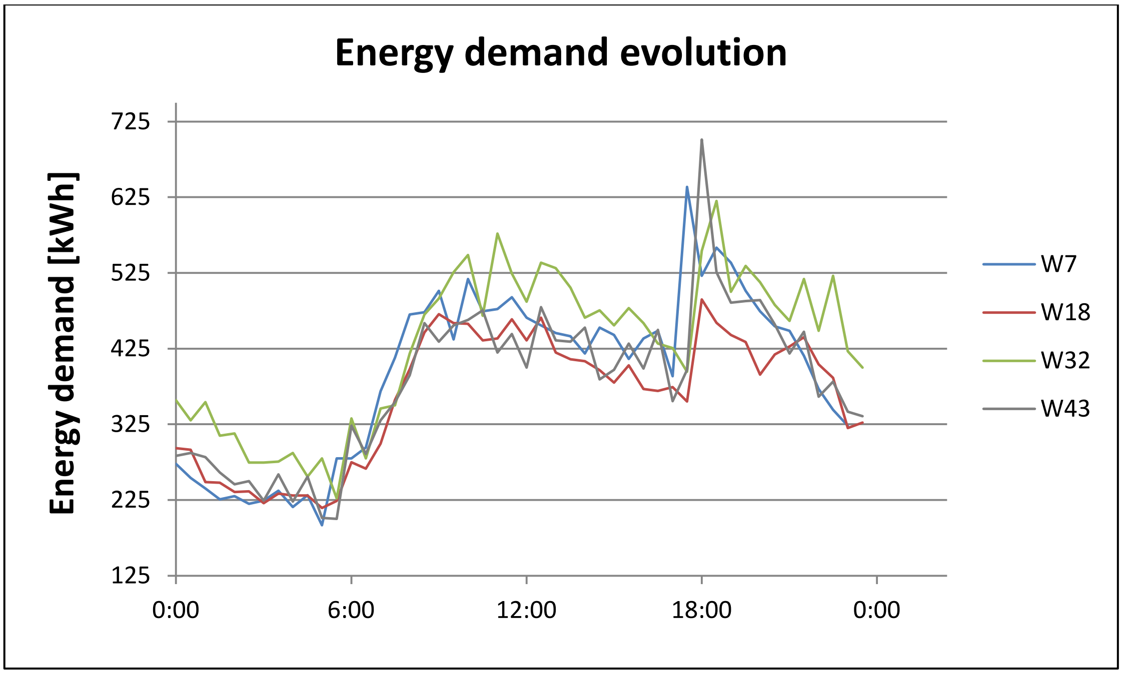


Graph 2-A: Peak power demand recorded and forecasted by the AEL [11]

In terms of energy, it has been a significant decrease from the 6,912 MWh of 2013 to the 6,648 MWh of 2014 and the forecasted 5,800 MWh of 2015 [11]. Apart from the August and winter peaks, the energy demand is quite stable between seasons as it can be seen in the following figures extracted from the demand analysis realized in the Appendix A.



Graph 2-B: Power demand evolution during average days.



Graph 2-C: Energy demand evolution during average days.

As it can be stated, the electricity demand peaks during the midday and afternoon/night period in all the different weeks. This demand mainly comes from residential properties and small business consumption as well as from the hospital and the generation power plant [7].

Nowadays the power generation in Alderney relies upon diesel due to all the electricity supply being provided through a diesel power plant run by Alderney Electricity Limited (AEL). AEL has been run as a non-profit company for many years and its primary purpose is to meet the energy needs of the island on behalf of the community. AEL was created at 1938 and in 1953 received the exclusive right to supply electricity in the island that is provided by means of a diesel power plant [12] [13]. This plant is located close to the Braye Harbour where the ships with the diesel and kerosene, for the heating system, arrive via Guernsey which has the highest priority. Then the fuel is pumped through a pipeline to the power station where it is stored in 13 tanks, which provide at least 3 weeks of reserve with an average cost of £8K/yr [7] [14].

Picture 2-A: Diesel and kerosene storage tanks

From those tanks, the diesel is supplied to one of the seven generators where the diesel is burned to obtain the electricity. This power plant had an annual consumption of 1.8 million litres in 2014 with a cost of 0.397GBP/L and an efficiency of 3.56 kWh/L. There are installed three different kinds of generator: three Paxman generators of 2MW from 1999 installed in 2007 and four Blackstones generators two of 450kW from 1968and another two of 750 kW from 1972 [6] [15].

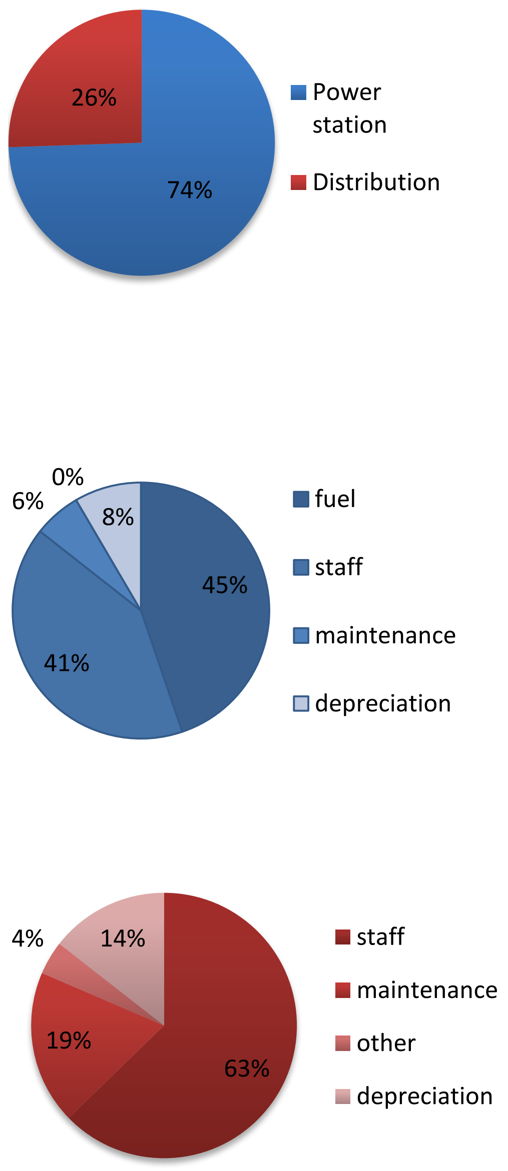
Picture 2-B: Paxman (left) and Blackstones diesel generator (right)

The Paxman generators require top overhauls every 10,000 engine hours with a cost of 54,000GBP and major overhauls which are realized in Colchester with a cost of 120,000GBP every 30,000 engine hours [14]. In the case of small maintenance such as oil and injector changes and major overhauls of the Blackstones can be realized inside the power plant with the spare parts stocked in the top of the plant. Following the maintenance schedule predicted by the AEL, by 2020 as a maximum two Blackstones generators will be decommissioned and it will be required a new generator which should cost around £350k [15].

Picture 2-C: Spare parts to realize minor maintenance and repairs

Currently if all the generators are run in parallel, they can provide a maximum of 8.4 MW and hence, the system is over-sized. It has to be stated that to minimise the maintenance cost, AEL employs the Paxman during high demand periods with balanced loads and the Blackstones generators with lower demand periods [15].

Nowadays, AEL is making a small profit for the electricity supply that it shares with the different shareholders which mainly are the SoA [4]. The current cost of energy is around 37p/kWh with the following breakdown between generation and distribution costs [16].



Graph 2-D: Energy generation and distribution cost breakdown [12]

The majority of these costs such as infrastructure, oil storage and maintenance, administrative and staff costs are independent of the oil price. As a result, reducing the Alderney's electricity demand by installing private RE systems such as solar photovoltaic (PV) roofs panels will lead to a higher cost per unit due to those fixed costs as well as the higher oil prices related to the smaller amount of fuel importation [6].

For the above reasons, in the near term and long term it is very unlikely to see huge reductions in the electricity cost [6] until a new grid connection links to the mainland or distributed generation like RE microgeneration systems with energy storage are developed. Those developments will provide a more affordable, secure and sustainable energy supply. However, they will require severe improvements in the current electrical grid connection that will be detailed in the following points [6].

2.3 Alderney Electricity Grid

Nowadays Alderney's electrical grid system is an isolated grid due to not being linked to any other surrounding electrical grid as the ones in Guernsey or to the French mainland. As a result, all the electricity supply is provided from the power plant and it is distributed through a grid distribution system of 11 kV. This electricity distribution system, which is displayed below, is mainly buried underground (except one overhead section in the northeast of the island) in order to avoid the severe weather conditions of Alderney. In that figure, it can be seen as well the 20 different substation where by means of 100 - 500 KVA transformers the high voltage electricity is reduced to 1000 V and then to 440/250 V [15]. This low voltage electricity is transmitted to the different consumption points by underground lines.

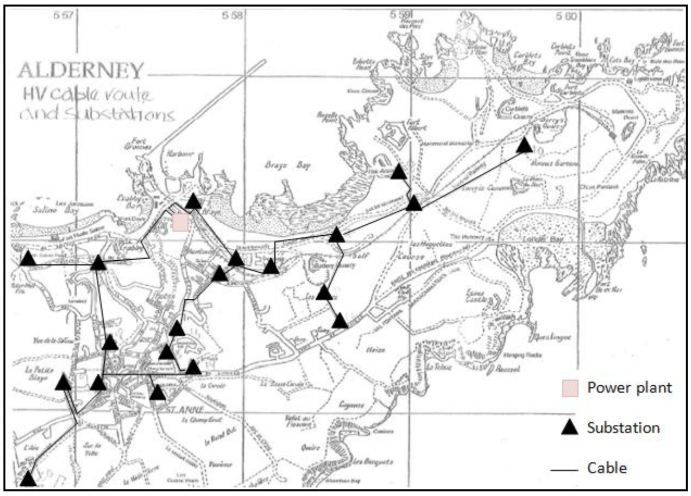


Figure 2-C: Alderney's electricity transmission system [11]

Despite it was estimated that the current grid system can support loads of a maximum 6MW and the asset management programme launched in 2007 by the AEL, the last major upgrade was in 1950's [6] [17] [18]. As a result, the current network does not meet the modern standards and it has several risks in terms of safety, security and supply vulnerability. In addition, the majority of the AEL's staff which are responsible to maintain and operate the system safely have an aging workforce over 50 and it is very difficult to train new people [17] [18]. Consequently, the AEL has proposed an accelerated infrastructure three years plan in order to solve these problems focused on key assets as the 8 most important substations, the Airport and Whitegates cable and the B station close to the power plant [15] [17] [18]. In addition, it includes the high voltage infrastructure upgrade to the most suitable areas for large-scale developments as community RE projects like large scale PV or other kind of microgeneration systems [6] [15] [17] [18]. Moreover, AEL has planned the construction of three control loops in the network in order to increase the reliability of the system in case that a failure happens in one part of it [15] [17] [18]. The cost of the programme is estimated at £1.49m and AEL is working with SoA to identify the best funding mechanism which allows this necessary development while not increasing the long term debt neither the electricity costs [17] [18]. Following, there are some pictures of a modern and old substation as well as the underground cable arriving to the fire substation in the centre of St Anne.

Picture 2-D: Switchgear and main switches of a modern substation

Picture 2-E: Switchgear and main switches of an old substation

Picture 2-F: Underground cable arriving to the under construction fire station substation

2.4 Challenges and future for the Alderney's islanded energy systems

As explained previously, nowadays the Alderney's electrical grid system is isolated and relies upon the diesel price fluctuations, which increased the double and triple during the last decade, and the situation in the diesel exporter countries. Moreover, as detailed before, the diesel supply is related to high maintenance costs due to minor and major overhauls and tank refurbishment [6]. As a result, the current scenario is not the ideal one for Alderney and it is necessary to design a more reliable, environmental friendly and affordable energy system. There are different possibilities to achieve that goal as integrating RE to the electrical grid or buying low carbon energy from other countries.

One solution could be the RE integration through microgeneration systems to the Alderney's electrical grid. These microgeneration systems can exploit diverse RE resources as solar, wind, tidal, wave, biomass and geothermal. However that integration in the stand-alone power systems of Alderney will lead to several economical, technical and operational challenges. The first one is the required improvements in the electrical network and the linked high investment costs in order to operate the grid in terms of health and safety standards as well to allow the generated electricity to be fed back to the grid. In addition, the main issue is the poor power quality and reliability related to the instantaneous, daily and seasonal energy output fluctuations. As a result, there will be a mismatch between generation and demand due to the limitations to forecast this and hence energy storage systems will be required. Furthermore, the investment costs are high with low recovery factors as well as the O&M costs due to the prices of the spare parts that they are not in stock and the difficulties to get technical assistance [19]. EES will solve most of these challenges as well as optimising the electricity supply by converting and storing the excess of electricity into another energy source and feeding back to the grid at peak electricity demand.

Apart from the possible microgeneration systems, a 300MW tidal stream energy system by Alderney Renewable Energy (ARE) and Open Hydro is planned by the earliest on 2021 [6] [20]. The tidal stream array will be located in the Alderney Race area and theoretically will be divided in three phases of 100MW each between 2020 and 2023 [20]. However, there are some uncertainties around this operational time because it is highly linked with the construction of an interconnector between France and UK through Alderney called France Alderney Britain (FAB) link which is planned to be fully operational by 2022 [21]. The main purpose of this interconnector of 220km of high voltage cable is to provide a way to extract green energy from the big Alderney's tidal resources and sell it to areas that requires electricity from RE resources as the UK and France. Furthermore, it will increase the security of supply in the UK and European countries by allowing the positive and negative power exchange between grids of cheap and sustainable energy [21].

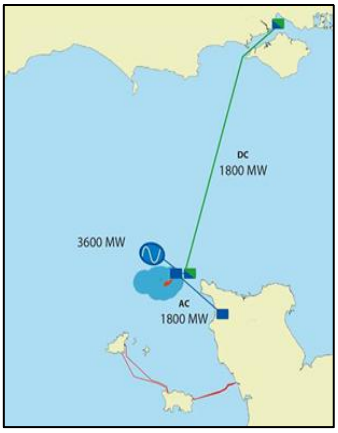


Figure 2-D: Initial layout of the FAB link [22]

Additionally, the FAB link may positively affect the Alderney's energy system by connecting it to the FAB link's onshore converter station through a conditioning station. This conditioning station will be required in order to reduce the high voltage of the 700 MW converter station to the 11kV voltage of the Alderney's network. However, nowadays there are some doubts regarding the Alderney connection to the FAB link because is not 100% clear who will be responsible for the huge investment related to the conditioning station.

Figure 2-E: ARE developments location [20]

Picture 2-G: FAB link departure point to the UK (left) and France (right)

Picture 2-H: Manez quarry where the converter station should be located

Another option to provide Alderney with a reliable, affordable and environmental friendly energy system could be investing in a 20km link to the French grid point. However, the required investment of this scenario should be very high [15].

3 AIM AND OBJECTIVE OF THE PROJECT

All the different alternatives presented previously and other ones that will appear in later stages of the report are correct and there is not an optimum scheme to provide Alderney with green energy. However, it has to be stated that this report will be focused on supplying the Alderney's electricity demand by the integration of a combination of RE apart from the FAB link and the tidal stream array developments.

As a result, the main goal of this thesis is to study the potential and feasibility of supplying all the electricity demand of the island of Alderney by means of onshore and offshore RE with the support of an EES system. It is useful to compare the electricity management and the different energy fuels of the proposed scenario in terms of price, security of supply and sustainability with three more: the current one which uses diesel fuel, the current one with EES and using imported hydrogen as fuel. In addition, the different funding strategies are assessed in order to propose the more suitable for the Alderney case study.

Before starting with the assessment process, it has to be defined the different constraints of the project. First, it is fixed a peak electricity demand to be supplied of 1.5 MW by means of different RE systems due to the uncertainty of predicting the future demand. Because of the different risk and uncertainties related to the construction of the FAB link and the tidal stream system by 2022, this study is focused on a solution to supply the Alderney's electricity demand as an isolated system. Furthermore, the possibility of continuing to supply the electricity from other RE systems after these developments is analysed and take it into account as a very probable scenario. Finally, it is borne in mind as realistic as possible the different stakeholders involved on this process as well as the current facilities and infrastructure in Alderney.

4 RENEWABLE ENERGY RESOURCES AROUND ALDERNEY

The geographical location of Alderney offers the opportunity to exploit many onshore and offshore RE resources to get electricity. In order to exploit those resources while preserving the surrounding environment, different commissions, groups and companies such as the Alderney Commission for Renewable Energy (ACRE), Alderney Renewable Energy (ARE) and AWT have been created during the last years. The ACRE was created in 2007 and it has the power to "licence and regulate the operation, deployment, use or management of all forms of renewable energy in the island of Alderney and its territorial waters" [23]. For example, ACRE has collaborated with the creation of guidance for decommissioning RE systems [24] or for the licensing and consents process [25] which facilitates the development of RE systems in Alderney. In the case of ARE, it is a tidal energy developer founded in 2004 that tries to maximise the tidal resources in Alderney's territorial waters which has secured a 65 year licence from the ACRE of 48 square miles [26]. In addition, several documents regarding RE in Alderney have been created such as [4] [6] [7] [27] with the collaboration of different Alderney associations.

In this section, it will be generally introduced all the RE resources that can be exploited with the current technology and their potential in the case study of Alderney will be assessed.

4.1 Introduction to the current renewable energy systems

4.1.1 Solar photovoltaic energy

Solar PV energy is based on the energy conversion of solar radiation into electricity in the PV cell through the PV effect. This cell is composed by two thin semiconductor layers, which absorb the maximum incident light in order to stimulate enough the electrons to cross the potential barrier and then generate electricity.

This technology has been enhanced from the first silicon cell converter in 1954 to the current one by increasing the solar cell technologies, reducing the thickness and improving their reliability and cost. During the 1990s the first PV roofs and power station were installed as a result of the fast evolution led by the use of solar PV in spaceships and satellites [28].

Along the last five years, the use of PV solar cells has increased by 55% per year because of the reduction in panel prices due to manufacturing improvements and the intense competition between manufacturers especially after the boom of Chinese companies. At the same time, the price per watt has been decreased thanks to efficiency enhancements [29]. As a result, solar PV cells have been installed specially in Europe which accounts for 73% of the global market [7]. These cells are employed in isolated installations as well as in electrically connected systems as household solar panels or solar farms in order to sell the generated electricity [28].

4.1.2 Wind energy

Wind energy is based on the conversion of kinetic wind energy into mechanical energy through the lift effect on the blades of the Wind Turbine (WT) and then it is transformed into electricity by the generator.

Along the last years the WT's technology has been enhanced by increasing the tower height, the blade length and the power coefficient as well as by improving blades' design, new materials, reducing noise emissions and cost reductions on CAPEX and O&M. As a result, the wind energy has been expanded in new countries especially in the relatively new markets of China, US and Latin America [30]. Regarding the consolidated EU market, Germany and UK are leading in the installation of new onshore and offshore WTs. At the end of the 2014, as displayed below in the figure 6, the EU total wind capacity was 128,751.4 MW representing the 14.1% of the EU power mix with Germany, Spain and UK leading respectively the installed wind capacity [31].

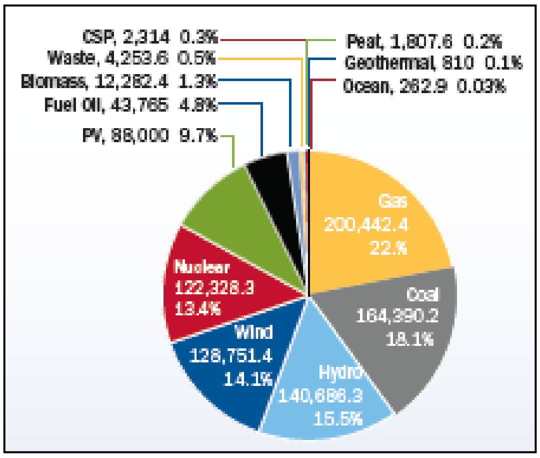


Figure 4-A: EU power mix 2014 (MW) [32]

WTs can be installed in an onshore or offshore environment where the blade length constraints are lower than onshore and allow the installation of higher capacity WTs. Basically, as a function of the axis configuration WTs are divided into horizontal axis WTs, which are more deployed and have better performance, and vertical axis WTs. In addition, as a function of the power capacity, WTs can be classified as micro WT (up to 1.5 kW), small WT (up to 50 kW), medium WT (50 - 500 kW) and big WT (up to 8 MW) [33] [34].

4.1.3 Hydropower

Basically, hydropower systems convert the kinetic energy as well as the potential and pressure energy carried by the water into mechanical energy through a turbine and then into electricity.

Hydropower is the most mature technology and the most common form on the RE sector with a global capacity of 1,055GW in 2014 [32]. Despite its maturity, hydropower capacity has grown during 2014 to 39 GW mainly because of the development in China. In mature markets as in the EU, despite the growth being smaller, in 2014 it was the first RE in terms of capacity with 140,683.3 MW (15.5%) [32]. This increase is related with renovating old plants as well as with the installation of Pumped-Hydro Energy Storage (PHES) systems [28] [32].

As a RE, hydropower is the most reliable and efficient system, however the required investment and its impact on the surrounding environment are important drawbacks to consider before the construction of a new plant [7].

4.1.4 Marine energy

4.1.4.1 Tidal energy

As a kind of hydropower energy, tidal energy systems convert the energy carried by the surge of the ocean during the rise and fall of tides into mechanical and then into electricity. Tidal energy can be harnessed in two different ways: tidal range or tidal stream. Tidal range systems have been producing electricity from the water's kinetic power since 1966 [35]. Despite being more mature than the stream one, only a few projects are underway due to the required high investment and their impact on the environment. In the case of tidal stream, the kinetic energy of the current, especially from the sea, is exploited in a similar way to wind energy but with a fluid thousand times more dense.

Along the last years tidal energy is emerging as an alternative RE with a few turbines installed and some planned or under construction. As a result of the government grants and facilities, several technology improvements have been done in order to extract this low-carbon, predictable and reliable energy source. Especially in countries like the UK and France that have some of the most suitable locations to develop tidal stream systems [36].

4.1.4.2 Wave energy

Waves can be originated by different factors but the most common is due to the influence of the wind on the ocean surface. Wave energy converters are very immature technologies, which intercept the potential and kinetic energy of the waves by pitching, heaving and/or surging their structure. Then, this motion is converted into electricity through different power take-off systems and delivered to the grid. It is estimated there is a global wave potential of 1TW, however the different kinds and designs of wave energy converters are still in a very low technology readiness level with a few devices in the commercial and system testing phase [37].

4.1.4.3 Other

Apart from tidal and wave energy, there are other marine energy systems as ocean thermal energy and ocean osmotic energy which are in a research stages. Ocean thermal energy systems exploit the high temperature difference between the water surface and deeper areas to generate electricity and they have an estimated global potential of 10000 TWh/year, mainly in tropical waters. In the case of osmotic energy, the salinity gradient between fresh and sea water in the river's mouth is exploited to produce an estimated global power potential of 2000 TWh/year [38].

4.1.5 Thermal energy generation

Thermal power plants are the most common electricity generation systems which are usually run by fossil fuels as coal, diesel and gas or nuclear resources. These plants are based on thermodynamic conversions to generate electricity from the heat produced by the combustion of fossil fuels as well as renewable resources. The most important renewable thermal power generation systems are geothermal power, thermodynamic solar power as well as cogeneration and Anaerobic Digestion (AD) from biomass [28].

In the case of geothermal power, it uses the temperature gradient within the Earth, which can reach 1000ºC/km, and it is presented as hydrothermal or hot dry rock resources. Another renewable thermal resource is the solar radiation which can be concentrated to a specific point of the thermodynamic solar plant, by special designs of mirrors and collectors as towers, in order to increase the fluid's temperature and hence the thermodynamic conversion efficiency. Furthermore, the necessary heat to generate electricity can be produced by burning biomass and waste.

4.1.5.1 Anaerobic digestion (AD)

The AD process is based on the conversion from biomass to biogas in a digester with absence of oxygen by means of 4 microbiological and biochemical processes: hydrolysis, acidogenesis, acetogenesis, methanogenesis [39] [40]. The inputs of the process or feedstock are organic material from the agriculture and farm like animal manure as well as from different organic waste like industrial and food processing waste [41] [42] [43] [44]. The outputs of the process are biogas and thermal energy which the amount of biogas per tonne of feedstock and the different calorific characteristics can vary in function of the mix of feedstock introduced into the digester [42] [43] [44]. Then, the biogas is burned to produce renewable power and heat and the remaining material can be used as fertiliser [28] [41] [42] [43].

4.2 Alderney characteristics for the integration of RE systems

As introduced before, the location of Alderney allows the exploitation of diverse RE resources making technically feasible the idea of transforming Alderney into a green island as discussed on [7].

In terms of solar irradiation, Alderney has a Global Horizontal Irradiation (GHI) around 3.4kWh/m^2/day with a year optimal inclination angle of 37º and an annual irradiation deficit due to shadowing almost 0% in all the territory [45]. In the following section, PV technology will be analysed and selected the different tracking options, the total peak PV power and the most suitable locations for the construction of a solar PV park.

Regarding wind energy, based on the measurements at the Alderney airport the average wind speed is 13kts with a variation slightly higher than 30% [46]. Despite offshore WTs having higher energy capacity, the following studied locations will be onshore due to the characteristics of onshore WT suiting better the low energy demand of Alderney with lower capital and operational expenditures.

Despite ARE having the right to exploit the best Alderney's territorial waters, the tidal currents in the other areas are high enough to consider the installation of a single or a small array of turbines to supply the required velocity. The deployment of wave energy converters and other marine technologies as a electricity source is discarded due to their low maturity and reliability which will not allow to supply the required demand with enough energy security.

Hydropower energy systems are not considered due to the mainland space limitation and the huge capital investment. However, in later stages the suitability of a PHES will be assessed.

Alderney soil is mainly composed of sedimentary volcanic rock as Granodiorite and Bibette Head granite which are covered by superficial sands and gravel [7]. This kind of soil generally has the following properties:

	Mean thermal conductivity (W/mK)	Mean thermal diffusivity (mm^2/s)	Mean heat capacity (MJ/m^3K)
At 20ºC	3.62	1.69	2.15
At 80ºC	3.42	1.36	2.53

Table 4-A: Characteristics for the Alderney's typology soil [47]

Despite these characteristics permitting the possibility of exploit geothermal energy, this kind of energy system is not further discussed due to the high installation cost and the necessity of having skilled staff [48].

Finally, the development of an AD in Alderney can provide the island with a reliable and secure electrical and thermal energy, at the same time as solving the waste management problem. Therefore, the feasibility of an AD plant, like the estimated in [49], is compared against the other suitable RE resources in the next section.

5 SIZING AND SELECTING A FEASIBLE RENEWABLE ENERGY SCHEME IN ALDERNEY

After introduced the different RE systems and their suitability in the case study of Alderney, for the chosen RE schemes (solar PV, onshore wind, tidal, geothermal power and AD) a rough estimation of their cost of energy, reliability and environmental impact is carried out. Then, based on those estimations, a feasible combination of these REs is chosen to supply the electricity in Alderney in an affordable, sustainable and reliable way.

In terms of cost, the RE are compared with its different Levelised Cost Of Energy (LCOE) which is estimated based on previous studies and extrapolating the results as accurate as possible in the Alderney case study. The LCOE is a parameter used in the industry to compare the cost of electricity produced by different generation systems. The LCOE takes into account all the systems' lifetime costs like construction, fuel and maintenance among others and divide them per the lifetime power output. Furthermore, two more parameters as the lifespan and the capacity factor of the system are assessed.

In terms of reliability, the RE are compared by system and output reliability. The system reliability takes into account the number and how often the system fails. In the case of the output reliability analysis the output fluctuations depend on external parameters as well as the requirements for an EES.

Finally, the different RE systems are compared in terms of Green House Gas (GHG) emissions as well as their positive and negative impact to the surrounding environment. Despite it not being required since Alderney is not a member of the EU, an environmental assessment of RE [27] was carried out to protect Alderney's environment. That report realizes an exhaustive Environmental Impact Assessment focused on marine and onshore wind energy which identifies the different stressors with possible cumulative effects to the Alderney's receptors and proposes some mitigation works [27].

As recommended by AEL, the RE system should not be oversized due to the batteries that can be charged from the current diesel generators easily as well as these generators can supply the gap between the RE production and the demand during peak times.

5.1 Solar

The fundamental components of a solar PV park are the PV cells. These are arranged in parallel as modules to increase the current and then in series as panels to have enough high voltage for the inverters. The inverters are responsible to convert the DC power generated by the PV panel to AC power that can be fed back to the grid or consumed. In addition to these components, a solar PV installation could require other power converters as transformers and choppers in order to adjust some magnitudes as well as the active and reactive power [28].

In terms of solar cell technologies, there are different options in function of the material and structure. The most common material is silicon which can be crystallised as a single or several crystals or not crystallised as amorphous silicon. Single crystal silicon cells have the higher standard efficiency and the higher costs, followed by polycrystalline and amorphous silicon. As alternatives to silicon cells, new technologies as CIS, CIGS and CdTe has been developed with generally lower cost, efficiency and lifespan than the crystalline silicon ones [28]. The following table displays a summary of the different solar PV technologies.

Technology	Efficiency	Lifespan	Main uses
Single crystal silicon	12 to 20%	30 years	Space, modules for roofs, façades, etc.
Polycrystalline silicon	11 to 15%	30 years	Modules for roofs, façades, generators, farms on ground, etc.
Amorphous	5 to 10%	10 years	Electronic instruments (watches, calculators), integration in the building
CIS	9 to 11%	>20 years	Integration in the building
Multi-junctions	Up to 40%		Space
CdTe	6 to 10%	>20 years	Electronic instruments (watches, calculators), integration in the building, farms on ground
CIGS	19.9% in laboratories	-	Space, integration in the building
Organic	5.9% in laboratories	-	Under development

Table 5-A: Characteristics of the different available solar PV technologies [28]

Based on the information described above in terms of cost, efficiency, lifespan as well as technology maturity, performance degradation, available data, energy pay-back and global warming potential [50] [51]; polycrystalline silicon cells are chosen for this study. Furthermore, in order to estimate further the electricity output of the solar PV park a panel of 230Wp of peak power is selected from the available standard solar cells [52].

The chosen solar cells will be installed on a mounting system which can be fixed to the ground or allow the movement by a single or dual axis solar tracker in order to optimize the panel position daily and seasonally as a function of the solar radiation. Then, an estimation of the electricity production in Alderney for the fixed mounted structure with optimum slope, vertical axis solar tracker and dual axis solar tracker scenario is carried out with the following results:

	Monthly average of Global Irradiation [kWh/m^2]
Fixed structure	120
Vertical axis tracking	104
Inclined axis tracking	140
Dual axis solar tracker	162

Table 5-B: Monthly average global irradiation for the 4 different tracking systems [45]

Finally a fixed mounted structure with an optimum slope is chosen due to the low performance difference between the other two better scenarios and the related lower CAPEX and OPEX cost thanks to its simpler design without movable parts.

5.1.1 Cost analysis

In the case of solar PV and based on [53], the following values are estimated for a ground-mounted utility scale with a GHI of 1200 kWh/m^{2}a; taking into account that Alderney has a GHI of 1241 kWh/m^{2}a:

Annual fixed operation cost	Annual reduction of output	LCOE
35 €/kW	0.2 %	0.079 - 0.098 €/kWh

Table 5-C: LCOE, Annual OPEX and output reduction for the Alderney solar scenario [53]

5.1.2 Reliability analysis

The output reliability of a solar PV system is very bad due to there being a variable output depending on the amount of solar irradiation which varies between day and night and between hours due to clouds. Therefore, EES will be required in order to have a reliable electrical energy source.

Furthermore, in order to design solar PV systems, it is important to analyse the reliability of the components and connections as well as how those failures can impact on the system's availability. The reliability of the solar PV system along its lifespan, usually around 20 - 25 years [53], is affected by different factors as the temperature, load level, power losses and ambient environments as well as the variability of the solar radiation and power input [54]. Consequently, the system is less reliable during the last years of its lifespan due to the higher failure probability of components. Moreover, the integration of that system to the grid has to be assessed since it can lead to higher maintenance costs on the power distribution network.

Consequently, as detailed in [54], a risk assessment is necessary for the reliable PV generation integration to the active distribution network. After the assessment, the failure modes of the most vulnerable components are determined such as the PV module and the inverter as well as the connection, controller, battery and module failures. In addition, the reliability degradation of the system due to the intermittent behaviour is also analysed [55].

Despite the PV module being composed of different PV cells which are the most reliable component, the PV panels can fail or degrade significantly along the lifecycle. The main degradation modes are front surface soiling, mismatched cells, optical, cell, light-induced and temperature-induced degradation [56]. In the case of the inverter, its reliability is correlated to the failure rate of the power electronic switches and the capacitor which are influenced by the thermal overstress [54].

5.1.3 Environmental analysis

The development of a solar PV park has some benefits and drawbacks to the surrounding environment along the system's lifecycle which are analysed through an Environment Impact Assessment. The principal stressors are the panels themselves, cables, lightning, fencing and the traffic from the construction and decommissioning [56]. These stressors affect the soil structure, the wildlife habitat, the landscape and the geological and archaeological features [57] [58].

Solar PV parks have an important visual effect on the landscape as well as they can create glint and glare due to the reflection of the sunlight. However, after a glint and glare assessment displayed below it is concluded that they can be installed close to the airports like the ones installed close to the Gatwick, Saarbrücken, Indianapolis, Dusseldorf and Denver Airport among others [56] [59].

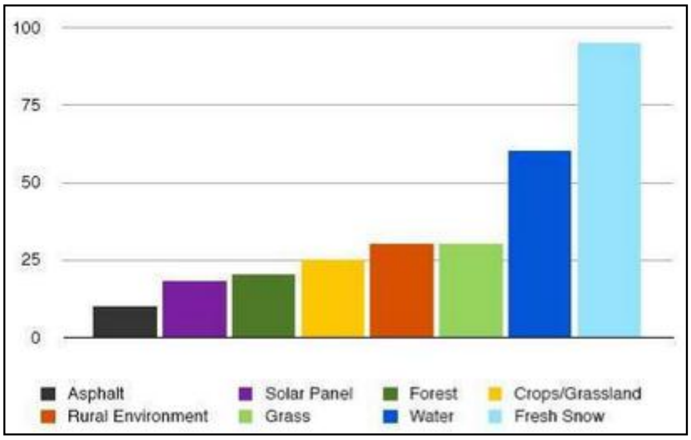


Figure 5-A: Comparative reflection analysis [59]

Other possible negative effects could be the loss of agricultural land, water run-off implications and ground and soil impact. In order to avoid the last one, intrusive development as trenching and foundations should be minimised by the installation of pile-driven or screw foundations [56] [58].

On the other hand, the development of solar PV parks has beneficial implications as enhancements of the ecological potential by removing the land from intensive agricultural exploitation and promoting diverse habitats within the park as meadows, bats and cattle [56].

Picture 5-A: Examples of positive environmental impact of solar PV on animals [56]

Furthermore, as low carbon energy, solar PV contributes to reduce the GHG emissions. Based on different Life Cycle Analysis, a mean GHG emissions around 78.7 g CO_2-eq·kWh^{-1} [60] and 91.1gCO_2-eq·kWh^{-1} [61]is estimated for crystalline silicon technology where the 71.3% of these are emitted during the material cultivation and fabrication stage [60].

5.2 Onshore wind

An onshore wind farm is mainly composed by a group of WTs, the interconnection and collector power system, the communication network and a substation. The most important component is the WT where the electricity is generated. There are two kinds of WT in function of the axis direction: Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT). For the Alderney's case study, a HAWT is selected due to its better performance, power control system, technology maturity and cost efficiency [62].

Furthermore the HAWT should be medium size with a hub height around the 30 metres and a blade length of 15 metres to not disturb the surrounding environment. The HAWT should be three-bladed due to its balanced gyroscopic forces, lower noise, less bird strikes, commercial maturity and better power coefficient [63]. Apart from the blades, a HAWT has several sub-systems that contain up to 8,000 different components.

Taking into account the wind direction variability in Alderney, as displayed below, an active yaw system will be required to allow the turbine to face the wind always in the optimum direction.

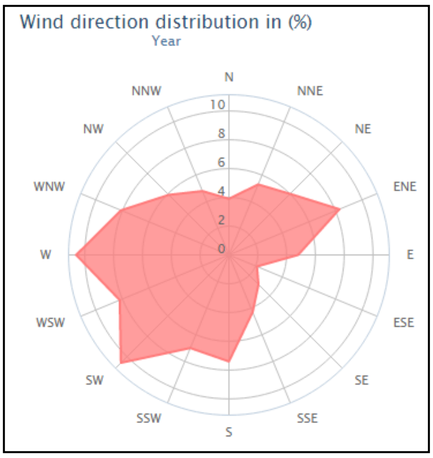


Figure 5-B: Annually Wind direction distribution at Alderney airport

Variable speed HAWTs will maximise the power extraction, reduce the loads with high winds, facilitate the integration to the electrical grid and reduce the power fluctuation [28]. Apart from these control systems, HAWTs usually have a pitch control in order to limit the power and improve the turbine's performance by modifying the power coefficient.

5.2.1 Cost analysis

In terms of cost, the following values can be estimated for an onshore WT in the less-beneficial conditions of 1300h/year at full load:

Annual operation cost	Annual reduction of output	LCOE
0.018 €/kWh	0%	0.084 - 0.107 €/kWh

Table 5-D: LCOE, annual OPEX and output reduction for the Alderney wind scenario [53]

Despite the good wind conditions of Alderney, the less-favourable condition is chosen due to the very difficult access to the island in order to transport and install the WT and the related equipment. Another reason is the difficulties to have on the island spare parts and skilled personnel to realize the O&M that will lead to higher downtimes.

5.2.2 Reliability analysis

In terms of reliable and steady output, like solar PV, WT requires EES to compensate the seasonally and daily output variance as well as simultaneous changes due to wind gusts [28].

Onshore WT can achieve availabilities close to 98% [64] with regular maintenance and a quick repair response. However, as explained before, the Alderney's case study will have a lower availability with higher downtime level due to the limited access to the island, the limitation to have available spare parts and the lack of experienced personnel for the O&M. Therefore, a very reliable system is required in order to have a cost-effective onshore wind farm.

Some studies suggest that the reliability of the system is related with the wind output average and wind output variance [65] as well as with the external weather conditions. Despite there being a huge diversity of failure modes within a WT, it is estimated that 25% of these faults are causing 95% of the total downtime [66]. The subsystems with higher failure rates are the converter, pitch, yaw and gearbox that is the one with the highest downtime per failure around the 13 days/failure [66].

It is general accepted an average annual failure rate per onshore turbine of 2.20 number of failures/year with a lifespan around 25 years [67]. This value should be reduced for the Alderney scenario which can be achieved by means of robust designs, proven technology, adding redundancies to the most vulnerable sub-systems or components and reducing as low as possible the use of rotating parts and hydraulic systems [65] [68]. Furthermore, Enercon has experimentally estimated a failure rate less than 1 failure/WT/year and they guarantee an annual technical availability of 97% [68].

5.2.3 Environmental analysis

The development of a wind farm has an impact in the short and long term to the surrounding environment. As a RE technology, along the WT lifecycle the GHG emissions as well as water consumption are reduced [69]. In terms of emissions, a mean value around the34gCO2-eq/kWh [60] [61]is estimated and the 71% of those emissions are produced during the cultivation and fabrication stages [60].

On the other hand, the development of a wind farm can affect negatively the environment, specially on the wildlife. The principal environmental stressors are the physical presence of the device, noise and visual impact. The most critical environmental impact is the noise which can be divided into mechanical noise which is developed by the moving components and aerodynamic noise which is originated by the flow of air over the blades and increases with the rotor speed [69] [70]. The produced noise can generate sleep disturbances and hearing loss on the neighbours [70]. Regarding the visual effect of WT, its impact increases during the moving condition and to the closest residential areas to the wind farm. WTs produce shadow flickering by the moving blades and the reflection of the sun's rays which leads to important visual pollution depending on the WT height [69]. For that reason and taking into account the proximity of the residential areas to fields and probable wind farm locations, it will be preferred to have more smaller WTs than one higher WTs.

In addition to the residents close to the farm, the consequences of these stressors affect directly to the wildlife by increasing the collision risk and indirectly by habitat disruption and displacement [69]. It is generally accepted that WTs increase the bird mortality significantly, however, several studies found that the mortality rate due to the WT is twenty times lower than fossil fuels rate [69]. The bats colonies, as the ones in Alderney, are more affected by the wind farm development with a significant increase on the mortality rate [69]. Other plants and animal species are affected during the construction, operation and decommissioning of the wind farm as well as the geological and archaeological features [71]. Moreover, the installation of WTs near airports will require a specific safety assessment because WTs can affect the safety of aircraft operations due to the produced electromagnetic interferences and the physical presence of the turbine [71] [72].

5.3 Tidal stream

As previously stated, the RE system should have the maximum reliability due to the constraints related with Alderney location. Despite tidal stream not being a mature technology, the chosen turbine should be a proven technology with a robust design which minimises the failure rate of the system. Therefore, an horizontal axis Tidal Stream Turbine (TST) is selected because of its higher reliability and the ease to predict and solve the O&M challenges. Furthermore, horizontal axis TSTs are more efficient and can harness high amounts of energy with simpler and more reliable designs than vertical axis turbines [36].

In this case, a three-bladed horizontal axis TST is chosen with a monopile structure and gravity base foundation. The rated power output of the turbine should be around 1MW at current speeds above the 2.60 m/s and it is preferred a yaw system and a fixed pitch.

5.3.1 Cost analysis

In the case of a three bladed horizontal axis TST with a gravity base foundation in a remote location as the one studied on [36], it can be roughly estimated the following costs:

Capital cost	Operational cost	LCOE
0.15 £/kWh	0.001 £/kWh	0.158 £/kWh

Table 5-E: LCOE, annual OPEX and output reduction for the Alderney tidal scenario [36].

It can be highlighted that the 63% of the CAPEX comes from the cost of the support system and the turbine as well as that 62% of the OPEX is planned [36].

5.3.2 Reliability analysis

Tidal current cycles and their current velocity are very predictable and therefore the power output of the Tidal Stream Turbine (TST). Despite this very reliable power output, a single TST can not supply the electricity demand of Alderney due to the low current periods along the flood-ebb and spring-neap cycles as well as the down time caused by a component failure.

In spite of tidal stream technology using proven technology from the wind energy, the extreme loads and conditions of the harsh subsea environment can lead to higher failure rates. Because of the poor reliability data available from TST, the failure rates are predicted based on the previous experience from WT. In that case the most vulnerable subsystems are the ones with moving parts and electrical and hydraulic systems as the generator, rotor blades and the yaw control. Furthermore, it is estimated for different TST subassembly possibilities a failure rate range from 1.5 to 2 times higher than WT of similar size [73]. Apart of higher failure rate than WT, the downtime related with those failures will be higher as a result of the weather conditions which make the access to the site, the transport, installation and O&M.

5.3.3 Environmental analysis

The development of a TST affects the surrounding environment by means of different stressors along the installation, transport, operation and decommissioning [27]. One of the most important stressor is the underwater acoustic emissions generated by the TST, the required ship and seismic surveys which can produce loss of hearing in animals and influencing their behaviour. The physical presence of the device alters the seabed, food availability, predation and reproduction patterns by becoming an artificial reef which will increase the habitat and the predators and the consequently risk of collision [74]. Other stressors related with the TST development are the energy removal effects on the sediment erosion, chemicals released by anti-fouling paints and the fuel of ships or the electric and magnetic fields generated by the cables and the device [74] [75]. These stressors can affect several environmental receptors that are presented and some protected in Alderney as fishes, marine birds, marine mammals and the benthic and pelagic habitat [10] [27] [74] [75].

As a low carbon energy, the generation of electricity from currents contributes to reduce the GHG emissions compared to fossil fuels and other energy schemes with a full life cycle mean GHG emissions of 15g CO2-eq/kWh [61].

5.4 AD

As stated before, the AD plant discussed in this report is based on that proposed on [49]. In this example, the AD plant uses as a main feedstock clean wood chip apart of typical farm materials and "blag bag waste" to produce 1.5 - 2MW and the associated heat [49]. An annual supply of 12,000 tonnes of wood is estimated for Alderney that can be transported via Southampton to the island through 20ft containers with 10 tonnes [15].

5.4.1 Cost analysis

In terms of costs, it can be extracted different estimations based on EU experience and adapting them to the Alderney scenario. In this case, the following cost and revenues are estimated based on the formulas presented in [76]:

CAPEX (€)	OPEX (€/ton)	Revenue (€/ton)
155,455	3,828	19.7

Table 5-F: CAPEX, OPEX and revenue for the Alderney's AD scenario

Regarding the LCOE, selecting that the Alderney plant will have high substrate cost (high fuel costs) and it will work 7,000 h/year at full load, it is obtained a LCOE between 0.18 - 0.20 €/kWh [53].

5.4.2 Reliability analysis

The production of power from biomass through biogas has a steady and reliable output along the approximately 30 years of lifespan [67]. However, the production of biogas depends on the feedstock mix and it can affect the electrical output. Despite this, the output variance is not as high as in the case of solar PV, onshore wind and tidal stream.

In terms of plant availability, it can be learnt from experience that high availability can be achieved as 98% (without taking into account the planned maintenance) along 16 years [77]. Moreover, the plant's annual availability can be around 90% due to routine maintenance [77] [78]. However, in the Alderney case study is estimated a worse scenario with higher down times due to the limited access to the island and the lack of spare parts and skilled personnel.

5.4.3 Environmental analysis

The development of an AD has several impacts to the environment which can be different as a function of the employed feedstock, the kind of fuel that the biogas substitutes and the use of the digestate which can be used as fertilizer. Regarding the GHG emissions, some studies have considered that biomass plants are carbon neutral due to the produced GHG having the same amount that the plants and trees have captured before from the atmosphere [61]. However, AD with wood chips feedstock are estimated to have between 54 - 108 gCO_2eq/kWh [61].

In addition, AD have a beneficial impact to the environment because the use of waste as a feedstock allows to reduce or eliminate the GHG emissions related with landfill practices which are around 90gCO_2eq/kWh over a 25 year lifespan [39]. Furthermore, the reutilization of the digestate solid will reduce the consumption of toxic fertilizer in the agriculture.

5.5 Proposed locations to host RE developments in Alderney

Before deciding which are the most suitable RE systems for the Alderney case study, the different possible locations to host those systems should be analysed. This selection takes into account as realistic as possible the area, network and environmental constraints as well as the current infrastructure.

In the case of the solar PV park, this could be located in many of the fields around the island. Especially, this assessment is focused on the fields surrounding the airport due to its height, no shadowing, the grid connection point as well as the current low usage of this area.

Picture 5-B: Surrounding fields to the airport

Regarding the WT farm, one of the best location could be in the south-west of the island where 4 gun emplacement from the World War II could be used as a foundation. In addition, this area is located out of the airplanes landing and take-off area and it is an area without infrastructure interference.

Picture 5-C: Proposed South-West WT location

However, this area has to be refused due to environmental constraints because it is situated in front of the les Etacs Ramsar site where live Gannet colonies [79].

Picture 5-D: Views of les Etacs and the Gannet colony from the proposed WT location

An alternative could be on the breakwater but there will be problems with the foundation of the WTs [79]. Finally, a field area on the middle of the island is selected as the most suitable due to the high wind on that area meanwhile not interfering with the flight path neither with the environmental constraints. The main drawback is the proximity to residential areas, which requires a deeper visual impact of the WTs.

Picture 5-E: Finally recommended location for the WT

In the case of the TST, the optimum location should meet the following requirements [36] [80]:

- Fast flowing water, mean spring peak higher than 2 m/s.
- A water depth above the 15m at low tide and no more than 40 or 50m at high tide.
- Uniform seabed to minimise the turbulence.

- As close as possible to an onshore grid connection point.
- Should affect as low as possible the environment and any protected areas.
- Should not disturb the activities developed by other stakeholders and sea users as fishing zones, shipping lines and local communities.

However, it has to bear in mind that ARE owns the 50% more suitable blocks of the Alderney's seabed. Between the four possible locations selected on [4] to exploit economically the tidal stream resources, the north eastern part of the Swinge area is chosen due to the other three being exploited by ARE. In addition, this area is very close to the power station and a grid point connection. The characteristics of this site are a water depth up to 45m and a mean spring tidal currents of 2.2 m/s [4]. However, before the deployment of any tidal device on that area should be analysed the impact on the sand banks due to AWT predicting some sedimentation problems in the Swinge area [79].

Picture 5-F: View of the Swinge area, proposed location for tidal stream array

Finally, the AD could be located in different sites of the island such as the north-east area in the Mannez Quarry close to the old train station and the light house. The main problem of that area is the space availability because currently there is the green waste disposal and the converter station of the FAB link should be located on that area.

Picture 5-G: Mannez quarry, proposed location for the AD

Another probable location for an AD could be the recycle station just in front of the power station. This location has many benefits like its proximity to the port which will ease the transportation and storage of the clean wood chip as well as the digestate solids to be sold as fertilizer. Furthermore, this location close to the power plant, the hospital, the fire station, the port and some residential areas will permit the use of the produced heat in the AD to be used as a district heating.

Picture 5-H: View of the recycling centre from the power plant, proposed location for the AD

As a summary, an Alderney map with the different proposed locations is displayed below.

Figure 5-C: Different proposed locations in Alderney to harness RE

5.6 Conclusions: Proposed RE system for the Alderney case study

The following table summarises the different RE assessed previously in order to select the most suitable mix for the Alderney case study.

	Solar PV	Onshore Wind	Tidal stream	AD
LCOE (€/kWh)	0.079-0.098	0.084 - 0.107	0.223	0.18 - 0.20
Lifespan (years)	20 - 25	20	25	25
Capacity factor (%)	20	30	20	80
Output reliability /EES requirement	Very high (day/ night fluctuations)	High	Very high	Low
System reliability/failures	Medium	High	Very high	Low
Environmental impact	Medium	Negative	Negative	Positive
GHG emissions (g CO_2-eq·kWh^{-1})	78.7 - 91.1	34	15	90
Other requirements			Harsh environment and O&M difficulties	Waste management benefit and saving

Table 5-G: Summary of the characteristics of the RE analysed

In order to make the decision easier, the different parameters are arranged as a function of the priority from the highest, LCOE, to the lowest priority, GHG emissions. Moreover, a colour-coded criteria is used to facilitate the decision taking, where the dark green is the best one and the dark red is the worst one.

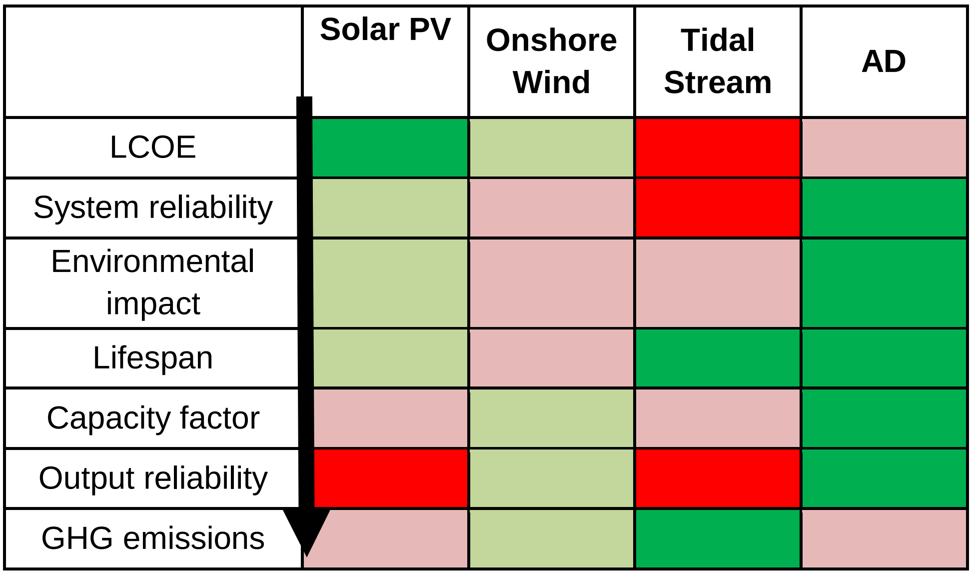


Figure 5-D: Characteristics of the RE

As stated before, a mix of RE is selected in order to avoid the energy dependence on one source as a function of the different priorities which can change depending on the assessment preferences. In this case, the main RE system chosen is an AD with a capacity of 1.5MW which uses clean wood chips as a main feedstock and it will have occupy 5.25 acre [81]. The main benefits of this system are the low output fluctuations, the high reliability and maturity compared to other RE systems. Furthermore, using part of the organic waste as feedstock will reduce the waste disposal cost that in the case of Alderney is approximately £500k per year [15]. Despite that benefit, this analysis is considering a constant feedstock of only clean wood chip without other components in order to approximate better the biogas production and electricity output [42] [43] [44]. The relative high cost of energy could be decreased by using the outputs of the AD apart from the biogas and getting some revenue. For example, the remaining digestate rich in phosphate is generally exported as fertiliser to EU countries with a phosphate deficiency [82]. In addition to this agricultural use, the digestate can be employed as livestock bedding, compost, fuel pellets, and construction material [83]. Moreover, the produced heat can be utilised within the plant to improve the AD efficiency or exported outside [82].

Apart from the AD, in order to have a 100% RE penetration level due to the capacity factor of the AD plant, the installation of a solar PV park or an onshore wind farm is analysed. Finally, a solar PV park is selected due to its higher reliability and lower maintenance due to there are no moving parts [84] as well as its lower environmental impact [58]. In addition, the arrangement of different solar panels reduces the effect to the output in case of a failure as well as with installing them with different inclinations will permit to have a more homogeneous output along the year. Moreover, the installation of the same solar cells allows having some small spare parts and easier logistics than onshore wind which the spare parts are more costly and bigger.

Following, the dimensions of the proposed solar park are estimated. In order to calculate the required area as detailed in the Appendix B, a standard polycrystalline silicon panel of 230W [52] and a rated power output of 475kW is selected. Then, 2,065 panels are estimated as well as an area of 5,365 m^2. Below, it can be seen displayed in the map of the proposed areas with the solar park development which occupies less than 160m long and 35m wide.

Figure 5-E: Proposed Location for the solar PV park

As it can be seen in the above map, the solar capacity can be easily increased due to there is plenty of space to allocate more solar PV panels. As an alternative to the solar park or as a part of a other RE combination, the dimensions and the energy output of a wind farm are estimated. In this case, as described in the Appendix B, a 13 knots wind speed at a measurement height of 10m, an air density of 1.225 kg/m^3, a tower height of 34m and blade length of 17m is selected [85]. By means of the log law the hub height velocity is calculated [86] and rated power of 250kW [85]. A relative small WT is chosen due to the main roadblock of the wind farm being a visual impact to the surrounding residential areas. Accordingly to this calculation, a wind farm of two WTs could be a very good alternative to supply part of the Alderney's electricity demand which should have a 136m (4 diameters) separation in the perpendicular direction to the prevailing wind [87]. In order to assess the real feasibility of that idea, a more accurate wind distribution will be required in order to calculate the energy output through the power curve of the turbine. Other options could be the development of more micro wind generators in combination with the AD or a solar PV park. Despite the potential of this scenario, the feasibility of the wind farm development is not analysed more in this report due to time and data limitations.

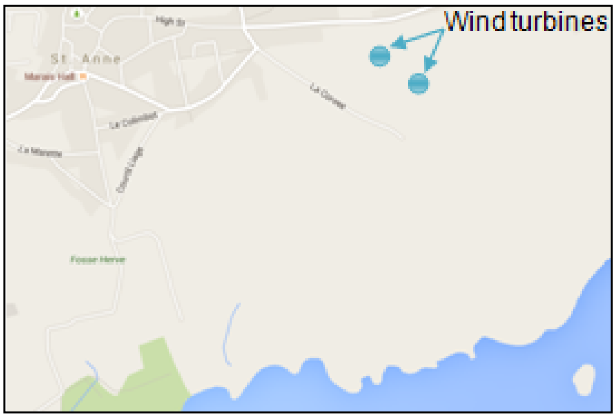


Figure 5-F: Proposed location of the two WTs

Once selected the RE mix, it has to be highlighted that the integration of RE production into the grid is linked with important challenges. The biggest problem is the variable output of some RE systems like solar PV with significant gaps related with irradiation changes during the day and night as well as influenced by the presence of clouds or orientation changes [28]. Furthermore, as the aim of this report is to achieve a 100% RE penetration to the Alderney's electrical network, the RE system should participate in ancillary services. However these technologies have a limited capacity to offer these services due to the intermittence of their resources. As a result, an EES system is required in order to realize the ancillary functions as the restoration of the network, voltage and frequency regulation as well as to maintain or improve the power quality [88].

6 ELECTRICAL ENERGY STORAGE

6.1 Introduction to EES systems

The installation of an EES systems will assure the integration and optimization of the proposed RE generation scheme for Alderney as well it will provide more benefits as fuel costs reduction, reduce the dependence to the volatility of market prices, reduction of network losses and improvements on reactive power compensation and supply quality [88].

The main roadblock for the globally implementation of EES is the economic profitability which depending on the scenario will be fulfilled or not. Therefore, following the implementation of different EES is assessed for the special case of Alderney with a 100% integration of RE.

In order to carry out this assessment as realistic as possible, it is borne in mind the different constraints set up before as the limited area for the construction of a new EES, the peak electricity demand to be supplied of 1.5 MW and the current and planned grid. Furthermore, it is tried to minimise the CAPEX to get the maximum project cost efficiency. Apart from these constraints, the different desirable characteristics of the EES are defined as follows:

<table>
<tr><td>Efficiency</td><td>Round Trip Efficiency (RTE)</td><td>Above 60%</td></tr>
<tr><td rowspan="3">Electrical Capacity</td><td>Power rating</td><td>1 MW</td></tr>
<tr><td>Energy storage capacity</td><td>6MWh</td></tr>
<tr><td>Energy mass density</td><td>As lighter a possible</td></tr>
<tr><td rowspan="2">Storage/Discharge behaviour</td><td>Response time</td><td>Minutes</td></tr>
<tr><td>Discharge duration</td><td>4 - 6 hours</td></tr>
<tr><td>Lifetime</td><td>Lifespan/Longevity</td><td>10 - 15 years</td></tr>
<tr><td colspan="2">Maturity</td><td>Commercial/Mature level</td></tr>
<tr><td colspan="2">Applications</td><td>Long term</td></tr>
</table>

Table 6-A: Desirable characteristics for the Alderney's EES

Once set up the desirable requirements and constraints, the commercial available EESs are briefly assessed in order to compare deeper the most suitable technologies. EES can be classified in two groups depending on their characteristics in those designed for power applications and those for energy applications [19]. In the Alderney case study, a mix of properties of both applications is required due to the 100% RE integration. The main characteristics of the EES for power applications are high power outputs for short discharge duration and with a quick response of time. On the other hand, EES technologies for energy applications have larger storage capacities and slower discharge and response time [19] [89]. Finally, another application with rapid response and discharge times up to an hour can be defined as bridging power applications [88] [89].

After assessing the specifications of different available EES, the following EES technologies are not further discussed but are summed up on the following table:

EES Technology	Application	Characteristics	Reason
Flywheels Energy Storage Systems (FESS)	Power	-Fastest time response (<4ms) -Power rating (up to 20MW) -Discharge duration (<1 hour) -RTE (80%-95%) -Commercial technology -Lifespan (Up to 40 yrs) -Costs (up to 8,800 $/kWh)	More suitable for: -Short-term -Generally high power output -Quickest response -Continuous cycling -Power quality applications (frequency control)
Superconducting Magnetic Energy Storage (SMES)		Idem as FEES except -Quick response time (ms) -Power rating (up to 100 MW) -Discharge duration (sec-min) -Costs (2,000-82,000 $/kWh)	
Super-Capacitors Energy Storage		Idem as SMES except -Power rating (<0.25MW)	

(SCES)		-RTE (~95%) -Costs (82,000 $/kWh)	
Pumped Hydro-power Energy Storage (PHES)	Energy	-Response time (sec-min) - Power rating (up to 4,000MW) -Discharge duration (hr-days) -RTE (65%-80%) -Mature technology -Lifespan (up to 50 yrs) -Costs (5-430 $/kWh) -Huge site requirements -99% of the ES market share	More suitable for: -Very long-term -Utility scale storage -Higher power rating -Slower discharge and response time Related with: -High CAPEX -Long construction time -Environmental affection
Compressed Air Energy Storage (CAES)	Energy	Idem as PHES except -Power rating (up to 500MW) -Costs (3-150 $/kWh) -Underground storage cavern requirements -Rely on fossil fuels	
Thermal Energy Storage (TES)	Energy	-Power rating (up to 200MW) -Discharge duration (hrs) -RTE (<60%) -Mature technology -Costs (3,500-7,000 $/kWh)	Idem as PHES and CAES but with lower RTE and higher costs.
Hydrogen Energy Storage System (HESS)	Bridging	-Power rating (up to 200MW) -RTE (34%-42%) -Unproven technology -Lifespan (up to 20yrs) -Costs (2-15 $/kWh) -Provide fuel for electricity and combustion engines -Variety of applications	-Low maturity of fuel cells and hydrogen storage materials -High CAPEX -Low efficiency
Nickel Cadmium (NiCd) Battery Energy Storage System	Bridging	-Quick response time (ms) -Discharge duration (min-hrs) -RTE (65%) -Long lifespan (2,000 cycles) -Costs (up to	-Limited durability for large-amplitude cycling -Environmental unfriendly (toxic heavy metals) -High self-

		5,000$/kWh)-Lower maintenance cost -Monthly self-discharge (>20%) -Mature technology	discharge -Higher costs than other proven BESS
Ni metal hydride (NiMH)	Bridging	Idem as NiCd BESS except -Power rating (900W/kg) -Improved efficiency -Lifespan (1,500 cycles) -Monthly self-discharge (>30%) -More environmental friendly	-Very high self-discharge (inefficient for long-term energy storage)
Zn-air BESS	Bridging	-RTE (50%) -Costs (up to 200 €/kWh) -Low lifespan (100 cycles) 450–650 Wh/kg - Negligible self-discharge	-Difficulties to recharge efficiently - Low lifespan and efficiency
Flow Batteries Energy Storage	Energy & Power	Different types: zinc (ZnBr), sodium (NaBr) and Vanadium (VBr). -Power rating (up to 25MW) -Quick response time -Discharge duration (hrs) -RTE (60 - 80%) -Long lifespan (1,000 - 13,000 cycles) -Mature technology -Costs (up to 800$/kWh) -Negligible self-discharge	-Increased capital and running cost due to the necessity of a chemical plant. -Low power density

Table 6-B: Discarded EES technologies based on [19] [88] [89] [90] [91] [92] [93]

To sum up this general assessment, some of the most common EES technologies have been discarded in this analysis due to the author of the report deciding based on the available information and their main characteristics that they are not the most suitable one for the Alderney case study. However, as stated previously, there is not an optimum solution for the Alderney energy challenge and this challenge can be achieved by using other EES. For example, ARE was working on the possible development of a tidal PHES in Fort Albert by means of the construction of a 6m high tank of 50,000 m^3 filled by sea water [94].

Picture 6-A: Current image of the forth Albert's inside

Despite this could be a viable solution for the Alderney scenario, this report is more focused on smaller and more efficient EES options as Lead-acid BESS, Li-ion BESS and NaS BESS.

6.2 Characteristics and selection of the most suitable EES technologies

Finally the following EES are the ones selected as the most suitable for the Alderney case study.

EES Technology	Application	Characteristics
Lead-acid BESS	Bridging	-Quick response time (ms) -Power rating (up to 10MW with peak power 700W/kg) -Energy density (30 - 50 Wh/kg) -Discharge duration (min-hrs) -Charge duration (between 8 to 16hours) -RTE (75%) -Lifespan (200 - 300 cycles with 80% discharge) -Monthly self-discharge (5%) -Maintenance required approximately every 6 months -Mature technology

Li-ion BESS	Bridging	-Quick response time (ms) -Power rating (up to 10MW with peak power between 500 - 1,000W/kg) -Highest energy density (100 - 200 Wh/kg) -Discharge duration (min-hrs) -Charge duration (<4h, usually around 1h or less) -RTE (almost 100%) -Lifespan (500 - 200 cycles with 80% discharge) -Monthly self-discharge (<10%) -Maintenance not required -Commercial technology
NaS BESS	Energy & Power	-Quick response time (ms) -Power rating (up to 10MW) -Energy density (100Wh/kg) -Longer discharge duration (hrs) -Longer charge duration (hrs) -RTE (89%) -Lifespan (2,500 cycles at 100% discharge) -Negligible self-discharge -Minimal planned maintenance -Operating temperature around 325ºC -Mature technology

Table 6-C: Summary of the most suitable EES technologies for the Alderney's scenario [19] [88] [89] [90] [91] [92] [93] [95]

Li-ion BESS is the leader in portable electronic devices and now it is taking a share in the RE's EES market. Thanks to its higher efficiency and high energy density [90]. Despite the maturity in this sector, Li-ion BESS are an unproven technology for long term applications with power ratings of MWs. Furthermore, the deployment of Li-ion BESS requires a precise control of the charge management as well as a high investment [90]. As a result, in this assessment it is discarded but it has to be stated that in the upcoming years Li-ion batteries will be employed for this functions due to the several technology developments [90].

Lead-acid BESS are the oldest chemical energy storage and nowadays they are still used in several isolated systems as detailed in [19]. Furthermore, this study suggest that lead-acid BESS are the most suitable for isolated systems with rating lower than 5MW and discharges up to 12h. However, in this report lead-acid are discarded due to the limited lifespan, high failure rate with continuous cycling and the required O&M [90]. Therefore, a 1MW (6MWh) NaS BESS are suggested as the most suitable technology for the Alderney scenario due to the following advantages:

	NaS BESS
Advantages	• Most widely deployed BESS with 182 projects (316MW) [89] and consequently it is a mature technology particularly for grid-scale and RE integration functions [96]. • Better discharge duration, lifetime, efficiency and minimal maintenance as well as more suitable for energy management [92]. • Similar €/kWh than lead-acid BESS but better costs per charge-discharge cycle [92].
Disadvantages	• Over dimensioned due to this technology can support loads higher than 50 MW and discharge times up to 24h [19] [96]. • Hazards due to the operation temperature (over 300ºC) and the spontaneity to burn with air and moisture of Na [88] [90].

Table 6-D: Advantages and disadvantages of NaS BESS

As a conclusion, it can be stated that NaS BESS have several economic benefits compared to the lead-acid BESS specially in the cost per charge cycle and lifecycle cost due to their longer lifespan and durability as well as higher availability. Moreover, NaS BESS are more reliable because of the technology maturity and experience as well as the minimal maintenance. As a chemical storage, despite that during the operation the environment is slightly affected by the heat generated from the internal and isolated heaters, the disposal of the electrodes and electrolytes will have an important footprint in the environment. However, because of the higher energy density, the impact of this development affects a smaller area.

7 FEASIBILITY OF SUPPLYING THE ELECTRICITY FROM RE IN ALDERNEY

Once the selected the energy system of 1,5MW AD, 475kW solar PV park and 1MW NaS BESS, the technical feasibility of the scenario is assessed as detailed in the Appendix C. The inputs of this analysis are the energy demand, the solar irradiation and the amount of clean wood chip.

Regarding the energy demand used the weekly energy produced in 2014 supplied by the AEL. Then, the demand every half an hour is calculated through a weekly average demand of the month. By assuming that the daily demand is independent from the weekday as well as the hourly distribution is the same along the year.

In the case of the solar PV park, the electricity output is calculated every 30 minutes and it takes into account the GHI for a daily sample of each month. In addition, different losses are considered such as PV degradation, temperature losses, inverter losses, availability and grid connection losses among others.

For the AD scenario, the electricity output depends on the amount of clean wood chip as well as the conversion efficiency of organic fraction to biogas, the methane production per kg of biogas, the calorific values and the conversion efficiency to electricity. The electricity output is supposed to be constant along the year with a capacity factor of 80%.

Finally, it is assumed that the energy accumulated on the NaS batteries at the beginning of the month is always constant and equal to half of its capacity, 3000kWh. In addition, if the energy level on the batteries is lower than 600 kWh the 450 kW diesel generator will start running at full capacity 30 minutes later. In order to make the use of the generator more efficient, once the generator is started it will continue until the energy on the batteries is higher than 3000 kWh.

Taking into account these considerations, as explained with more detail in the Appendix C, the results of this scenario are the following ones:

In the case of the solar PV park, the electricity output is calculated every 30 minutes and it takes into account the GHI for a daily sample of each month. In addition, different losses are considered such as PV degradation, temperature losses, inverter losses, availability and grid connection losses among others.

For the AD scenario, the electricity output depends on the amount of clean wood chip as well as the conversion efficient of organic fraction to biogas, the methane production per kg of biogas, the calorific values and the conversion efficiency to electricity. The electricity output is supposed constant along the year with a capacity factor of 80%.

Taking into account these considerations, as explained with more detail in the Appendix C, the results of this scenario are the following ones:

Scenario 1	
Fuel	12,000 tones clean wood chip
Batteries usage	20,400 kWh (9% of the total demand)
Batteries working time	54% of time
Batteries energy storage level	68% of the full capacity
Saving compared to the current scenario	1,867,112L of diesel (741k GBP)
Extracost compared to the current scenario	12,000 tn of wood chip and BESS investment

Table 7-A: Summary of the results obtained in the Appendix C for the scenario 1

Hence, based on this analysis, it can be concluded that this scenario is technologically feasible. However, taking into account that no diesel is required as well as the high level of energy storage capacity, this system could be optimised. Therefore, a second scenario with lower clean wood chip fuel is assessed.

In this case, a 1MW AD which uses 8,000tn of clean wood chip as feedstock is analysed in the same way as the previous case. The following results are obtained taking the same considerations as before:

Scenario 2	
Fuel	8,000tn clean wood chip and 14,005 L of diesel
Batteries usage	45,639 kWh (21% of the total demand)
Batteries working time	59% of time
Diesel generator usage	54,900 kWh (25% of the total demand)
Diesel generator working time	22%
Saving compared to the current scenario	1,853,107 L of diesel (736k GBP)
Extracost compared to the current scenario	8,000 tn of wood chip and BESS investment

Table 7-B: Summary of the results obtained in the Appendix C for the scenario 2

In the feasibility analysis of this scenario, diesel supply is required to meet the electricity demand and usually the diesel generator works around 5 hours every 24 hours. However, more diesel supply will be necessary especially during the months of higher energy demand such as January, February, August, November and December due to at the end of the day the energy storage level on the batteries is quite low compared to the initial one. This scenario with a mix of fuels could be an intermediate stage of the change from the current situation to the scenario 1 RE system.

8 CONCLUSIONS

8.1 Required grid improvements and funding strategies

As stated before, the current Alderney electric grid requires several upgrades in order to fulfil with the current health and safety standards as well as to improve the energy security of supply. Apart from these improvements, the proposed scenario of RE with EES needs further updates as the installation of high voltage cable at least in the area affected by this development. Therefore, an important budget is required to fund all these improvements. The accelerated programme to update the Alderney's electrical grid is scheduled in different phases to ease the funding mechanism. Following the different funding strategies under study for the Alderney accelerated programme are introduced [17] [18]:

- Philanthropic donation.
- 3rd party investment or loan.
- Revenue funding which will lead to a 15-20% price increase.
- Lease funding between AEL and SoA.
- Offering new shares to shareholders.
- Grant funding from SoA.
- SoA purchase the network and at the end of the project own the assets.
- AEL borrow the money and improve the network while SoA pay back the money and the interest (5%). At the end of the project SoA will own the assets and SoA will grant AEL to operate it.

So far, AEL is looking the last option as the preferable one for funding the accelerated programme.

Regarding the funding strategy for a RE system in Alderney, the different options should be very similar to the previous ones. Specially, it has to be highlighted the probable predisposition of the SoA to invest in infrastructure, with short-medium return period, and grant AEL to operate it [9]. In addition, there is a very interesting funding alternative which is developing the project as a community owned and operated system. There are several examples of

Community Owned Renewable Energy (CORE) projects around the World particularly in European countries such as Denmark and Germany where CORE represents a big share of the energy market [97]. Examples of CORE systems around the World can be found in the following literature [1] [2] [6] [97] [98] [99] [100] [101] [102] [103] [104] [105] [106] [107] [108] [109] [110] [111] [112]. In the UK, CORE developments have been growing very fast and in 2012 there were 43 CORE planned, underdevelopment or constructed [105]. This report wants to highlight some examples of Green Islands with CORE projects as the isle of Eigg in Scotland and Samso in Denmark. The isle of Eigg through the community owned company Eigg Electric became the first standalone energy system in the World with a production from RE higher than 90% [2] [104]. In this Scottish small island, the electricity is supplied from three hydroelectric generators, four small WT and a small PV array [2]. Regarding the Samso example, the power capacity of the CORE developments is higher and they are connected to the Danish mainland. In this case there are installed 10 offshore WTs, 11 onshore WTs and 4 district heating systems [1]. As a result, the community since 2007 is selling electricity to mainland grid [98]. From these two experiences and other CORE, it can be extracted the main benefits of CORE systems:

Community benefits	• Educational benefits as awareness of the technology to invest and the environmental benefits for the community. • Promotion of stronger and healthier communities by working together to achieve one goal. • Public acceptance by involving the citizens in the decisions. • Promotion of using efficiently the energy. • Creation by the developer of small scale community initiatives in the CORE area as playgrounds, trails and buildings among others • As owners of the system, the financial benefits stay in the community.
Environmental benefits	• Reduction of the GHG emissions and the climate change effects
Local economy benefits	• Creation of new jobs during the construction and maintenance. • Harnessing residents' skills.

Table 8-A: Benefits of CORE systems [1] [6] [102] [103] [112]

Coming back to the Alderney case study, there are different ways to achieve a CORE project. Firstly it should be promoted among the community and create an awareness of the benefits of RE for the community. Moreover, a group within the community should be proposed to represent them in front of companies and institutions as well as to manage the energy system. As operator of the energy system, the community will require technical knowledge and capacities to manage properly the system that could be provided through collaborating with the AEL. In addition, this community involvement can lead to other CORE projects to power other energy systems such as the heating and transportation ones. Furthermore, an awareness of the energy consumption can benefit the community by promoting energy efficiency, improving the buildings insulation or decreasing the electricity consumption.

8.2 Economic, environmental and reliability assessment of other fuels and energy scenarios

After the RE and EES assessment and selection for the Alderney case study, it is compared as a conclusion the chosen energy system which uses clean wood chips and solar irradiation as a fuel with three different scenarios: the current one using diesel fuel, adding a EES to the current situation and one buying hydrogen and using it as an energy fuel.

In the first scenario there is an important dependency on diesel and the related cost fluctuation and uncertainties. Despite the current relative low cost of fuel, it is expected to increase again in the following years and hence the Alderney cost of energy. Nowadays the LCOE with that system is around 33.5 p/kWh which the major part of the cost is independent of the oil price.

It can be highlighted that nowadays the fuel cost is around 0.397 GBP/L and its average storage cost is 8k GBP/year. In addition, there are expensive major maintenances for the Paxman generators which have to be realized outside the island, every 30,000 engine hours. Furthermore, it is important to bear in mind that with the current scenario in 2020 2 Blackstones generators will be retired and hence, a new generator will be required with an estimated cost of 350k GBP.

As stated before, this energy system has a big dependency on the diesel importation. Therefore, the LCOE and the security of supply rely upon the fossil fuel market and the producer countries making the reliability of this system very low. Furthermore, it has a negative impact to the environment due to the higher GHG emissions and hazards to the environment compared to other energy fuels.

This current system with a peak power of 8MW is oversized compared to the electricity demand that can peak at 1.5MW but with an average around the 0.6 – 0.7 MW [11]. Therefore, an alternative energy system is to use one of the new Paxman generators at full capacity (2MW) during one day and storing the non-consumed energy in a large-scale EES. Based on the current demand estimations of 600 kV, this scenario will supply the electricity demand of three days by using only one day the generator. Taking into account that there are three Paxman generators in the power plant, each will be used every nine days which will theoretically reduce the O&M cost, increase the lifespan of the generators as well as reducing the fuel consumed and the GHG emissions [14]. In this case, it is estimated in the Appendix D a saving of around the 549,000 L and 218k GBP which could increase due to the reduction of one shipment per year of diesel [14]. In terms of the environment this scenario is slightly better with less GHG emissions and it is a little bit more reliable thanks to the EES with 2 days of storage. However, despite the better efficiencies due to the higher load factor and the related lower fuel consumption, the LCOE should be higher than the previous one because of the CAPEX, OPEX and energy conversion and transmission losses related to the required EES. Moreover, this EES should be quite expensive because of the energy storage capacity requirements. Furthermore, the higher generation cost during the starting process and the maintenance problems related to the daily starting and stopping cycle make this scenario not feasible.

Another feasible scenario could be changing the fuel from diesel to cheap hydrogen produced in the close region of La Manche. In this case, the produced hydrogen from nuclear energy will be stored and transported to the island as a gas in steel reinforced with composite carbon fibres cylinders or in a cryogenic or super-cooled liquid state in large pressurized tanks on ships and barges [113]. Once transported, the hydrogen is introduced to a fuel-cell where through on electrochemical process reaction electricity is obtained. The main benefits of a fuel-cell against a diesel generator are the higher efficiency and the no pollutant products being only water and heat [114] [115]. In terms of cost, the LCOE for this case will mainly depend on the generation, storage and transportation of the hydrogen. It is roughly estimated in the Appendix D that for the Alderney scenario the total hydrogen production cost from nuclear power is around 1.39USD/kg and the delivery cost around 17- 21 USD/kg [116]. In the Alderney example, taking into account a fuel consumption of 33 kWh/kg [117] [118] a total monthly amount of 14,500 kg will be required with a total cost of around 267k $ which could be transported once per month or as accorded as a function of the capacity of the vessel tank and inland storage infrastructure. Compared to the current scenario, the shift of fuel will lead to approximately a cost increase of 110k GBP as detailed in the Appendix D.

In terms of the environment, hydrogen fuel cells release 0 emissions and taking into account the generation and transport of the hydrogen the GHG emissions are 30% less than fossil fuels [114]. Moreover, by generating water as a product, it improves the air quality.

The main drawback of this technology is the high risk during the storage and transport related to the flammability and explosive properties of the hydrogen gas [113]. As a result, during the last decade, several research groups have been working on materials and techniques to improve the safety and cost efficiency of the hydrogen storage and transportation as [119] [120]. Nowadays, the reliability of this scenario is very low due to the different risk and hazards, the low technology maturity and the associated high costs in the generation and especially on the hydrogen storage and transport.

However, in the forthcoming years this scenario will be more feasible because the hydrogen fuel could be generated in Alderney through the electricity produced from the tidal stream array or the installation of other RE systems.

Hence it would be more economically self-sufficient and energy independent from other countries and markets [121]. Moreover, hydrogen fuel cell has some added value as the possibility of using the hydrogen as a fuel for the combustion motors and hence reducing more the diesel dependency of the inland transport of Alderney. Moreover, the produced heat during the generation process can be utilized for district heating.

Other possibility could be linking the Alderney grid to an inland network as the French one by means of a subsea cable. For this case, the required high investment can not be justified just for electrical purposes. To make this investment more profitable could be linked the electrical connection to the arrival of optical fibre to Alderney which will increase the investment of e-gambling and ecommerce companies into the island.

Finally, the RE systems are compared to the previous fuels. As stated before and in the Appendix C, the technical feasibility of energy systems based on AD, solar PV and NaS BESS has been checked. In the case of the 1.5 MW AD with a feedstock of 12,000 tonnes of clean chip wood does not require any litre of diesel as a back-up. Therefore, there will be a saving of 1,867,112L and 741k GBP comparing to the current scenario, taking into account the current diesel price in Alderney. In addition, along this scenario the batteries supply 9% of demand by operating 54% of time with an average level of 68% of the total energy storage capacity. It can be concluded that this scenario does not rely upon the diesel supply and hence it is more sustainable and its costs more predictable. Despite these important benefits, this system could be oversized due to the low energy supplied from the batteries. Hence, a more cost efficient solution can be found.

The second RE scenario is a combination of a 1MW AD with 8,000 tonnes of fuel and a solar PV park. This case requires a back up of 14,000L of diesel with an approximate cost of 5.5k GBP. In addition, the batteries supply 21% of demand by working 59% of time which could justify the high investment required. The usage of the Blackstones generator as part of the simulation is not the most efficient due to it working in cycles of a few hours, usually around 5 hours, and hence it will have lower efficiencies and higher diesel consumption due to the starting process. Economically, both proposed scenarios should be compared to the current one in terms of fuel, storage, O&M cost. In this paper, this comparison is not carried out due to the lack of reliable data regarding the transportation cost of the clean wood chip as well as the maintenance cost of the AD and batteries system.

Hence, this scenario could be a transitory stage of the changing process from diesel to RE fuel where a combination of both supplies meets Alderney's electricity demand. Then, with the experienced gained the system could optimise the quantity of clean wood chip and diesel required in order to have the most sustainable and reliable energy system with the lowest cost taking into account the raw material and transport costs. Moreover, with the time the amount of fuel imported could be reduced by generating in the island the wood chip or another kind of organic feedstock, with higher biogas production rate, for the AD and hence become more energy independent. Another possibility is to increase progressively the capacity of the AD to generate more biogas and heat which can reduce the fossil fuel consumption in the transportation and heating systems.

Other RE resources can be exploited such as analysed previously as wind and tidal currents. For example, the high wind resources of Alderney can be harnessed by a couple of onshore WTs as explained before. An option could be using recycled WTs from other projects that will have a lower CAPEX and a theoretically lower LCOE [122]. The fantastic tidal resources around the island can be exploited in different locations by different technology proven tidal turbines and provide the necessary electricity demand.

Following, a summary table is displayed with the advantages and disadvantages of the different fuels and scenarios.

	Advantages	Disadvantages
Current (diesel)	▪ Past experience ▪ Current low cost	▪ Price and security of supply risks
Current (diesel) + EES	▪ Reduction of 549,000 L, 218k GBP and GHG emissions	▪ Higher O&M costs ▪ Expensive EES costs
Imported hydrogen	▪ Efficiency and emissions ▪ Heating and transportation	▪ Risks and low maturity ▪ Current higher cost
RE source	▪ Higher energy security ▪ Sustainability ▪ Predictable fuel prices	▪ Relative higher price ▪ Socioeconomic constraints
Link to France	▪ Cheap energy	▪ High CAPEX

Table 8-B: Summary table with the most important advantages and disadvantages of the different fuels and scenarios

8.3 Final conclusions and recommendations

To conclude this master thesis, the author wants to state as it has been explained during the report that there is not any optimum solution for the Alderney energy case study. As described above, the electricity demand can be supplied through different energy fuels which are all applicable and they have important advantages to be implemented in Alderney. Depending on which are the main priorities in the selection criteria and taking into account a near or long term strategy, one energy system can be selected.

For example, if the main priority is the security of supply and energy independence, the RE fuels and the hydrogen will be the most suitable scenario. On the other hand, if the preference is one fuel that can be used also for the transportation and heating systems; hydrogen, diesel and the biogas from the AD will be the more appropriate fuels. In the case of the heating system, by means of a Combined Heat and Power (CHP) plant, the produced thermal energy as a waste heat in the electricity generation process from diesel, hydrogen or biogas can be used for space and water heating. In the Alderney scenario, this could be distributed as a district heating system to the buildings close to the power station such as the hospital, the fire station, the port and some residential areas.

Picture 8-A: View of the power plant from the fire station and map with the possible district heating area

In that case, the heating demand of these buildings should be analysed deeper to assess the investment profitability of converting the current power plant to a CHP plant with much higher energy efficiencies. Another option to power the transportation and heating system could be using the excess of electricity produced by RE as a fuel.

As part of this thesis, different energy scenarios for the Alderney case study have been reviewed with a special focus on the RE resources. Furthermore, the technical feasibility of supplying the electricity demand by a combination of RE resources with EES has been checked. Then, the principal roadblock to solve is the socioeconomic constraints such as lack of education and training, negative image, lack of awareness, the perception of a lot of work to do, lack of money or limitations in financial support. An important tool to unblock these limitations is the involvement of the government and its policy instruments. In this case, theoretically, there is not any political constraint due to the SoA being interested to promote RE around the island and collaborate more with the AEL, as a major shareholder, to improve the energy costs and security of supply for the community. Another important factor to achieve the introduction of RE in Alderney is the involvement of the community in the energy decisions. This awareness could be increased by promoting RE through different developments such as electrical bikes charged by hydrogen [123]. Previously, it has been highlighted the community benefits of CORE systems. Apart from that, another option to promote the active participation of the community in the energy system could be linking a representative group to the AEL as shareholders or consultants. That community involvement and the related energy awareness are key factors for the future energy developments in Alderney. This could lead to reducing the energy demand by improving the building insulations and the appliance efficiencies. In addition, with this community participation, the arduous goal of converting Alderney into a Green Island will be much easier to achieve.

In conclusion, Alderney is a small community but big enough to lead a worldwide change and become more energy sufficient and sustainable. The island offers different RE resources to be harnessed and the community and the responsible institutions should take this opportunity, which has not been taken in the past, before it is too late. Maybe the upcoming CAPEX investment in a new generator by 2020 could be the trigger to start investing and promoting other energy systems. As discussed as part of this paper, the Alderney's electrical system can be improved with minor changes to the current system such as optimising the diesel transport, using the generated heating or adapting the generators to the current demand which is more suitable for Blackstones than Paxman generators. Alternatively to those small and beneficial changes, major developments can be done such as powering the electrical system through RE resources as well as the transportation and heating systems. However, these developments are very difficult and there is not an instant change. In this paper a technical and technological feasible RE system, based on clean wood chip and solar energy fuel with NaS batteries, is proposed which should be the first stage to change Alderney into a Green Island. In order to assure the electrical generation with energy sufficiency and no diesel dependency, different transitory scenarios should exist where the energy generation is not the most efficient one but the experience gained of that time will facilitate the optimum dimensioning of the RE system and its batteries. In this case, two scenarios has been suggested to facilitate the migration to a fuel that will be price stable, more sustainable and reliable for the foreseeable future.

9 FURTHER WORK

The time and word constraints do not allow the author of this thesis to assess as detailed as desired the Alderney case study. Hence, several points can be improved in further analysis such as the LCOE estimations that can be based on real data provided by suppliers for this special case instead of previous studies adapted in the Alderney scenario. In that case, more accurate efficiencies, capacity factors and power outputs could be extracted. For the feasibility study, more precise and real data and simulations will optimise the capacities of the RE, EES and diesel back-up system. Moreover, the evolution of some parameters such as the weather conditions, demographic characteristics and energy demand has to be assessed and forecasted. This is because they influence the inputs and hence, the design requirements of the energy system.

In addition, the fuel comparison can be improved by analysing deeper the different scenarios in order to ease the selection as a function of the main priorities. Especially, those fuels that can supply energy to the electricity, heat and transportation systems at the same time that energy independence such as hydrogen and biogas. In the case of the biogas and methane generation, the possibility of using other feedstock with higher biogas yield as suggested in [6] [42] as well as other generation process like gasification and pyrolysis could be analysed in order to find the most cost-efficient, energy independent and reliable solution. Other RE resources, especially wind and tidal, should be analysed deeper to determine their feasibility in Alderney as well as other EES systems like Li-ion BESS whose technology had several improvements in the last months.

As stated in the conclusions, a RE system is technically and technological feasible to supply the Alderney's electricity demand. However, some roadblocks have to be sorted out to achieve that goal. One of them is the inclusion in the legislation of an Environmental Impact Assessment framework taking into account the environmental and socioeconomic characteristics for Alderney in order to assure the sustainability of the upcoming developments [79]. Another roadblock is the socioeconomic constraint, which has to be assessed deeper to propose a strategy to involve more in this important change either the community, the government and other institutions and companies. This plan should comprise different actions such as a promotion, education and training schedule into the local community, a financial analysis of the required expenditure, assessment of possible financial support from the governments and the expected revenues and return period of the project. Furthermore, the current RE policy framework could be analysed and improvements proposed to promote community developments in Alderney and other Channel Islands.

Converting the Alderney's electrical system into a more sustainable and reliable network by introducing RE fuels is the starting point of a more ambitious goal that is Alderney becoming a Green Island. Therefore, a further analysis of the transportation and heating system as well as different energy reduction actions has to be done in order to propose a sustainable energy system for Alderney aligned with the electricity developments. These developments are not easy and an integration plan should be defined. Hence, different stages should be developed in order to assure that the Alderney's energy demand is met by the different fuel combinations at any time. This is a difficult and long term project, but the community of Alderney has the opportunity to use its fantastic RE resources to lead a worldwide change and they should take it.

10 REFERENCES

1. SAMSO'S Renewable Energy. Available online: <http://energiakademiet.dk/en/vedvarende-energi-o/>.

2. ISLAND Going Green: Eigg Electric. Available online: <http://islandsgoinggreen.org/about/eigg-electric/>.

3. GORONA del viento, August 2015. Available online: <http://www.goronadelviento.es/index.php?accion=articulo&IdArticulo=161&IdSeccion=89>. Accessed August 2015.

4. CALDWELL, D. **Optimising the location of tidal turbines in Alderney water to minimise power output variability**. Cranfield University. 2011.

5. STATES OF GUERNSEY. Available online: <http://www.gov.gg/article/1891/Guernsey-and-the-Bailiwick>. Accessed August 2015.

6. DEACON, A.; AYLING, G.; SHREEVE, G. **Supporting the Development of the States of Alderney Island Energy Policy**. Energy Saving Trust.

7. JAGUARIBE, C. T. **Study to convert the island of Alderney into a Green Island**. Cranfield University. 2012.

8. OPEN Street Map. Available online: <https://www.openstreetmap.org/?mlat=49.713333&mlon=-2.205833&zoom=12#map=8/50.001/-2.247&layers=Q>.

9. Meeting with Robert McDowall: Chairman of the Alderney's Policy and Finance Committee. Alderney. 2015.

10. ALDERNEY Wildlife Trust. Available online: <http://www.alderneywildlife.org/>. Accessed July 2015.

11. ALDERNEY ELECTRICITY LTD. **Energy production and demand data**

from the power plant. 2015.

12. STATES OF ALDERNEY. **The Alderney Electricity Concession Law**. 1953.

13. ALDERNEY ELECTRICITY LTD. Alderney Electricity. Available online: <http://www.alderney-elec.com/>. Accessed 2015.

14. GRACA, A. **AEL Gen set maintenance schedule 2014 to 2024; Generators efficiencies 2011 to 2014; AEL Fuel Stock and Deliveries 2011 - 2013**. Alderney Electricity Ltd.

15. Visit to Alderney Electricity Ltd, the AEL's power plant and distribution network and personal communications with AEL's director. Alderney. 2015.

16. ALDERNEY ELECTRICITY LTD. **Dynamic Pricing model 2015**. 2015.

17. ALDERNEY ELECTRICITY LTD. **Proposal for infrastructure funding**. 2015.

18. ALDERNEY ELECTRICITY LTD. **Annual General Meeting**. 2015.

19. BIZUAYEHU, A. W. et al. **Analysis of Electrical Energy Storage Technologies' State-of-the -Art and Applications on Islanded Grid Systems**. Institute of Electrical and Electronic Engineers. 2014.

20. Meeting with Declan Gaudion: Executive Director of Alderney Renewable Energy. Alderney. 2015.

21. FRANCE-ALDERNEY-BRITAIN Link. Available online: <http://www.fablink.net/>. Accessed 2015.

22. SUBSEA World News, 2012. Available online: <http://subseaworldnews.com/2012/02/20/are-signs-tidal-array-and-anglo-french-interconnector-agreements/>. Accessed 2015.

23. ALDERNEY Comission for Renewable Energy. Available online: <http://www.acre.gov.gg/>. Accessed 2015.

24. ACRE. **Guidance for Decommissioning of Renewable Energy Systems**.

25. ACRE. **Guide to the Licensing and Consents Process for obtaining a Licence in relation to land based renewable energy system**. 2007.

26. ALDERNEY Renewable Energy. Available online: <http://www.are.gg/>.

27. ABP MARINE ENVIRONMENTAL RESEARCH LTD; ACRE. **Alderney Regional Environmental Assessment of Renewable Energy: Environmental Report**. 2014.

28. ROBYNS, B. et al. **Electricity Production from Renewable Energies**. Wiley-ISTE, 2012.

29. HAZLEHURST, A. **Economic Analysis of Solar Power: Achieving Grid Parity**. Stanford Graduate School of Business.

30. INTERNACIONAL ENERGY AGENCY. **Technology Roadmap: Wind energy**. 2013.

31. THE EUROPEAN WIND ENERGY ASSOCIATION. **Wind in power: 2014 European Stadistics**. 2015.

32. INTERNATIONAL HYROPOWER ASSOCIATION. **2015 key trends in hydropower**. 2015.

33. RENAWABLEUK. Small & Medium Wind Technologies. Available online: <http://www.renewableuk.com/en/renewable-energy/wind-energy/small-and-medium-scale-wind/technologies.cfm>.

34. WIND POWER MONTHLY. The 10 biggest turbines in the world. Available online: <http://www.windpowermonthly.com/10-biggest-turbines>.

Accessed 2015.

35. WYRE TIDAL ENERGY. La Rance Barrage. Available online: <http://www.wyretidalenergy.com/tidal-barrage/la-rance-barrage>.

36. SANCHO, A. et al. **Design Requirements of Tidal Energy Systems in Pentland Firth**. Cranfield University. 2015.

37. KARA, F. **Offshore Renewable Energy: Lecture 7 Energy Absorption from Ocean Wave**. Cranfield University. 2015.

38. EUROPEAN OCEAN ENERGY ASSOCIATION; EUROPEAN RENEWABLE ENERGY COUNCIL.

39. DAVIS, R. C. **Anaerobic Digestion: Pathways for using waste as energy in urban settings**. 2014.

40. VILLA, R. **Fundamentals of Anaerobic microbiology and biochemistry**. Cranfield University.2014.

41. HOLM-NIELSEN, J. B.; SEADI, T. A.; OLESKOWICZ-POPIEL, P. **The future of anaerobic digestion and biogas utilization**. 2008.

42. NNFCC BIOECONOMY CONSULTANTS. The Official Information Portal on Anaerobic Digestion. Available online: <http://www.biogas-info.co.uk>.

43. IMPACT BIOENERGY. **How Anaerobic Digestion, Composting, and Wood Biomass systems work together**. 2014.

44. KIRK, D. M.; FAIVOR, L. Feedstocks for Biogas. Available online: <http://www.extension.org/pages/26617/feedstocks-for-biogas#.VeiEO_ntmkp>.

45. EUROPEAN COMISSION. Photovoltaic Geographical Information System - Interactive Maps and PV Performance Calculator. Available online: <http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php#>. Accessed 2015.

46. WINDFINDER. Wind and weather statistics Alderney Airport. Available online: <http://www.windfinder.com/windstatistics/alderney>. Accessed 2015.

47. ADL-ZARRABI, B. **Thermal properties: heat conductivity and heat capacity determined using the TPS method and mineralogical composition by modal analysis**. SP Swedish National Testing and Research Institute. 2004.

48. CARBON TRUST R&D. **Ground source heat pumps: development of GeoReports for potential site characterisation, issue 1.2.** British Geological Survey.

49. SUSTAINABLE DIRECTION LTD. **SDL Supplying Energy for Alderney**. 2015.

50. RAUGEI, M.; BARGIGLI, S.; ULGIATI, S. **Life cycle assessment and energy pay-back time of advanced photovoltaic modules: CdTe and CIS compared to poly-Si**. Energy and Environment Research Unit, Dep. of Chemistry, University of Siena. 2006.

51. MEYER, E. L.; ERNEST VAN DYK, E. Assessing the Reliability and Degradation of Photovoltaic Module Performance Parameters. **IEEE TRANSACTIONS ON RELIABILITY**, v. 53, n. 1, March 2004.

52. INVENSUN. INVENSUN SUNDRAGON 230W SOLAR PANEL. Available online: <http://www.invensun.com/solar-panels/230w-solar-panel>. Accessed 2015.

53. FRAUNHOFER INSTITUT FOR SOLAR ENERGY SYSTEMS ISE. **Levelized Cost Of Electricity Renewable Energy Technologies Study**. 2013.

54. ZHANG, P. et al. **Reliability assessment of photovoltaic power systems: Review of current status and future perspectives**. 2012.

55. MOHARIL, R. M.; KULKARNI, P. S. **Reliability analysis of solar photovoltaic system using hourly mean solar radiation data**. 2009.

56. BRE NATIONAL SOLAR CENTRE. **Planning guidance for the development of large scale ground mounted solar PV systems**.

57. NATURAL ENGLAND. **Solar parks: maximising environmental benefits**. 2011.

58. INSTITUT OF ENVIRONMENTAL MANAGEMENT ASSESSMENT. **The environmental assessment of solar parks**.

59. MARTIN, J. Solar farm projects near airports: Is glare an issue?, 2013. Available online: <http://www.solarchoice.net.au/blog/solar-panels-near-airports-glare-issue/>. Accessed 2015.

60. NUGENT, D.; K.SOVACOOL, B. **Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey**. 2013.

61. AMPONSAH, N. Y. et al. **Green house gas emissions from renewable energy sources: A review**. 2014.

62. ERIKSSON, S.; BERNHOFF, H.; LEIJON, M. **Evaluation of different turbine concepts for wind power**. Swedish Centre for Renewable Electric Energy Conversion. 2006.

63. KARA, F. **Offshore Renewable Energy:** Lecture 4 Aerodynamics Of Wind Turbine. Cranfield University. 2015.

64. BUSSEL, G. J. W. V.; ZAAIJER, M. B. **Reliability, Availability and Maintenance aspects of large-scale offshore wind farms, a concepts study**. Delft University of Technology.

65. ZHAO, S.; SINGH, C. **Reliability study of onshore and offshore wind generation and impact of location**. PES General Meeting | Conference

& Exposition, 2014 IEEE. 2014.

66. SHENG, S. S. **Report on Wind Turbine Subsystem Reliability ─ A Survey of Various Databases**. National Renewable Energy Laboratory. 2013.

67. CENTER FOR CLIMATE AND ENERGY DECISION MAKING. **Technology Information Sheets**. 2013.

68. ENERCON CANADA INC. **Innovative Wind & Hybrid Systems for Mines & Remote Microgrids**. 2013.

69. SAIDUR, R. et al. **Environmental impact of wind energy**. 2011.

70. LEUNG, D. Y. C.; YANG, Y. **Wind energy development and its environmental impact: A review**. 2011.

71. UNITED NATIONS DEVELOPMENT PROGRAMME (UNDP) SERBIA. **Guidelines on the Environmental Impact Assessment for Wind Farms**. 2010.

72. GEEST, P. J. V. D. **Problems and solutions for wind turbine siting in the vicinity of airports**. NRL Air Transport Safety Institute.

73. DELORM, T. M.; ZAPPALÀ, D.; TAVNER, P. J. **Tidal stream device reliability comparison models**. Durham University. 2012.

74. SHIELDS et al. **Strategic priorities for assessing ecological impacts of marine renewable energy devices in the Pentland Firth (Scotland, UK)**. 2008.

75. BOEHLERT, G. W.; GILL, A. B. Environmental and ecological effects of ocean renewable energy development: A current synthesis. In: **Marine Renewable Energy | In a Regulatory Environment**. 2010. Vol.23, No.2.

76. TSILEMOU, K.; PANAGIOTAKOPOULOS, D. **Approximate cost**

functions for solid waste treatment facilities. 2006.

77. WILTSEE, G. **Lessons Learned from Existing Biomass Power Plants**. National Renewable Energy Laboratory. 2000.

78. BIOENERGY RE-GENERATION PROJECT. **Quality Assured Combined Heat and Power (CHPQA) & Enhanced Capital Allowances (ECA) for Biomass Projects**.

79. Meeting with Roland Gauvain: Alderney Wildlife Trust's Manager. Alderney. 2015.

80. KARA, F. **Offshore Renewable Energy: Lecture 8 Power Extraction From Tides & Tidal Currents**. Cranfield University. 2015.

81. NATIONAL RENEWABLE ENERGY LABORATORY. Land Use by System Technology. Available online: <http://www.nrel.gov/analysis/tech_size.html>. Accessed 2015.

82. GEBREZGABHER, S. A. et al. Economic analysis of anaerobic digestion—A case of Green power biogas plant in The Netherlands. **NJAS - Wageningen Journal of Life Sciences**, 2009.

83. KIRK, D. M.; GOULD, M. C. Uses of Solids and By-Products of Anaerobic Digestion. Available online: <http://www.extension.org/pages/30310/uses-of-solids-and-by-products-of-anaerobic-digestion#.VeiFOvntmkp>. Accessed 2015.

84. CONSERVE ENERGY FUTURE. Advantages of Solar Energy. Available online: <http://www.conserve-energy-future.com/Advantages_SolarEnergy.php>. Accessed 2015.

85. TURBOWINDS. Turbowinds T400-34. Available online: <http://www.turbowinds.com/index.php?page=t400-34>. Accessed 2015.

86. RAY, M. L.; ROGERS, A. L.; MCGOWAN, J. G. **Analysis of wind shear**

models and trends in different terrain. Renewable Energy Research Laboratory of the University of Massachusetts. 2006.

87. SAMORANI, M. **The Wind Farm Layout Optimization Problem**. 2013.

88. BRUNET, Y. **Energy Storage:** Electric Drives. ISTE Ltd, 2010.

89. BIZUAYEHU, A. W. et al. **Electrical Energy Storage Systems:** Technologies’ State-of-the-Art, Techno-Economic Benefits and Applications Analysis. 47th Hawaii International Conference on System Science. Hawaii: 2014.

90. NAIR, N.-K. C.; GARIMELLA, N. **Battery energy storage systems: Assessment for small-scale renewable energy integration**. The University of Auckland. 2010.

91. KALDELLIS, J. K.; KAVADIAS, K.; ZAFIRAKIS, D. **The role of hydrogen-based energy storage in the support of large-scale wind energy integration in island grids**. Technological Education Institute of Piraeus. 2013.

92. IBRAHIM, H.; ILINCA, A.; PERRON, J. **Energy storage systems—Characteristics and comparisons**. Wind Energy Research Laboratory (WERL), Université du Québec. 2007.

93. DENHOLM, P. et al. **The Role of Energy Storage with Renewable Electricity Generation**. National Renewable Energy Laboratory. 2010.

94. THE ALDERNEY PRESS. Energy from the sea next year, 2011. Available online: <http://www.alderneypress.com/2011/03/energy-from-the-sea-next-year/>.

95. DIVYA, K. C.; ØSTERGAARD, J. **Battery energy storage technology for power systems—An overview**. Technical University of Denmark. 2008.

96. NGK INSULATORS LTD. **NaS Battery Energy Storage System**. 2013.

97. HICKS, J. et al. **Community-owned renewable energy. A How To Guide**. Community power agency. 2014.

98. SPEAR, S. Samso: World's First 100% Renewable Energy-Powered Island Is a Beacon for Sustainable Communities, 2014. Available online: <http://ecowatch.com/2014/05/01/samso-renewable-energy-island-sustainable-communities/>.

99. CAMERON, C. German Village Produces 500% of its Energy from Renewable Sources. Available online: <http://inhabitat.com/german-village-produces-500-of-its-energy-from-renewable-sources/?theme=responsive>.

100. NORTHWEST COMUNITY ENERGY. Ellensburg, Washington's Community Solar Project. Available online: <http://nwcommunityenergy.org/solar/solar-case-studies/chelan-pud>.

101. LOHRENGEL, H. **Civil society engaging in local renewable energy production**. Bioenergy Village Jühnde. 2015.

102. WILLIS, R.; WILLIS, J. **Co-operative renewable energy in the UK: A guide to a growing sector**. Co-operatives UK. 2012.

103. OXFORD COMUNITY ENERGY CO-OPERATIVE. Everyone wins with Community Owned Renewable Energy. Available online: <http://oxfordcommunityenergycoop.wildapricot.org/page-1741086>.

104. SCOTTISH LAND ACTION MOVEMENT. Energy democracy: from Inverness to Indonesia, 2015. Available online: <http://www.scottishlandactionmovement.org/slam-news/2015/5/18/energy-democracy-from-inverness-to-indonesia>.

105. WILDPOLSRIED Das Energiedorf. Available online:

<http://www.wildpoldsried.de/index.shtml?energie_homepage>.

106. HEPBURN Wind Community. Available online: <http://www.hepburnwind.com.au/community/>.

107. WESTMILL Solar. Available online: <http://www.westmillsolar.coop/>.

108. THE Danish Wind Turbine Owners' Association. Available online: <http://www.dkvind.dk/html/eng/eng.html>.

109. MIDDELGRUNDENS VINDMøLLELAUG: OFFSHORE WIND FARM OUTSIDE THE HARBOUR OF COPENHAGEN. About Middelgrunden Wind Cooperative. Available online: <http://www.middelgrunden.dk/middelgrunden/?q=en/node/35>.

110. U.S. DEPARTMENT OF ENERGY. **Community Renewable Energy Deployment Provides Replicable Examples of Clean Energy Projects**.

111. BAYWIND Energy Co-operative Ltd. Available online: <http://www.baywind.coop/baywind_home.asp>.

112. INSPIRING Stories of Community power projects across Europe. Available online: <http://www.communitypower.eu/en/inspiring-stories.html>.

113. ALTERNATIVE ENERGY. Hydrogen and Fuel Cells - Transportation and Distribution. Available online: <http://www.altenergy.org/renewables/hydrogen_and_fuel_cells_transportationdistribution.html>.

114. BALLARD. Addressing Climate Change with Fuel Cell Technology. Available online: <http://www.fuelcells.org/uploads/fuelcellsclimatechange.pdf>.

115. THE Electropaedia: Battery and Energy Technologies. Available online: <http://www.mpoweruk.com/>.

116. LIPMAN, T. **An overview of hydrogen production and storage systems with renewable hydrogen case studies**. Clean Energy States Alliance. 2011.

117. ELERT, G. Energy Density of Hydrogen. Available online: <http://hypertextbook.com/facts/2005/MichelleFung.shtml>.

118. THE HYDROGEN AND FUEL CELL INFORMATION SYSTEM. Hydrogen Data. Available online: <http://www.h2data.de/>.

119. HYDROGEN Storage Engineering Center of Excellence. Available online: <http://hsecoe.org/>.

120. OFFICE OF ENERGY & RENEWABLE ENERGY. National Hydrogen Storage Profect. Available online: <http://energy.gov/eere/fuelcells/national-hydrogen-storage-project>.

121. GLANDT, J. D. **Fuel Cell Power as a Primary Energy Source for Remote Communities**. Ballard. 2012.

122. REPOWERING SOLUTIONS. Used, refurbished and remanufactured wind turbines. Available online: <http://www.repoweringsolutions.com/english/products/used_wind_turbine/index.htm>. Accessed 2015.

123. BROWNLEES, V. **Decentralized hydrogen solutions for stationary applications**. Atawey. 2015.

124. KYMAKIS, E.; KALYKAKIS, S.; PAPAZOGLOU, T. M. **Performance analysis of a grid connected photovoltaic park on the island of Crete**. 2009.

125. ZHANG, Y. **Anaerobic digestion fundamentals II: Thermodynamics**. University of Southampton. 2013.

11 APPENDICES

Appendix A : Energy Demand Analysis

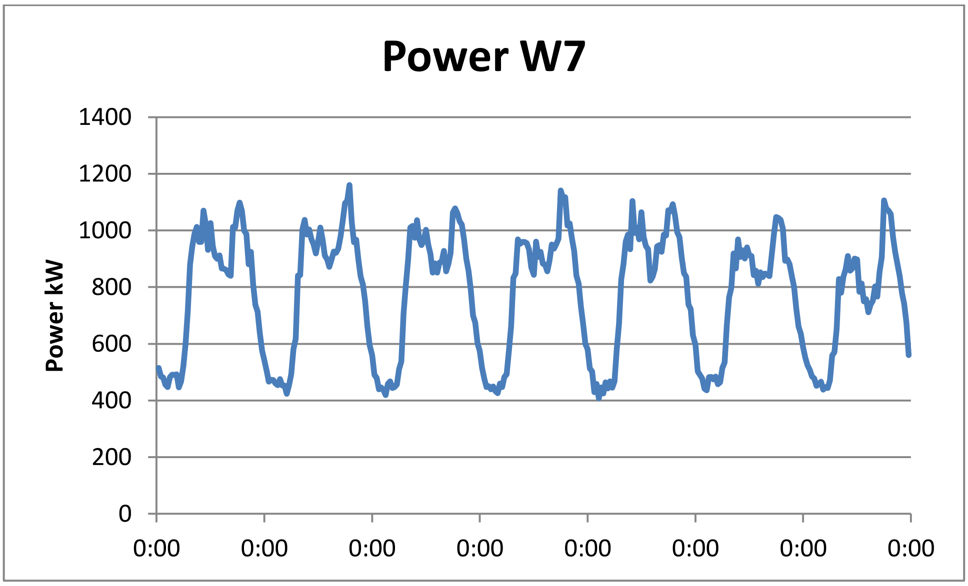
In this annex, the energy demand along four different weeks provided by AEL is analysed in order to determine the energy and power variation along the day, week and year in function of the season. Firstly, the power, energy and fuel consumption in the four different weeks are examined. In all four weeks the energy was supplied by means of one of the three 2 MW Paxman diesel generator.

A.1 Week 7 Energy Analysis

During the week 7, there was a diesel fuel consumption of 37,107 L with a daily average of 5,301 L and an efficiency of 3.52 kWh/L. The power and energy evolution were the following ones.

A.1.1 Power Data

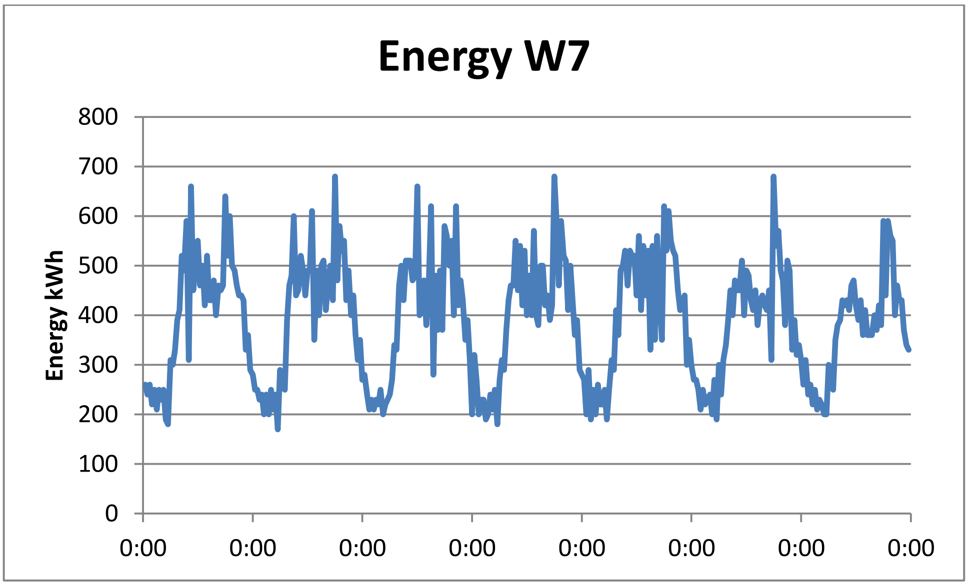
In terms of power week 7 had a peak of 1,104 kW and a minimum and a minimum power of 676.96 kW. The evolution along the week is the following one:



Graph 11-A: Power evolution along the W7

A.1.2 Energy Data

In terms of energy demand, along the week 7 there was a total energy consumption of 130,590 kWh with a daily average of 18,655.71 kWh. The energy evolution along the week is the following one with a maximum demand of 660 kWh and a minimum of 341.8 kWh:



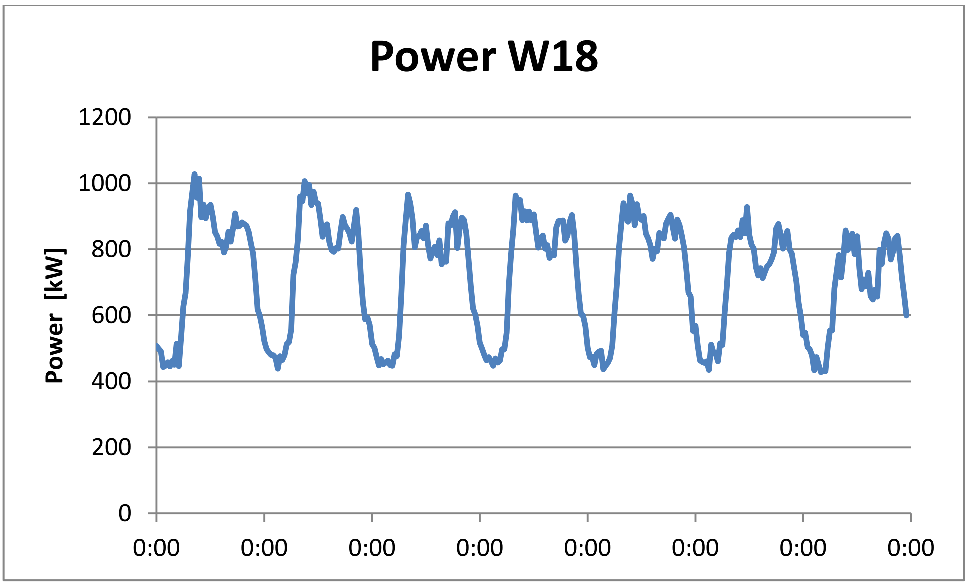
Graph 11-B: Energy evolution along the W7

A.2 Week 18 Energy Analysis

During the week 18, there was a diesel fuel consumption of 34,562 L with a daily average of 4,937 L and an efficiency of 3.52 kWh/L. The power and energy evolution were the following ones.

A.2.1 Power Data

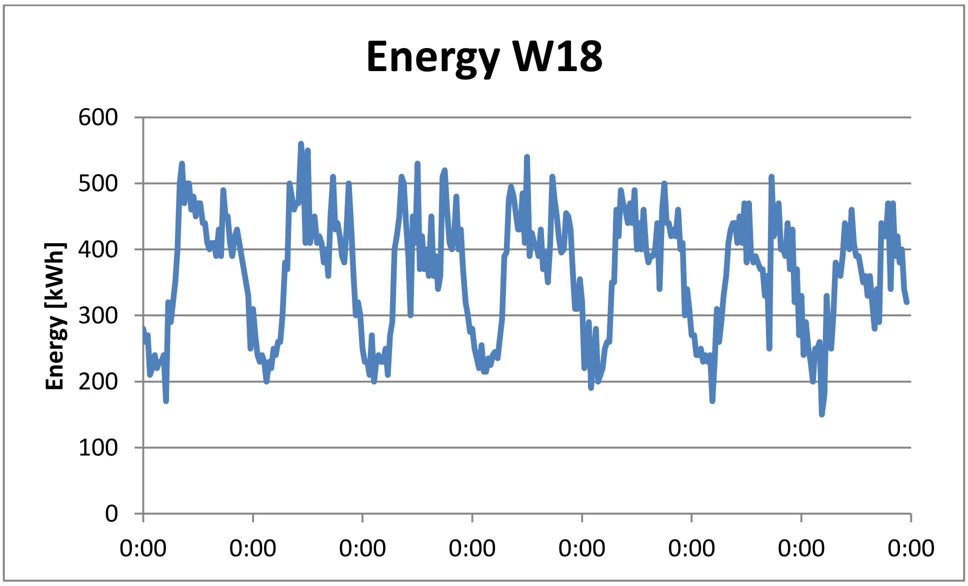
In terms of power week 18 had a peak of 1,028 kW and a minimum power of 428 kW. The evolution along the week is the following one:



Graph 11-C: Power evolution along the W18

A.2.2 Energy Data

In terms of energy demand, along the week 18 there was a total energy consumption of 121,530 kWh with a daily average of 17,361 kWh. The energy evolution along the week is the following one with a maximum demand of 560 kWh and a minimum of 150 kWh:



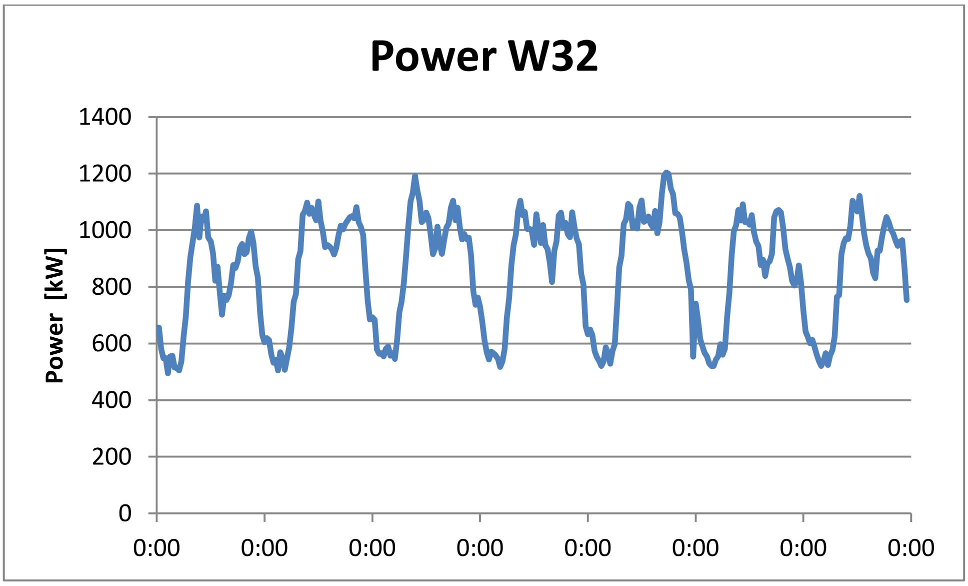
Graph 11-D: Energy evolution along the W18

A.3 Week 32 Energy Analysis

During the week 32, there was a diesel fuel consumption of 39,766 L with a daily average of 5,681 L and an efficiency of 3.60 kWh/L. The power and energy evolution were the following ones.

A.3.1 Power Data

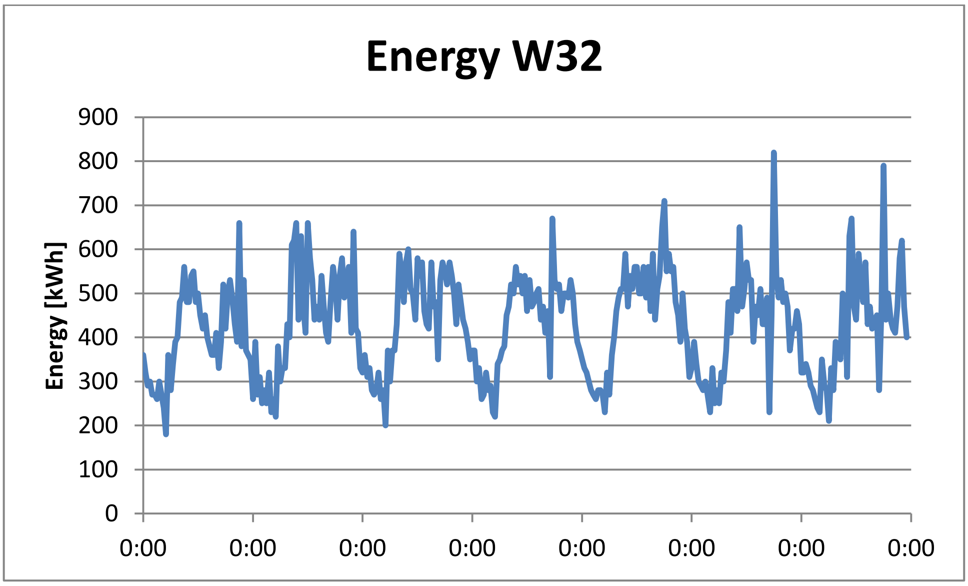
In terms of power week 32 had a peak of 1,204 kW and a minimum power of 495 kW. The evolution along the week is the following one:



Graph 11-E: Power evolution along the W32

A.3.2 Energy Data

In terms of energy demand, along the week 32 there was a total energy consumption of 143,180 kWh with a daily average of 20,454 kWh. The energy evolution along the week is the following one with a maximum demand of 820 kWh and a minimum of 180 kWh:



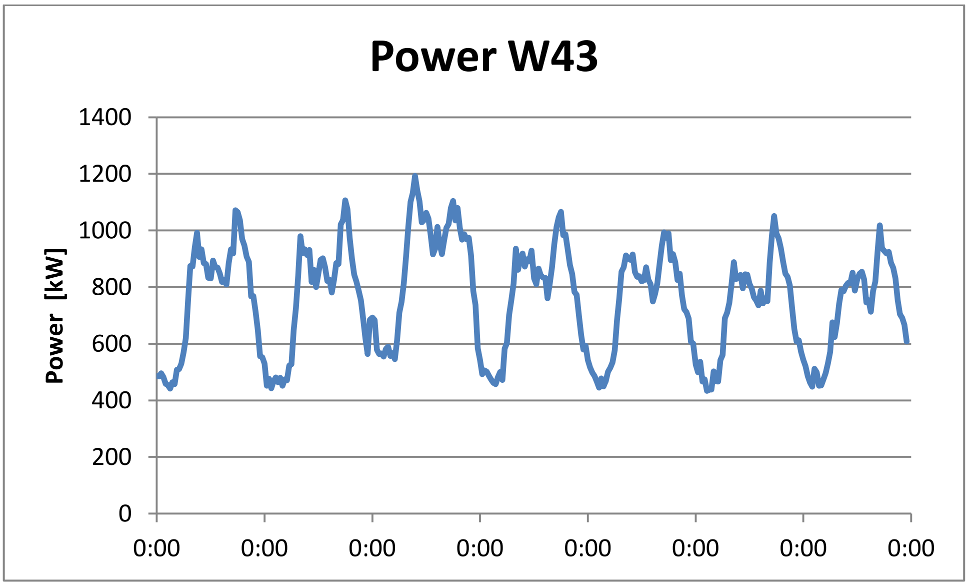
Graph 11-F: Energy evolution along the W32

A.4 Week 43 Energy Analysis

During the week 43, there was a diesel fuel consumption of 35,419 L with a daily average of 5,060 L and an efficiency of 3.53 kWh/L. The power and energy evolution were the following ones.

A.4.1 Power Data

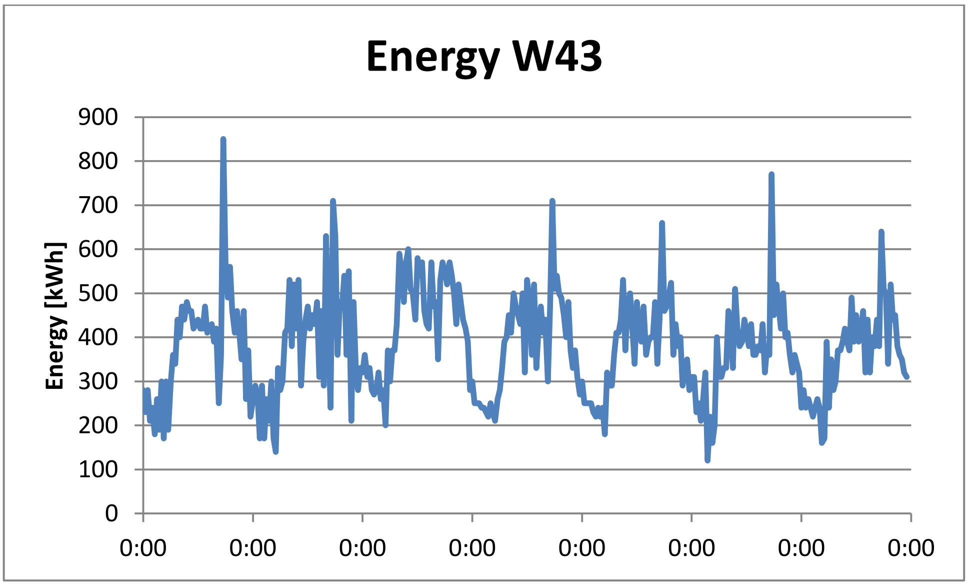
In terms of power week 43 had a peak of 1,193 kW and a minimum power of 433 kW. The evolution along the week is the following one:



Graph 11-G: Power evolution along the W43

A.4.2 Energy Data

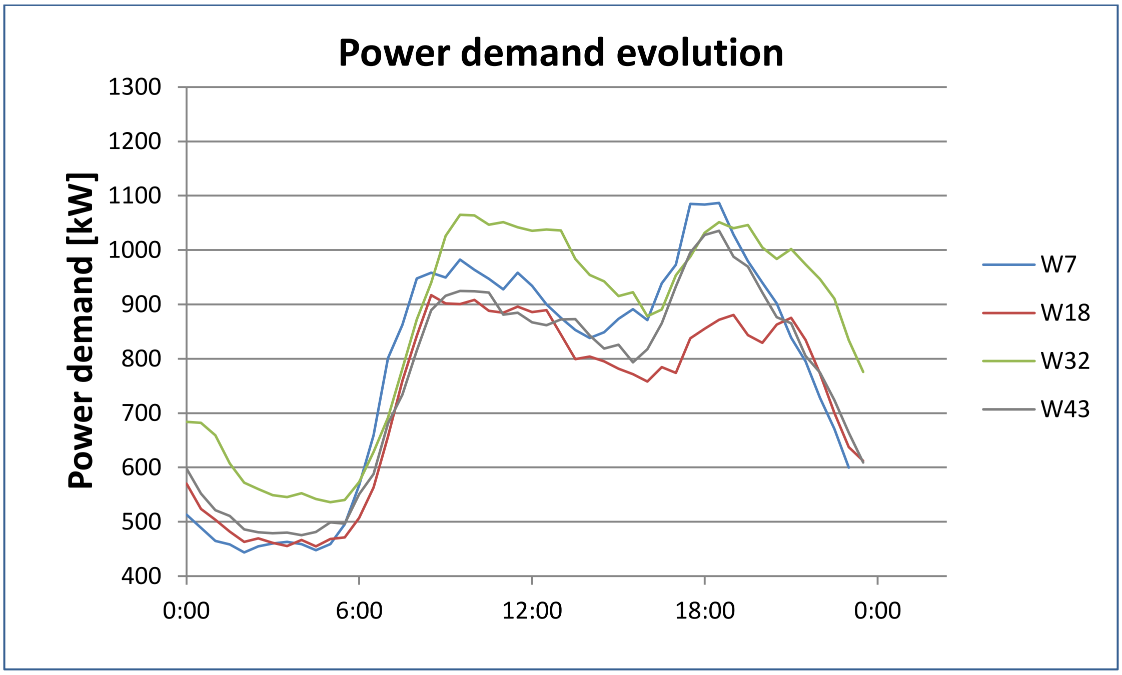
In terms of energy demand, along the week 43 there was a total energy consumption of 124,900 kWh with a daily average of 17,843 kWh. The energy evolution along the week is the following one with a maximum demand of 850 kWh and a minimum of 120 kWh:



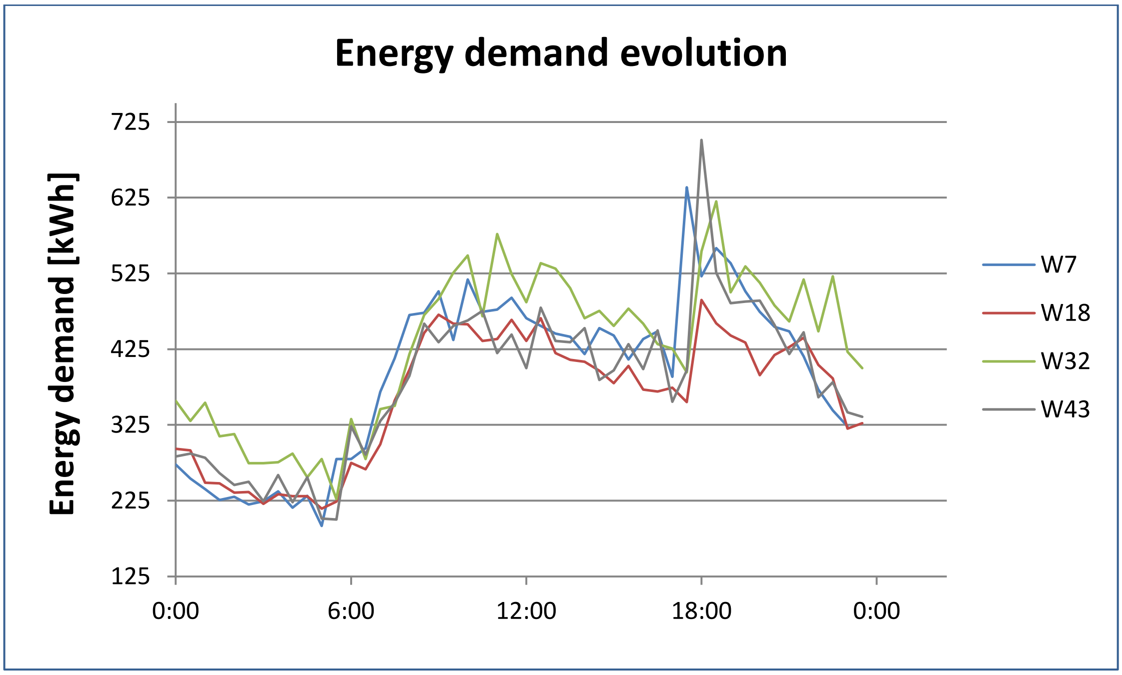
Graph 11-H: Energy evolution along the W43

A.5 Summary and Seasonally Comparison

Finally, an average day per week is calculated in order to compare the power and energy between seasons. As it can be seen in the following figures, the energy and power demand are very similar along the different weeks with slightly higher values during the Alderney Week (W32) and the winter weeks.



Graph 11-I: Power evolution along a day



Graph 11-J: Power evolution along a day

Appendix B : Dimensioning the Solar PV Park and Wind Farm

In this annex, the dimensions of the proposed solar PV park and wind farm are estimated.

In the case of the solar PV park, the dimensions are estimated as follows by selecting a standard 230W PV panel [52] and fixing the rated power output of the park at 475 kW. As a result of these assumptions, it is estimated that should be necessary 2065 panels of 1.632x0.995 m [52] which require a total area of PV panels of 3,353.58 m^2. However, it is estimated a real area of 1.6 times the panels area due to inclination losses, distance between panels and perimeter fences. Hence, the solar PV park will require 5,366 m^2 of area which in the example was divided approximately in a rectangle of 160x35 m.

Regarding the wind farm and turbine dimensions, firstly it is assumed a measured wind at 10m height of 13 knots [46] with an air density of 1.225 kg/m^3, equivalent to an air temperature of 15ºC. Then, the hub height of the turbine is fixed by selecting a WT of 34m hub height and 34m of rotor diameter [85]. The selection of the turbine characteristics is realized by trying to minimise as possible the visual impact to the surrounding areas while having a cost-efficient energy output. Once fixed these parameters, a hub height velocity of 11 m/s is estimated by using the log law with a terrain parameter of 1.5 (equivalent to suburbs and small town areas) [86].

$$u_{hub\ height} = \frac{\ln\left(\frac{hub\ height}{terrain\ parameter}\right)}{\ln\left(\frac{measurement\ height}{terrain\ parameter}\right)} \times u_{measured}$$

Equation 11-A: Log law equation

Then, a rated power of 250 kW is obtained by using the hub height velocity in the power curve of the selected turbine.

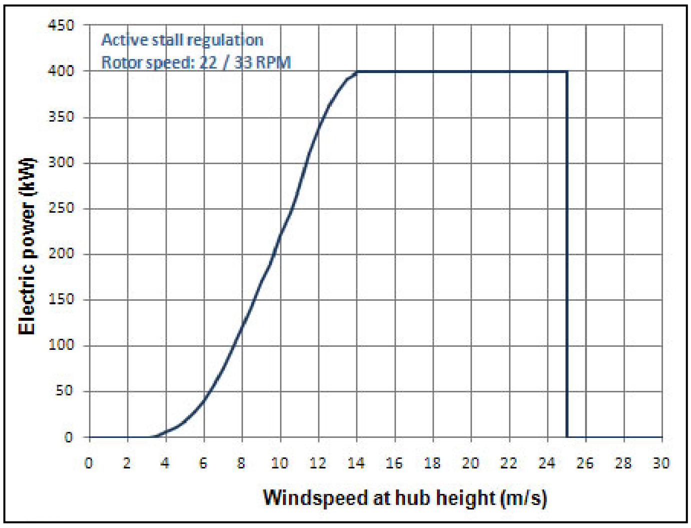


Figure 11-A: Power curve of the T400-34

In addition, a power coefficient of 0.337 is estimated through calculating the total power in the wind at 11 m/s which is 741.29 kW.

$$P = \frac{1}{2} \times \rho_{air(15ºC)} \times A \times u^3 [W]$$

Equation 11-B: Total power in the wind

$$A = \pi \times R_{turbine}{}^2$$

Equation 11-C: Swept area of a WT

Finally, two WTs are proposed which can supply 250 kW each at the average hub height of 11m/s. A separation of 136m (4 turbine's diameter) is estimated in the perpendicular direction to the prevailing wind [87].

Appendix C : Feasibility Analysis

As explained along the paper, this feasibility analysis compares the energy produced by the RE systems against the energy demand in order to determine the storage level in the NaS batteries as well as the necessity of diesel. In this annex, first it will be detailed how the inputs of the assessment are calculated and then the detailed analysis for the different months and scenarios.

C.1 Energy demand calculation

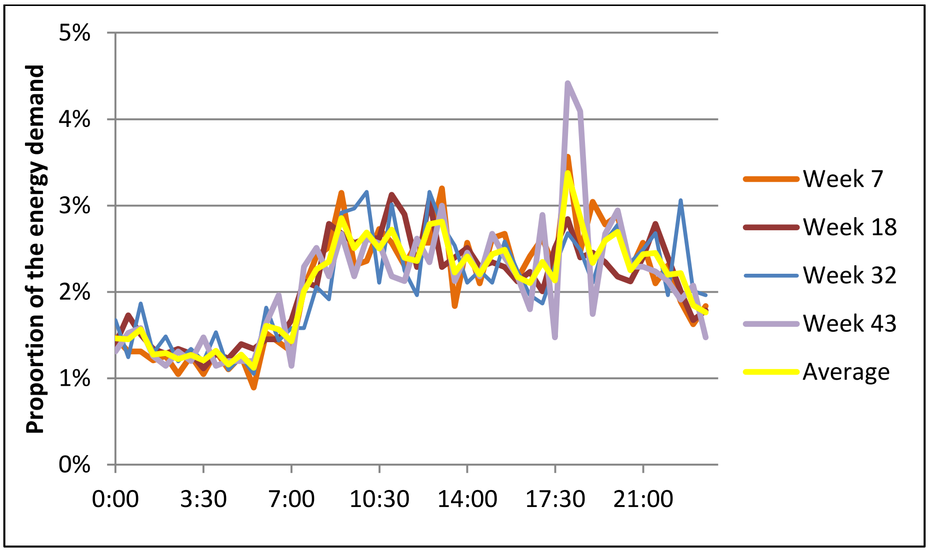
The energy demand estimations are based on data supplied by the AEL such as the energy demand of all the weeks along the 2014 and the daily demand for 4 different weeks during 2014 and 2015. From the first document, the different weeks are arranged according to the calendar in the 12 months in order to get an average weekly and daily demand per month as follows:

Week	Energy demand[kWh]	Weekly average energy [kWh]	Daily average energy [kWh]
1	138,010	133,561	19,080
2	131,040		
3	131,690		
4	132,340		
5	134,723		
6	134,190	132,490	18,927
7	134,560		
8	131,140		
9	130,070		
10	127,440	126,748	18,107
11	128,170		
12	127,600		
13	125,380		
14	125,151		
15	122,880	122,885	17,555
16	122,940		
17	123,760		
18	121,960		
19	121,290	121,715	17,388
20	118,050		
21	123,310		
22	124,210		

Week	Energy demand[kWh]	Weekly average energy [kWh]	Daily average energy [kWh]
23	121,250	120,790	17,256
24	120,159		
25	121,052		
26	120,700		
27	123,826	127,763	18,252
28	123,694		
29	125,922		
30	128,629		
31	136,746		
32	143,520	135,571	19,367
33	137,690		
34	130,580		
35	130,495		
36	125,753	123,877	17,697
37	122,616		
38	124,440		
39	122,698		
40	118,878	122,992	17,570
41	120,650		
42	123,567		
43	126,693		
44	125,170		
45	127,560	128,930	18,419
46	127,550		
47	130,240		
48	130,370		
49	139,010	136,815	19,545
50	137,790		
51	138,400		
52	132,060		

Table 11-A: Energy demand during the different weeks, month and a daily average

Once the daily demand per month is estimated, from the detailed weekly demand, the proportion of energy consumed every half an hour is calculated for the weeks 7, 18, 32 and 43. Then, a constant average energy demand distribution along the day is chosen due to the similarities between the energy consumption per hour between the weeks as shown below.



Graph 11-K: Distribution of the energy demand along average days

After that, the energy demand every half an hour is estimated by taking using the average daily demand distribution and the monthly average day demand. The results are displayed in the table below.

Time	Average Distribution	January [kWh]	February [kWh]	March [kWh]	April [kWh]	May [kWh]	June [kWh]	July [kWh]	August [kWh]	September [kWh]	October [kWh]	November [kWh]	December [kWh]
0:00	0.0146	279	277	265	257	254	252	267	283	259	257	269	286
0:30	0.0145	277	275	263	255	253	251	265	281	257	255	268	284
1:00	0.0157	299	296	284	275	272	270	286	303	277	275	288	306
1:30	0.0127	243	241	230	223	221	220	232	246	225	224	234	249
2:00	0.0129	247	245	234	227	225	223	236	250	229	227	238	253
2:30	0.0122	233	231	221	215	213	211	223	237	216	215	225	239
3:00	0.0127	242	240	230	223	221	219	232	246	225	223	234	248
3:30	0.0121	231	229	219	212	210	208	221	234	214	212	223	236
4:00	0.0132	251	249	239	231	229	227	240	255	233	231	243	257
4:30	0.0116	221	219	210	203	201	200	211	224	205	203	213	226
5:00	0.0127	243	241	231	224	222	220	233	247	225	224	235	249
5:30	0.0112	214	212	203	197	195	193	205	217	198	197	206	219
6:00	0.0161	306	304	291	282	279	277	293	311	284	282	296	314
6:30	0.0157	299	296	284	275	272	270	286	303	277	275	288	306
7:00	0.0143	272	270	258	251	248	246	260	276	253	251	263	279
7:30	0.0201	383	380	364	353	349	347	367	389	355	353	370	393
8:00	0.0226	431	428	409	397	393	390	413	438	400	397	416	442
8:30	0.0235	448	445	426	413	409	406	429	455	416	413	433	459
9:00	0.0285	544	540	517	501	496	492	521	553	505	501	526	558
9:30	0.0251	478	474	454	440	436	432	457	485	443	440	461	490
10:00	0.0269	513	509	487	472	468	464	491	521	476	472	495	526
10:30	0.0250	478	474	453	440	435	432	457	485	443	440	461	489
11:00	0.0272	519	515	493	478	473	470	497	527	482	478	501	532
11:30	0.0240	457	453	434	421	417	413	437	464	424	421	441	468
12:00	0.0236	450	446	427	414	410	407	431	457	417	414	434	461

Time	Average Distribution	January [kWh]	February [kWh]	March [kWh]	April [kWh]	May [kWh]	June [kWh]	July [kWh]	August [kWh]	September [kWh]	October [kWh]	November [kWh]	December [kWh]
12:30	0.0278	531	527	504	489	484	481	508	539	493	489	513	544
13:00	0.0281	537	533	510	494	489	486	514	545	498	495	518	550
13:30	0.0222	424	421	403	390	387	384	406	431	394	391	410	435
14:00	0.0241	460	456	436	423	419	416	440	467	426	423	444	471
14:30	0.0220	420	417	399	387	383	380	402	427	390	387	406	431
15:00	0.0244	465	461	441	428	423	420	444	472	431	428	449	476
15:30	0.0249	474	471	450	436	432	429	454	481	440	437	458	486
16:00	0.0217	415	412	394	382	378	375	397	421	385	382	401	425
16:30	0.0210	401	398	380	369	365	363	383	407	372	369	387	411
17:00	0.0235	448	444	425	412	408	405	428	454	415	412	432	459
17:30	0.0213	407	404	386	375	371	368	389	413	378	375	393	417
18:00	0.0338	644	639	611	593	587	583	616	654	598	593	622	660
18:30	0.0286	546	541	518	502	497	494	522	554	506	503	527	559
19:00	0.0234	446	442	423	410	406	403	426	452	413	411	430	457
19:30	0.0259	495	491	470	455	451	448	474	502	459	456	478	507
20:00	0.0269	514	510	488	473	469	465	492	522	477	473	496	527
20:30	0.0225	430	426	408	395	392	389	411	436	399	396	415	440
21:00	0.0244	465	461	441	428	424	420	445	472	431	428	449	476
21:30	0.0245	468	464	444	430	426	423	447	475	434	431	451	479
22:00	0.0220	419	416	398	386	382	379	401	426	389	386	405	430
22:30	0.0222	423	420	401	389	385	382	405	429	392	389	408	433
23:00	0.0185	352	349	334	324	321	318	337	357	327	324	340	361
23:30	0.0176	336	334	319	310	307	304	322	342	312	310	325	345

Table 11-B: Average daily energy distribution and energy demand of the different months per each half an hour

C.2 Energy generation the solar PV park

To calculate the energy harnessed by the 475 kW solar PV park proposed before, the GHI for the selected location is estimated from [45]. Then the GHI is multiplied by the total PV area and the following efficiencies and losses are applied in the presented order:

Efficiency at Standard Test Conditions	15%
PV degradation losses	5%
Temperature losses	7.12%
Soiling losses	5.86%
Internal network losses	6%
Inverter losses	7.84%
Transformer losses	2%
Availability and grid connection losses	4.54%

Table 11-C:Efficiencies and losses of the solar PV park [124]

As a result of these operations, the following table for the different months can be extracted where it can be seen the different sunrise and sunset times along the year.

Time	January [kWh]	February [kWh]	March [kWh]	April [kWh]	May [kWh]	June [kWh]	July [kWh]	August [kWh]	September [kWh]	October [kWh]	November [kWh]	December [kWh]
0:00												
0:30												
1:00												
1:30												
2:00												
2:30												
3:00												
3:30												
4:00												
4:30						3.27	2.97					
5:00					3.73	5.22	4.45					
5:30				3.22	5.73	6.74	6.06	3.82				
6:00				5.56	9.25	10.86	10.01	6.83	3.05			
6:30			5.00	11.15	14.80	16.58	15.65	12.13	6.49			
7:00			9.29	17.73	20.91	22.56	21.76	18.07	12.47	5.43		
7:30		4.88	15.14	24.64	27.10	28.67	27.91	24.26	18.83	9.37		
8:00	3.90	9.50	21.08	31.43	33.12	34.61	33.97	30.37	25.28	14.25	4.83	
8:30	6.53	13.91	26.76	37.83	38.85	40.08	39.61	36.13	31.47	18.83	8.91	4.07
9:00	9.84	18.02	32.02	43.64	44.02	45.13	44.79	41.35	37.15	23.07	12.55	6.57
9:30	12.64	21.63	36.60	48.77	48.56	49.49	49.28	46.02	42.16	26.72	15.78	9.67
10:00	15.01	24.68	40.50	53.06	52.34	53.18	53.10	49.88	46.40	29.77	18.45	12.21
10:30	16.84	27.06	43.60	56.45	55.35	56.11	56.07	52.93	49.75	32.19	20.57	14.29
11:00	18.15	28.84	45.80	58.95	57.55	58.19	58.23	55.18	52.17	33.93	22.14	15.86
11:30	18.96	29.86	47.16	60.39	58.82	59.42	59.55	56.53	53.65	34.95	23.07	16.92
12:00	19.25	30.20	47.59	60.90	59.29	59.88	59.97	57.00	54.12	35.29	23.41	17.47

Time	January [kWh]	February [kWh]	March [kWh]	April [kWh]	May [kWh]	June [kWh]	July [kWh]	August [kWh]	September [kWh]	October [kWh]	November [kWh]	December [kWh]
12:30	18.96	29.86	47.16	60.39	58.82	59.42	59.55	56.53	53.65	34.95	23.07	17.47
13:00	18.15	28.84	45.80	58.95	57.55	58.19	58.23	55.18	52.17	33.93	22.14	16.92
13:30	16.84	27.06	43.60	56.45	55.35	56.11	56.07	52.93	49.75	32.19	20.57	15.86
14:00	15.01	24.68	40.50	53.06	52.34	53.18	53.10	49.88	46.40	29.77	18.45	14.29
14:30	12.64	21.63	36.60	48.77	48.56	49.49	49.28	46.02	42.16	26.72	15.78	12.21
15:00	9.84	18.02	32.02	43.64	44.02	45.13	44.79	41.35	37.15	23.07	12.55	9.67
15:30	6.53	13.91	26.76	37.83	38.85	40.08	39.61	36.13	31.47	18.83	8.91	6.57
16:00	2.63	9.50	21.08	31.43	33.12	34.61	33.97	30.37	25.28	14.25	4.83	2.67
16:30		4.88	15.14	24.64	27.10	28.67	27.91	24.26	18.83	9.37	1.36	
17:00		1.36	9.29	17.73	20.91	22.56	21.76	18.07	12.47	3.82		
17:30			3.99	11.15	14.80	16.58	15.65	12.13	6.49			
18:00				5.56	9.25	10.86	10.01	6.83	2.33			
18:30				2.67	5.73	6.74	6.06	3.82				
19:00					3.73	5.22	4.45	2.21				
19:30					2.12	3.27	2.46					
20:00						1.78						
20:30												
21:00												
21:30												
22:00												
22:30												
23:00												
23:30												

Table 11-D: Solar energy harnessed by the solar PV park in the different months

C.3 Energy generation from the AD

Regarding the energy generated from an AD, this will depend on the amount of clean wood chip used. In this case the 12,000 tonnes are converted to electricity by means of the following efficiencies:

Conversion of organic fraction to biogas	70%
Methane production (m^3) per kg of biogas	0.31 m^3/kg
Methane calorific value	35.7 MJ/m^3
Conversion efficiency to electricity	32%

Table 11-E: Estimated efficiencies for the AD [39] [125]

Once calculated the annually electricity production from the wood chips, the capacity factor of 80% is applied and the value divided per 365 in order to get daily production. Finally, the energy every half an hour is calculated by diving the daily per 48 and it is constant along all the hours and months.

C.4 Scenario 1: AD (12,000 tonnes) and 475 kW solar PV park

After explaining how the different inputs are calculated, a monthly example is displayed in the following pages where it can be seen the energy evolution along the month of January. As shown in that table, the energy storage in the batteries at the beginning of the day is half of the total energy storage capacity and in order to protect the batteries the energy stored is fixed between 200MWh and 5800MWh. In the analysis, the energy stored in the batteries increase or decrease depending on the energy produced and the energy demand.

Time	Solar PV [kWh]	AD [kWh]	Energy generation [kWh]	Energy demand [kWh]	BESS energy [kWh]	Required diesel
0:00	0.00	376.89	376.89	279	3,000	-
0:30	0.00	376.89	376.89	277	3,100	-
1:00	0.00	376.89	376.89	299	3,178	-
1:30	0.00	376.89	376.89	243	3,312	-
2:00	0.00	376.89	376.89	247	3,442	-
2:30	0.00	376.89	376.89	233	3,586	-
3:00	0.00	376.89	376.89	242	3,720	-
3:30	0.00	376.89	376.89	231	3,867	-
4:00	0.00	376.89	376.89	251	3,992	-
4:30	0.00	376.89	376.89	221	4,148	-
5:00	0.00	376.89	376.89	243	4,282	-
5:30	0.00	376.89	376.89	214	4,445	-
6:00	0.00	376.89	376.89	306	4,516	-
6:30	0.00	376.89	376.89	299	4,594	-
7:00	0.00	376.89	376.89	272	4,698	-
7:30	0.00	376.89	376.89	383	4,692	-
8:00	3.90	376.89	380.79	431	4,642	-
8:30	6.53	376.89	383.42	448	4,577	-
9:00	9.84	376.89	386.73	544	4,419	-
9:30	12.64	376.89	389.53	478	4,330	-
10:00	15.01	376.89	391.91	513	4,209	-
10:30	16.84	376.89	393.73	478	4,125	-
11:00	18.15	376.89	395.04	519	4,001	-
11:30	18.96	376.89	395.85	457	3,940	-
12:00	19.25	376.89	396.15	450	3,886	-

Time	Solar PV [kWh]	AD [kWh]	Energy generation [kWh]	Energy demand [kWh]	BESS energy [kWh]	Required diesel
12:30	18.96	376.89	395.85	531	3,750	-
13:00	18.15	376.89	395.04	537	3,608	-
13:30	16.84	376.89	393.73	424	3,577	-
14:00	15.01	376.89	391.91	460	3,510	-
14:30	12.64	376.89	389.53	420	3,479	-
15:00	9.84	376.89	386.73	465	3,401	-
15:30	6.53	376.89	383.42	474	3,310	-
16:00	2.63	376.89	379.52	415	3,274	-
16:30	0.00	376.89	376.89	401	3,250	-
17:00	0.00	376.89	376.89	448	3,180	-
17:30	0.00	376.89	376.89	407	3,149	-
18:00	0.00	376.89	376.89	644	2,882	-
18:30	0.00	376.89	376.89	546	2,713	-
19:00	0.00	376.89	376.89	446	2,644	-
19:30	0.00	376.89	376.89	495	2,526	-
20:00	0.00	376.89	376.89	514	2,389	-
20:30	0.00	376.89	376.89	430	2,336	-
21:00	0.00	376.89	376.89	465	2,248	-
21:30	0.00	376.89	376.89	468	2,158	-
22:00	0.00	376.89	376.89	419	2,115	-
22:30	0.00	376.89	376.89	423	2,069	-
23:00	0.00	376.89	376.89	352	2,094	-
23:30	0.00	376.89	376.89	336	2,134	-

Table 11-F: January example of the energy management using the scenario 1

Once analysed all the different month, it is conclude that diesel supply is not required in this scenario and hence there is saving of 1,867,112 L of diesel and 741k GBP. In addition, a summary table is realized where appears different parameters regarding the usage of the NaS batteries.

	January	February	March	April	May	June	July
kWh battery use	2629.35	2347.72	1507.82	1025.35	928.02	846.06	1388.67
%battery usage	14%	12%	8%	6%	5%	5%	8%
%battery time	66%	64%	55%	43%	43%	38%	51%
%battery full	0%	0%	0%	0%	0%	0%	0%
%BESS energy level	58%	60%	69%	75%	77%	78%	71%

	August	September	October	November	December	Total/ Average
kWh battery use	2196.56	1179.83	1311.82	2076.59	3012.29	9777.10
%battery usage	11%	7%	7%	11%	15%	4%
%battery time	64%	47%	53%	64%	66%	59%
%battery full	0%	0%	0%	0%	0%	0%
%BESS energy level	62%	73%	71%	63%	54%	65%

Table 11-G: Scenario 1 summary table

C.5 Scenario 2: AD (8,000 tonnes) and 475 kW solar PV park

Regarding the second scenario with 8,000 tonnes of clean wood chip, the only input that is different compared to the previous one is the amount of feedstock used which now produce 251.26 kWh. As a result, in this scenario some diesel supply will be required to meet the energy demand as well as to recharge the batteries until the energy level surpasses the initial 3,000 kWh. Following, the summary table and the January example are displayed.

	January	February	March	April	May	June	July
kWh battery use	4630.37	5106.34	3456.78	2910.46	3052.63	3010.96	3418.53
%battery usage	24%	27%	19%	17%	18%	17%	19%
%battery time	60%	62%	55%	57%	57%	57%	57%
total kWh diesel	4950	4,050	4950	4500	4500	4050	4500
%diesel time	23%	19%	23%	21%	21%	19%	21%
total L diesel	1262.7551	1033.1633	1262.7551	1147.9592	1147.9592	1033.1633	1147.9592

	August	September	October	November	December	Total / Average
kWh battery use	4492.56	3144.26	3494.63	4330.14	4664.59	20126.18
%battery usage	23%	18%	20%	24%	24%	9%
%battery time	62%	57%	57%	60%	60%	59%
total kWh diesel	4500	4500	4500	4500	5400	54900 (25%)
%diesel time	21%	21%	21%	21%	26%	22%
total L diesel	1147.9592	1147.9592	1147.9592	1147.9592	1377.551	14005.12

Table 11-H: Scenario 2 summary table

In this case 14,000 L of diesel are required with a cost around the 5,560 GBP which compare to the current scenario will suppose a saving of 1,853,107 L and 736k GBP.

Time	Solar PV [kWh]	AD [kWh]	Energy generation [kWh]	Energy demand [kWh]	BESS energy [kWh]	Required diesel [kWh]
0:00	0.00	251.26	251.26	279	3,000	0
0:30	0.00	251.26	251.26	277	2,974	0
1:00	0.00	251.26	251.26	299	2,927	0
1:30	0.00	251.26	251.26	243	2,935	0
2:00	0.00	251.26	251.26	247	2,940	0
2:30	0.00	251.26	251.26	233	2,958	0
3:00	0.00	251.26	251.26	242	2,966	0
3:30	0.00	251.26	251.26	231	2,987	0
4:00	0.00	251.26	251.26	251	2,987	0
4:30	0.00	251.26	251.26	221	3,018	0
5:00	0.00	251.26	251.26	243	3,026	0
5:30	0.00	251.26	251.26	214	3,063	0
6:00	0.00	251.26	251.26	306	3,008	0
6:30	0.00	251.26	251.26	299	2,960	0
7:00	0.00	251.26	251.26	272	2,939	0
7:30	0.00	251.26	251.26	383	2,808	0
8:00	3.90	251.26	255.16	431	2,631	0
8:30	6.53	251.26	257.79	448	2,441	0
9:00	9.84	251.26	261.10	544	2,157	0
9:30	12.64	251.26	263.90	478	1,943	0
10:00	15.01	251.26	266.27	513	1,697	0
10:30	16.84	251.26	268.10	478	1,487	0
11:00	18.15	251.26	269.41	519	1,237	0
11:30	18.96	251.26	270.22	457	1,050	0

Time	Solar PV [kWh]	AD [kWh]	Energy generation [kWh]	Energy demand [kWh]	BESS energy [kWh]	Required diesel [kWh]
12:00	19.25	251.26	270.52	450	871	0
12:30	18.96	251.26	270.22	531	610	0
13:00	18.15	251.26	269.41	537	342	0
13:30	16.84	251.26	268.10	424	636	450
14:00	15.01	251.26	266.27	460	892	450
14:30	12.64	251.26	263.90	420	1,186	450
15:00	9.84	251.26	261.10	465	1,432	450
15:30	6.53	251.26	257.79	474	1,666	450
16:00	2.63	251.26	253.89	415	1,955	450
16:30	0.00	251.26	251.26	401	2,255	450
17:00	0.00	251.26	251.26	448	2,509	450
17:30	0.00	251.26	251.26	407	2,803	450
18:00	0.00	251.26	251.26	644	2,860	450
18:30	0.00	251.26	251.26	546	3,016	450
19:00	0.00	251.26	251.26	446	2,821	0
19:30	0.00	251.26	251.26	495	2,577	0
20:00	0.00	251.26	251.26	514	2,314	0
20:30	0.00	251.26	251.26	430	2,136	0
21:00	0.00	251.26	251.26	465	1,922	0
21:30	0.00	251.26	251.26	468	1,706	0
22:00	0.00	251.26	251.26	419	1,538	0
22:30	0.00	251.26	251.26	423	1,366	0
23:00	0.00	251.26	251.26	352	1,265	0
23:30	0.00	251.26	251.26	336	1,180	0

Table 11-I: January example of the energy management using the scenario 2

Appendix D : Conclusions calculations

D.1 Calculations current system with EES

The main benefit of using the Paxman generator at full load is the higher efficiency compare to the current scenario. In this case and based on [14], the efficiency of the generator should be equal or lower to 4.4 kWh/L. Then, the litres of diesel required along the year are 1,318,182 L if a annually consumption of 5,800 MWh is assumed [11]. Hence, a saving of 548,930 L and 218k GBP is estimated, taking into account the current diesel cost of 0.397 GBP/L [16], compared to the current scenario.

D.2 Calculations hydrogen scenario

In order to calculate the kg of hydrogen required, an annually energy demand of 5,800 MWh and a hydrogen fuel consumption of 33 kWh/kg [117] [118] is assumed. As a result, an annually hydrogen demand of 174,017 kg, monthly of 14,501 kg, will be required. This amount of hydrogen should cost around 266,682 USD per month if a hydrogen generation cost and transportation of 1.39 USD/kg and 17 USD/kg are assumed respectively [116].

Compared to the current scenario and taking into account an exchange rate of 1.556562 USD/GBP, there will be a cost increase of 109,557 GBP.