Department of Mechanical and Aerospace Engineering

Feasibility of small scale energy storage technologies in rural areas

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ABSTRACT

This thesis examines the feasibility of electrical and electrical thermal storage in the community of Dalavich for a microgrid project. The on-site generation is a run of river hydropower plant. The energy storage technologies involved in this study are batteries (Li-ion, Lead-acid), flow batteries, hot water storage tank and electrical storage heaters.

A software has been developed for this study in order to simulate the microgrid and the implementation of the energy storage technologies in the community. In addition, it has been useful to fill the gaps of HOMER. This last one has a broad number of features to simulate the batteries and the characteristics of the microgrid. Therefore, it has been the main one to develop the simulations in this study.

The electrical storage technologies are not feasible for the microgrid project in the community of Dalavich due to their high capital cost. However, electrical thermal storage systems have resulted profitable before and after the curtailment. The hot water storage tank has obtained the highest economic benefit in this study and is the one suggested to be deployed in the houses of Dalavich.

ACKNOWLEDGEMENTS

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NOMENCLATURE

P	Density
η	Efficiency
A	Ampere
AC	Alternative current
Amp-h	Ampere hour
CAES	Compressed air energy storage
C^o	Celsius degree
C_p	Specific heat capacity
DC	Direct current
DCF	Discount cash flow
DIG	Dalavich improvement group
DSM	Design side management
EES	Electrical energy storage
F	Faraday
FIT	Feed in tariff
h	Height
I	Electric Current
K	Kelvin
KJ	Kilo Joule
LAES	Liquid air energy storage
O&M	Operating and maintenance
PSH	Pumped hydroelectric storage
P	Power
PV	Photovoltaic
Q	Flow
RACH	River Avich Community Hydro

UTES	Underground thermal energy storage
V	Volt
VDC	Volts of direct current
VRFB	Vanadium Redox Flow Battery
Wh	Watts hour

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1. INTRODUCTION

Dalavich is a village situated in the council areas of Argyll and Bute, Scotland. It is located on the western shore of Loch Awe and has a population of 109. This village has different issues, like the rest of the rural areas in United Kingdom, such as oil heating or low energy efficiency level housing stock. In addition, Dalavich and the local surrounding towns also have these specific problems:

- An aging population
- Dependency of oil heating
- A lack of accessible employment to attract and retain young families
- Fuel poverty
- Isolation
- Distance to high schools

To solve these issues the towns of Dalavich, Inverinan and Kilmaha have created the Dalavich Improvement Group (DIG). The board of DIG suggested the construction of a 350kW run of river hydroelectric scheme on the River Avich which will bring some long-term benefits such as job creation, environmental and ecological improvements and sustainable tourism for the area. This scheme has had a support from the communities of 65.1 %. This percentage is based on a ballot in June 2014 (DIG, 2014).

The river Avich is fed by the Loch Avich (Figure 1). The water level of the loch depends on the rain and snow falls along the year. Therefore, summer is the season when the river has the lowest flow during the year. A previous investigation about the possible environmental issues generated by the construction of the run of river hydropower plant has been done (Gregor Cameron Consultancy LTD, 2014). The study has been carried out with the requirements imposed by SEPA (Scottish Environment Protection Agency).

The output energy from the hydroelectric plant has been estimated in 1084MWh per year, based on the flow water data from the river Avich in 2012 (DIG, 2014). However, the local grids are currently being upgraded and accept a maximum power of 50 kW. The restriction of the electricity exported will remain until 2021. Because of the grid restriction, 823 MWh would be wasted incurring in a revenue loss of approximately £145,000.

DIG has suggested different projects to take advantage the electricity curtailed. Among others, one of the projects proposed from this charitable organisation is to set up a microgrid in the community of Dalavich. The microgrid is connected to the grid as well as the run of river hydropower plant. The benefits brought from the microgrid are less consumption of fossil fuels, as heating in Dalavich comes almost all from the burned of oil, and a decrease of electricity imports from the grid. Both of them incur a reduction of greenhouse gas emissions.

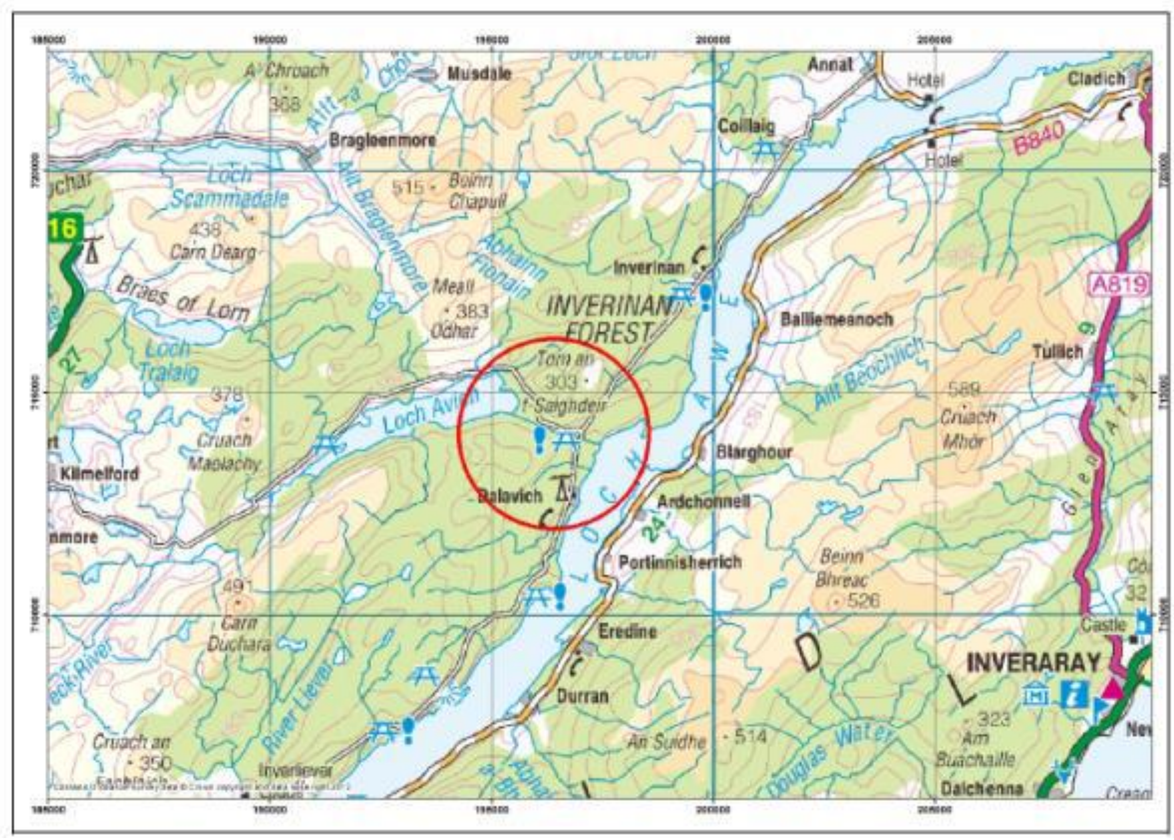


Figure 1 Dalavich site map. (Gregor Cameron Consultancy LTD, 2014)

The run of river hydropower plant is a renewable system which transforms the potential energy from the difference in the water height into electricity. It has the same issues as the rest of the renewable energy systems such as variability, intermittency and unpredictability of the power output. Therefore, it is a non-dispatchable power generation.

Energy storage technologies have appeared in the last years as a possible solution for the renewable energy systems issues commented before. The run of river plant generates different power outputs along the year, the month or even the day. Storage systems moderate this electrical output variability making it smooth and easier to meet the demand. The energy profile demand of the community of Dalavich is the same as the usual United Kingdom trend, low peak at night and high energy consumption during the day. Therefore, small scale storage systems could be deploy to improve the reliability of the electricity supplied from the hydropower plant and reduce the imports from the grid.

1.2 AIMS AND OBJECTIVES

This work aims to determine the feasibility of setting up a microgrid in the community of Dalavich and what technical, economic and environmental improvements the energy storage technologies can bring to the microgrid.

- The execution of different objectives has been necessary to complete the investigation and the achievement of its aim.
- Understand the different economic and technical characteristics which affect the microgrid before and after 2021.
- Calculate the run of river plant output and energy consumption in Dalavich.
- Determine the scale and type of energy storage technologies which match with the technical characteristics of the microgrid.
- Select the adequate software to simulate in quick runs the demand of Dalavich, the hydropower plant output, the grid and the energy storage technologies, HOMER.
- Analyse the functionalities of HOMER in order to determine the limitations of it.
- Develop a tool which complements HOMER to increase the possible simulations and improve the accuracy of the results.
- Design a proper scheme for the simulations focus in the aim.
- Evaluate, interpret and analyse the results generated by the simulations.
- Demonstrate with the results obtained that the tool developed to fill the gaps of HOMER is reliable.
- Carry out an economic analysis to determine the feasibility of the microgrid and the energy storage systems.

1.3 OUTLINE OF THE REPORT

The report has been divided in five chapters. Chapter one is the first approach for the reader to the project. Why the project should be carried out in order to solve the current problems. In addition, the aim and objectives of the work have been included as well as a brief explanation of the chapters, where currently we are.

The second chapter is a deep theoretical study about the different small scale energy storage technologies, their technical and economical characteristics, and their benefits working together with a renewable energy production in a microgrid.

The third chapter contains the scheme followed, the methodology developed to carry out the simulations with HOMER, and the complementary program and the economic and technical calculations to obtain the proper results.

Throughout the fourth chapter all the results obtained are shown. The simulations generated are analysed, compared and evaluated. In addition, a deep economic analysis is carried out in order to figure out the feasibility of the microgrid and the energy storage technologies in the community of Dalavich.

The last two chapters contain the outcomes of the report. The results obtained in the chapter before are interpreted and discussed, and the final outcomes are summarised. In addition, further studies are suggested.

2. LITERATURE REVIEW

2.1 ENERGY STORAGE

The energy storage accumulates energy in order to perform a useful process afterwards. The energy stored can be used at a later time to produce electricity, heat or vehicle's motion. There are different storage technologies which used different techniques to accumulate the energy such as mechanical, chemical, electrochemical, electrical, thermochemical and thermal.

2.1.1 Energy storage benefits

The electrical energy has been used in the age of Tesla and Edison, being nowadays the most used form of energy. One of the main issues of this energy is the difficulty in its storage. Therefore, the best option of this form of energy is been consumed at the same time in which is produced. However, in the last decades renewable energy systems have had a rapid development and have been deploy around the world. The output of many renewable energy systems is variable due to the unpredictability of the solar radiation, wind, waves, rain, etc. This issue can make fluctuations of the electricity supplied to the grid incurring in a mismatch between supply and demand. This imbalance generates problems in power quality and instability.

Energy storage technologies have been postulated as a solution for this lack in the grid reliability, making easier the introduction of renewable energy systems into the electrical network. Storage techniques can be a suitable complement for intermittent energy production as well as a moderator of the peak demands. Therefore, more ways of generation, such as distributed energy or plants with a low modifiable output, would be installed because of an improvement in their feasibility. In addition, energy storage systems can benefit autonomous grids in isolated areas and to serve as a stand-by power source for distribution lines and on-site substations.

Energy storage systems also have economic benefits. The energy storage system can store electricity at night to be used during the day when the price of electricity from the grid is more expensive. It assists the freeing of the power sector from speculations and the uncertainty imposed by traditional fuels, playing a central role on stabilizing the electricity market. Isolated sites, small towns, rural areas or even countries will have a good opportunity to have an economic and social development whit these technologies. Renewable systems will receive more investments, developing this sector and receiving incentives due to the reduction of greenhouse gas emissions.

2.1.2 Energy storage technologies

There are different energy storage technologies with a variety of characteristics such as scalability, energy form of storage, discharge power or discharge duration. The most common techniques which are being used nowadays are detailed below:

- Pumped-hydro energy storage (PHES)

Compared with the rest of technologies, it is the most mature and feasible one. It is a mechanical way of storage, increasing the potential energy of the water. It works pumping up the water into the dam of the hydropower plant for its later use.

- Compressed air energy storage (CAES)

It has a fast respond (seconds-minutes) and is also a mechanical form of store the energy. This technology needs a suitable ground cavern to store the compressed air. Therefore, it can be placed just in specific areas. It works compressing the air, with the surplus energy, and decompressing it again when is required generating electricity (Medina, Rodrigues, & Contreras, 2014).

There is a new technology which liquefied the air, Liquid Air energy storage (LAES). This technology can be set up above the ground, increasing the possible installation areas.

- Thermal energy storage

Low efficiency compared with the two technologies above. It works storing heat in a material, usually salts, and using it afterwards to generate steam from the water and generate electricity.

- Hydrogen energy storage system

It uses different techniques to store the Hydrogen. The Hydrogen is a product generated by electrolysis. This fuel is used later for combustion engines or fuel cells. It is a electrochemical way of energy storage.

- Chemical energy storage system

It has a rapid respond (milliseconds). There are some environmental issues due to the chemical products contained. It transforms the electricity into chemical energy (Luo, Wang, Dooner, & Clarke, 2015).

- Flow batteries energy storage (FBES)

It has a longer discharge duration compare to chemical energy storage. The storage of the electricity is produced by redox reactions.

- Flywheel energy storage system (FESS)

It has the fastest respond compared with the rest of the energy storage technologies but low discharge duration. The flywheel is a rotating mechanical device (Tang, Lim, & Wang, 2013).

- Super-capacitors energy storage (SCES)

It has a quick response and a high efficiency. The energy is storage in form of electric field.

- Electric vehicles (EVs)

This is a new way to store the electricity and reduce the consumption of fossil fuels for transportation. However, this sector has some restrictions such as few places to recharge the vehicle. This restricts the distance they can travel.

A summary of the energy storage techniques explain before depending on the power output and the energy stored are gathered below (Figure 2).

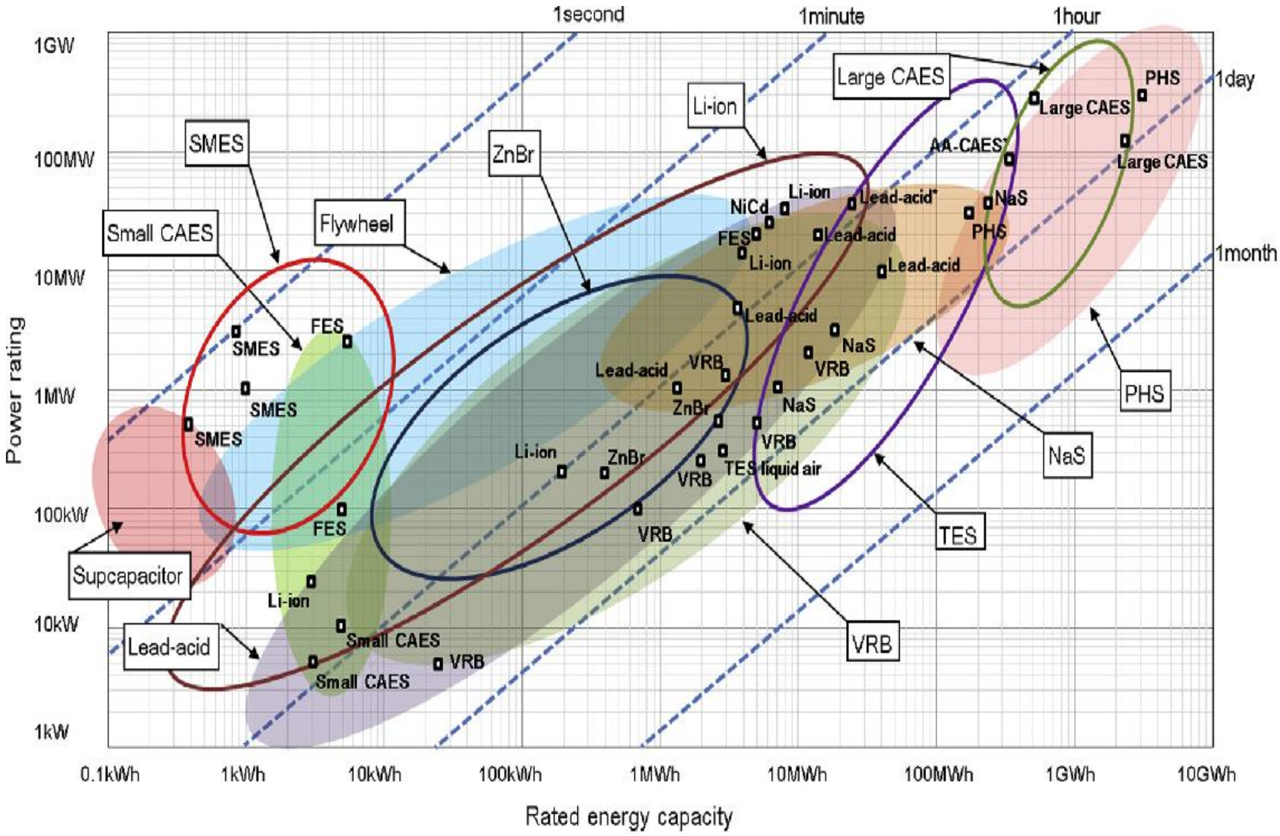


Figure 2 Energy storage technologies according to rated energy capacity and power rating (Luo, Wang, Dooner, & Clarke, 2015)

2.1.3 Energy storage in United Kingdom

Electrical and thermal rechargeable energy storage already exists in United Kingdom. The main ones are: pumped hydro storage (PHS), hot water, electrical storage heaters and fossil fuel storage (ERP, 2011). However, some private companies have installed different cutting-edge technologies such as liquid air energy storage (LAES).

2.2 SMALL SCALE ENERGY STORAGE TECHNOLOGIES

This section is divided in electrical energy storage (EES) technologies and thermal energy storage such as hot water storage tanks and electrical storage heaters. The design side management (DSM) is necessary in order to select the most suitable size and technology to store energy and minimise the issues due to DG.

2.2.1 Electrical energy storage technologies

There are different storage technologies which are generally used in microgrids projects such as supercapacitors, chemical energy storage or batteries (Lead-acid, Nickel-Iron, Nickel-

Cadmium, Nickel-Methal Hydride or Lithium ion), flow batteries (Zinc Bromine and VRB). All these technologies need an inverter for its charging process to convert the Alternative current (AC) from the distributed generation (DG) to Direct current (DC). However, some flow batteries works with AC current. In addition, a control system is necessary in microgrids to manage the energy from intermittent renewable energy systems to the local grid and houses.

In order to select the best energy storage technology it is necessary to know the different characteristics of each technique such as response time, discharge duration, depth of discharge, self-discharge and round trip efficiency. The response time is how fast the required power is reached. The discharge duration is how long the discharge process last. Depth of discharge is the percentage of the battery capacity which must remain in a discharge process to avoid problems in the technology. The efficiency is the percentage of energy output compare with the input one. The self-discharge is the percentage of energy loses by itself when the device is not working. The main characteristics are explained in **Error! Reference source not found.**.

The response time from all the technologies explained below is small enough for the purpose of a microgrid.

2.2.1.1 Supercapacitors

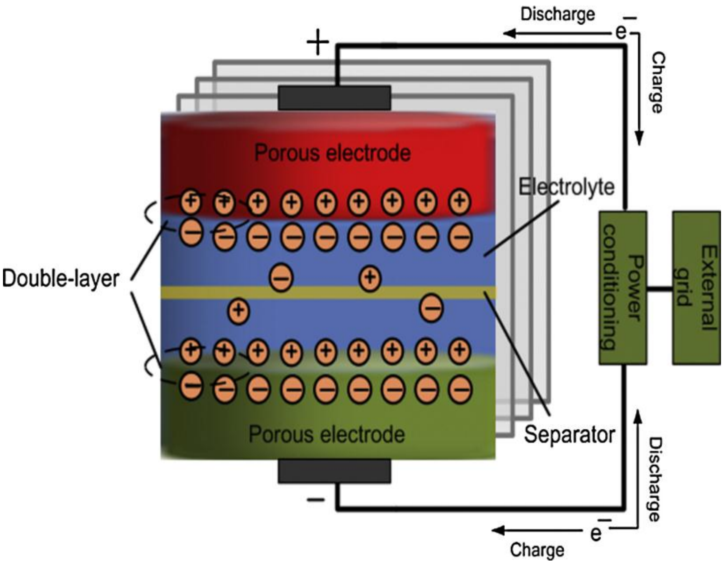


Figure 3 Schematic diagram of a supercapacitor system (Luo, Wang, Dooner, & Clarke, 2015)

The energy is storage in the form of an electric field between two electrodes. Due to its structure supercapacitors can have the characteristics of electrochemical batteries and conventional capacitors. The main features of supercapacitors are the long cycling times, more than $1x10^5$, and the high efficiency, between 84 and 97 per cent. However, this technology has a low rated energy capacity, a high self-discharge rate and a high capital cost. Currently there are supercapacitors ranging from 5 Faradays (F) to 2700 F, rated at 2.5 Volts (V) of direct current (VDC) per cell. The specific energy of cell storage is low, 3 or 4 Wh/kg. Due to the low cell voltage is necessary to connect in series multiple cells to obtain a typical 48 VDC application (Tang, Lim, & Wang, 2013).

2.2.1.2 Batteries

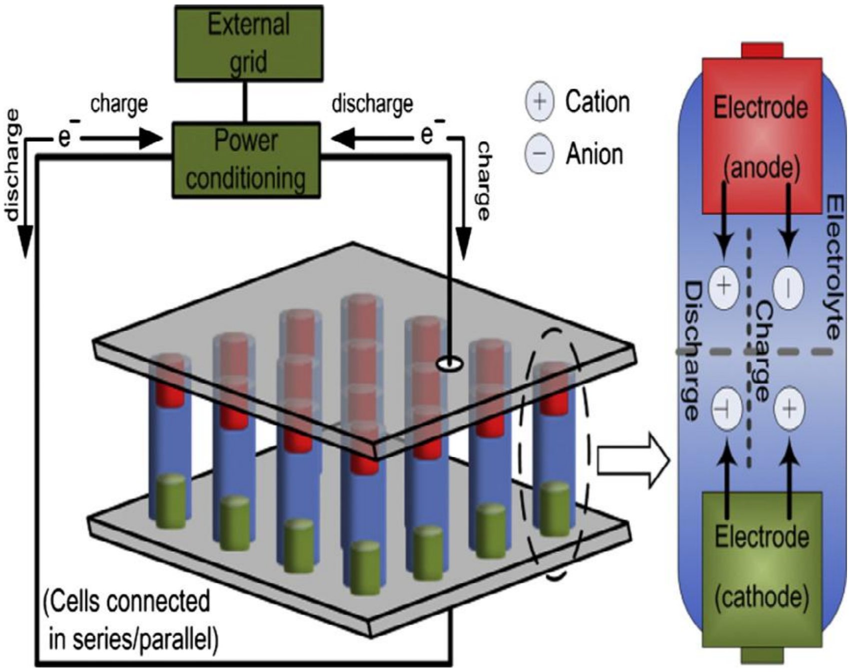


Figure 4 Schematic diagram of a battery energy storage system operation (Luo, Wang, Dooner, & Clarke, 2015)

This technology is based on generating electricity from chemical reactions. The batteries consist in two electrodes, one anode and one cathode, and an electrolyte. Due to the chemical character of these batteries many of them cannot be neither completely discharge nor overcharged in order to stretch on the life of the devices. Rechargeable batteries are the only possibility to store the electricity from DG. Therefore, these are going to be explained in this report.

The batteries have different sizes and energy capacities, from hundreds of Watts to several Megawatts. The overall round trip efficiency of the batteries is between 60 and 80 per cent, depending on the electrochemistry type within the battery and the operational cycle. The main batteries are Lead-acid, Nickel-Iron, Nickel-Cadmium, Nickel-Methal Hybride and Lithium ion. Depending on the designer the capacity of the battery is given in Wh or Ampere hour. A battery which can supply 2 Amps for 10 hours has a capacity of 20 Ah.

- *Lead-acid*

Lead-acid is the cheapest and most mature energy storage device over the rest of batteries technologies available. The cathode and anode are made by PbO_2 and Pb respectively. The electrolyte is sulphuric acid. On the one hand, Lead-acid batteries have a small self-discharge, less than 0.3 daily per cent, relatively high round trip efficiency (60-90 per cent) and low capital cost. On the other hand, the cycling times is low (up to 2000), poor performance at low temperatures (sometimes a thermal management system is required) and low specific energy. The research and development stage of this device is focused on extending the cycling times and the deep discharge capability.

There are different types of Lead acid batteries depending on the internal structure. Flooded/ wet Lead acid batteries and Tubular gel Lead acid. The first one is not sealed and does not recombine the gases into liquids internally. The gases are release externally. The second type is sealed and turns the sulphuric acid into a jelly. These differences modify the technical characteristics of both.

- *Nickel-Iron*

This battery has a cathode of nickel (III) oxide-hydroxide and an iron anode, with an electrolyte of potassium hydroxide. It is a very robust battery. Thus, it can support overcharging, deep discharging and short circuiting. Although, it has a high cost of manufacture, it can last for 40 years. It has efficiency between 65 and 85 per cent and a low specific energy (30-50 Wh/kg). One of the main issues is the high maintenance due to corrosion processes. This technique is not so popular and in 1975 this technology was abandoned in United States.

- *Nickel-Cadmium*

The electrodes are Nickel hydroxide and Cadmium with an aqueous alkaline solution as the electrolyte. The Nickel-Cadmium battery has a high robust reliability and low maintenance requirements. Thus, it can support overcharge and deep discharge processes. These batteries can be used for different applications, from supply energy from different devices such as toys to microgrids. The round trip efficiency is between 60 and 83 per cent with a low self-discharge rate. Cadmium is a toxic heavy metal which needs a special care during its disposal. In addition, this technology suffered from memory effect.

- *Nickel-Methal Hybride*

NiMH battery has a faster recharge process than Ni-Cd (about 1 hour for a complete charge (Electropaedia, 2005)) and is less harmful for the environment. The negative electrodes use mixture of metals, which absorbs hydrogen, instead of Cadmium. The round trip efficiency of this technology is approximately 66 per cent. The charging voltage is in the range of 1.4 and

1.6 volts per cell (Energizer Battery Manufacture Inc., 2010). The maintenance is based on a regular full discharge to prevent crystalline formation. In addition, it has a low overcharge tolerance. (Battery University, 2010).

- *Lithium Ion*

The battery has a lithiated metal oxide as the cathode and a layering structure graphitic carbon anode. The electrolyte is a lithium salt. It is consider one of the most suitable energy storage technologies for quick response times and small occupancy requirements. Its specific energy is between 75 and 200 Wh/kg with round trip efficiencies around 97 per cent. The main issue from this technology is a reduction of its life due to depth of discharge and a low tolerance to an overcharge. It is recommended to not discharge the battery below 15 per cent of the total capacity to avoid deep discharge problems. The battery needs an on-board computer to manage its operation (increasing its capital cost). Therefore, the high cost is another problem for this battery (Chen, Ngoc Cong, Yang, Tan, Li, & Ding, 2009).

2.2.1.3 Flow batteries

Flow batteries store energy in two soluble redox couples contained in external liquid electrolyte tanks with an ion selective membrane. During the charging process one electrolyte is oxidised at the anode and other one is reduced at the cathode. Depending on the electroactive components dissolved in the electrolyte there are two different types of flow batteries: redox and hybrid flow batteries.

- *Vanadium Redox Flow Battery (VRFB)*

The Vanadium Redox flow battery stores energy by using Vanadium redox couples (in different oxidation states) in two electrolytes tanks. H^+ ions are exchange through the ion selective membrane Figure 5. It has a high maturity within flow battery technologies. This battery has a quick respond and between 10,000

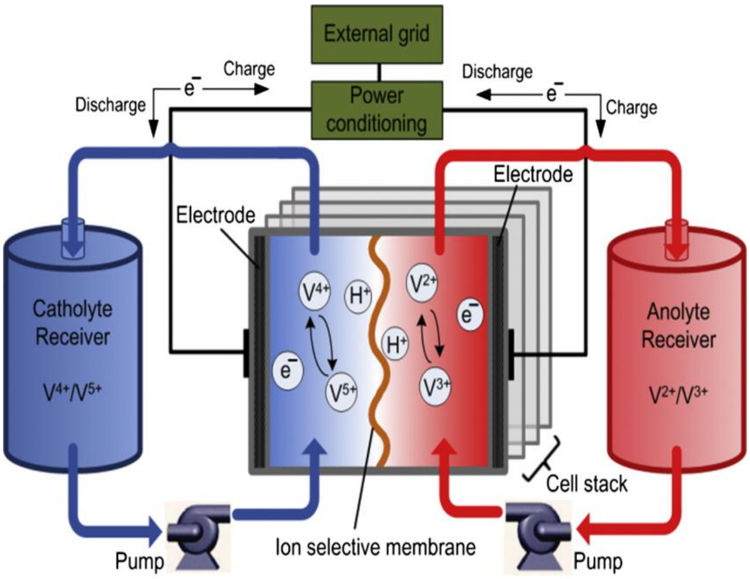


Figure 5 Schematic diagram of a vanadium redox flow battery system (Luo, Wang, Dooner, & Clarke, 2015)

and 16,000 of cycling life. The discharge duration time can be more than 24 hours and the round trip efficiency can reach 85 per cent. Nowadays two different small scale projects with VRB are running in United Kingdom (Luo, Wang, Dooner, & Clarke, 2015). In Portugal and Florida (USA) there are two 5 kW batteries already installed.

- *Zinc bromine flow battery*

It has two tanks with the electrolytes (a solution of Zinc Bromide). These solutions are pumped through a reactor stack and back to the tanks during the charging and discharging process. One tanks store the positive electrolytes in the reaction and the other the negative ones. This battery can be discharged 100 per cent of its capacity. The specific energy for these batteries is between 34 and 54 Wh/kg. It has a cycling life above 2000 cycles. It is a non-perishable battery in contrast to Lead-acid and Lithium ion batteries. There are fewer projects with this battery than VRB and almost all of them are in United States or China (M. Rose & R. Ferrerira, 2013).

2.2.2 Electric thermal energy storage technologies

The domestic electric thermal energy storage technologies are hot water storage tanks and electrical storage heaters.

2.2.2.1 Hot water storage tanks

Store electricity in form of hot water is an attractive proposition for the lack of coordination between DG and domestic demand. Between 17 and 39 per cent of dwellings demand is associated with domestic hot water usage (Wong & Megnevitsky, 2012). The Figure 6 shows the diagram of how this technology works. The water contained in the tanks has a convection movement due to the heat source is situated in the bottom.

This technology is based on an electrical resistor (wire) which heats up the water for domestic uses. It can store warm water for hours or days. The more thermal insulation in the walls of the tank, the longer the water is maintained warm. The tank has to be designed properly in order to avoid the discomfort of take a cold shower.

The capital cost depends on the capacity of the tank and the insulated material. (Armstrong & McCulloch, 2014). From 100 litres (L) to 400 L, the capital cost vary from approximately £300 and £2,000. A tank with 400L (3 or 4 showers per day) can be used for houses between two and four residents (Consumer report, 2015).

The energy consumed by heating water depends on the amount of litres in the tank, the ambient temperature and the inlet water temperature. The specific heat capacity (C_p) of the water is 75.38 J / mol·K. This property is the amount of heat (energy) removed or added to an object to reduce or increase its temperature.

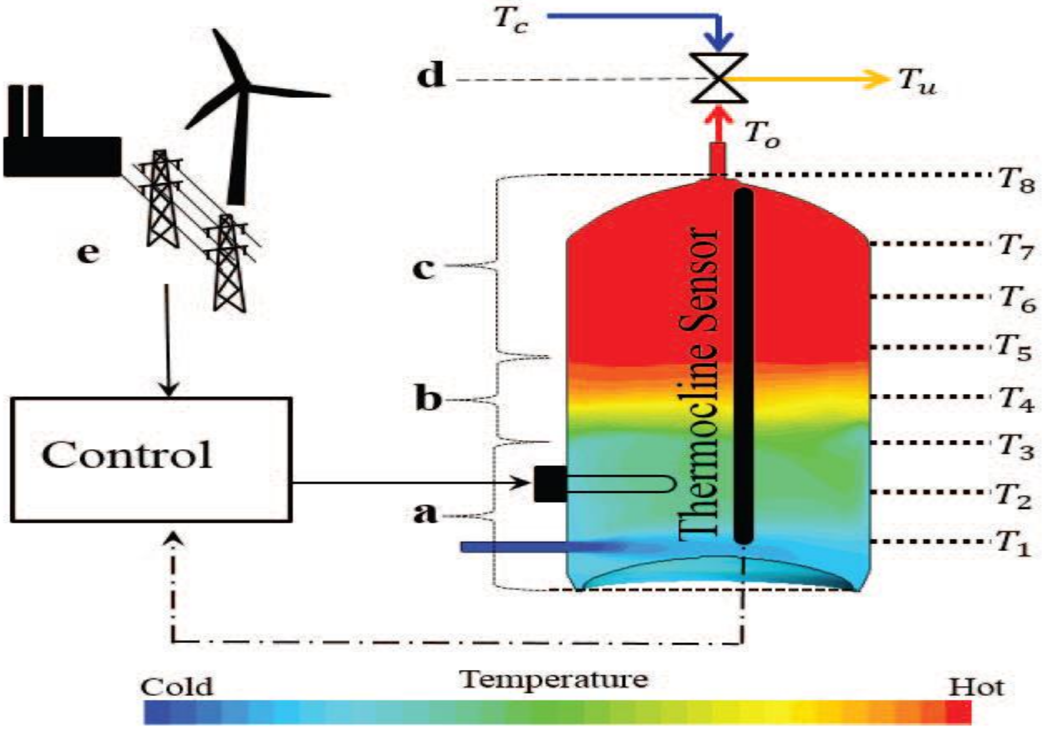


Figure 6 Schematic of hot water storage tanks.

To maintain the hot water inside the tank for long time it is necessary to use proper insulation. To maintain a suitable domestic temperature it is necessary for suitable materials such as artificial wool. The R-Value is very important in order to know the thermal conductivity of the insulate material.

2.2.2.2 Electrical storage heaters

Electrical storage heaters transform electricity into heat. This heat is stored in high density materials which accumulate the heat. The main reason of the electrical storage heaters is to reduce the expenses of domestic heating moving its load at night, when the price of the electricity is cheaper. A storage heater accumulates thermal energy during the low peak demand (night) and releases the heat during the high peak demand (during the day). Its efficiency is lower than a normal electrical heater and consumes more energy. However, the economic aftermath is a reduction in the electricity expenses.

This technology uses materials which accumulate the thermal energy such as ceramic or clay bricks materials. The highest is the density of the material, the longer the heat is storage. The heating source is a wire set inside the bricks. This wire is a resistor which generates heat when the electricity is flowing within it. The Figure 7 shows an image about the different parts of the heater (Renovation experts, 2010).

The heater has some temperature restrictions such as the outside temperature of the block. This cannot exceed 90 ^{o}C to avoid injure the residents of the house especially the kids (Griffith, 1964). However, the heater must maintain a comfortable temperature in the room of approximately 21 ^{o}C.

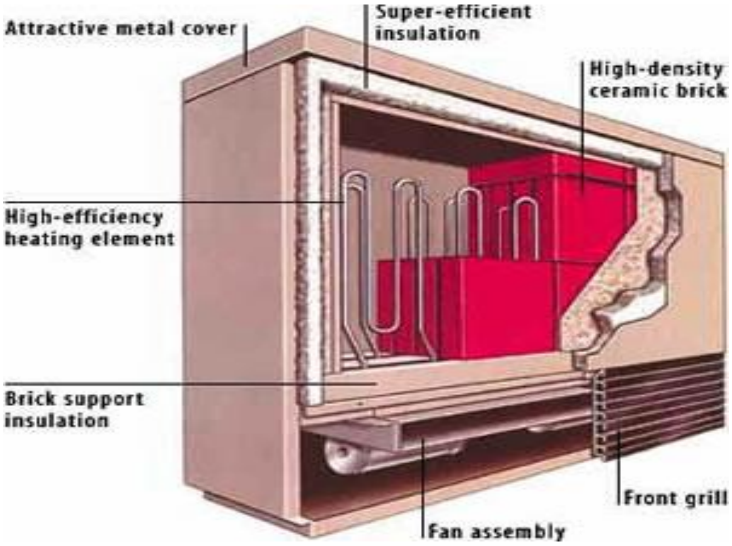


Figure 7 Schematic of an electrical storage heater (Renovation experts, 2010).

The average price of an electrical storage heater is between £2,000 for a 7kW heater and £700 for a 1kW one (Storage heater, 2010). The electrical storage heaters do not incur any extra cost for the assembly. It has the same connection to the house grid as the normal heaters.

The main disadvantages are the lack of controlling the temperature of the heater and the high weight of the device due to the bricks. In addition, some electrical storage heaters include a fan to release the heat and it can reduce the air quality of the house because of the dust accumulated inside (Mueller & Bengsch, 2014). This sector is currently researching for new brick materials to improve the efficiency and reduce the weight.

Table 1 Main small scale energy storage characteristics (J.C. Copera, 2004) (Fierro, Venkatesan, Gifford, & Koch, 1999) (Tang, Lim, & Wang, 2013) (Electropaedia, 2005) (Battery University, 2010) (Luo, Wang, Dooner, & Clarke, 2015)

Technology	**Supercapacitors**	**Lead-acid**	**Nickel-Iron**	**Nickel-Cadmium**	**Nickel-Methal Hybride**	**Lithium ion**	**Zinc-Bromine**	**VRFB**
Specific energy (Wh/kg)	0.05-15	25-50	30-50 (Iron Edison, 2014)	50-80	60-120	75-200	30-80	10-30
Power rating (kW)	0-300	0-1000+	0.1 (Specific power kW/kg)	0-1000+	0.63 (Specific power kW/kg)	0-1000+	50-1000+	30-1000+
Daily self-discharge (%)	5-40	0.1-0.3	10-15 (1 month)	0.03-0.6	20-50 (6 months)	0.1-0.3	small	very low
Cycling times	50,000-100,000	200-1800	1800+	2,000-3,500	500-2000 (Tang, Lim, & Wang, 2013)	1,000-20,000	1,500-2,000	10,000-16,000
Round trip efficiency (%)	84-97	60-90	65-85	60-83	60-85	75-97	65-80	65-85
Discharge efficiency (%)	95-98	85	85	85	66	85	60-70	75-82
Suitable storage duration	seconds-hours	minutes-days	seconds-hours	minutes-days	seconds-hours	minutes-days	hours-months	hours-months
Energy capital cost ($/kWh)	300-2,000	50-400	750-800 (Iron Edison, 2014)	400-2,400	150	600-3,800	150-1,000	150-1,000
Main issues	Low specific energy, High cost	Heavy, Low Cycle Life, Toxic Materials	Heavy, High Maintenance	Toxic materials, maintenance, high cost	Low tolerance overcharging and discharging	Calendar Life, high Cost	Hazardous components, bulky	High maintenance

2.3 RENEWABLE ENERGY

Renewable energy is defined as the energy that comes from unlimited natural resources such as wind, sunlight, waves, tides, rain and geothermal heat. Renewable energy sources can be exploited for the production of electricity, heat, fuel transportation or off grid energy services. Thus, different benefits come along these alternatives energies like replacing traditional fuels and mitigating climate change. In addition, it is a clean solution to increase the autonomy and energy security in rural areas.

This is a brief summary about the different types of renewable energy resources exploited nowadays:

- Solar Energy
- Wind Energy
- Geothermal Energy
- Bioenergy
- Hydropower
- Ocean Energy

These resources are not available in all the countries around the world. There are areas with no coastline, places with low speed winds or locations more rainy and cloudy than others. In addition, the sunlight, wind, rain and waves are intermittent natural phenomenon. Thus, the generation of energy from clean and unlimited sources is non-dispatchable. The heat and electricity produced from renewable energy systems cannot address the fluctuations from the demand. The mismatch between the generation of electricity and the demand can have a significant impact on grid reliability and security of supply (Chatzivasileiadi, Ampatzi, & Knight, 2012). Energy storage technologies have been postured as a solution for this lack of coordination.

2.3.1 Renewable energy in Scotland

The primary energy consumption from sustainable generation is around 13 per cent in United Kingdom. Scotland is the largest contributor to this clean energy production. Energy policies in Scotland have created a renewable energy route map for 2020. The target for renewable electricity generation is to produce the equivalent of 100 per cent of gross annual consumption by 2020 (gov.scot, 2013).

Scotland is one of the best countries in Europe for the deployment of renewable energy. It is the best place in Europe for onshore and offshore wind energy, being the windiest area. It has the most powerful swells making it appropriate for wave energy. Scotland has big tides from the Atlantic Ocean and the suitable geography for the deployment of tidal energy. In addition, it is the only place of United Kingdom with suitable differences of altitude, due to the mountains, for the installation of hydropower plants.

2.3.2 Run of river hydropower plant

This technology is a renewable energy system which needs a significant difference of height on a river flow in order to take advantage of the potential energy from the water situated in elevated areas. Conventional hydropower plants can control the electricity output adjusting the wicket gates opening in contrast to run of river schemes. Thus, the generation of electricity depends on the flow of the river. There is a correlation between the water river flow and the rain and snowfall. Therefore, the electric generation is, as well as the majority of the renewable energy systems, intermittent.

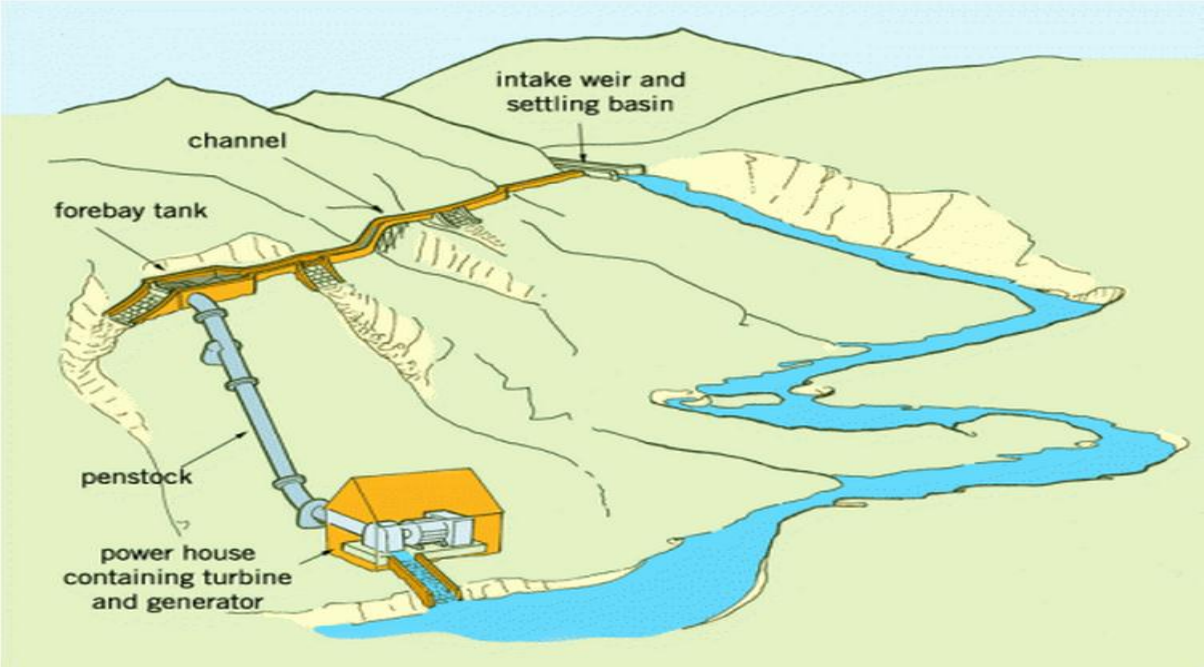


Figure 8 Run of river hydropower plant (Carrasco, Pain, & Spuhler, 2012)

The concern about the environmental effects from large dams in river basins is emerging. Run of river hydropower plants are increasingly gained importance around the world due to its low environmental impact compared with the traditional hydropower plants. The operation strategy of conventional plants can become to fluctuating hydrological patterns in the downstream river, causing in some causes considerable ecological damage (Omkar, Kishor, Fraile-Ardanuy, Soumya, Perez, & Sarasua, 2011).

The run of river hydropower plant has a weir in the elevated area of the river (intake of water) where the river water is diverted. One diversion continues the natural flow of the river and the other one goes to an artificial channel. This artificial channel is the first stage of the hydropower plant where sand and slit is removed from the water. The end of the channel is a small tank (forebay tank). The water preserves a high level until this point. From the forebay tank, the water passes through a closed pipe (penstock) to the turbines. The penstock directs the water flow with a uniform stream to the turbine which is situated in a low altitude. The rotation of the blades of the turbine generates electricity which is draw to the grid or to a nearby village (Figure 8).

3. APPROACHING AND METHODOLOGY

The aim of this report is to figure out the most suitable energy storage technology for the possible microgrid project deployed in Dalabich. Thus, it is necessary to model the demand of the community, the electric generation of the hydropower plant and the energy storage technologies in order to match all of them. To achieve this is necessary:

1. Calculate the hourly energy demand of the community over the year.
2. Calculate the hourly output of the hydropower plant over the year.
3. Use a software to match demand, generation and energy storage technologies.
4. Study different scenarios.
5. Figure out the best energy storage technology.
6. Economic analysis.
7. Environmental assessment.

3.1 CALCULATE THE ELECTRIC DEMAND IN DALAVICH

The description of the community is below (Gutierrez, Troddy, Browne, & Diderich, 2015):

- Only domestic properties have been considered
- 45 end-terrace type houses in Dalavich
- 45 detached holiday chalets North of Dalavich
- Houses in Dalavich occupied for 100% of the year
- Holiday Chalets occupied for January and May-October inclusive
- Only 60% of Holiday Chalets used

<u>For Dalavich Village</u>

- 75% of homes in Dalavich have no electric heating as indicated in the survey
- 25% of homes in Dalavich use secondary electric heating as indicated in the survey
- Electricity consumption of homes in Dalavich is based on national statics (Gutierrez, Troddy, Browne, & Diderich, 2015) (4.2MWh per household per year)
- Non-electric heating consumption of homes in Dalavich is based on national statics from reference given in main body (Gutierrez, Troddy, Browne, & Diderich, 2015) (non 15.29MWh per household per year)

- For homes in Dalavich 92% of non-electric heating is oil-fired as indicated in the survey
- For homes in Dalavich 8% of non-electric heating is biomass/wood as indicated in the survey. This way of heating is not going to be replaced.

For Holiday Chalets North of Dalavich Village

- 17% of holiday chalets have non electric heating as indicated in the survey
- 50% of holiday chalets use secondary electric heating as indicated in the survey
- Electricity consumption of holiday chalets is based on national statics from reference given in main body text1 (3.0MWh per household per year)
- Non-electric heating consumption of holiday chalets is based taken from the survey as seasonal variations for holiday homes mean national statistics cannot be used (4.333MWh per household per year)
- For holiday chalets 100% of non-electric heating is biomass/wood

All of the oil heating will be replaced by electric heating. However, the old heating will remain as back up. There is information about the oil heating demand per day for each property in the community of Dalavich.

The first step is to calculate the electric demand per hour for each house in the community assuming the new electric heaters. After the replacement of the heaters the houses without biomass are going to be supplied completely by electricity. There are 45 houses in Dalavich. 25 % of them use electric heating. Thus, 11 houses use electric heating and 34 fuels. From which 31 have oil heating and 3 have biomass heating. There are 8 holiday chalets using biomass/wood like fuel. During January and from May to October, 60 % of these chalets are inhabited. During the period when people live in the Chalets, it is going to be considered that 4 of them use biomass heating (Assumption). Therefore, 23 of them use electric heating and 4 of them biomass heating.

In conclusion, after replacing the oil heating there will be 3 houses in Dalavich with biomass heating and 4 in the holiday chalets located in the north of Dalavich. This means 42 houses in Dalavich with just electric consumption the whole year and 23 in the holiday chalets during January and from May until October.

To produce the hourly electric demand profile (Table 3) it is necessary to calculate the total energy demand per day in the community (Table 2). Although, the monthly energy demand data from the community of Dalavich is given by Xero Energy (Gutierrez, Troddy, Browne, & Diderich, 2015), the daily demand profile is not. Thus, the daily trend energy consumption in the community is going to be generated by HOMER. This software simulates different microgrid systems.

Table 2 Monthly and daily electric and heating demand from the community of Dalavich (Gutierrez, Troddy, Browne, & Diderich, 2015)

Months	**Total annual Heating (MWh)**	**Total annual Power (MWh)**	**Total demand per day (MWh)**
Jan	102	22	4
Feb	85	14	3.54
Mar	91	15	3.42
Apr	68	14	2.73
May	39	21	1.95
Jun	20	21	1.4
Jul	21	21	1.35
Aug	22	22	1.35
Sep	42	20	2.07
Oct	48	21	2.23
Nov	58	14	2.4
Dec	61	15	2.45

HOMER has generated two different profiles, one for weekdays and other for weekends. These profiles do not have changes during a whole month. This means, every weekday (Monday, Tuesday…) or weekend of a certain month has the same energy consumption. Therefore, it is assumed that the energy consumed during the weekdays and weekends is going to be the same for each month. The next step is to calculate with the demand profile generated by HOMER, the percentage of energy consumed per hour.

$$Total\ demand\ per\ day\ \times percentage\ of\ energy\ consumed\ per\ hour\ = Energy\ consumed\ by\ the\ community\ per\ hour\ (MWh)$$

Equation 1.

The monthly data from Xero Energy and the percentage of energy consumed hourly are used in Equation 1 to calculate the real energy profile consumption of the community of Dalavich. The Table 3 shows an example of all the calculations said before.

Table 3 Percentage of the energy consumed hourly to design the demand profile and the energy consumed hourly during the weekdays in the community of Dalavich (January)

Time	Percentage of energy consumed per hour (%)	Energy consumed by the community per hour (kWh)
00:00-05:00	1.17	46.8
05:00-06:00	1.7	68
06:00-07:00	2.9	116
07:00-16:00	4.7	188
16:00-17:00	5.25	210
17:00-18:00	5.85	234
18:00-22:00	7	280
22:00-23:00	5.25	210
23:00-00:00	2.9	116

The weekend has another energy consumption profile which is going to be calculated by the same way like the weekdays energy demand profile explained before (Appendix 1). Figure 9 shows different weekday and weekend demand profiles in the community of Dalavich as well as different month’s demand profiles. All the hourly demand data is gathered in the appendix of this report (Appendix 1 and 2). The electric demand has a peak during the evening and the night when more people are in their houses. There are huge differences in the energy consumption between the seasons. Winter has the highest energy demand over the year due to the climate in Scotland. The heating is the key element in the energy consumption for this community because of the cold winters and mild summers. Comparing the weekdays and weekends demand is significant that the trend is the same but the peaks are reached later during the weekends. This is because the people used to wake up later and less energy consumption is required.

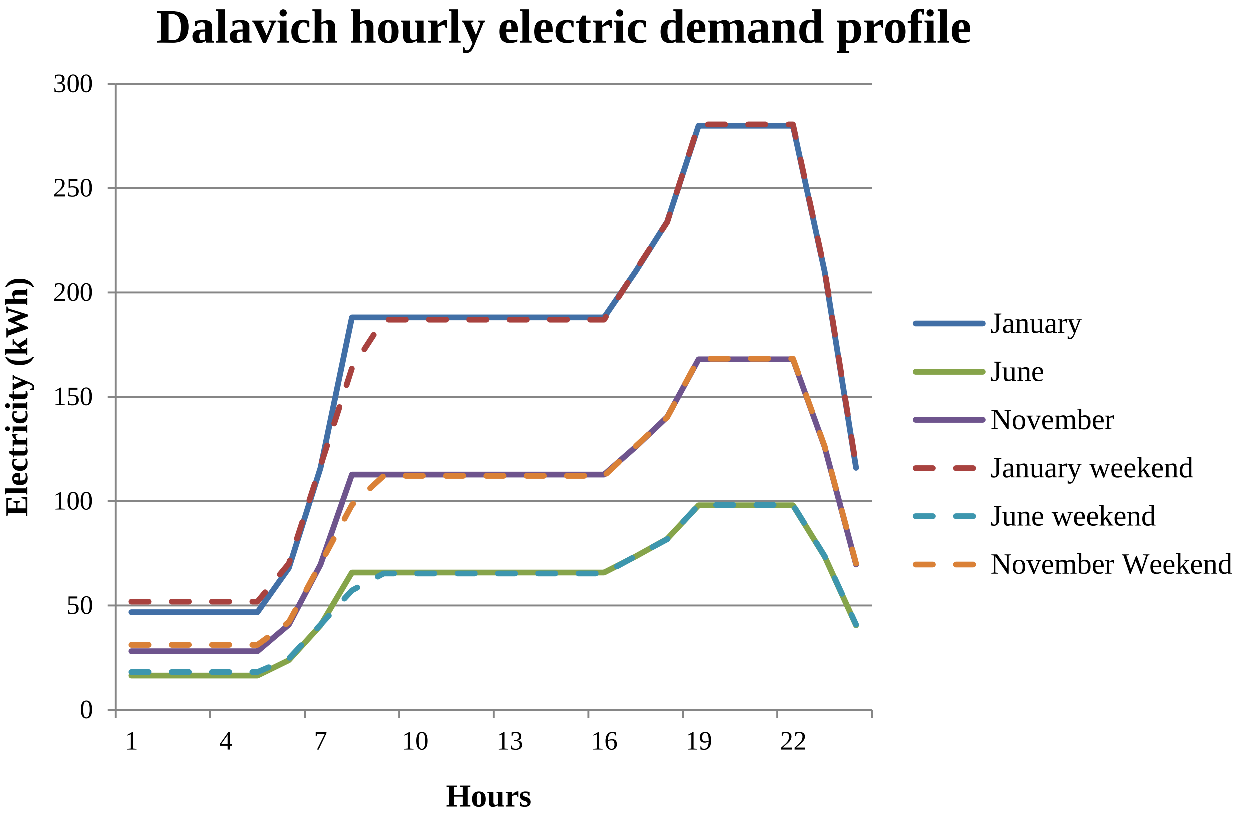


Figure 9 Examples of different hourly profile during weekdays and weekends in Dalavich community for January, June and November

3.2 POWER OUTPUT FROM THE RUN RIVER HYDROPOWER PLANT

The turbine for the hydropower plant is a Francis design with a maximum water flow acceptance of 2.12 m^3/s and a minimum one of 0.32 m^3/s (Gutierrez, Troddy, Browne, & Diderich, 2015). Above the technical maximum flow the turbine will generate an output of 350 kWh and below the minimum one the turbine will not produce electricity.

The water flow of a river depends on the rainfall. The amount of water from rain depends on the day, the season or the year. The river Avich has higher flows during the winter than in summer (Figure 10). The mean water flow for 2012 was 1.967 m^3/s. The data has been supplied by SEPA (Scottish environment protection agency) and CEH (Centre foe ecology and hydrology). 2012 has the average water flow from the last years. Therefore, it is going to be used in this project for further calculations.

The run river hydropower plant cannot take the entire watercourse of the river to produce electricity due to it can produce some environmental problems. The river must keep a minimum flow in order to do not destroy its fauna. Because of that, before the built up of the power plant it is necessary to make a study to decide which is the optimal percentage of the river's flow that must continue circulating. There is a previous study which addresses this technical issue (Gregor Cameron Consultancy LTD, 2014). This study has been made by the requirements of SEPA.

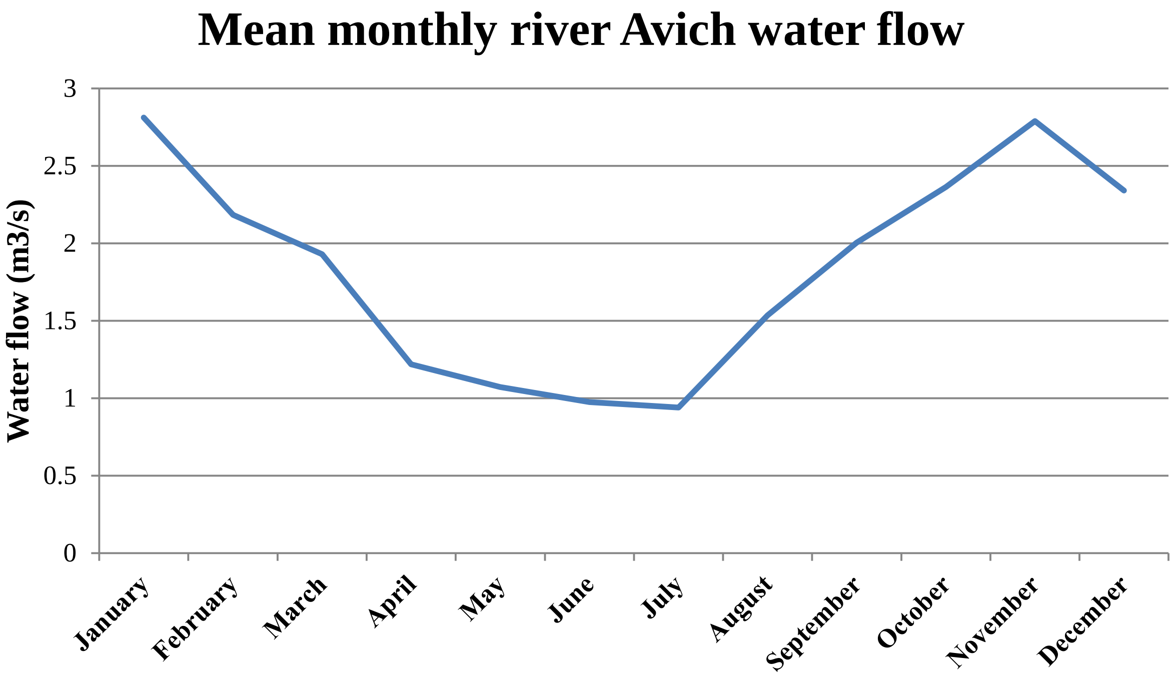


Figure 10 Monthly average water flow in the river Avich for 2012 (Centre for ecology and hydrology, natural environmental research council, 2015)

The flow duration curve is the tool used to decide the water flow diversion of the river (Figure 11) (Sivanagaraju, Malasubda Reddy, & Srilatha, 2010). This graph represents the percentage of time during a year when a specific flow is exceeded. For example, the 10 % of the time over a year (Qn_{10}) the water flow exceeds 4 m^3/s.

The potential annual output of the hydropower plant is over 0.35 GWh. This means a maximum allowable abstraction of 1.5 times the average daily flow (ADF) (Gregor Cameron Consultancy LTD, 2013). Although 1.5 times the ADF (1.967 m^3/s) is 2.95 m^3/s, the turbine has a maximum technical flow capability which cannot overtake 2.12 m^3/s.

There is a compensation flow to avoid the drying up of the river's watercourse. This compensation flow is different for streams larger and smaller than the ADF. Over the ADF, the compensation flow is Qn_{80} (0.64 m^3/s) and below it is Qn_{95} (0.255 m^3/s). This is called the hands-off flow which means the minimum water flow that must remain in the course of the river.

To simplify calculations in HOMER is assumed a residual flow of Qn_{80} due the limitations of the simulator. The result for the year 2012 is shown in Table 4. However, the calculations performed either manually or by my own software take into account both, compensation flow and hands-off flow.

Table 4 Potential abstraction regime for the run of river hydropower plant in the river Avich, 2012 (Gregor Cameron Consultancy LTD, 2013) (Sivanagaraju, Malasubda Reddy, & Srilatha, 2010)

Flow rate	Natural (m^3/s)	Maximun available for abstraction (m^3/s)	Residual (m^3/s)
Qn_5	4.79	2.12	2.67
Qn_{10}	4.15	2.12	2.03
Qn_{20}	3.27	2.12	1.15
Qn_{30}	2.41	1.77	0.64
ADF	1.97	1.72	0.25
Qn_{40}	1.92	1.67	0.25
Qn_{50}	1.53	1.28	0.25
Qn_{60}	1.18	0.93	0.25
Qn_{70}	0.86	0.61	0.25
Qn_{80}	0.64	0.39	0.25

Below Qn_{82} the turbine cannot generate electricity due to the flow limitations. Besides, for flows over Qn_{25} the turbine generates its maximum power output. This means, the capacity factor of the hydropower plant of 2012 is 25 %. At Qn_{25} the flow is 2.76 m^3/s. Thus, making the difference between this value and the compensation flow (Qn_{80}), the result is 2.12 m^3/s. These are the technical flow restrictions for the hydropower plant.

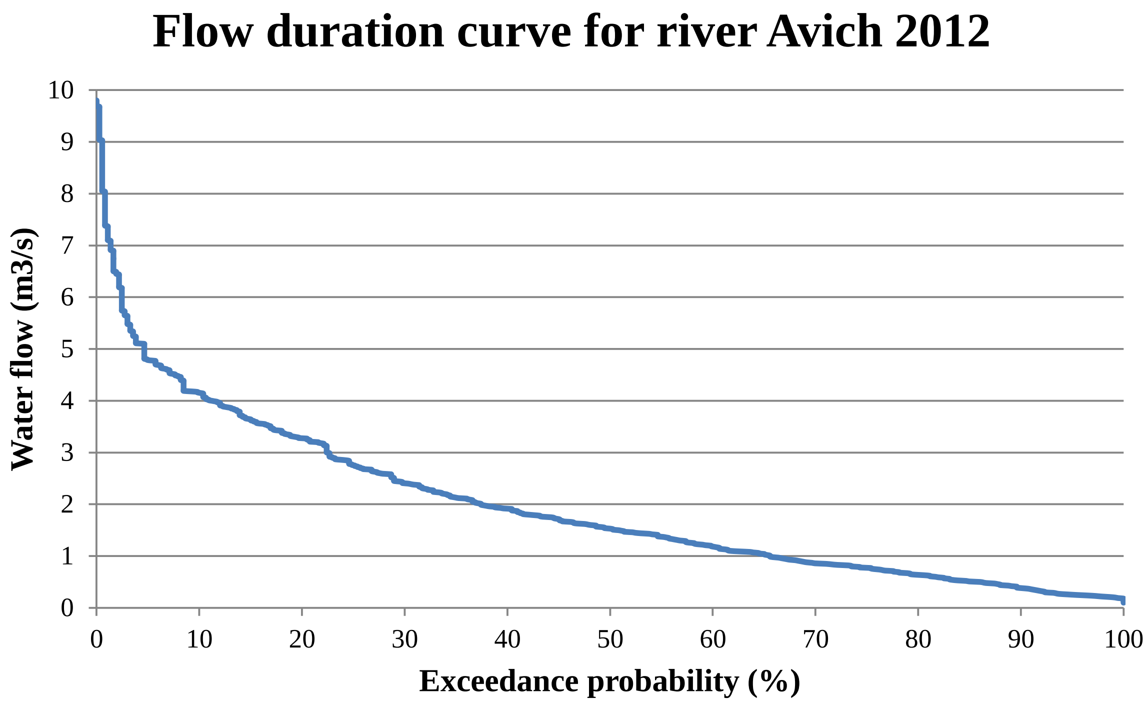


Figure 11 Flow duration curve for river Avich during 2012 (Sivanagaraju, Malasubda Reddy, & Srilatha, 2010) (Gregor Cameron Consultancy LTD, 2013)

The power output (P) of the run river hydropower plant is calculated with Equation 2 (Ahmed, 2012) . The height (h) in meters, the efficiency of the turbine (ɳ) in %, the density of the water (ρ) in kg/m^3 and the gravity constant (9.81 m/s^2) are considered in this equation.

$P = Q \times h \times \rho \times \eta \times 9.81$ Equation 2

The hydrostatic head available at the site is 20m. The efficiency of the generator is 95 %. The maximum flow capability for the turbine is 2,12 m^3/s (Gutierrez, Troddy, Browne, & Diderich, 2015). The efficiency of the turbine is assumed to be 64% (Gregor Cameron Consultancy LTD, 2013). The efficiency of the turbine is assumed to be constant for different water flows in HOMER calculations.

The turbine has some flow restrictions which must be taken into account. Thus, the steps to calculate the power output are detailed below:

1. Water flows above 2.76 m^3/s, maximum turbine flow capability (2.12 m^3/s) plus the compensation flow (0.64 m^3/s), produce 266.2 kW. This power has to be multiply by the efficiency of the generator (95%). Resulting in a maximum power output for the hydropower plant of 253 kW.

2. Water flows above ADF has the same compensation flow (Qn_{80}). The ones below ADF have the hands-off flow (Qn_{95}).

3. Water flows below 0.575 m^3/s, minimum turbine flow capacity (0.32 m^3/s) plus the hands-off flow (0.255 m^3/s), produce 0 kW. Therefore, the turbine is constrained by the river flow between 2.76 m^3/s and 0.575 m^3/s.

With the requirements said above, and the Equation 2, it is possible to calculate a more accurate real power output. The water flow data introduced in Equation 2 is hourly. This means the turbine has a constant power generation (kW) during one hour. Besides, this is equal to the energy generated during one hour (kWh). In other words, if the turbine generates 253 kW of power during one hour it produces 253 kWh of energy.

To calculate the final power supplied to Dalavich community 50kW, which are exported to the grid, must be subtracted from the turbine power output. This means, 203 kW is the maximum power supplied to the community from the hydropower plant.

The annual energy supplied to Dalavich has been calculated in 860 MWh. Xero energy has estimated this value in 823 MWh. One of the parameter which has not been taken into account in the calculations is the efficiency of the turbines depending on the input flow (Figure 12).

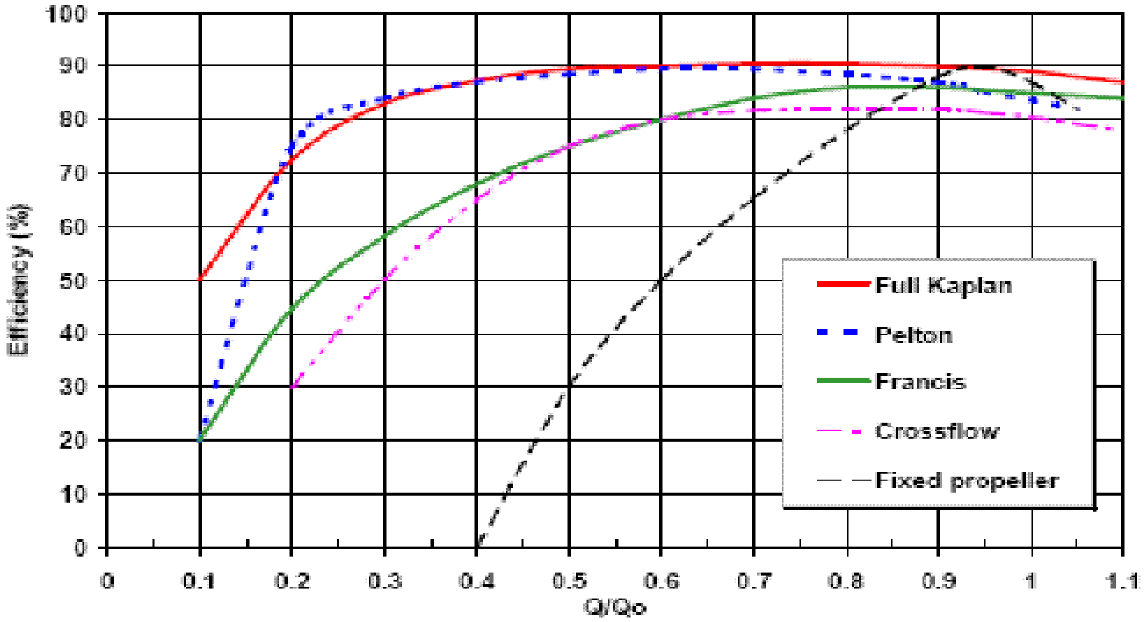


Figure 12 Efficiencies comparison of different turbines at reduced flow rates (University of Strathclyde, 2006)

Assuming the same average efficiency for the turbine (64 %) as previous studies and taking this efficiency for the maximum power output (corresponding with 2.12 m^3/s of water flow). It is necessary to extrapolate down the curve efficiency. The **Error! Reference source not found.** shows the efficiencies used in the manually calculations for different flows (University of Strathclyde, 2006). The average of the final efficiencies is 64 %, one per cent less than previous studies (Gregor Cameron Consultancy LTD, 2013).

Table 5 Efficiency of the turbine, for the manual calculation of the power output, depending on the inlet flow

Flow	Efficiency (%)
Above 2.76 (m^3/s)	64
2.76 m^3/s - ADF	69
ADF - 0.575 m^3/s	58

Calculating the annual energy output, with the new specifications for the turbine, the result is 823 MWh. This result is the same as the one estimated by Xero energy.

3.3 SOTWARE AND SIMULATORS

Once the demand and the output has been calculated is time to see how well the energy storage fits in the system. For this dissertation, HOMER software and my own software (created by Visual Basic) has been used to model the output power and demand of the community in order to figure out the most suitable energy storage technology. Although HOMER is going to be used for almost all the calculations, it has some restrictions. It has a lack of functionalities to simulate the electrical storage heaters and hot water tanks. Therefore, these will be simulated by my own software as long as my own software are verified during the previous calculations with the results of HOMER. Since now until the completion of this report, my own software is going to be named SOFTWARE1.

3.3.1 HOMER

The main software used in this project is HOMER Pro ® microgrid software, by HOMER Energy. This program is a simulator for microgrids, communities and off-grid isolated sites to grid-connected locations. Originally developed at the National Renewable Energy Laboratory, and enhanced and distributed by HOMER Energy, HOMER (Hybrid Optimization Model for Multiple Energy Resources). It has three powerful tools such as simulation, optimization and sensitivity analysis.

3.3.1.1 Simulation

This software allows the user to simulate different energy demands, renewable energy systems, energy supplied from fuels or grid and natural sources. The inputs introduced in HOMER to simulate the system are the load data, the turbine requirements, the electricity price, the battery characteristics and the natural hydro resource data (water flow from river Avich). The system is connected to the grid in order to not have a lack of electricity in the community.

- *Load demand*

To simulate the demand, HOMER has an option to build a synthetic load using measured data (Appendix 1 and 2). This data is taken from previous calculations explained in this report (Chapter 4.1). The Figure 13 represents the load profile for the community of Dalavich which has been generated by HOMER. The right Y axis are kWh, the left one hours (during a day) and the X axis days over a year. It is easy to see the different energy consumption depending on the season, as well as the different demand during the weekdays and weekends.

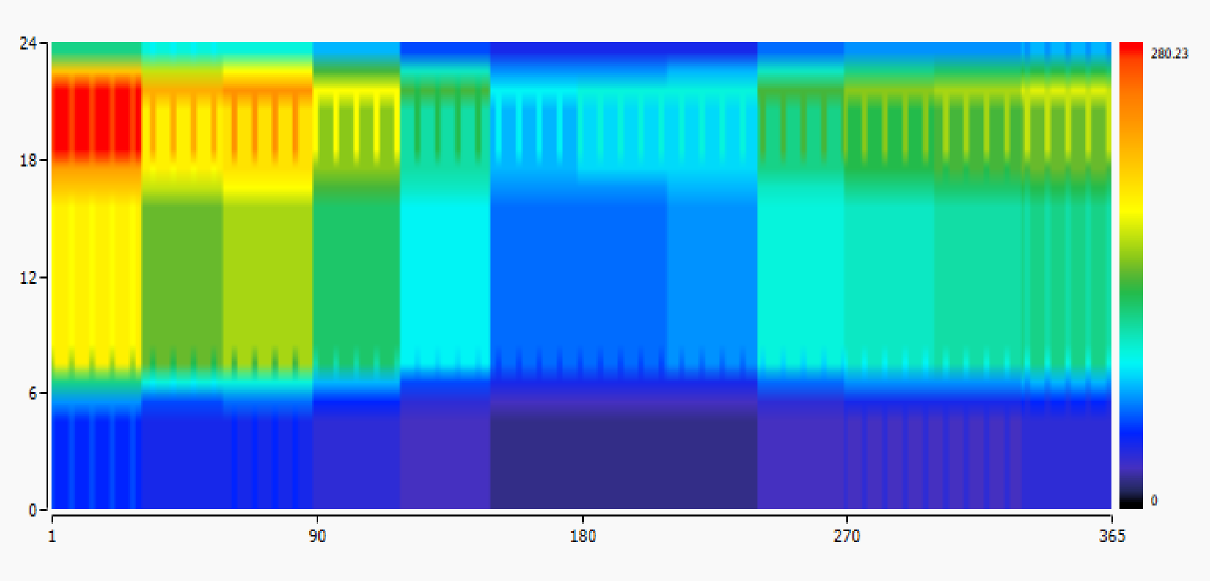


Figure 13 Demand profile for Dalavich community over a year (generated by HOMER with Xero Energy data)

- *Hydropower plant*

Once the load profile has been uploaded to HOMER, it is necessary to create a hydropower plant with the same characteristics described by Xero Energy. This simulator has modifiable variables for the turbine in order to match the real hydropower plant to the one developed by HOMER. These variables are: available head (m), design flow rate (L/s), maximum flow ratio (%), minimum flow ratio (%) and efficiency (%). The efficiency of the hydropower plant is 60.8% due to the 64% of turbine efficiency and 95 % of the generator efficiency.

Introducing the same water flow data from SEPA and the turbine requirements from previous studies and Xero energy (Gutierrez, Troddy, Browne, & Diderich, 2015) (Gregor Cameron Consultancy LTD, 2013), HOMER has generated a maximum power output of 253 kW. This power output is the same as the one calculated manually.

The main problem found in the simulation of the turbine is modelling the 50 kW power output which are exported to the grid. HOMER does not have the possibility to modify the nominal output of the hydropower plant. The easiest parameter to modify in order to reduce in 50 kW the power output of the hydropower plant is the efficiency. The final efficiency for the simulated turbine is 48.8%. This is just a way to simulate the exports to the grid and the real efficiency of the hydropower plant. However, this value cannot be taken in reference for anything apart from the simulation.

The total power output estimated by Xero energy without the grid restriction is 1084 MWh per year. The simulated turbine generates an annual energy output of 823 MWh with a maximum power output of 203 kW. Xero Energy (Gutierrez, Troddy, Browne, & Diderich, 2015) has estimated an annual energy supply to the community of 823 MWh. Therefore, the annual energy generation estimated by Xero energy and the one simulated y HOMER are the same.

- *Grid connection*

The grid is going to supply the community of Dalavich when neither the hydropower plant nor the energy storage system can meet the demand from the site. In addition, the community will import electricity at night (low price period) even if there is energy stored, just when the hydropower plant cannot reach the load.

The 2015 fixed price of the electricity has been obtained from Scottish Power (Scottish Power, 2015). The price of electricity is £0.136/kWh during the day and £0.0652/kWh from 24:00 to 7:00 a.m. (considered night).

- *Energy storage*

After see the different characteristics about the energy storage technologies analyse in Chapter 2 (**Error! Reference source not found.**). The ones which look more suitable for

Dalavich community are Lead-acid, Li-ion, Zinc-Bromine and VRFB. Nickel batteries have low suitable discharging time or are expensive compare with the rest. Supercapacitors have a high self-discharge which cannot be feasible in this project.

The energy is supposed to be stored at night and discharged during the day because of the difference of the electricity prices. At night the electricity is cheaper than during the day (Scottish Power, 2015). Thus, the system is based on supplying electricity to the community from the grid at low peak price period (at night) and from the energy storage device during high price periods (during the day).

The different modifiable variables for batteries in HOMER are: nominal voltage (V), round trip efficiency (%), minimum state of charge (%), maximum charge rate (A/Ah), maximum charge current (A), maximum discharge current (A), nominal capacity (Ah) and lifetime (years or lifetime throughput (kWh)).

The maximum charge rate is the same for all of the energy storage technologies (1 A/Ah), the nominal capacity is one of the results to obtain in this project and the lifetime of the devices is summarised in Table 14. This lifetime is assumed in order to maintain the energy storage system until 2021 when the export's restriction will be eliminated. The rest of the characteristics for each technology are summarised below (Table 6).

Table 6 Characteristics for the energy storage technologies to introduce in the simulations run by HOMER

	Li ion	**Flooded/Wet Lead acid**	**Tubular gel Lead acid**	**Zinc Bromine**	**VRFB**
Nominal voltage (V)	6.00	6.00	12.00	60.00	48.00
Round trip efficiency (%)	90.00	81.00	85.00	72.00	64.00
Max. charge current (A)	166.67	78.33	57.00	250.00	200.00
Max. discharge current (A)	500.00	251.33	133.90	500.00	312.50
Minimun state of charge (%)	20.00	20.00	20.00	0.00	0.00
Lifetime (years)	5.00	5.00	5.00	5.00	5.00

This information has been taken from HOMER software. These data are the default characteristics appeared in the simulator from the manufacturers (Hittinger, Wiley, Kluza, & Whitacre, 2015).

The energy storage device has to reach a proper power output to meet the load. This power must be around 285 kW to supply the load in case of no renewable energy output. However, this configuration could be too expensive for this project. This load could be reached connecting different batteries together. The Ohm's law has been used to simplify the calculation. Equation 3 can be used to calculate the final power output from the new battery configuration. The voltage is increased by series configuration and the current by parallel one.

$$P = V \times I \qquad \text{Equation 3.}$$

Power (P), voltage (V) and current (I). The configuration will be different in order to decide the most suitable capacity. In addition, a possible off-grid configuration for specific periods will be analysed. This configuration needs to reach the maximum peak load. Therefore, a power output of 300 kW from the batteries must be necessary.

- *Converter*

This device converts DC current to AC and vice versa. The batteries used for this project work with DC and the hydropower generated AC. Thus, it is necessary to modify the current due to the energy storage. The only energy storage device which does not need a converter is the VRFB, which works with AC.

The converter has the default characteristics shown below (Table 7). The only modification has been the capacity in order to meet the load power depending on the size of the batteries.

Table 7 Characteristics of the converter in HOMER.

	Inverter Input	**Rectifier Input**
Efficiency (%)	90	85
Relative capacity (%)	-	100
Capacity (kW)	300	
Lifetime (years)	5	

- *Hot water storage tank*

There are 109 people living in the community. During the peak morning the hot water demand is responsible of 25% of the demand and during the evenings is around 17% (Wong

& Megnevitsky, 2012). The next assumptions have been considered for modelling this storage technique.

- Assuming half of Dalavich's residents take a shower in the morning and the other half at the evening.
- Every day the whole amount of hot water is used and as a consequence every night the tank has to warm up the water.
- Everybody takes a shower every day (109 showers).
- The holiday chalets are considered to have a tank of 200 L each.
- A tank of 400 Litres is used for 4 showers. It has a total estimated cost of £2,000 (Consumer report, 2015).

The results obtained with the consumption demand percentage and the assumptions made before are summarised in Table 8.

It is assumed a deployment of 10 hot water tanks with 400 L of capacity (40 showers and 10 houses with tanks) and 35 of them with 200 L of capacity (2 showers and 35 houses with tanks). In total 110 showers for the population of Dalavich and every house of the community with hot water tank. In addition, 27 hot water tanks of 200L of capacity for the rest of the holiday chalets.

Table 8 Energy consumed for hot water in the community of Dalavich per day.

	Energy consumed by the hot water storage tanks (kWh)
January	613
February	552
March	521
April	414
May	291
June	215
July	207
August	207
September	321
October	341
November	349
December	375

The most accurate way to simulate a hot water tank with the tools available is increasing the demand at night and decreasing it during the day. The demand increased corresponds with the energy needed by the tanks to warm up the water (night time). The reduction of the load is because the water is already warmed to be used during the day. However, there are different issues which have not been taken into account such as the storage of energy during the day from the renewable source. The load would be lower at night if the water is warmed up to 60 ^{o}C (maximum temperature) before 12:00 a.m. However, the case to have an energy surplus from the hydropower plant during the day and suddenly after 12:00 a.m. an output reduction below the demand is rare. The electricity generated by the hydropower plant use to change smoothly because of the small variation of the water flow from the river. Therefore, this specific case is not going to be considered.

The sizes of the tanks can be calculated easily with the volume's cylinder formula. Thus, the shape of the tank is a cylinder and the results are: 1.75 meters of height and 0.60 meters of width for the big tank (400 L) and 0.45 meters of width and 1.60 m of height for the small one (200L).

OPTIMIZATION

The basic system simulated in HOMER for the project is the hydropower plant, grid connexion, energy storage and a converter (AC to DC). HOMER has some specifications which do not allow simulating impossible combinations such as different electric bus or electricity load shortage. To optimize the system is necessary an economic analysis. This is necessary to decide the most suitable energy storage. The economic part is the one which in the end decide the energy storage technology for the community. For the same technical energy storage performance the cheapest one will be selected.

There are two different inputs to study in the economic analysis, the electricity purchased and the total cost of the energy storage technology. In the total cost of the energy storage system has been included capital cost, replacement cost and operating and maintenance cost. The capital cost is taken from **Error! Reference source not found.**, and the rest are taken from HOMER as default software values.

SENSITIVITY ANALYSIS

HOMER has the option to compare same variable with different values. This means, the possibility to compare for example different efficiencies for turbine, different price for the same battery or different converter capacity. The calculation is made running once the simulator and it generates the results for all the sensitive variables. In addition, HOMER has different utilities to compare all these variables in order to decide the most suitable for the customer.

3.4.2 SOFTWARE1

This tool has been developed with Visual Basic in Excel. It is a simple program which matches the on-site generation, demand and energy storage system. It has different functions explained below:

- Modifiable hourly demand and hourly water flow in order to simulate different energy consumptions and different rainfalls.
- Calculate the hourly power output from the hydropower plant with the formula and characteristics described in 4.2.
- Calculate the hourly energy storage taking into account different variables such as energy storage capacity (kWh), round-trip efficiency (%), self-discharge (%), charging rate (kW/hour) and discharging rate (kW/hour).
- Modifiable energy storage characteristics (described in the point above). It is assumed that charging rate and discharging rate has the same value for the calculations.
- Calculate hourly energy wasted (energy which cannot be neither stored from the storage device nor exported due to the grid restrictions).
- Calculate hourly energy imports (energy demand which cannot be supplied neither by the hydropower plant or the storage device).
- Calculate the percentage of the deficit (energy which is not met by the hydropower plant) met by the energy storage technology. The rest of the percentage must be imported from the grid.
- Calculate the percentage of hours when the community is autonomous (during this time the community could be off-grid).
- Calculate percentage of energy wasted. This energy wasted happens when the energy storage device is already full charged and the hydropower plant generates more energy than the demand. Therefore, no energy can be store or exported due to the grid restrictions.

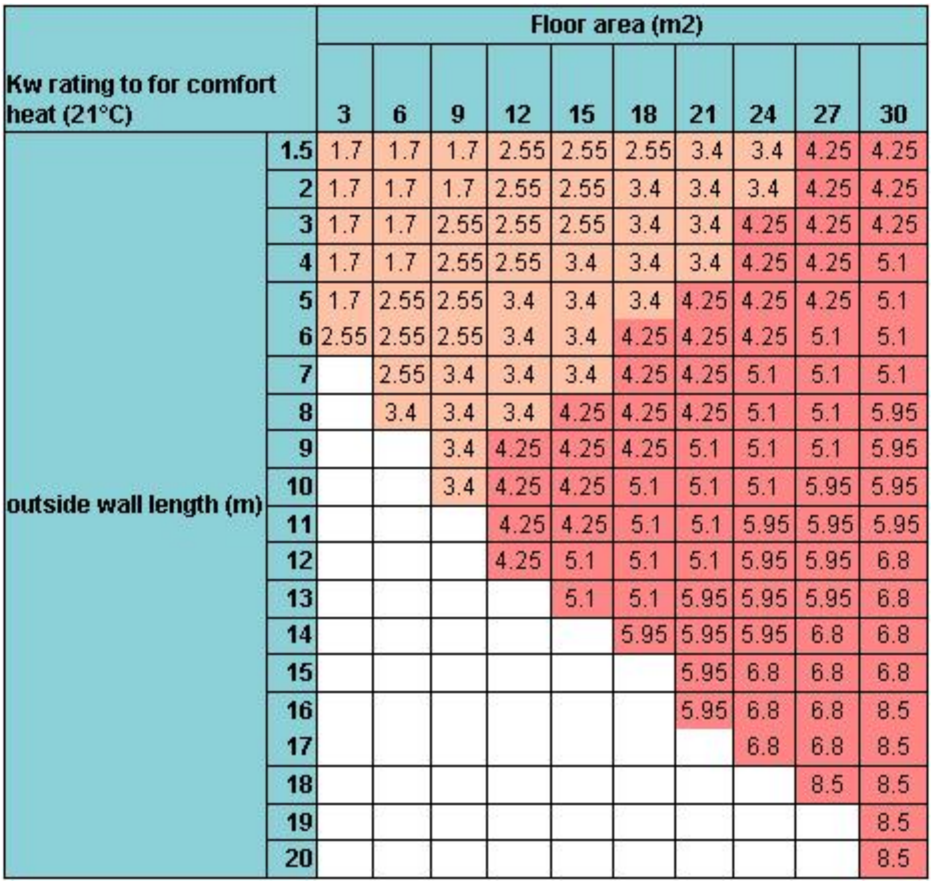
This software has a big range of improvement due to the modifiable code. Thus, the software can be developed to a really accurate model for every project. The code has been modified in order to fit suitable with Dalavich project. However, to develop a really accurate code for this specific project could take a long time. Therefore, this software is quite simple compare with HOMER.

HOMER does not have any functionality to simulate the electrical storage heaters. The data given by Xero Energy

- *Electrical storage heaters and hot water tanks.*

The energy consumption of an electrical storage heater depends on the floor area, volume of the room and the walls insulation. Table 9 is based on average ceiling heights of 2.4m, with no cavity wall insulation and an average external temperature of -2 C° and roof insulation of 100mm. For a comfort temperature of 21 C° the heater must be working for 7 hours (low peak period demand) at a specific power. This is an example about how to calculate the suitable heater or heaters for a house (Storage heater, 2010).

Table 9 Electrical storage heater consumption (KW rating) to maintain the rooms in the comfortable temperature of 21°C (Storage heater, 2010)



Kw rating to for comfort heat (21°C)		Floor area (m2)									
		3	6	9	12	15	18	21	24	27	30
outside wall length (m)	1.5	1.7	1.7	1.7	2.55	2.55	2.55	3.4	3.4	4.25	4.25
	2	1.7	1.7	1.7	2.55	2.55	3.4	3.4	3.4	4.25	4.25
	3	1.7	1.7	2.55	2.55	2.55	3.4	3.4	4.25	4.25	4.25
	4	1.7	1.7	2.55	2.55	3.4	3.4	3.4	4.25	4.25	5.1
	5	1.7	2.55	2.55	3.4	3.4	3.4	4.25	4.25	4.25	5.1
	6	2.55	2.55	2.55	3.4	3.4	4.25	4.25	4.25	5.1	5.1
	7		2.55	3.4	3.4	3.4	4.25	4.25	5.1	5.1	5.1
	8		3.4	3.4	3.4	4.25	4.25	4.25	5.1	5.1	5.95
	9			3.4	4.25	4.25	4.25	5.1	5.1	5.1	5.95
	10			3.4	4.25	4.25	5.1	5.1	5.1	5.95	5.95
	11				4.25	4.25	5.1	5.1	5.95	5.95	5.95
	12				4.25	5.1	5.1	5.1	5.95	5.95	6.8
	13					5.1	5.1	5.95	5.95	5.95	6.8
	14						5.95	5.95	5.95	6.8	6.8
	15							5.95	6.8	6.8	6.8
	16							5.95	6.8	6.8	8.5
	17								6.8	6.8	8.5
	18									8.5	8.5
	19										8.5
	20										8.5

The price of an electrical storage heater is between £2,000 for a 7kW heater and £700 for a 1kW one (Storage heater, 2010). Assuming an average house with two bedrooms, two bathrooms, one kitchen and one living room, there are 6 rooms. However the only electric storage heaters are set up in the living room, one bathroom, and the bedrooms. The sizes of the rooms are assumed below Table 10. In addition, an outside wall of 3 meters is assumed.

Table 10 Assumed sizes for the different rooms in an average house in Dalavich

Room	Size (m^2)
Bedroom x 2	9
Bathroom x 2	6
Living room	15
Kitchen	9

The electric heater from the bathroom has a power of 1.7 kW. The bedroom, kitchen and the living room have a power of 2.55 kW. The sum of all of them is 13.6 kW. It is assumed the heating demand of 4 houses over a year represents the total consumption of the holiday chalets in the months of January and from May until October. This number is decide with a really simple calculation about the time which the heaters are running during the year compare with the time of the heaters in 23 holiday chalets in 4 months and three of them in warm months. Therefore, it is assumed 46 houses out of the 65 with a total heating consumption of 625.57 kW. It would be necessary a total energy consumption during the 7 night hours of 4,379 kWh. This is supposed to be in the coldest month of the year, January. The rest of the months have been calculated multiplying this energy consumption by the percentage heating consumption along the year (Table 11).

Table 11 Heating consumption, percentage of heating depending on the month compared with January and daily heating consumption. Normal electric heaters.

	Monthly heating energy consumption (MWh)	Percentage of heating compare with January (%)	Daily heating energy consumed (kWh)
January	102.00	100.00	3,290.32
February	85.00	83.33	3,035.71
March	91.00	89.22	2,935.48
April	68.00	66.67	2,266.67
May	39.00	38.24	1,258.06
June	20.00	19.61	666.67
July	21.00	20.59	677.42
August	22.00	21.57	709.68
September	62.00	60.78	2,066.67
October	48.00	47.06	1,548.39
November	58.00	56.86	1,933.33
December	61.00	59.80	1,967.74

The Table 11 shows the new heating demand with the electrical storage heaters for the community of Dalavich. The original electric consumption is lower than the electrical storage heaters one (Table 12). Although the electricity consumed by the normal heating is lower, the electrical storage heaters are consuming electricity during the night (low price period).

Table 12 Daily and hourly consumption of the electrical storage heaters

	Energy consumed by the electrical heaters (kWh)	Energy consumed per hour (kWh)
January	4,379.00	625.57
February	3,649.17	521.31
March	3,906.75	558.11
April	2,919.33	417.05
May	1,674.32	239.19
June	858.63	122.66
July	901.56	128.79
August	944.49	134.93
September	2,661.75	380.25
October	2,060.71	294.39
November	2,490.02	355.72
December	2,618.81	374.12

The electricity demand which is not used for heating represents the 20,5 %. This calculation has been made with the demand data supplied by Xero Energy (Gutierrez, Troddy, Browne, & Diderich, 2015). The energy for hot domestic water (hot water tanks) is within the remaining 79.5 % of demand. The assumption made before to model the hot water tanks, balance the load, cannot be made in this situation due the high percentage of energy coming from heating. Therefore, SOFTWARE1 is used to simulate the heating demand. The study has been done for every month to make a more accurate simulation. The capacity of the electrical storage heater have been modified every month in order to adjust the energy absorbed by it as well as the output power which has been modified to simulate a maximum discharging rate. This has been calculated with the average demand for each month multiply by the percentage of heating demand (79.5%). This modification has been done in order to do not influence in the electricity for lighting or for other uses. During June, July and August it is assumed the heaters are switched off and the data is taken from the hot water tank results. The energy consumed for heating during these months is assumed to be just for domestic water.

The demand for heating has been calculated multiplying the new heating demand (Table 12) by the percentage of energy consumed hourly in Dalavich (The monthly data from Xero Energy and the percentage of energy consumed hourly are used in Equation 1 to calculate the real energy profile consumption of the community of Dalavich. The Table 3 shows an example of all the calculations said before.

Table 3). The original demand has been multiplied by the demand percentage, 20.5% (just electricity for other duties different than heating), and added to it the hourly heating demand from the electrical storage heaters calculated before.

Table 13 Data introduce in SOFTWARE1 to simulate the electrical storage heaters and the hot water tanks.

	Storage capacity (kWh)	Maximum discharging rate (kW)
January	4,385.15	90
February	3,654.29	75
March	3,912.24	80.29
April	2,923.43	60
May	1,676.68	34.41
June	-	17.65
July	-	18.53
August	-	19.41
September	2,665.48	54.70

October	2,063.60	42.35
November	2,493.52	51.17
December	2,622.49	53.82

SOFTWARE1 cannot simulate the interaction of the energy storage with the grid. Because of that, it is necessary to understand better how the electrical heaters have been simulated. The surplus of electricity from the hydropower plant is taken into the electrical heaters even if it is during the day to charge them. However, the simulation of the imports is more complex. The total demand has increased due to the new electrical storage heaters but the imports for this technology are just during the night. It is assumed that 79.5% of the imports are for heating. Therefore, it happens at night. Even though, this is not completely accurate, it is the most accurate simulation with the available tools.

3.4 ECONOMIC ANALYSIS

It has been assumed for the economic analysis the price of the electricity and not the oil one due to its volatility. Therefore the calculations have not been taken into account the expenses saved from the heating oil in the community.

The estimated annual net income from the scheme Feed in Tariff is £154,276 when the total amount of energy generated by the hydropower plant is used (1084 MWh). The Feed in Tariff price is 0.142 £/kWh. The estimated annual income from the exports to the grid is £49,930 and the price per kWh is £0.0461. The total consumption of the electricity generated by the hydropower plant produces an approximately profit of £200,000.

In the first five years the exports are constrained in 50 kW due to grid restrictions. It is estimated by Xero Energy a total energy exported to the grid along this period of 261 MWh, generating £12,032 of profit. In the case of the Feed in tariff (FIT) the amount of money received is £37,062. Therefore, £155,000 is wasted due to the restriction (exports and FITs). The money for the exports cannot be generated due to the grid limitations but the FITs can be taken in advantage for other projects. The electricity which is not consumed does not receive FITs.

The annual repayment for the hydropower plant is around £150,000 (DIG, 2014). The money which could be used for other projects by FITs with the grid restriction in one year is £117,214.

The microgrid project has been set up in order to take advantage of the energy wasted and generate a profit. A previous study from Xero energy has been done in order to estimate the cost of setting up a microgrid (without taking into account energy storage technologies) and the price amounted to £390,500.

There is a method which evaluates the economic attractiveness of a project. This method is called the Discount Cash Flow (DCF). This method analysis future cash flows and estimate its present value (Equation 4). The value of each year savings or profits is calculated by this equation. Therefore, this method generates a yearly value of the profit making easy the determination of the payback time.

$$DCF = \frac{CF_1}{(1+r)^t} + \frac{CF_2}{(1+r)^{t+1}} + \cdots + \frac{CF_n}{(1+r)^{t+n}} \qquad \text{Equation 4.}$$

DCF is the discount cash flow. It means the currently value of the saving or profit generated by the project each future year. CF is the cash flows of the project, economic inputs and outputs. In this report the usual inputs are the savings from the electricity imported and the outputs the exports. r is the discount rate. This rate takes into account different variables such as the risk or uncertainty of the future cash or interest charged for commercial banks which will be charged in the loans. Therefore, it has been calculated for the different projects analysed in this report. t is the year of the project in which the DCF wants to be calculated.

Moreover, for further calculations is necessary to exchange the currencies. HOMER works with Euros. Thus, the exchange currency between Euros and Sterling pounds has been taken from the average price during the summer of 2015 (XE, 2015). One pound is equal to 1.40 Euros.

3.4.1 Batteries

The theoretically capital cost of the energy storage batteries is assumed the mean value of the one shown in Table 1. The final capital cost for the economic analysis are summarised in Table 14. The exchange ratio of the currency has been don with an average price during the summer of 2015 (1.10 Dollar = 1 Euro, (XE, 2015)).

Table 14 Capital cost of the batteries in bibliography and HOMER, replacement cost in HOMER and O&M cost in HOMER.

	Theoretically	**HOMER**		
	Capital cost (€/kWh)	*Capital cost (€/battery)*	*Replacement cost (€/battery)*	*Operating and maintenance cost per year (€)*
Li-ion	1045,45	700	700	10
Zinc Bromine	522,73	5000	1000	100
VRFB	522,73	5000	1000	100
Flooded/wet Lead acid	204,54	300	300	10
Tubular Lead acid	204,54	300	300	10

The prices are different in HOMER than from the references because one depends on the capacity and the other one on the number of batteries. The replacement cost and the O&M cost are taking from the default ones from HOMER.

Although HOMER has a default lifetime for the batteries supplied from different manufacturers, this data has some technical restrictions (Hittinger, Wiley, Kluza, & Whitacre, 2015). These technical restrictions are about discharging rates and number of cycles during a period of time. This lifetime expectancy is compared with other studies which cover the same issue (Australian Renewable Energy Agency, 2015) and the average of them is the one decided for this project. The results are gathered in Table 15.

Table 15 Expected lifetime for the batteries (HOMER).

	Life time (years)
Li-ion	15
VRFB	20
Zinc Bromine	20
Tubular Gel Lead acid	12
Flooded/Wet Lead acid	12

To calculate the money saved from imports is not an easy task. One of the requirements introduce in HOMER is to purchase electricity from the grid during the nights when the hydropower plant cannot reach the load even if the energy storage has energy.

On the one hand, due to the low load peak demand during the nights, the implementing of batteries does not make a big difference in move the imports at night and used them during the day. However, the characteristics of the grid can be modified to improve the profit of the project.

On the other hand, the hot water tanks and the electrical storage heaters move the demand to night time. This increases the imports from the grid at night, generating a higher profit in proportion to the energy storage systems.

3.4.2 Hot water tanks and electrical storage heaters

There are 67 hot water tanks for this study with different capacities. Ten tanks can contain 400 L of water and 55 ones 200 L. The capital cost for the 400 L tank has been estimated in £2,000 pounds and the small one in £1,000 (Consumer report, 2015). Thus, the total capital cost is £75,000.

There are 46 houses which would use electrical storage heaters and all of them assuming the same configuration. There are two small heaters for the bathroom (1.7 kW) and two big ones for the bedrooms, living room and kitchen (2.55 kW). The capital cost for a heater of 1kW of power is £700 and £2,000 for 7 kW one (Storage heater, 2010). The small heater is assumed to cost £800 and the big one £1,100. Therefore, the total capital cost for this project is £276,000. Moreover, the hot water tanks must be taken into account. This generates a total capital cost of £351,000.

3.5 ENVIRONMENTAL ASSESMENT

The environmental assessment is a simple calculation for the CO_2 emissions saved due to the hydropower plant and the deployment of the energy storage technologies. The first step is to calculate the greenhouse gases emissions produced by the community if it is supplied just by electricity from the grid and after compare with the rest of systems. The relation between CO_2 emissions and kWh of electricity is 0.523 Kg CO_2/kWh (UK government, 2012).

3.6 DIFFERENT SCENARIOS

All the situations analysed are based on the data from 2012. The energy storage technologies said before are going to be simulated in different scenarios in order to determine the most suitable energy storage for each and decide the best one for the Dalavich community in the end. SOFTWARE1 is going to be compare with HOMER in this report in order to see the reliability of it. HOMER as a commercial product manufacture by professionals from the energy industry is going to be more trustworthy.

The first calculation is going to be without energy storage system in order to compare further results with this one and see how well the energy storage system works. This study is split in two different scenarios. The first one is before the restriction of the power output from the hydropower plant to the grid (2017-2021) and the second one after this curtailment. Actually the main difference between these two scenarios is the economic part. This one decides the size of the energy storage technology and if it is feasible or not.

3.6.1 Scenario before 2021

The first study is made during the short term between the beginning of the project and 2021. The project supposes to start the 1st of January 2017 in order to have more than one year for the constructions of the hydropower plant and the preparation of the community for the microgrid. The end of this term is the 31st of December 2021. After the power output from the hydropower plant could be entirely exported to the grid.

The main issue for a short term period is the economic part due to the short time for paying back the money invests on the project. Therefore, the economic analysis in this scenario is simple without taking into account inflation, loans, interests, etc.

3.6.2 Scenario after 2021

The second scenario studies how the elimination of the grid curtailment affects to the microgrid scheme. The total amount of energy generated by the hydropower plant would be exported. The economic analysis in this scenario is more detailed than in the short term. In this case the project could be paid back in more than 5 years. This means, more parameters must be taken into account, among others the inflation.

3.6.3 Increment in the imports price

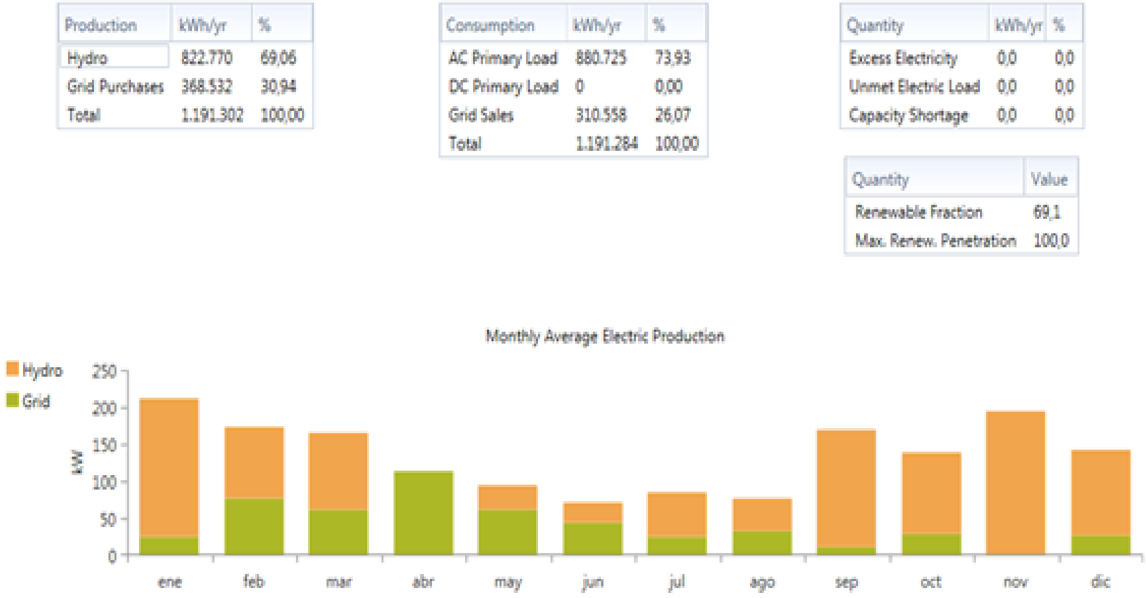
The price of electricity in UK could be increased due to the introducing of more renewable energy energy in the main grid. Therefore, a possible scenario to simulate is an increase in the price of the imports of 5 % and 10 %. This could help to the energy storage technologies to be more feasible than nowadays.

3.6.4 Reduction of battery capital cost

There are some studies which suggest that the price of the batteries could drop dramatically in the next years (Australian Renewable Energy Agency, 2015). This study estimated a possible fall in the price of batteries, such as Li-ion and Flow batteries of 60 % and 40 % respectively, in the next 5 years. Lead-acid, due to its maturity, is assumed with the same price.

4. SIMULATIONS AND RESULTS

In this chapter the calculations and results will be divided in the different scenarios said before in Chapter 3. The first simulation has been done without energy storage in order to see the electricity purchased and wasted after the installation of the microgrid. This result has been obtained with HOMER (Figure 14).



Production	kWh/yr	%
Hydro	822.770	69,06
Grid Purchases	368.532	30,94
Total	1.191.302	100,00

Consumption	kWh/yr	%
AC Primary Load	880.725	73,93
DC Primary Load	0	0,00
Grid Sales	310.558	26,07
Total	1.191.284	100,00

Quantity	kWh/yr	%
Excess Electricity	0,0	0,0
Unmet Electric Load	0,0	0,0
Capacity Shortage	0,0	0,0

Quantity	Value
Renewable Fraction	69,1
Max. Renew. Penetration	100,0

Figure 14 Results obtained from the microgrid simulation without energy storage by HOMER in the community of Dalavich

The grid purchase is 368.5 MWh per year and the grid sales are 310.6 MWh per year. The energy sold should be the one taken in advantage from the energy storage system. The grid sales and the purchases must be reduced with energy storage systems. The energetic benefit of the microgrid is summarised below (Table 16).

Table 16 Energy imported and wasted with microgrid and without it

	No microgrid	Microgrid	Energetic improvement (%)
Energy wasted (kWh)	883.00	310.60	64.82
Energy imported (kWh)	880.60	368.50	58.15

In addition, there is a percentage of the renewable energy fraction in this project (69.1 %) and a graph which shows the power supply from the grid and from the hydropower plant. The month of April is the one which more percentage of energy supplied by the grid due to the low water flow in the river Avich.

The same simulation has been done by SOFTWARE1 with different results. These results are shown in Table 17. There is less than 4 % of difference between both simulations.

Table 17 Comparison of the results in HOMER and my SOFTWARE1 for a normal system without storage.

	HOMER	SOFTWARE1	% of difference
Surplus electricity generated (kWh/year)	310.56	317.98	2.33
Electricity imported from grid (kWh/year)	365.53	380.73	3.99

Thus, the best situation is 0 kWh/year of electricity surplus and electricity imported from the grid. This means take advantage of all the amount of electricity produced which cannot be exported to the grid due to the restrictions and save money due to the purchases of electricity. This is the target to achieve for the energy storage system. Although the capacity of the energy storage device reducing the electricity surplus and imported to 0 will be oversize, is a good beginning to compare all the energy storage technologies.

4.1 BEFORE 2021

The first result is in the short term scenario and before removing the exports limitation of the hydropower plant to the grid. The analysis made is different depending of the scenario and it is significant the different results due to the time. Above all, the economic analysis is simpler in the short term than the the long one.

4.1.1 Batteries

4.1.1.1 Technical analysis

The Li-ion battery has been analysed with the characteristics shown in Table 6, as an example with a significant result (Figure 15). Nevertheless, this study has been done to every energy storage technology in order to compare the best technical result.

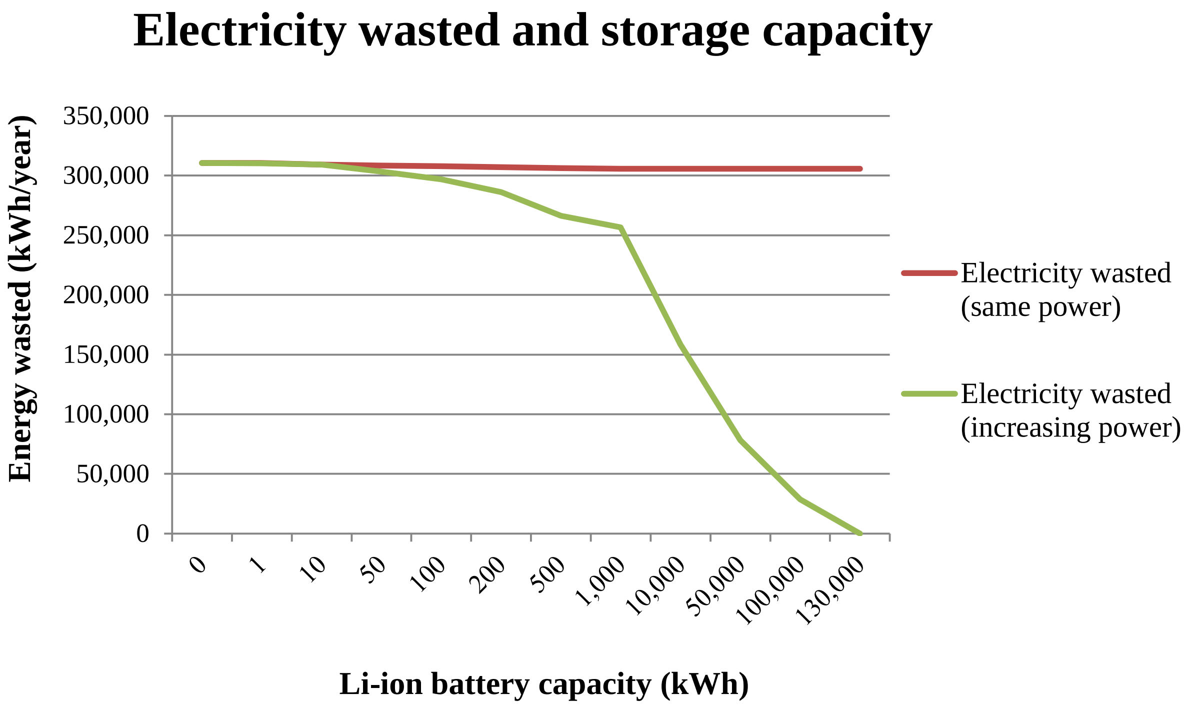


Figure 15 Electricity wasted due to the capacity of the Li-ion increasing the power of the battery or just the capacity

On the one hand, a battery with the same power output (minimum one) but increasing the capacity is not capable to reduce the electricity wasted after a certain capacity. In this case this capacity is 1,000 kWh. However, increasing the power of the battery, which raises the capacity as well, is the best way to reduce the energy wasted to 0kWh/year but the power output achieve in the end is above 5,000 kW. Therefore, it is necessary to find a balance between the power output and the capacity. The normal power output for the batteries in this microgrid scale must be between 25 and 50 kW and the capacity between 50 and 250 kWh (Electric Power Research Institute, 2010). Besides, the capacity is quite large when the battery achieves 0 kWh/year of electricity surplus, generating an oversize battery with a low technical performance and a high capital cost.

On the other hand, the electricity imported from the grid has a limit (Figure 16). Once the battery achieves a certain capacity it cannot reduce the amount of electricity purchased. This effect happens because the hydropower plant has some periods throughout the year with no power output. Therefore, the storage device during some periods is empty and the load has to be supplied by the grid. It is worthless to size the energy storage battery with a capacity above the limit point. This limit point is reached at 50,000 kWh of capacity. However, at this capacity the oversize problem said before occurred.

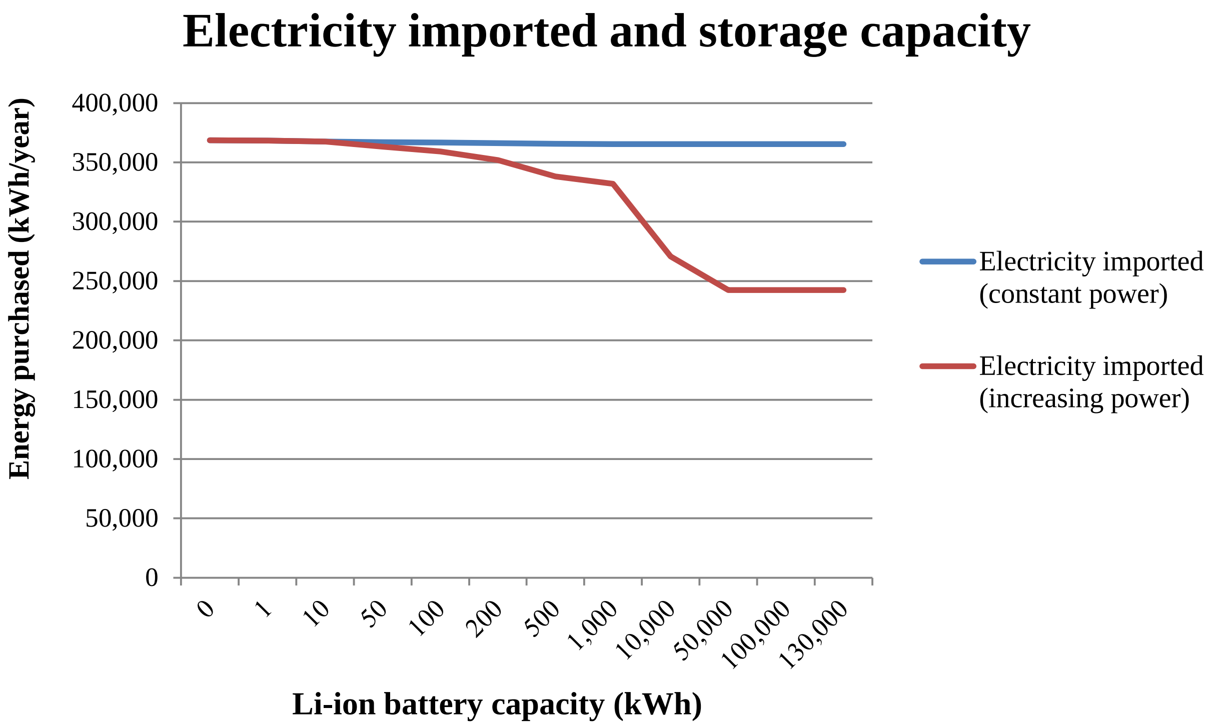


Figure 16 Electricity purchase from the grid depending on the capacity of the Li-ion battery with a constant power output and an increasing one

In conclusion, the maximum capacity to reduce the energy imported by Li-ion batteries is 50,000 kWh of capacity and to avoid waste energy from the hydropower plant is 130,000 kWh. The rest of the batteries have been calculated with the characteristics shown in Table 6.

The technical results determining the most suitable energy storage without taken into account the economic part are shown in Figure 17. This graph shows the technology which is capable to store the entire electricity surplus from the hydropower plant with the smallest capacity. VRFB reduces to 0 kWh/year the energy wasted with 72,160 kWh of capacity. Thus, the performance of this battery in this specific project is the most suitable in comparison with the rest. In contrast, the Li-ion battery has the worst performance. It has achieved 0kWh/year of electricity wasted with 130,000 kWh of capacity.

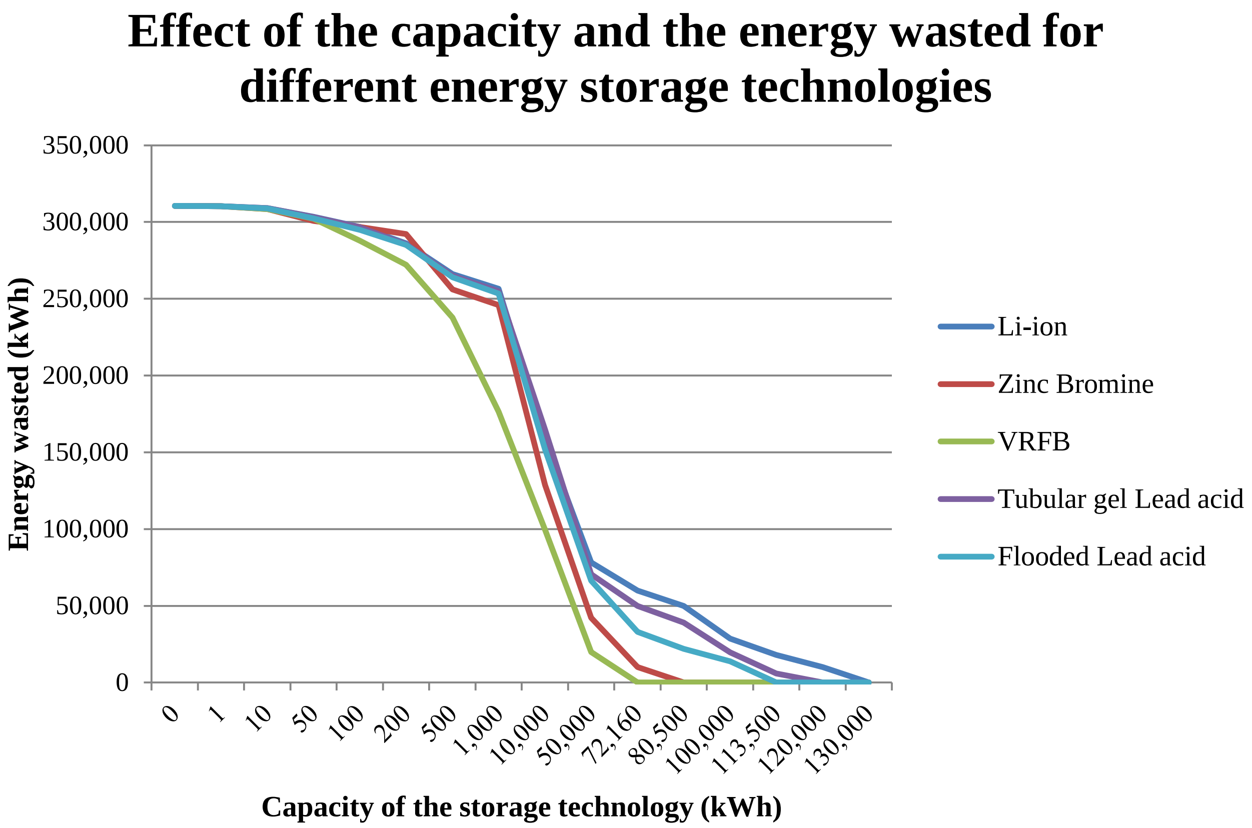


Figure 17 Effect of different energy storage technologies capacity with the energy wasted from the hydropower plant.

The other effect produced by the batteries is a reduction of the electricity imported from the grid because more energy can be supplied by the storage system (Figure 18). There is a limit in all the storage techniques due to the configuration of the system. This configuration has been developed to purchase electricity from the grid at night when the price of the electricity is low and just during the periods when the hydropower plant cannot meet the demand. Therefore, at night the energy storage cannot supply the loads and must be some imports from the grid.

The performance of the storage technologies in the reduction of the imports has the opposite result than in the reduction of the energy surplus from the hydropower plant. Thus, VRFB is the technology which has the highest amount of imports from the grid and Li-ion is the one with the lowest one. In this case, Li-ion batteries are the technique which reduces more the electricity imported from the grid and as a consequence more money is saved in the project.

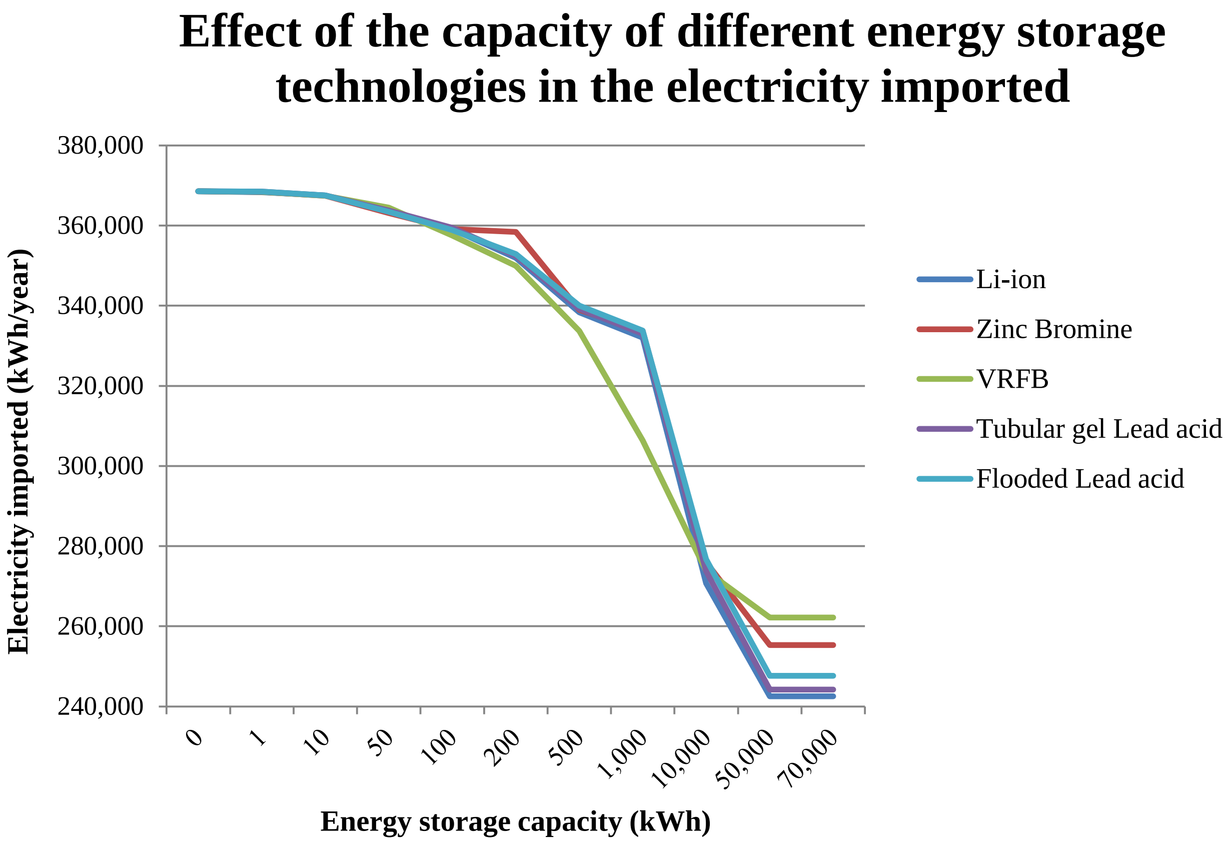


Figure 18 Effect of different energy storage technologies capacity with the energy imported from the grid.

These opposite results, in the reduction of the energy wasted and the energy imported, are due to the efficiency of the battery**.** Nevertheless, VRFB has a fewer amount of imports with capacities below 10,000 kWh.

On the one hand, the less efficiency a battery has, the more energy is wasted in the charge and discharge process. Therefore, more energy is necessary in the charging process of a battery and less energy is available to be wasted.

On the other hand, the less efficiency a battery has, the more energy is imported from the grid. A battery with low discharge efficiency will need more energy to meet the same load than a system with a high efficiency. Therefore, the battery has more probabilities to be totally discharge and as a consequence more energy has to be imported from the grid. A battery with a huge capacity does not necessary means that has fewer probabilities to be totally discharge. This depends on the load and the energy generated on-site. At his point, the energy storage system which is going to make a higher profit is Li-ion due the reduction of the imports from the grid.

4.1.1.2 Economic analysis

Microgrid

The first calculation must be the feasibility of the microgrid in order to take advantage of the FITs produced by it. The energy used by the community from the hydropower plant with the microgrid but without the energy storage techniques is the difference between the energy generated and the energy wasted (823,000 - 310,558 kWh = 512,442 kWh). This electricity generates £72,767 in FITs. This money would not be generated without the midrogrid. Therefore, it can generate a profit for the community, producing money to pay back the hydropower plant. In addition, this energy supplied by the hydropower plant produces savings in the imports. This saving must has been taken into account for the economic analysis. The yearly amount of money generate by the import savings is £59,853. Using Equation 4 (DCF), the cash flow is the difference of the money generated without microgrid (£0) and with it (£72,767 + £59,853). This calculation has been done for five years.

The price of the electricity during the day is 0,136 £/kWh, at night 0.0652 £/kWh and the daily hours are 17 hours. The total average price for imports is 0.1168 £/kWh.

$$price\ electricity\ during\ the\ day \times \left(\frac{daily\ houurs}{24\ hours}\right) + \ price\ electricity\ at\ night \times \left(\frac{Night\ hours}{24\ hours}\right) = average\ price\ of\ imports \qquad \text{Equation 5.}$$

The total capital cost for the previous construction for the microgrid is £390,500. This cost allows the hydropower plant to drawn electricity to the community. Without the microgrid the FITs could be wasted or invested in other feasible projects. The profit for the community due to FITs and import savings is shown in the graph below (Figure 19). The maximum discount rate feasible for this project is 9 %. It has been assumed for this project a discount rate of 3 %. The profit generated by this project is £155,500 in 5 years.

As it has been said before, the money necessary to pay the hydropower plant's loan is £150,000 each year (DIG, 2014). The microgrid project can generate at least one year of loan repayment for hydropower plant in the first 5 years. Further studies could analyses the profitability of other projects in the community different than the microgrid.

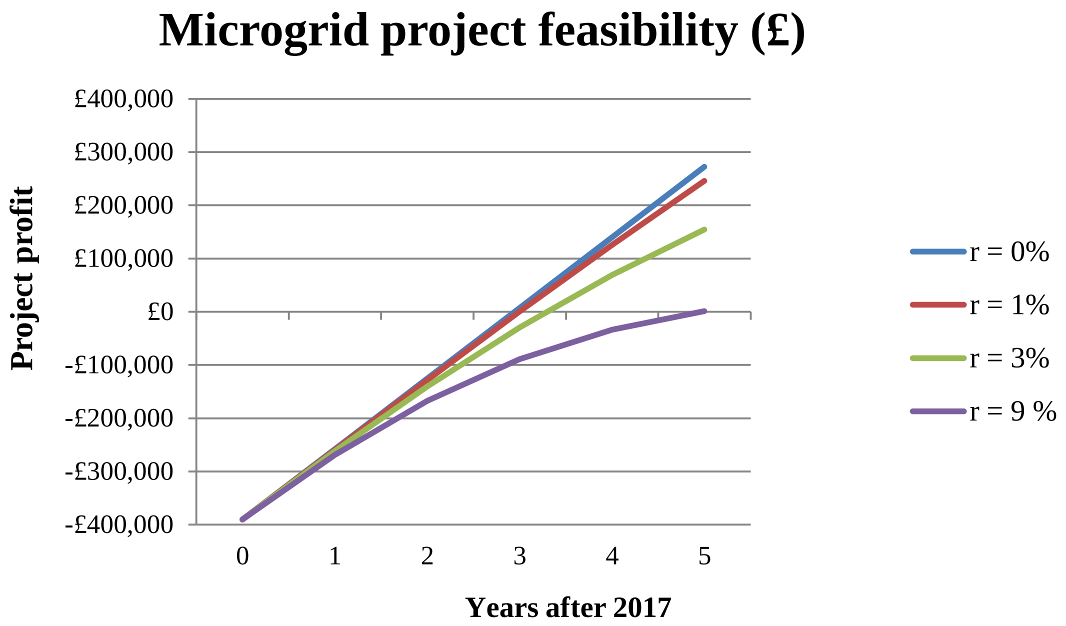


Figure 19 Feasibility of the microgrid project in the community of Dalavich depending on the discount rate

Batteries

The battery which achieves 0 kWh of energy wasted with the smallest capacity, around 70,000 kWh, is VRFB. To reduce the energy wasted to 0 kWh the batteries must be oversize and the prices are expensive (Figure 20). Therefore, the capacity achieved cannot be the most suitable for the correct performance of the energy storage device.

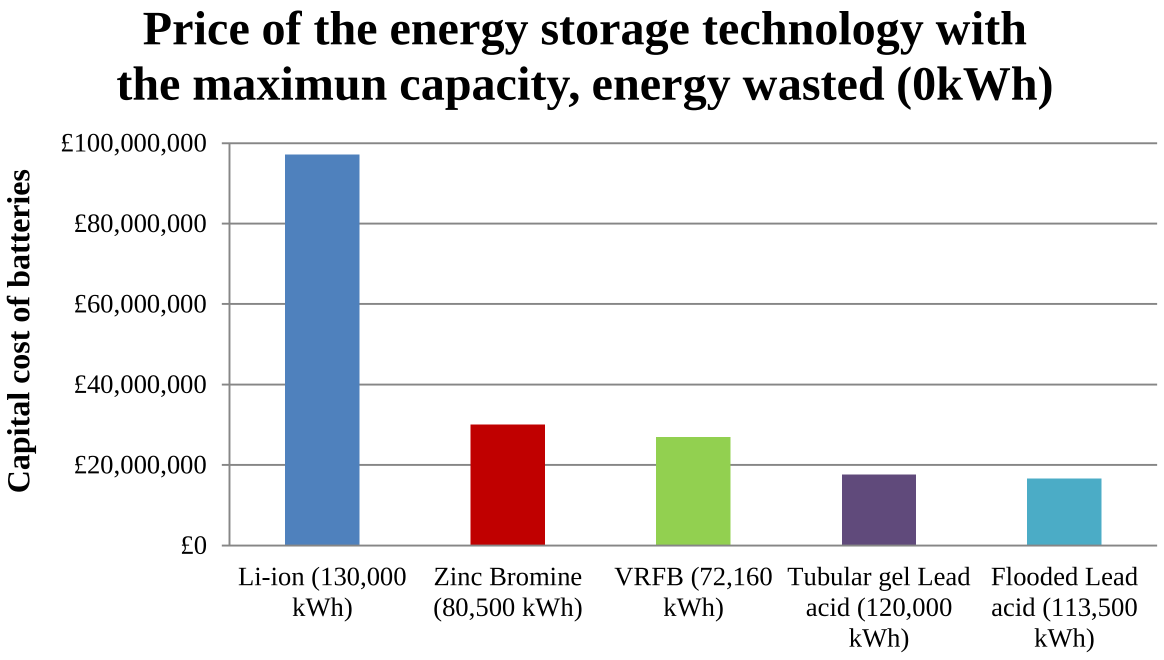


Figure 20 Capital cost of the energy storage technologies at the best technical performance, 0kWh/year of energy wasted

For the years between 2017, assumed as the year when the energy storage technologies will be implemented, and 2021 it is assumed the inflation affects to all the economic variables in the same proportion and therefore is cancelled. The inflation has not been taken into account to simplify the calculations.

The size of the energy storage capacity has to be decided according to the budget for the project. It is necessary to calculate the energy wasted and the energy imported depending on the capacity of each technique. The price of the imports has been estimated with the price from Scottish Power (Scottish Power, 2015)and used for the simulation of the demand in the Chapter 4.

- *Selection of the most suitable battery*

The bigger the capacity of energy storage system, the less energy wasted. However, the capital cost of the storage technique is high (Figure 20). Therefore, it is necessary to find the relation between the energy imported, energy wasted and capital cost when the system is more profitable. This relationship will generate the most suitable technology for the project of Dalavich in a period of 5 years, in case this project could be feasible.

The non-used of electricity generated from the hydropower plant does not produce any profit. The energy absorbed from the energy storage techniques is profit for DIG. However, it is also a loss of money because the battery has a cost which must be repaid. The Figure 21 shows the relation between capital cost, energy wasted and imports for 5 years. To simplify the calculations the profit from the microgrid has not been taken into account in order to analyse the profitability of the batteries by them. This value is named the profit value. It is the result of the division between the sum of the profit from FITs (generated by the energy absorbed by the battery) and imports saved and the capital cost. Therefore, more than one means a profit for the community (more profit than losses).

$$Profit\ value = \frac{FITs\ (£) + Imports\ saved\ (£)}{Cost\ of\ the\ battery\ (£)} \qquad \text{Equation 6.}$$

In this case, the profit value is the same as a DCF with a discount rate of 0 %. The benefit of this new equation is the possible calculation of the profit related with the capital cost of the battery and the simplification of the calculations without the microgrid economic part. In addition, it is easy to find the capacity for the battery which generates profit and calculate it. The money generated is the profit value multiplied by the capital cost of the battery.

In order to have a feasible project in five years, the profit value must be at least 2. The FITs are used to pay back the hydropower plant investment.

Although, the only two technologies which can generate more profit than its capital cost are Tubular gel Lead acid and Flooded/wet Lead acid, the most feasible one is Tubular gel Lead acid. The money generated by this technology depends on its size and it is summarised in Table 18. The maximum profit generated by it is 1.18 times the battery capital cost. This happened with the smallest capacity due to the big influence of the capital cost in the batteries. However, the highest profit has been generated by the battery of 100 kWh of capacity (Table 18).

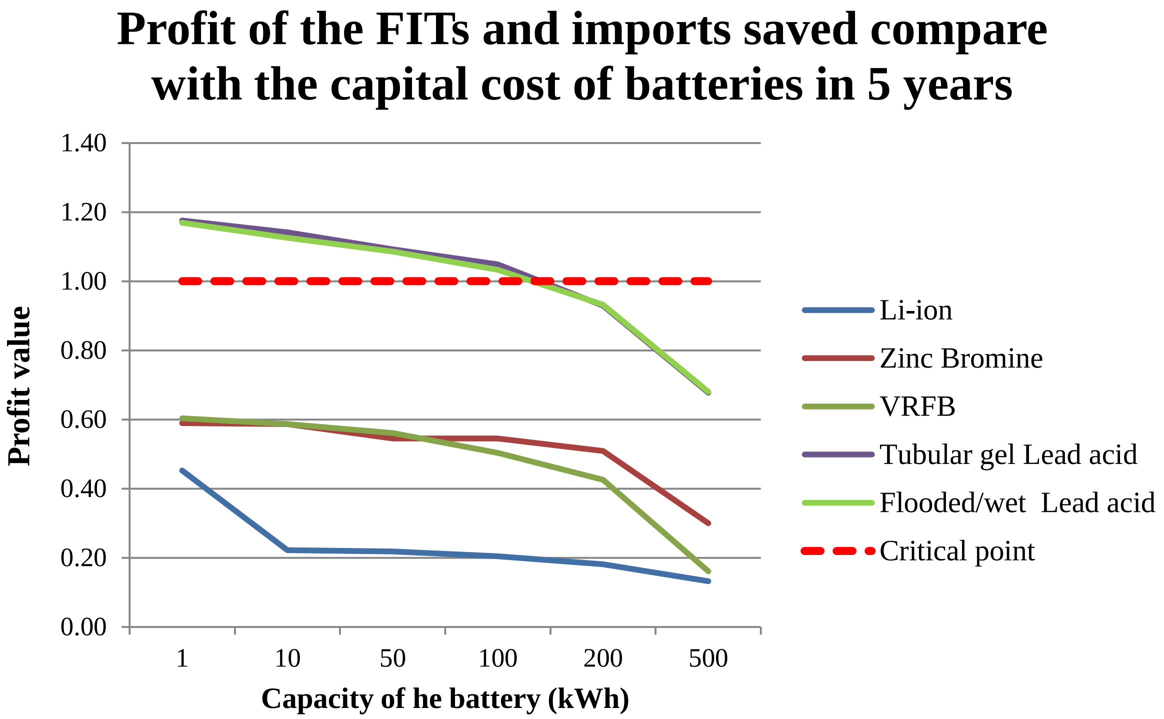


Figure 21 Profit of FITs and imports saved for the community compare with the cost of different battery capacities in 5 years.

The replacement cost, the O&M cost and the converter cost have not been taken into account. The profit in five years of the Tubular gel Lea acid battery is 1.18 times £205 (capital cost of Tubular gel Lead acid), the result is £241. However, the rest of the costs said before which are involved within the total cost of the battery have made this project not profitable for the five years term.

Table 18 Money generated by the Tubular gel Lead acid battery by FITs and imports saved depending on its capacity. Fraction of profitability (FITs + imports saved / capital cost).

Tubular Gel Lead acid						
Capacity (kWh)	**0.00**	**1.00**	**10.00**	**50.00**	**100.00**	**200.00**
FITs (£)	72766.8	72789.2	72984.59	73806.77	74768.96	76315.91
FITs generated by battery (£)	0	112.18	1,089.14	5,200.04	10,011	17,745.74
Energy wasted (kWh)	310558	310400	309024	303234	296458	285564
Capital cost (€)	0	205	2,045	10,227	20,454	40,908
Capital cost (£)		146	1,461	7,305	14,610	29,220
Imports (kWh)	368,532	368,430	367,541	363,770	359,430	352,413
Money saved by imports (£)		60	579	2,781	5,316	9,413
Fraction of profitability		1.18	1.14	1.09	1.05	0.93
Total benefit (£)		***26.28***	***204.54***	***657.45***	***730.50***	***-2,054.00***

These two different scenarios has been analysed together in this short term due to the small effect they have had in the project. An increase of 10 % in the import prices has incurred in a total benefit of £1,330 for a 100 kWh of capacity and £66 for 1 kWh. It is still far away for the repayment of the total cost of the batteries.

- *Increment of import price and reduction of the battery capital cost*

A reduction of the capital cost of 20% in Li-ion batteries and 10 % in Flow batteries has been assumed. This estimation has been made due to the possibility of a gradual reduction of their capital cost in the next five years (Australian Renewable Energy Agency, 2015). The Li-ion batteries achieved a profit value of 0.57 and the Flow batteries of 0.75. Neither battery had achieved any profit in 5 years.

4.1.1.3 Comparison of the results with SOFTWARE1

The best economic result obtained for batteries has been for Tubular gel Lead acid. The same simulation has been done with SOFTWARE1 to compare the results. The characteristics of the battery to simulate the Tubular Gel Lead acid has been a capacity of 100 kWh, a round-trip efficiency of 85% a self-discharge per hour of 0.001%, and a maximum discharging and charging rate of 42 kW. These characteristics are the same as the one simulated in HOMER.

Table 19 Comparison of the results between HOMER and SOFTWARE1 for a system with Tubular Gel Lead acid battery.

	HOMER	**SOFTWARE1**	**% difference**
Energy wasted (kWh)	296,458	302,461	2.07
Energy imported (kWh)	359,430	356,653	2.94

The results obtained by SOFTWARE1 are lower than HOMER. This time the percentage of difference is slightly smaller than the previous comparison without the energy storage system (Table 17). Therefore, SOFTWARE1 is a reliable tool to develop further simulations.

4.1.2 Electric thermal storage

The simulations for these thermal storage techniques are done with different software. HOMER has enough features to develop a proper simulation for the hot water tank but not for the electrical storage heater. The last one is simulated with SOFTWARE1.

The calculation of the electrical storage heaters have to be done together with the hot water tanks due to the information known. The data supplied by Xero Energy comprises both of them and cannot be divided.

4.1.2.1 Technical analysis

- *Hot water tanks*

The model with the new demand profile, it was explained in Chapter 3, has been compared with the normal demand (Figure 22). This comparison has been done in HOMER. The total amount of electricity supplied by the grid with the normal configuration, without the hot water tanks, is 368,532 kWh. The new system results in a reduction of 35,256 kWh in the imports and in the energy wasted of around 25,270 kWh.

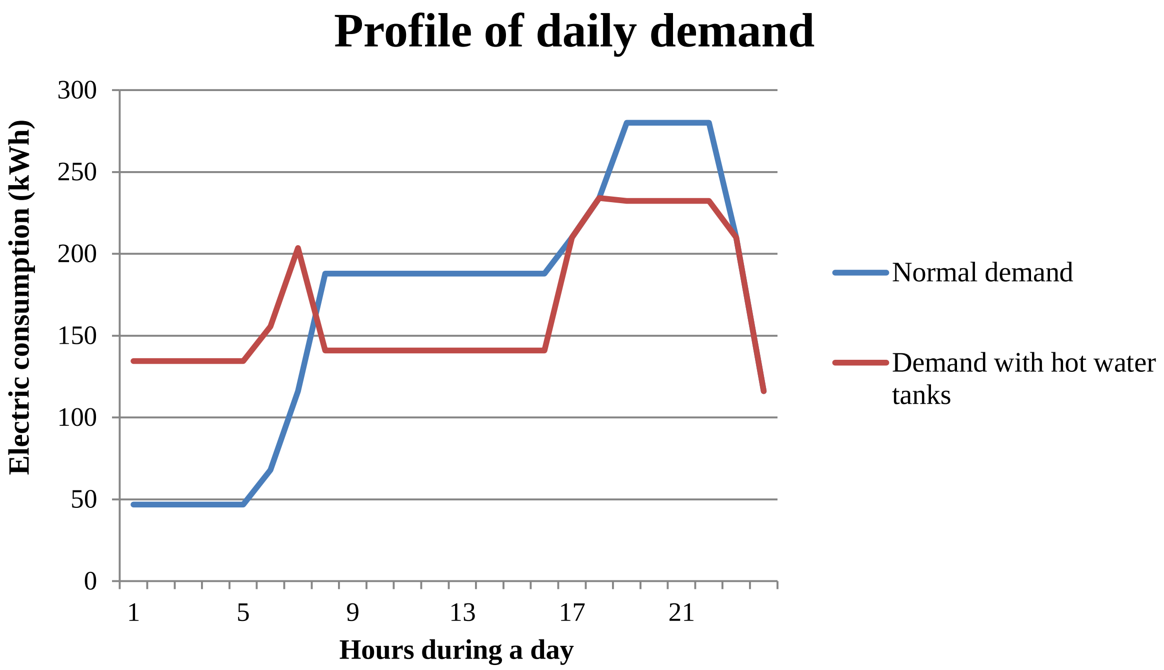


Figure 22 Comparison of the different demand profiles with and without the hot water tanks for January.

- *Electrical storage heater and hot water tank*

The results have been simulated with the different characteristics summarised in Table 13 (Chapter 3) by SOFTWARE1. The results have been performance by each month and are gathered in Table 20.

The total energy imported during the year is 440,110 kWh and the total energy wasted is 171,912 kWh. The energy wasted is 138,648 kWh less than without energy storage systems. This is a reduction in the energy wasted of 45%. However, the electricity imported from the grid has an increase of 74,580 kWh. This represents an increase in 17 % of the imports. This increase of the imports is because more of them happened during the night to store the energy in the electrical storage heaters due to the new demand.

Table 20 Energy imported and wasted with the electrical storage heaters and hot water tanks.

	Energy imported (kWh)	Energy wasted (kWh)
January	20,432	0
February	66,503	0
March	63,425	24.34
April	103,108	0
May	47,338	7,218
June	31,388	9,134
July	18,600	20,733
August	23,242	14,390
September	13,783	32,929
October	22,252	22,338
November	0	50,539
December	30,039	14,607
Total	**440,110**	**171,912.34**

The advantage of this electrical storage is the reduction of the energy wasted from the hydropower plant. In addition, 79.5% of the imports are assumed to be supplied from the grid at night. Thus, this could make a difference in the economic analysis.

4.1.2.2 Economic analysis

Hot water tank

The imports from the original system (without hot water tanks) are 368,532 kWh during the year. The imports from the system with the storage technology decrease until 333,276 kWh. In addition, the imports at night has increased and during the day decrease. The money paid for the imports is calculated multiplying the import at each hour by the price in this moment. This information is generated by HOMER. The system with the hot water tanks save £25,255.

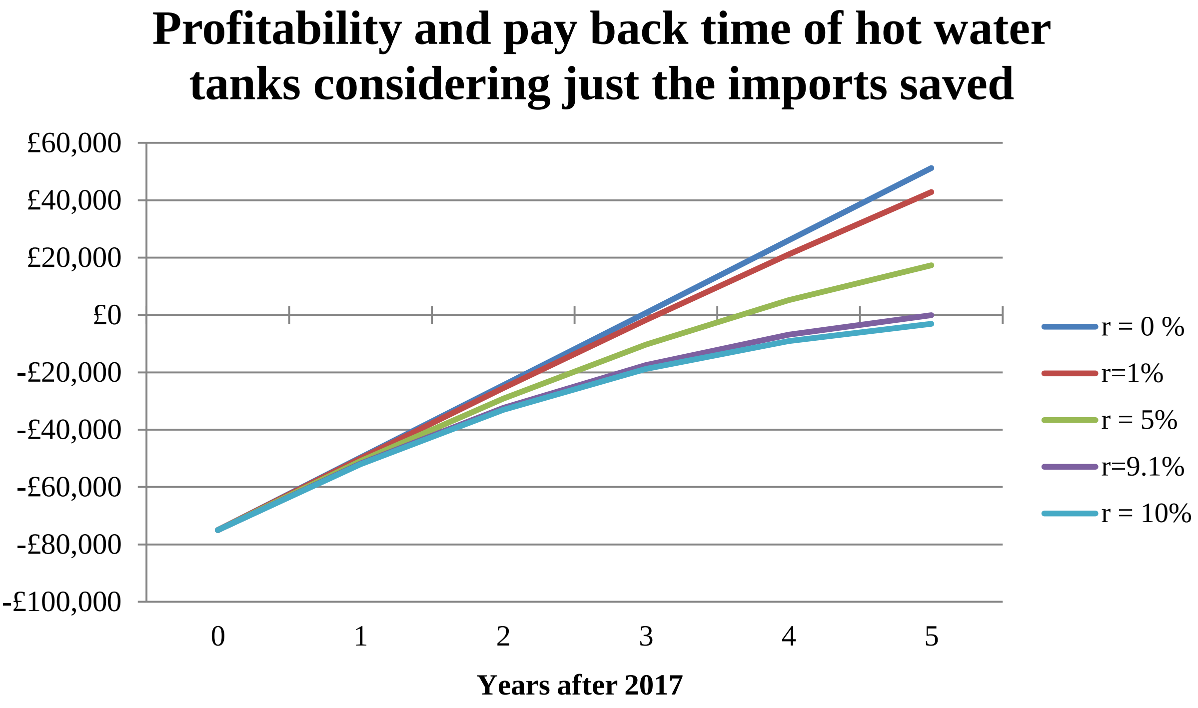


Figure 23 Profitability and return payback time of hot water tanks in the short term with different discount rates

The capital cost of the new system is £75,000 and the profit of the community per year due to the hot water tanks imports savings is £25,255. The results of the payback time of the hot water tanks just in order of the imports saved by it are shown in Figure 23. Using the DCF equation (Equation 4), the payback period for the hot water tanks taking into account just the imports saved is 2.97 years for a discount rate of 0 % and 5 years for a discount rate of 9.1 %. The total profit obtained with a discount rate of 3 % (assumed the same as in previous calculations) with a payback period of 3.1 years was £40,874 in five years.

In addition, the energy wasted has been reduced in 138,648 kWh compared with the batteries project (Tubular gel Lead acid with 100 kWh of capacity). Moreover, more FITs have been received for hot water tanks than for batteries. The total amount is £19,688 in one year and £98,440 in five (rate discount of 0 %). Therefore, the project of the hot water tanks is feasible and can generate a total profit in five years with a discount rate of 3 % of £130,000.

This amount of money added to the money generated by the microgrid is £280,000 in five years. As it has been said before, the total amount of money needed to payback the hydropower plant is an annual repayment of £150,000. In this case the microgrid project can achieve the pay back of almost two years.

- *Increment of import price*

Nevertheless, supposing the price of the imports rise 5 % or 10 % in 2017 and this price remain stable for the next 5 years, the aftermath is more advantageous. With an increase of the price of 5 %, the total profit due to the imports savings is £26,517. In this case the capital cost of the storage device would be repaid in 3 years with a rate discount of 3 % and the total profit of the project is £55,000. In case the import price increases 10 %, the savings from them are £27,780 and the years for repayment the capital cost of the tanks is 2.9 years. Therefore, the total profit is £61,000.

- *Electrical storage heater and hot water tank*

The energy wasted has been reduced to 24,411 kWh due to the thermal storage. This reduction is the biggest one compare with the other two studies made before. Therefore, more FITs have been received, £40,633.

Table 21 Money paid by the community due to imports and wasted

	Money (£)	
	Imports	**Wasted**
January	1,519.12	0.00
February	4,944.50	0.00
March	4,715.65	3.46
April	7,666.08	0.00
May	3,519.58	1,024.96
June	2,333.70	1,297.03
July	1,382.91	2,944.09
August	1,728.04	2,043.38
September	1,024.77	4,675.92
October	1,654.44	3,172.00
November	0.00	7,176.54
December	2,233.40	2,074.19
Total	32,722.18	24,411.55

The energy imported is 440,110 kWh but is assumed that just 20.5% is consumed during the day. Therefore, 79.5% of the electricity imported goes straight to the heaters and tanks at night. To calculate the price of the kWh of energy imported is necessary to multiply the amount of import by 79.5% and by the price of the energy at night (0.06 £/kWh) and by 20.5% and 0.13 £/kWh (price during the day). The average price for the imports in the original project (without energy storage system) is 0.1168 £/kWh.

The total amount of imports for the original system is the one calculated by SOTWARE1 (Table 17) instead of HOMER, in order to compare the results from the same software. The amount of imports from the original system is 380,730 kWh. The cost of it is £45,155 and the cost to import electricity in the new system is £32,722. Therefore, there is a saving of £12,433.

The capital cost of the electrical storage heaters and the hot water tanks is £351,000. The amount of money saved by imports is £12,433. The amount of money received for FITs due to the storage system is £40,633.

The storage system could not generate a profit in the 5 years term period. The capital cost of the electrical storage heaters is high in comparison with the hot water tanks. There is a gap of £133,000, with a rated discount of 3 %, to achieve at least no losses for the project (Figure 24). The microgrid project generated £155,000 pounds of benefit. Therefore, this project can be deploy but with less profitability than just the hot water tanks scheme.

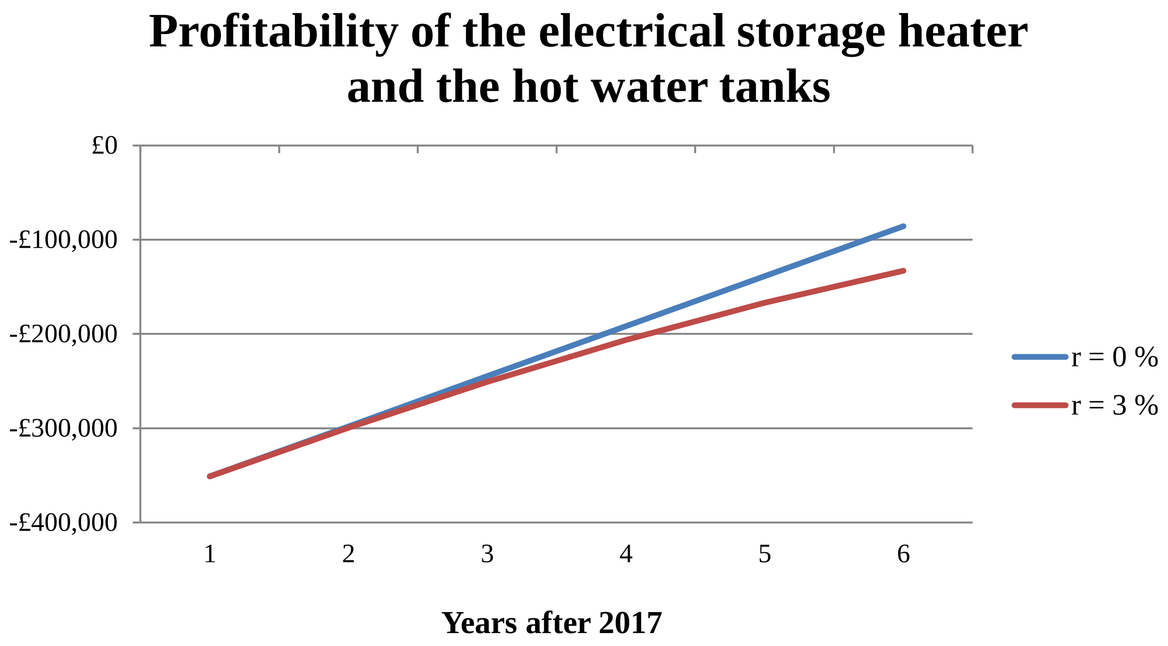


Figure 24 Profitability of the electrical storage heater and hot water tank project with different discount rates (0% and 3%)

4.2 AFTER 2021

The second scenario is without the grid restriction. After 2021 the grid will be able to take all the electricity produced by the hydropower plant. Therefore, a new study of this scenario has been necessary to determine the feasibility of the microgrid plan in the long term.

	2017-2021	**2021-future**
Situation	The surplus from the hydropower plant must be used for the community.	The hydropower plant is allowed to drawn the whole electricity production to the grid.
Economic aspect	• FITs for the energy consumed. • No FITs for the energy wasted.	• FITs for DIG in any case. • Import saving and export profit with the microgrid plan. • Export profit for the electricity sold to the grid.

It has been supposed the total surplus from the hydropower plant can be drawn to the grid or to the microgrid. This means, the total hydropower output is used and the FITs are paid for the DIG. The total amount of money generated due to FITs has been £153,928. That corresponds with 1084 MWh of hydropower plant annual output. The price of the export is 0.05 £/kWh and 0.1168 £/kWh for imports.

To compare the profitability of the microgrid the same amount of electricity supplied before 2021 by the hydropower plant to the community is assumed to remain the same after 2021. Because of the FITs are paid either for the electricity exported or the one supplied to the community, the Feed in tariff has not been taken into account in this first calculation. The calculations have been made for 20 years and the results obtained are shown in the graph below (Figure 25). The CDF equation was used for the generation of the results.

The microgrid project is profitable above a discount rate of 10 %. The profit of the microgrid project with a 0 % of discount rate is £806,500 in 20 years. The economic benefit of do not deploy a microgrid in the community has been determine lower than the microgrid, £385,000. Thus, the microgrid project has more benefits than detriments for the community.

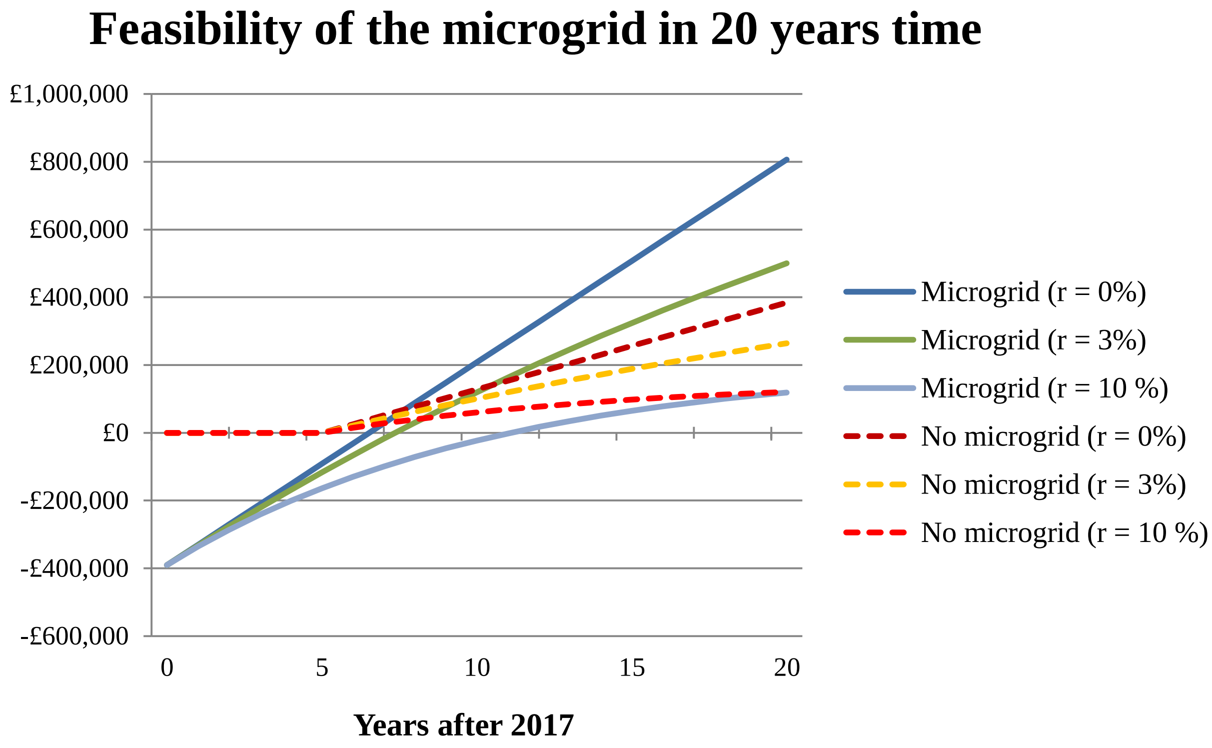


Figure 25 Feasibility of the microgrid in 20 years compare with the profit of exports the electricity

The cost of the hydropower plant was estimated in £950,000 (worst case scenario) and the payback time in 12 years (DIG, 2014). The profit due to FITs and exports in the first five years comes from the 261 MWh of electricity drawn to the grid. £37,062 is received from FITs and £13,050 from exports, in total £50,112. After 2021, the whole amount of electricity generated by the hydropower plant (1084 MWh) would be drawn to the grid. Therefore, the money earned by the community would be £208,128 without the microgrid.

The project with the microgrid after 2021 would receive the same amount of FITs than without microgrid. The profit generated by the difference of electricity supplied to the community and the one generated by the hydropower plant would be sold to the grid which incurred in more profit for the microgrid project. Therefore, the benefit from exports is (1,084,000kWh (generated) – (consumed) 512,442 kWh) £28,577. This profit has been added to the imports saved, generating £88,430. In total the profit from the microgrid project with the hydropower plant after 2021 is £242,358.

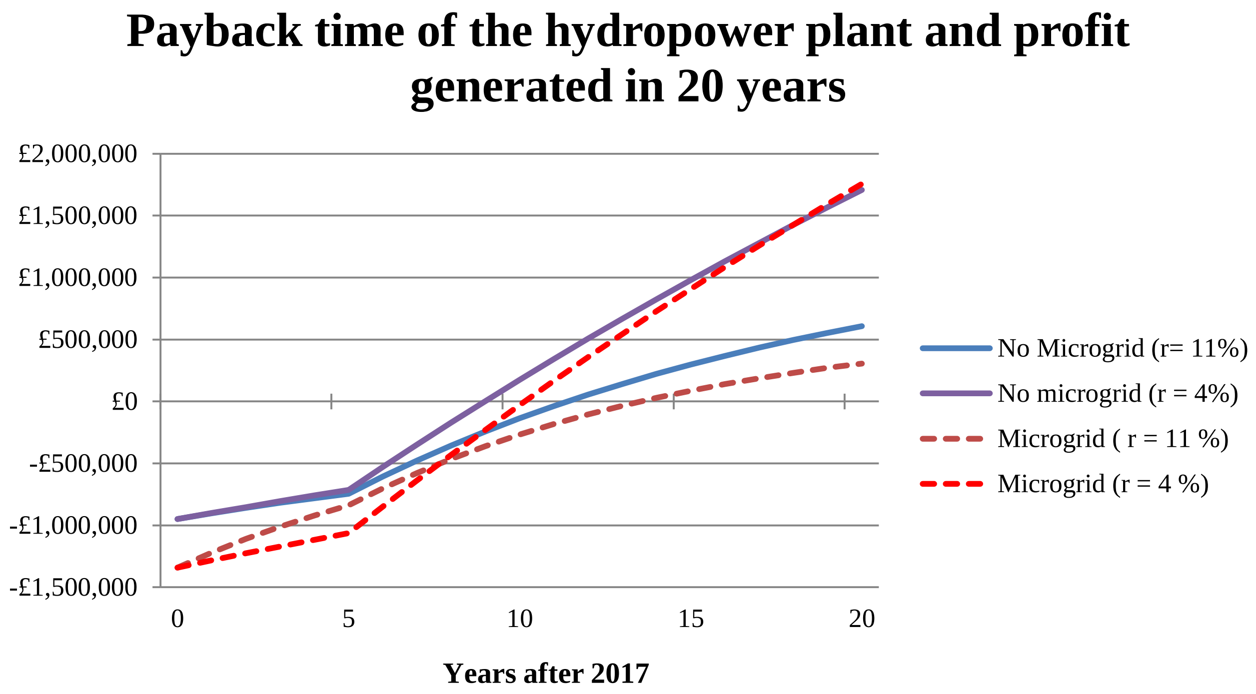


Figure 26 Payback period and profit generated by the exports and the microgrid. Rate discount obtained (r = 11 %).

The discount rate value used for DIG in the worst case scenario of the hydropower plant capital cost is 11 %. The profit generated by the electricity exported can repaid the hydropower plant in 12 years (Figure 26). The discount rate where the microgrid has obtained the same final profit than the hydropower plant without the microgrid is 5 %. Therefore, the discount rate assumed for further calculations in order to have a profit from the microgrid project is 3%. The profit generated by the microgrid is £1,757,000. This is the same profit for the hydropower plant if its discount rate were 3%. Nevertheless, further economic studies have to determine the viability of a discount rate below 5% for the microgrid project in the community of Dalavich.

4.2.1 Batteries

The batteries have different lifetime (Table 15). Therefore, it is necessary to have the full investment payback before its lifetime. HOMER has calculated the price of the converter with the size of 300 kW (90,000€) and the replacement cost (38,185€). However, the price of it varies depending of the capacity of it. Converters with 1 kW which are enough for battery capacities of 1 kWh cost £307 in total.

To calculate the feasibility of the batteries the DCF equation has been used in order to evaluate the savings and the profit of the scheme. The FITs has not been taken into account in this calculation. The total cost of the battery project is the cost of the batteries (capital cost, replacement cost and O&M) and the converter. The feasibility study has been done with the imports saved by the battery and the FITs produced by the batteries in the first five years. The discount rate used has been 3 %. The batteries with better results have been with the smaller capacities because of the high capital cost of them and the cost of the converter.

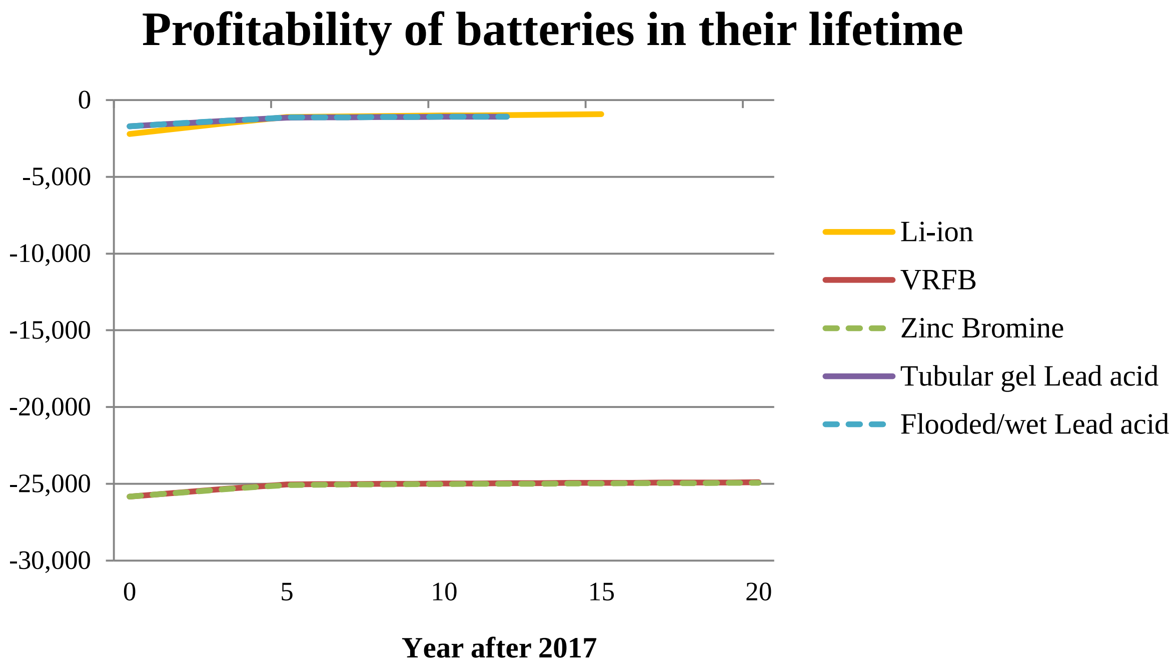


Figure 27 Profitability of batteries (1 kWh) in their lifetime. The analysis has been done with the cost of the batteries and converters as negative inputs and imports saved as positive ones.

Neither battery achieves a profit. The electricity saved from imports by them is small due to the small capacity. The battery which achieves the best result is the Li ion. The Lead acid batteries have a similar performance than Li ion but with shorter life. The worst result has been obtained for flow batteries due to their high capital cost. Therefore, the implementation of batteries in the microgrid is not feasible.

- *Increment of the import price*

An increase of 10 % has been applied to the price of the imports. The difference is small. It has been calculated an increase of 13,000% of the price of the imports to make a profitable project without FITs after 2021.

- *Reduction of battery capital cost*

A reduction of 60% in the capital cost in Li-ion batteries and 40% in Flow batteries do not generate a profit. In addition, a study taking into account the increase of the import price and the decrease of the battery capital cost with the Li ion battery, the one which has achieved the best result, does not generate a profitable project Figure 28.

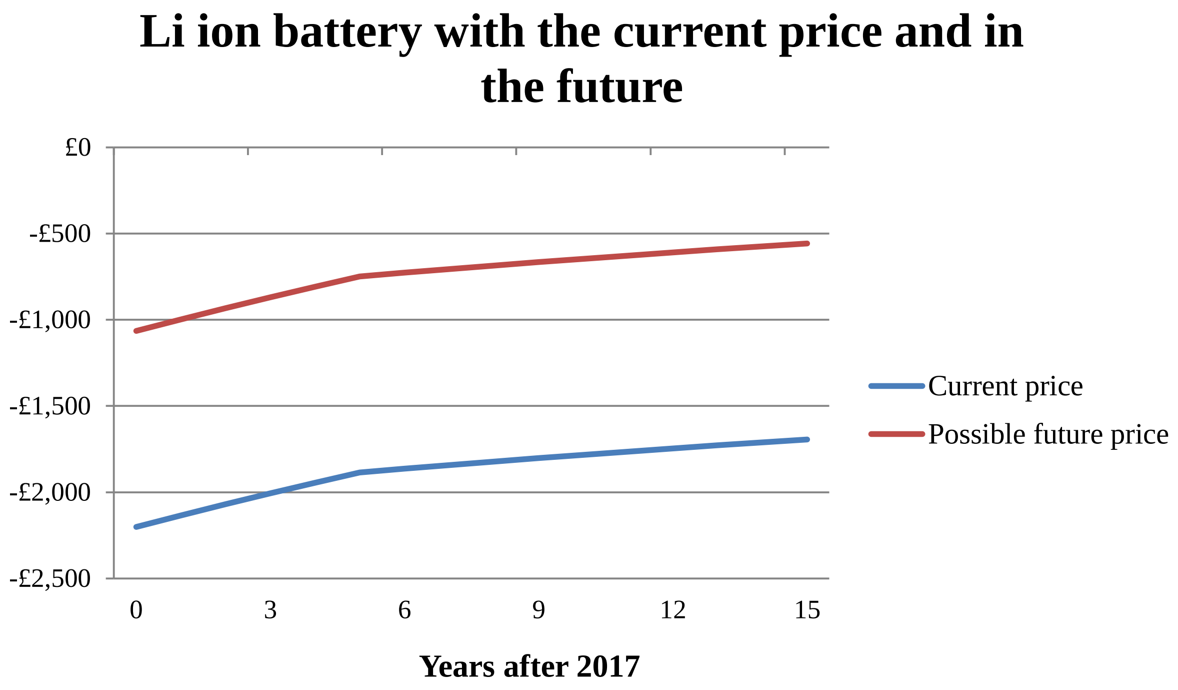


Figure 28 Comparison of the current capital cost of Li ion battery and the price of the imports with the possible decrease of the battery cost and increase of the import price (10%) in the future.

Any electrical energy storage has a feasible deploy in the community of Dalavich. Therefore, the electrical energy storage technologies are not feasible for this project.

4.2.2 Electric thermal storage

- *Hot water tank*

The lifetime of the hot water tanks has been estimated in 10 years. The FITs generated by the energy consumption of the hot water tanks during the first 5 years is £19,688. The yearly savings from the imports have been £25,255 and the capital cost of the storage device is £75,000. To calculate the feasibility of this project the DCF equation has been used. The discount rate assumed has been 3 %. The results obtained are shown in the graph below (Figure 29).

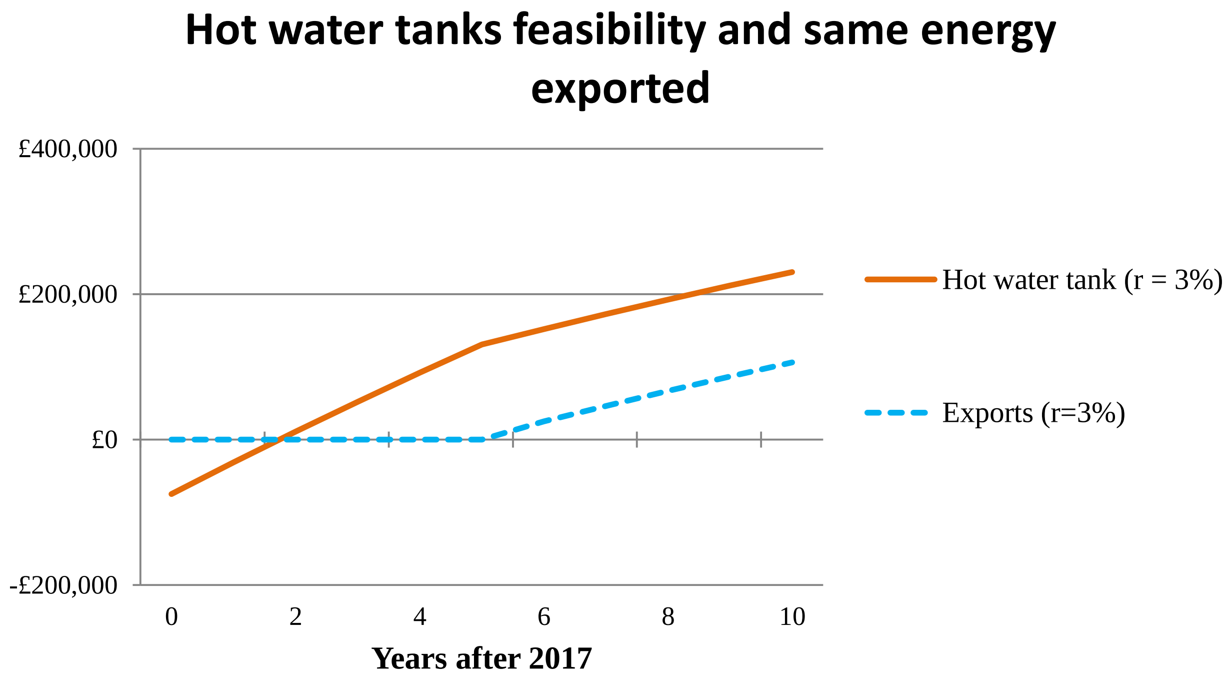


Figure 29 Hot water tank feasibility compared with the same situation without microgrid. Discount rate of 3 %.

The hot water tank project has a profitability of £230,600. It is higher than the profit obtained by drawn the same amount of electricity to the grid. The profit obtained by hot water tanks and the microgrid is £1,987,600. Therefore, implementing hot water tanks in the microgrid has increased the profitability of the microgid scheme.

- *Increment of the import price*

Although, an increase in the import price has generated even more profits for the hot water tanks, this economic benefit has just grown the total money generated to approximately £2,050,000.

4.2.3 Electrical storage heater and hot water tanks

The capital cost of the electrical storage heaters and the hot water tanks is £351,000. This system achieved the highest reduction of the energy wasted before 2021. The amount of money saved by imports is £12,433. The amount of money received for FITs due to the storage system is £40,633. The lifetime of this thermal storage system has been assumed in 20 years. The payback time for this system is 17.5 years (Figure 30).The electrical storage heater does not achieve the same profitability than hot water tanks.

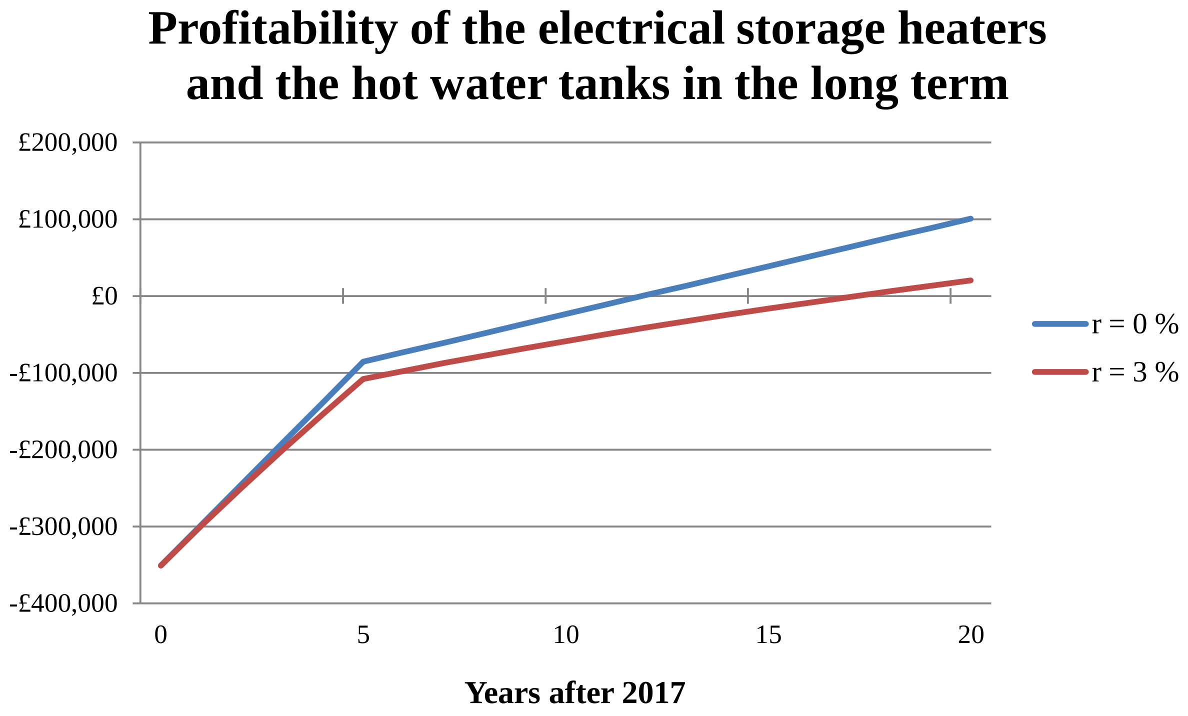


Figure 30 Profitability of the electrical storage heaters and the hot water tanks in the long term with discount rates of 0% and 3%.

The increase of the import price in 10 % has not affected to the feasibility of the project because this variable has the same effect in the hot water tank system than in the electrical storage heater. Therefore, this study has not been made.

4.3 ENVIRONMENTAL ASSESMENT

The annual electricity consumed by the community of Dalavich is the sum of the energy supplied by the hydropower plant with no energy storage system, 512,442 kWh, and the energy imported from the grid, 365,530 kWh. This amount of electricity multiplied by the CO_2 emission factor (0.523 CO_2kg/kWh) generates a total production of 459,179 kg of CO_2.

The same procedure has been done after the installation of the microgrid with hot water tanks and without it. The system selected has been hot water tanks because is the most suitable energy storage system achieved in this study. The results obtained are summarised in the table below (Table 22).

Table 22 Annual reduction of CO_2 emissions (kg) due to the hydropower plant and the microgrid

Supplier	Electricity (kWh)	CO2 emissions (kg)	% of reduction
Grid	877,972	459,179	0.00
Microgrid	512,442	-268,007	58.37
Hot water tanks	547,698	-286,446	62.38

The implementation of the hot water tanks in the microgrid has assisted to reduce in 4 % the CO_2 emissions. The total reduction of greenhouse gases emissions generated by the electricity imported from the grid has been 62.38 %.

The greenhouse gases emissions from the original heating, oil heating, has not been taken into account in this calculation. Therefore, the reduction of the pollutants is even higher than the percentage obtained.

5. RESULTS DISCUSSION

5.1 TECHNICAL RESULTS

The hydropower plant would waste 823 MWh per year if no project is developed in the community of Dalavich. The microgrid reduces more than 55 % of the electricity purchased and more than 60 % the energy is wasted. This percentage is increased due to the implementation of energy storage technologies.

The batteries have reduced the energy wasted to zero with large capacities. The electricity purchased cannot overtake a certain limit due to the hydropower plant generation. It has some long periods during the year, especially in summer, with no output when the batteries reach the full discharge. Therefore, it is necessary to import energy from the grid to meet the demand of the community during these periods.

The batteries eliminate the energy wasted with high power outputs (above 5,000 kW). A battery with the minimum power output (between 0.2 kW and 3 kW,) reaches a technical limit at a certain capacity which cannot reduce the energy imported. The curtailment is produced because the low output of the battery cannot meet the power demanded. Therefore, an increase of the capacity after this point does not generate any reduction of the energy wasted or imported. Each battery reaches this limit with different power outputs at different capacities.

Vanadium Redox Flow Battery (VRFB) is the technology which achieves zero energy wasted with the smallest capacity (72,160 kWh). The Li-ion technique is the one with the worst performance reducing the energy wasted. It absorbs the total energy surplus from the hydropower plant with 130,000 kWh of capacity. In contrast, the Li-ion battery reduces the electricity imported more than the rest and VRFB is the one with the worst performance. This happens due to the round trip efficiency. Nevertheless, an oversized battery has a low performance and it may incur in a large percentage of self-discharge.

On the one hand the less efficiency a battery has, more energy is wasted in the charge and discharge process. Therefore, more energy is necessary in the charging process of a battery and less energy is available to be wasted.

On the other hand, the less efficiency a battery has, the more energy is imported from the grid. A battery with low discharge efficiency will need more energy to meet the same load than a system with a high efficiency. Therefore, the chemical storage technology has more probabilities to be totally discharged and as a consequence more energy has to be imported from the grid.

The tool developed by myself (SOFTWARE 1) has been compared with HOMER and the results obtained by both software have been close enough (less than 5 % of difference). Although, SOFTWARE1 has to include different technical characteristics for batteries and improve the code, the results are reliable to simulate a microgrid.

The electrical storage heaters, compared with the rest of the energy storage technologies, are the one which reduces the biggest amount of energy wasted. However, it is the one with more electricity imported due to the high energy consumption. In addition, it has a high capital cost compared with hot water tanks which are the storage system which has resulted as the most feasible one for the microgrid and the community of Dalavich.

5.2 ECONOMIC RESULTS

The maximum percentage of the discount rate, variable obtained from the discount cash flow equation (Equation 4), is 5%. The profit to set up a microgrid, and the electricity exported from the hydropower plant without the microgrid, is the same in the 20 years period with this discount rate. Nevertheless, if the lifetime of the microgrid is considered longer, the percentage of the discount rate is higher.

The key element in the economic part is the money received from FITs. The restriction of the grid before 2021 makes necessary the use of the electricity curtailed in order to receive the incentive. This added to the imports saved generates the main profit of the microgrid project. In addition, the price of saving one kWh of imports is more profitable than exporting the same amount of energy to the grid. Despite this, the efficiency of the converter and the energy storage has to be considered in order to determine the actual amount of the electricity saved.

The capital cost of the batteries with the best technical result, eliminating the energy wasted and reaching the lowest limit of energy imported, is high. The cheapest capital cost battery is Flooded/wet Lead acid, almost £20,000,000 with more than 100,000 kWh of capacity. This cost is outwith the budget generated by the microgrid.

The study of the feasibility of the batteries in the microgrid, comparing their capital cost and the electricity saved from imports, has generated a significant result. The smaller the capacity of the battery is, the higher the profit generated is. The batteries increase their capital cost more than the profit generated from reducing the energy imported with the same increment of capacity. The batteries with capacities of 1kWh are the most profitable for the microgrid. However, the battery which generates the highest profit is the Tubular gel Lead acid of 100 kWh. Over this capacity the battery is not profitable. Despite of that, including the price of the converter, the cost of the replacement and the operating and maintenance cost the batteries are not feasible for the community of Dalavich.

The feasibility is not achieved either for the short term period (before 2021) or the long one (until the end of the lifetime battery). Even when reducing the price of the total cost of the batteries, 60% for Li-ion and 40% for Flow batteries, and/or increasing the price of the imports 10 % no battery became feasible.

One of the advantageous of the electrical thermal storage is the non-use of converters. Therefore, the total cost of the installation is lower. In spite of that, the capital cost of electrical storage heaters is high £276,000. However, the capital cost of the hot water storage tanks is cheaper, £75,000.

Hot water storage tanks achieve feasibility in five years due to the low capital cost. However, the electrical storage heaters become a feasible technology after 6 years, after 2021. Although the lifetime of the hot water tanks is 10 years and 20 for the heater technology, this first one is more feasible.

The profit generated with the hot water storage tanks is higher than with the electrical storage heaters and batteries because of the lower capital cost and a higher reduction of the imports. The reduction of the electricity imported is due to the demand profile balance, reducing the load during the day (high peak price of electricity) and increasing it at night (low peak price). The total profit generated by the microgrid with the hot water tanks due to the FITs generated and the energy imported saved is almost £2,000,000 in the assumed lifetime of the hot water tanks (10 years).

6. **CONCLUSIONS**

The microgrid project is feasible for the community of Dalavich. The cost of setting up the microgrid is already repaid in the first five years of the curtailment, before 2021. In addition, the profit generated after 2021 is higher than the money produced by exporting the electricity.

Although, the microgrid does not achieve an off-grid configuration for the community of Dalavich, it is more than 50 % of the time autonomous. However, the community must be connected to the grid. The month with the lowest autonomy is April.

SOFTWARE1 is a reliable to develop simulations of microgrids and energy storage technologies.

Any electrical storage technology is feasible for the community of Dalavich due to their high cost. Although the Tubular gel Lead acid of 100 kWh of capacity is the battery which has achieved the lowest loss, it is not feasible for the microgrid scheme.

Electrical thermal energy storage is feasible for the microgrid project. The most feasible energy storage technology has been achieved with hot water storage tanks. In addition, it produces some benefits for the microgrid such as balancing the demand profile and reducing the electricity imported from the grid.

The total profit generated by the microgrid and the hot water tanks reaches almost £2,000,000 in 10 years.

6.1 FURTHER RESEARCH

- Study different projects in the community of Dalavich during the curtailment period, before 2021, in order to compare the feasibility and profitability of them with the microgrid one.
- The investment risk in microgrid projects in order to decide a suitable percentage of the discount rate for similar projects.
- Investigate different energy efficiency improvements in the community of Dalavich before investing money in large projects such as better insulation in the household.

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7. APPENDIX

Appendix 1. Weekdays hourly energy demand from Dalavich community over a year.

Time	January	February	March	May	April	June	July	August	September	October	November	December
00:00-01:00	46.8	42.12	39.78	31.59	22.23	16.38	15.795	15.795	24.57	26.091	28.08	28.665
01:00-02:00	46.8	42.12	39.78	31.59	22.23	16.38	15.795	15.795	24.57	26.091	28.08	28.665
02:00-03:00	46.8	42.12	39.78	31.59	22.23	16.38	15.795	15.795	24.57	26.091	28.08	28.665
03:00-04:00	46.8	42.12	39.78	31.59	22.23	16.38	15.795	15.795	24.57	26.091	28.08	28.665
04:00-05:00	46.8	42.12	39.78	31.59	22.23	16.38	15.795	15.795	24.57	26.091	28.08	28.665
05:00-06:00	68	61.2	57.8	45.9	32.3	23.8	22.95	22.95	35.7	37.91	40.8	41.65
06:00-07:00	116	104.4	98.6	78.3	55.1	40.6	39.15	39.15	60.9	64.67	69.6	71.05
07:00-08:00	188	169.2	159.8	126.9	89.3	65.8	63.45	63.45	98.7	104.81	112.8	115.15
08:00-09:00	188	169.2	159.8	126.9	89.3	65.8	63.45	63.45	98.7	104.81	112.8	115.15
09:00-10:00	188	169.2	159.8	126.9	89.3	65.8	63.45	63.45	98.7	104.81	112.8	115.15
10:00-11:00	188	169.2	159.8	126.9	89.3	65.8	63.45	63.45	98.7	104.81	112.8	115.15
11:00-12:00	188	169.2	159.8	126.9	89.3	65.8	63.45	63.45	98.7	104.81	112.8	115.15
12:00-13:00	188	169.2	159.8	126.9	89.3	65.8	63.45	63.45	98.7	104.81	112.8	115.15
13:00-14:00	188	169.2	159.8	126.9	89.3	65.8	63.45	63.45	98.7	104.81	112.8	115.15
14:00-15:00	188	169.2	159.8	126.9	89.3	65.8	63.45	63.45	98.7	104.81	112.8	115.15
15:00-16:00	188	169.2	159.8	126.9	89.3	65.8	63.45	63.45	98.7	104.81	112.8	115.15
16:00-17:00	210	189	178.5	141.75	99.75	73.5	70.875	70.875	110.25	117.075	126	128.625
17:00-18:00	234	210.6	198.9	157.95	111.15	81.9	78.975	78.975	122.85	130.455	140.4	143.325
18:00-19:00	280	252	238	189	133	98	94.5	94.5	147	156.1	168	171.5
19:00-20:00	280	252	238	189	133	98	94.5	94.5	147	156.1	168	171.5
20:00-21:00	280	252	238	189	133	98	94.5	94.5	147	156.1	168	171.5
21:00-22:00	280	252	238	189	133	98	94.5	94.5	147	156.1	168	171.5
22:00-23:00	210	189	178.5	141.75	99.75	73.5	70.875	70.875	110.25	117.075	126	128.625
23:00-00:00	116	104.4	98.6	78.3	55.1	40.6	39.15	39.15	60.9	64.67	69.6	71.05

Appendix 2. Weekend hourly energy demand from Dalavich community over a year.

Time	January	February	March	April	May	June	July	August	September	October	November	December
00:00-01:00	51.95	46.75	44.16	35.06	24.68	18.18	17.53	17.53	27.27	28.96	31.17	31.82
01:00-02:00	51.95	46.75	44.16	35.06	24.68	18.18	17.53	17.53	27.27	28.96	31.17	31.82
02:00-03:00	51.95	46.75	44.16	35.06	24.68	18.18	17.53	17.53	27.27	28.96	31.17	31.82
03:00-04:00	51.95	46.75	44.16	35.06	24.68	18.18	17.53	17.53	27.27	28.96	31.17	31.82
04:00-05:00	51.95	46.75	44.16	35.06	24.68	18.18	17.53	17.53	27.27	28.96	31.17	31.82
05:00-06:00	70.13	63.12	59.61	47.34	33.31	24.55	23.67	23.67	36.82	39.10	42.08	42.95
06:00-07:00	116.88	105.19	99.35	78.90	55.52	40.91	39.45	39.45	61.36	65.16	70.13	71.59
07:00-08:00	163.64	147.27	139.09	110.45	77.73	57.27	55.23	55.23	85.91	91.23	98.18	100.23
08:00-09:00	187.01	168.31	158.96	126.23	88.83	65.45	63.12	63.12	98.18	104.26	112.21	114.55
09:00-10:00	187.01	168.31	158.96	126.23	88.83	65.45	63.12	63.12	98.18	104.26	112.21	114.55
10:00-11:00	187.01	168.31	158.96	126.23	88.83	65.45	63.12	63.12	98.18	104.26	112.21	114.55
11:00-12:00	187.01	168.31	158.96	126.23	88.83	65.45	63.12	63.12	98.18	104.26	112.21	114.55
12:00-13:00	187.01	168.31	158.96	126.23	88.83	65.45	63.12	63.12	98.18	104.26	112.21	114.55
13:00-14:00	187.01	168.31	158.96	126.23	88.83	65.45	63.12	63.12	98.18	104.26	112.21	114.55
14:00-15:00	187.01	168.31	158.96	126.23	88.83	65.45	63.12	63.12	98.18	104.26	112.21	114.55
15:00-16:00	187.01	168.31	158.96	126.23	88.83	65.45	63.12	63.12	98.18	104.26	112.21	114.55
16:00-17:00	210.39	189.35	178.83	142.01	99.94	73.64	71.01	71.01	110.45	117.29	126.23	128.86
17:00-18:00	233.77	210.39	198.70	157.79	111.04	81.82	78.90	78.90	122.73	130.32	140.26	143.18
18:00-19:00	280.52	252.47	238.44	189.35	133.25	98.18	94.68	94.68	147.27	156.39	168.31	171.82
19:00-20:00	280.52	252.47	238.44	189.35	133.25	98.18	94.68	94.68	147.27	156.39	168.31	171.82
20:00-21:00	280.52	252.47	238.44	189.35	133.25	98.18	94.68	94.68	147.27	156.39	168.31	171.82
21:00-22:00	280.52	252.47	238.44	189.35	133.25	98.18	94.68	94.68	147.27	156.39	168.31	171.82
22:00-23:00	210.39	189.35	178.83	142.01	99.94	73.64	71.01	71.01	110.45	117.29	126.23	128.86
23:00-00:00	116.88	105.19	99.35	78.90	55.52	40.91	39.45	39.45	61.36	65.16	70.13	71.59

Appendix 3 Hourly heating demand by holiday’s chalets in Dalavich

Time		**Demand (kWh)**											
Start	**Finish**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
00:00	**01:00**	1.58	0	0	0	0.76	0.43	0.43	0.43	0.54	0.56	0	0
01:00	**02:00**	1.17	0	0	0	0.41	0.1	0.1	0.1	0.23	0.25	0	0
02:00	**03:00**	1.42	0	0	0	0.6	0.2	0.2	0.2	0.46	0.5	0	0
03:00	**04:00**	1.73	0	0	0	0.82	0.36	0.36	0.36	0.68	0.71	0	0
04:00	**05:00**	1.86	0	0	0	0.95	0.5	0.5	0.5	0.78	0.82	0	0
05:00	**06:00**	1.91	0	0	0	1.02	0.56	0.56	0.56	0.83	0.87	0	0
06:00	**07:00**	1.93	0	0	0	1	0.49	0.49	0.49	0.85	0.89	0	0
07:00	**08:00**	2.7	0	0	0	1.55	0.9	0.9	0.9	1.49	1.55	0	0
08:00	**09:00**	3.62	0	0	0	2.01	1.21	1.21	1.21	2.12	2.22	0	0
09:00	**10:00**	2.63	0	0	0	1.25	0.72	0.72	0.72	1.4	1.48	0	0
10:00	**11:00**	1.18	0	0	0	0.63	0.47	0.47	0.47	0.75	0.79	0	0
11:00	**12:00**	0.98	0	0	0	0.41	0.31	0.31	0.31	0.54	0.58	0	0
12:00	**13:00**	0.88	0	0	0	0.29	0.22	0.22	0.22	0.44	0.48	0	0
13:00	**14:00**	0.82	0	0	0	0.24	0.2	0.2	0.2	0.38	0.42	0	0
14:00	**15:00**	0.78	0	0	0	0.18	0.14	0.14	0.14	0.34	0.38	0	0
15:00	**16:00**	0.74	0	0	0	0.16	0.11	0.11	0.11	0.32	0.36	0	0
16:00	**17:00**	0.74	0	0	0	0.14	0.1	0.1	0.1	0.32	0.37	0	0
17:00	**18:00**	0.76	0	0	0	0.15	0.1	0.1	0.1	0.37	0.42	0	0
18:00	**19:00**	2.55	0	0	0	0.8	0.41	0.41	0.41	1.22	1.33	0	0
19:00	**20:00**	3.72	0	0	0	1.14	0.46	0.46	0.46	1.63	1.79	0	0
20:00	**21:00**	3.6	0	0	0	1.14	0.38	0.38	0.38	1.56	1.71	0	0
21:00	**22:00**	3.03	0	0	0	1.17	0.52	0.52	0.52	1.45	1.57	0	0
22:00	**23:00**	2.91	0	0	0	1.32	0.73	0.73	0.73	1.47	1.56	0	0
23:00	**00:00**	2.93	0	0	0	1.49	0.95	0.95	0.95	1.54	1.61	0	0

Appendix 4 Demand profile of Dalavich with the hot water tanks

	Demand of electricity with hot water tanks (kWh)											
Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00:00-01:00	134.43	120.99	114.26	90.74	63.85	47.05	45.37	45.37	70.58	74.94	80.66	82.34
01:00-02:00	134.43	120.99	114.26	90.74	63.85	47.05	45.37	45.37	70.58	74.94	80.66	82.34
02:00-03:00	134.43	120.99	114.26	90.74	63.85	47.05	45.37	45.37	70.58	74.94	80.66	82.34
03:00-04:00	134.43	120.99	114.26	90.74	63.85	47.05	45.37	45.37	70.58	74.94	80.66	82.34
04:00-05:00	134.43	120.99	114.26	90.74	63.85	47.05	45.37	45.37	70.58	74.94	80.66	82.34
05:00-06:00	155.63	140.07	132.28	105.05	73.92	54.47	52.52	52.52	81.71	86.76	93.38	95.32
06:00-07:00	203.63	183.27	173.08	137.45	96.72	71.27	68.72	68.72	106.91	113.52	122.18	124.72
07:00-08:00	141.00	126.90	119.85	95.18	66.98	49.35	47.59	47.59	74.03	78.61	84.60	86.36
08:00-09:00	141.00	126.90	119.85	95.18	66.98	49.35	47.59	47.59	74.03	78.61	84.60	86.36
09:00-10:00	141.00	126.90	119.85	95.18	66.98	49.35	47.59	47.59	74.03	78.61	84.60	86.36
10:00-11:00	141.00	126.90	119.85	95.18	66.98	49.35	47.59	47.59	74.03	78.61	84.60	86.36
11:00-12:00	141.00	126.90	119.85	95.18	66.98	49.35	47.59	47.59	74.03	78.61	84.60	86.36
12:00-13:00	141.00	126.90	119.85	95.18	66.98	49.35	47.59	47.59	74.03	78.61	84.60	86.36
13:00-14:00	141.00	126.90	119.85	95.18	66.98	49.35	47.59	47.59	74.03	78.61	84.60	86.36
14:00-15:00	141.00	126.90	119.85	95.18	66.98	49.35	47.59	47.59	74.03	78.61	84.60	86.36
15:00-16:00	141.00	126.90	119.85	95.18	66.98	49.35	47.59	47.59	74.03	78.61	84.60	86.36
16:00-17:00	210.00	189.00	178.50	141.75	99.75	73.50	70.88	70.88	110.25	117.08	126.00	128.63
17:00-18:00	234.00	210.60	198.90	157.95	111.15	81.90	78.98	78.98	122.85	130.46	140.40	143.33
18:00-19:00	232.40	209.16	197.54	156.87	110.39	81.34	78.44	78.44	122.01	129.56	139.44	142.35
19:00-20:00	232.40	209.16	197.54	156.87	110.39	81.34	78.44	78.44	122.01	129.56	139.44	142.35
20:00-21:00	232.40	209.16	197.54	156.87	110.39	81.34	78.44	78.44	122.01	129.56	139.44	142.35
21:00-22:00	232.40	209.16	197.54	156.87	110.39	81.34	78.44	78.44	122.01	129.56	139.44	142.35
22:00-23:00	210.00	189.00	178.50	141.75	99.75	73.50	70.88	70.88	110.25	117.08	126.00	128.63

Appendix 5 Demand profile of Dalavich with the hot water tank

Heaters and water tank												
Time	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
00:00-01:00	192.29	160.88	171.15	128.28	74.36	47.05	45.37	45.37	116.04	91.35	109.56	115.13
01:00-02:00	192.29	160.88	171.15	128.28	74.36	47.05	45.37	45.37	116.04	91.35	109.56	115.13
02:00-03:00	192.29	160.88	171.15	128.28	74.36	47.05	45.37	45.37	116.04	91.35	109.56	115.13
03:00-04:00	192.29	160.88	171.15	128.28	74.36	47.05	45.37	45.37	116.04	91.35	109.56	115.13
04:00-05:00	192.29	160.88	171.15	128.28	74.36	47.05	45.37	45.37	116.04	91.35	109.56	115.13
05:00-06:00	196.64	164.80	174.85	131.21	76.42	54.47	52.52	52.52	118.32	93.77	112.16	117.79
06:00-07:00	206.48	173.65	183.21	137.85	81.10	71.27	68.72	68.72	123.48	99.26	118.07	123.82
07:00-08:00	221.24	186.94	195.76	147.81	88.11	49.35	47.59	47.59	131.23	107.49	126.92	132.86
08:00-09:00	221.24	186.94	195.76	147.81	88.11	49.35	47.59	47.59	131.23	107.49	126.92	132.86
09:00-10:00	221.24	186.94	195.76	147.81	88.11	49.35	47.59	47.59	131.23	107.49	126.92	132.86
10:00-11:00	221.24	186.94	195.76	147.81	88.11	49.35	47.59	47.59	131.23	107.49	126.92	132.86
11:00-12:00	221.24	186.94	195.76	147.81	88.11	49.35	47.59	47.59	131.23	107.49	126.92	132.86
12:00-13:00	221.24	186.94	195.76	147.81	88.11	49.35	47.59	47.59	131.23	107.49	126.92	132.86
13:00-14:00	221.24	186.94	195.76	147.81	88.11	49.35	47.59	47.59	131.23	107.49	126.92	132.86
14:00-15:00	221.24	186.94	195.76	147.81	88.11	49.35	47.59	47.59	131.23	107.49	126.92	132.86
15:00-16:00	221.24	186.94	195.76	147.81	88.11	49.35	47.59	47.59	131.23	107.49	126.92	132.86
16:00-17:00	225.75	191.00	199.59	150.86	90.25	73.50	70.88	70.88	133.60	110.00	129.63	135.62
17:00-18:00	230.67	195.42	203.77	154.18	92.59	81.90	78.98	78.98	136.18	112.74	132.58	138.63
18:00-19:00	240.10	203.91	211.79	160.55	97.07	81.34	78.44	78.44	141.14	118.00	138.24	144.41
19:00-20:00	240.10	203.91	211.79	160.55	97.07	81.34	78.44	78.44	141.14	118.00	138.24	144.41
20:00-21:00	240.10	203.91	211.79	160.55	97.07	81.34	78.44	78.44	141.14	118.00	138.24	144.41
21:00-22:00	240.10	203.91	211.79	160.55	97.07	81.34	78.44	78.44	141.14	118.00	138.24	144.41
22:00-23:00	225.75	191.00	199.59	150.86	90.25	73.50	70.88	70.88	133.60	110.00	129.63	135.62
23:00-00:00	206.48	173.65	183.21	137.85	81.10	40.60	39.15	39.15	123.48	99.26	118.07	123.82