Department of Mechanical and Aerospace Engineering

Project

Title

Using Storage to Increase the Viability of Community Energy Schemes

Author:

Apostolos Kelepouris

Supervisor:

Dr Nicolas Kelly

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Abstract

The purpose of this thesis is to investigate the potential of energy storage systems (ESS) to increase the viability of community energy schemes. Significant barriers, like grid constraints, oppose the expansion of those schemes and place obstacles to fully utilise their potential.

The possibility of energy storage use in combination with a renewable energy scheme (hydropower plant, wind power, PV power) in a community is investigated. The system is modelled and its operation principles are analysed.

A simulation tool has been developed for the purpose of this thesis after the modelling process. This tool along with a corresponding methodology are being used in practice to assess a real life project which has been cancelled and was initially planned to operate under grid constraints.

A financial approach is included in order to identify the effect of an ESS on a community's financial benefit from a renewable energy scheme.

A sensitivity analysis is carried out to provide an insight on the relation of the investigated parameters and assist in their calculation and prediction.

Finally, the results of the system's modelling and the assessment of the case study are analysed and important conclusions arise. Those conclusions give answers to the problem presented in the initial stages of the thesis.

The thesis concludes that the use of ESS in combination with a community's renewable energy scheme, under grid constraints, increases the efficiency of the overall system and reduces the impact of grid constraints.

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1 Introduction

The community energy projects have a great potential but they are still a relatively new approach in the UK [43]. This means that their benefit is not yet entirely profound and many investigations are required to provide an insight of their operation, draw some knowledge on their barriers, identify opportunities, provide solutions on issues related to those schemes and if necessary contribute to their expansion.

One of the most common barriers in the expansion of renewable energy projects in small communities is the grid constraints. In many cases, communities are situated in remote areas where the grid is either non-existent or old and weak and cannot support a local energy scheme. As a result, the potential of those areas for energy generation is not fully exploited and many renewable energy projects are being postponed until a grid upgrade is completed.

There are numerous approaches on this issue targeted on utilising the surplus power of the local generation for various activities (electric vehicle charging, wood-pellet production etc) or identifying a way of overcoming the grid constraints. One of those approaches is the use of energy storage systems (ESS).

Energy storage systems are being used in a plethora of ways and for different purposes. They can be thermal, mechanical, chemical or electrical storage systems and they can be used for charging plug-in vehicles, T&D deferral, frequency regulation etc [2],[10],[12]. Even though they have been developed and expanded significantly in some sectors (like mobile phones and laptops), there is still a long way to go before being fully utilised in electrical power systems [2],[4].

The main aspects that will be analysed and investigated in this thesis are related to the aforementioned subjects. These are renewable energy schemes for communities, issues that grid constraints pose to those schemes and energy storage systems as a possible solution to the barriers of grid constraints in communities.

2 Objectives

The purpose of the current thesis was to investigate the barrier of grid constraints on the efficient operation of renewable energy schemes in communities. As mentioned before, one of the ways of addressing this issue is by combining the local energy production with energy storage systems (ESS). The aim of this thesis was to identify the effects of an ESS on the parameters related to local generation under grid constraints. Those parameters are:

- curtailed energy,
- energy imported from the grid,
- energy exported to the grid and
- autonomy of the community.

More specifically, it was investigated whether or to what extent an ESS can overcome the grid constraints in a community. For this reason, the performance of a renewable energy system under grid constraints was compared before and after the integration of energy storage. As a final objective, the optimum storage choice was identified along with its potential to overcome the grid constraints.

The final and most significant outcome of this thesis was to provide an insight on the following problem:

'Given a community, the area's potential to generate electricity locally to support this community and significant grid constraints that oppose the full exploitation of local generation, what effect an energy storage system (ESS) is expected to have on the efficiency of the overall system'.

3 Scope and Methodology

In order to address the aforementioned objectives and reach the desirable results of the problem stated in the previous section, a suitable scope and methodology were established in order to define the necessary steps and the limits of this thesis.

The constituent parts of a community energy scheme (local generation, load demand, energy storage system and grid) were investigated and analysed in detail. This means that each part was modelled separately and all together as an interconnected system. In the modelling process the equations that describe each part and the whole system were identified and generated and the system's operation was analysed in detail. The suitable parameters that represent each one of these constituent parts were also identified and/or generated.

An algorithm depicting the previous investigation was developed. It was focused on the power exchange between each part of the system and it was used to create a tool in Excel/Visual Basic. This tool was able to simulate a community energy scheme in a typical year of operation and gave results on the corresponding parameters (curtailed energy, energy imported from the grid, energy exported to the grid and autonomy of the community).

In order to apply the previous investigation in practice, a case study was assessed that fit the objectives of this thesis. For the assessment of the case study, several energy storage options were simulated and the results were compared to the system that does not incorporate an ESS. They were also compared to a system with no grid constraints in order to investigate in depth the effect of an ESS on the system's efficiency.

A financial approach was included to identify the financial benefits that a renewable energy scheme provides for the community by taking advantage of the local generation and the current subsidies. The effect of an ESS on the financial benefits for the community was investigated as well.

Finally, based on the results of the case study, a sensitivity analysis was conducted on the particular system to assess the relation of the system's parameters and reach certain conclusions on the calculation and prediction of their values.

4 Literature Review

4.1 Storage Systems

4.1.1 Characteristics of a Typical ESS

There is a big variety of ESS with different technical and operational characteristics, suitable for different applications. In order to identify the optimum choice of the corresponding arrangement it is essential to classify the ESS according to these characteristics. The following attributes are common in every storage systems and they are essential when making a comparison between them.

Energy storage capacity

Storage capacity is the quantity that determines the size of a storage system [8]. It is measured in kWh or MWh according to the size of the storage and represents the total available energy after full charging of the storage system [9].

Rated power

Also known as available power, the rated power of an ESS represents the maximum power that can be imported to the storage system or exported from the storage system [9]. It is measured in kW or MW depending on the scale of the storage system [5],[9].

Discharge time

Discharge time is the maximum time required from the storage system to extract the energy stored [9]. It is a value that depends on the storage capacity, the power rating and the reaction time of the storage system [8]. It is measured in hours (h).

State of charge

State of charge is a value that represents the current state of a storage system. It shows how much energy is stored in relation to the system's capacity and it is usually measured in percentage values (%) of the capacity [8],[9].

Self-discharge

The self-discharge value of a storage system is a result of the imperfection of the corresponding system. During the time that the energy is stored, losses occur which are either high or insignificant depending on the storage technology and affect directly the system's available energy [8].

Efficiency

In many cases this characteristic is separated in cycle efficiency and round-trip-efficiency [8]. In its more simplistic representation it is the ratio between released and stored energy and it is measured in percentage values (%) [9].

Cycling capacity

This attribute is also known as durability but it can also be found as 'cycles'. It represents the number of times the storage system is capable of releasing the amount of energy it was designed to store [9]. Each cycle represents one charge and one discharge [9].

4.1.2 Energy Storage Classification

There are many ways to classify energy storage depending on the attributes one focuses on. One of the most popular classifications is related to the energy used in those storage systems. Thus, there are five broad categories [2]:

- Mechanical,
- Electrochemical,
- Chemical,
- Electrical and
- Thermal.

The following table demonstrates the most popular ESS and the category they belong:

Table 1: Classification of ESS according to the type of energy used

Mechanical [2],[3],[4]	**Electro-chemical [2],[3],[4],[5]**	**Chemical [2],[3],[4]**	**Electrical [2],[3],[4],[5]**	**Thermal [5]**
Flywheel energy storage systems (FESS)	Lead-Acid battery	Hydrogen (H2)	Superconducting magnetic energy storage (SMES)	Low Temperature Thermal Energy Storage
Pumped hydro storage (PHS)	Nickel–Cadmium battery (Ni–Cd)	Synthetic natural gas (SNG)	Supercapacitor energy storage system	High Temperature Thermal Energy Storage
Compressed air energy storage (CAES)	Sodium–Sulphur battery (NaS)		Capacitor bank storage	
	Lithium-ion battery (Li-ion)		Double-layer capacitors (DLC)	
	Flow battery energy storage system (FBESS)			
	Metal air battery (Me-air)			
	Sodium nickel chloride battery (NaNiCl)			

The following large scale storage systems are considered possible choices for use in power systems.

Flywheel Energy Storage Systems (FESS)

Flywheel energy storage system (FESS) belongs to the mechanical storage category and it is an electromechanical system that stores kinetic energy [4]. Its main components are: a rotating mass/cylinder, the the magnetic or mechanical bearings and a motor/generator which is mounted onto the stator [2]. The whole structure is placed inside a vacuum housing in order to reduce wind shear [4]. A typical FESS structure is depicted below.

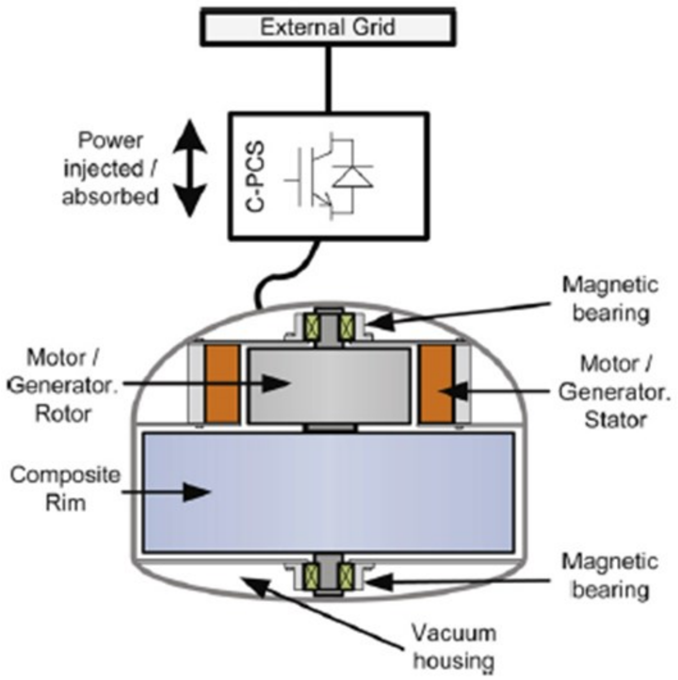

Figure 1: Topology of flywheel energy storage system [4]

In a FESS the energy is stored inside the rotating mass/cylinder (rotor) [2],[3]. In order to preserve this energy it is essential to keep the rotating mass at a constant speed [2]. The change in speed can have two results: a speed increase results to a corresponding increase in the energy stored in the rotating mass whereas a speed decrease results to energy being transferred from the flywheel storage system to the external grid [2]. Speed acceleration can be achieved by importing electricity from the grid [2]. In other words, when the FESS operates as a motor, the storage device is charged (acceleration of the rotating mass) whereas, when the FESS operates as a generator, the storage device discharges (speed decrease of rotating mass) [4].

The amount of energy that can be stored in a FESS depends on the square of rotating speed as well as on its inertia [4]. Also the materials used for the rotating disk construction are critical for the overall performance of the system and they should be lightweight with high strength [4].

There are certain advantages and disadvantages of FESS which make them useful only on certain applications. Their main advantages are their high efficiency which is around 90% at rated power, their excellent cycle stability, their broad operating range of temperature, the high power density as well as their little maintenance requirements [2],[4]. Their main drawbacks are their significantly high losses related to high levels of self-discharge because of air resistance [2],[3],[4]. In fact, the self-discharging losses can reach up to 20% of stored capacity per hour [4].

Mostly because of their drawbacks, FESS are used for short term energy storage [4]. Currently, efforts are being made to achieve energy discharge of several hours in order to utilise those systems for energy storage in vehicles or even power systems [2],[3].

Pumped Hydro Storage Systems (PHSS)

PHSS belong to the mechanical storage category, is one of the large scale energy storage systems and the only large scale technique which is widely used in power systems [2],[3],[4]. It is used mainly for the following cases: non-spinning reserve, supply reserve and energy management via time shift [2].

Its operation is based on the use of two reservoirs by managing the gravitational energy of water [4]. The following parts are used in a pumped hydro storage: upper reservoir, waterways, pump-turbine, motor-generator and lower reservoir [3].

The two reservoirs are located on a different level in order to take advantage of the gravitational energy of water [2],[3],[4]. The energy that can be stored in a pumped hydro system is directly related to the volume of water the upper reservoir can store and its height in comparison to the lower reservoir [4]. For this reason, water is pumped from the lower reservoir to the upper reservoir which is used as a storage device during off-peak hours resulting in charging of the storage system [2],[3],[4]. When the power demand is high (peak hours), the water from the upper reservoir flows to the lower reservoir in order to turn the turbines that drive the generator and produce electricity [2],[3],[4]. During peak hours the storage system discharges [2],[3],[4].

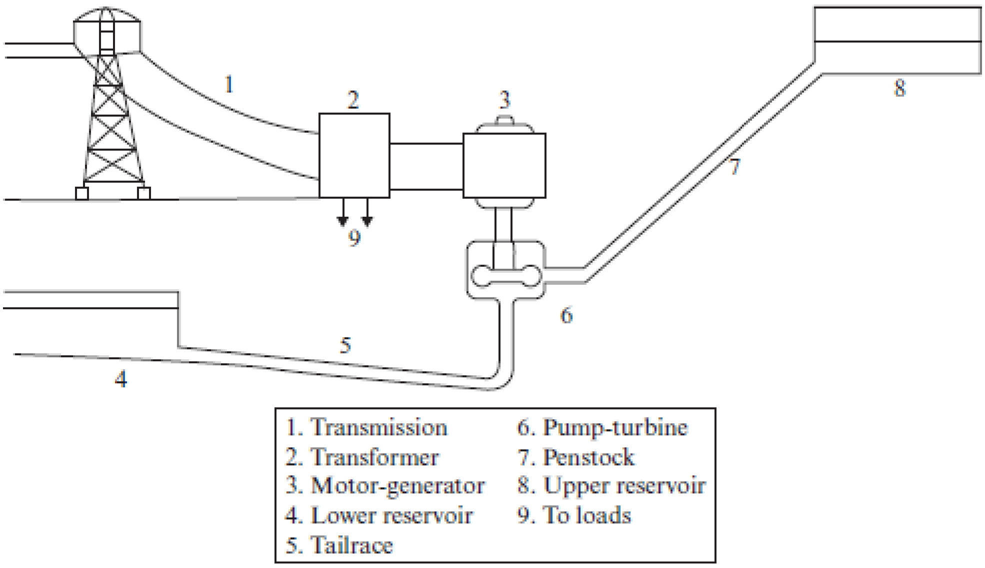

Figure 2: Pumped hydroelectric energy storage [3]

The options for the upper and lower reservoirs vary according to the application. For the upper reservoir, high dams are usually used whereas for the lower reservoir, flooded mine shafts are a common choice, other options being underground cavities or even open sea [2].

In every stage, from the hydro storage system to the energy generation there are losses that need to be taken into consideration. These losses can be: frictional losses, turbulence, viscous drag, turbine's efficiency which is always less than 100% as well as losses in the generator where electricity is generated [3]. As a result, the efficiency of a plant that utilises a pumped hydro storage system is usually between 70% and 85% [2].

The advantages of PHSS are their long lifetime as well as their practically infinite cycle stability of the whole installation [2]. Their main disadvantages are related to their specific topographical circumstances in order to be installed and work efficiently (i.e. different elevations between the two reservoirs) and they also require large space for their installation [2].

Compressed Air Energy Storage Systems (CAESS)

Compressed air energy storage (CAES) belongs to the mechanical storage category, it is based on the conventional gas turbine technology and utilises air as a storage medium [2],[4]. It is a combination of pure storage (like pumped hydro) and generating plant (conventional gas turbine) [3].

The main components of a compressed air energy storage system are: a motor, a compressor, an underground storage cavern, a recuperator, two turbines (high/low pressure) and a generator [4]. The air is compressed using electricity and stored in an underground cavern or an above ground system of vessels and pipes [2],[4]. Other options for underground storage can be aquifers or abandoned mines [2].

When there is need for electricity to be injected into the grid, an energy conversion process takes place [3]. The compressed air is extracted from the place it is stored, it is heated and expanded to the turbines where the energy enclosed in the form of compressed air is converted into kinetic energy [4]. In the next stage, the turbines turn the generators which produce electricity [4]. In the stages of expansion, in the high and low pressure turbines, the air is mixed with natural gas and combusted [2],[4]. The exhaust of the turbines is subsequently used to heat the air from the cavern [4]. The process described can be seen in the following figure.

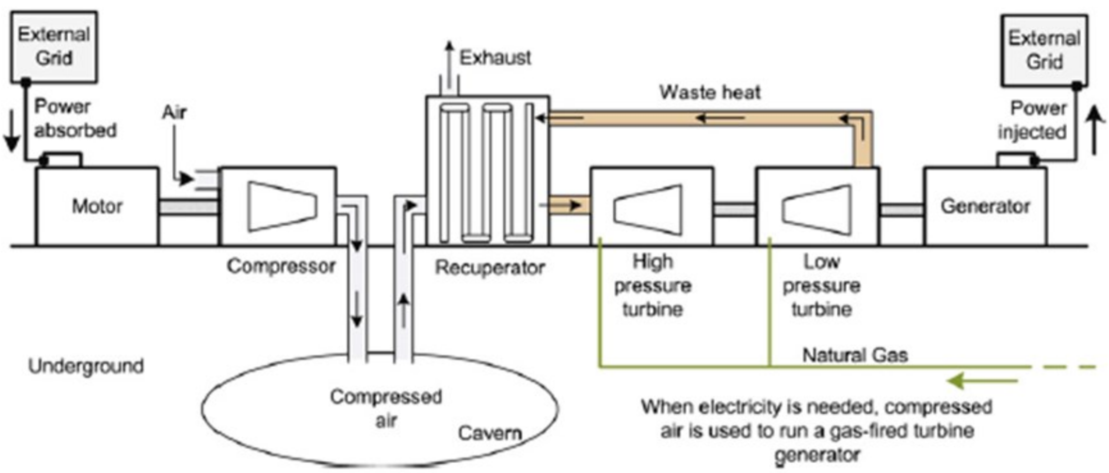

Figure 3: System description of a CAESS [4]

CAESS have a lifetime of approximately 40 years and energy efficiency of 71% [4]. The major advantage of CAESS is their large capacity and their major drawbacks are the need to use clear fuels like natural gas or distillate oil (whose prices are expected to increase in the future), the low round-trip efficiency and the fact that they require specific topographical circumstances in order to be installed [2],[3]. Finally, CAESS are considered long-term time scale installations because of the low self-discharge of the system and can compete with pumped hydro storage systems [4].

Battery Energy Storage Systems (BESS)

Battery energy storage systems (BESS) belong to the electrochemical storage category and they are one of the most commonly energy storage technologies used [4]. The electrochemical energy storage (ESS) can be briefly divided in three categories:

- primary batteries,
- secondary batteries and
- fuel cells [3].

All those categories have in common that energy is stored in the form of chemical energy and is transformed into electrical energy [3].

In primary and secondary batteries, the energy is stored in multiple cells which are connected in series, in parallel or using a combination of both depending on the voltage or the capacity that needs to be achieved in each case [4]. The main components of those batteries are: two electrodes, an electrolyte and a container. The electrolyte is placed inside the container and the electrodes are sub-merged inside the electrolyte and connected to a load [4]. Their operation is based on the exchange of ions between the electrodes when at the same time electrons flow though the circuit to the load [4]. The difference between batteries and fuel cells is that in fuel cells the chemical energy is supplied externally in the form of synthetic fuel (e.g. hydrogen, methanol etc) [2]. The difference between primary and secondary batteries is that primary batteries cannot be recharged which means that only secondary batteries have a potential of being used in power systems [2].

- Lead-Acid Batteries

Lead-Acid battery is one of the oldest and most mature electrochemical storage technology and it was invented in 1859 [4],[5]. Its main components are: stacked cells, sulphuric acid as electrolyte, a positive electrode made of lead dioxide and a negative electrode made of sponge lead [4],[5]. During the discharge process, the electrodes change into lead sulphate and the electrolyte turns into water because sulphuric ions get electrochemically bonded on the electrodes and are removed from the aqueous solution constituting the acid. [4],[5]. However, when lead-acid batteries are charged they return again into their initial state [4].

There are particular advantages and disadvantages in lead-acid batteries. Their main advantages are low cost, high efficiency (70%-90%) and high reliability [2], [5]. Their main disadvantages are decline in performance because of temperature which means that they require a thermal management system, decrease in capacity when a big percentage of power is discharged, low energy density and relatively short lifetime [2],[4],[5].

The most popular uses of lead-acid batteries include: improvement of power quality, UPS and spinning reserve applications [5]. They are divided in two categories according to the applications they are used: mobile and stationary with the latter having higher cost [2]. The main applications include: starter devices in vehicles, emergency power supply systems, mitigation devices of output fluctuation in wind power systems as well as stand-alone systems with PV panels [2]. However, their use in energy management is limited because of their short life-cycle (500-1000 cycles) and their low energy density [5].

- Lithium-ion Batteries (Li-ion)

Lithium-ion (Li-ion) battery belongs to the electrochemical energy storage category. Its main components are: a cathode made of lithiated metal oxide, an anode made of graphitic carbon and the electrolyte which is made of lithium salts [5]. During the charge process, atoms in the cathode get charged and are transformed into ions that travel through the electrolyte to the anode where their positive charge merges with external electrons and they 're-turn' into lithium atoms [5]. This process is reversed during the discharge of the battery [5].

Li-ion batteries have some major advantages as well as some disadvantages which make them applicable in certain situations and pose limitations to their expansion. They have a very high efficiency compared to other batteries which ranges between 95% and 98% and their discharge time ranges from seconds to weeks [2],[5]. Their main drawback is the relatively high cost because of the special packaging required and the internal overcharge protection circuit [2],[5].

Because of their increased cost, Li-ion batteries are mostly used in small applications like mobile phones, laptops and other portable electronic devices [2],[4]. Also they have been used to slightly bigger scale applications like electric bicycle and electric cars [4]. Since Li-ion batteries are still expensive, they can only compete with lead-acid batteries in applications that require short discharge time and there are significant challenges that need to be overcome in order to be applicable in large scale utilities [2],[5].

- Sodium Sulphur Batteries (NaS)

Sodium sulphur (NaS) battery belongs to the electrochemical energy storage category. Its main components are: liquid sulphur at the positive electrode, liquid sodium at the negative electrode and electrodes are separated by a solid beta alumina ceramic electrolyte [2],[5]. NaS battery requires a temperature between 300 ^{0}C and 350 ^{0}C in order to retain the electrodes molten [2],[4],[5]. The electrolyte allows the positive sodium ions to be transferred through it to the cathode where they are combined with sulphur and form polysulphides [5]. During the discharge process, when positive Na^+ flow through the electrolyte, electrons flow through the external battery circuit which produces a voltage of 2V [5]. During the charging process, the whole procedure is reversed [5]. The following pictures depicts the previous description.

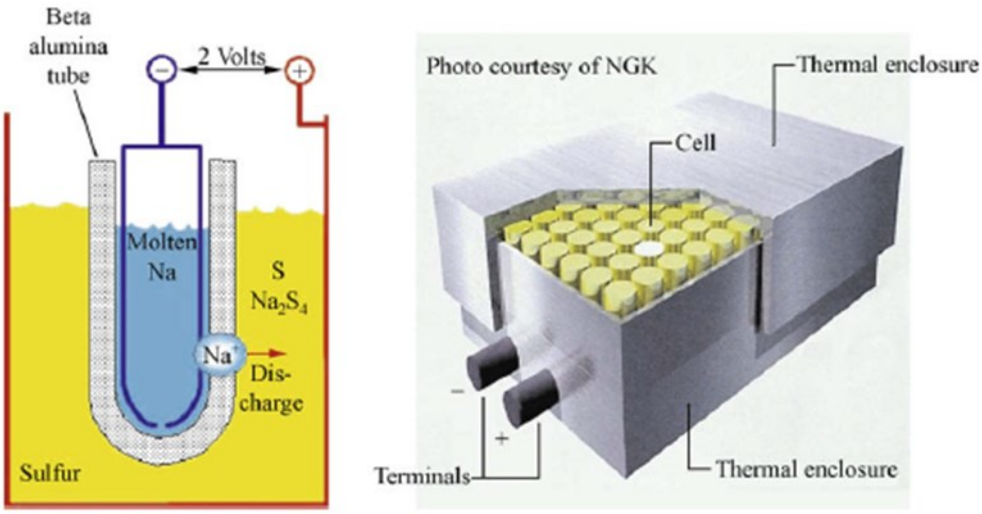

Figure 4: NaS battery [5]

There are particular advantages and disadvantages in NaS batteries. Their advantages are: no self-discharge feature, low maintenance requirements, the fact that they are 99% recyclable, they are relatively efficient (around 75%) and have fast response [2],[4],[5]. Their most significant drawbacks are: a heat source is required to retain the battery's high temperature and it uses the battery's own stored energy to achieve that, thus reducing slightly the battery's performance [2],[5]. They also have a high initial capital cost but it is expected to drop in the future [5].

NaS batteries are considered a popular option for high power energy storage applications due to their high efficiency and fast response [2],[4]. Because of the fact that their response time is in the range of milliseconds and that they also meet the requirements for grid stabilisation, the technology of NaS batteries can be used for utilities and generally large consumers [2].

- Flow Battery Energy Storage Systems (FBESS)

FBESS belong to the electrochemical energy storage technology. Their operation principle is based on dissolved electroactive species contained in an electrolyte that flow through a power cell/reactor where the chemical energy is turned into electricity [2],[5]. The additional electrolyte is stored externally inside tanks and it is pumped through the electrochemical cells of the reactor [2],[5]. The cells are connected in series, parallel or using combination of both according to the desired voltage level [4]. The whole process is reversible which means that flow batteries can be charged, discharged and recharged [2],[4],[5]. The following figure shows the main components of a flow battery.

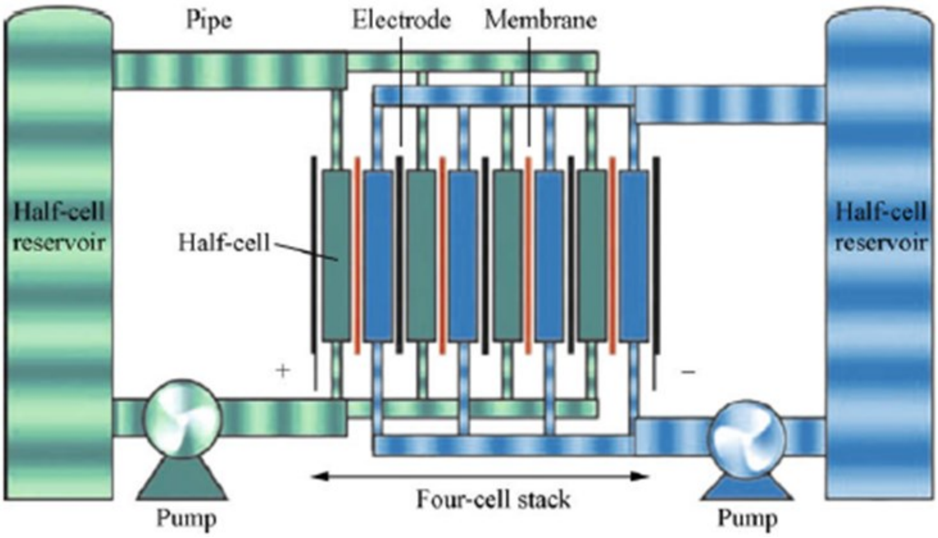

Figure 5: Schematic of a flow battery [5]

In FBESS power and energy are independent and their values depend on different parameters. The power of a flow battery is defined by the size and design of the battery whereas the energy is defined by the size of the tanks (or else the quantity of the electrolyte) [2],[5].

There are particular advantages and disadvantages in flow batteries. They can release energy continuously for up to 10 hours and they can store energy for hours or days with a power that reaches up to several MW [2],[5]. Moreover, they have very low self-discharge and they can become fully discharged without risk of damage [4]. As a result, flow batteries are considered storage systems with low maintenance and long life, capable of storing energy for long periods [4]. Their major drawback is the operating cost which is due to the need for controlling the electrolyte's flow and the pumps' operation [4].

Flow batteries are distinguished in two categories: redox flow batteries and hybrid flow batteries [4].

Hydrogen-based Energy Storage Systems (HESS)

Chemical energy storage may refer to storage of hydrogen, synthetic natural gas or any other synthetic fuel which are produced when there is excess energy production and are stored for use when there is need for peak energy generation [3].

Some of the most common ways to obtain hydrogen is by means of water electrolysis, renewable energies (wind or solar), gasifying biomass, large hydro-plants, base-load nuclear or coal-fired power plants [2],[4]. There are various approaches for hydrogen storage: compressed gas, chemical compounds, liquid hydrogen (very low temperature) and metallic hydrides [2],[3].

However, hydrogen is only the medium, which means that a hydrogen storage system also requires a power transformation system and a central store [3]. A typical hydrogen storage system consists of the following components: an electrolyser, a hydrogen storage tank and a fuel cell [2],[4]. During the charging procedure (off-peak hours), hydrogen is produced by an electrolyser which splits water into hydrogen and oxygen (the latter being released in the atmosphere) using electricity [2],[3]. Hydrogen is then stored under pressure inside the storage tank and can be used for peak energy generation [2]. In order to produce electricity (discharge procedure), both gases, hydrogen and oxygen (the latter being produced from the armosphere this time), flow into the fuel cell where a reverse electrochemical reaction takes place [2],[3]. The products of this reaction are water, heat (which is released) and electricity [2].

There are particular advantages and disadvantages in hydrogen-based storage systems. Hydrogen storage and generally chemical energy storage is the only technology that allows energy to be stored in large quantities (up to TWh range) and for great amount of time (seasonal storage) [2]. Chemical energy storage has practically zero self-discharge which is the main reason of its use as seasonal storage [4]. Finally, their lifetime is over 15 years and 20,000 charge and discharge cycles [4]. The major drawback of these systems is the low efficiency because of the low efficiencies of the electrolyser and the fuel cell [2],[4].

The hydrogen-based energy storage systems can achieve high energy (more than 100 MWh) and high peak power (more than 10 MW) which make them appropriate for stationary applications [4]. Other applications (besides fuel cells) include: gas motors, gas turbines, as well as combined cycles of gas and steam turbines for power generation [2]. Particularly, hydrogen storage in combination with fuel cells (less than 1 MW) or gas motors (less than 10 MW) can both be used for combined heat and power generation in decentralized applications [2]. On the other hand, hydrogen storage in combination with gas and steam turbines (several hundred MW) can be used as peaking power plants [2].

Superconducting Magnetic Energy Storage Systems (SMESS)

SMESS belong to the electrical energy storage technology. Their operation principle is based on storing energy inside a magnetic field which is created by a DC current which passes through an inductor (coil) [2],[3],[4],[5]. The main components of such a system are: a superconducting unit, a cryostat system and a power conversion system [5]. The coil is made of a superconducting material whose temperature is retained below its superconducting critical temperature with the help of the cryostat system [5]. The cryostat system is composed of a cryogenic refrigerator and a vacuum-insulated vessel [5]. The coil is placed inside liquid helium which is contained in the vacuum insulated vessel [5]. The power conversion system is used to convert the DC current generated by the SMES into AC so that it can be coupled to a constant voltage AC power system [3]. The following figure demonstrates the main components.

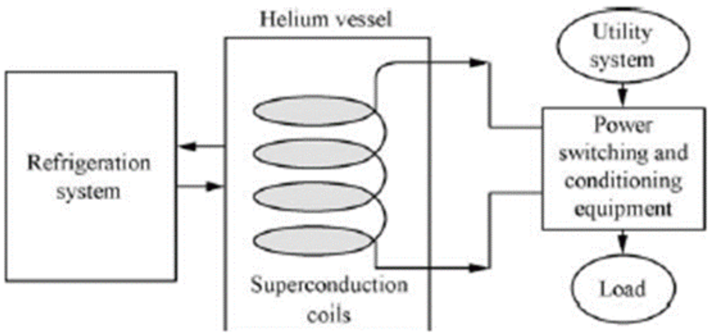

Figure 6: SMES system [5]

The amount of energy that can be stored inside a superconducting magnetic energy storage system is the product of the self-inductance of the coil and the square of the current: $E=0.5LI^2$, where L is the inductance of the coil and I is the current which passes through it [5].

There are particular advantages and disadvantages in SMESS. They have high energy storage efficiency (>97%), they are able to inject and absorb energy in a very short time (milliseconds), their losses are negligible and they have long life cycles with tens of thousands of cycles [2],[3],[4],[5]. They can also provide a high power output but only for a short period of time [2]. Their major drawbacks are related to their high installation cost and the environmental issues that may rise because of the strong magnetic field [5].

Because of their high cycle life, SMESS are suitable for applications that require constant, full cycling and continuous operation [5]. For this reason, they are appropriate for voltage stability and power quality for large industrial customers [5]. The typical storage is around 1 to 10 MW but there also applications of 10 to 100 MW which are mostly used for physics experiments [2],[5].

Cryogenic Energy Storage Systems (CESS)

CESS belong to the thermal storage systems category. Their operation principle is based on the electricity generation with the use of stored cryogen (liquid air or liquid nitrogen). The main components of a cryogenic energy storage system are: a liquefaction plant, liquefied and cold-air reservoirs and a power recovery plant [7]. Cryogen is generated during off-peak hours when electricity is cheap and demand is low, in the liquefaction plant [5],[6],[7]. It is then stored inside the cold-air reservoirs (cryogenic tanks) at temperature close to the atmospheric [6],[7]. During peak time, liquid cryogen is heated by exploiting the heat from the surrounding environment and then superheated, using other heat sources, thus creating a high pressure gas [5],[6],[7]. This gas expands in a series of expansion turbines which drive synchronous generators and generate electricity [5],[6],[7]. The following figure demonstrates the main components and the procedure.

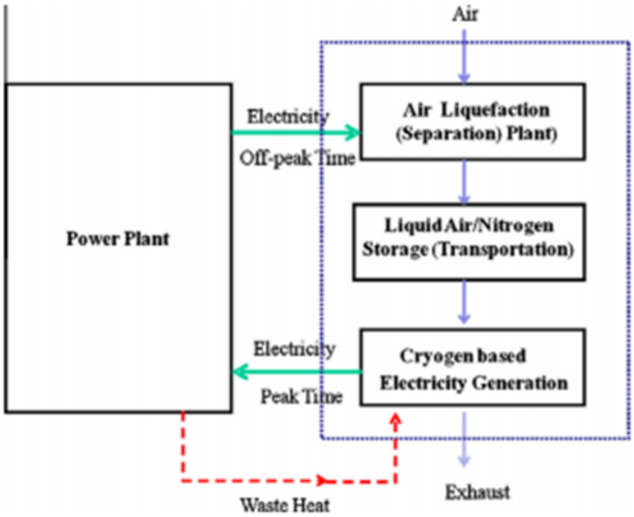

Figure 7: Schematic diagram of a CES system [6]

There are particular advantages and disadvantages in cryogenic energy storage CESS. The heat-to-power conversion in energy extraction process is highly efficient and the CES reservoir is significantly inexpensive and does not occupy much space because of the high energy density [6],[7]. The main drawback is that the CESS have relatively low efficiency (40-50%) [5].

4.1.3 Classification According to Application Type

In order to assign the most suitable ESS to the corresponding application it is essential to identify the uses of energy storage and its potential to address various application types. There is a huge variety of energy storage choices, whether it is related to the point of connection or the issues that the storage is meant to address in each application.

After identifying the basic storage characteristics (capacity, power rate, state-of-charge etc) that assist in the initial comparison between them, classifying the storage systems according to the energy they use and analysing the most important systems in each category, it is crucial to classify them according to the various applications they can address.

Power Quality

Possible causes of disturbance in the smooth operation of a power system that result in poor power quality are: presence of harmonic signals, spikes or instantaneous low voltages, transience in supply voltage and poor electric system grounding [10],[12],[14]. Unwanted harmonic signals are injected because of power converters used in combination with photovoltaics and wind power [14]. Moreover, brownouts are usually caused by the reconnection of wind turbines, and spikes can be caused by solar power due to sudden and unexpected interruption like clouds or objects that cast shadows on the panels [14]. Finally, wind turbine oscillations due to wind variation result in significant issues in power quality [14]. The usual results are loss of work output and instability in transmission lines [12].

The ESS that can possibly address those issues require high cyclability and fast response rates [14]. The most suitable storage systems for this purpose are: super-capacitors (or ECs), SMESS, flywheels, batteries (excluding conventional lead-acid batteries), flow batteries and fuel cells [11],[12],[14]. The most appropriate point of connection for a storage system is the distribution level where transient fluctuation of power can disrupt the smooth operation of many industrial or commercial customers [10].

Frequency Regulation

Frequency regulation is related to the deviation of the normal operating frequency because of the mismatch between supply and demand [10],[12]. This mismatch is usually caused by high penetration of wind power (or generally intermittent renewable generation) which in this case is the result of sudden reduction in wind power supply [10]. This deviation can possibly cause damage to equipment, tripping of generating units, shedding of loads or in some cases it can cause a whole system to collapse [10],[12].

This imbalance between supply and demand can be addressed with the use of ESS which could make up for a sudden reduction in supply [10]. In order to achieve frequency stabilisation, a chosen energy storage system needs to be able to discharge power in a short amount of time in order to meet the demand, thus providing power for a short period in order to retain the frequency as close to its nominal value as possible [10]. The most appropriate ESS for this type of applications, which require fast response and power delivery for a short duration, are ECs, flywheels, SMES, batteries and flow batteries [10],[12],[14].

Load Following

Intermittent power supply, most of the times, fails to match demand because of its stochastic power generation [10],[11],[12]. Supply peaks during weekdays between 9 a.m. and 5 p.m. and when it is not matched with renewable generation it results to economic and technical problems [10],[12]. The technical problems may affect the whole power system because mismatch between supply and demand leads to frequency and voltage variations [11],[12]. A load following strategy with storage has the potential to address this issue effectively. Power is stored when the generation is at peak and is released to the load when demand is high in a controlled manner [10],[12].

For this application type, a suitable storage system needs to be able to provide power in the scale of minutes to hours and it needs to be able to store big amounts of energy during off-peak periods of demand [10],[11],[12],[14]. For this reason, the most appropriate ESS are PHS, CAES, batteries, flow batteries and hydrogen based storage systems [10],[11],[12],[14].

Peak Shaving

This application type of energy storage aims to reduce the cost of electricity. The strategy is to store energy during off-peak hours when the cost of electricity is significantly low and discharge energy during peak hours, thus saving money by utilizing the cheap stored energy [11].

For this reason, the energy storage system operates within the time frame of 1-10 hours [11]. The most suitable technologies are: batteries, flow batteries, CAES, HESS and PHS [11].
The following table demonstrates the previous description of the application types of ESS and the corresponding technologies for each application.

Table 2: Classification of energy storage systems according to the type of application

Classification According to Application Type		
	Time Range	**Appropriate Technologies**
Power Quality	Seconds to minutes (short discharge time) [1]	ECs, SMES Systems, Flywheels, Batteries (excluding conventional lead-acid batteries), Flow Batteries, Fuel Cells
Frequency Regulation	Seconds to minutes (short discharge time) [1]	ECs, Flywheels, SMES, Batteries, Flow Batteries
Load Following	Minutes to hours (medium discharge time) [1]	PHS, CAES, Batteries, Flow Batteries, Hydrogen Based Storage Systems
Peak Shaving	Hours (medium discharge time) [1]	Batteries, Flow Batteries, CAES, HESS and PHS

4.1.4 Discharge Time

In the previous review, the discharge time was initially introduced as a means to categorise energy storage according to the energy used and the application type. In combination with the application which requires energy storage, it is essential to determine the suitable discharge time that would give the desirable result.

Two are the factors determining the time frame of discharge time: power density and energy density [1]. Power density refers to the ability of the ESS to provide instantaneous power which means that a high value of power density corresponds to a large amount of power being discharged instantly [1]. On the other hand, energy density refers to the ability of the storage system to provide energy continuously [1]. In most cases, an ESS with high power density has a low energy density and vice versa [1].

The following table depicts the classification of ESS according to their discharge time.

Table 3: Classification of energy storage systems according to their discharge time [1]

Classification according to discharge time	
Short discharge time (seconds to minutes)	DLCs, SMES, Flywheels
Medium discharge time (minutes to hours)	Batteries (lead acid, lithium ion, sodium sulphur), Flywheels
Medium-to-long discharge time (hours to days)	PHS, CAES, RFBs
Long discharge time (days to months)	Hydrogen, SNG

4.1.5 Connection Point of Storage

From the review of storage so far, it is obvious that the variety of ESS is vast. The choices given vary significantly in every sector whether they are related to the energy used, the storage capacity, the application type or the operation principles of the corresponding system. Depending on the purpose of the storage integration, ESS can provide a variety of application solutions throughout the entire electricity value chain.

The traditional electricity value chain consists of five distinct parts: the fuel/energy source, the generation, the transmission, the distribution and finally the customer/demand side [5]. Each one of these "chain links" requires different treatment and not every storage option is suitable to address the issues that rise in each case.

<u>Generation Side</u>

The purpose of the generation-side ESS is to transform the intermittent nature of renewable generation into a controllable and predictable one [1],[13]. The generation side uses of the ESS are:

Time shifting: energy stored whenever the generator produces it and discharges this energy when it is required [1],[13].

Output smoothing/flattening: even in the case when the renewable generation produces energy when it is needed, ESS can be used to smooth the overall power output by minimizing fluctuation in frequency and voltage [1].

Transmission utilization efficiency: The renewable energy generation is mostly dependent on the location [1]. As a result, it is not always possible to move energy to loads especially when the transmission lines are congested [1],[13]. ESS can assist the transmission of energy to loads by temporarily storing the energy and injecting it when congestion has cleared [1],[13].

Grid Side

The grid-side use of ESS has the widest range of applications and it carries the responsibility to provide flexibility and to mitigate variability and uncertainty for the entire grid [1].

The tasks of ESS on the grid side of the electric power system vary and depend on the needs of the grid operator. Briefly, those roles are: time shifting, seasonal shifting, load following, power quality, frequency regulation, spinning reserves, supplemental reserves, efficient use of transmission network, isolated grid support and emergency power supply [1].

Demand Side

The applications of this type of storage are related mostly to the needs of the consumers and the smooth integration of renewable generation [1]. The demand side consists of commercial and industrial customers as well as small scale loads (houses) [13]. The purpose of storage in those cases is to provide power quality and reliability (mostly to commercial customers), reduce time of use (TOU) energy charges, shift retail load to reduce time of use (TOU) energy and demand charges and finally provide backup power for home offices with high reliability value [13].

4.2 Community Energy

4.2.1 Introduction

Community energy is a term referred to the collective action of community members to generate, reduce, purchase energy and generally be responsible of the management of a local energy scheme [17]. A community can be a small city, a town, a village or even a smaller group within one of those regions. A project is characterised as a community energy project when the community controls its operation and benefits from its outcomes [17].

Not every renewable energy technology is applicable in every community. It is essential to assess the potential of the area before deciding on the most suitable technology [15]. There are three broad categories of renewable projects which are appropriate for communities regarding the type of energy they generate. If the project is intended to produce electricity then the available renewable technologies are hydro, solar and wind [16]. If the purpose of the project is to produce heat for the community then heat pumps is the most suitable technology [16]. Finally for the combined generation of heat and power, the most suitable technologies are biomass and energy from waste [16]. In any case, the combination of the previous technologies can give variable results depending on the type of application.

This project focuses mainly on the aspects of electricity generation from renewable sources to support a community, the intermittent nature of renewable energy and its effects on the viability of a corresponding project. For this reason, the technologies that will be analysed are run-of-river hydro schemes, solar power and wind power.

4.2.2 Run-of-river Hydro

Hydro power is one of the oldest and most well established renewable energy technologies with the first applications being established over 2000 years ago [15]. The development of the modern hydropower dates back in 1827 in France where the water turbine was initially invented and the first large scale application for the production of electricity took place in 1880s [18].

Small scale hydroelectric power schemes are in most cases ‘run-of-river’ [20],[22]. However, there is no internationally acclaimed definition of “small” even though there is a division of this term in three categories:

- small hydropower (in most cases the upper limit is 10 MW capacity),
- mini hydropower (usually <2 MW capacity),
- micro hydropower (commonly <500 kW capacity) [15],[18],[19],[22].

There are two major factors that define the output of a small scale hydroelectric power plant, the water flow and the height of the head [18]. The magnitude of water flow depends on the area’s annual precipitation and the height of head depends mainly on the area’s topography [18]. The major characteristic of such a scheme is the lack of dam or generally storage which means that its operation is based on water which is diverted from the local river [19],[21].

The main parts of a typical run-of-river hydroelectric plant are classified in two broad sections: civil works and electromechanical equipment [21]. Civil works consist of: the diversion weir and intake from which a quantity of the river’s water is diverted, the desilting chamber where water is slowed down so that impurities are separated, the headrace channel through which water flows to the forebay where water is filtered from trash that might damage the turbine, the penstock which leads the filtered water to the powerhouse building and finally the tailrace which will lead the water again back to the river [18],[21],[22]. Electrochemical equipment consists of: the turbine which is turned from the flowing water and the generation which produces electricity and is accompanied by an excitation system, a switch gear and control and protection equipment [18],[21],[22]. The following picture demonstrates the main components described above.

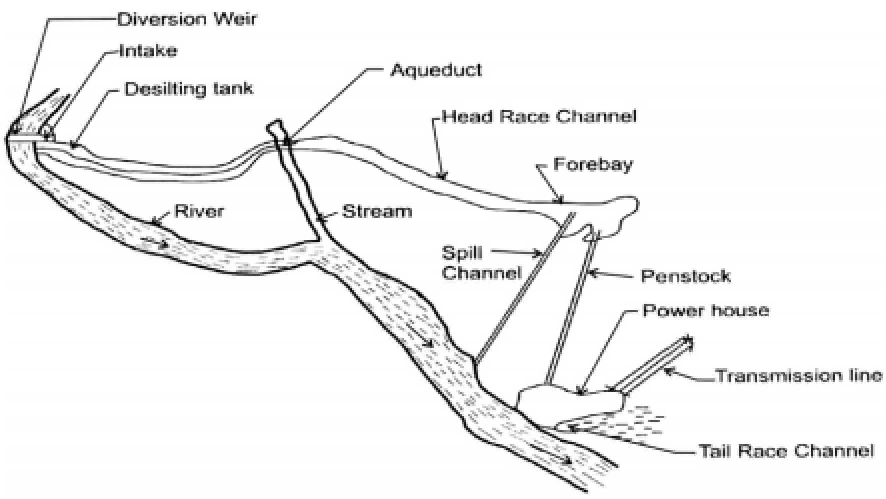

Figure 8: Layout of a typical run-of-river hydroelectric scheme [21]

As previously described, the turbines in a hydroelectric plant convert water pressure into mechanical power on the shaft which drives a generator to produce electricity [22]. The general formula of the power output for any hydroelectric plant is:

$$P = n \times \rho \times g \times Q \times H \quad (4.1)$$

where P is the mechanical power produced at the turbine shaft (W), n is the hydraulic efficiency of the turbine, ρ is the water density (kg/m^3), g is the gravity acceleration (m/s^2), Q is the volume flow rate of the water that passes through the turbine (m^3/s) and H is the height of head (m) [18],[19],[22].

During the 20^{th} century, because of the rapid development of hydropower, the efficiency of turbines reached almost 100% [18]. Typically, the larger the turbine the higher its efficiency [18]. In numbers this means that turbines that produce several hundred kW have efficiency above 90% whereas turbines that produce around 10 kW have efficiency between 60% and 80% [18].

The two main types of generators that are being used in small hydroelectric schemes are synchronous and asynchronous [18]. Synchronous generators have higher efficiency but are more expensive than asynchronous [18]. As a result of the significantly high efficiencies of the generators (98%-99%), the overall efficiency of small hydro plant depends on the efficiency of the turbine [18].

4.2.3 Solar Power

The market of the photovoltaic (PV) systems has grown significantly during the last few years as a result of the current recognition that fossil fuels cause significant damage to the environment and also due to national and international programmes that raise awareness and promote sustainable energy generation [23], [26]. However, the solar photovoltaic power is not a recent technology development. The initial relation between light and electricity was demonstrated by Becquerel in 1839 and the first solar cell based on silicon was created by Bell Labs in 1955 [18].

In general, the applications of solar photovoltaic systems can be separated in two broad categories: grid-connected and stand-alone [25]. The grid-connected PV systems can also be separated in building-integrated applications and grid-support power whereas the stand-alone systems can be sub-divided to industrial and domestic applications [18].

Grid connected PV systems consist of: one or more PV modules, one or several inverters that transform the DC power from the modules to AC power, cabling, a mounting structure and they are connected to the grid through an inverter [25]. In those applications, the electricity can either be used immediately or sold to the grid [18]. Also power can be bought back from the grid when the PV system is unable to produce electricity in which case the grid acts as a power storage system [18].

Stand-alone systems are mostly used in cases where the area or the community is not easily accessible or the connection to the grid is uneconomic [18]. Those systems consist of one or more PV modules, a battery for energy storage, cabling, mounting structure and a charge controller [25]. An inverter can also be used to convert the DC current to AC where necessary [18].

It is crucial to classify the PV systems according to their size in order to identify the most suitable choice for each application. The following table gives a general idea of the requirements of each application.

Table 4: Classification of applications according to size [18]

Size of PV installation	Applications
<10W	Pocket calculators, radios, remote wireless sensors, small chargers, electric fences.
10W-100W	Small illumination systems, call boxes, traffic signals, parking meters, navigation lights, small communication systems, weather stations, solar home systems, medical refrigeration, cathodic protection, small stand-alone systems for isolated dwellings.
0.1kW-1kW	Medium-sized pumping systems and irrigation systems, desalination plants, propulsion of smaller recreation boats, stand-alone systems for isolated buildings, small rooftop systems, small hybrid system.
1kW-10kW	Medium-sized, grid-connected building and infrastructure-integrated systems; large stand-alone systems for isolated buildings; medium-sized hybrid systems.
10kW-100kW	Large grid-connected systems either building and infrastructure integrated or ground-based.
0.1MW-1MW and >1MW	Very large grid-connected systems - either building integrated or ground-based.

4.2.4 Wind Power

The use of wind as a power source is not a new innovation since the first traces of its appearance are dated centuries back to the emergence of the windmills for milling grain and pumping water [18],[30]. However, the transition from the mechanical use of the wind energy to the electrical use was made in 1888 in the U.S.A when Charles F. Brush developed the first wind machine that operated at rated power of 12 kW direct current [18]. The first AC wind turbine was also constructed in the U.S.A. in the 1930s and during the early 1970s the wind power started attracting significant attention due to energy emergencies in World War II and the oil crisis [18].

Wind energy belongs to the category of renewable powers since it comes from the kinetic energy of the wind on the surface of the earth [33]. Wind turbines harvest this energy and convert it into electricity which is then sent through the transmission and/or the distribution lines to customers [33]. The main components of a wind power system that performs this task are: a rotor, a generator (induction or synchronous generator), a directional system, a protection system and a tower [18],[36]. As the wind spins the blades of the rotor, the generator, which is connected to the rotor, is put into a rotating motion and generates electricity [18]. Gearing is also used to increase the rotation speed [18]. The generated electricity is then sent to the grid or a storage system [18].

The wind energy systems can be separated in three categories according to their type of operation. Those types are:

- Systems feeding into the grid.

This is the most common arrangement for small (50 kW), medium (250 kW) and large (3 MW) machines where a public utility or a large capacity grid is available [35]. This case can either be applied to wind farms (10-1000 turbines) which are all feeding into the grid or smaller systems where the owner of the machine can utilise the power directly, sell the surplus to the grid and import power from the grid when the turbine cannot cover the load demand [35]. They are coupled to a medium or high voltage connecting point and under normal circumstances the frequency is considered constant and the variations in voltage are within specified values [36]. A system like this is shown in the following figure.

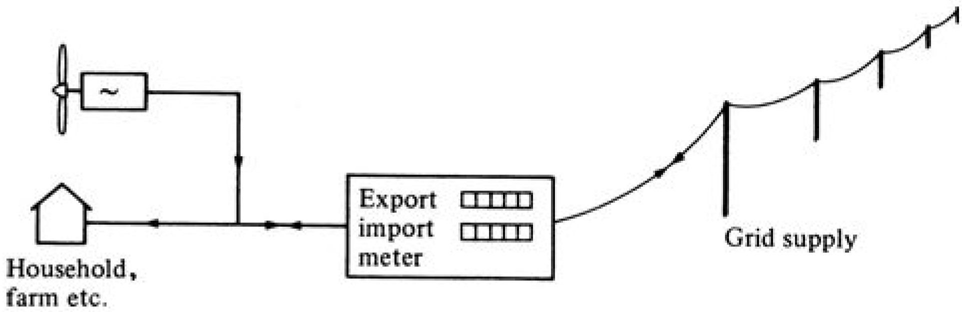

Figure 9: Grid linked wind turbine slaved in a large system

- Systems for island supply.

These wind energy systems provide energy to a remote grid where a utility is absent [36]. The arrangement of such a system may also include other types of generation like diesel generators and photovoltaic units as well as energy storage devices [36]. Those types of generation and storage are mostly used to compensate the lack of supply from the wind turbines during periods of weak wind [35].

- Single autonomous stand-alone machine.

In this arrangement there is no grid connection, no generators for secondary support whereas a battery is usually necessary in order to stabilise the voltage and store the energy [35]. The capacity of this arrangement is expected to be between 2 kW and 10 kW and it is most likely to be used for household supply that also includes heating [35].

The general formula of the power output for any wind turbine is:

$$P = \frac{1}{2} \times C_P \times \rho \times A \times V^3 \qquad (4.2)$$

where P is the nominal power of a wind turbine (W), CP power coefficient, ρ air density (kg/m^3), A swept area of rotor (m^2) and V free wind speed (m/sec) [30],[32],[34].

Just like every technology, wind energy comes with significant advantages and disadvantages. The following ones are some of the most important:

- Advantages

Wind power is the most mature and cost-effective from all the renewable energy technologies that have been developed to date [33].

Ultimately wind energy derives from solar energy and as a result it is an inexhaustible power source [33].

It produces no greenhouse gases and it does not contribute to global warming [31],[33].

Wind power can benefit the rural economy and turbines do not obstruct the work of farmers and ranchers since they can easily be erected in farms and ranches without occupying too much space [33].

- Disadvantages

The windy areas are usually remote and as a result it is difficult to easily deliver the energy to the centres of load demand [33].

Some of the major issues of wind turbines are noise, visual impact on landscapes and birds killed on the rotors [33].

The intermittent and unpredictable nature of wind energy [31],[33].

5 Analysis

5.1 Modelling of Overall System

5.1.1 Community Energy

This section demonstrates the steps required to calculate the power output from a renewable energy scheme in a community which can be a run-of-river hydro plant, solar panels and wind turbine(s). This investigation is the initial and most critical step before the simulation of a renewable energy scheme in a community during a typical year of operation. The steps of the system's simulation are presented in detail in the 'System Simulation' section.

Run-of-river Hydro Power

The feasibility study of a run-of-river hydro plant requires information on the topology of the area, precipitation data and characteristics of the turbine. As given in the previous chapter, the formula to calculate the power output of a hydroelectric power plant is the following [18],[19],[22]:

$$P = n \times \rho \times g \times Q \times H \qquad (5.1)$$

where:

P: nominal power of the hydroelectric power plant [W],

n: hydraulic efficiency of the turbine,

ρ: water density [kg/m^3],

g: gravity acceleration [m/s^2],

Q: volume flow rate of the water that passes through the turbine [m^3/s] and

H: height of head [m].

The value of water density depends on its temperature. Since this value between zero degrees and room temperature changes insignificantly it can be considered constant and equal with 1000 kg/m^3. A divergence of +-2 °C, in the most extreme cases, is not expected to affect the final result significantly.

Even though the gravity acceleration is expected to vary in different parts of the world depending on the region's altitude and latitude, it can be considered constant with a value of approximately 9.8 m/s^2 since a divergence of +-0.05 does not affect the final result significantly.

The volume flow rate of the water that passes through the turbine depends on the available flow rate of the river. The river's flow rate varies throughout the whole year according to the rain frequency in the corresponding area. The most efficient way to determine the value of the river's flow rate is to use data taken from previous measurements. The measurements are expected to vary throughout the year according to the rainfall variations between seasons. This means that an average value of water flow rate throughout the year will give significant divergence in comparison to a warm season when the rainfall is low or a wet season when the rainfall takes its highest values. Depending on the results that someone wants to extract from a corresponding study, it is essential to take into account all those parameters.

Solar Power

In order to conduct a feasibility study of a PV system, it is essential to be familiar with the basic solar geometry parameters as well as the power generation and performance formulas used in those systems. This section is separated in two distinct parts, the first part demonstrates the formulas and the necessary procedure in order to calculate the solar irradiance on a PV module and the second part shows the procedure of calculating the power output of a PV installation given the parameters that were calculated in the first part.

First Part (Solar Irradiance)

The following picture displays the parameters of solar geometry in relation to a PV panel.

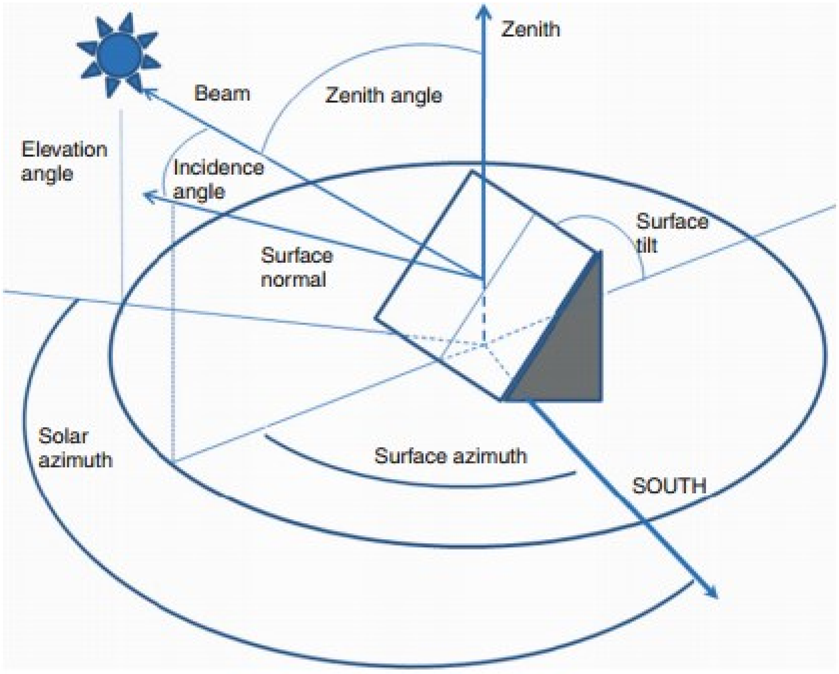

Figure 10: Solar geometry terms in a general case of PV module [23]

The position of the sun can be found at any given time if the values of solar altitude (elevation angle) and solar azimuth are known [28]. If the value of incident radiation is provided then the value of radiation on a horizontal panel can be found from the following formula [24]:

$$I_{horizontal} = I_{incident} \times \sin a \qquad (5.2)$$

or

$$I_{horizontal} = I_{incident} \times \cos \theta_z \qquad (5.3)$$

where

a: solar altitude (or elevation angle),

θ_z: solar azimuth,

$I_{horizontal}$: solar radiation measured on horizontal surface [W/m^2] and

$I_{incident}$: solar radiation measured perpendicular to the sun [W/m^2].

The solar radiation incident on the tilted surface can be found from the following formula if the $I_{ncident}$ is known [24]:

$$I_{module} = I_{incident} \times \sin(a + b) \tag{5.4}$$

or

from the following equation if the $I_{horizontal}$ is known [24]:

$$I_{module} = \frac{I_{horizontal} \times \sin(a + b)}{\sin a} \tag{5.5}$$

In order to calculate the sun's elevation angle (a) as shown in figure 10, it is required to know beforehand the site's latitude (φ) and the declination angle (δ). The elevation angle at solar noon can be calculated from the following formula for the northern hemisphere:

$$a = 90 - \varphi + \delta \tag{5.6}$$

or

from the following formula for the southern hemisphere:

$$a = 90 + \varphi - \delta \tag{5.7}$$

For more accurate calculations the elevation angle can be found by the following equation [28]:

$$a = \sin^{-1}(\sin\varphi \sin\delta + \cos\varphi \cos\omega) \tag{5.8}$$

where

ω: hour angle.

Finally, in order to calculate the declination angle, the only information required to know is the day of the year (d). Then the declinations angle (δ) is calculated from the following equation [28]:

$$\delta = 23{,}45 \times \sin[\frac{360}{365} \times (284 + d)] \tag{5.9}$$

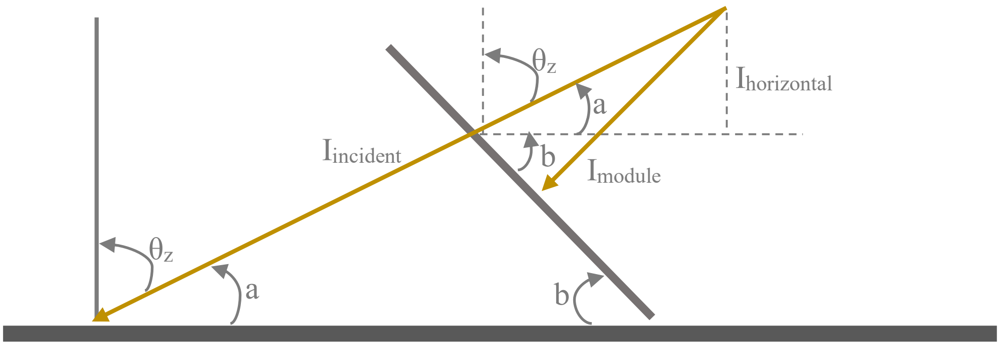

Figure 11: Demonstration of irradiation vectors in relation to a module

Second Part (Power Output)

After calculating the solar parameters, the power output of the PV installation can be calculated from the following formula [29]:

$$P = I \times A \times r \times PR \qquad (5.10)$$

where

I: the solar radiation incident on the tilted surface in [W/m^2],

A: the total area of the solar panels in [m^2],

r: the solar panel yield [%] and

PR: the performance ratio.

The total area of the solar panels can be calculated by multiplying the area of each panel with the number of panels in the installation.

The solar panel yield can be calculated from the following formula [26]:

$$r = \frac{P_m}{A \times G_{STC}} \qquad (5.11)$$

where

P_m: nominal power of each panel is given in Wp,

A: surface of each panel given in m^2 and

G_{STC}: STC irradiance measured in W/m^2 and it is equal to 1000.

The Performance Ratio (PR) includes all the losses and it is ratio of the actual power output of the PV installation and the theoretical power output [27].

Wind Power

A wind power scheme consists of one or more turbines and each turbine can have different characteristics according to the power output expected from the overall system. As given in the previous chapter, for a single turbine the power output can be calculated from the following formula [30],[32],[34]:

$$P = \frac{1}{2} \times C_P \times \rho \times A \times V^3 \qquad (5.12)$$

where

P: nominal power of a wind turbine [W],

C_P: power coefficient,

ρ: air density [kg/m3],

A: swept area of rotor [m^2] and

V: free wind speed [m/sec].

Power coefficient is the ratio of power extracted by the turbine to the total power contained in the wind resource [30],[35],[36]. The maximum possible value of the C_P is called the Betz limit and it is equal with 16/27 [30],[35],[36]. Wind turbine manufacturers usually provide the clients with a table of wind speeds and the corresponding power coefficient values. Depending on the value of wind speed chosen, the corresponding value of power coefficient needs to be selected in order to extract accurate results.

Air density depends on the area's altitude, the temperature and the humidity. The values vary mostly according to the temperature but usually an intermediate value of 1.21 kg/m^3 is used since this variation does not affect the final result significantly [35].

The swept area of the rotor is calculated from the wind turbine's rotor diameter by using the formula of the area of a circle:

$$A = \pi \times (\frac{d}{2})^2 \qquad (5.13)$$

where

d: the rotor diameter of the wind turbine [m].

The wind speed is one of the most important parameters in the estimation of a wind turbine's power output. It is separated in three categories, the cut-in speed, the rated speed and the cut-out speed [30],[35],[36]. The cut-in speed is the speed at which the turbine first starts to rotate and generate power [30],[35],[36]. Below this speed, the turbine's power output is zero. Rated speed is the speed at which the turbine generates the maximum possible power [36]. Above this speed, the power output does not increase any more. Finally, the cut-out speed is the limit at which the wind turbine activates a braking system in order to avoid possible damage to the turbine [30],[35],[36].

For an accurate estimation of a wind turbine's power output, it is essential that the wind data were measured at the height of the turbine hub [36]. If the data are given for a different height then the following formula can be used to adjust the results for the corresponding case [37]:

$$\frac{V}{V_O} = (\frac{H_O}{H})^{a} \qquad (5.14)$$

where

V: the new speed [m/sec],

H: the new height [m],

V_o: the original speed [m/sec],

H_o: the original height [m] and

a: the frictional coefficient or Hellman exponent.

The frictional coefficient is a function of the topography at a specific site and frequently assumed as a value of 1/7 for open land [37]. The following table shows the different values of the friction coefficient in common locations.

Table 5: Friction coefficients of various land spots [37]

Landscape type	Friction coefficient α
Lakes, ocean and smooth hard ground	0.10
Grasslands (ground level)	0.15
Tall crops, hedges and shrubs	0.20
Heavily forested land	0.25
Small town with some trees and shrubs	0.30
City areas with high rise buildings	0.40

If more than one wind turbine is used in an energy scheme, the total power output can be calculated by adding the corresponding output of each wind turbine.

5.1.2 Energy Storage System

From the literature review, that was conducted prior to the project analysis, it was clear that Energy Storage Systems (ESS) have certain common attributes that make it possible to conduct a comparison between them, regarding their performance and efficiency. For the differences between them, it was necessary to make certain assumptions. For this reason, a generic ESS was modelled, in which the common attributes of each technology could be applied, thus leading to the creation of case studies which were simulated and assessed separately.

In order to model a generic ESS, as precisely as possible, it was aimed to take into account as many storage characteristics as possible. Of course, only those characteristics that the storage systems have in common could be considered in the modelling process. Those attributes are:

- Energy storage capacity [MWh]

The energy storage capacity represents the amount of energy that can be stored in the system.

- Rated power [MW]

The rated power shows the amount of power that can be extracted from the ESS at any given moment, considering there is available stored energy in it. For example, a 1.5MW of rated power, given that the capacity is 3MWh, means that 1.5MW can be extracted for 2 hours until the storage capacity reaches zero. If the available energy is 1MWh, the ESS will reach zero energy in less than an hour.

- Charging rate [MW]

Charging rate depicts the amount of power that can be injected into the ESS, considering there is adequate storage capacity. For example, a 1.5MW of charging rate, given that the capacity is 3MWh and the storage system is empty, means that 1.5MW can be injected for 2 hours until the storage is fully charged.

- State of charge [MWh]

State of charge represents the amount of energy that is stored in the ESS at any given moment. Alternatively it could have been represented in percentage values but it was more convenient for the simulation process to represent it as available energy in MWh.

- Self-discharge [% of self-discharge per hour]

The self-discharge shows the energy loss in the ESS every hour. For example, a 2% energy loss every hour with a current state of charge of 10MWh means that the next hour the available energy will be 9.8MWh.

- Efficiency [%]

The efficiency depicts the amount of energy that can be extracted from the ESS given its state of charge. For example, 75% efficiency with a current state of charge of 10MWh, means that the energy that can be extracted is 7.5MWh.

A simplified way to represent the generic ESS is with a water tank. The tank's volume represents its capacity, the water volume inside the tank at any given moment depicts the state of charge at that moment, the quantity of water that can be extracted at any given time is the power rating, the amount of water than can be injected is the charging rate and considering that the water tank has a small leakage, the quantity of water that leaks is the self-discharge. The following picture demonstrates the previous description.

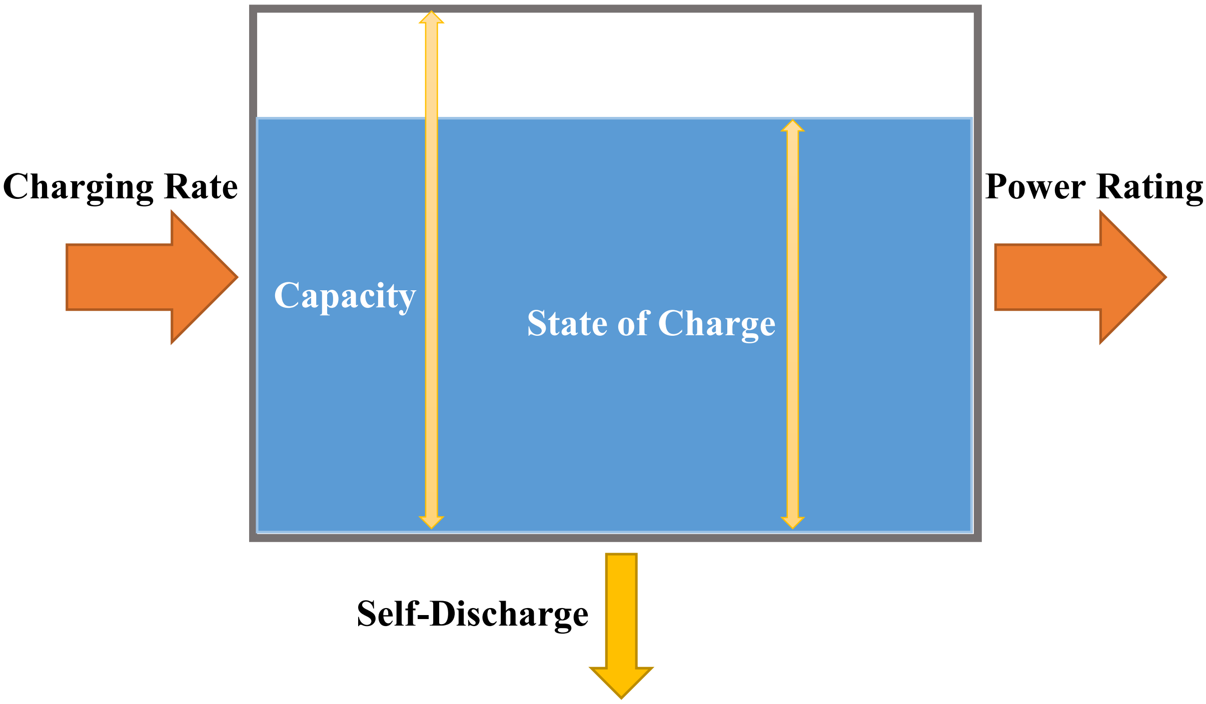

Figure 12: Simplified representation of an energy storage system in the form of a water tank

5.1.3 Power Control Equations

The most integral part of the analysis is to define the constituent parts of a community energy scheme that utilises an ESS, the power exchange between those parts and the limitations in each case. Those parts are:

- Renewable energy generation (run-of-river hydro, wind turbines, PV panels)

The generation is located near the community.

- Energy storage system (ESS)

It is located near the generation.

- Load

It represents the local community.

- Grid

It is the power network that supplies the community with energy.

The values of power are represented in each part as shown below:

P_W: power generated from the renewable energy scheme (run-of-river hydro, wind turbine, photovoltaics) in the local community,

P_S: power injected to the storage system or exported from that,

P_L: power 'requested' from the local community to cover the load demand,

P_G: power exported/imported to/from the grid,

P_{LIMIT}: maximum power that can be exported/imported to/from the grid,

P_{OUT}: combined power from the local generation and the storage system,

P_{CURT}: curtailed power.

The following picture demonstrates the interconnection of the scheme's constituent parts.

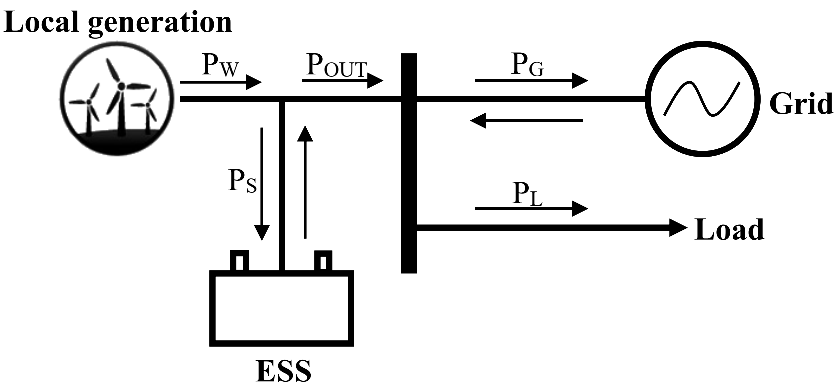

Figure 13: Interconnection of the constituent parts in the community energy scheme

The following equations depict the power flow inside the system.

$$P_{OUT} = P_W \pm P_S \quad (5.15)$$

In the equation (5.15) "+" is used when the power supplied by the local generation is not enough to cover the load demand in the community and additional stored energy is required. On the other hand, "-" is used when the local power generation is bigger than the demand and the surplus power can be stored in the ESS.

1. If the load demand is higher than the local generation ($P_W<P_L$) then the extra power is extracted from the storage system:

$$P_S = P_L - P_W \quad (5.16)$$

$$P_{OUT} = P_W + P_S \quad (5.17)$$

   a. If the combined power of local generation and storage is capable of covering the load demand in the community then:

$$P_L = P_{OUT} \quad (5.18)$$

$$P_G = 0 \quad (5.19)$$

$$P_{CURT} = 0 \quad (5.20)$$

   b. If the combined power is lower than the load demand ($P_{OUT}<P_L$) then the extra power is imported from the grid:

$$P_G = P_L - P_{OUT} \quad (5.21)$$

      i. If the extra power which is required from the grid is higher than the grid constraints ($P_G>P_{LIMIT}$) then:

$$P_L = P_{OUT} + P_{LIMIT} \quad (5.22)$$

2. If the load demand is equal with the local generation ($P_W=P_L$) then:

$$P_S = 0 \quad (5.23)$$

$$P_L = P_{OUT} \tag{5.24}$$

$$P_G = 0 \tag{5.25}$$

$$P_{CURT} = 0 \tag{5.26}$$

3. If the local generation exceeds the load demand in the community ($P_W > P_L$) then:
   a. If there is adequate capacity in the storage system, the surplus power is stored.

$$P_S = P_W - P_L \tag{5.27}$$

$$P_G = 0 \tag{5.28}$$

$$P_{CURT} = 0 \tag{5.29}$$

   b. If the storage capacity is not adequate to store the surplus power then this extra power can either be exported to the grid or a portion can be exported to the grid and the rest would be curtailed.
      i. If the surplus power exceeds the grid constraints then:

$$P_G = P_{LIMIT} \tag{5.30}$$

$$P_{CURT} = P_W - P_S - P_L - P_{LIMIT} \tag{5.31}$$

      ii. If the surplus power is smaller than the grid constraints, it can be fully exported to the grid then:

$$P_G = P_W - P_S - P_L \tag{5.32}$$

$$P_{CURT} = 0 \tag{5.33}$$

The previous equations can be combined in a single one and applied according to each case:

$$P_W = P_L \pm P_S \pm P_i + P_{CURT} \tag{5.34}$$

where: i='G' or i='LIMIT'.

5.1.4 Power Flow Algorithm

Based on the equations from the previous section, a power flow algorithm was created that depicts the power exchange between the constituent parts of the overall system (renewable generation, ESS, community and grid). The algorithms that describe the operation of the ESS are presented separately in two different flow charts.

Overall system

The algorithm is presented below in the form of a flow chart. Three new variables are introduced in this graph which were not given in the previous section:

- P_{GIN}: power imported from the grid,
- P_{GOUT}: power exported to the grid,
- P_{TOLOAD}: power sent to the local community.

The flow chart is separated in three distinct sections which resulted from the comparison between the local power generation and the load demand in the community.

P_W<P_L: in this section the load demand exceeds the power generated from the renewable energy scheme. Additional power is either exported from the ESS (Capacity>0) or power is imported from the grid (taking into account the grid constraints).

$P_W=P_L$: in this case, no power is needed from the ESS or the grid and the local generation provides all the necessary power in the community.

P_W>P_L: finally in the third section, the local renewable energy scheme generates more power than the power needed in the community. The surplus power is either stored in the ESS, or exported to the grid (taking into account the grid constraints) or curtailed if the previous options are not available.

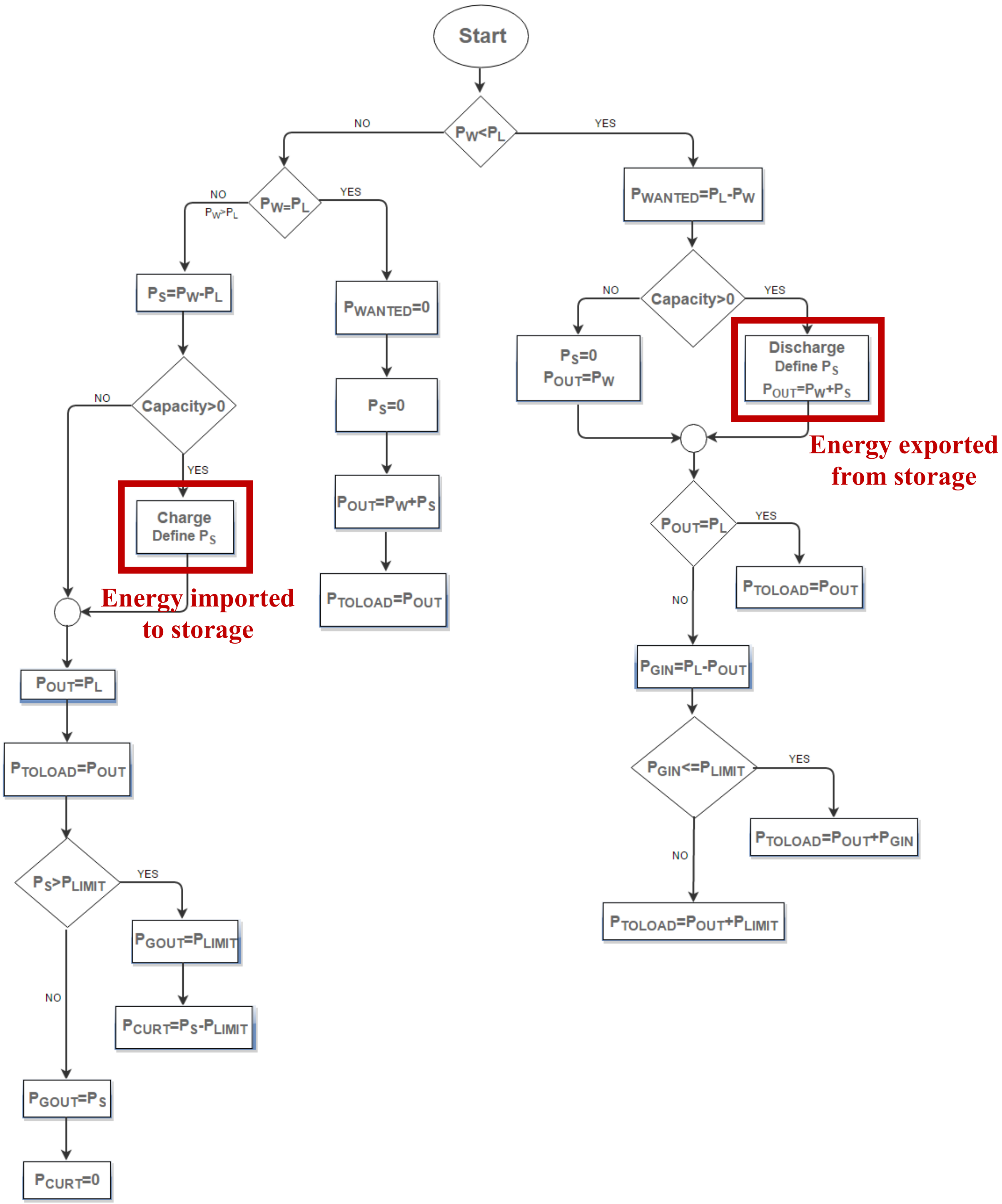

Figure 14: Flow chart demonstrating the power flow in the system

There are two more major algorithms which are not shown in the previous flow chart. These are the algorithms that demonstrate the operation of the ESS in the cases of importing and exporting energy. The rectangles which are highlighted in the previous flow chart are the points inside the overall algorithm where the smaller algorithms for charging and discharging energy are placed. Those two algorithms are presented below in the following flow charts.

Discharge from ESS

A new variable is introduced in the discharge graph which was not given in the previous section:

Useful_Power: the energy available for extraction from the ESS after taking into account the efficiency and self-discharge of the ESS.

The variables SOC (State of Charge) and Power_Rating were explained in the 5.1.2 section (Energy Storage System) in detail.

The discharge flow chart is separated in two distinct sections:

P_{WANTED}<=Useful_Power: the useful energy stored in the ESS is higher than the energy required to be extracted. This section is also divided in two more distinct cases where the wanted energy from the storage is compared with the system's Power Rating value for an hour (the Power Rating is given in MW but for an hour the result is the value of energy in MWh) to decide whether this energy can be fully extracted or not.

P_{WANTED}>Useful_Power: the useful energy stored in the ESS is less than the wanted energy. This section is also divided in two more distinct cases where the wanted energy from the storage is compared with the system's Power Rating value for an hour (the Power Rating is given in MW but for an hour the result is the value of energy in MWh) to decide whether this energy can be fully extracted or not. When the algorithm decides that the Power Rating value is bigger than the wanted energy (which means that it has the "ability" to extract the wanted energy if this energy is stored), it still needs to determine whether the stored energy is bigger than the Power Rating of the system or not.

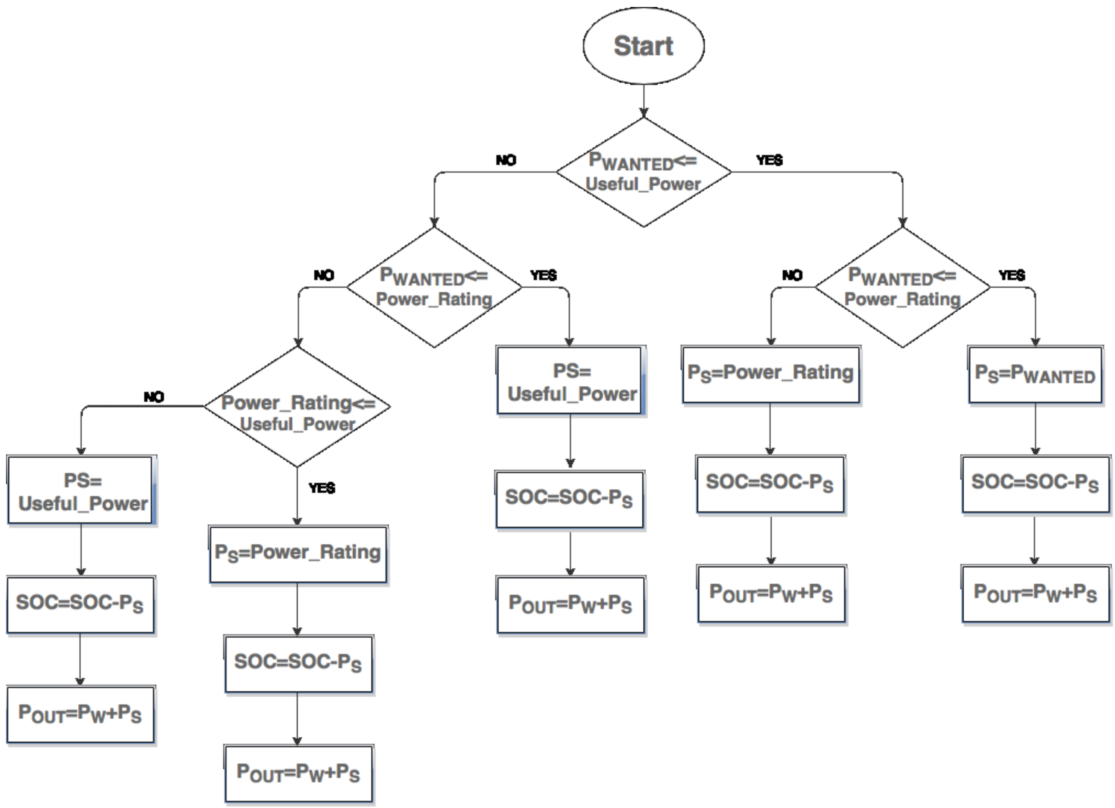

Figure 15: Flow chart demonstrating the power discharge from the ESS

ESS charging

The variable Charging_Rate was explained in the 5.1.2 section (Energy Storage System) in detail.

The discharge flow chart is separated in two distinct sections:

SOC<Capacity: in this case the algorithm decides that the ESS is not fully charged and can potentially store more energy. This section is then divided in two parts where the algorithm decides whether the energy to be imported in the ESS is smaller than the system's Charging Rate value for an hour (the Charging Rate is given in MW but for an hour the result is the value of energy in MWh) or not (which would mean that not all of the energy can be transferred in the storage system). Depending on the previous outcome, where it was decided whether the whole energy would be transmitted or just the amount which is equal to the system's Charging Rate, the algorithm then checks whether the system's state of charge is adequate to store this energy or part of it.

SOC>=Capacity: in this case, the ESS is fully charged and no more energy can be imported.

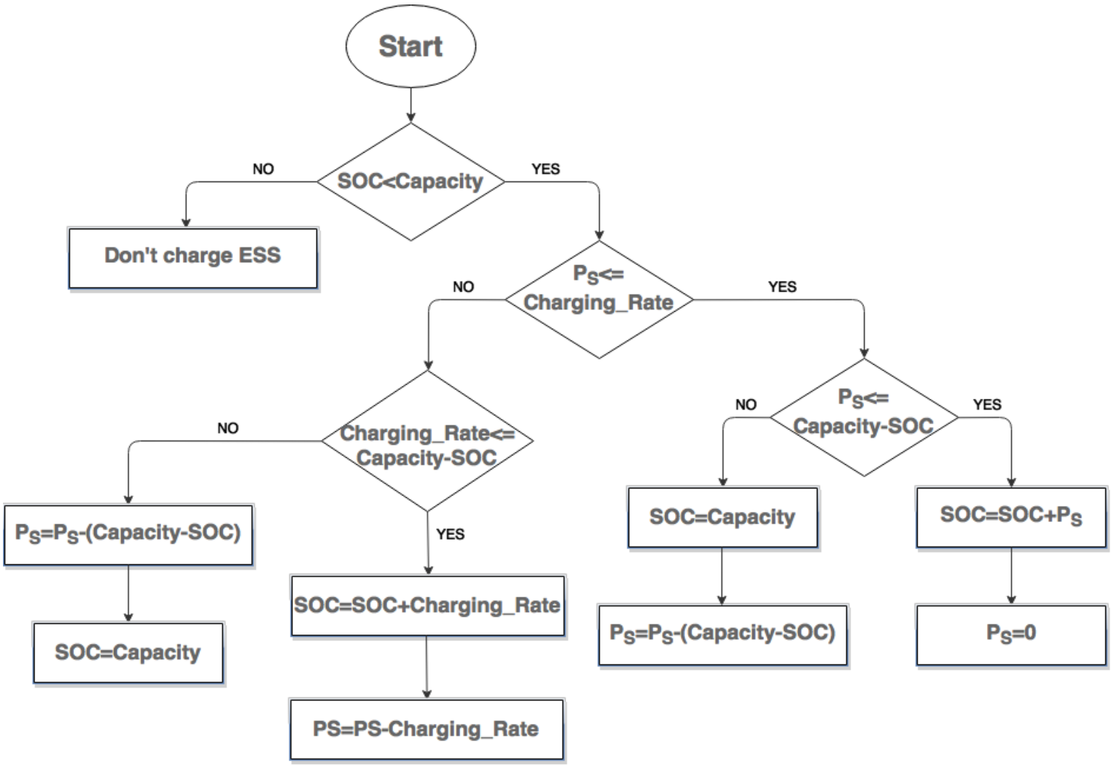

Figure 16: Flow chart demonstrating the charging process in the ESS

5.1.5 System Simulation

The analysis which was conducted in the sections 5.1.1, 5.1.2, 5.1.3 and 5.1.4 was used to simulate a system that consists of a renewable energy generation scheme, an ESS, the load demand (which represents the local community) and the grid that supports this community.

In order to simulate such a system, a code in Visual Basic was developed in Excel that utilizes the equations and the algorithms of power flow (as shown in the previous sections) in order to analyse the operation of the system as accurately as possible. The tool was developed to perform hourly simulations for an entire year. The data provided in the simulation tool and the results extracted are analysed below.

Data for power generation

The formulas (5.1), (5.10) and (5.12) are used to calculate the power output from a run-of-river hydro plant, a PV panel scheme and a wind turbine system accordingly. The data required to calculate the power output depend on the renewable energy scheme that the community uses and are given in detail in the corresponding sections. Considering that the energy comes from a run-of river hydro plant, the following data are necessary to do the calculations:

- Q: water volume flow rate of the river [m^3/sec].
- Hands-off flow: the water volume flow rate that must remain in the water course at all times. It is usually defined by the EIA conducted for a corresponding project.
- Available water flow rate: it is calculated from the subtraction of the river's flow rate and the hands-off flow.
- Water volume flow rate through the turbine: depending on the turbine chosen for the hydro plant, the manufacturer provides the corresponding parameters and one of them is its operating flow range. For example, 0.3 m^3/sec-2.2 m^3/sec means that the minimum flow rate through the turbine is 0.3 m^3/sec and the maximum water flow rate is 2.2 m^3/sec. This is calculated directly from the available water flow rate. If the available water flow rate is less than 0.3 m^3/sec, the hydro plant generates zero power whereas if the available water flow rate is higher than 2.2 m^3/sec, the turbine allows only 2.2 m^3/sec to flow, thus limiting its power output accordingly.
- Turbine efficiency, n [%].
- Water density, ρ [kg/m^3].
- Gravitational acceleration, g [m/s^2].
- Head, H [m].

Given the values of the previous parameters, the power output of a run-of river hydro plant is calculated in MW and the output for each hour is energy in MWh. Since the simulation is conducted hourly for a whole year, it is essential to obtain hourly data of the river's water flow rate which usually come from measurements conducted by competent groups and organisations. The hourly data of the water volume flow rate will then generate hourly data of the water volume flow rate through the turbine. This means that for a year with 8760 hours, a list of 8760 values of hourly power production will be generated.

Demand data

Finally, in order to compare the energy supply with the community's load demand, it is essential to acquire or assume hourly demand data for an entire year. These can be obtained by measurements conducted in the community which is the most accurate solution or generated by statistical data and assume that they represent the community.

Energy Storage System (ESS) data

- Capacity [MWh]
- Power_Rating [MW]
- Charging_Rate [MW]
- Self-discharge [% per hour]
- Efficiency [%]

Finally, the value of grid constraints in MW which is an integral part of the investigation is also provided.

Results

The tool performs a repeat loop which compares the energy supply with the energy demand for all 8760 hours of the year. Then, it generates hourly results of the following values:

- Curtailed Energy: energy which can neither be stored in the ESS, nor utilized in the load demand, nor exported to grid.
- Sum of curtailed energy for the entire year:

$$SUM1 = \sum_{i=1}^{8760} Curtailed\_Energy(i) \qquad (5.35)$$

- Energy from Grid: energy imported from the grid when the local production and ESS cannot cover the load demand in the community.

- Energy from grid sum for the entire year:

$$SUM2 = \sum_{i=1}^{8760} Energy\_from\_Grid(i) \qquad (5.36)$$

- Energy to Grid: energy exported to the grid when this energy cannot be utilized in the load demand or stored in the ESS and does not exceed the grid constraints.

- Energy to grid sum for the entire year:

$$SUM3 = \sum_{i=1}^{8760} Energy\_to\_Grid(i) \qquad (5.37)$$

- Autonomy [%]: it represents the percentage of time in the entire year, the community operates without support from the grid.

$$Autonomy = (1 - \frac{8760 - H\_o\_A}{8760}) * 100 \qquad (5.38)$$

where:

H_o_A: Hours of autonomy, the sum of hours throughout the entire year that the community is autonomous.

The visual basic code which was used for the simulation is given in Appendix A.

5.2 Case Study

5.2.1 Dalavich Hydropower Scheme

In order to test the previous assessment methodology, developed in the section (5.1), a case study was chosen that fits the criteria and the purpose of the current thesis. The Dalavich Hydro-Power Scheme is a run-of-river hydropower plant which was proposed by the Dalavich Improvement Group (DIG) [38],[39]. Due to the Feed-In Tariff (FIT) value going down over time, this made the hydro non-viable. The scheme was also scheduled to operate under grid constraints [39]. This was the result of the transmission line to the sub-station at Taynuilt that required an upgrade [39]. The following analysis aims to provide an insight on the effect that an ESS would have on the operation of this scheme if it was built under the current grid constraints.

Location

According to the hydrology report for the Dalavich Community Hydro Scheme, the Dalavich village is situated to the west of Loch Awe in Argyll & Bute whereas the river Avich, where the run-of-river hydro plant was scheduled to be constructed, is situated approximately 500 m to the north as shown in the following map [38],[39].

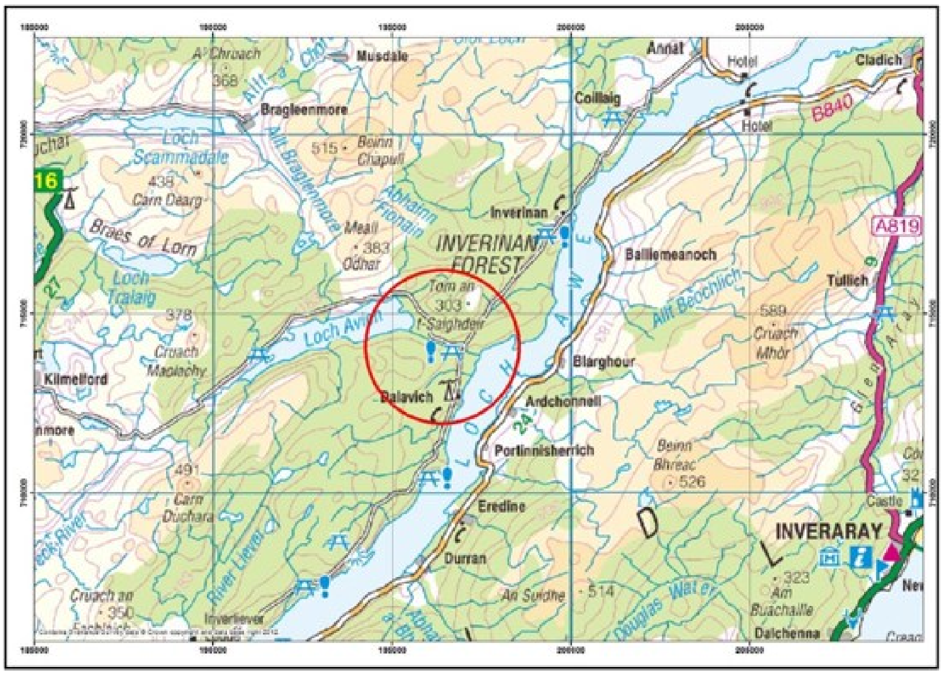

Figure 17: Dalavich general location map [38],[39].

The river drains from Loch Avich flowing east for around 2.3km before entering Loch Awe as shown in the picture below [38],[39].

Figure 18: River Avich

<u>Renewable generation scheme</u>

The community close to the river Avich and the location of the power house is the Dalavich village which is located approximately 1.3 km on the south of the proposed location. North of the Dalavich community there are holiday chalets and approximately 4.85 km on the north of the power house there is another community, Inverinan. The locations are displayed in the map (Figure 19) taken from Google Earth.

The proposed idea is to create a micro-grid in which the main energy supply will come from the run-of-river hydro in the river Avich. For this reason, the supply from the proposed renewable energy scheme is not the only parameter that needs to be considered. The load demand is also very important in order to assess its feasibility.

This micro-grid will be supported from the grid. When the power supply cannot cover the load demand, the extra energy will be imported from the grid and when the energy generation exceeds the demand, the surplus will be exported. However, the smooth operation of this scheme is obstructed by the grid constraints because the maximum power that can be imported/exported from/to the grid is 50 kW [39]. As a result, a significant amount of energy is expected to be curtailed. In order to overcome this obstacle and increase the feasibility of this scheme, the energy supply can be combined with an ESS. The assessment aims to determine the extent that an ESS can improve the feasibility of the renewable energy scheme.

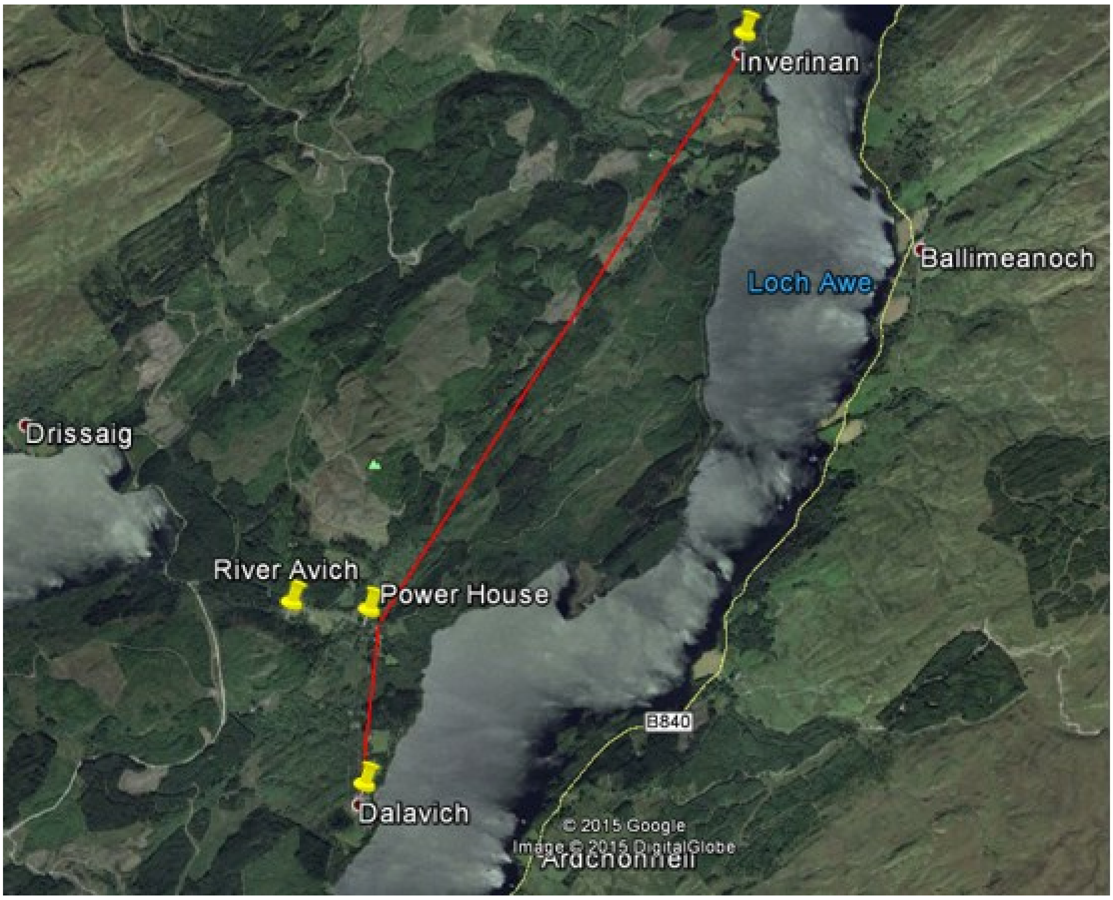

Figure 19: Local communities and run-of-river hydro scheme

Part of the assessment is to determine which of the communities can be covered from the local energy generation. The village of Dalavich along with the chalets on the north are considerably closer to the power house which means that at first sight they are considered the best choice to be included in the micro-grid. However, the possibility of creating a micro-grid of bigger scale which will also include the village of Inverinan will be assessed as well.

Xero Energy Limited has provided the necessary data, related to the renewable energy scheme, to calculate the power output of the run-of-river hydro plant. The information includes:

- The hydrostatic head available at the site, H [m].
- The type of turbine and its operating flow range.
- The generator efficiency.

For the calculation of the power output, the following parameters were also used:

- The water volume flow rate in river Avich which will be analysed in the "Hydrology Data" section. It was used in combination with the turbine's operating flow range to determine hourly data of the water flow rate through the turbine.
- Turbine efficiency, n, which was assumed to be 0.64 [38],[39].
- Water density, ρ, was assumed to be equal with 1,000 kg/m^3.
- Gravitational acceleration, g=9.81 m/s^2.

Hydrology data

In order to make an accurate estimation of the hourly power output of the run-of-river hydropower plant, it is essential to use hourly data of the water volume flow rate. For this reason, SEPA agreed to provide the necessary information. As indicated by the agency, this site was downgraded from a flow site to a "level only" site in 2011, and so no flow measurements have been carried out since that time. As a result the rating equation for the site will not be particularly accurate, and any flows supplied should be treated with caution.

SEPA provided 15 minute data from January 2014 until December 2015. However, the simulation tool required hourly data. For this reason, the 15 minute data were turned into hourly data by calculating the average water volume flow rate every hour.

As expected, the volume flow rate of the river Avich varies each season which means that the energy generation is intermittent and cannot be accurately predicted. The following table and figure show the average values of water volume flow rate each month. “Contains SEPA data © Scottish Environment Protection Agency and database right [2015]. All rights reserved”

Table 6: Mean water volume flow rate each month

Month	Q_{mean} [m^3/sec]
January	3.3
February	3.6
March	2.9
April	1.4
May	1.4
June	0.5
July	0.8
August	1.9
September	0.5
October	3.7
November	2.7
December	3.8

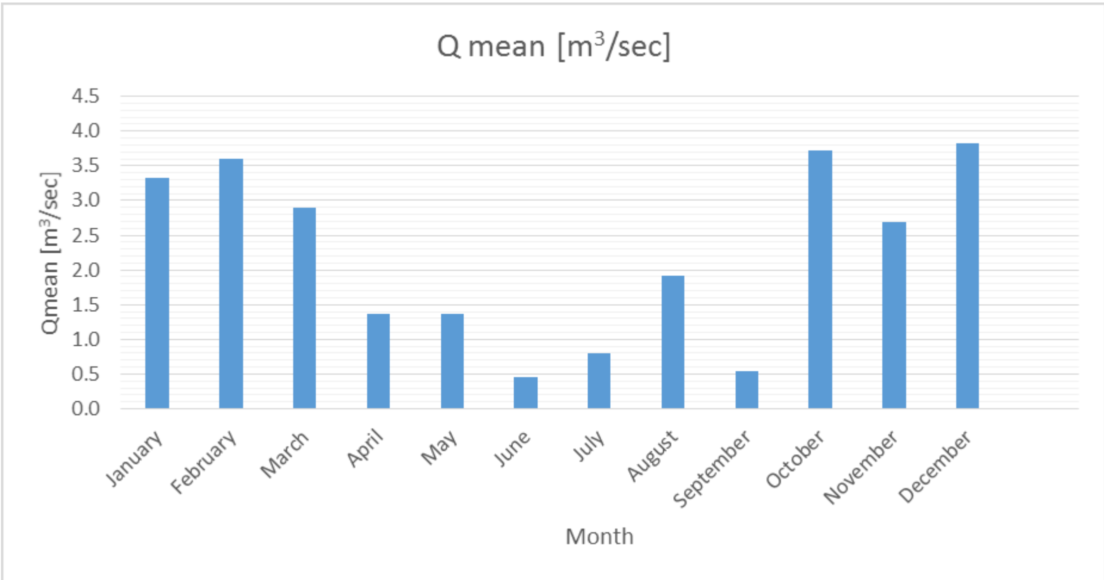

Figure 20: Mean water volume flow rate each month

After creating the hourly data of the water volume flow rate, the available water volume flow rate had to be determined. This means that the whole flow rate of the river cannot be utilised for energy generation and a portion needs to be untouched. This is called the hands-off-flow. The hands-off-flow is usually estimated by an EIA before the project is created. In this case it was assumed to be [38],[39]:

Hands-off-flow: $Q_{hands\text{-}off}$=0.548 m^3/sec.

Available flow rate: $Q_{available}=Q_{river}-Q_{hands\text{-}off}$

where,

$Q_{available}$ is the available flow rate and Q_{river} is the water volume flow rate of the river Avich. Thus, a new set of hourly data was created that depicted the available water volume flow rate for the whole year.

From the information provided by Xero Energy Limited (the turbine's operating flow range), the water volume flow rate through the turbine was also determined. From the hourly data of the available flow rate, the values of flow rate below the minimum operating flow rate were considered zero because the power plant cannot generate energy under this limit. Furthermore, the values of available flow rate above the maximum operating flow rate were replaced with the value of maximum operating flow rate of the turbine because the turbine cannot exceed this value and regulates its output.

Thus, the final set of hourly data which was used for the power output estimation was the water volume flow rate through the turbine.

Community demand data

In order to complete the set of data and simulate the operation of the community's renewable energy scheme, the load demand data had to be determined. This information is the most difficult to acquire and predict because the load demand has a seasonal variation and depends on the habits of the residents in the community.

In order to estimate the load demand in the most accurate way, the statistical data on "Household Average Electrical Use" published by the Department of Energy & Climate Change were used [40]. The table shows hourly average values of each electric appliance in a UK household and can be found in Appendix B.

Xero Energy Limited provided useful information on the load demand in the village of Dalavich, the holiday Chalets and the village of Inverinan. This information was used to adjust the statistical data from the Department of Energy & Climate Change to the load demand in those communities.

According to "Household Electricity Survey: A study of domestic electrical product usage", cold appliances, laundry, dish-washing, cleaning appliances, cooking appliances, lighting consumption, space heating and water heating follow an annual "seasonality effect" in energy consumption [41]. However, for the demand modelling, average daily values of consumption were used to represent the load due to lack of monitored data in those areas.

The load demand was separated in two categories and the feasibility of both was tested. In the first category, the village of Dalavich with the holiday Chalets were considered to be the community's load demand which would be supported by the run-of-river hydro scheme. In the second category, a broader micro-grid was taken as the community's load demand which also includes the village of Inverinan.

The following table shows the load demand of the first category (Dalavich/Chalets).

Table 7: Mean hourly load demand in Dalavich and holiday Chalets

	Dalavich	**Chalets**	**D/C**
Hour	**Total demand [MWh]**	**Total demand [MWh]**	**Total [MWh]**
1	0.01503972	0.008729	0.023769
2	0.0120429	0.007001	0.019044
3	0.01089288	0.006323	0.017216
4	0.0102888	0.006011	0.0163
5	0.01055493	0.006128	0.016683
6	0.01059264	0.006215	0.016808
7	0.01336968	0.007883	0.021252
8	0.01965564	0.011627	0.031283
9	0.02232369	0.013236	0.035559
10	0.02212443	0.013122	0.035247
11	0.02135268	0.012672	0.034025

12	0.02126907	0.012652	0.033921
13	0.02217672	0.013194	0.035371
14	0.0209934	0.012476	0.033469
15	0.02011635	0.011942	0.032058
16	0.0212454	0.012601	0.033846
17	0.02502009	0.014838	0.039858
18	0.03031362	0.018008	0.048322
19	0.03203604	0.01904	0.051076
20	0.03174453	0.018858	0.050602
21	0.03034233	0.018011	0.048354
22	0.02805201	0.016655	0.044707
23	0.02464227	0.014603	0.039245
24	0.01993527	0.011674	0.031609

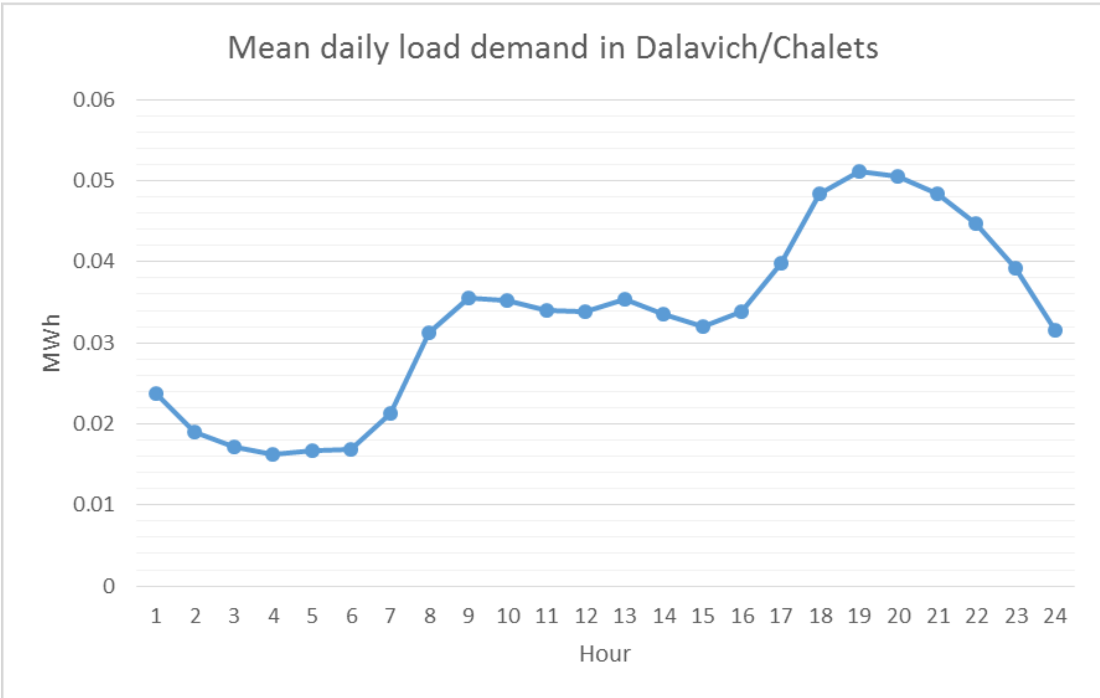

Figure 21: Mean daily variation of load demand in Dalavich and holiday Chalets

The following table shows the load demand of the second category (Dalavich/Chalets/Inverinan).

Table 8: Mean hourly load demand in Dalavich, holiday Chalets and Inverinan

	Dalavich	**Chalets**	**Inverinan**	**D/C/I**
Hour	**Total demand [MWh]**	**Total demand [MWh]**	**Total demand [MWh]**	**Total [MWh]**
1	0.01503972	0.008729	0.00487788	0.028646418
2	0.0120429	0.007001	0.0039111	0.022954818
3	0.01089288	0.006323	0.00353352	0.02074976
4	0.0102888	0.006011	0.0033552	0.019655127
5	0.01055493	0.006128	0.00342447	0.020107836
6	0.01059264	0.006215	0.00346656	0.0202746
7	0.01336968	0.007883	0.00439272	0.02564507
8	0.01965564	0.011627	0.00647556	0.037758246
9	0.02232369	0.013236	0.00736851	0.042927922
10	0.02212443	0.013122	0.00730497	0.042551843
11	0.02135268	0.012672	0.00705372	0.04107887
12	0.02126907	0.012652	0.00703953	0.040960719
13	0.02217672	0.013194	0.00734088	0.042711694
14	0.0209934	0.012476	0.0069426	0.040411733
15	0.02011635	0.011942	0.00664665	0.038704657
16	0.0212454	0.012601	0.0070146	0.040860779
17	0.02502009	0.014838	0.00826011	0.04811807
18	0.03031362	0.018008	0.01002198	0.058343834
19	0.03203604	0.01904	0.01059516	0.061670794
20	0.03174453	0.018858	0.01049487	0.061097288
21	0.03034233	0.018011	0.01002507	0.058378737
22	0.02805201	0.016655	0.00926979	0.05397673
23	0.02464227	0.014603	0.00813033	0.047375409
24	0.01993527	0.011674	0.00651333	0.038122594

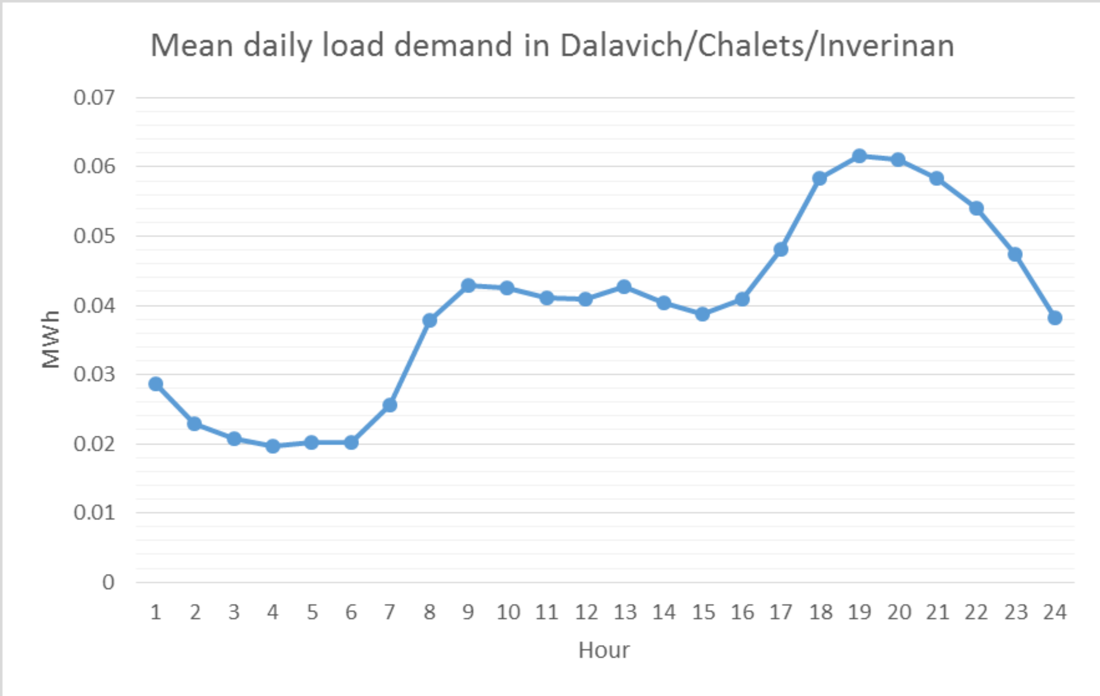

Figure 22: Mean daily variation of load demand in Dalavich, Chalets and Inverinan

From the figures 21 and 22, it is obvious that the load demand variation throughout an average day is almost identical in both cases. The only significant difference between the two load demands is that every hour, the demand in the second category (Dalavich, Chalets and Inverinan) is higher than the first.

These two cases of load demand were simulated separately and it was assumed that the mean hourly load demand is the same every day throughout a typical year of operation.

5.2.2 Energy Storage Case Studies

In order to assess the feasibility of a renewable energy scheme in a community which utilises an energy storage system, it was decided to simulate the overall system in distinct case studies regarding the available storage technologies for this operation and the corresponding scales. This way, the most suitable technology along with the most suitable storage scale can be identified, depending on the desirable outcome.

The case studies that were simulated in the renewable energy scheme were constructed according to the literature review. They were separated in two broad categories, megawatt scale and kilowatt scale.

Megawatt scale

The "Electricity Energy Storage Technology Options" from EPRI, for Transmission and Distribution Grid Support Applications, provided a list and characteristics of available energy storage options [42]. In cases where a range of capacity was given for a storage option, four intermediate case studies were created using the interpolation method. A maximum value of 15 MWh was assumed for all case studies with a range higher than this value.

Kilowatt scale

The "Electricity Energy Storage Technology Options" from EPRI, for Distributed (DESS) Applications, provided a list and characteristics of available energy storage options [42]. In cases where a range of capacity was given for a storage option, four intermediate case studies were created using the interpolation method. The full range of capacity was taken into account.

The tables below show the various cases of the Megawatt-scale case studies [42].

Table 9: Advanced Lead-Acid and Vanadium Redox Flow Batteries (MW-scale)

	Advanced Lead-Acid Batteries				**Vanadium Redox Flow Batteries**			
Case Studies	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Capacity [MWh]	3.2	7.12	11.1	15	4	7.67	11.2	15
Power Rating [MW]	1	3.88	6.8	9.64	1	1.9175	2.8	3.75
Efficiency [%]	75	76.3	77.5	78.8	65	65.4	66	66.4
Cycles	4500	4500	4500	4500	10000	10000	10000	10000

Self-Discharge/h [%]	0	0	0	0	0	0	0	0

Table 10: Zn/Br Flow and Li-ion Batteries (MW-scale)

	Zn/Br Flow				**Li-ion**			
Case Studies	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Capacity [MWh]	5	8.2	11.7	15	4	7.67	11.2	15
Power Rating [MW]	1	1.64	2.34	3	1	2.64	4.24	5.95
Efficiency [%]	60	60.4	60.7	61	90	90.72	91.44	92.2
Cycles	10000	10000	10000	10000	4500	4500	4500	4500
Self-Discharge/h [%]	-	-	-	-	-	-	-	-

Table 11: Sodium-Sulfur, Fe/Cr Flow, Zn/Air and CAES storage systems (MW-scale)

	Sodium-Sulfur	**Fe/Cr Flow**	**Zn/air**	**CAES (aboveground)**
Capacity [MWh]	7.2	4	5.4	250

Power Rating [MW]	1	1	1	50
Efficiency [%]	75	75	75	71
Cycles	4500	10000	4500	10000
Self-Discharge/h [%]	-	-	-	-

The table below shows the various cases of the Kilowatt-scale case studies [42].

Table 12: Advanced Lead-Acid, Li-ion and Zn/Br Flow Batteries (Kw-scale)

	Advanced Lead-Acid				**Li-ion**				**Zn/Br Flow**
Case Studies	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**
Capacity [kWh]	100	150	200	250	25	33.3	41.7	50	100
Power Rating [kW]	25	33.3	41.7	50	25	33.3	41.7	50	50
Efficiency [%]	85	86.7	88.3	90	80	84.2	88.7	93	60
Cycles	4500	4500	4500	4500	5000	5000	5000	5000	10000
Self-Discharge/h [%]	-	-	-	-	-	-	-	-	-

5.2.3 Results

The simulation of the run-of-river hydro power plant generated the following results regarding the maximum, minimum and average power output throughout the entire year as shown in the table below.

Table 13: Maximum, minimum and average power output in a typical year

	Maximum	**Minimum**	**Average**
Power Output (kW)	266.2	0	135.7

The case of power output equal with 0 kW was the outcome of low available water volume flow rate in the river Avich. When this value is smaller than the minimum flow rate of the operating flow range of the turbine, then the power output of the turbine is zero.

The following table compares the energy supply from the run-off-river hydropower plant with the demand options. These load demand options will be assessed separately.

Table 14: Supply and demand options

Total Energy Supply [MWh]	**Total Load Demand (Dalavich, Chalets) [MWh]**	**Surplus [MWh]**	**Total Load Demand (Dalavich, Chalets, Inverinan) [MWh]**	**Surplus [MWh]**
1188.4	244.2	944.2	303.9	884.6

The following graph illustrates a comparison of the varying power output of the run-of-river hydro plant throughout a typical year of operation and the grid constraints in order to provide an insight of the divergence between those two values.

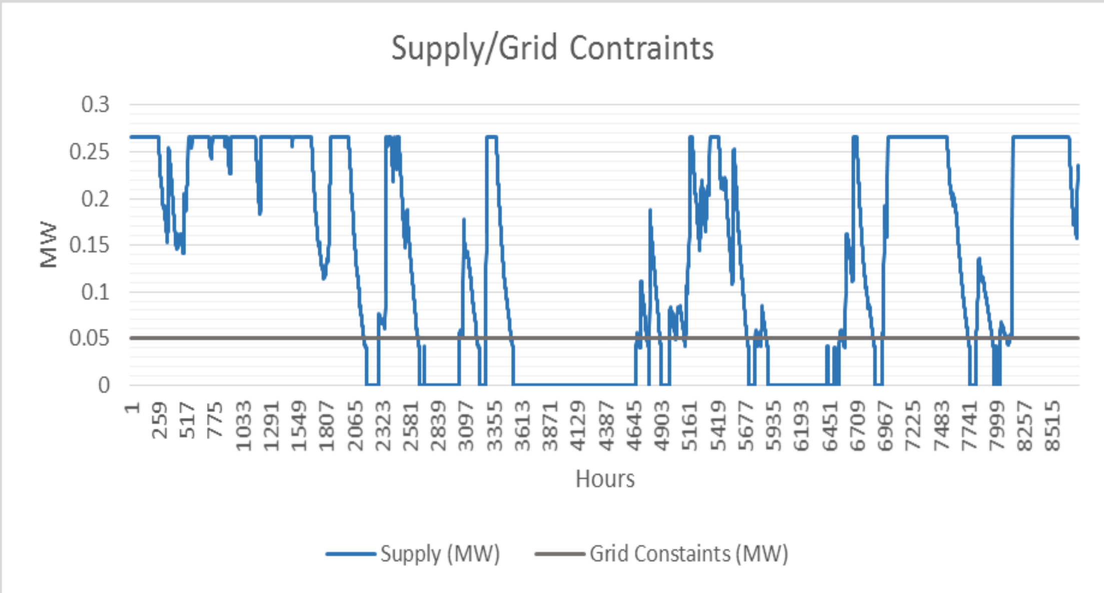

Figure 23: Power supply from hydropower plant and grid constraints

The results are separated in two categories according to the two cases of load demand which were created in the "Community Demand Data" section.

1. Dalavich and holiday Chalets

The following graph demonstrates a comparison between the energy supply from the hydropower plant and the load demand in the village of Dalavich and the holiday Chalets.

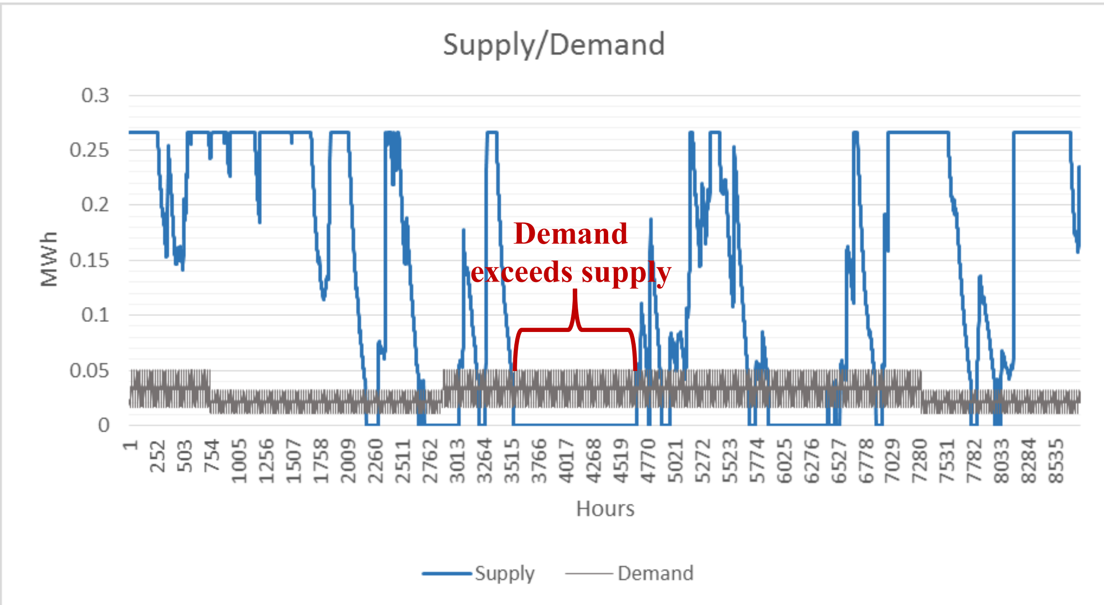

Figure 24: Energy supply and load demand in Dalavich/Chalets

The following table shows the results of the most efficient energy storage case studies. The values of interest are the sum of curtailed energy, the sum of energy imported from the grid, the sum of energy exported to the grid and the autonomy of the community. All the results depict the system's operation in a typical year. A breakdown of the results extracted from the system's simulation for every energy storage case study for Dalavich/Chalets can be found in Appendix C.

Table 15: Optimum results from the energy storage case studies simulation

	Total curtailed energy [MWh]	**Total energy imported from the grid [MWh]**	**Total energy exported to the grid [MWh]**	**Autonomy of community [%]**
No Energy Storage/Grid Constraints	0	80.87	1025.09	69.8
No Energy Storage	742.00	80.87	283.09	69.8
CAES (Capacity=250MWh)	509.23	0.00	185.59	84.0
Batteries (Capacity=15MWh)	709.85	28.13	247.99	79.5

The following table shows the percentage of improvement that CAES and the batteries achieved in each case in comparison to the case of no energy storage use.

Table 16: Percentage of improvement in the operation of the community

Storage Type	Percentage reduction in curtailed energy	Percentage reduction in energy imported from the grid	Percentage reduction in energy exported to the grid	Percentage Increase in autonomy of community
CAES (Capacity=250MWh)	31.4	100.0	34.4	16.9
Batteries (Capacity=15MWh)	4.3	65.2	12.4	12.2

Discussion

The results indicated that the kilowatt scale has no significant effect on the efficiency of the overall system. The quantity of curtailed energy remained practically the same. The same conclusion applies for the values of "Energy from the grid", "Energy to the grid" and "Autonomy". Those results are found in Appendix C.

The megawatt scale had a significantly bigger impact on the system's operation. Even though the case studies had different values in the "Efficiency" and "Power Rating" parameters, the results showed that the values were mostly altered from the system's "Capacity" value. This is clear in the case study "4" in "Advanced Lead-Acid Batteries", "Vanadium Redox Flow Batteries", "Zn/Br Flow" and "Li-ion" in which the capacity is 15 MWh in all of them. The rest of the values vary but the results are identical. This result is reasonable because the load demand in those cases is significantly lower than the energy that can be extracted from those four storage systems. If the load demand was comparable, the effect of those parameters would be more evident. Those results are found in Appendix C.

No energy storage option gave 100% autonomy and 0 MWh of curtailed energy. Even the storage system with the biggest capacity value (CAES) gave 31.4% decrease in curtailed energy, almost 100% decrease in energy imported from the grid, 34.4% decrease in energy exported to the grid and 16.9% increase in the autonomy of the community as shown in the Table 15.

The four prevailing battery options with a capacity of 15MWh gave 4.3% decrease in curtailed energy, 65.2% decrease in energy imported from the grid, 12.4% decrease in energy exported to the grid and 12.2% increase in the autonomy of the community as shown in the Table 15.

From the literature review, the prevailing battery option is "**Vanadium Redox Flow Batteries**" because flow batteries can release energy continuously for up to 10 hours and they can store energy for hours or days with a power that reaches up to several MW. Moreover, they have very low self-discharge and they can become fully discharged without risk of damage. As a result, flow batteries are considered storage systems with low maintenance and long life, capable of storing energy for long periods. In comparison to the "Zn/Br Flow" battery option, they have bigger values of efficiency and Power Rating.

Lead-Acid Batteries have short life-cycle and low energy density and their use in energy management is limited.

Because of their increased cost, Li-ion batteries are mostly used in small applications like mobile phones, laptops and other portable electronic devices. Since Li-ion batteries are still expensive, they can only compete with lead-acid batteries in applications that require short discharge time and there are significant challenges that need to be overcome in order to be applicable in large scale utilities.

For the "Sodium-Sulfur", "Fe/Cr Flow" and "Zn/air" batteries there was no case study of the same scale for comparison but since the capacity affected the results in this energy scheme, the final results are expected to be exactly the same. Furthermore, their low Power Rating in comparison to "Vanadium Redox Flow Batteries" places them lower in the hierarchy option.

Those results cannot be applied to every energy scheme and a corresponding analysis needs to be conducted. Furthermore, a financial analysis is essential to define the viability of any of those ESS.

2. Dalavich, holiday Chalets and Inverinan

Since the energy supply from the run-of-river hydro plant exceeds the load demand of Dalavich and the nearby chalets by 944.2 MWh, it is reasonable to consider alternative ways to utilize this energy surplus. One option is to expand the micro-grid to Inverinan, the nearby village. By taking into account the extra load demand of Inverinan the surplus energy decreases by 6.3% to 884.6 MWh.

The following graph demonstrates a comparison between the energy supply from the hydropower plant and the combined load demand in the village of Dalavich, the holiday Chalets and the village of Inverinan.

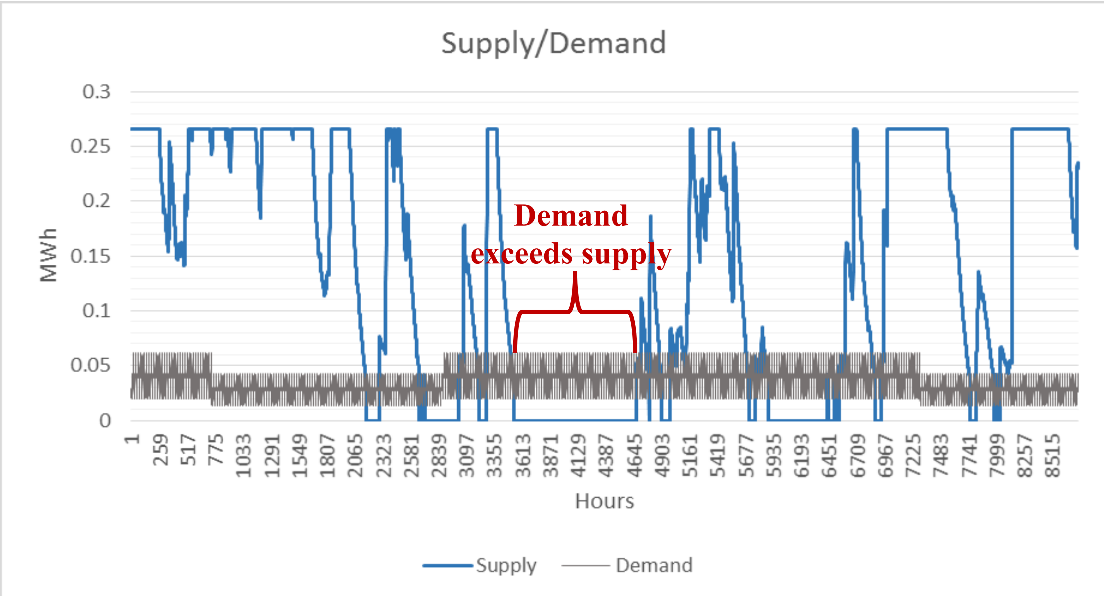

Figure 25: Energy supply and load demand in Dalavich/Chalets/Inverinan

The following table shows the results of the most efficient energy storage case studies. The values of interest are the sum of curtailed energy, the sum of energy imported from the grid, the sum of energy exported to the grid and the autonomy of the community. All the results depict the system's operation in a typical year. A breakdown of the results extracted from the system's simulation for every energy storage case study for Dalavich/Chalets/Inverinan can be found in Appendix D.

Table 17: Optimum results from the energy storage case studies simulation

	Total curtailed energy [MWh]	Total energy imported from the grid [MWh]	Total energy exported to the grid [MWh]	Autonomy of community [%]
No Energy Storage/Grid Constraints	0	80.87	1025.09	69.8
No Energy Storage	742.00	80.87	283.09	69.8
CAES (Capacity=250MWh)	465.70	0.00	169.22	89.5
Batteries (Capacity=15MWh)	672.89	41.04	238.42	81.1

The following table shows the percentage of improvement that CAES and the batteries achieved in each case in comparison to the case of no energy storage use.

Table 18: Percentage of improvement in the operation of the community

Storage Type	Percentage reduction in curtailed energy	Percentage reduction in energy imported from the	Percentage reduction in energy exported to the grid	Percentage Increase in autonomy of community
CAES (Capacity=250MWh)	34.2	100.0	38.7	23.2
Batteries (Capacity=15MWh)	4.9	58.7	13.7	15.3

Discussion

The results indicated that the kilowatt scale has no significant effect on the efficiency of the overall system. The megawatt scale had a significantly bigger impact on the system's operation. Even though the case studies had different values in the "Efficiency" and "Power Rating" parameters, the results showed that the results were mostly altered from the system's "Capacity" value. Thus, the results of the second case (Dalavich/Chalets/Inverinan) lead to the same conclusions as in first case where the load demand consisted only of the village of Dalavich and the holiday Chalets.

The option of a broader micro-grid that combines the Dalavich village, the holiday Chalets and the Inverinan village appears to be more efficient even though the energy demand is higher.

No energy storage option gave 100% autonomy and 0 MWh of curtailed energy. Even the storage system with the biggest capacity value (CAES) gave 34.2% decrease (in case 1 it was 31.4%) in curtailed energy, almost 100% decrease in energy imported from the grid, 38.7% decrease (in case 1 it was 34.4%) in energy exported to the grid and 23.2% increase (in case 1 it was 16.9%) in the autonomy of the community as shown in the Table 17.

The four prevailing battery options with a capacity of 15MWh gave 4.9% decrease (in case 1 it was 4.3%) in curtailed energy, 58.7% decrease (in case 1 it was 65.2%) in energy imported from the grid, 13.7% decrease (in case 1 it was 12.4%) in energy exported to the grid and 15.3% increase (in case 1 it was 12.2%) in the autonomy of the community as shown in the Table 17. The energy imported from the grid is higher in this case due to the bigger load demand of the combined system.

5.2.4 Financial Approach

The previous segments demonstrated a comparison between the two load demand options for the micro-grid scheme. The result was that the load demand that consists of the village of Dalavich, the holiday Chalets and the village of Inverinan (broader micro-grid) is more efficient. Additionally, the most suitable ESS was found to be the Vanadium Redox Flow Batteries for the reasons explained above. As a result, the financial estimation and comparison of the two load demand options that utilise Vanadium Redox Flow Batteries is expected to give similar results.

The run-of-river hydro scheme is expected to benefit the community financially in many ways. The energy generated locally can reduce the energy required from the grid to cover the load demand, thus leading to reduction of the bills for the whole micro-grid. Additionally, a relatively new programme that takes place in the UK called Feed-In Tariff (FIT) which was created to promote the expansion of small scale renewable energy generation schemes is expected to contribute significantly to the financial viability of the community energy generation scheme. In this section, the financial benefit of the run-of-river hydro for the community is investigated in a typical year, in the following cases:

- No energy storage and no grid constraints.
- No energy storage.
- ESS with 4 MWh capacity.
- ESS with 15 MWh capacity.

The same investigation is shown for both load demand options.

The Feed-In Tariff (FIT) is an environmental programme designed by the government to promote renewable energy generation and low carbon electricity generation schemes [44], [45]. Whether it is a householder, a business or a whole community, if the installation is eligible and the proper procedures to apply for FITs have taken place, the Feed-In Tariff Scheme pays a tariff for the electricity that is generated and also a tariff for the electricity which is exported to grid [45].

The financial approach of the run-of-river hydro plant is based on the current tariff values which include the tariff for energy generated locally, the tariff for energy exported to the grid (export tariff) and the cost of electricity for the energy used for the load demand.

- For a hydro generating station with total installed capacity between 100kW and 500kW, the tariff for local generation between 1 April 2015 and 31 March 2016 is 12.67 p/kWh [46].

- The "export tariff", which is referred to the surplus energy exported to the grid is 4.77 p/kWh [47].

- The average price of electricity for England, Wales and Scotland is 14.05 p/kWh [48].

Taking these values into account, the benefit for the community per year was calculated as shown below.

a. Benefit from local generation = (Total generation kWh) * (12.67 p/kWh)

b. Benefit from export tariff = (Total exported energy kWh) * (4.77 p/kWh)

c. Benefit from energy used locally = (Total energy used kWh) * (14.05 p/kWh)

Benefit for community per year = a + b + c

1. Dalavich and holiday Chalets

The load demand that consists of the village of Dalavich and the holiday Chalets is the first case of the financial approach. The following table shows the benefit for the community (Dalavich and Chalets) in a typical year for each case study.

Table 19: Benefit for the community in a typical year (Dalavich/Chalets)

	Total Supply (MWh)	**Total Demand (MWh)**	**Energy from Grid (MWh)**	**Energy to Grid (MWh)**	**Energy Used (MWh)**	**Benefit for community (£/year)**
No Energy Storage/Grid Constraints	1188.4	244.2	80.9	1025.1	163.3	222414.6
No Energy Storage	1188.4	244.2	80.9	283.1	163.3	187021.3
Batteries 4MWh	1188.4	244.2	55.3	264.1	188.8	189702.2
Batteries 15MWh	1188.4	244.2	28.1	248.0	216.1	192756.7

Where
Energy Used = Total Demand - Energy from Grid.

2. Dalavich, holiday Chalets and Inverinan

The load demand that consists of the village of Dalavich, the holiday Chalets and the village of Inverinan is the second case of the financial approach. The following table shows the benefit for the community (Dalavich, Chalets and Inverinan) in a typical year for each case study.

Table 20: Benefit for the community in a typical year (Dalavich/Chalets/Inverinan)

	Total Supply (MWh)	Total Demand (MWh)	Energy from Grid (MWh)	Energy to Grid (MWh)	Energy Used (MWh)	Benefit for community (£/year)
No Energy Storage/Grid Constraints	1188.4	303.9	99.5	984.0	204.4	226226.3
No Energy Storage	1188.4	303.9	99.5	276.1	204.4	192460.0
Batteries 4MWh	1188.4	303.9	70.7	255.7	233.1	195521.3
Batteries 15MWh	1188.4	303.9	41.0	238.4	262.8	198868.2

Where
Energy Used = Total Demand - Energy from Grid.

<u>Discussion</u>

As explained at the beginning of this section, the benefits for the community were calculated for the two micro-grid options, one that includes the village of Inverinan and one that does not. As expected, the broader micro-grid that consists of the Dalavich village, the holiday Chalets and the Inverinan Village is more beneficial. In the case of 4MWh battery capacity, it is expected to produce 195,521.3£/year compared to 189,702.2£/year in case 1. In the case of 15MWh battery capacity, it is expected to produce 198,868.2£/year compared to 192,756.7£/year in case 1.

In the tables 19 and 20, it is shown that the use of ESS produces higher benefit to the community compared to the case of run-of-river hydro with no storage. In fact, in case 2 as shown in table 20, an ESS with a capacity of 15MWh can produce 198,868.2£/year which is higher by approximately 6,000£/year than the benefit in the case of no ESS which is 192,460.0£/year.

This financial approach is only the first step to evaluate the potential of an ESS in the community. A more detailed analysis that includes the overall cost of an ESS along with the payback period is essential for a complete evaluation.

5.2.5 Sensitivity Analysis

A sensitivity analysis was conducted for the Dalavich run-of-river hydropower scheme. The purpose was to identify the relation of the scale of an energy storage system with the following parameters:

- curtailed energy,
- energy imported from the grid,
- energy exported to the grid and
- autonomy.

The sensitivity analysis was conducted for the Vanadium Redox Flow Batteries because it was considered the optimum choice among the energy storage options that were simulated. The load demand that was taken into account was the sum of Dalavich, the accompanying holiday Chalets and the nearby village of Inverinan because the simulation showed that the overall system operates more efficiently in this case.

Nineteen case studies were created for the Vanadium Redox Flow Batteries based on their capacity (MWh) and they were simulated separately, taking each time the corresponding results for the parameters mentioned above. The results are shown in the following table.

Table 21: Sensitivity analysis results

Case Studies	Capacity (MWh)	Curtailed energy (MWh)	Energy from grid (MWh)	Energy to grid (MWh)	Autonomy (%)
1	4	696.08	70.72	255.67	0.75
2	6	691.57	64.72	252.42	0.76
3	8	687.63	58.72	248.47	0.77
4	10	684.04	52.72	244.09	0.79
5	12	679.11	47.04	241.02	0.80
6	14	675.10	43.04	239.07	0.81
7	16	670.55	39.04	237.72	0.82
8	18	666.11	35.04	236.37	0.82
9	20	661.37	31.04	234.92	0.83
10	22	656.88	27.04	233.22	0.84
11	24	652.84	23.04	231.42	0.85
12	26	648.96	19.05	229.12	0.86
13	28	646.09	17.02	227.97	0.86
14	30	643.49	15.02	226.72	0.86
15	32	640.59	13.02	225.47	0.87
16	34	637.69	11.02	224.47	0.87
17	36	634.63	9.02	223.42	0.88
18	38	631.89	7.02	222.27	0.88
19	40	628.91	5.02	221.07	0.88

The following graph demonstrates the relation between the storage capacity and the curtailed energy.

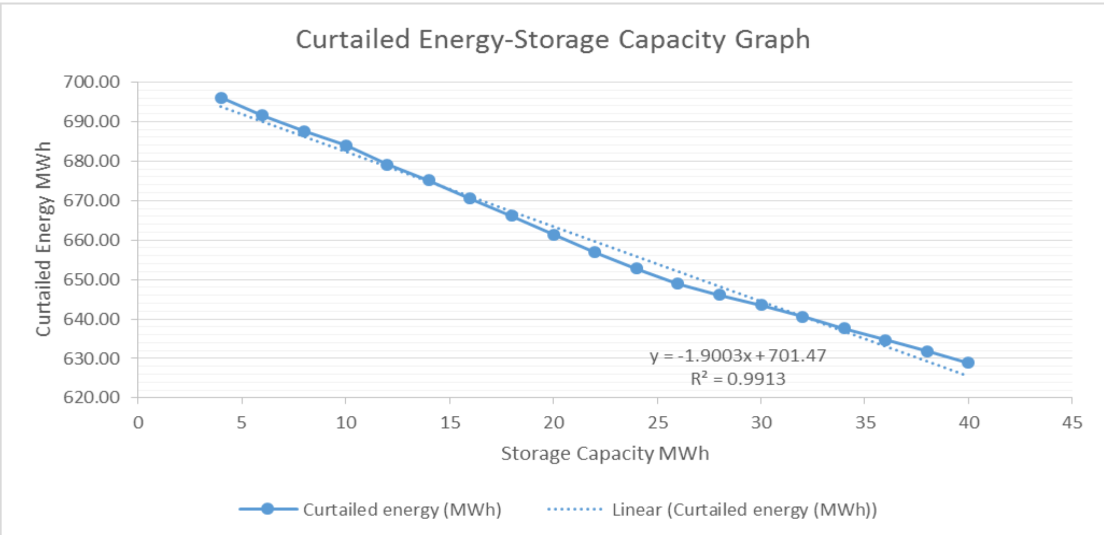

Figure 26: Relation between storage capacity and curtailed energy

The curtailed energy depends almost linearly on the value of capacity. The following formula resulted from the sensitivity analysis.

$$y = -1.9003x + 701.47 \qquad (5.39)$$

where:

y, dependant variable that represents the curtailed energy, [MWh],

x, explanatory variable that represents the capacity of the ESS, [MWh].

With a coefficient of determination:

R^2=0.9913.

R^2 shows how close the data are to the regression line. A value of one shows a perfect fit of the linear model with the simulation data whereas a value of zero represents the case when the linear model cannot represent the data.

The following graph demonstrates the relation between the storage capacity and the energy from the grid.

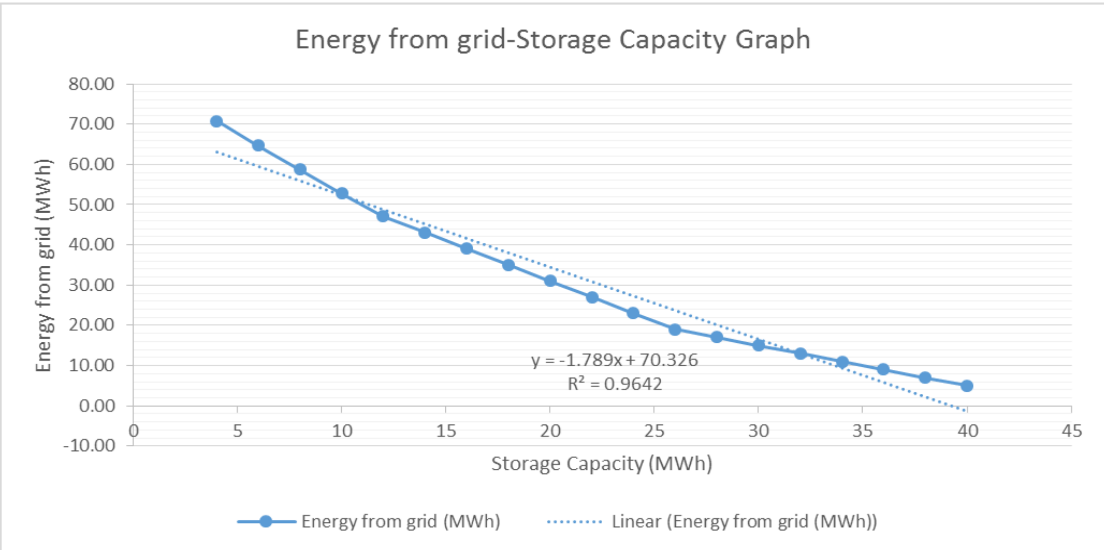

Figure 27: Relation between storage capacity and energy from grid

The energy imported from the grid depends almost linearly on the value of capacity.

The following formula resulted from the sensitivity analysis.

$$y = -1.789x + 70.326 \quad (5.40)$$

where:

y, dependant variable that represents the energy imported from the grid, [MWh],

x, explanatory variable that represents the capacity of the ESS, [MWh].

With a coefficient of determination:

R^2=0.9642.

The following graph demonstrates the relation between the storage capacity and the energy exported to the grid.

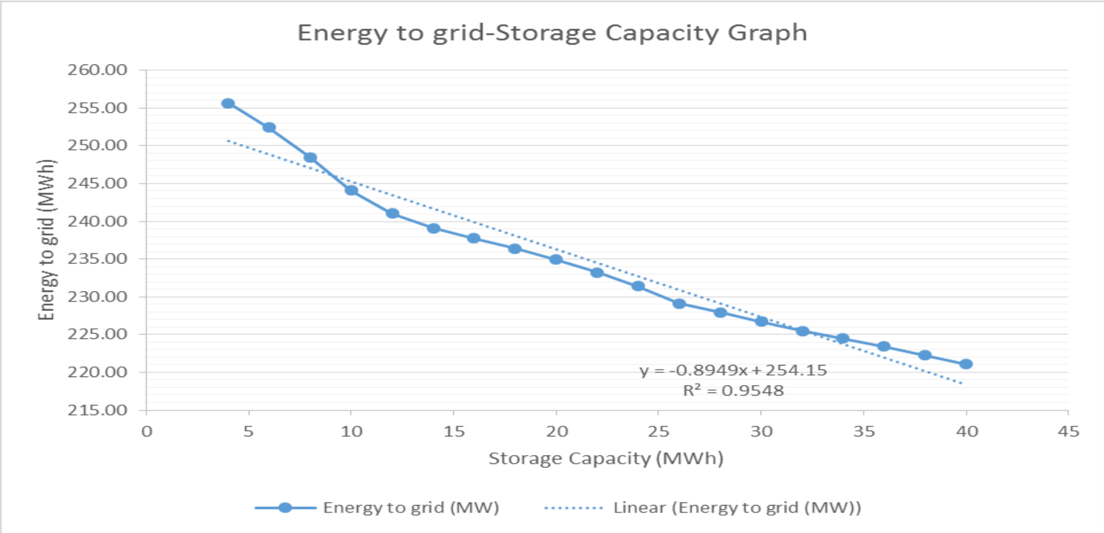

Figure 28: Relation between storage capacity and energy to grid

The energy sent to the grid depends almost linearly on the value of capacity. The following formula resulted from the sensitivity analysis.

$$y = -0.8949x + 254.15 \quad (5.41)$$

where:

y, dependant variable that represents the energy exported to the grid, [MWh],

x, explanatory variable that represents the capacity of the ESS, [MWh].

With a coefficient of determination:

R^2=0.9548.

The following graph demonstrates the relation between the storage capacity and the autonomy of the community (Dalavich, holiday Chalets and Inverinan).

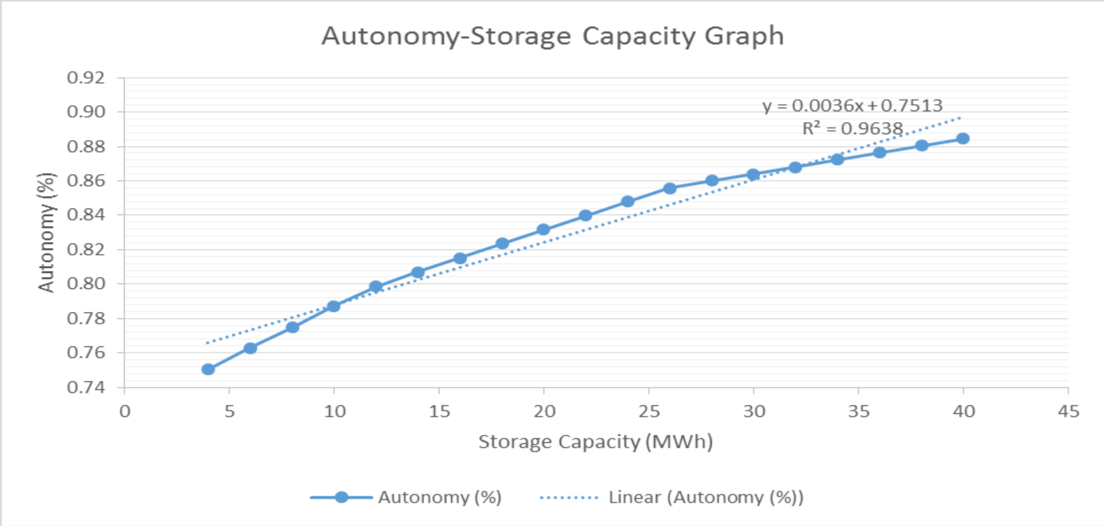

Figure 29: Relation between storage capacity and autonomy

The autonomy of the community depends almost linearly on the value of capacity. The following formula resulted from the sensitivity analysis.

$$y = 0.0036x + 0.7513 \qquad (5.42)$$

where:

y, dependant variable that represents the autonomy of the community, [MWh],

x, explanatory variable that represents the capacity of the ESS, [MWh].

With a coefficient of determination:

R^2=0.9638.

A sensitivity analysis was also conducted for the case of a community load demand that consists of the Dalavich village and the holiday Chalets. The results can be found in the Appendix E.

6 Conclusions

Energy Storage System Modelling

For the purpose of the current thesis, the energy storage system was modelled in a generic form that represents the operation of the majority of systems. **In order to assess a specific technology, it is essential to take into account the unique characteristics of an ESS in order to generate more accurate results.**

Power Flow Equations/Algorithm

The results in this section were generated by having in mind the interconnection of the constituent parts of the case study which was analysed afterwards. **Before using the same algorithm and equations in a relative assessment it is necessary to confirm that the corresponding system shares the same operation principles as the one in the case study.**

Community Demand Data

For the modelling of the demand data in the case study of the run-of-river hydro, mean hourly statistical data were used, related to a UK household. However, the demand might have significant divergence from country to country and from year to year. Depending on the analysis conducted, this modelling process should be used with caution.

Energy Storage Case Studies

The case studies of energy storage which were simulated in the case study were created by having in mind a community energy scheme and all the parameters related to such a system. The magnitude of a storage system and the technology can vary significantly depending on the application.

Case Study Results

Due to the intermittent nature of the run-of river hydro scheme, the load demand cannot be covered throughout the entire year. Even though the months with the smallest energy generation can be briefly predicted, the exact periods the demand is fully covered cannot be defined with absolute accuracy. In figures 24 and 25 which depict the comparison between supply and demand, in both cases it is obvious that even though the supply is significantly higher than the demand during a big part of the year, there is also a big part when demand exceeds supply.

The community requires a massive ESS to achieve 100% autonomy and this is not practically viable. The purpose of an ESS is to supply the community with energy during the period when demand exceeds the supply, thus increasing the community's autonomy. The results in the tables 15 and 17 showed that even a massive energy storage system like CAES with capacity of 250 MWh could not achieve 100% autonomy even though it increased the autonomy significantly. Theoretically, as the capacity increases, the autonomy increases as well. Their exact relation is demonstrated in the sensitivity analysis.

The community requires a massive ESS to reduce the curtailed energy to zero and this is not practically viable. Besides increasing the autonomy of a community, another important parameter studied in this thesis was the curtailed energy from a run-of-river hydro. The purpose of the ESS is to store as much of the excess energy as possible and provide it to the community when demand exceeds supply or sell it to the grid. This way, the energy instead of being curtailed it is utilised to increase the efficiency of the system. The results in tables 15 and 17 showed that even a massive energy storage system like CAES with capacity of 250 MWh could not reduce to zero the curtailed energy even though it achieved a maximum decrease of 34.2%. Theoretically, as the capacity increases, the curtailed energy reduces. Their exact relation is demonstrated in the sensitivity analysis.

The use of ESS results in reducing both the energy imported from the grid and the energy exported to the grid. This is shown in tables 15 and 17 and it means that the community's energy exchange with the grid is reduced in general. This was expected since the ESS also increases the autonomy of the community.

The sole reason why the generated energy is partially curtailed are the local grid constraints. Regarding the grid constraint and the limits it places to the efficiency of a community, the results in tables 15 and 17 proved that this is the only reason of energy curtailment. This was expected because without grid constraints, all the surplus energy would be exported to the grid which is also depicted in the results.

The only parameter of the ESS that has an effect on the energy exchange inside the system is the Capacity. This is obvious from the simulation results of the various case studies of ESS. Parameters like Power Rating and Efficiency have no effect whatsoever. This is shown in the analytical results of the case studies in Appendices C and D. This outcome derives from the fact that the energy required by the community compared to the values of Power Rating and the effect of the storage's Efficiency are significantly lower. The Capacity on the other hand has a big effect because the amount of energy stored affected the amount of curtailed energy and the autonomy. This outcome cannot be generalised to every energy scheme.

The most suitable ESS for the Dalavich run-of-river hydro project is the Vanadium Redox Flow Batteries. This outcome derived from the simulation results that demonstrated the effect of this technology on the system's operation and also the detailed literature review. In page 79, a detailed explanation is provided.

The option of a broader micro-grid that includes the Dalavich village, the holiday Chalets and the Inverinan village is more beneficial than the micro-grid option that does not include the village of Inverinan. The parameters studied (curtailed energy, energy imported from the grid, energy exported to the grid and autonomy) gave better results for the broader micro-grid. This is shown in the results section in page 82 where the two micro-grid options are compared. As expected, the financial approach concluded to the same thing.

Financial Approach

The grid constraints have a big negative impact on the community's overall financial benefit.

The use of ESS increases the financial benefit of the community.

As the capacity of the ESS increases, the financial benefit for the community increases as well.

These outcomes derived from the results depicted in the tables 19 and 20 where the financial benefit for the community is given in four different cases (no ESS and no grid constraints, no ESS, ESS with 4MWh capacity and ESS with 16MWh capacity).

Sensitivity Analysis

Overall, depending on the results that someone wishes to achieve in the efficient operation of a community, they would have to decide on the most suitable capacity of the ESS. **The sensitivity analysis showed that the parameters studied (curtailed energy, energy imported from the grid, energy exported to the grid and autonomy) are linearly related to the system's capacity.** This means that the capacity of the ESS can be calculated with small error variance by deciding on the desirable values of one of the previous parameters (curtailed energy, energy imported from the grid, energy exported to the grid and autonomy). This is practically useful when it is necessary to make a quick estimation with small error variance. This result can vary significantly for a different system and cannot be generalised.

Overall

The purpose of this thesis was to identify the effect that an ESS would have on the operation of a community energy scheme under grid constraints. **The use of ESS increases the efficiency of a community energy scheme and reduces the impact of grid constraints.** However, a detailed financial evaluation is essential in order to conclude which energy storage technology, which storage capacity and under which circumstances an ESS is actually beneficial for a community that generates its own energy under grid constraints.

7 Further Work

After the completion of this thesis, the main results showed the effect that an ESS has on a community that generates its own energy and operates under grid constraints. It is essential to conduct a feasibility analysis on the financial parameters of an ESS in this particular case and decide whether an ESS can actually provide a long term solution on the grid constraints without having a negative effect financially.

The thesis concluded that in this case study, Vanadium Redox Flow Batteries is one of the best choices of energy storage technologies. A more focused study can be conducted on the renewable energy production in a community under grid constraints, using the specific or a similar technology. Also, combining the research with a financial analysis as indicated above would provide a holistic approach on a corresponding project.

The approach of this thesis was to evaluate the effect of an ESS in a system with grid constraints. However, this is not the only way of approaching such a problem. Alternative solutions of utilising the surplus energy can be investigated. Also, instead of focusing on the energy production part of the system, the load demand could be the main focus and aspects like demand side management (DSM) can be investigated in relation to curtailed energy, grid constraints and power exchange.

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Appendix A-Excel/Visual Basic Code

```
Private Sub CommandButton1_Click()

   Dim PWANTED As Single 'Indicates the energy needed to be drawn from the
storage
   Dim USEFUL_POWER As Single 'Indicates the useful energy from the storage
   Dim PS As Single 'Indicates the energy that is injected into or injected from the
storage
   Dim PCURT As Single 'Indicates the energy which is going to be curtailed
   Dim POUT As Single 'Indicates the output energy both from the storage and the
plant
   Dim CURTAILED_POWER As Single 'Indicates the total curtailed energy
   Dim PGIN As Single 'Indicates the energy that will be imported from the grid
   Dim PGOUT As Single 'Indicates the energy that will be exported to the grid
   Dim PTOLOAD As Single 'Indicates the final energy that will be sent to the load
   Dim PWTOT As Single 'Indicates the output energy from the plant
   Dim PL As Single 'Indicates the energy required by the load

   Dim PLIMIT As Single 'Indicates the power that can be transmitted by the line
   PLIMIT = Range("O2").Value

   Dim CAPACITY As Single 'Indicates the capacity of the storage
   CAPACITY = Range("P2").Value

   Dim POWER_RATING As Single 'Indicates the power that can be exported
immediately from the storage
   POWER_RATING = Range("Q2").Value

   Dim CHARGING_RATE As Single 'Indicates the power that can be imported
immediately to the storage
   CHARGING_RATE = Range("R2").Value

   Dim SELF_DISCHARGE As Single 'Indicates the percentage of self-discharge
every hour of the storage
   SELF_DISCHARGE = Range("S2").Value

   Dim EFFICIENCY As Single 'Indicates the efficiency of the storage
   EFFICIENCY = Range("T2").Value

   Dim SOC As Single 'Indicates the state of charge of the storage

For I = 2 To 8761

   PWTOT = Cells(I, "K").Value
   PL = Cells(I, "L").Value
```

```
   USEFUL_POWER = SOC * EFFICIENCY ENERGY THAT CAN BE
EXTRACTED FROM THE STORAGE

      'DECIDE IF THE LOAD REQUIRES ENERGY FROM STORAGE AND/OR
GRID
      If PWTOT < PL Then  'THE LOAD REQUIRES ENERGY FROM STORAGE
         PWANTED = Round(PL - PWTOT, 6) ENERGGY WANTED FROM
STORAGE

         'DISCHARGE FROM STORAGE
         If CAPACITY > 0 Then 'CHECK IF THERE IS STORAGE SYSTEM
            If PWANTED <= USEFUL_POWER Then
               If PWANTED <= POWER_RATING Then
                  PS = PWANTED
                  SOC = Round(SOC - PS, 6)
                  POUT = PWTOT + PS
               ElseIf PWANTED > POWER_RATING Then
                  PS = POWER_RATING
                  SOC = Round(SOC - PS, 6)
                  POUT = PWTOT + PS
               End If
            ElseIf PWANTED > USEFUL_POWER Then
               If PWANTED <= POWER_RATING Then
                  PS = USEFUL_POWER
                  SOC = Round(SOC - PS, 6)
                  POUT = PWTOT + PS
               ElseIf PWANTED > POWER_RATING Then
                  If POWER_RATING <= USEFUL_POWER Then
                     PS = POWER_RATING
                     SOC = Round(SOC - PS, 6)
                     POUT = PWTOT + PS
                  ElseIf POWER_RATING > USEFUL_POWER Then
                     PS = USEFUL_POWER
                     SOC = Round(SOC - PS, 6)
                     POUT = PWTOT + PS
                  End If
               End If
            End If
         Else
            PS = 0
            POUT = PWTOT + PS
         End If
         'DISCHARGE FROM STORAGE

         If POUT = PL Then
            PTOLOAD = POUT
         ElseIf POUT < PL Then
            PGIN = PL - POUT
            If PGIN <= PLIMIT Then
```

```
            PTOLOAD = POUT + PGIN
        ElseIf PGIN > PLIMIT Then
            PTOLOAD = POUT + PLIMIT
        End If
    End If

ElseIf PWTOT = PL Then 'THE LOAD DOESN'T REQUIRE ENERGY FROM
STORAGE AND/OR GRID
    PWANTED = 0 ENERGY WANTED FROM STORAGE
    PS = PWANTED
    POUT = PWTOT + PS
    PTOLOAD = POUT
ElseIf PWTOT > PL Then
    PS = PWTOT - PL

    'CHECK WHETHER THERE IS ADEQUEATE CAPACITY IN THE
STORAGE SYSTEM FOR THE EXCESS ENERGY OR CURTAIL IT
    If CAPACITY > 0 Then 'CHECK IF THERE IS STORAGE SYSTEM
        If SOC < CAPACITY Then
            If PS <= CHARGING_RATE Then
                If PS <= Round(CAPACITY - SOC, 6) Then
                    SOC = SOC + PS
                    PS = 0
                ElseIf PS > Round(CAPACITY - SOC, 6) Then
                    SOC = CAPACITY
                    PS = Round(PS - (CAPACITY - SOC), 6)
                End If
            ElseIf PS > CHARGING_RATE Then
                If CHARGING_RATE <= Round(CAPACITY - SOC, 6) Then
                    SOC = SOC + CHARGING_RATE
                    PS = Round(PS - CHARGING_RATE, 6)
                ElseIf CHARGING_RATE > Round(CAPACITY - SOC, 6) Then
                    PS = Round(PS - (CAPACITY - SOC), 6)
                    SOC = CAPACITY
                End If
            End If
        End If
    End If
    'CHECK WHETHER THERE IS ADEQUEATE CAPACITY IN THE
STORAGE SYSTEM FOR THE EXCESS ENERGY

    POUT = PL
    PTOLOAD = POUT
    If PS > PLIMIT Then
        PGOUT = PLIMIT
        PCURT = PS - PLIMIT
        CURTAILED_POWER = CURTAILED_POWER + PCURT
    ElseIf PS <= PLIMIT Then
        PGOUT = PS
```

```
            PCURT = 0
            CURTAILED_POWER = CURTAILED_POWER + PCURT
          End If

        End If

    Cells(I, "W").Value = SOC

    SOC = Round(SOC - SOC * SELF_DISCHARGE, 6)

    Cells(I, "M") = CURTAILED_POWER
    CURTAILED_POWER = 0

    Cells(I, "U") = PGIN
    PGIN = 0

    Cells(I, "V") = PGOUT
    PGOUT = 0

    Cells(I, "X") = POUT
    POUT = 0

    Cells(I, "Y") = PTOLOAD
    PTOLOAD = 0

    PWANTED = 0
    PS = 0
    PCURT = 0

Next I

USEFUL_POWER = 0
POUT = 0
PWTOT = 0
PL = 0
SOC = 0

End Sub
```

Appendix B–Household Average Daily Electrical Use

Household Average Daily Electrical Use [40]													
Time	Cold Appliances	Cooking	Lighting	Audio-visual	ICT	Washing/drying/ dishwasher	Water heating	Heating	Other	Unknown	Showers	Total	% of Daily Total
00:00	63.6	6.6	39.4	43.8	17.5	26.7	7.7	48.7	14.3	67.2	2.1	337.5	3.0%
01:00	62.2	5.8	24.0	30.9	14.9	12.6	8.7	34.3	13.2	61.7	1.9	270.0	2.0%
02:00	61.6	5.2	18.6	25.2	13.8	8.2	14.6	26.0	12.8	57.3	1.2	244.4	2.0%
03:00	61.4	5.3	16.9	23.2	13.6	7.6	11.0	20.0	13.0	56.6	1.9	230.3	2.0%
04:00	60.9	6.6	16.2	22.0	13.5	5.2	20.2	18.9	12.6	59.5	1.3	236.9	2.0%
05:00	59.6	11.5	17.8	22.6	13.4	4.9	7.9	18.9	12.9	61.9	5.6	236.9	2.0%
06:00	59.3	28.6	23.8	27.2	14.0	11.9	11.7	14.9	13.9	76.5	16.9	298.8	3.0%
07:00	61.3	59.6	45.7	38.1	16.2	34.7	13.8	18.0	18.3	87.0	46.0	438.6	4.0%
08:00	62.6	65.2	48.9	48.7	19.7	65.0	9.9	20.4	21.4	99.8	36.3	498.0	4.0%
09:00	62.3	55.4	34.6	51.1	23.1	82.0	8.8	20.3	22.2	107.0	26.6	493.5	4.0%
10:00	62.6	53.2	29.3	51.3	25.1	85.0	7.1	19.5	23.1	104.5	15.4	476.0	4.0%
11:00	63.6	62.1	26.6	50.8	26.1	81.4	5.7	15.2	26.6	99.0	16.8	474.0	4.0%
12:00	65.4	75.9	26.6	57.4	26.9	76.2	6.4	15.0	26.5	102.3	15.5	493.9	4.0%
13:00	66.1	63.8	25.4	64.2	27.5	70.9	6.7	16.3	24.2	94.9	7.9	467.9	4.0%
14:00	66.2	48.7	26.5	66.0	28.5	66.9	6.9	17.6	23.7	92.2	5.3	448.3	4.0%
15:00	67.3	54.4	29.9	68.9	29.2	67.9	7.4	20.6	25.5	95.1	7.6	473.8	4.0%
16:00	67.8	92.1	50.6	79.2	31.2	63.5	9.4	23.9	26.6	104.6	9.1	557.9	5.0%
17:00	70.2	135.5	82.0	90.0	32.2	59.7	9.2	25.2	24.8	130.7	16.2	675.8	6.0%
18:00	70.8	129.3	108.8	102.6	32.2	62.0	9.5	25.3	24.6	131.8	17.1	714.3	6.0%

19:00	70.3	93.7	125.3	108.3	33.2	73.7	10.2	25.9	22.3	127.7	17.0	707.5	6.0%
20:00	68.7	63.7	127.9	114.7	32.8	69.0	11.3	25.8	19.7	127.7	15.2	676.6	6.0%
21:00	67.9	42.3	133.2	115.0	31.1	55.6	12.8	20.9	19.1	119.7	7.8	625.5	6.0%
22:00	66.7	27.9	121.1	100.0	27.9	44.1	7.2	27.7	17.5	103.6	6.0	549.8	5.0%
23:00	65.4	14.1	74.0	68.6	22.2	37.1	4.5	50.4	15.4	88.4	6.2	446.4	4.0%
Total	1,554.0	1,206.2	1,273.2	1,469.8	565.5	1,171.6	228.6	569.7	474.1	2,257.0	302.8	11,072.4	100%
This table shows the average electricity use profiles from 250 households, monitored over 12 months using meters on total electricity use and most appliances.													
Source: Household Electricity Use Survey 2010-11													

Appendix C-Simulation Results: Dalavich/Chalets

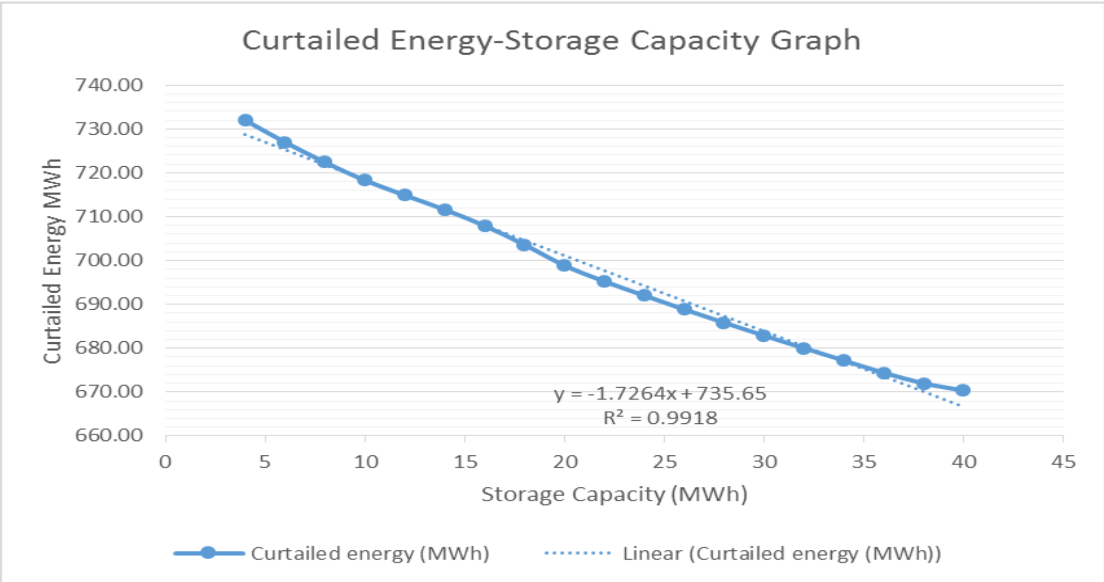
Dalavich-Holiday Chalets					
Storage Type	**Case study**	**Curtailed energy (MWh)**	**Energy from grid (MWh)**	**Energy to grid (MWh)**	**Autonomy (%)**
No Energy Storage/Grid Constraints	-	0.00	80.87	1025.09	69.8
No Storage	-	742.00	80.87	283.09	69.8
Megawatt Scale Energy Storage					
Advanced Lead-Acid Batteries	1	733.63	57.75	265.52	74.7
	2	724.19	45.99	259.32	76.7
	3	716.39	35.93	253.19	78.3
	4	709.85	28.13	247.99	79.5
Vanadium Redox Flow Batteries	1	731.98	55.35	264.12	75.2
	2	722.98	44.34	258.32	76.9
	3	716.01	35.73	252.99	78.3
	4	**709.85**	**28.13**	**247.99**	**79.5**
Zn/Br Flow	1	729.36	52.35	262.72	75.6
	2	722.00	42.75	257.22	77.2
	3	715.27	34.73	252.29	78.5
	4	709.85	28.13	247.99	79.5
Li-ion	1	731.98	55.35	264.12	75.2
	2	722.98	44.34	258.32	76.9
	3	716.01	35.73	252.99	78.3
	4	709.85	28.13	247.99	79.5
Sodium-Sulfur	-	724.04	45.75	259.17	76.7
Fe/Cr Flow	-	731.98	55.35	264.12	75.2
Zn/air	-	728.34	51.15	262.12	75.8
CAES	-	509.23	0.00	185.59	84.0
Kilowatt Scale Energy Storage					
Advanced Lead-Acid	1	741.83	79.20	281.58	70.2
	2	741.73	78.53	281.00	70.3
	3	741.66	77.96	280.49	70.4
	4	741.60	77.41	280.01	70.6
Li-ion	1	741.97	80.31	282.67	70.0
	2	741.96	80.15	282.54	70.1
	3	741.95	80.02	282.50	70.2
	4	741.95	79.90	282.41	70.2
Zn/Br Flow	-	741.88	79.20	281.70	70.3

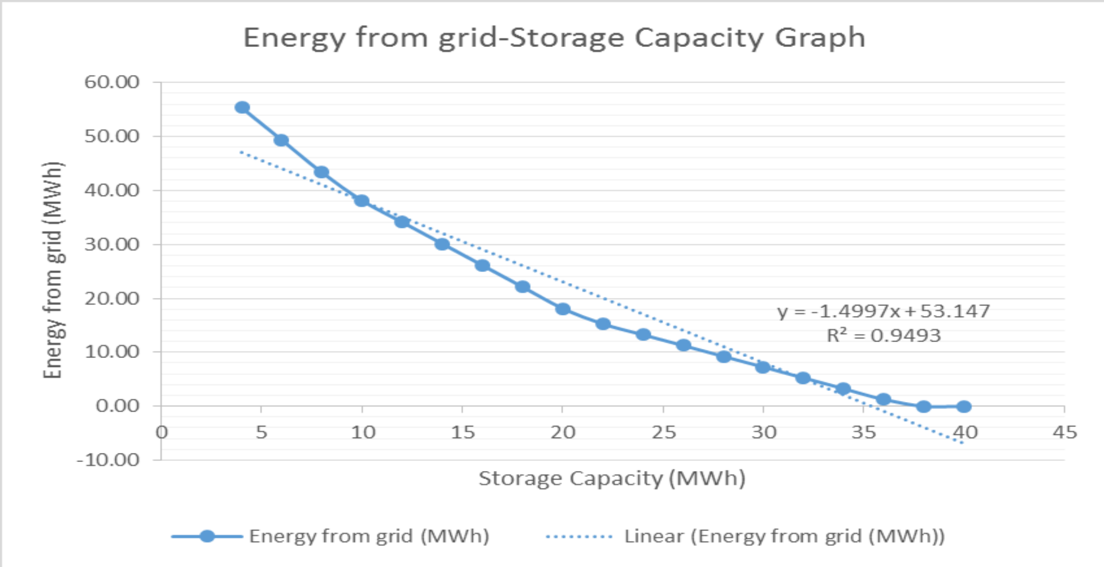
Appendix D-Simulation Results: Dalavich/Chalets/Inverinan

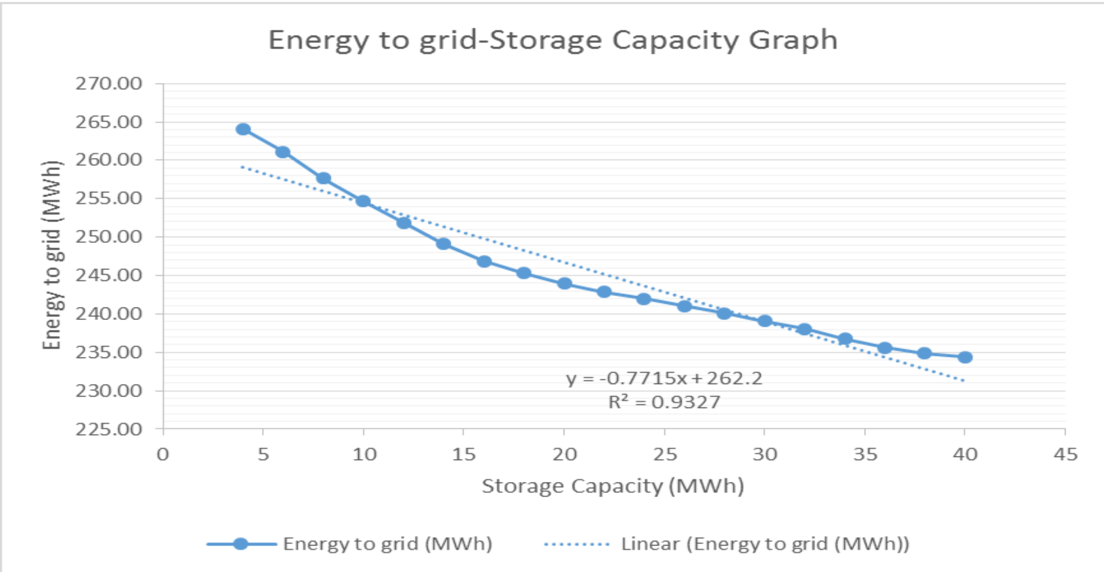
Dalavich-Holiday Chalets-Inverinan					
Storage Type	**Case study**	**Curtailed energy (MWh)**	**Energy from grid (MWh)**	**Energy to grid (MWh)**	**Autonomy (%)**
No Energy Storage/Grid Constraints	-	0.00	99.46	984.01	68.7
No Energy Storage	-	707.89	99.46	276.13	68.7
Megawatt Scale Energy Storage					
Advanced Lead-Acid Batteries	1	698.26	73.12	256.82	74.6
	2	689.32	61.36	250.22	77.0
	3	681.49	49.42	242.24	79.4
	4	672.89	41.04	238.42	81.1
Vanadium Redox Flow Batteries	1	696.08	70.72	255.67	75.0
	2	688.12	59.71	249.02	77.3
	3	680.97	49.12	242.01	79.5
	4	**672.89**	**41.04**	**238.42**	**81.1**
Zn/Br Flow	1	693.82	67.72	254.07	75.6
	2	687.21	58.12	248.07	77.6
	3	679.76	47.65	241.37	79.7
	4	672.89	41.04	238.42	81.1
Li-ion	1	696.08	70.72	255.67	75.0
	2	688.12	59.71	249.02	77.3
	3	680.97	49.12	242.01	79.5
	4	672.89	41.04	238.42	81.1
Sodium-Sulfur	-	689.06	61.12	249.97	77.0
Fe/Cr Flow	-	696.08	70.72	255.67	75.0
Zn/air	-	693.01	66.52	253.37	75.9
CAES	-	465.70	0.00	169.22	89.5
Kilowatt Scale Energy Storage					
Advanced Lead-Acid	1	707.71	97.23	274.15	69.4
	2	707.59	96.60	273.69	69.5
	3	707.48	96.00	273.22	69.8
	4	707.39	95.46	272.68	70.0
Li-ion	1	707.86	98.66	275.50	69.1
	2	707.85	98.44	275.43	69.1
	3	707.85	98.24	275.23	69.2
	4	707.84	98.06	275.12	69.3
Zn/Br Flow	-	707.75	97.23	274.36	69.5

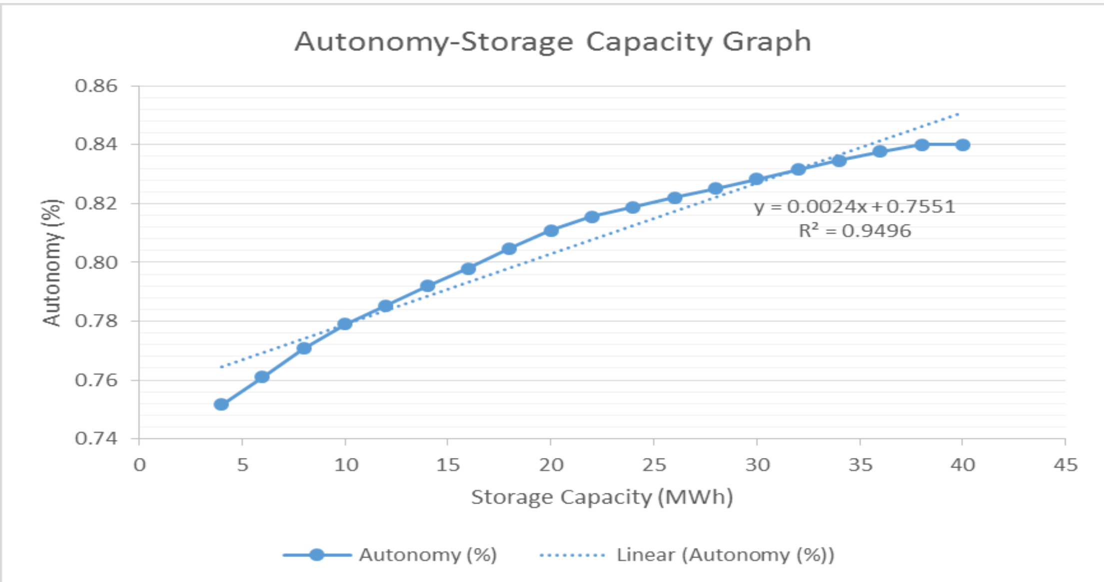
Appendix E-Sensitivity Analysis: Dalavich/Chalets

Case Studies	Capacity (MWh)	Curtailed energy (MWh)	Energy from grid (MWh)	Energy to grid (MWh)	Autonomy (%)
1	4	731.98	55.35	264.12	0.75
2	6	726.99	49.35	261.12	0.76
3	8	722.42	43.35	257.62	0.77
4	10	718.29	38.13	254.67	0.78
5	12	714.91	34.13	251.90	0.79
6	14	711.62	30.13	249.13	0.79
7	16	707.95	26.13	246.89	0.80
8	18	703.62	22.13	245.29	0.80
9	20	698.89	18.13	243.94	0.81
10	22	695.26	15.26	242.84	0.82
11	24	692.03	13.26	241.99	0.82
12	26	688.87	11.26	241.04	0.82
13	28	685.86	9.26	240.09	0.83
14	30	682.89	7.26	239.09	0.83
15	32	680.05	5.26	238.04	0.83
16	34	677.24	3.26	236.74	0.83
17	36	674.44	1.26	235.64	0.84
18	38	672.01	0.00	234.84	0.84
19	40	670.39	0.00	234.39	0.84




Energy from grid-Storage Capacity Graph
60.00
50.00
40.00
30.00
20.00
10.00
0.00
-10.00
Energy from grid (MWh)
0
5
10
15
20
25
30
35
40
45
Storage Capacity (MWh)
y = -1.4997x + 53.147
R² = 0.9493
Energy from grid (MWh)
Linear (Energy from grid (MWh))


Energy to grid-Storage Capacity Graph
270.00
265.00
260.00
255.00
250.00
245.00
240.00
235.00
230.00
225.00
Energy to grid (MWh)
0
5
10
15
20
25
30
35
40
45
Storage Capacity (MWh)
y = -0.7715x + 262.2
R² = 0.9327
Energy to grid (MWh)
Linear (Energy to grid (MWh))


Autonomy-Storage Capacity Graph
0.86
0.84
0.82
0.80
0.78
0.76
0.74
Autonomy (%)
0
5
10
15
20
25
30
35
40
45
Storage Capacity (MWh)
y = 0.0024x + 0.7551
R² = 0.9496
Autonomy (%)
Linear (Autonomy (%))