Department of Mechanical and Aerospace Engineering

Strategies for harnessing and integrating renewables into electricity consumption and their application to ecovillages

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Copyright Declaration

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Abstract

The overarching goal of the dissertation is to study strategies to increase the integration of renewable energy systems by better align supply with demand. Indeed, the recent increase in renewable-generated electricity has raised concerns about orchestrating supply with demand in order to maximise renewable use.

The optimisation of system design offers opportunities to cope with this challenge and allows for better energy management. The diversification of the electricity generation mix by adding renewable capacities and storage development have been investigated and applied to the electrical system of real ecovillages. The Findhorn and the Tamera communities have been selected to conduct the study as they differ on a great number of points and a general methodology to investigate energy system design opportunities has been defined. The technical and financial feasibility of alternative systems has been conducted by using a standard software package for microgrid system optimization. Through the investigation, the capabilities of the software have been underlined and limitations not mentioned in the literature review have been determined. Also, potential developments have been suggested to address these gaps.

After a complete investigation of technology opportunities for the Findhorn ecovillage, it has been seen that adding solar capacity to the current generation mix would result in more local renewable use than adding the same wind capacity. In regard to storage systems, the energy performance of traditional lead-acid batteries has been compared to those of newer technologies such as vanadium redox flow batteries and lithium-ion batteries. It has been seen that for a same useable capacity, lithium-ion batteries would result in better demand/supply matching due to high efficiency and high discharge power capability. Also, adding 50 kW of solar capacity coupled with 38 kWh of lithium-ion batteries to the current system would result in +15.9% of local renewable use. For the Tamera ecovillage, it has been seen that adding two battery banks of 84 kWh each would absorb the excess of electricity and avoid photovoltaic (PV) output curtailment as grid frequency would be maintained.

Finally, future work has been suggested to complete the current study and achieve another step towards energy autonomy for communities.

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Table of Contents

List of Figures

List of Tables

List of Equations

Chapter 1: Introduction and objectives

Sustainability as a framework for renewable penetration

1.1 Background

Energy has been harnessed through ages and has fuelled the past in an interruptible way. However, most of the energy sources which have been used so far are finite supplies and their actual reserves are decreasing (Mackay, 2009). Here is the current challenge: future energy supplies must deliver reliable energy to power life without creating unnecessary damage to the environment.

In recent years, sustainability has been brought to the forefront of an increasing number of construction and design projects and the production of renewable energy is of interest more than ever as three topical issues have to be faced in the 21st century:

- A social issue: the world population growth
- An economic issue: the rise of oil price due to depleted reserves
- An environmental issue: the increasing level of CO_2 emissions

An increased use of renewable energy has the potential to reduce dependency on fossil fuels which is a twofold incentive. Indeed, not only fossil fuel reserves are depleting but the intensive production of energy from fossil fuel releases carbon in the atmosphere which contributes to climate change. Although the trend is to reduce energy consumption over time, dependency on fossil fuel is still high and stays from far the main source of energy. For example, it accounted for more than 85% of the UK total primary energy consumption in 2012 as shown below in Figure 1.

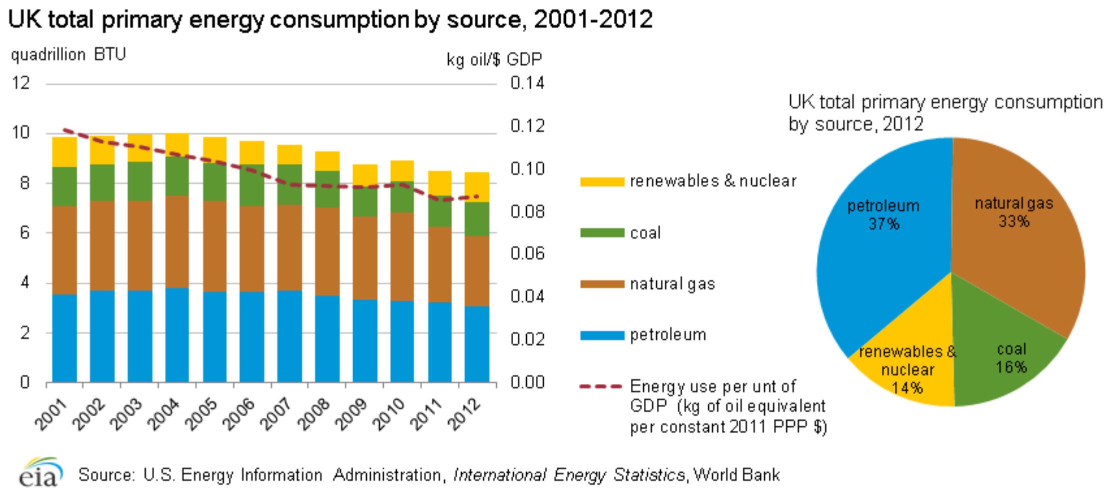

Figure 1: UK total energy consumption from 2001 to 2012. Source: EIA, 2014.

In order to reduce its use of fossil fuel and consequently its reliance on imports, the UK has undertaken a vast decarbonisation policy promoting the use of renewable energy. The concepts of community energy systems and smart grids have been developed by technology improvements to lead to energy efficiency. Also, trade agreements have been altered to financial incentives for local renewable manufacture and microgeneration within communities. Regulations such as Feed in tariffs (FIT) have been set to ensure revenue for local producers per unit of electricity produced from renewables. Excess of renewable energy production can be sold to the grid and tariff models are available to provide customers with potential money savings on electricity bills if they shrewdly control their energy systems (Healy and MacGill, 2012).

However, the decreasing use of fossil fuel is slow as low-carbon energy production requires important investment for infrastructure and investing in renewables might not appear attractive to producers. Indeed, the first challenge of producing electricity from renewables is to match supply and demand (Boyle, 2007). Although the UK has important wind resources, forecast is not infallible and wind power is unpredictable in the medium term and the long term. As the development of renewable technologies has been supported in recent years, more and more households, commercial buildings and communities have installed renewable energy systems and there is still a massive need to achieve greener buildings. This increased amount of renewable-generated electricity raises all the more problems of matching supply and demand and this is expected to be intensified in the coming years. Figure 2 illustrates the evolution of the electrical generating capacity of renewable energy in the UK from 2000 to 2012.

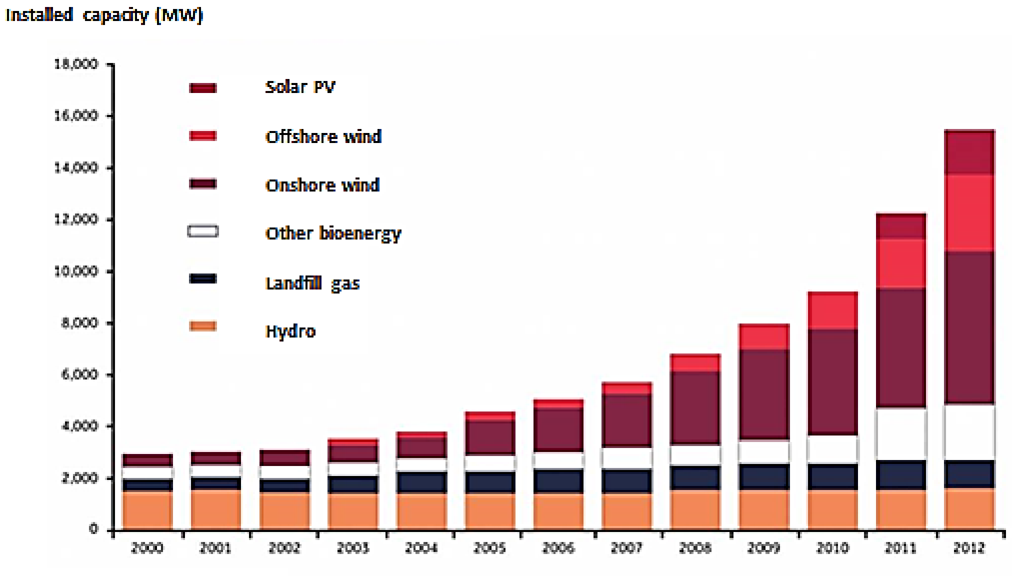

Figure 2: Electrical generating capacity of renewable energy in the UK. Source: DECC, 2012.

It can be seen that the UK has considerably increased its renewable energy production capacity in the last decade although the renewable penetration in energy consumption still accounts for a minority. As a case in point, the UK government announced in the Digest of United Kingdom Energy Statistics (2015) that the contribution of renewables to the UK gross electricity consumption was 17.8% in 2014. The low penetration of renewable power in energy consumption is due to the mismatching of renewable supply with demand, requiring energy imports and exports and resulting in important dependency on the local grid. This can cause problems of grid stability, security and reliability of power supply.

Managing carefully the different energy sources, load and energy storage within microgrids could help to achieve the Scottish target which aims to cover 100% of electricity demand from renewables by 2020. Consequently, it is of interest to develop strategies to increase renewable penetration and maximize the share of renewables in electricity consumption. This is especially beneficial for communities willing to increase their energy autonomy.

Currently, rechargeable energy storage is expensive compared to storage offered through fossil fuel but electrical storage has received much interest in recent years due to deployment of electric vehicles and electric space heating. The learning process on energy storage is pursued and storage technologies are expected to play an essential role in the future energy system. Following pioneering research conducted by The Energy Research Partnership in 2011, it has been shown that possible pathways for the future UK's energy system will very likely put large-scale energy storage in a critical position.

Even though a great number of challenges are posed by society's transition to a low carbon economy, a decrease in prices, improved energy systems efficiency and better acceptance of the technology would allow for a quicker way to a low carbon electricity production.

1.2 Project objectives

The overarching goal of this dissertation is to study strategies to harness renewables and increase their integration into the electrical system by better aligning supply with demand. It also deals with developing a methodology to integrate them into energy systems and to analyse their impact on the overall energy performance. These strategies have been tested on real energy systems of ecovillages in order to develop a general procedure for auxiliary technology analysis. Microgrid energy system analysis has been conducted by means of industry standard software and another objective is to test capabilities and limitations of computing tools. The final objective is to provide a deliverable which advices each community on future alternative energy system designs to optimize community energy management.

The objectives of the project have been refined once the literature review has been conducted and has scoped the project. They are presented in Chapter 3 in the methodology section of the thesis.

Chapter 2: Literature review

The electricity system in context

Electricity is used every day without consideration for the complex energy system behind this. Various actors such as electricity generators, distribution network operators and suppliers play an important role in the energy system.

2.1 The National Grid

The National Grid is the transmission network in Great Britain that ensures the transport of bulk energy via high-voltage power lines. It connects power stations to substations and so carries electricity from generating centres to demand centres.

The electricity transport from generating plants to customers through the National Grid is shown in Figure 3.

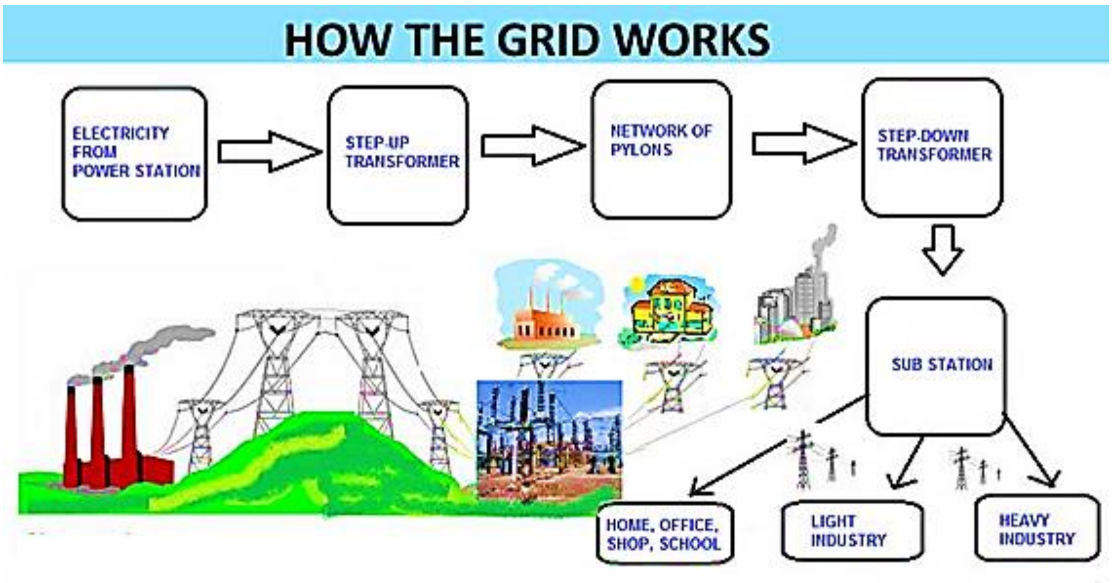

Figure 3: Principle of the national grid operation. Source: ABB, 2007.

The transport of electricity from generating power plants to consumers involves the combination of two different networks, the electric-power transmission network and the electric power distribution network.

First of all, electricity is generated from power stations and then goes to step-up transformers to increase voltage and reduce energy loss. It passes through transmission lines to be carried near the demand centres before going through step-down transformers to adjust voltage to customer requirements. The next step is to reach sub stations which distribute power through transmission lines to the different customers with different power needs. Usually, transmission and distribution losses are rated at 6% of the total energy produced (ABB, 2007). This is explained by the fact that generating plants are usually far from demand centres which results in non-negligible energy wastage. Wind and solar plants are ideally situated in areas of high average wind speed and high average solar radiation, respectively. Such areas are usually distant from sites of electricity demand and transmission and distribution networks often need to be extended to connect sources of energy supply with electricity demand sites. This results in grid interconnection costs for wind and solar energy which is a current challenge for the UK and the North of Germany as these costs have been estimated at 0.9 c/kWh in the EU and must be covered either by producers or consumers (IEA, 2011).

Also, a key limitation of electricity generation is that electrical energy cannot be stored directly, and consequently has to be produced according to demand. Thus, energy management has to be finely controlled to ensure that generation is well-adjusted to a demand coming from a vast range of customers, including industrial, commercial and domestic users. It is critical that the energy system stays balance at all times. The grid is responsible for providing reserve services and frequency response to ensure available generating capacity in case of disruption to the supply (Gomez-Exposito, Conejo and Canizares, 2009). If the electrical demand exceeds supply, generation and transmission can be shut down and lead to major blackouts as experienced in the US in 2011. In order to reduce the risk of such shortage, electric transmission networks are interconnected into regional, national or continent wide networks and hence provide various alternative routes to supply power in case of equipment failures. Also, adding local and small scale energy sources in the energy generation mix has opportunities in grid services.

2.2 From centralized towards decentralized power generation

The ambitious EU's target of 20% renewable energy by 2020 requires a transformation of the energy system. The UK government has developed plans to maximise the potential of decentralised supply and distributed generation. Distributed energy can harness a wide range of smaller-scale renewable and low carbon energy sources (DECC, 2012). If it is developed locally, it requires community involvement and investment.

A great number of communities are already investigating ways of developing more integrated local energy systems, involving the orchestration of locally-produced renewable electricity, local heat networks, storage devices, and electricity distribution systems. This is physically expressed by means of microgrids, or small-scale power networks, which allow for possible export of the excess of locally-generated power to the main grid. This can provide services to the grid and reduce the risks of blackouts during peak loads. However, the modernization of the grid is of concern to avoid problems of stability due to the reception of important amount of renewable energy coming from microgrids. This is especially true for grid-tied systems in remote areas which often have an interconnection with aging and weak grids. Kirby and Hirst (1997) explain that fluctuations in active and reactive power can cause problems such as flickers, voltage fluctuation and harmonic distortion which can be expected if the grid is not properly set. Consequently, increasing energy independency of the grid can be a safety and security concern.

Also, decentralized systems allow for active energy consumption by providing flexible decision-making. Better capacity use of renewables as well as reduction in CO_2 emissions are expected to be achieved through decentralized generation. The transition from centralized power systems to decentralized power systems is illustrated in Figure 4.

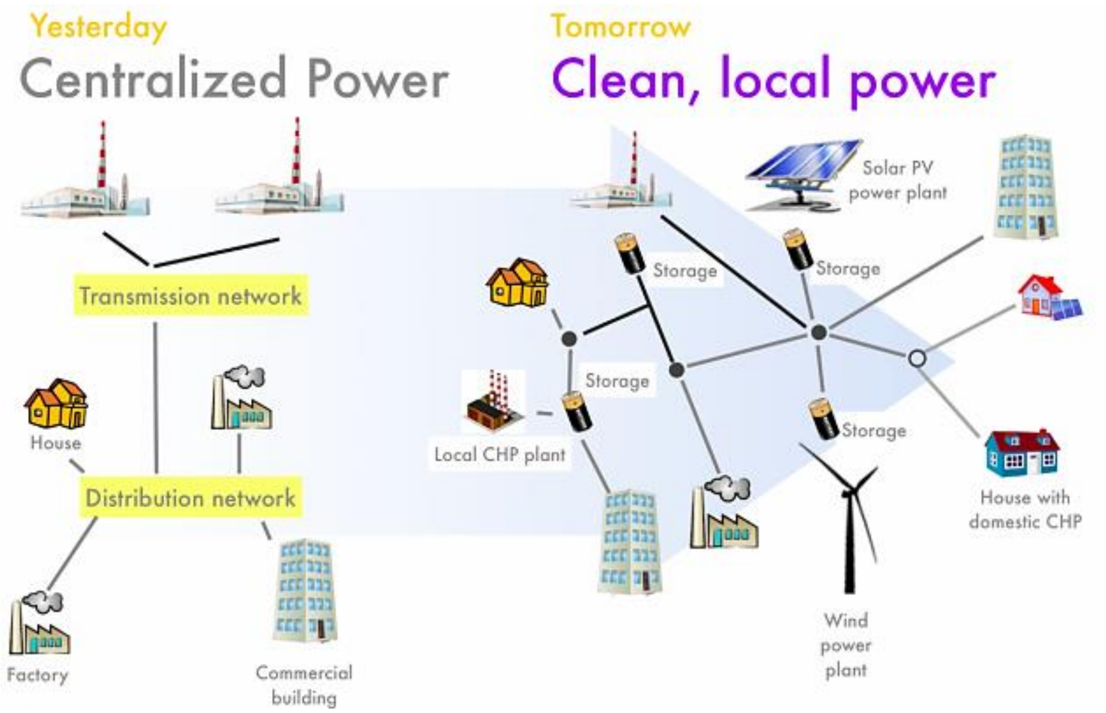

Figure 4: From centralized to decentralized power system. Source: Farrell, 2011.

It can be seen in Figure 4 that the future energy system required to produce clean power locally would involve more actors than the energy system of yesterday. According to The Energy Research Partnership (2011), renewable sources are expected to play a critical role in the future energy system by adding diversity to electricity generation mix. Indeed, electrical demand might increase due to a rapid decarbonisation of power production through the electrification of heat and transport. Also, increasing renewable generating capacity coupled with storage has the ability to improve renewable energy penetration in electricity consumption and so to reduce climate change.

However, the shift from a centralized power generation to a decentralized power production raises concerns about energy management and improved efficiency. If correctly implemented, distributed generation can allow for the benefits shown in Figure 5.

DG Services	Energy Cost Savings	Savings in T&D Losses and Congestion Costs	Deferred Generation Capacity	Deferred T&D Capacity	System Reliability Benefits	Power Quality Benefits	Land Use Effects	Reduced Vulnerability to Terrorism
	Benefit Categories							
Reduction in Peak Power Requirements	✓	✓	✓	✓	✓	✓	✓	✓
Provision of Ancillary Services –Operating Reserves – Regulation – Blackstart –Reactive Power	✓	✓	✓	✓	✓	✓	✓	✓
Emergency Power Supply	✓	✓			✓	✓		

T&D= transmission and distribution.

Figure 5: Matrix of distributed generation and services. Sources: Consortium on Energy Restructuring, Virginia Tech, 2007.

Some of the benefits provided by distributed generation and especially of interest for communities are increased system reliability, emergency power supply, reduction of peak power requirements, operating reserves and money savings.

2.3 Distributed generation towards the energy cloud

In recent years, decentralized systems such as communities and small and medium enterprise-based systems have opted for hybrid microgrids as power systems. This involves distributed generation which is shrewdly controlled to supply the different loads. To further the benefits of distributed generation while mitigating its weaknesses, certain projects are currently developing energy systems based on cloud computing to maximise energy efficiency. This is the case of the ORIGIN (Orchestration of Renewable Integrated Generation in Neighbourhoods) project which is currently developed in three ecovillages and will be presented in Section 2.7 of the thesis. Figure 6 represents the main characteristics between centralized, distributed and energy cloud systems.

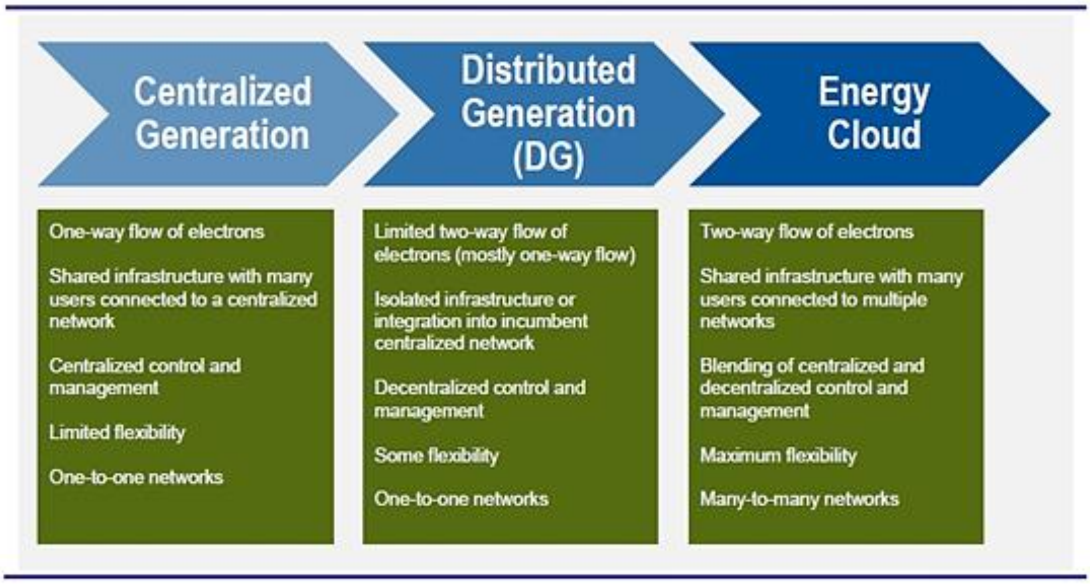

Figure 6: Evolution to the energy cloud from centralized and distributed generation. Source: ABB, 2007.

Firstly, centralized generation involves a one-way flow of energy that brings the energy configuration in one-to-one networks with centralized control and management, which significantly reduces flexibility.

Secondly, distributed generation involves a limited two-way flow of energy with decentralized control which allows for some flexibility in energy management. Such systems usually involved smart meters and energy storage.

Thirdly, the energy cloud concept can be developed to obtain maximum flexibility in the energy system via a two-way flow of energy that involves centralized and decentralized control at the same time. Such a system can be built to provide solutions to challenges in energy efficiency and demand-side management. They also allow for disaster recovery, automatic software update, increased collaboration, competitiveness and are environmentally-friendly (Lee and Zomaya, 2010)

2.4 Distributed Energy systems challenges

In the transition to a low carbon economy, efforts are focused on developing technologies able to achieve the functionality of fossil fuels that show high energy densities, are easy to store and transport in the existing infrastructure that has been built over decades and centuries. As mentioned in the previous section, the current pathways to the future UK energy system could lead to increasing electricity demand and increasing renewable generation that could provide significant low-carbon electricity generation. However, renewable energy integration into the electricity system is challenging due to greater variability in the supply/demand relationship introduced by increasing renewable energy production. The Energy Research Partnership (2011) defines a three-way challenge in the current energy system which consists in achieving reliable supply in a cost-effective manner while meeting carbon reduction targets.

Energy challenges occur on different timescales as shown in Table 1.

Timescale	Challenges
Seconds	Renewable generation introduces harmonics and affects power supply quality
Minutes	Rapid ramping to respond to changing supply from renewable generation affects power frequency
Hours	Daily peak for electricity is greater to meet heat demand
Hours-days	Variability of renewable generation needs backup supply or demand response
Months	Increased use of electricity for heat leads to strong seasonal demand profile

Table 1: Energy challenges according to timescales. Source: The Energy Research Partnership, 2011.

Several strategies are suggested to meet these challenges and are as follows:

- Diverse generation mix associating renewables with flexible plants, including nuclear and fossil fuel, that provide dispatchable energy to adapt generation in a cost-effective way and meet extra demand when renewable output is not available
- Demand side management, currently quite limited but might be developed by the use of smarts meters and user interfaces that provide opportunities for money savings and load shifting
- Grid interconnection to provide flexibility through additional energy capacity or load

- Hydrogen considered as an energy vector and storage option
- Energy storage which has the potential to meet current energy challenges by time-shifting supply and demand

The diversification of generating resources, demand-side management and energy storage are further discussed as they are options of interests for the present study to increase supply and demand matching in ecovillages.

2.5 Strategies for meeting energy challenges

Building an efficient renewable grid might appear challenging but has the potential to create job and stimulate the economy through investment in green infrastructure. According to Schneider Electric, renewables bring new challenges to grid managers but also stimulate new technical opportunities. Some potential strategies to cope with the intermittency and unpredictability of renewable energy output and so to ensure a reliable green energy supply are detailed in this section.

2.5.1 Demand side management (DSM)

The move towards a low carbon economy with increased renewable energy production will bring centre-stage the need for matching peak demand and renewable supply which often do not coincide. According to Qureshi et al. (2011), demand side management is "the planning, implementation, and monitoring of distribution network utility activities" which is used as a load shaping tool to influence customer's electricity behaviors. Changes in load can happen on time scale or on magnitude scale. Usually, the goal of DSM is to raise consumer awareness and encourage him to use less energy during peak hours, usually by moving the time of energy demand to off-peak hours, for examples at nights and on weekends. Smart meters and other smart technologies generate data that can be used to utilise electricity efficiently while advance control systems can send control signals to appliances in order to achieve demand side response. Figure 7 shows benefits of DSM on demand load profile. .

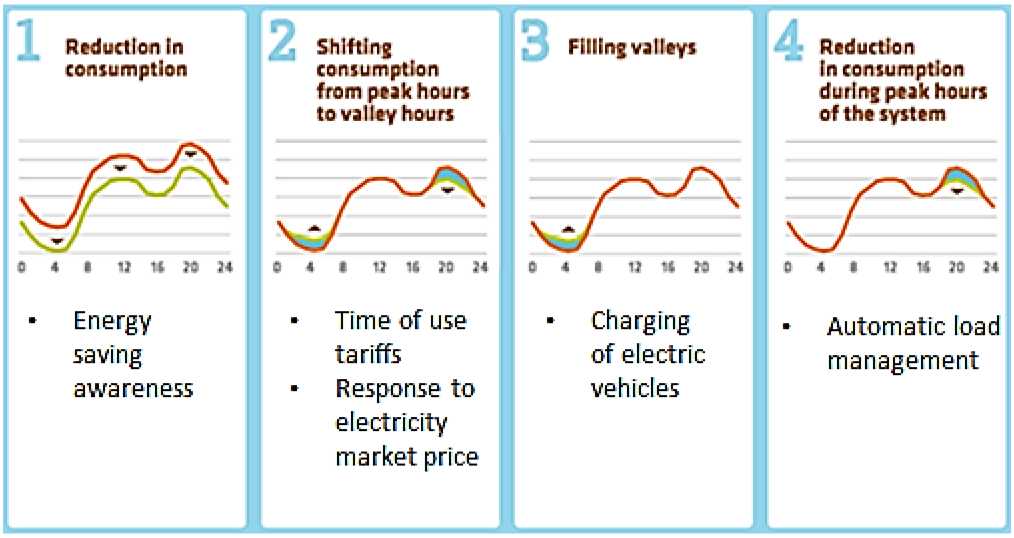

Figure 7: Main objectives of demand side management. Qureshi et al., 2011.

It can be seen that different strategies in DSM have different effects on load profile. DSM is basically a strategy to take advantage of electricity market price which varies according to the time of the day. Customers can shift their electricity demand from peak hours to off-peak hours to aim money savings or use load shifting to consume electricity when renewable output is high and increase the share of renewables in electricity consumption. It also aims to reduce energy consumption and by means of smart devices, consumers do not need to make conscious decision on switching on or off appliances if an automatic load management is set.

In sum, DSM is a mechanism to achieve load shifting and so orchestrate supply with demand.

2.5.2 Dispatchable and non-dispatchable generation mix

Another strategy usually proposed to overcome the unscheduled output of renewables is to diversify the mix of energy sources, associating both dispatchable and non-dispatchable energy whose generation is coordinated by a smart electronic grid management system. Dispatchable generation refers to generating plants that can be turned on or off, or can adjust their output according to demand. This is the case of hydropower plant while wind farm and solar plant do not have this ability. It is important to combine non-dispatchable energy generation with dispatchable generation to offset the intermittency of renewable output and ensure that load can still be met in the event of unavailability of renewable resources. Flexible power sources can smooth out the stochastic output of renewable and consequently ensure the balance of the system at all times. Typical load profiles of seasons explain why diverse energy mix in power generation ensures easily the synchronization between load and generation.

Figure 8 shows typical load curves for electricity grid.

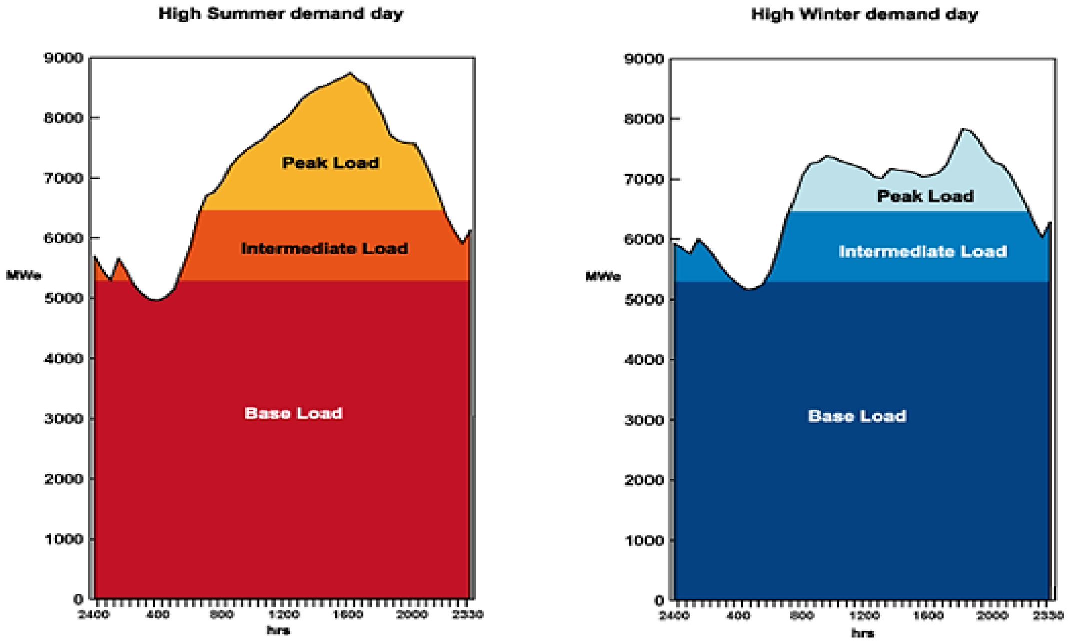

Figure 8: Typical load curves of electricity grid. Source: World Nuclear Association, 2015.

It can be seen that the load curve diagram is separated in three types of load; base load, intermediate load and peak load. Base load accounts for most of the electricity demand which is for a continuous and reliable supply while intermediate load accounts for less energy and is required around three quarters of the day. Finally, variable but predictable peak demand is required around half of the day and accounts for even less energy. Part of the overnight demand comes from domestic hot water systems which take advantage of cheap night tariffs and from refrigerators and cold storage which are never turn off. Usually, fossil fuel and nuclear power are used to meet base load demand as they provide reliable supply. Given the potential of development of electric vehicles in coming years, it can be seen easily how overnight charging of electric vehicles would increase the base load proportion, increasing at the same time the scope for nuclear and other plants which produce base load power.

Load matching refers to changes in power demand during the day which requires changes in power supply as well, for example less power is usually used at night than during the day. Load matching is important to keep a balanced system at all times. Peak matching refers to short periods of time over which demand is higher than the generation of load matching plants. It corresponds to the highest demand during the day and usually happens at predictable times which depend on culture and climate. Also, there is often a lack of synchronization between renewable output and peak load. As a case in point, locations with hot weather are usually the hottest around 4pm when the output of PV panels can be expected to be the highest while electricity peak demand is typically around 7pm when people go back home from work and start using electrical equipment. Similarly, countries with high wind resources have usually the highest wind speed at night and so the highest wind power output when the demand is the lowest. Consequently, renewable energy sources have to be associated with dispatchable power sources which provide the flexible generation required to accommodate peak loads and which has to be deployed in time frame of minutes or hours. In sum, the combination of dispatchable and non-dispatchable generation is required for both load matching and peak matching.

However, the integration of renewable energy supply in both base load demand and peak load demand is limited without energy storage. Indeed, most of renewable energy sources, apart from hydro power, do not have in-built storage and their output cannot be adapted to demand. Hence, the intermittency of renewable sources raises the issue of back-up capacity and for stand-alone systems, energy storage appears to be the main challenge. Apart from pumped-storage hydro systems, there is no available storage technology on any large scale which makes large-scale energy storage of special interest.

2.5.3 Energy storage opportunities

This is arguable that renewable energy sources have significant potential to meet mainstream electricity needs. The utilisation of solar and wind energy has spectacularly soared in recent years and now that the issue of harnessing them has been solved, the further challenge of their integration into the supply system arises.

By increasing the penetration of renewables in electricity use, it would considerably reduce peak electricity cost and develop the renewable technologies market. Thus, this challenge directly puts at stake the future of renewable energy systems. Energy storage technologies have the potential to increase the share of renewables in electricity consumption by storing energy during generating times rather than wasting it or selling it to the grid. Then, the electricity stored in devices can be drawn during periods when generation is lower than demand and optimize the use of green electricity.

Figure 9 illustrates the impact of storage on a typical load profile over a day.

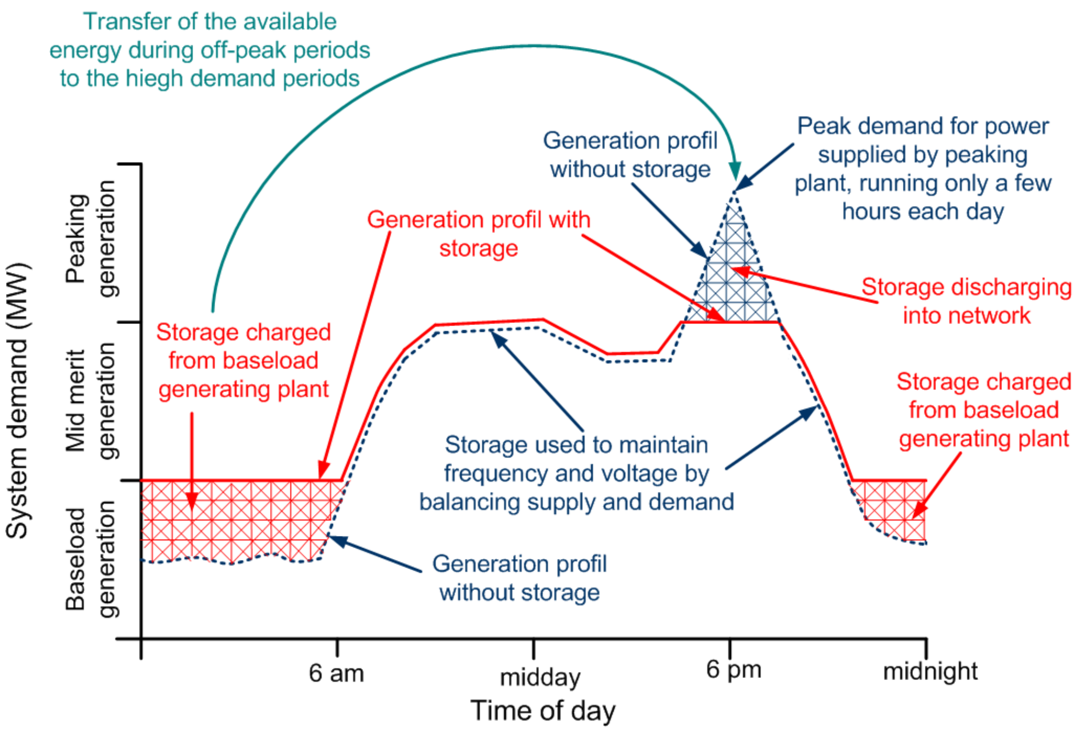

Figure 9: Load shaping strategy based on energy storage. Source: Ibrahim and Ilinca, 2013.

As shown in Figure 9, the integration of energy storage into energy systems plays an important role in shaping the load. Indeed, it tends to flatten the load by achieving energy conservation, load shifting and peak shaving. In the model proposed by Jiang, et al. (2014), load shaping strategy based on energy storage is coupled with dynamic pricing in smart grid. In the developed strategy, a consumer is encouraged to draw a certain amount of energy (i.e., quota) from the grid. When the actual energy demand is higher than the quota, the consumer is charged with a higher electricity price. By means of energy storage, the consumer can draw less electricity from the grid by discharging energy from storage devices when the demand is higher than the quota.

Conversely, the consumer can draw more electricity from the grid at a lower price and charge storage when the demand is lower than the quota. Consequently, the utility can implement load shaping while consumers can achieve money savings. Associated with renewable energy, energy storage has the ability to increase renewable capacity use and to synchronise supply with demand.

2.6 Energy storage technologies

"A next-generation smart grid without energy storage is like a computer without a hard drive: severely limited", Katie Fehrenbacher, GigaOM.

Using electrical and thermal energy storage has the ability to avoid some of the need for new plants and so the associated costs. Also, storage could improve the use of the existing and new infrastructure. According to The Energy Research Partnership (2011), installing electrical storage capability near end-use has the ability to provide real economic and environmental benefits for the energy system. Pumped hydro is the most reliable and commercially used electric storage. The Electric Power Research Institute reported in 2012 that pumped-hydro storage represented 99% of the total installed storage capacity globally with 127 GW. However, the expansion of pumped hydroelectric storage is greatly limited by the availability of space, especially in the UK. Given that and the potential for the decarbonisation of electricity, developing electrical storage has been an important focus of research in recent years (The Energy Research Partnership, 2011). Figure 10 shows that the UK energy system might be one of the energy systems in which storage would play a considerable role in future years.

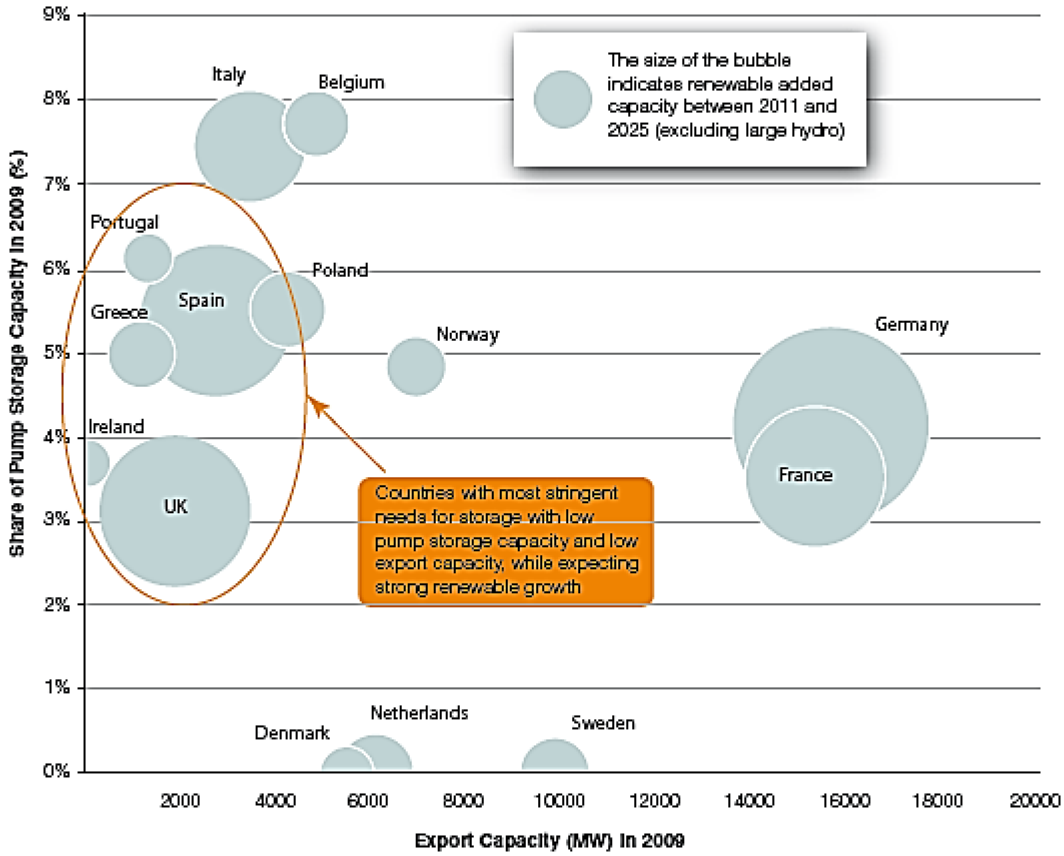

Figure 10: Comparison of the pumped storage capacity of European countries as a proportion of domestic generation capacity against their electrical export capacity. Source: IHS Emerging Energy Research, figuring in The Energy Research Partnership Report, 2011.

It can be seen in Figure 10 that the UK and Portugal are countries with high need for electrical storage as they have low pumped storage capacity and low export capacity, while their renewable penetration is expected to rise significantly in the coming years. Consequently, they appear to be countries in which increased storage capacity could be of interest.

Through this section, a brief review of the storage technologies currently available is conducted, with further focus on battery storage which is of interest for the present study. Different types of energy storage are available and have to be selected according to the energy system characteristics as they might be used on different scales and can show various efficiencies according to scale.

2.6.1 Pump hydroelectric (PHS)

It relies on a simple principle that involves two reservoirs at different altitudes to produce energy using gravitational potential. When the demand is low, water is pumped from the lower reservoir to the upper reservoir. When the demand is high, water is released from the upper reservoir to the lower reservoir. The water passes through a turbine and a generator to produce electricity. Even if it is the most established energy storage, it requires massive capital and appropriate field with difference in level. Consequently, this technology is not applicable to all sites and other types of energy storage have to be considered to ensure storage opportunities to a greater extent.

2.6.2 Compressed air energy storage (CAES)

Firstly, the ambient air is compressed by electrically driven compressors and then is stored under pressure in an underground cavern when the demand is low. Energy is stored as form of elastic potential energy. When electricity is required, the compressed air is heated and expanded through an expansion turbine which drives a generator to produce electricity. Although it can release power very quickly, the efficiency is low, approximately 42% due to waste heat (EASE/EERA, 2013). Also, a site restriction has to be considered as for pumped hydro storage.

2.6.3 Flywheel

It is a rotating mechanical device used to store rotational energy. Energy is transferred to a flywheel when a torque is applied to it, which increases its rotational speed and stores energy. Conversely, the energy is released by applying a torque to a mechanical load, slowing the rotational speed. Flywheels offer short-term back up power. However, they are generally limited to a revolution speed of a few thousand rotations per minute because of significant centrifugal forces for higher rotational speeds.

2.6.4 Solid state batteries

Solid state battery overview

Basically, batteries are devices which consist in one or more electrochemical cells that store chemical energy and then convert it into electrical energy. Each cell contains an anode and a cathode which are separated by an electrolyte. This electrolyte is used to ensure the move of ions which allows the current to flow out of the batteries. When connected in a circuit, a chemical reaction takes place and produces positive ions and electrons at the cathode. The positive ions flow through the electrolyte to reach the anode while the electrons flow round the circuit to the anode. When the flow of ions happens this way, the battery is discharged. The battery can be recharged by applying a current across the electrodes, as the reaction is reversed and the ions return to their original state. Continued innovation has created new technologies like supercapacitors that bridge the gap between electrolytic capacitors and rechargeable batteries, and can be fully charged and discharged in about 10 seconds.

Distinction between batteries can be made according to the type of chemicals that are used, such as lithium-ion batteries, nickel-cadmium batteries and sodium-sulfur batteries. Two kinds of rechargeable batteries are presented below in more details as they have been used in the modelling part of this thesis as storage opportunities for ecovillages. It deals with lead-acid batteries and lithium-ion batteries.

Lead-acid batteries

Lead-acid batteries are the oldest rechargeable type of battery, invented in 1859 by French physicist Gaston Planté. Consequently, they are well-established technologies and are currently the most widely used battery type due to low cost compared to newer technologies. They have low self-discharge and high tolerance to overcharge. Also, cells have a large power-to-weight ratio which makes them attractive as starter batteries of vehicles. Consequently, their most common applications are as starter batteries in vehicles, storage for stand-alone PV houses and they can even be found in wind farms to smoother output fluctuations. (IEC, 2011).

The schematic of a lead-acid battery is illustrated in Figure 11.

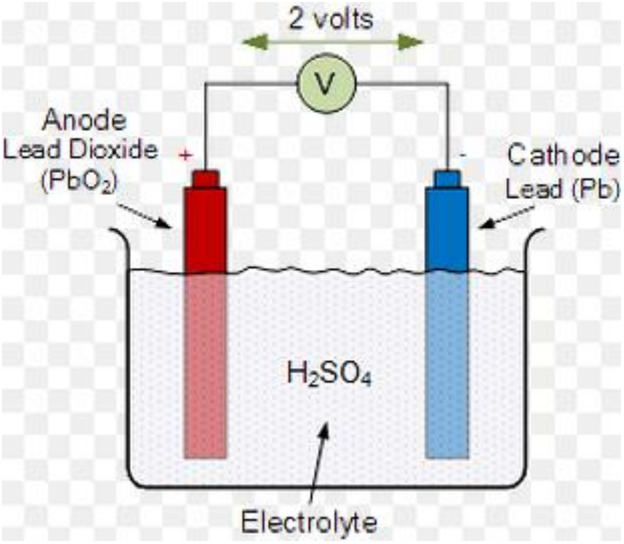

Figure 11: Schematic of a lead-acid battery. Source: Energy Storage Association.

In the lead-acid battery model, the negative electrode is made of PbO_2 while the positive electrode is made of Pb and the electrolyte is dissolved in sulfuric acid. When the battery is discharged, the chemical reaction taking place converts both Pb and PbO_2 into $PbSO_4$ which creates sulphate crystals are created at both electrodes. When the battery is charged, the crystals are dissolved and converted back into PbO_2 and Pb on the positive and negative electrode, respectively. However, if the battery is not operated properly, such as left at a low state of charge (SoC) for a long period of time, operated at high temperature or with repeated deep battery discharge, large sulphate crystals are created (Dyer, et al., 2010). These large crystals cannot be dissolved easily when the battery is charged, which results in hard or irreversible sulphation. The sulfate layer which is formed has for consequence an irreversible capacity loss as the sulphated part of the active material is not active anymore. Also, the sulphate crystals cause higher mechanical stress on the electrodes due to higher weight.

The application of this type of battery is limited as lead-acid batteries are slow to charge due to their low energy-to-weight ratio, they cannot be fully discharged and have short cycle life (Poullikkas, 2013). They are greatly sensitive to operating conditions that influence ageing mechanisms. The operation of batteries strongly depends on temperature, voltage and current. According to Bindner, et al. (2005), the main stress factors are as follows:

- Discharge rate: longer discharge times provide higher capacity readings because of lower losses
- Time at low SoC: longer times at low SoC (under 35%) results in higher loss of capacity
- Ah throughput: this factor is defined as the cumulative Ah discharge in a one-year period normalised in units of the battery nominal capacity
- Charge factor: the charge factor is defined as the Ah charged divided by the Ah discharged over the period of analysis. It represents Ah-losses associated with the operation of the battery
- Time between subsequent full charges: This is the average time between recharges above 90% of state of charge
- Partial cycling: the partial cycling factor represents the cumulative Ah throughput sorted in state of charge ranges
- Temperature: the optimum operating temperature of the lead-acid battery is 25°C. Elevated temperature reduces longevity. As a guideline, every 8°C rise in temperature cuts the battery life in half. Charging temperatures usually range between -35°C and 45°C and thermal runaway can happen if improperly charged.

From a sustainable point of view, this kind of battery is not considered as environmentally-friendly since dangerous chemical components are involved such as lead and sulfuric acid. They are toxic material, hazardous for the environment and need to be disposed with special measures.

Lithium-ion battery

This is the fastest growing battery system. Lithium-ion batteries have achieved a wide penetration in consumer electronics and they are the favourite battery type for portable electronics due to a high energy density and a slow self-discharge (Battery University, 2013). Also, they are expected to be a key component in automobile by making the transition towards hybrid and electric vehicles powered by lithium-ion batteries. They show a wide range of energy storage applications, from residential use with batteries of a few kilowatt-hours connected to building-integrated photovoltaics to batteries of multi-megawatts that provide ancillary services to the grid. They have high geometric flexibility and high energy density. In recent years, they have shown successful operation in various projects, particularly in wind and solar integration and ancillary services in the US. They offer grid stabilization and solar and energy smoothing.

Figure 12 shows the principle of lithium-ion batteries.

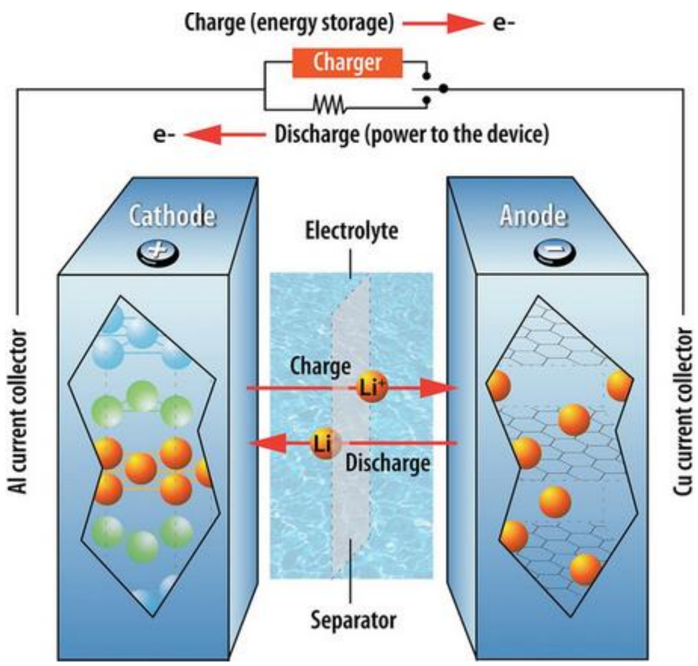

Figure 12: Principle of lithium-ion battery. Source: Future Science, 2012.

Cathode and anode containing respectively carbon and lithium metal oxide are typically used for the lithium battery model. During charging time when the power source supplies the battery, lithium ions move from the cathode to the anode, while power is discharge to meet load when they flow back from the anode to the cathode.

Although lithium-ion batteries should operate efficiently for years, they can see their lifetime significantly reduce under certain operating conditions such as elevated temperatures, charge effects and contamination with other chemicals may cause an internal short circuit (Poullikkas, 2013). These effects can lead to irreversible cell degradation which results in loss in energy capacity, lifetime and safety.

From a sustainable point of view, lithium is an abundant and non-polluting material which is recyclable and has seen its price decrease in recent years.

Recent improvements in battery chemistry and battery design have already reduced certain concerns. Undergoing research continues focussing on improving safety, lifetime and power output over a range of high and low temperatures.

2.6.5 Flow batteries

Flow battery overview

A flow battery is a type of rechargeable battery in which electrolyte contains two chemical components called active species and usually separated by a membrane. The species flow through the membrane which converts chemical energy to electricity. One of the main advantages of such a battery is that it can be recharged very quickly by changing the electrolyte while the spent material can be recovered to be reused in a further step. Additional electrolytes are stored in external tanks and usually pumped to the cells. Different types of flow batteries have been developed in recent years, including redox batteries, hybrid batteries and membraneless batteries. In this section, the only type of flow battery described is the vanadium flow battery which is the most common type of redox flow battery (Eyer and Corey, 2010).

Vanadium flow battery

The major advantage of flow batteries is that energy and power are totally independent as the electrolyte and electro active materials are stored in external tanks (Nguyen and Savinall, 2010). Redox flow batteries can be completely discharged for long periods without any effect. Due to extremely large capacities provided by vanadium redox batteries, these technologies are especially appropriate in large-scale storage applications involving important renewable generation sources with highly variable output such as wind and solar energies. Due to quick response times, they are especially well-suited for uninterruptible power supply applications. Another advantage of this technology mentioned by Poullikkas (2010) is that vanadium is a ready available material which has experienced an important decrease in price in recent years.

The schematic of a vanadium redox battery is shown in Figure 13.

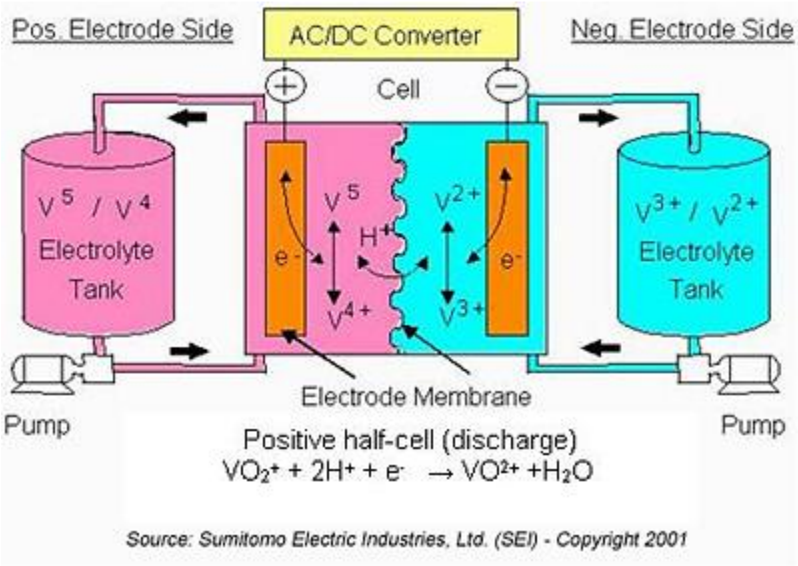

Figure 13: Schematic of vanadium battery

The vanadium redox battery stores energy by using vanadium redox couples which are V_2^+/V_3^+ in the negative half-cell and V_4^+/V_5^+ in the positive half-cell. These active species are dissolved in sulfuric acid electrolyte. During the discharge cycle, the oxidation reaction of vanadium takes place in the negative cell while the reduction reaction of vanadium takes place in the positive cell. The electron released by the oxidation reaction travels through the external circuit while the hydrogen ions produced by the reduction reaction diffuse through the membrane which separates the two half cells.

The vanadium redox battery offers high power and high energy density due to relatively high cell voltage. However, this high voltage also increases stress on electrodes, membranes and fluid handling components (Nguyen and Savinall, 2010). Also, the operating temperature of flow batteries is usually between 10°C and 40°C and high temperatures at the electrodes can cause vanadium precipitation which results in capacity loss. Finally, expensive ion-exchange membranes are required to minimise losses but they are subject to fouling and maintenance is required.

Research efforts are now focussed on reducing self-discharge losses and achieving lower cost of electrode structures as the system complexity is greater than the one of other standard storage batteries (Poullikkas, 2013).

2.6.6 Comparison of large-scale energy storage systems

Table 2 summarises the main advantages and disadvantages of the different storage technologies presented previously and which determine the application area of each technology. The efficiency is also mentioned as a point of comparison.

Energy storage technology	Advantages	Disadvantages	Applications	Efficiency
Lead-acid batteries	Mature technology, low capital cost	Limited cycle life when deeply discharge	Integration of renewables, emergency back-up, T&D stabilisation, load leveling	60 to 95
Lithium-ion batteries	High power and high energy densities, low self-discharge	High capital, loss of capacity for high temperature, protection circuit required	Integration of renewables, emergency back-up, T&D stabilisation, load leveling	80 to 90
Flow batteries	High energy density, independent power and energy ratings	Low efficiency, high-self discharge	Integration of renewables, emergency back-up, T&D stabilisation, load leveling	65 to 80
Flywheels	High power density and high efficiency	Low energy density	Renewable integration, peak generation	90
PHS	High capacity	Special site requirement (mountains)	Renewable integration, renewables back-up, load leveling	70 to 85
CAES	High capacity	Special site requirement (caverns), gas fuel required, low efficiency	Emergency back-up, load leveling, renewables back-up, renewable integration	50 to 60

Table 2: Comparison of energy storage technologies

Two main pieces of information about storage device specification have to be considered to choose the optimal storage type according to the application which is desired. The first one is power rating which refers to the power which can be drawn from the storage device to meet demand and the second one is the time of discharge at power rating.

Figure 14 illustrates energy storage applications according to the characteristics of energy storage technologies.

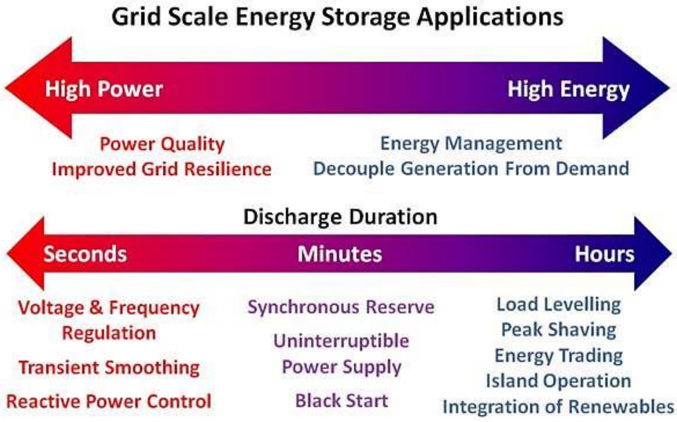

Figure 14: Energy storage applications according to energy storage specifications. Source: Electropaedia, 2005.

Figure 15 shows the potential response of different energy storage technologies to the future challenges in the UK energy system presented in Section 3 of the thesis.

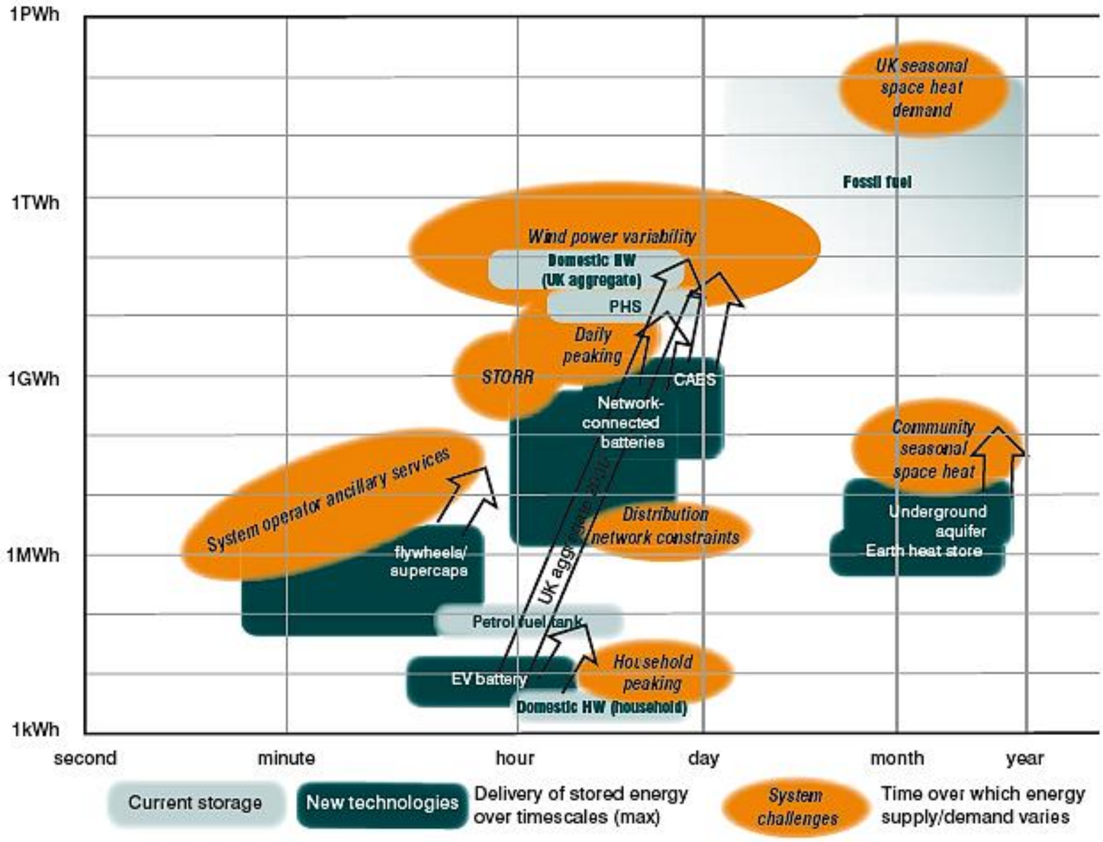

Figure 15: Challenges to the UK energy system posed by increased wind and an increased use of electricity and how they can be met by energy storage technologies. Source: The Energy Research Partnership, 2011.

It can be seen that energy storage technologies can respond to the different UK challenges according to their power and response time characteristics. Also, they have the ability to substitute for new peaking power plants and allows for a better use of energy management. Interestingly, CAES, PHS and batteries can help to manage the large-scale deployment of intermittent renewable generation. It is possible to notice the significant usefulness of storage when combined with wind power to handle its variability. Given that it has been the fastest growing renewable in recent years, wind power is likely to be one of the main drivers of the deployment of energy storage.

2.7 The ORIGIN project

It has been seen previously that the increasing renewable electricity generation has raised the issue of matching supply with demand to maximise the local use of green energy. Typical strategies to overcome this challenge have been presented; using demand side management, diversifying the energy sources of power generation and implementing energy storage. To put these strategies into application, their integration into the energy system of real communities has been conducted. The focus of this section is on the ORIGIN project which aims to use DSM to maximise the local use of renewables in three ecovillages in different locations.

2.7.1 The context

Usually, communities benefit from small-scale power network, or microgrid, which can operate independently or in cooperation with the main grid. Such systems combine both conventional and renewable energy sources to produce and consume electricity locally. Microgrids provide an orchestration of generation, storage, loads, transportation and power import and hence appear to be new paradigms for power generation and transmission. However, one main limitation of the efficiency of these systems is the intermittence of renewable power output which varies according to hours and seasons, as the energy demand does. Figure 16 illustrates typical community electricity demand and renewable electricity generation.

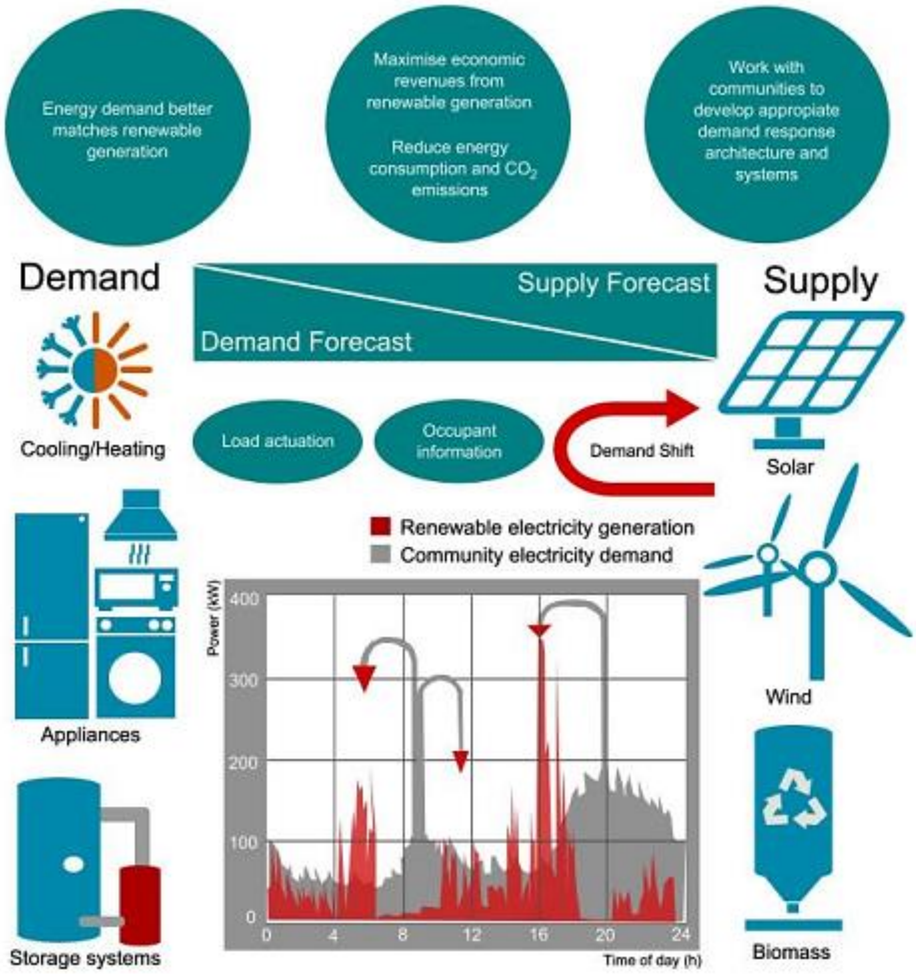

Figure 16: Overview of community energy system. Source: ORIGIN, 2013.

It can be seen that there is a significant mismatch between community electricity demand and renewable power output. Indeed, peak loads are usually experienced at 9am and 8pm while these hours refer to very low electricity generation from renewables. On the contrary, renewable energy output is high around 5am when people are sleeping and around 4pm when people are at work. However, load shifting opportunities are also presented in the figure above.

2.7.2 The objectives

The ORIGIN project was launched in November 2012 and has developed an energy orchestration system launched in November 2014 which is to be run until November 2015. Led by Heriot Watt University, the ORIGIN research aims to shape energy demand within a community to synchronise it to local renewable generation. ORIGIN is a project funded under the EU's Seventh Framework Programme (FP7) which is developing strategies to integrate renewables and end-user engagement to improve energy management. The ORIGIN energy target has been set to +20% of local renewable use by November 2015 (Tuohy et al., 2015). The developed strategies are being validated in three eco-communities in three different climatic setting in Findhorn in northern Scotland, in Tamera in southern Portugal and in Damanhur in the Italian alpine foothills. Their location across the EU is shown in Figure 17:

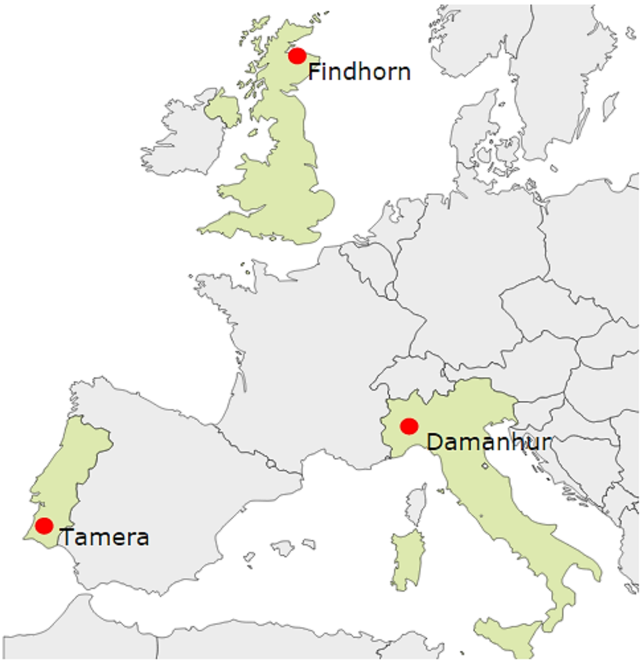

Figure 17: Locations of the three ecovillages involved in the ORIGIN project. Source: ORIGIN Concept.

Due to various locations, the three ecovillages have different types of renewable technologies and features according to their local climate and available resources. By tackling the issue of the orchestration of renewable integrated generation in such different environments, the ORIGIN project will have the ability to establish a general procedure to propose alternative energy plans for any ecovillage. Indeed, one of the objectives of the project is to create pathways for other communities to follow.

2.7.3 Presentation of the ecovillages

According to Global Ecovillage Network Europe, an ecovillage is an intentional community based on 4 dimensions of sustainability; economic, ecological, social and cultural. All these aspects are fully-integrated to consciously design a sustainable community through participatory processes to reduce carbon emissions. A pioneering synergy between energy systems, the environment and human behaviors is a key element in any strategic proposals towards a global sustainable culture. Ecological buildings and renewable energy systems are the main features of the three ecovillages to increase energy performance in a sustainable way. Ecovillages can be seen as a solution to the major issues of the 21st century aforementioned in the introduction and as we are experiencing the limits to growth. All the three communities are seeking food and energy autonomy. They believe that the future energy supply will be ensured by decentralized and autonomous systems to fully integrate renewable energy sources offered by nature. Figure 18 presents the main characteristics and technologies developed by the ecovillages to increase the energy autonomy.

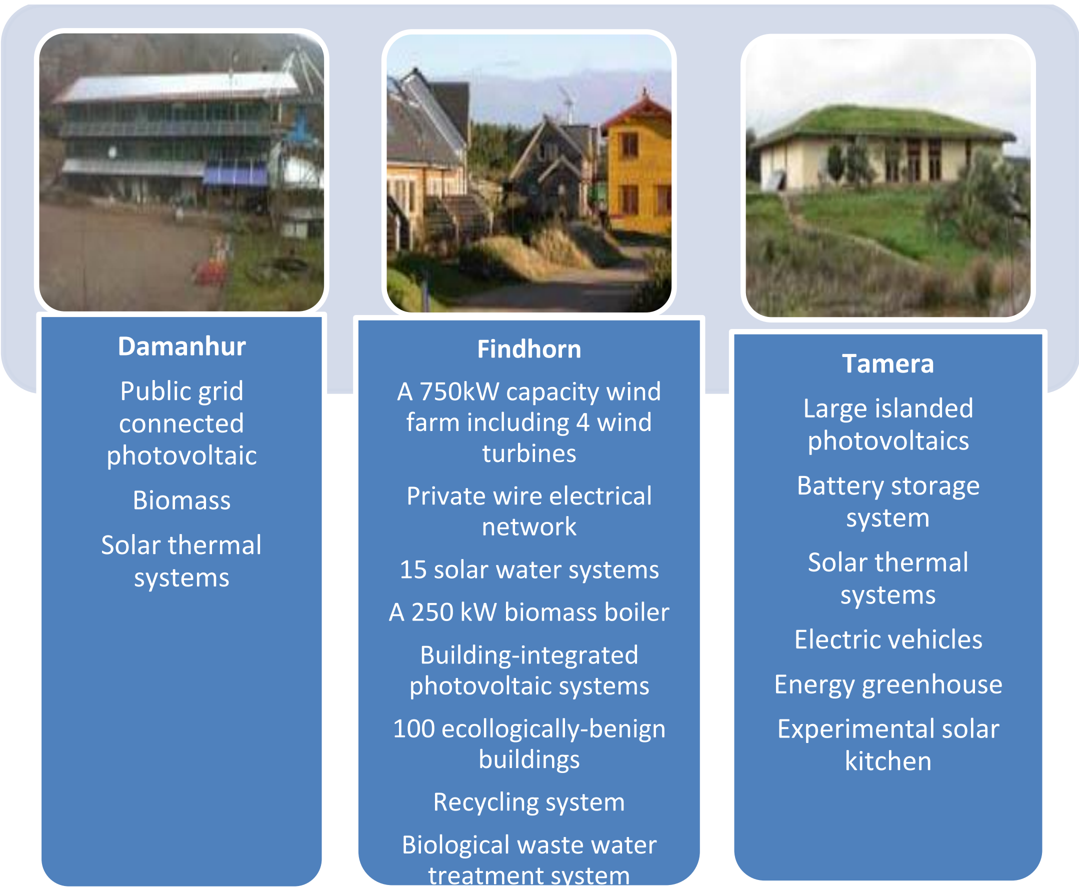

Figure 18: Technologies and features of the ecovillages

2.7.4 The ORIGIN project mechanisms

The overview of the energy system of each ecovillage presented in the previous section shows that a great number of energy flows occurs in each microgrid. This requires complex control systems to manage interactions in an optimal way. To achieve the ORIGIN objective, the project will orchestrate demand to match local supplies by identifying load shift opportunities that can be classified into three categories (Tuohy et al., 2015):

- People Controlled Loads to be influenced by information and tariffs (PCLs)
- Electrical Controllable Loads: Pumps, EV (electric vehicles) charging, Batteries, Appliances (ECLs)
- Thermal Controllable Loads: Space and Water heating or cooling (TCLs)

The mechanisms deployed to achieve this objective are as follows:

- Demand Side Management based on the ability to 'coast' (delay) inputs or 'precharge' (advance) inputs
- Energy use reduction by avoiding unnecessary loads using 'coast' function to reduce the total energy consumption

The ORIGIN system is cloud based and is in accordance in the energy cloud principle presented in Section 2.3. It involves monitoring and control devices which provide inputs that are used by algorithms to generate information and control outputs. The methods used to develop corresponding controlled load algorithms are as follows:

- Information flows by means of the ORIGIN portal available online which provide an user interface to inform individuals so they can adapt their behavior and change their operation of systems (PCLs)
- Automated actuation by means of remote control which directly impact electrical loads and thermal loads (ECLs, TCLs)

Weather, demand and generation prediction algorithms can be developed as well as models capturing community energy habits. As a result, opportunities for load shifting can be noticed. Finally, orchestration algorithms can be developed to maximize local renewable use.

Chapter 3: Project approach, scope and methodology

Creative thinking

3.1 Approach

The biggest concern of the 21st century about energy system could be summurised as follows: where can we save energy and how can we manage energy to prioritise the use of renewable energy? As the ORIGIN project focuses on energy management requiring people's commitment to increase renewable penetration in the electricity consumption of the ecovillages, it has been decided to approach the same matter from a more technical point of view based on the development energy technologies. Thus, the aim of the present study is to investigate complementary technologies to maximise the orchestration of renewable generation to use more renewables locally.

Two kinds of complementary technologies to better match supply with demand can be considered. The first one is the generating technology category. Some options are photovoltaic panels, tidal power devices, hydropower, wind turbines and combined heat and power. As it has been seen previously, adding diversity to the generation mix could result in better use of renewables. The second kind of complementary technologies is storage device. It has also been seen that such systems play an important role in distributed generation and allow for a better integration of renewables. Energy storage can store the excess of energy during off-peak periods and supply it when electricity demand is high. This increases the energy autonomy of communities as the system can operate in stand-alone mode more often by consuming the energy produced locally. Storage opportunities can be of special interest for these communities as they might have decided in the first place to install no or little energy storage capacity. Indeed, some energy storage technologies are still quite immature and very expensive, hence relying on the main grid appeared to best a cheaper option. However, large-scale storage is expected to play an increasing role in the renewable power grid and the ecovillages are willing to develop and diversify their technologies as research makes progress to achieve viability.

First of all, the next section develops a general methodology to advise arbitrary community on energy system design improvements. Then, the scope of the project is refined and the corresponding methodology is presented.

3.2 General research methodology

Actual issues facing by communities comprise the question of how to improve the orchestration of renewable supply with electrical demand to make the most of their renewable production. This increase in demand and supply matching implies the investigation of alternative energy system designs to optimise community energy management. The suggestion of better system configurations will lead to imported energy savings and associated financial, as well as on and off-site emission benefits.

In order to study the impact of complementary technologies on the energy performance of community electrical system, a general research methodology has been developed as follows:

- Select the most appropriate energy microgrid software according to the requirements and the desired depth of study
- Define energy demand profile for the community of interest
- Choose the location of the project
- Input meteorological resources
- Add the energy components of the current system
- Simulate the original energy performance

- Add complimentary technologies (generating and/or storage technologies) to allow for new scenarios of power supply
- Simulate the energy performance of the new systems
- Compare the results to define the best scenario according to the project objectives (economic minimisation, environmental impact minimisation, increase of energy autonomy…)
- Reset the procedure with other software to validate the results and the conclusions of the study

The main steps of the modelling methodology are summarised in Figure 19.

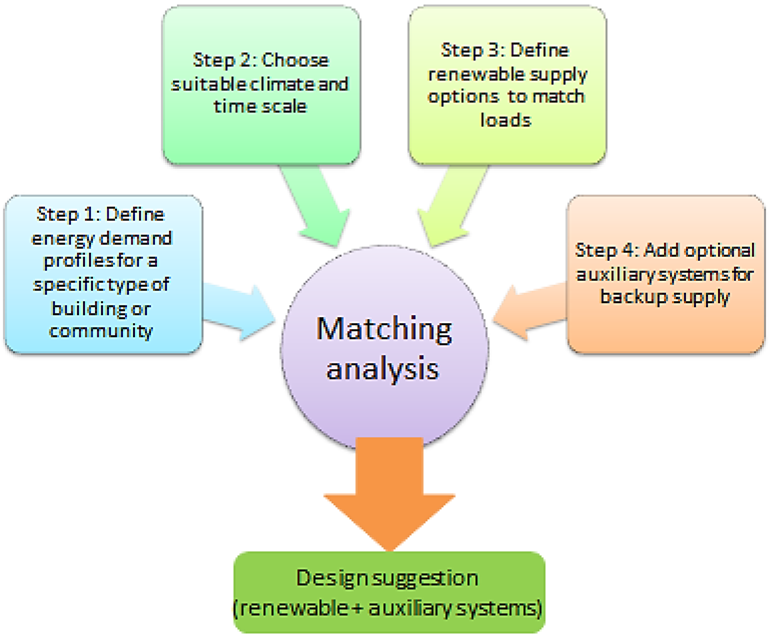

Figure 19: Methodology in energy microgrid simulation

This general methodology could be applied to the energy system of all ecovillages to study potential design improvements in order to increase their local renewable use. However, the tasks have been restricted due to time constraints, but the limited scope still demonstrates the proposed approach and generates useful results for communities. The restrictions are presented in Section 3.3 and the project methodology in Section 3.4.

3.3 Individual project scope

The current situation of the energy system of each ecovillage, its baseline energy usage and the associated potential improvements are the main drivers to define the scope of the project. Also, the time allowed for this project plays an important role in the scope of work. Consequently, study restrictions have had to be made in regards to ecovillages, complimentary technologies and energy microgrid software. All the considerations to take into account to limit the scope of the project are presented through this section.

3.3.1 Ecovillages selection

Minimising the energy flows from outside for each community would result in a better share of renewables in the electricity consumption. For all ecovillages, demand and generation involve both thermal and electrical energy flows that are presented hereinafter.

Findhorn (Scotland)

The Findhorn ecovillage has both thermal and electrical systems as presented in Section 2.7.3. The boundaries of the energy system are shown in Figure 20.

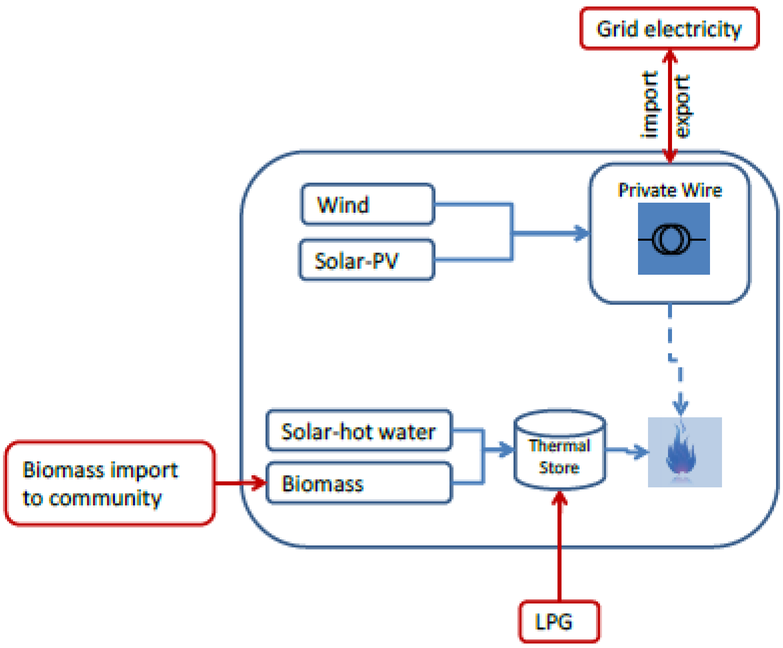

Figure 20: Boundaries of the Findhorn energy system. Source: ORIGIN, 2013

The main feature of the Findhorn ecovillage is its wind park that has been developed from 1989. The Findhorn wind energy project started with the installation of the first wind turbine; a Vestas V17 with a capacity of 75 kW and an initial investment of £75,000 repaid in five years. After the success of this wind turbine which supplied 20% of the electricity needs of the Ecovillage, three additional second-hand wind turbines were erected in 2006; three Vestas V29 with a capacity of 225kW each. The wind park extension has cost £605,000 and the total capacity of 750kW of the wind farm supplies more than 100% of the community's electricity need, making the community net exporter of electricity. However, the community mentions that only 50% is used on site while the excess of electricity obtained when production is higher than demand is sent to the grid.

Tamera (Portugal)

Unlike the Findhorn ecovillage, Tamera has storage which is made of two battery banks of lead-acid batteries connected to photovoltaic panels. The boundaries of the energy system presented in Section 2.7.3 are shown in Figure 21.

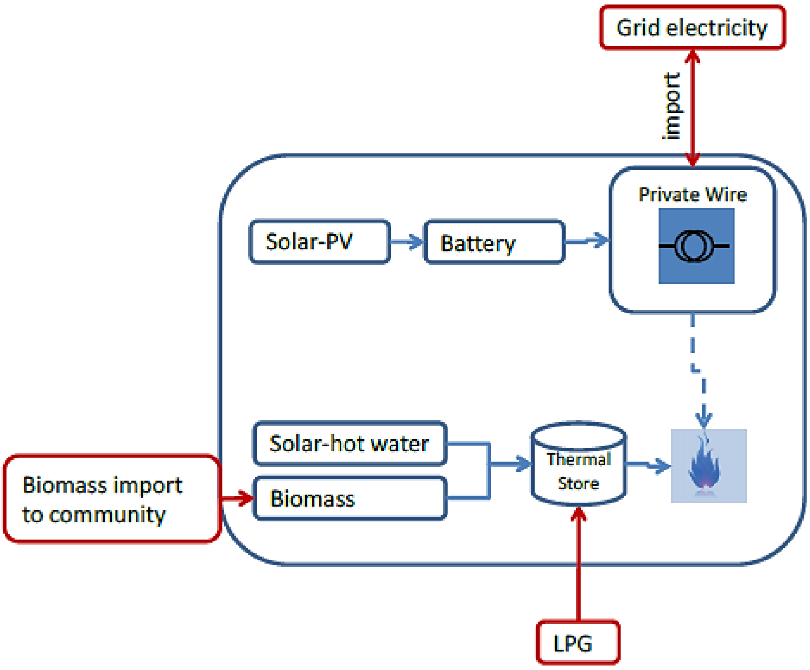

Figure 21: Boundaries of the Tamera energy system. Source: ORIGIN, 2013.

Tamera's power is supplied by a large grid-connected island photovoltaic system which cannot export to the grid the surplus of electricity which is produced. It comprises a 20 kW of solar-PV arranged in two clusters, one of 12 kW and one of 8 kW. The control of supply with demand of electricity through the Tamera private wire is ensured by using two Sunny Island 5048 off-grid inverters which control the generation of PV, the charge and discharge of batteries and the electricity imported from the Portuguese grid (ORIGIN, 2014). The connection with the grid is a one-way flow only as there is no export arrangement with the local grid. According to the Tamera's website, 50% of the community's energy needs are currently covered by solar energy but the ORIGIN measuring devices depict the following picture: even though the community needs more energy than what it regionally produces, it does not use all the electricity produced from solar energy. Indeed, electricity export is not allowed and this has a consequence on the frequency stabilization of the microgrid. When the batteries are fully charged, increased electricity generation from PV arrays leads to the increase in the grid frequency and the inverters have to limit the power output of the PV arrays which is curtailed for the safety and the security of the microgrid. The principal aim of the ORIGIN project is to increase the share of locally-generated renewable power in the electricity consumption. However, this is already 100% in Tamera as there is no arrangement for grid export. Nevertheless, the addition of storage devices could reduce import by avoiding PV power curtailment. They would accommodate renewable output intermittency and complete the energy autonomy of the community. The ORIGIN energy analysis has revealed that even if Portugal has a huge potential for renewables, most of the electricity used comes from centrally-generated energy as the big hydro-electric power plants produce most of the energy consumed in winter. In summer, almost all the electricity used comes from coal, gas and imported Spanish production as almost any solar energy produced is fed into the public grid (ORIGIN, 2014).

Damanhur (Italy)

The thermal system and the electrical system are separated in two networks. The electrical demand of the Damanhur ecovillage is met by a combination of solar PV and grid electricity. The boundaries of the system are shown in Figure 22.

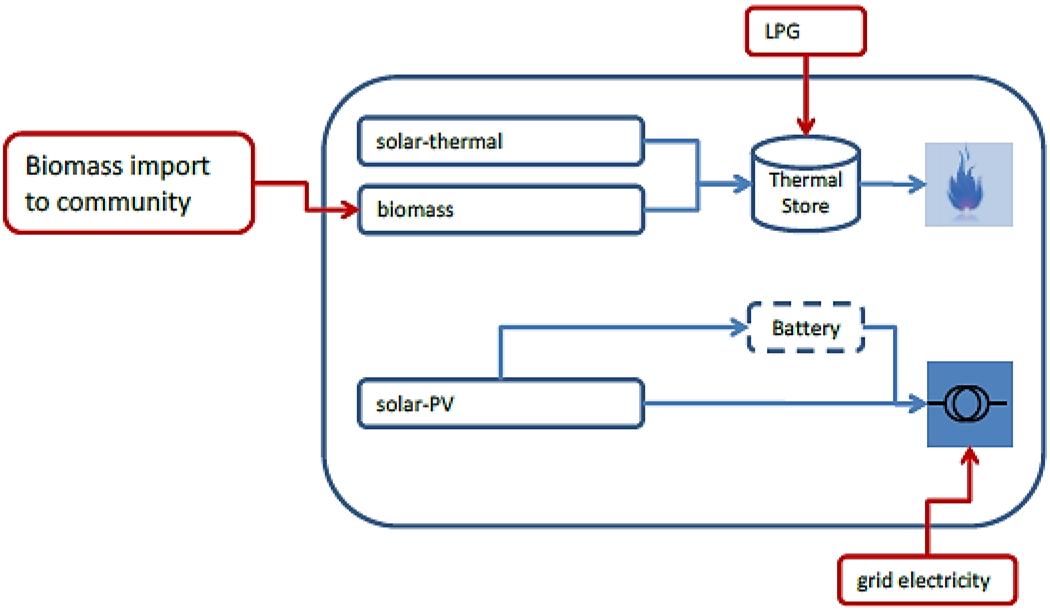

Figure 22: Boundaries of the Damanhur energy system. Source: ORIGIN, 2013

A large commercial and retail building plus some dwelling houses are featured with PV arrays and one residential building has battery storage. All the rest of surplus goes to the local grid, which maintains a strong relationship with the local grid.

Ecovillage selection

Similarly to the ORIGIN project, the overarching goal of this study is to investigate strategies to better match renewable energy supply with demand to increase the use of locally-generated green electricity. However, a different approach is used to achieve the same objective. Unlike the ORIGIN project which aims to ensure the orchestration of demand to better match locally generated renewable energy, this project is studying the orchestration of supply to better match the variable demand. For reasons of brevity, only two ecovillages are studying; the Findhorn community which has a great number of renewable technologies but lack of storage considerably limits renewable penetration in the local electricity consumption, and the Tamera community with the partly islanded energy system which causes problem of grid stability and energy wastage if demand and supply are not well-synchronised. By selecting two very different communities for applying the energy strategies, analyses of two different energy system profiles can be compared. It has been seen previously that the development of storage systems would improve local renewable use as well as provide a reliable and consistent energy supply. Consequently, it has been decided that the study would investigate storage opportunities for both ecovillages and that electrical storage devices only would be included. To the extent that the Findhorn community is currently considering the addition of wind or solar capacity to its renewable generation, adding renewable capacity is also included in design opportunities for this ecovillage.

3.3.2 Battery storage selection

Battery opportunities

It has been seen in Chapter 2 that certain battery storage technologies are technically efficient, economically reasonable and relatively environmentally friendly. Also, they take small space which is a great asset given the current economy of scale. So, these technologies have the ability to time-shift the electricity produced from renewables in order to get a better share of renewables in energy consumption.

Based on the past success in consumer products, battery manufacturers are willing to develop large scale battery storage (Poullikkas, 2013). This enables the rise of investments in his technology, the growth of Gross Domestic Product (GDP), the creation of jobs and a better productivity. By replacing fossil-fuel based technologies by the combination of renewable energy with advanced energy storage technologies, the advantage is twofold; climate change is reduced while the energy independence of countries from foreign energy suppliers is increased.

Application of battery storage to an off-grid system

Increasing local use of renewable electricity is even more critical in case of off-grid systems in rural remote area which cannot rely on the main grid to act as power back up. Generating electricity from renewables is a thing, but harnessing and integrating them efficiently into the power supply is another one. The islanded hybrid microgrid system of the Isle of Eigg is a relevant example of the importance of battery storage to ensure energy autonomy.

The energy supply of the community comes from a mix of renewable energy generations which is produced by three hydroelectric generators, four small wind turbines and an array of photovoltaic panels. These technologies are situated in optimal locations in terms of availability of resource. The hydroelectric capacity is approximately 110 kW and the maximum output of the wind farm and the photovoltaic panels is 24 kW and 50 kW, respectively. Thus, the total generating capacity of the system is around 184 kW and the electricity produced is a mix of both dispatchable and non-dispatchable generations. Also, there are two 80 kW diesel generators that can act as backup to supply power when the renewable output is lower than demand. According to the Isle of Eigg Heritage, they provide less than 10% of the yearly electricity consumption. Auxiliary backup is ensured by 60 kW of lead-acid batteries that represent 220 kWh of storage capacity.

It is at the Control Building that the whole system is regulated, to ensure a continuous supply of electricity to the island. The basic parameters of the control of the system are the state of charge of the batteries and the frequency, when it rises above the normal operating frequency of the system. There are ninety-six 4volt batteries at the control building that occupy half of the building and are housed under well-ventilated conditions and separate from the control room. Their configuration is illustrated in Figure 23.

Figure 23: Configuration of the Eigg's batteries. Source : Green Eigg, 2014.

The batteries are organised into parallel arrays of 48 volts each and connected to the system via four clusters of three inverters with a maximum output capacity of 5 kW each. Inverters monitor continually the state of charge of the batteries. If it falls down to 50%, the inverters signal for the backup generator to start producing power to complement the power generated by the renewable sources and the batteries become recharged. When the state of charge of the batteries reaches 90%, the inverters signal for the generator to be disconnected and stop producing power. In case of emergency, the only use of the generator can provide power to the entire island. If the renewable resources produce more power than what is consumed locally and finally the batteries become fully charged and no more power is absorbed. Thus, there is a surplus of electricity that is converted into thermal energy by resistive heaters to meet the thermal load at community facilities. To avoid the possibility of overload and excessive use of the diesel generators, the power delivered to domestic premises is capped at 5 kW.

Battery selection

The increasing role of batteries in large-scale storage application and their continuous improvement have been presented previously and justify the choice of investigating their implementation in the current energy system of the ecovillages to increase their local renewable use. Also, they have their place in the being created green society as materials used can be recovered and recycled easily after their useful lifetimes. However, continuous progress in battery technologies has resulted in a wide range of available options, and older batteries which are the most used batteries such as lead-acid batteries, to newer batteries such as vanadium redox flow batteries and lithium-ion batteries have been investigated as storage opportunities for the ecovillages. Also, this is the occasion to compare the energy performance of these different battery types to select the most appropriate one.

3.3.3 Software tool for hybrid system analysis selection

After a brief review of the software currently available to model hybrid energy systems and their capabilities, it has been chosen to conduct the simulation exercise with the HOMER software (Hybrid Optimisation Model for Electric Renewables) developed by NREL (National Renewable Energy Laboratory). It has been found that it is the most suitable tool for the range of the study. The HOMER software is the world’s leading microgrid software which allows for the evaluation of a range of technology combinations over different constraints and sensitivity inputs to optimize energy systems (Givler and Lilienthal, 2005). The main capabilities and limitations of the HOMER software are presented hereinafter.

HOMER capabilities

This piece of software is well-established for microgrid design optimization and feasibility, and helps to determine the best scenario that combines traditionally generated and renewable power, storage, and load management to ensure a consistent and reliable microgrid. It is a flexible computing tool which takes into account variations in both technology costs and energy resource costs. This is extremely useful in the evaluation of design issues in the planning and early decision-making phase of rural electrification projects in order to avoid costly design mistakes (Givler and Lilienthal, 2005). HOMER inputs are numerous and include various renewable and non-renewable technology options, component costs, weather resources and manufacturer’s data. It simulates a system for 8 760 hours in a year and presents the feasible configurations for the system which are sorted by Net Present Cost (NPC), which is the present value of all the costs of installing and operating components minus the present value of all the revenues that it earns over the project lifetime. RETScreen and MERIT are other potential tools for modelling hybrid renewable energy system, but do not perform time-series simulations (Lambert, Gilman and Lilienthal, 2006). Also, they are classified as pre-feasibility tools only able to conduct rough size analysis and simple financial study while HOMER belongs to the sizing tool category and can perform detailed size analysis to find the optimal system design (Sinha and Chandel, 2014).

The schematic representation of the HOMER simulation which leads to the optimal energy system design is illustrated in Figure 24.

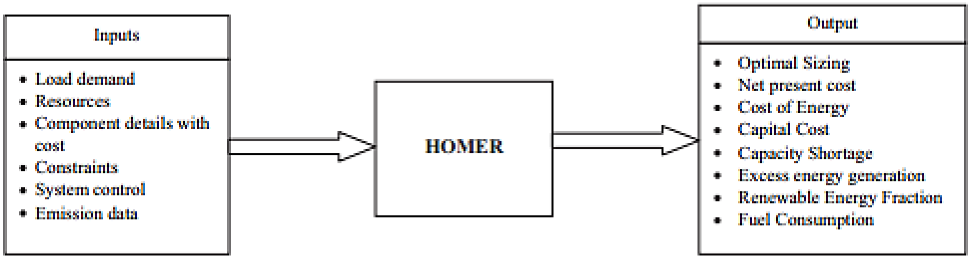

Figure 24: Schematic representation of HOMER. Source: Sinha and Chandel, 2014.

HOMER limitations

It is critical to be aware of limitations and assumptions used by software before modelling energy systems in order to accommodate their design. As HOMER has been widely used in literature for hybrid renewable energy system analysis and case studies, certain of its limitations have been highlighted. Sinha and Chandel (2014) emphasize on the following shortcomings of HOMER:

- Multiple objective problems cannot be formulated, only one objective is used to minimise the Net Present Cost (NPC)
- HOMER does not take into account intra-hour variability
- HOMER uses first degree linear equations based
- HOMER does not accept time series data import in a form of daily data

Through their micropower analysis of a hybrid energy system in Sri Lanka, Givler and Lilienthal (2005) specify other limitations which are as follows:

- The resolution of the search space of HOMER is limited
- Obtaining inputs data and choosing which of them are of interest for the study. However, a sensitivity analysis can improve the accuracy of the input variable if rough values are given in the first place

Finally, Lambert, Gilman and Lilienthal (2006) suggest that adding flexibility for selecting the optimization technique that suits the most a particular system analysis would enhance HOMER's robustness and would make easier the comparison of results given by different techniques.

Homer-based microgrid studies

As aforementioned, HOMER appeared to be the favourite tool in the literature to model hybrid renewable energy systems. As the energy system configuration tends to be more and more decentralized and distributed, the HOMER software is of great interest to inform the decision-making process in regards to the energy system design. In this section, some hybrid renewable energy systems simulated with HOMER are briefly discussed, in order to illustrate the wide capabilities of HOMER to model such systems.

Al-Karaghouli and Kazmerski (2010) used HOMER to design a power system of a remote health clinic situated in southern Iraq with a load estimated at 31.6 kWh/day. The system was composed of PV modules, batteries, charge controller, inverter, auxiliary diesel generator and necessary wiring and safety devices. Several decision variables were studied by means of the search space offered by HOMER for input data. The diverse sizes of equipment which were considered are as follows:

- PV capacities: 0,1,2,3,4,5,6,8 and 10 kW
- Number of batteries: 0,80,100,120,140,160 and 180 kW
- Inverter capacities: 0,2,3,4,5,6,8 and 10 kW
- Generator capacities: 0,1,2,3,4,5,6,8 and 10 kW

The economic minimization of the system conducted by HOMER suggested the following system design: 6kW PV module, 80 batteries (225 Ah and 6 V), 3kW inverter and no generator. The study included an economic and environmental analysis and specified that the electricity produced from renewable sources is four times cheaper that the electricity produced from diesel generator and also prevents release of greenhouse gases and suspended particles. This shows the interest of using the PV system in remote areas rather than the diesel generator.

Chmiel and Bhattacharyya (2015) used the HOMER software to model the off-grid energy system of the island of Eigg in Scotland. This simulation was conducted to investigate if the existing system has been appropriately designed and to suggest alternative configurations to improve electricity generation and decrease the reliance on diesel generator. From the sensitivity analysis carried out by HOMER, it appeared that the optimal system configuration for the current load of 856 kWh/day differed from the current configuration. Indeed, HOMER suggested an alternative configuration with 32 kW of PV panels instead of the existing PV capacity of 53 kW. Also, a 40 kW diesel generator was selected instead of the 80 kW generator actually used. In conclusion, the equipment has been slightly oversized to meet the current load but could accommodate increased load. It was also find that it would be more beneficial for the site to increase wind penetration than solar penetration.

These two examples of hybrid system analysis show how the sensitivity study of HOMER allows for the optimization of existing and future energy systems by selecting the best technology combination for a specific project. Indeed, it is possible to ensure that the current design system is optimal, and if necessary, to suggest alternative scenarios to reduce the cost of energy.

In sum, HOMER has been found to be the most suitable software for this study given the following reasons:

- International standard for microgrid design and optimization
- Ability to determine the optimum power system combination
- Flexible computing tool which takes into account variations in both technology costs and energy resource costs
- Feasibility of storage technologies which are still quite immature and costly

3.4 Individual project methodology

The main objectives of the dissertation are to study auxiliary technologies to the current energy system of Findhorn and Tamera in order to better aligning renewable supply with demand. The analysis is conducted by means of the HOMER industry standard software and another objective is to test its abilities and underline potential limitations for modelling microgrid energy systems. As a result of the project scope, the tasks to be completed are as follows:

- Model the energy performance of the two ecovillages of interest with the HOMER software

For Findhorn:

- Study the effect of an increase in renewable capacity on the renewable share in the electricity consumption
- Determine what strategy between adding wind capacity or solar capacity is the most beneficial for maximizing local renewable use

For both Findhorn and Tamera:

- Define the optimal electrical storage system for each location given that the optimal storage system should:
  - ✓ Lead to a reliable all-year-round energy supply
  - ✓ Minimize cost
  - ✓ Accommodate any future increases in energy demand (surplus opportunities)
  - ✓ Ensure renewable penetration
- Compare storage impact and their application for the different locations
- Conclude on large-scale storage opportunities for communities according to their amount and nature of renewable production

In order to meet these sub tasks, a rigorous methodology has to be established and is presented hereinafter:

- Collection of data from the community for current electrical systems
- Modelling of the annual electricity generation and comparison with measured data
- Establishment of demand profiles with data provided by the ORIGIN project
- Simulation of the current energy system and comparison with the measured system performance
- Study of peak demands in specific periods of the year (in summer and winter periods) and the answer of the energy system to define the corresponding energy performance

- Investigation of the effect of different battery types as auxiliary systems on the energy performance (annual and targeted periods) and local renewable use
- Investigation of the addition of renewable capacity on the local renewable use (Findhorn ecovillage only)
- Comparison of the results of the different scenarios in terms of cost (Net Present Cost (NPC) and Cost Of Electricity (COE)) and energy (green electricity used, import and export)

Chapter 4: Model description of the Findhorn electrical system

The objective of this simulation exercise is to model the electrical system of the ecovillages and to compare the results with their actual energy performance. By doing so, it is possible to determine the appropriateness of HOMER to model the microgrid of Findhorn, and then to investigate system design opportunities to maximise the renewable fraction in electricity use. This would increase the energy autonomy of the community as the dependence on the main grid would be reduced. As part of this overarching goal, addition of renewable capacity and implementation of storage devices are investigated and appropriate models are developed in each case.

As it has been seen in Section 3.3.3, HOMER is a powerful tool to simulate hybrid energy systems and microgrid optimization. Through this section, the input data used in the HOMER simulation are presented.

4.1 Modelling of the Findhorn energy system using HOMER

Three main types of data are required to model an energy system. It deals with meteorological resource assessment, component characteristics and load assessment. The procedure of their determination is specified hereinafter.

4.1.1 Resources assessment

For study purpose, the location of ecovillages has to be defined. Findhorn is identified in Morray (latitude 57.40 °N and longitude 3.37 °W). As mentioned in Section 2.7.3, the Findhorn community harnesses wind and solar resources to produce electricity. These two categories of weather resources are of interest considering the two different renewable technologies used in the system; solar resource for the PV panels and wind resource for the wind turbines.

HOMER has the ability either to download directly resource data from the internet using the NASA Surface meteorology and Solar Energy database, or to import a time series data file.

Solar resources

To model a system containing a PV array, the HOMER user must provide solar resource data for the location of interest. In the case of flat plate PV component, the solar global horizontal irradiance has to be input. The solar radiation data from NASA Surface meteorology and Solar Energy database are used directly by Homer to create the solar radiation profile of Findhorn. For each month, Homer calculates the average solar radiation values in $kWh/m^2/day$.

The solar radiation profile is shown in Figure 25.

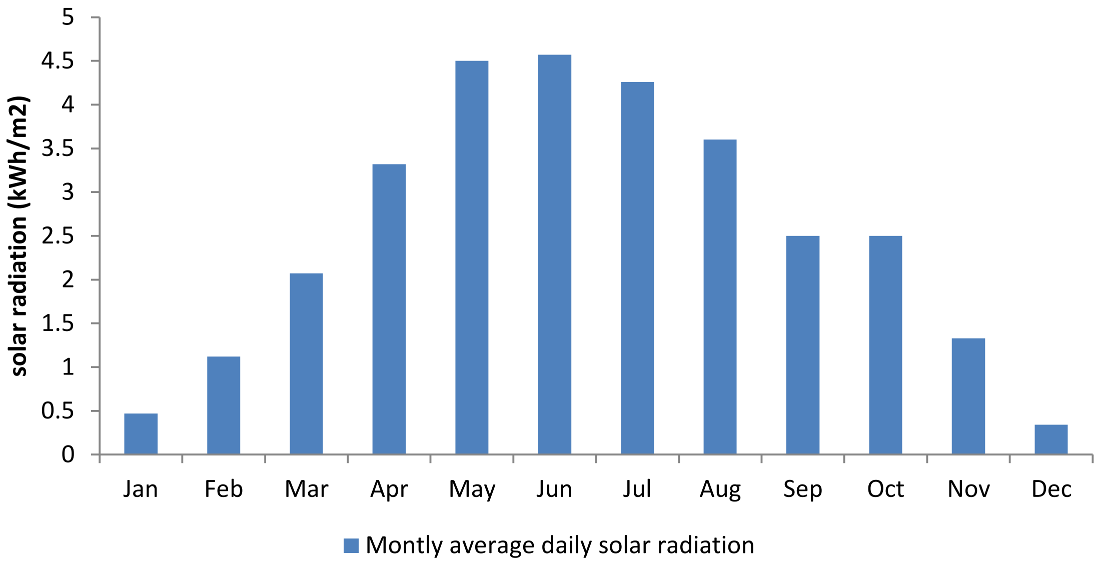

Figure 25: Findhorn solar radiation profile

Minimum and maximum monthly average solar radiation values are observed in January and June, with 0.47 kWh/m^2/day and 4.57 kWh/m^2/day respectively. On the basis of the project location and the local meteorological data, the annual average daily solar radiation is assessed at 2.39 kWh/m^2/day. As these data are consistent with those provided by the ORIGIN project, this profile is kept for the study.

Temperature resources

The temperature data from NASA Surface meteorology and Solar Energy database are used directly by Homer to create the solar radiation profile of Findhorn. The temperature profile is shown in Figure 26.

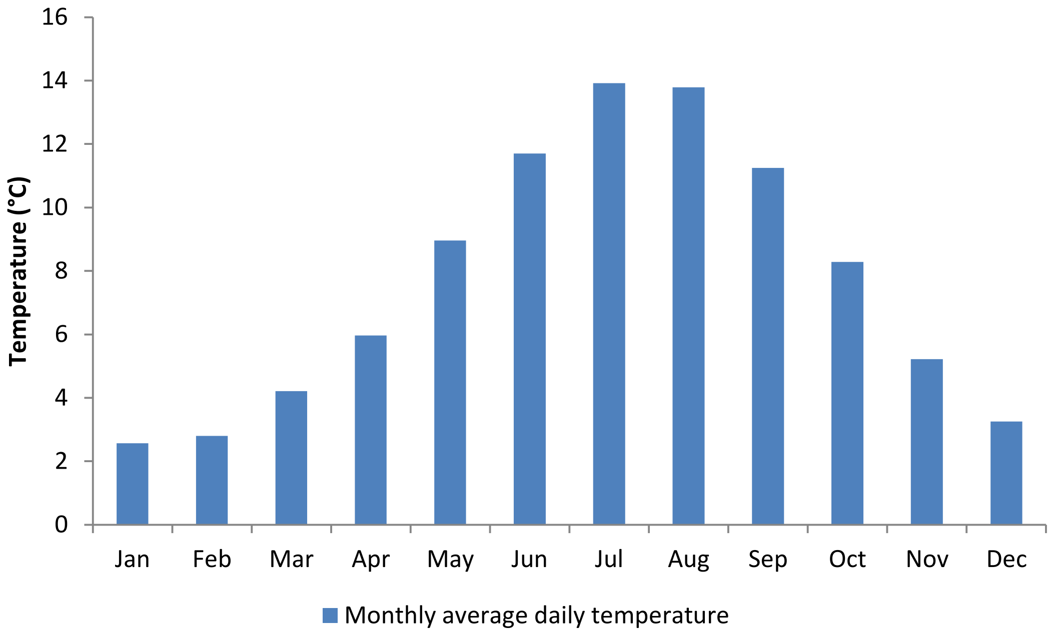

Figure 26: Findhorn temperature profile

Minimum and maximum monthly average temperature values are observed in January and July, with 2.57°C and 13.92°C respectively. The scaled annual average temperature is 7.66°C.

Wind resources

To model a system comprising one or more wind turbines, the HOMER user must provide wind resource data indicating the annual wind speed profile for the location. This profile has to be built carefully as the turbine output strongly depends on it and little variation of wind speed can result in great variation of turbine output. It is recommended to provide hourly wind speed data if available. It has appeared that the data values downloaded from the NASA Surface meteorology database are greatly over-estimated and lead to an annual mean wind speed of 7.50 m/s. More reliable data are obtained from the ORIGIN portal and are compared with those provided by a local weather website (MyWeather2). Considering the weather data for the years 2014 and 2015 over which the ORIGIN project is conducted, the average wind speed is assessed at 5 m/s which is far from the value given by the initial database. This highlights a limitation in the HOMER resource database which uses monthly average values over 22 year period (July 1983-June 2005) and appear to be outdated.

As the data extracted from the NASA Surface Meteorology and Solar Energy database give erroneous results for the wind electricity generation of the wind park, 12 monthly average wind speeds are imported in HOMER which generates from them synthetic hourly data. To do so, the advanced inputs shown in Table 3 are required:

Advanced input data	Definition	Value
Weibull K	Mesure of the long term distribution of wind speeds	2
1 hour Autocorrelation Factor	Mesure of the hour to hour randomness of wind speeds	0.85
Diurnal Pattern Strength	Mesure of the dependence of the wind speeds on the time of the day	0.25
Hour of Peak Wind Speed	Time of the day that is the windiest on average	15

Table 3: Advanced input data to generate synthetic wind speed profile

Homer provides default values for each of these parameters which are kept for the study. The user indicates the anemometer height, which is the height above ground at which the wind speed data were measured and was set at 30 m while the elevation of the wind park was set at 6 m above the sea level. These data are important as they determine the air density which is used to calculate the output of the turbine.

Figure 27 presents the wind speed profile of Findhorn.

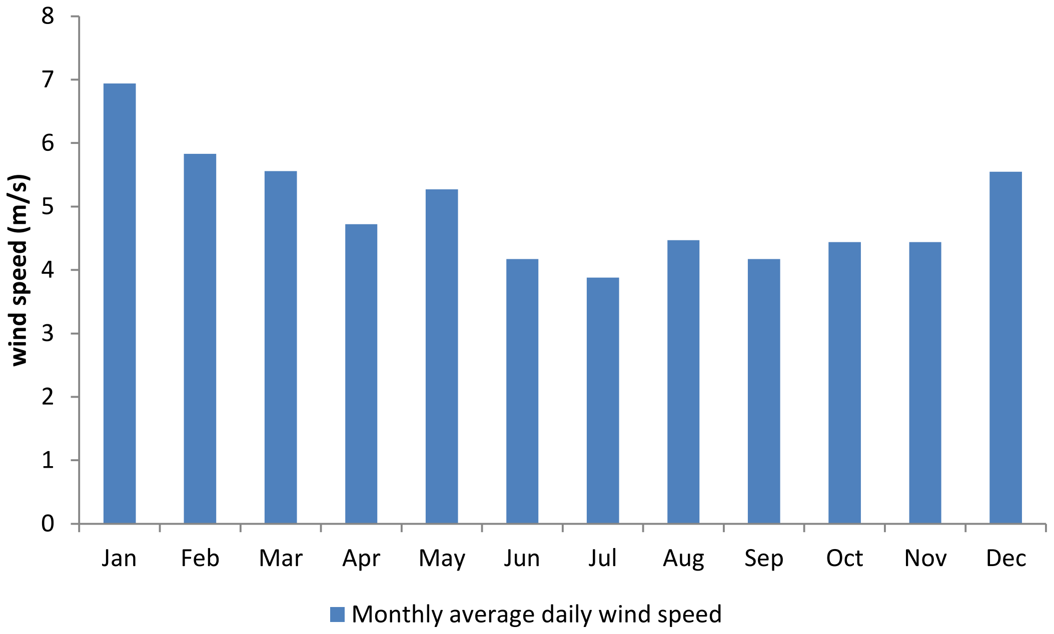

Figure 27: Findhorn wind speed profile:

Minimum and maximum monthly average wind speed values are observed in July and January, with 3.88 m/s and 6.94 m/s respectively. The annual average wind speed is scaled at 5 m/s.

4.1.2 The Findhorn PV-wind system

Solar system

PV panels of various sizes are roof-mounted on different types of buildings, leading to a total solar capacity size of 25 kW. Although the solar system in Findhorn is not made of a single 25 kW array, a large PV panel of 25 kW is considered for the simulation. By lack of data about the different panels and given that the total solar capacity is small compared to the total wind capacity, the assumption is made that this simplification has negligible effect on the solar generation in Findhorn. Also, the electricity produced is directly used in buildings to preheat hot water.

The solar systems in Findhorn were manufactured and installed by the community company AES solar systems. For the simulation exercise, polycrystalline solar cells with a typical efficiency of 13% are considered, and solar arrays are connected to a 90% efficient inverter with a lifetime set at 15 years. The slope of the arrays is an important parameter as it directly impacts the PV panel output. It is set at 45° to match the reality. Also, the panel lifetime is set at 25 years and the derating factor at 80% to take into account the ageing effect.

Wind system

The wind system of Findhorn is made of one V17 wind turbine of 75 kW and three V29 wind turbines of 225 kW each. All of them were manufactured by Vesta. HOMER has its own database for the most popular wind turbine models but the turbines used in Findhorn are not included. In order to add these models to the HOMER database, their power curves (power output vs wind speed) are created with data from their specification sheets. These power curves for the V17 and V29 turbines are available in Appendix 1 and Appendix 2, respectively. Other necessary data to model the wind system are the turbine hub heights; they are set at 17 m and 30 m for the V17 and V29 turbines, respectively. The surface roughness length characterizes the roughness of the surrounding terrain and is set at 0.01 m for rough pastures. Also, the lifetime of turbines is set at 20 years.

Overall energy system

The total energy system capacity is 775 kW; 25 kW of solar PV capacity and 750 kW of wind capacity.

4.1.3 Load assessment

ORIGIN is mostly concerned with the orchestration of community energy demand to better match locally-generated renewable energy. Demand and generation involve both thermal and electrical energy flows and consequently, protocols have been included to account for both. Within this overarching aim, each participating building in the ORIGIN project has its electrical demand monitored and computed to reflect individual building and community energy performance. From these data, baseline energy uses in all three communities have been established and will be used in the later phases of the project to identify any increase in local renewable use, which is expected to be an outcome of the ORIGIN system.Consequently, data are available from the monitoring sources of the ORIGIN project and are extracted to get a reliable demand profile all year round. The load profile shown in Figure 28 is imported in HOMER.

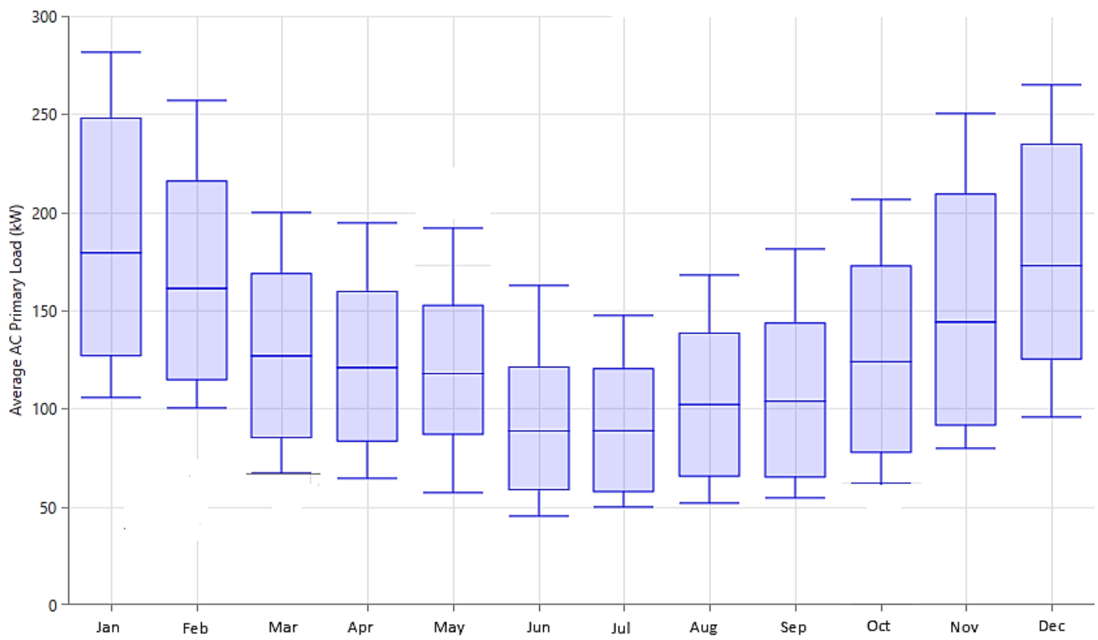

Figure 28: AC primary load monthly average of Findhorn

HOMER gives five data for each month and they are as follows:

- The maximum primary load
- The average day maximum primary load
- The average primary load
- The average day minimum primary load
- The minimum primary load

The annual average electric load is 3 056 kWh/d with a peak load of 285.86 kW in January. The random day-to-day variability is assessed at 8% by HOMER. Consequently, an alternative scenario with an annual average of 3 300 kWh/d was also modelled as a sensitivity analysis case. Figure 29 shows the hourly load profile of January.

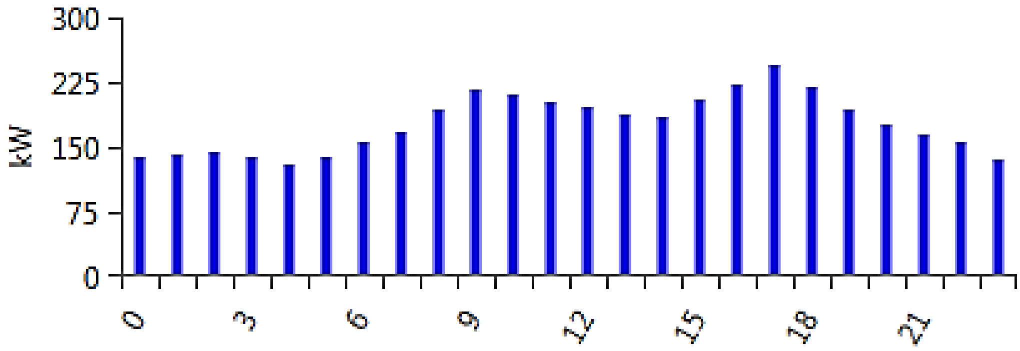

Figure 29: Average hourly January profile of Findhorn

January is found to be the peak month with an average peak load of 245.6 kW experienced at 5pm and a daily average demand of 179.5 kW. It can be seen how demand varies according to the hour of the day due to people's activity requiring electricity.

Figure 30 compares the shape of the baseline data daily demand profiles in January and July.

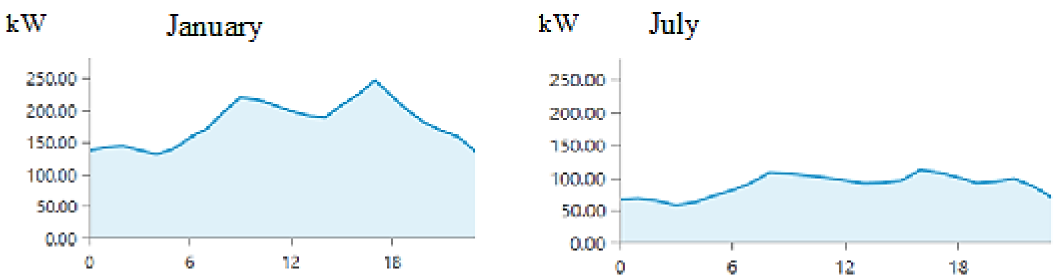

Figure 30: Baseline data load profiles of Findhorn for January and July

Peak demand happens at 9am and 5pm for both months, and this observation can be extended all year round. However, peak demand in a typical winter day reaches 245.6 kW while it is reduced to 112.9 kW in summer. The load profile tends to be flatter in summer as no space heating is used and peak demand is reduced.

4.1.4 System configuration

Figure 31 presents the system configuration used in HOMER to model the electrical system of the Findhorn ecovillage.

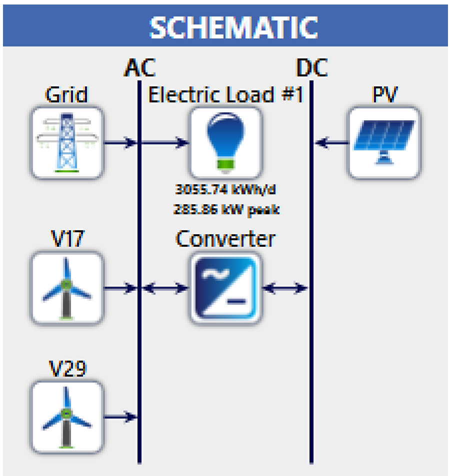

Figure 31: System configuration of the Findhorn ecovillage

The energy system is grid-tied and can use electricity from the two renewable energy sources and from the main grid to meet the electric load. The two kinds of wind turbines are connected to the AC electrical bus. They are directly connected to the public utility and the load. As the electricity consumption is AC electric load in the households, no converter is required. On the contrary, PV panels are connected to the DC electrical bus and require the use of a converter to use the electricity produced in home outlets.

4.1.5 Financial input data

Technology costs

The initial cost of PV panel is set at £3 000/kW while the replacement cost is set at £2 800/kW. The operation and maintenance cost is set at £40/kW/year. The initial cost and replacement cost of the converter are set at £1 000/kW while the O&M cost is set at £10/kW/year. The initial cost of a new V17-75kW wind turbine is assumed to be £115 000 and the replacement cost is set at £110 000, while those for the V29-225 kW turbine are set at £230 000 and £217 000, respectively. The initial costs of the wind turbines refer to new turbines and not to second-hand turbines. The yearly average O&M for turbines in the UK is assessed to be 1.2p/kWh over the total lifetime of the turbine, so for the V17 and the three V29 wind turbines it is set at £1 111/year and £12 263/year, respectively. For each renewable technology, the replacement cost is set lower than the initial cost for several reasons. Firstly, due to an expected higher penetration of renewables, the cost of renewable technologies might decrease as progress in manufacturing, efficiency and practicability will happen. Also, replacement cost is a reducing fund factor to cover long-term replacements and repairing of major components. In the case of a wind turbine, not all of the component may require replacement at the end of its life. As a case in point, the wind turbine nacelle might need replacement but the tower might not.

The financial data of the system components which are used in the simulation are summarised in Table 4.

Component	Initial cost	Replacement cost	O&M cost	Lifetime (year)
PV panels	£75 000	£70 000	£1 000/year	25
V17 wind turbine	£115 000	£100 000	£1 111/year	20
V29 wind turbines	£690 000	£650 000	£12 253/year	20
Converter	£1 000/kW	£1 000/kW	£10/kW/year	15

Table 4: Component costs of the Findhorn energy system

Power prices

Net metering is considered for the simulation exercise. However, costs and available subsidies are changing constantly, the latter very rapidly at present. Also, the Park Private Grid is not a single entity and FIT regulations mean tariffs change depending on the point of connection within the private grid. Consequently, defining fix values for power prices is not easy. However, the power price values do not affect the modelling of different generation scenarios in terms of units generated and grid import and export. This could provide input data for further financial modelling of different internal connection strategies using the relevant price information, now or in the future. The buy power price from the grid is set at £0.173/ kWh and refers to the average price of electricity paid in the UK while the sale power price to the grid is initially set at £0.0487/kWh and refers to the current UK legislation regarding electricity produced from renewables.

4.1.6 Additional input data

HOMER can perform a sensitivity analysis by accepting multiple values for input variables such as the average load. For each simulation, the best configuration of the system is selected for the annual average load of 3 056 kWh/day as assessed from the Findhorn load profile. Then, the same simulation is run for a higher demand scaled at 3 300 kWh/day to analyse the impact of an increase in load on the system and its performance. For simplicity reasons, the shape of the load profile is kept the same while it is scaled in size. It is assumed that it has negligible effect on the load shape as the increase in load is relatively small. For the financial analysis, a discount rate of 8% and an inflation rate of 2% are used.

4.2 Energy storage modelling using HOMER

This section only focuses on modelling battery storage with HOMER, as it has been found to be the most promising storage opportunities for the study of the ecovillages. It is suitable to present the model used in HOMER to simulate battery storage as modelling batteries is challenging in energy microgrid software.

4.2.1 Battery properties

HOMER considers battery storage as form of battery bank which is an assembly of one or more individual batteries. Each single battery is seen as a storage device capable of absorbing DC electricity that can then be discharged to meet electrical load. The amount of energy that can be retrieved from the battery is limited by the round-trip efficiency that accounts for heat and other losses. The way this electricity can be charged or discharged is limited by the times of charge and discharge of batteries, their depth of discharge and the lifetime throughput.

Consequently, the key battery properties for HOMER to calculate the battery output are as follows:

- The capacity curve that shows the discharge capacity of the battery in ampere-hours versus the discharge current in ampere. Usually, capacity decreases when discharge current increases.
- The lifetime curve that shows the number of discharge/charge cycles that the battery can withstand versus the cycle depth. Usually, the number of cycles before failure typically decreases with increasing cycle depth.
- The initial and minimum state of charge of the battery which indicates the state of charge at the beginning of the HOMER simulation and the state of charge below which the battery must not be discharged to avoid permanent damage, respectively.

4.2.2 Battery modelling issues and assumptions

- The battery's capacity to be charged and discharged

HOMER allows for two different kinds of storage models, the idealized and the kinetic storage models. The first one considers a simple one-tank model with a fixed capacity and no limit on the maximum charge and discharge rates. However, the last one is a more complicated model that considers two tanks as illustrated in Figure 32.

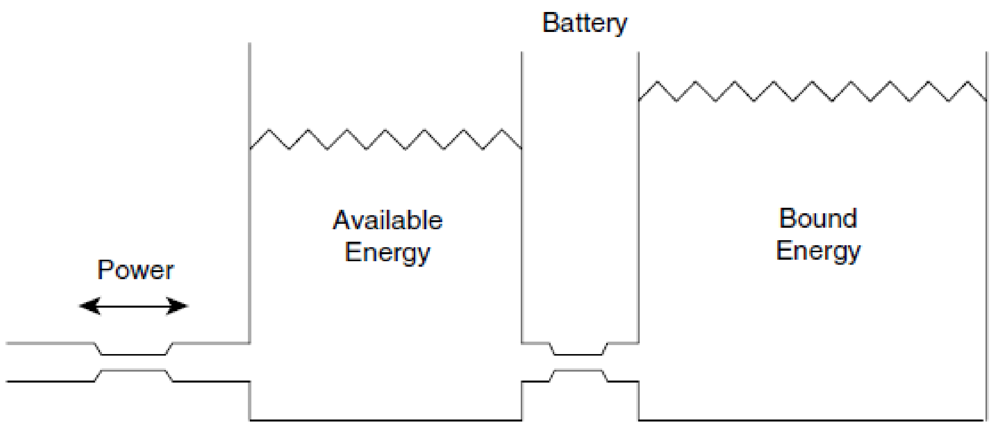

Figure 32: Concept of the kinetic battery model. Source: Lambert, Gilman and Lilienthal, 2006.

Such model requires the import of the capacity curve to take into accounts the fact that capacity typically decreases when the discharge current increases. Consequently, this model sets more restriction on the amount of energy that can be charged or discharged.

- Voltage applied to the battery

Homer simulation makes the assumption that the voltage applied to the battery is constant and equal to the nominal voltage while the actual voltage varies according to the conditions of operation of the batteries and their state of charge. Modelling batteries with internal resistance could account for the variation of the voltage when charging or discharging.

- Round-trip efficiency

Homer simulation considers that the battery has a constant round-trip efficiency, independent of the rate of charge/discharge and independent of the state of charge of the battery.

- Battery lifetime modeling

Homer simulation allows for the use of two different methods to determine the lifetime of batteries. These models are presented below.

The float life model

The float life of the battery is the length of time that the battery will last before it needs replacement.

The lifetime throughput model

The lifetime throughput model simply limits the battery lifetime to a certain amount of kWh of battery throughput. It is calculated from the lifetime curve provided by manufacturers which represents the number of cycles to failures according to the depth of discharge. Here is an example for a 2.1 kW lead-acid battery:

Depth of discharge (%)	# of cycles to failure	Calculated throughput (kWh)
10	3800	798
20	2850	1197
30	2050	1292
40	1300	1092
50	1050	1103
60	900	1134
70	750	1103
80	650	1092
90	600	1134
100	550	1155

Table 5: Battery lifetime according to depth of discharge

Both methods can be used simultaneously to limit the lifetime of batteries which typically decreases with increasing cycle depth.

4.2.3 Storage system control

In the system control of Homer, it is possible to choose between two dispatch strategies. The first one is the load-following strategy (LF) in which the battery bank is only charged by the surplus of electricity, consequently there is no cost to charge the batteries. On the contrary, in the cycle-charging (CC) strategy, a generator is used to charge the battery and so extra electricity is produced from fuel on this purpose. As a result, there is a cost to charge the batteries. When batteries are used, a converter is necessary to convert DC electric power into AC electric power. This process is called inversion while the reversed process is called rectification. The converter size is an input variable in Homer and refers to the inverter capacity which is the maximum amount of AC electric power that the device can produce by the inversion process. The user specifies the rectifier capacity, which is the maximum amount of DC power that the device can produce by rectification, and is taken as a percentage of the inverter capacity. Therefore, the rectifier capacity is coupled to the inverter capacity and is not an independent variable.

4.3 Battery technology models

Through this section, a brief description of the technologies modeled as storage opportunities for the Findhorn ecovillage is conducted.

4.3.1 Lead-acid battery: Roll Surrette 4 KS25P battery

4 KS25P lead-acid batteries are selected as they are flooded deep cycle batteries widely used for renewable energy and alternative energy applications, especially for off-grid and backup power systems. They have already been presented in Section 3.3.2 as they are the storage technology used by the islanded energy system of the Isle of Eigg. The manufacturer website specifies that this kind of battery has replaceable cells and small carbon footprint.

As the Roll Surrette battery is not in the HOMER database, input data are required to model its energy performance. The battery properties are extracted from the datasheet available on the manufacturer website and are presented in Table 6.

Nominal voltage (V)	4
Nominal capacity (Ah)	1 350
Nominal capacity (kWh)	5.4
Round trip efficiency (%)	64
Float life (years)	20
Maximum capacity	1 952
Suggested life throughput (kWh)	11 105
Max charge current (A)	383
Max discharge current (A)	459

Table 6: Lead-acid battery properties

Also, the kinetic battery model presented in Section 4.2.2 is used as the storage model and the capacity curve is entered in HOMER. This curve is available in Appendix 3. The lifetime curve is also added and can be seen in Appendix 4. The minimum state of charge is set at 60%, giving a useable nominal capacity of 0.4*5.4 = 2.16 kWh. According to the manufacturer, the commercial price of Surrette battery 4 KS25PS 4V, 1350 Ah (20 hour rate) flood lead-acid is £950 per unit. As a reduction in battery cost is expected in the next few years, the replacement cost is set at £900 and £10/year are allocated for operation and maintenance. As sensitivity input, the number of batteries is varied from 1 to 300.

4.3.2 Vanadium redox flow battery: Cellcube FB

"*Flow batteries increasing to 30% market by 2017 as leading energy storage technology*", Lux Research.

This kind of batteries is of interest as vanadium is widespread, environmentally friendly and a recyclable material. Gildemeister manufactures a large range of vanadium redox flow batteries of different capacities and different powers which can be seen in Appendix 5. According to the manufacturer website, this technology allows for a clean and quick provision of power ready for use instantly. The design of the energy storage in terms of energy capacity and rated power depends on storage applications. Different vanadium redox flow batteries found in the HOMER database are tested to see the effects of these battery properties. They are as follows: Cellcube FB 20kW-100kWh, FB 200kW-400kWh, and FB 200kW-1600kWh. Their technical data are available in Appendix 6. Through this section, these technologies are described in details to underline the differences between their properties and to illustrate examples of commercialised vanadium redox flow batteries.

- ***Cellcube FB 20kW-100kWh***

Cellcube FB 20kW-100kWh is widely used for individual applications. Application fields are numerous and include:

- Stabilisation of low and medium voltage grids,
- Ancillary reserve; peak shaving
- Smoothing of renewable energy output and compensating for fluctuation
- Providing reliable and safe power supply

Due to its redox technology, Cellcube batteries maintain a complete capacity of storage even after unlimited cycles of 100% depth of discharge. They are expensive technologies and require an import capital cost but 50% is recoverable as vanadium is recyclable and the price of vanadium is increasing. This type of battery is presented in the figure below.

Figure 33: CellCube FB 20-100 installation in Tournai, Belgien, Source : Gildemeister, 2010.

A critical parameter to select appropriate energy storage is the size of the device, especially for large-scale application as large storage volume can be an issue in regards to the space which is available. The storage dimensions are as follows; 4.66 m x 2.20 m x 2.42 m, being at total volume of 24.80 m^3.

The battery figures in the HOMER database and the battery properties used in HOMER to simulate the technology are summarised in Table 7.

Nominal voltage (V)	48
Nominal capacity (Ah)	2 083.33
Nominal capacity (kWh)	100
Round trip efficiency (%)	64
Float life (years)	20
Suggested life throughput (kWh)	1 752 000
Max charge current (A)	383.33
Max discharge current (A)	599.86

Table 7: FB 20-100 battery properties

The battery initially figures in HOMER database and is modelled with the idealized storage model presented in Section 4.2.2. It has already been seen in Section 4.2 that modelling battery systems in HOMER is challenging due to a great number of dynamic data required to determine the battery input and battery output. To model the Cellcube FB batteries, a special procedure has to be followed. When FB Cellcube batteries are chosen in the HOMER database, it is specified that as an AC-bus system, its round trip efficiency represents an AC-DC-AC conversion and that the configuration of the system has to be made in HOMER as follows:

- The converter size has to be at least twice the rated power
- All cost for the converter have to be zero and lifetime set to 20 years
- Efficiencies of inverter input and rectifier input have to be set at 100%

The minimum state of charge of this kind of battery is set at 0%, so the useable capacity equals the nominal capacity. According to the Gildemeister website, the capital cost is £320/kWh, being £32 000 for the all technology. The replacement cost is set at £30 000 and the O&M cost at £5/kWh/year, being £500/year. The lifetime of the battery is set at 20 years. The sensitivity input is the number of batteries which is varied from 1 and 20.

- ***The Cellcube FB 200kW–400 kWh***

This storage device has been tested and proven in practice for 5 years and is a milestone in the history of renewable energy management as large-scale storage devices are a special area of focus given the increasing number of community energy systems. This kind of storage device allows for a flexible energy management, can be charged very quickly and has a spontaneous response to load demand. This kind of device can be seen in the picture below.

Figure 34: Energy solution park, Belfield, Germany. Source: Gildemeister, 2010.

The issue of space available for the installation of energy storage might be seen in Figure 34. The battery dimensions are as follows; 6.000m x 2.438m x 5.792 m, being a volume of 85 m^3.

The battery figures in the HOMER database and the battery properties used in HOMER to simulate the technology are summarised in Table 8.

Nominal voltage (V)	700
Nominal capacity (Ah)	571.429
Nominal capacity (kWh)	400
Round trip efficiency (%)	65
Float life (years)	20
Maximum capacity (Ah)	822.186
Suggested life throughput (kWh)	17 520 000
Max charge current (A)	230.35
Max discharge current (A)	354.385

Table 8: FB 200-400 battery properties

The battery initially figures in HOMER database and is modelled with the kinetic storage model. The capacity curve present in HOMER is available in Appendix 7. The same procedure as for modelling Cellcule FB 20kW-100kWh batteries is followed. The minimum state of charge of the battery is set at 0%, so the useable capacity equals the nominal capacity. The capital cost is £320 /kWh, being £128 000. The replacement cost is set at £125 000 and the O&M is assessed at £5/kWh/year, being £2 000/year. The number of battery is varied from 1 to 4.

- ***Cellcube FB 200kW-1600kWh***

FB 200-1600 and FB 200-400 have the same properties, only their capacity is different, meaning that FB 200-1600 is more appropriate for larger energy systems which require to store more energy.

Table 9 shows the properties of this battery provided by the HOMER database.

Nominal voltage (V)	700
Nominal capacity (Ah)	2 286
Nominal capacity (kWh)	1 600
Round trip efficiency (%)	65
Float life (years)	20
Maximum capacity (Ah)	3 297.38
Suggested life throughput (kWh)	17 520 000
Max charge current (A)	230.35
Max discharge current (A)	354.358

Table 9: FB 200-1600 battery properties

The battery initially figures in HOMER database and is modelled with the kinetic storage model. The capacity curve present in HOMER can be seen in Appendix 8. Cellcube FB batteries are flexible storage devices and can be scaled according to needs. They can be combined in different ways as shown in Appendix 9. For example, 5 Cellcube FB 200kW-400kWh batteries put in parallel deliver a performance of 1MW and have a storage capacity of 2 MWh. However, one limitation when modelling batteries with HOMER is that each simulation can only take into account one kind of battery, so for instance it is not possible to combine FB 20-100 battery with FB 200-400 battery.

The same procedure as for modelling Cellcule FB 20kW-100kWh batteries is followed. The minimum state of charge of the battery is set at 0%, so the useable capacity equals the nominal capacity. The capital cost is £320 /kWh, being £686 000. The replacement cost is set at £680 000 and the O&M is assessed at £5/kWh/year, being £7 700/year. The number of battery is varied from 1 to 3.

4.3.3 Lithium-ion battery: Tesla Powerwall Li-ion

"*Tesla's bold approach to advancing battery technology will change the way we build our cities forever*", Susan Kennedy, co-founder and CEO of Advanced Microgrid Solutions (Tesla Motor, 2015).

The 30th of April, it is an energy revolution when Tesla Motor introduces Tesla Energy, a suite of batteries for homes, businesses, and utilities promoting a clean energy ecosystem, while scaling up to the megawatt levels necessary for utilities and reducing the dependence of the world on fossil fuels. Tesla Powerwall is a rechargeable lithium-ion battery designed to store energy at a residential, business or utility level. Powerwall comprises Tesla's lithium-ion battery pack, liquid thermal control system and software and receives dispatch commands from a solar inverter. The unit is wall-mounted and is connected to the local grid to harness excess of power and give customers the flexibility to draw energy from their storage device. Daily cycling has the ability to extend the environmental and cost benefit of solar power in the night when the sun is not shining and no energy is produced by PV panels.

According to the manufacturer website, the battery can provide a number of different services to the customers which include:

- Load shifting; the battery can provide economic benefits to its owner by charging during low rate periods when demand for electricity is low and by discharging during peak periods when electricity demand is higher and electricity from the grid is more expensive
- Increasing self-consumption of renewable power generation; the battery can store surplus of renewable energy when demand is lower than generation at the production time and use that energy later when renewable output is low
- Back-up power; the battery ensures reliable power supply even in the event of an outage

Powerwall is available in two capacity sizes which are 7 kWh and 10 kWh. This kind of battery can be seen in the figure below.

Figure 35: Tesla Powerwall lithium-ion battery. Source: Tesla Motor, 2015.

As the Tesla Powerwall battery has been announced to be commercialized in late summer, this type of battery is not in the HOMER database. Consequently, the battery properties are extracted from the datasheet available on the manufacturer website and are presented in Table 10.

Nominal voltage (V)	48
Nominal capacity (Ah)	208.33
Nominal capacity (kWh)	10
Round trip efficiency (%)	93
Float life (years)	10
Maximum capacity	166.7
Suggested life throughput (kWh)	28 980
Max charge current (A)	200
Max discharge current (A)	312.5

Table 10: Tesla Powerwall lithium-ion battery properties

The round trip efficiency is set at 93% as specified by the manufacturer. However, as there is no feedback yet about the actual battery performance, this value will need to be validated in practice. The Tesla Powerwall specifications are available in Appendix 10.

The minimum state of charge of the battery is set at 20%, giving a useable capacity of 0.8*10 = 8 kWh. The capital cost of one 10 kWh battery is set at £3 000 as announced by Tesla Power. Also, this price is kept for the replacement cost as the technology has just been released on the market. The O&M cost is set at £10/year.

4.3.4 System configuration

The five different types of battery presented before are considered and connected to the DC part of the system. However, HOMER can only consider one type of battery per simulation, meaning that a scenario with a mix of different batteries is not feasible. The configuration of the system is illustrated in Figure 36.

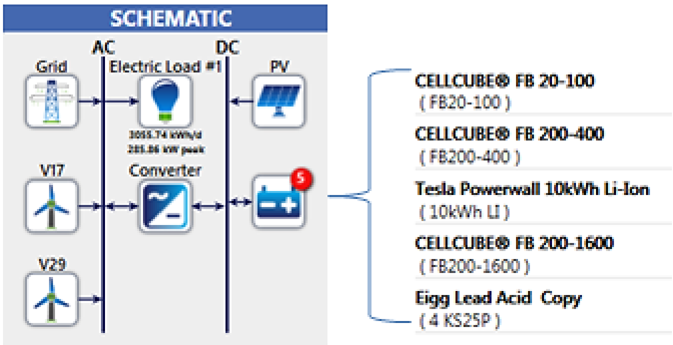

Figure 36: Configuration of the energy system of Findhorn with storage

All the equipment details for batteries can be seen in Appendix.

4.3.5 Sensitivity inputs

For this study, the sensitivity parameter of components is the number of batteries while the financial sensitivity parameter is the buy power price. Table 11 summarises the different input data considered for the simulation exercise.

Sensitivity input	4 KS25P Lead-acid	FB 20-100 vanadium	FB 200-400 vanadium	FB 200-1600 vanadium	Tesla Li-ion	Buy power price
Search space	1 to 300 batteries	1 to 20 batteries	1 to 4 batteries	1 to 3 batteries	1 to 200 batteries	£0.172/kWh £0.344/kWh £0.516/kWh

Table 11: Sensitivity inputs for storage simulation

4.3.6 Financial input data

All costs associated with the projects are taken into consideration to fully assess the economic aspect of each scenario. The next table summarises the different costs previously presented for each battery component of the system.

Component	Size (kWh)	Capital cost (£)	Replacement cost (£)	O&M cost (£/year)	Lifetime
4 KS25PS	5.4	950	900	10	11 105 kWh of throughput
FB 20 -100	100	32 000	30 000	500	1 752 000 kWh of throughput
FB 200 - 400	400	128 000	125 000	2 000	17 520 000 kWh of throughput
FB 200-1600	1 600	386 000	380 000	7 700	17 520 000 kWh of throughput
Tesla Li-ion	10	3 000	3 000	10	28 980 kWh of throughput

Table 12: Financial input data for storage devices

It has already been seen that the converter size is problematic when important DC capacity is used and different scenarios are modelled. In order not to limit the energy through the converter and focus on battery performance, its size is set at 1 000 kW and the price is set at £0.

4.3.7 Control of the storage system

The load-following strategy is used by HOMER to select the optimal storage technology as this is the strategy which leads to the best local renewable use as the batteries are only charged with the surplus of renewable output. The results given by HOMER are greatly influenced by the control of the system which needs to be carefully defined according to objectives. To optimise the role of batteries and decrease the reliance on the grid, advanced grid inputs are considered and are as follows; sale capacity, sellback rate, maximal annual purchase capacity and buy power price. The impact of the sellback rate plays a significant role in the optimal storage technology selected by HOMER. Indeed, it has to be adapted when energy systems are simulated with storage device to make HOMER prioritises the use of renewables by charging the batteries with the surplus of renewable power rather than selling it to the grid. To achieve this goal, grid sales are prohibited with a sale capacity set at 0 kW and the sellback rate is set at £-100/kWh.

The maximal purchase capacity is set at 300 kW, slightly higher than the peak load of 286 kW to still meet the load in case of unavailability of renewable output and increase in the load. As import is necessary to meet the load anytime and ensures the feasibility of all systems, power price has to be defined. It is an important parameter since HOMER optimisation determines if it is more beneficial to meet the load by drawing power from the grid or from the batteries. As an additional sensitivity input, the power price is varied to see the impact of the double and the triple of the initial power price on the system design.

Another control parameter set to maximise the use of locally-generated electricity is the prohibition of grid to charge the batteries. It means that the batteries are only charged by the surplus of electricity produced from renewable sources and they are discharged only to meet the primary load.

4.4 Control of systems in HOMER

4.4.1 Basic financial control in HOMER

HOMER determines the optimal system configuration on the basis of economic minimisation or fuel minimisation if a diesel generator is considered. Four financial variables which characterise the energy system created are given by HOMER; the initial cost, the operating cost, the cost of electricity (COE) and the total net present cost (NPC). The levelized cost of electricity (COE) is the average cost per kWh of useful electricity produced by the system. HOMER calculates it by dividing the total annualized cost of the system (£/year) by the total electrical load served (kWh/year). The variable output HOMER uses to represent the lifecycle cost of the system is the NPC which includes all costs and revenues that occur within the project lifetime, with future cash flows discounted to the present. The NPC considers the initial capital cost of the system components, the cost of any component replacements that occur over the project lifetime, the cost of maintenance and fuel, and the cost of power purchase from the grid. Also, any revenue from the sale of power to the grid reduces the total NPC. The optimization conducted by HOMER selects the system resulting in the lowest NPC as the most suitable configuration.

4.4.2 Restrictions and worst financial case analysis

However, modelling storage system in HOMER is challenging and imposes difficulties which need to be faced with restrictions. It has been stated in Section 4.3.7 that grid sales are prohibited and that the sellback rate is set at £-100/kWh. This is only a repetition of restriction to force HOMER to use the storage device in an optimal way. As HOMER does not export any energy due to this double restriction, the NPC is not affected by the negative sellback rate value. However, the NPC is impacted is by the loss of money induced by the prohibition of grid sales as the excess of electricity does not benefit of FIT regulations and is wasted. Consequently, the financial results can be considered for a one-way-flow energy system like the one of Tamera but does not suit the situation of Findhorn. Since the exports to the grid have 0 value, it refers to a worst case financial analysis as in practice there would be financial benefit from the grid interaction. This underlines the limitation in HOMER to model scenarios with a multiple approach and obtain consistent results in regards to both energy system performance and system cost.

Chapter 5: Simulation results of the Findhorn ecovillage

Through this section, the results of the simulation exercise are presented for the original energy system of Findhorn and for alternative system designs. The search space of HOMER allows for the consideration of alternative system configurations and HOMER’s optimization selects the most appropriate scenario for the given load and meteorological resources. This includes a financial analysis of the different system options and refers to a worst financial case analysis when storage is involved as explained in Section 4.4.2. Attention is given to both the economic impact and the energy performance of the system in terms of local renewable use. Indeed, increasing the performance of energy systems usually results in higher costs, meaning that a balance has to be achieved as different ways of optimization can lead to different system configurations Also, two alternative demand conditions are considered as mentioned in Section 4.1.6.

5.1 The Original system of Findhorn

5.1.1 Simulation results

Firstly, the simulation results are presented for the initial system since the point of this simulation exercise is to validate the model used in HOMER by comparing simulation results with data provided by the community. Attention is given to the electricity generations from the different renewable sources and their contribution to the load.

Electricity generation from PV panels

Figure 37 shows the PV power output over the year (x-axis) and according to the time (y-axis).

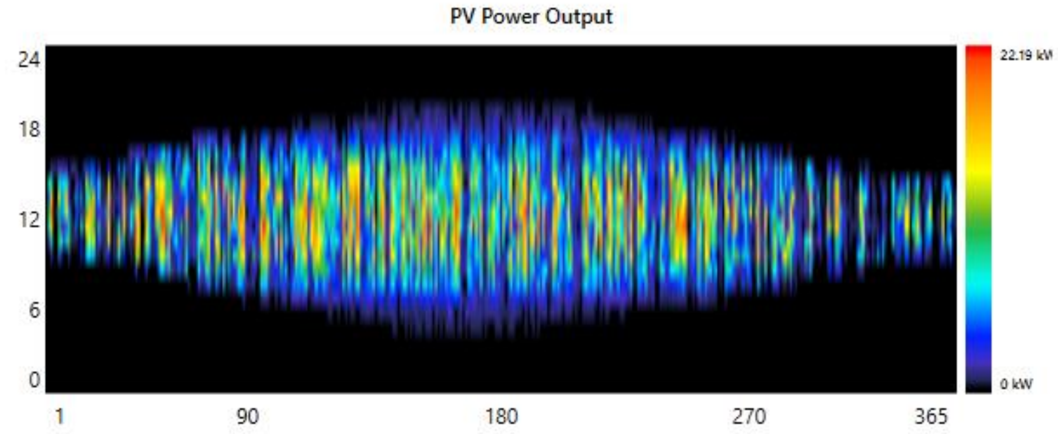

Figure 37: PV power output of Findhorn

The PV output is 22 116 kWh/year and the mean output is 2.52 kW. It can be seen in Figure 37 that the power output is stronger during summer and especially around midday due to stronger solar radiation. Also, the PV panel produces power more often in summer than in winter due to longer daytime.

Electricity generation from the three V29 wind turbines

Figure 38 shows the wind power output of the three V29 wind turbines over the year (x-axis) and according to the time (y-axis).

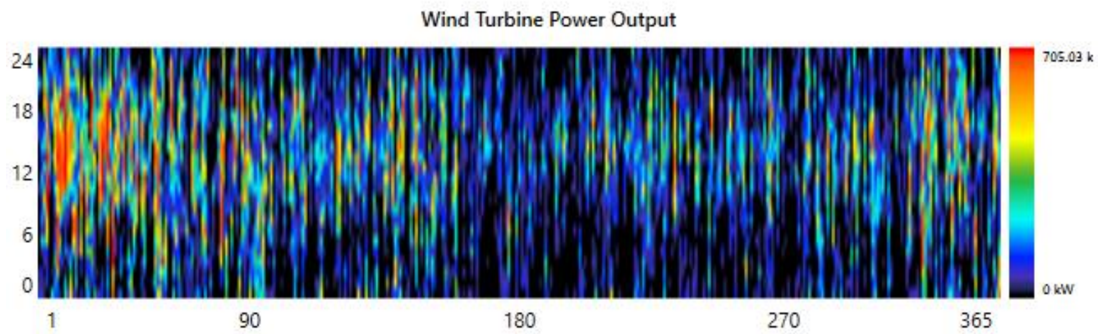

Figure 38: Wind turbine power output of the three V29

The three wind turbines produce 1 021 925 kWh/year. It can be seen in Figure 38 that the best power output is obtained in January and February with longer periods of power production over the day due to windier winter days. The same observations can be made for the V17 wind turbine which produces 92 624 kWh/year.

Comparison of the renewable energy outputs in a winter week

Figure 39 illustrates the electricity generation from wind energy and solar energy during a winter week.

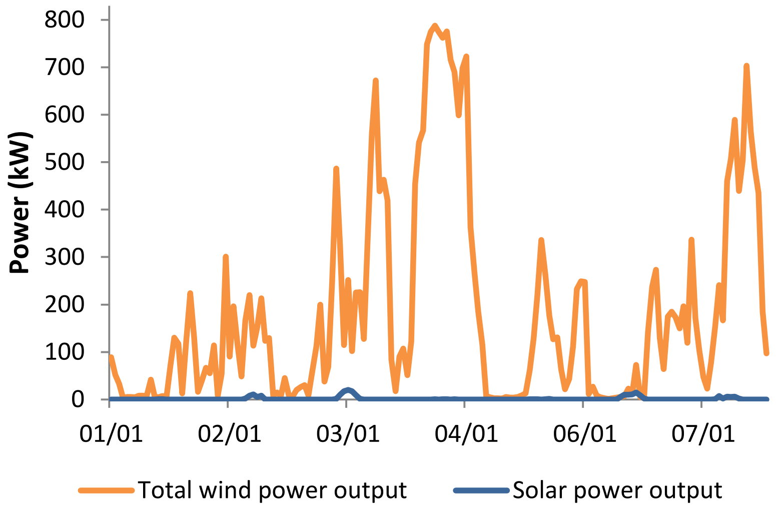

Figure 39: Renewable generation of Findhorn during a winter week

The figure above shows the significant unpredictability and variability of the renewable energy output. Indeed, the output varies significantly over a week, meaning that the availability of renewable resources is greatly changing within a same seasonal period. The wind power output is the one which varies the most with values from 3 kW to 775 kW while the solar energy output varies between 0 kW and 17 kW. Most of the time, there is no PV output as there is only solar radiation between 10am and 4pm in winter.

Comparison of the renewable energy outputs in a summer week

Figure 40 illustrates the electricity generation from wind energy and solar energy during a summer week.

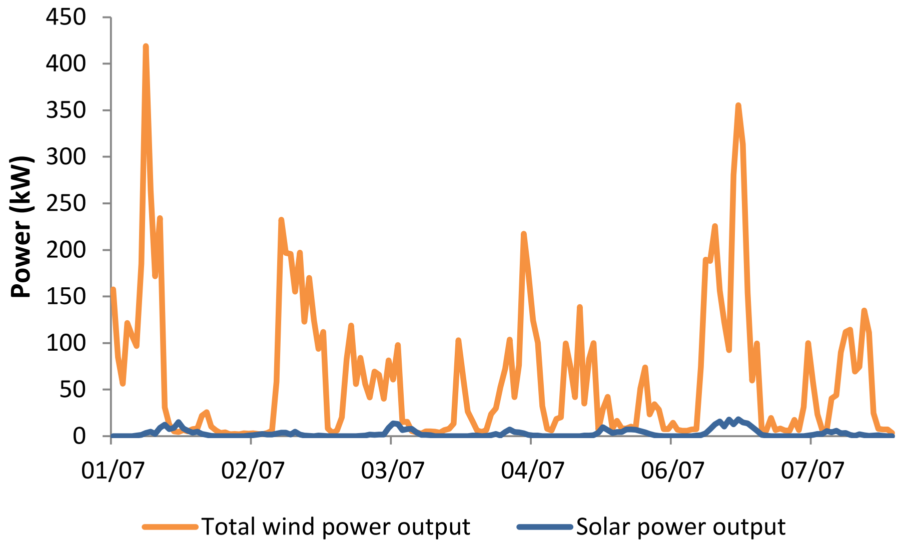

Figure 40: Renewable generation of Findhorn during a summer week

The previous observation about the variability of renewable energy output is also valid in summer, as illustrated in the figure above. The wind power output is the one which varies the most with values from 4 kW to 418 kW while the solar energy output varies between 0 kW and 20 kW. The operation time of PV panels is higher in summer than in winter as there is solar radiation from 5am to 9pm due to longer daytime.

Monthly power generation

Figure 41 represents the total power generation for each month of the year, including renewable power generation and grid purchases.

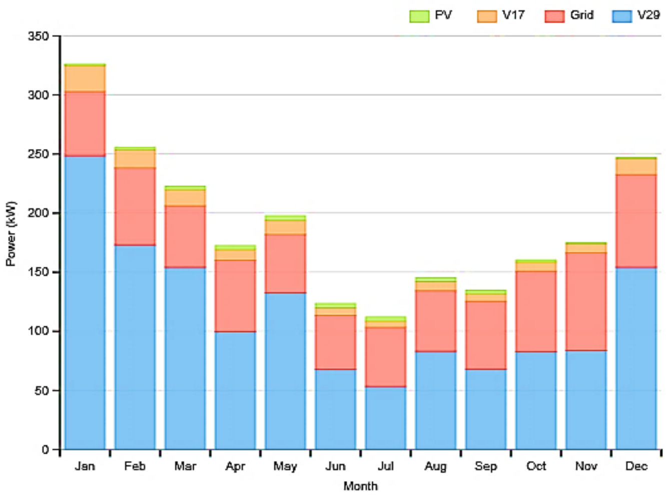

Figure 41: Monthly power generation of Findhorn

It can be seen that the highest electricity import occurs in November while the lowest occurs in June.

Total renewable electricity generation and electric load

As the matter of matching supply with demand is raised to improve local renewable use, Figure 42 illustrates the generation profile compared to the load profile over a year.

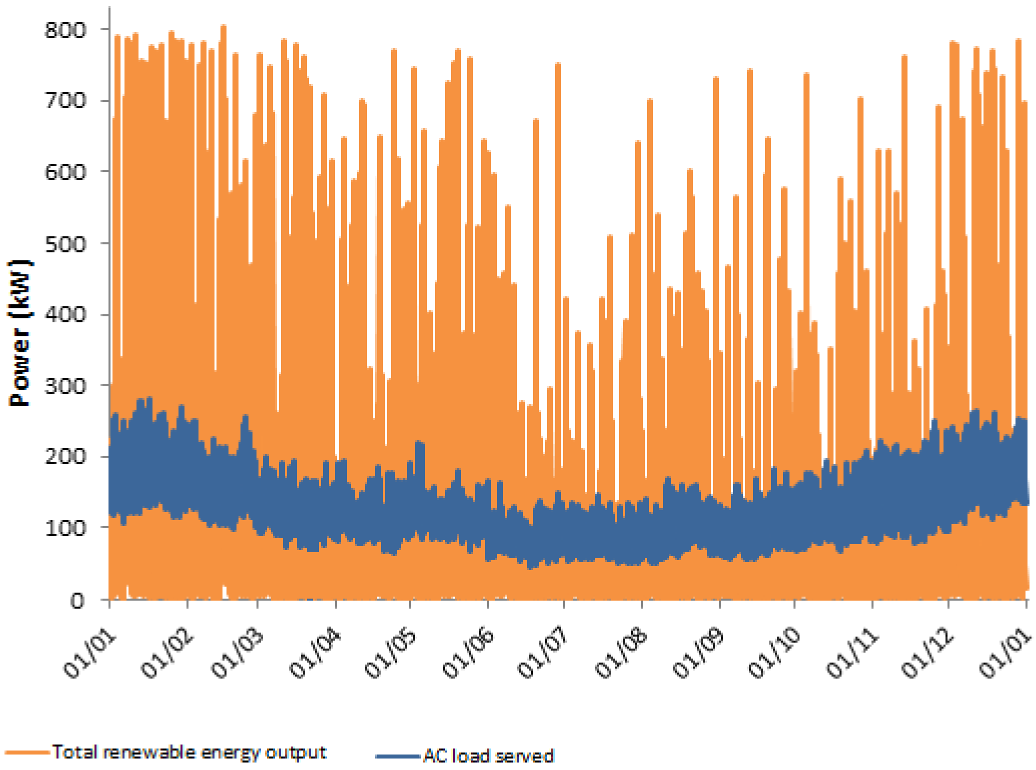

Figure 42: Annual renewable electricity generation and electricity demand of Findhorn

It can be seen in Figure 42 that harnessing renewable output has a potential to fully meet demand all over the year. The next graph illustrates load and generation for a typical winter period.

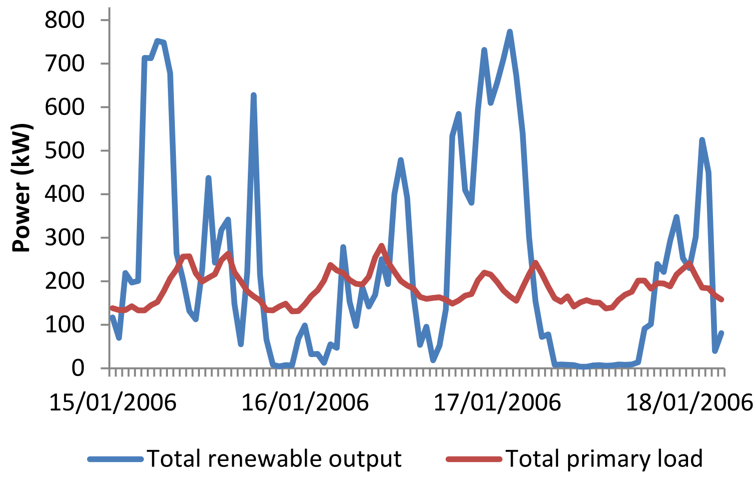

Figure 43: Load profile and generation profile of Findhorn in winter days

This energy profiles show that even if the yearly generation is higher than the annual load, the high variability of renewable output over day and hour results in the mismatch of generation and demand. Indeed, they are not well-synchronized as peak loads can happen when the renewable energy output is at the lowest point. On the contrary, the instant electricity generation can be four times higher than the instant load. All these observations result in electricity surplus and electricity deficit as illustrated in Figure 44 for the same winter days.

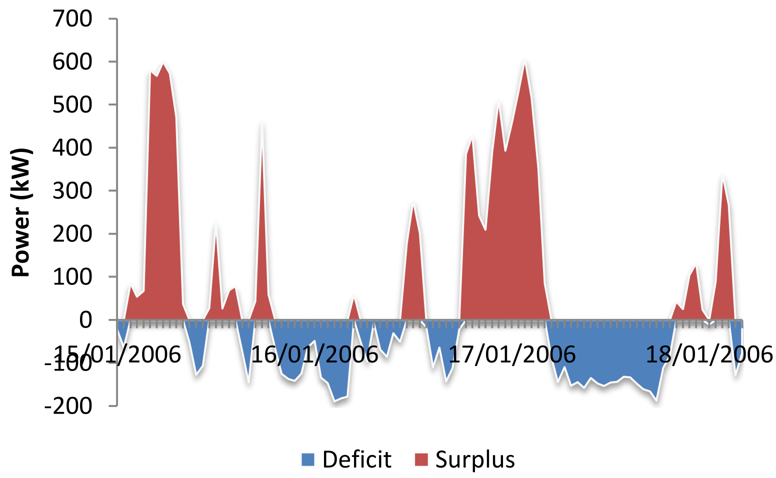

Figure 44: Power deficit and power surplus of Findhorn in winter days

In case of peak generation, there is a surplus of electricity which is not used to meet the load and is sold to the grid. On the contrary, in the event of low renewable output and high demand, electricity is purchased from the grid. The monthly import and export of electricity required by the energy system configuration are shown in Appendix 11.

5.1.2 Results analysis and model validation

Electricity balance

The results of this first set of simulations are summarized in Table 13.

Production source	kWh/yr	%
PV panels	22 116	1.3
V17 wind turbine	92 624	5.6
V29 wind turbines	1 021 925	61.7
Grid Purchases	521 046	31.4
Total	1 658 364	100

Consumption Source	kWh/yr	%
Primary Load	1 115 345	73.2
Grid Sales	540 155	32.6
Total	1 655 400	100

Table 13: Electricity balance of the initial system

The results of the simulation indicates that the total renewable generation reaches 1.14 MWh/year while the load is found to be 1.12 MWh/year, meaning that the renewable technologies have the potential to provide 102% of the community's energy requirements over a year. It is of interest to determine the green electricity used (E_{green}) which can be calculated as follows:

$$E_{green}(\%) = \left(\frac{\textit{Primary load}\left(\frac{kWh}{year}\right) - \textit{Import}\left(\frac{kWh}{year}\right)}{\textit{Total renewable generation}\left(\frac{kWh}{year}\right)} \right) \times 100$$

Equation 1: Green electricity used

Given that, the average use of green electricity over a year reaches 52.3% only. It can also be seen that more electricity is sold to the grid than purchased which shows the potential of Findhorn to better use its renewable production.

Discussion and model validation

In order to validate the values of the energy flows given by HOMER and so the system model considered, the ORIGIN portal is consulted. The user interface available online gives a daily electricity balance for the previous day, a monthly electricity balance and the electricity balance from the start of the ORIGIN project. An example of the dashboard is shown in Figure 45.

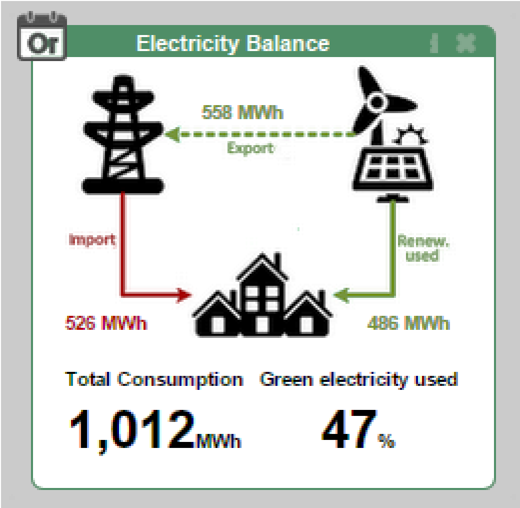

Figure 45: Electricity balance of Findhorn from the start of the ORIGIN project. Source: ORIGIN Concept.

The screen above gives information on the green electricity used which is the fraction of the electricity locally produced that is consumed on site. It tells that from the beginning of the Origin project in November 2014 to the end of June 2015, 47% of the locally-generated electricity is used to meet the load. Given the uncertainty of the data used in this portal and that the summer period with lower load is not included, it can be concluded that the Homer software gives a good model of the actual energy balance of Findhorn. Also, it can be found on the website of the Findhorn community that around 50% of the electricity generated is used on site while the rest is imported from the main grid. It is also specified that the community actually produces more than 100% of its energy needs. However, the energy produced from renewables strongly depends on meteorological resources, especially wind speed. Consequently, renewable output is difficult to predict and greatly varies from one year to another. As the system is rightly balanced in this configuration, it means that there might be important variation of surplus or shortfall from renewable generation and alternative scenarios should be considered.

In sum, the energy data provided by HOMER are aligned with the energy performance of the electrical system announced by the ecovillage which makes suitable the model used in HOMER to simulate this energy system.

5.1.3 Sensitivity analysis

Impact of the converter size

No data are available about the converter system actually used in Findhorn. Consequently, converter sizes ranging from 5 kW to 100 kW are used in the search space to find the optimal size. This is the only input variable as the system is constrained to the current configuration of the Findhorn. HOMER selects the optimal system shown in Figure 46 for both load cases.

Sensitivity	Architecture											Cost			
Electric Load #1 Scaled Average (kWh/d)							PV (kW)	V17	V29	Grid (kW)	Converter (kW)	COE (£)	NPC (£)	Operating cost (£)	Initial capital (£)
3055.7400							25.0	1	3	999 999	20.0	0,0648 £	1,39 £M	37 628 £	900 000 £
3300							25.0	1	3	999 999	20.0	0,0691 £	1,53 £M	48 840 £	900 000 £

Figure 46: Homer simulation results for the current energy system with two different loads

The best results are obtained with an inverter of 20 kW as the maximum inverter output was 19.973 kW. This means that an inverter with higher capacity has no effect on the electricity import and export while costs are increased. Interestingly, HOMER selects the same optimal converter size for both load cases as the load is connected on the AC bus. The optimal size of the converter is justified by the fact that the only DC component is the 25 kW PV panel and its output is the only electricity flowing through the inverter. However, an inverter with a lower capacity increases grid purchases and decreases grid sales as less electricity flowed through the inverter, which reduces the renewable penetration in the load.

Impact of load size

Table 14 shows the impact of load size on the electricity exchange with the grid.

Source	kWh/year for demand of 3 056 kWh/day	kWh/year for demand of 3 300 kWh/day
PV panel	22 116	22 116
V17 wind turbine	92 624	92 624
V29 wind turbines	1 021 925	1 021 925
Export	540 155	510 222
Import	521 046	580 269
Green electricity used (%)	52.3	54.9
Load met by green electricity (%)	53.3	51.8

Table 14: Impact of load size on renewable use

The fraction of the load met by green electricity is calculated as follows:

$$\textbf{Load met by green electricity}\ (\%) = \frac{E_{green}\left(\frac{kWh}{year}\right)}{Primary\ load\ \left(\frac{kWh}{year}\right)} \times 100$$

Equation 2: Load met by green electricity

It can be seen that an increase in load results in less export and more import as more electricity is required to meet the load. It means that if there is a demand growth, there is a potential to use more electricity produced from renewable sources. However, the percentage of community load met by renewables is lower in case of increased demand as import is significantly impacted.

5.2 Alternative system

"You can never change things by fighting the existing reality. To change something, build a new model that makes the existing obsolete", R. Buckminster Fuller.

It has been seen previously that the yearly energy deficit is 521 046 kWh while the surplus of electricity is 540 155 kWh. In order to reduce these power exchanges with the grid, especially in terms of import to maximise local renewable use, alternative system configurations are investigated according to two different strategies. The first method is adding renewable capacity to diversify the generation mix while the second method is to implement energy storage. The first strategy increases local renewable use to meet load directly as more power is produced while the second strategy achieves the same purpose by time-shifting the energy supply to meet the load when required.

5.2.1 Addition of renewable capacity to the Findhorn electrical system

Diverse sensitivity inputs are considered in HOMER simulation to determine if other configurations appear to be more efficient than the initial one. At this point, cost consideration plays an important role in the determination of the optimal system design. To take into account possible increase in electricity demand, the two daily average loads are still considered.

Addition of solar capacity to the current system

In this section, different capacity sizes of PV panels are studied to determine the effect of various scales of PV production on the green electricity used. PV installers advise that 807 units/annum/kWpk are obtained for well-oriented panels, while the ones used in HOMER gives 865 units/annum/kWpk. As some roofs may not be perfectly aligned, it was suggested by the ecovillage to do calculations on the basis of solar PV units produced rather than array size. However, the only sensitivity input used by HOMER for solar system is the PV capacity size which is the critical parameter to optimize the system.

The current size of PV panels is 25 kW, and increased sizes of 50, 100, 150, 200 and 250 kW are considered as suggested by the Findhorn ecovillage. Also, a total solar capacity of 1.5 MW is considered as an academic exercise to study the potential impact of a solar park on the energy system. The wind capacity is kept at 750 kW. This study is conducted to see the effect of solar capacity size on renewable electricity consumed on site versus export. The simulation is run for the current load of 3 056 kWh/year and then is repeated with the increased load of 3 300 kWh/year.

The results are shown for the first load in Table 15.

PV size (kW)	Solar energy (kWh/year)	Total generation (kWh/year)	Green electricity used (kWh/year)	Increase in green electricity use (%)	Fraction of the load met by green electricity (%)
25	22 116	1 136 665	594 299	/	53.3
50	44 232	1 158 781	605 251	1.8	54.3
100	88 464	1 203 013	625 585	5.3	56.1
150	132 696	1 247 245	643 369	8.3	57.7
200	176 928	1 291 477	658 204	10.8	59.0
250	221 160	1 335 709	670 394	12.8	60.1
1 500	1 326 978	2 441 527	764 181	28.6	68.5

Table 15: Impact of increased solar capacity on green electricity use for the current load

The increase in green electricity used is calculated as follows:

$$\boldsymbol{Increase\ in\ green\ electricity\ used}\ (\%) = \left(\frac{\boldsymbol{E_{green_{Alternative\ system}}} \left(\frac{\boldsymbol{kWh}}{\boldsymbol{year}}\right)}{\boldsymbol{E_{green_{Initial\ system}}} \left(\frac{\boldsymbol{kWh}}{\boldsymbol{year}}\right)} - \mathbf{1} \right) \times \mathbf{100}$$

Equation 3: Increase in green electricity used

It can be seen that increasing PV capacity size increases the local renewable use of electricity as it might be expected. As PV generation increases, the fraction of electricity coming from renewables used to meet the load increases as well. This allows for a better use of locally-generated electricity.

Figure 47 illustrates the increase in green electricity consumption according to solar capacity.

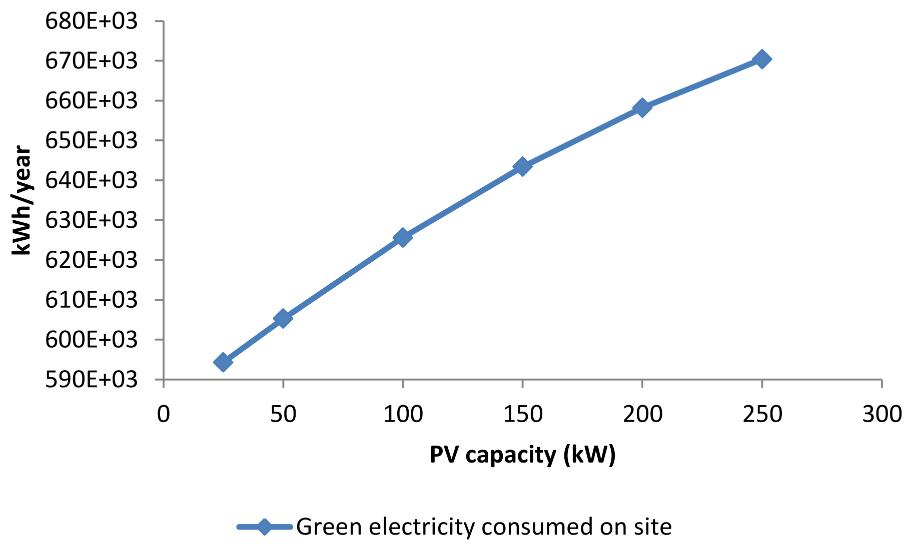

Figure 47: Green electricity consumption according to solar capacity

The modifications resulting from additional PV size on export and import are shown in Table 16.

Additional capacity (kW)	Additional energy generation (kWh/year)	Import reduction (%)	Export increase (%)	Fraction of the additional energy generation consumed locally (%)
+25	22 116	2.1	1.7	49.5
+75	66 348	6.0	5.3	47.2
+125	110 580	9.4	9.3	44.4
+175	154 812	12.3	14.0	41.3
+225	199 044	14.6	19.1	38.2
+1 475	1 304 862	36.2	186.0	13.0

Table 16: Impact of PV size on energy import/export for the current load

The fraction of the additional energy generation consumed locally (F_{add}) is calculated as follows:

$$F_{add}(\%) = \left(\frac{E_{green_{Alternative\ system}} \left(\frac{kWh}{year}\right) - E_{green_{Initial\ system}} \left(\frac{kWh}{year}\right)}{\text{Additional energy generation} \left(\frac{\text{kWh}}{\text{year}}\right)} \right) \times 100$$

Equation 4: Additional energy generation consumed locally

Table 16 shows that the addition of renewable capacity results in import reduction and export increase. However, as export increases faster than import decreases when capacity increases, the fraction of the additional energy generation which is consumed locally decreases. Indeed, almost half of the additional energy generation from the addition of 25 kW is consumed on site while it drops to 38.2% for an addition of 225 kW. It means that even if the number of units consumed on site increases with capacity, most of the electricity produced is exported. This shows the limitation of solar penetration.

In the case of the addition of 1 475 kW of solar capacity to achieve a solar park of 1.5 MW, import is reduced by 36.2% which considerably increases the green electricity consumption. However, the implementation of a PV park of 1.5 MW requires the availability of a large field assessed at 33 250 m^2 for the Conergy case study in Czech Republic. The project uses 4 534 PV arrays all over this area (Renewable Energy Focus, 2010). Given that the size of the Findhorn community is 30 000 m^2, it does not appear relevant to consider this capacity size that would lead to a solar park area higher than the community area. Also, the ecovillage is not interested in investigating solar park opportunities and is more willing to increase its solar capacity by installing either roof mounted systems connected to individual buildings, perhaps totalling 45kW, or by installing a ground mount array of up to 250kW.

The same simulation exercise is conducted with the increased load of 3 300 kWh/day. The main results are presented in Table 17.

Additional capacity (kW)	Import reduction (%)	Export increase (%)	Green electricity used (kWh/year)	Fraction of the additional energy generation consumed locally (%)
+25	2.0	1.7	626 443	61.6
+75	5.6	5.3	640 073	59.3
+125	8.9	9.4	665 789	56.8
+175	11.7	14.0	689 203	53.8
+225	14.0	19.2	709 683	50.8

Table 17: Impact of solar capacity on green electricity use for increased load

It can be seen that an increased load results in a better use of locally-generated electricity as the shape of the load has been kept the same while the average load has been scaled. Indeed, 61.9% of the energy generated by an additional renewable capacity of 25 kW is consumed locally while it only reaches 49.5% for the lower load. However, the shape of the load seems to be a limitation to the local renewable use as the magnitude of demand depends on the hour of the day and additional capacity inevitably results in increasing export.

Addition of wind capacity to the Findhorn energy system

In this section, different sizes of wind capacity are studied to determine the effect of various scales of wind production on the green electricity used. However, the number of wind turbine components accepted by HOMER is limited to two turbines, meaning that wind capacity can only be extended by increasing the number of current wind turbines. This narrows the capacity range that can be investigated. The current size of the wind capacity is 750 kW, and increased sizes of 825, 900, 975, 1 050 and 1 500 kW were considered. The solar capacity is kept at 25 kW. This study is conducted to see the effect of wind capacity size on renewable electricity consumed on site versus export. The simulation is run for the current load of 3 056 kWh/year and then is repeated with the increased load of 3 300 kWh/year. The results are shown below for the first load.

Wind capacity (kW)	Wind energy (kWh/year)	Total renewable generation (kWh/year)	Green electricity consumed (kWh/year)	Increase in green electricity use (%)	Fraction of the load met by green electricity (%)
750	1 114 549	1 136 665	594 299	/	53.3
825	1 207 173	1 229 289	612 256	3.0	54.9
900	1 299 796	1 321 912	628 875	5.8	56.4
975	1 392 420	1 414 536	644 252	8.4	57.8
1 050	1 485 045	1 507 161	659 303	10.9	59.1
1 500	2 365 371	2 387 487	778 686	31.0	69.8

Table 18: Impact of wind capacity on green electricity consumption for current load

It can be seen that increasing wind capacity size increases the local renewable use of electricity as it might be expected. As wind generation increases, the fraction of electricity coming from renewables used to meet the load increases as well. This allows for a better use of locally-generated electricity. The simulation has also shown that adding 225 kW of wind capacity by installing one big V29 turbine rather than three small V17 turbines leads to a better use of green electricity (3% higher) but the results are not detailed for brevity reasons. The best use of green electricity is obtained with 1.5 MW of wind capacity. However, such wind turbines usually have a hub height ranging from 65 m to 80 m and the Findhorn Wind Park has a 45m height limit imposed because of the neighbouring military runway. Consequently, a total wind capacity of 1.5 MW can be considered if smaller wind turbines that fulfill the height limit are added. As there is plenty of space in the Findhorn Wind Park, expanding its wind capacity this way could be an option to increase its local use of renewables, but this is without any financial considerations.

The modifications resulting from additional wind capacity on export and import are shown below in Table 19.

Additional capacity (kW)	Additional energy generation (kWh/year)	Import reduction (%)	Export increase (%)	Fraction of the additional energy generation consumed locally (%)
+75	92 624	3.5	13.8	19.4
+150	185 247	6.6	27.9	18.7
+225	277 871	9.6	42.2	18
+300	370 496	12.5	56.7	17.5
+750	1 250 822	35.4	193.8	14.7

Table 19: Impact of wind capacity on electricity import/export for current load

Table 19 shows that the addition of renewable capacity results in import reduction and export increase. However, an important quantity of electricity produced from wind is exported to the grid as the wind penetration is already around 100% in the current system configuration, meaning that the wind generation has potential to fully cover the load. Consequently, even if the green electricity consumption is improved, most of the additional power generation is sent to the grid.

In the case of an increased load, the same observations as in the case of increased solar capacity can be made. An increased load results in a better use of local renewable energy as the surplus of electricity produced is absorbed by the load. Also, increased import is required which maintain dependency on the main grid.

Wind power versus solar power

A different question could be to compare the on-site use of local generation when adding wind versus PV. It is feasible that diversifying the generation will result in higher on-site use but that this does not happen at one to one installed capacity. For example, does adding 100 kW PV capacity result in better on-site use than adding 100 kW wind capacity? Given that the maximum number of wind turbine components in HOMER is limited at two and that the system has to comprise at least its current components, two alternative scenarios are studied. It deals with the addition of 75 kW PV versus 75 kW wind and the addition of 225 kW PV versus 225 kW wind. The first scenario considers a 100 kW PV panel and is compared to a scenario considering the addition of one 75 kW V17 wind turbine. By doing so, it is possible to define the best scenario, either by adding 75 kW solar or 75 kW wind. Then, the same study is conducted with additional 225 kW capacity. Four 225 kW V29 wind turbines are modelled and the results are compared with those given by a 250 kW PV panel. In each case, the numbers of units/annum/kW installed is determined and the fraction of additional renewable generation consumed on site is calculated. Also, the renewable penetration of each renewable energy source is of interest to determine the best scenario.

The sensitivity inputs are summarised in Table 20.

Component	PV size (kW)	Converter size (kW)	V17 wind turbine	V29 wind turbine
Size	25, 100, 250	20, 100, 250	1, 2	3, 4

Table 20: Sensitivity parameters for HOMER optimisation

The different systems and results are presented below in Table 21.

System	PV capacity size (kW)	Converter size (kW)	V17	V29	Additonal capacity (kW)	PV penetration (%)	Wind penetration (%)	Import reduction (%)	Export increase (%)	Increase in green electricity consumption (%)
initial	25	20	1	3	/	1.8	99.9	/	/	/
1	25	20	2	3	75 wind	2.0	108.2	3.4	13.8	2.6
2	100	20	1	3	75 solar	7.9	99.9	3.3	2.2	2.5
3	100	100	1	3	75 solar	7.9	99.9	6.0	5.3	4.9
4	25	20	1	4	225 wind	2.0	130.5	9.6	53.8	8.0
5	250	20	1	3	225 solar	19.8	99.9	5.2	3.4	4.1
6	250	100	1	3	225 solar	19.8	99.9	14.2	14.8	12.0
7	250	250	1	3	225 solar	19.8	99.9	14.6	19.1	12.4

Table 21: Impact of scenarios on green electricity consumption

HOMER calculates the solar and wind penetrations as follows, respectively:

$$P_{PV}\,(\%) = \frac{P_{PV\ output}\left(\frac{kWh}{year}\right)}{Primary\ load\ \left(\frac{kWh}{year}\right)} \times 100$$

Equation 5: Solar penetration

$$P_{wind}\,(\%) = \frac{P_{wind\ output}\left(\frac{kWh}{year}\right)}{Primary\ load\ \left(\frac{kWh}{year}\right)} \times 100$$

Equation 6: Wind penetration

As the size of PV panel is varied, different converter sizes are modelled in order to determine the best configuration in terms of use of energy. It is important to adapt the size of the converter according to the PV panel capacity. Since the PV capacity size increases, more energy can flow through the converter which impacts the consumption of electricity coming from renewables. As the converter size increases, the energy output of the converter increases which reduces electricity import and increases export. For each PV size, the best results are obtained when the converter size is aligned with the PV size to allow for the maximum energy flow through the converter.

As expected, the increase in the system capacity results in higher on-site use of renewables. For both addition of 75 kW and 225 kW renewable capacities, the system which leads to the best consumption of renewable electricity is obtained for additional solar capacity. The increase in green electricity consumption for the scenarios of 100 kW PV and 250 kW PV is + 4.9% and + 12.4%, respectively, when compared to the initial scenario.

The increase in green electricity consumption is maximal for the following system configuration: 250 kW PV panel, 250 kW converter, one V17 wind turbine and three V29 wind turbines. This alternative system design allows for + 73 884 kWh/year of green electricity consumed on site compared to the current system. However, it only refers to 50.2% of the green electricity produced as the renewable output is increased, meaning that export is increased as well to accommodate the excess of electricity produced.

As a guideline, the table below illustrates the annual energy generation of the different renewable generating technologies per kW installed.

Technology	**PV panel**	**V17 wind turbine**	**V29 wind turbine**
kWh/annum/kW installed	865	1 235	1 510

Table 22: Renewable technology generation

It can be seen that for a same capacity installed, V29 wind turbine generates more energy over a year. However, the matter of how many units are consumed on site versus exported is raised to define which technologies result in more on-site use.
For each scenario, Table 23 shows the fraction of the additional renewable generation which is consumed locally.

System	Increase in renewable production (kWh/year)	Increase in green electricity consumption (kWh/year)	% of additional renewable consumed
1	92 624	17957	19.4
2	66 349	17231	26.0
3	66 349	31286	47.2
4	340 641	50170	14.7
5	199 047	26921	13.5
6	199 047	74065	37.2
7	199 047	76095	38.2

Table 23: Additional renewable generation consumed locally

In the table, the systems underlined in blue refer to increase in wind power capacity.
It can be seen that the better use of additional renewable is obtained for System 2 which is made of 100 kW PV panel, 100 kW converter, one V17 wind turbine and three V19 wind turbines. Indeed, 47.2% of the additional renewable generation due to increased renewable capacity is consumed locally. Although 100 kW of solar power results in less renewable power output than adding 100 kW of wind power, less import is required if the size of the converter is adapted. This means that solar energy is generated at more appropriate hours and tends to be more used to meet the load than wind power whose important quantity is exported. As the wind penetration of the initial system is 100%, increasing wind power capacity does not significantly improve the green electricity use. This might be explained by the fact that when wind resource is available, the wind power generated is often much higher than the load and the excess of electricity is sold to the grid.

So far, no financial data have been included in the analysis as the focus has been put on renewable electricity consumption within the ecovillage. The share of green electricity in the total energy consumption is totally independent of financial consideration. However, rough financial data have been included to act as a baseline and investigate the process of optimization to select the optimal scenario by using the HOMER tool.

The economic results of the different scenarios considered for the simulation are shown in Table 24.

	Initial system	Additional wind capacity		Additional solar capacity	
Additional capacity (kW)	/	75	225	75	225
COE (£/kWh)	0.0648	0.0629	0.0530	0.0766	0.100
NPC (M£)	1.39	1.41	**1.34**	1.67	2.28

Table 24: COE and NPC for each scenario

Considering the lowest NPC, HOMER selects the following energy system as the optimal one.

Architecture										Cost			
					PV (kW)	V17	V29	Grid (kW)	Converter (kW)	COE (£)	NPC (£)	Operating cost (£)	Initial capital (£)
					25.0	1	4	999 999	20.0	0,0530 £	1,33 £M	15 779 £	1,13 £M

Figure 48: HOMER optimization results for Findhorn

Taking into account the financial data input, the economic minimisation suggests that the best scenario is 25 kW PV panel, one V17 wind turbine and four V29 wind turbines, meaning that adding 225 kW of wind is financially more beneficial than adding 225 kW of solar. Indeed, the COE is sufficiently low to lead to a lower NPC than the one of the initial system and this is the only scenario that allows for this.

However, previous study conducted by the Findhorn ecovillage over the last year suggested that wind power at the Wind Park was not economically viable under the existing feed-in tariff regulations (FIT) applied to the community. These regulations provide a lower FIT if existing spare capacity in the connection cable and grid connection for additional wind capacity are used. This signifies that a lower FIT than £0.0487/kWh set by the current UK legislation and used for the simulation is actually applied to the community for additional wind capacity. However, this does not apply if a different renewable technology is used and the community now focuses on exploring the possibility of adding solar PV.

The fact that HOMER chooses additional wind capacity as the most profitable scenario might be explained by the fact that significant amount of wind is sold to the grid which leads to important revenue from the electrical system. In order to confirm this theory, the simulation is repeated with a new sensitivity input which is the sellback rate and the following additional inputs are considered: £0.02/ kWh and £0.01/ kWh. This time, HOMER selects additional solar capacity with a total capacity up to 40 kW to be the best economic option. From this analysis, it can be seen how the design of energy systems is impacted by regulations and incentives about renewable electricity production. Also, the optimization conducted by HOMER is greatly sensitive to the financial data input in the model.

5.2.2 Addition of storage capacity to the Findhorn electrical system

Storage devices can guarantee uninterruptible power supply, independently of weather variations, temperature, length of the day and unstable grid. There is no electrical storage device in Findhorn. In the first place, this decision was made as the connection with the main grid was a cheaper option to export electricity. Nowadays, the community has grown and the addition of the three V29 wind turbines has considerably increased the renewable electricity generation. The ecovillage is now willing to investigate storage opportunities, especially electrochemical batteries and flow batteries as they have been developed in recent years and become more and more cost-attractive. In order to see their difference of performance with old lead-acid batteries, the batteries used in the Eigg's electrical system and presented in Section 3.3.2 are also considered. Different power prices, meaning different costs of electricity drawn from the grid are considered as HOMER might use storage differently according to this sensitivity input.

Simulation results

HOMER runs the simulation by considering all the different scenarios created by means of the search space and presented in Section 4.3.5. The HOMER optimisation for each power price is shown in Figure 50.

Sensitivity	Architecture				Cost		System	Grid	
Power Price (£/kWh)	PV (kW)	V17	V29	FB200-400	COE (£)	NPC (£)	Excess Elec (kWh/yr)	Energy Purchased	Energy Sold
0.172	25.0	1	3	1	0,156 £	2,25 £M	370097	408 180	0
0.344	25.0	1	3	2	0,214 £	3,08 £M	285852.8	352 957	0
0.516	75.0	1	3	3	0,264 £	3,80 £M	247851.1	291 042	0

Figure 49: HOMER optimisation for different power prices

It can be seen that the optimal system design selected by HOMER is different for each power price considered in the simulation. However, the storage technology which is always selected is the FB 200-400 vanadium redox flow battery. As the power price increases, more energy is drawn from the batteries than from the grid to meet the load, which decreases import and increases local renewable use. Since grid sales are prohibited, there is no electricity sent to the grid but excess of electricity which has to be curtailed if it cannot be stored. Also, as the capacity of the storage device increases, there is less excess of electricity as more energy can be stored and then be discharged to meet the load when required. As expected for each technology, it has been seen that the higher the number of batteries, the better the consumption of green electricity. The highest number of batteries simulated for each technology gives the best use of renewables and the resulting green electricity consumption for each scenario is compared to the one without any storage. The results are presented in Table 25.

Storage system	300 4KS25P Lead-acid	20 FB 20-100	4 FB 200-400	200 Tesla Li-ion	3 FB 200-1600
Useable nominal capacity (kWh)	648	400	1 600	1 600	4 800
Green electricity consumed	+20.6%	+35.7%	+38.0%	+46.0%	+56.4%

Table 25: Best improvement in local renewable use for each scenario

The best results are obtained with 3 FB 200-1600 batteries which improve the use of renewables by 56.4% compared to the scenario without any storage. It can be seen that the bigger the useable nominal capacity, the better the local renewable use is. Indeed, more energy is stored and discharged to meet the load when required.

However, it can be seen that for a same capacity, the lithium-ion batteries give better results than the vanadium batteries as they can charge and discharge power more quickly to meet the load.

However, due to small capacity compared to the FB vanadium technologies which are large-scale storage, an important number of batteries are required for the lead-acid and lithium-ion technologies. Interestingly, the scenario with 300 lead-acid batteries allows for meeting the objective of the ORIGIN project which is to increase the local renewable use by 20%. However, a great number of batteries significantly increase the COE and the NPC. Another barrier to their installation is to achieve a realistic number of batteries and an appropriate storage volume in regards to the capacity required by the energy system. In practice, fewer batteries with higher capacity size would be installed to accommodate cost, practical feasibility and energy performance. Consequently, it appears that large-scale storage technologies are better storage opportunities given the availability of renewable resources and the load size.

It is a fact that the Findhorn ecovillage is willing to increase its consumption of locally-generated electricity. However, this objective cannot be meet regarless of cost. Considering the initial buy power price of £0.172/kWh, HOMER determines a restricted number of scenarios that allow for lower NPC and lower COE than the original system without storage. Grid sales are still prohibited for each scenario, including the original system, so the financial results are valid for a one-way-flow system only and cannot be applied to the Findhorn situation. Consequently, the financial exercise is conducted as an academic exercise and shows the worst financial case.

Results are presented in the Figure 50.

Architecture								Cost		Grid
PV (kW)	V17	V29	FB20-100	FB200-400	10kWh LI	FB200-1600	4 KS25P	COE (£)	NPC (£)	Energy Purchased
25.0	1	3		2				0,159 £	2,30 £M	352 957
25.0	1	3	5					0,161 £	2,32 £M	423 307
25.0	1	3			38			0,161 £	2,32 £M	426 638
25.0	1	3					52	0,161 £	2,33 £M	485 405
25.0	1	3						0,161 £	2,33 £M	519 802
25.0	1	3				1		0,168 £	2,42 £M	322 104

Figure 50: HOMER system selection for each scenario

It can be seen that the winning scenario selected by HOMER is the combination of two FB 200-400 batteries with a rated power of 400 kW and a capacity of 800 kWh. It decreases the energy purchased by 32%.

Also, it can be noticed that each technology allows for a scenario leading to a lower or equal NPC compared to the original system. However, this is not valid for FB 200-1600 which is the most expensive technology and only one unit leads to multiple costs that the benefit of local renewable use cannot financially compensate. Nevertheless, up to 2 and 3 FB 200-1600 are beneficial in the case of buy power prices of £0.344/kWh and £0.516/kWh, respectively. Once again, it shows the importance of grid tariffs on energy system design.

The systems resulting from the HOMER optimization and presented in Figure 51 are examined with special attention to import, excess of electricity and green electricity consumed. The results are shown in Table 26.

Batteries	Type	Import (kWh/year)	Import reduction (%)	Excess of electricity (kWh/year)	Green electricity consumed (kWh)	Increase in green electricity used (%)
No battery	/	519 802	/	541 123	595 543	/
52 4KS25P	Lead acid	485 405	6.6	487 580	629 940	5.8
38 10 kWh Tesla	Li-ion	426 638	17.9	441 261	688 707	15.6
5 FB 20-100	Vanadium Redox flow	423 307	18.6	390 973	692 038	16.2
2 FB 200-400	Vanadium Redox flow	352 957	32.1	285853	762 388	28.0
1 FB 200-1600	Vanadium Redox flow	322 104	38.0	239 226	793 241	33.2

Table 26: Green electricity consumed for each system

It can be seen that vanadium redox flow batteries are the technologies which provide the best energy performance and are cost-efficient, as long as their capacity is below 1MWh. However, one unit of FB 200-1600 is an option which allows for more local use of renewables.

Figure 51 illustrates the different scenarios in terms of deficit and surplus of energy for the 15th, 16th and 17th of January and the state of charge profile of the each storage combination is also represented.

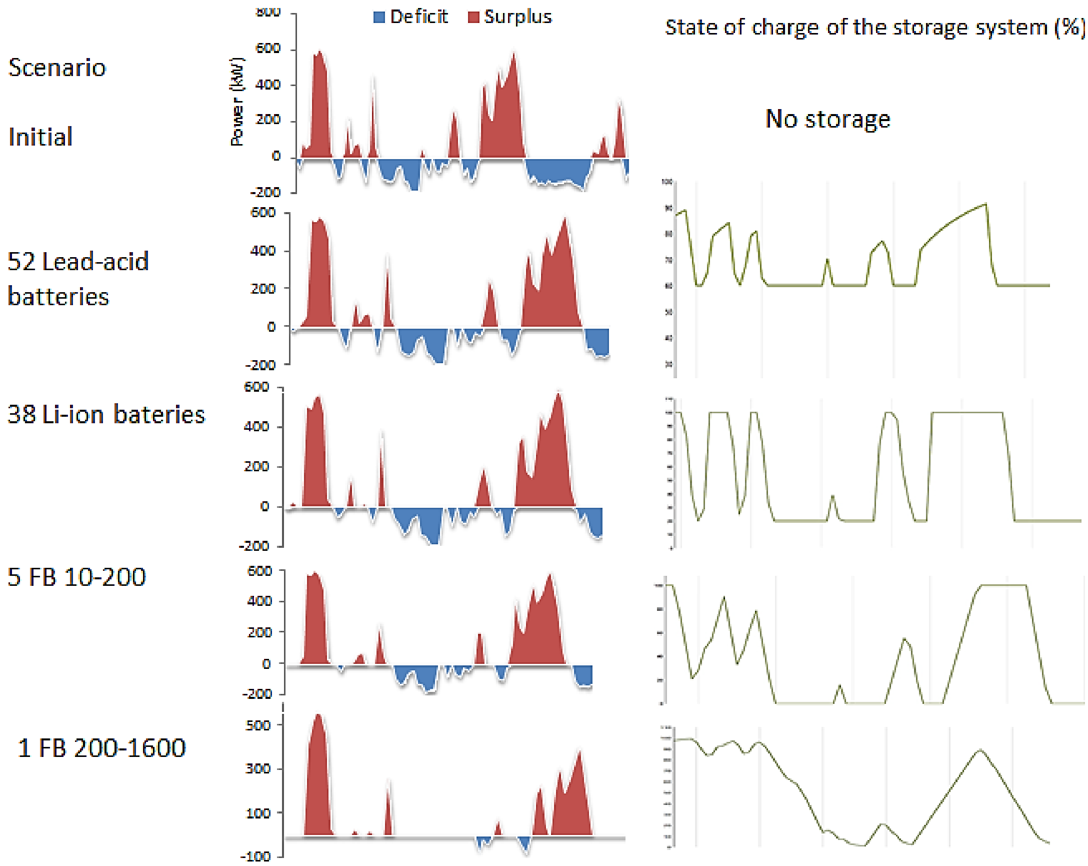

Figure 51: Deficit and surplus of energy and state of charge profile for each system

It can be seen that the storage technologies have various SoC profiles due to different times of charge/discharge and different depths of discharge. The FB 200-1600 is the battery which reduces the most the energy surplus as it has the highest capacity to store energy and it also reduces the most the energy deficit as it has the maximal discharge current and its maximal depth of discharge is 100%.

This scenario is further investigated from an energy point of view by studying its effect on the electrical system. Grid purchases in three winter days are represented in Figure 52 and compared to those required by the original system without storage.

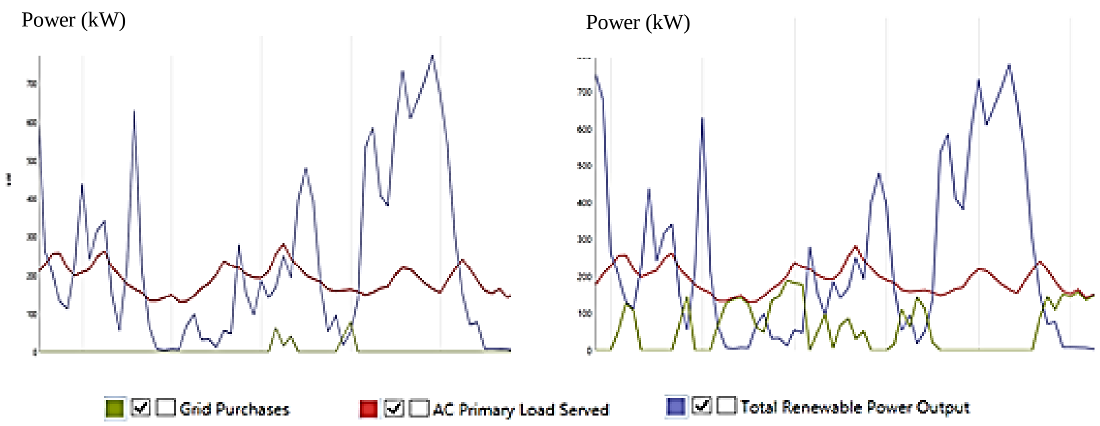

Figure 52: Scenario with one FB 200-1600 energy storage compared to scenario with no storage in 15, 16 and 17 January

It is noticeable in Figure 52 that the integration of a 1.6MWh storage device significantly reduces grid purchases in January which is the peak month. The frequency of the power drawn from the grid and its magnitude are greatly reduced which decreases the dependence on the main grid and increases renewable use. The decrease in electricity imported from the grid in each month is shown in Table 27.

Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total
Import reduction (%)	71	45	57	37	54	38	26	38	28	26	19	34	**38**

Table 27: Monthly import reduction with one FB 200-1600 storage

It can be seen that the best use of the energy storage is made in January which is the windiest month and allows for the storage of huge quantity of wind energy. The reduction of import is lower in summer as less wind is available. Indeed, the battery has a maximum state of charge of 45% while the battery is often full during winter. However, the lowest import improvement occurs in November as the load size growth significantly but the renewable output is not sufficient to charge the battery in a considerable way.

To compare the performance of the different technologies on a capacity basis, the percentage of deficit supplied by the same nominal capacity of each battery type is studied. In each case, the number of lead-acid batteries, lithium-ion batteries and vanadium redox flow batteries is adapted to obtain the storage capacity required for the simulations. Businesses and utilities usually opt for storage devices of a few MWh of capacity. Different scenarios are investigated to determine the impact of the different batteries on the system deficit which is usually filled by the grid.185 lead-acid batteries or 100 lithium-ion batteries are combined in battery bank to obtain 1MWh of capacity.

Results are obtained for 1MWh, 10MWh, 50MWh and 100MWh of storage capacity and are shown in Figure 53.

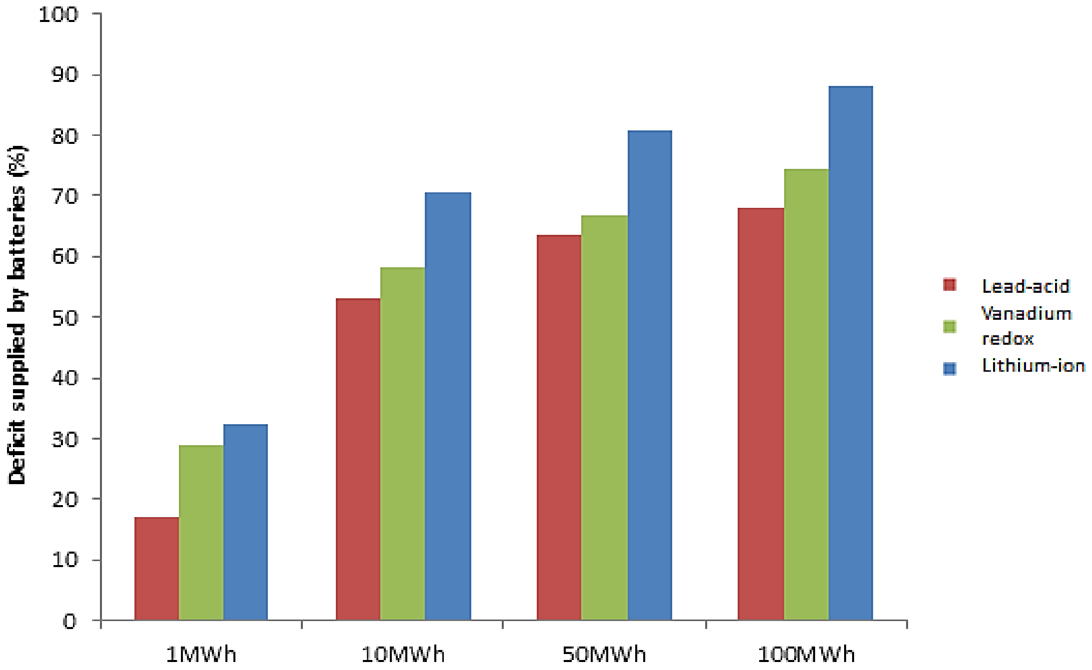

Figure 53: Deficit supplied by the different battery technologies of a same capacity

It can be seen that the lithium-ion batteries are those that provide the best percentage of the deficit experienced by the energy system and so maximise the local renewable use. The difference of performance between technologies is all the more noticeable when storage capacity increases. Also, it has been found that 180 MWh of this technology reduces the deficit to 0 all year round, while 270 MWh and 460 MWh of vanadium and lead-acid batteries respectively are required. This signifies that the lithium-ion battery is the most suitable battery type for load-following, load-leveling, uninterruptible power supply and emergency back-up. As import is reduced due to more energy deficit supplied by the batteries, it allows for better renewable integration.

5.2.3 Adding both renewable and storage capacities

It has been seen in Section 5.2.1 and Section 5.2.2 that adding solar capacity in one hand and installing lithium-ion batteries in the other hand are the options which result in the best local renewable use. However, their studies have been conducted separately. Consequently, a last simulation exercise is conducted to determine the impact of installing additional solar capacity coupled with lithium-ion batteries. Given that one type of focus buildings of the ORIGIN project are the Whins buildings and that some of them already have roof-mounted PV arrays, the scenario of adding PV panels on the top of the 25 buildings and one lithium-ion battery in each building could be investigated. By coupling solar technologies with storage, each building would have the ability to produce solar energy locally in order to preheat its own water. However, HOMER cannot model energy storage which would be charged by solar energy only as it stores in batteries the general excess of renewables. Consequently, a more realistic approach would be to consider lithium-ion batteries centralised in a battery hub on the local network rather than in every house. The total PV capacity considered is 75 kW, which can lead for example to PV arrays of 3 kW for each building, and the wind capacity is kept the same. The total useable nominal capacity of the 25 batteries of 10 kWh is 200 kWh as the minimum SoC of 20% is kept. Figure 54 illustrates the SoC of the batteries all over the year.

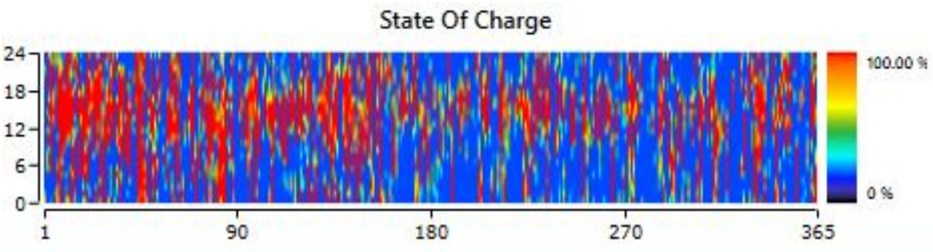

Figure 54: State of charge of the lithium-ion batteries

The activity of the batteries over a year can be seen through their SoC. They are usually full between 12pm and 6pm while they are emptied in the morning and in the evening. The total battery output is 71 018 kWh/year.

The buy power price is kept at £0.172/kWh. Table 28 compares the energy performance of the original system with the new scenario. Grid sales are prohibited for both scenarios to make possible a financial comparison in a one-way flow system.

PV size (kW)	Li-ion batteries	Excess of electricity (kWh/year)	Import (kWh/year)	Green electricity used (kWh/year)	Increase in green electricity used (%)	COE (£/kWh)
25	0	541123	519802	595543	/	0.161
75	25	485732	425318	690027	15.9	0.168

Table 28: Energy performance of 75 kW PV and 25 lithium-ion batteries

It can be seen that although PV capacity is increased, the association with batteries reduces the excess of renewable electricity which has to be exported to the grid in practice. Also, the green electricity locally used increases as batteries store the excess of renewable energy to discharge it when required. It appears that combining 25 PV panels of 3 kW each with 25 lithium-ion batteries of 200 kWh of useable capacity increases the local renewable use by 15.9%. However, the resulting COE is increased by £0.007/kWh due to important capital investment for new equipment which is not compensate by fewer grid purchases. However, it is important to bear in mind that the worst financial case has been modelled as grid sales have been prohibited and consequently the excess of energy is wasted while in practice it would result in financial incentive by means of FIT. As the main objective of this simulation has been to focus on more local renewable use only, the restriction of prohibiting grid sales has been necessary to make HOMER use storage device rather than taking financial advantage of selling the excess of power to the grid.

Chapter 6: Model description of the Tamera electrical system

Load profile, resource data and technology characteristics need to be established to model the energy performance of the ecovillage.

6.1 Resources assessment

For study purpose, the location of the Tamera ecovillages has to be defined and is identified in Odemira (latitude 37.31 °N and longitude 8.51 °W). As mentioned in

Section 2.7.3, the Tamera community harnesses solar resources to produce electricity by means of PV panels. Consequently solar resources need to be determined.

Solar resources

The solar radiation data from NASA Surface meteorology and Solar Energy are used directly in HOMER to create the solar radiation profile of Tamera. The solar radiation profile is shown in Figure 55.

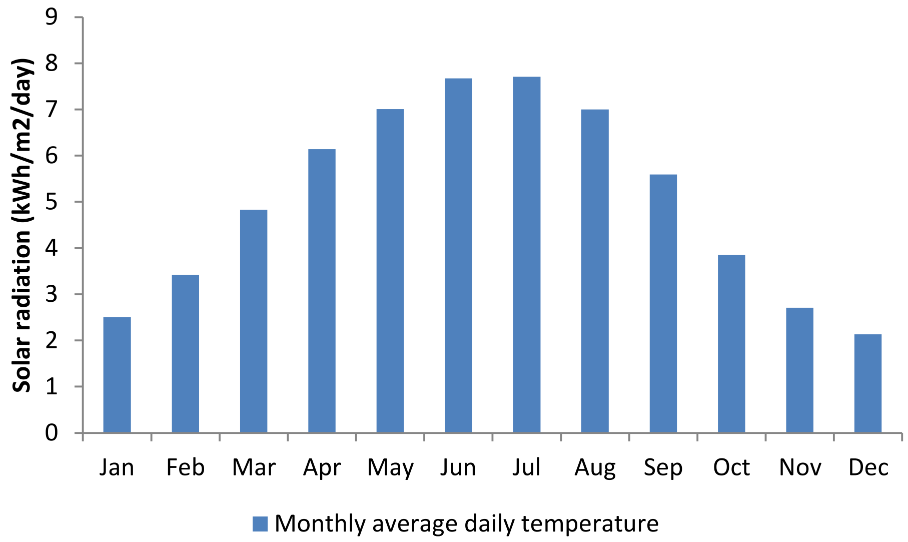

Figure 55: Tamera solar radiation profile

Minimum and maximum monthly average solar radiation values are observed in December and July, with 2.51 kWh/m^2/day and 7.71 kWh/m^2/day respectively. On the basis of the project location and the local meteorological data, the annual average daily solar radiation is assessed at 5.05 kWh/m^2/day. As these data are consistent with those provided by the ORIGIN project, this profile is kept for the study.

Temperature resources

The temperature data from NASA Surface meteorology and Solar Energy are used directly by Homer to create the temperature profile of Tamera. The temperature profile is shown in Figure 56.

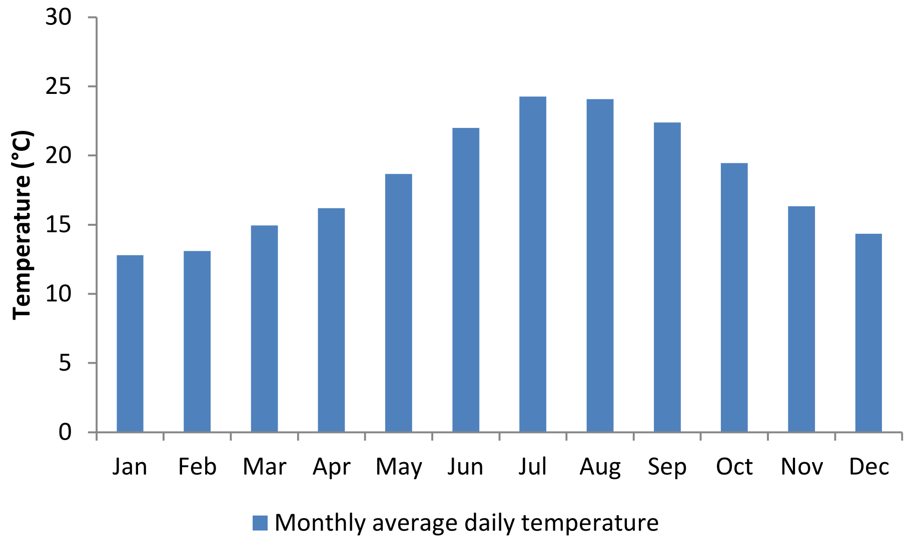

Figure 56: Tamera temperature profile

Minimum and maximum monthly average temperature values are observed in January and July, with 12.80°C and 24.26°C respectively. The scaled annual average temperature is 18.21°C.

6.2 The PV-battery system of Tamera

6.2.1 The PV system

The Tamera energy system is a grid-connected island system. Tamera has 20 kW of solar-PV arranged in two clusters, one of 8 kW and a second one of 12 kW which was added to the roof of the Tamera workshop thereafter. Each PV panel is connected to a Sunny Island 5048 off-grid inverter. However, HOMER only takes into account one converter and modelling one single array of 20 kW of capacity or two arrays with the same total capacity does not affect results if the PV array characteristics are the same. Consequently, one single array is modelled with one converter. Modelling the PV-inverter system of Tamera is challenging as the inverters limit the PV output when the grid frequency exceeds 51 Hz. The solar system is a sun-tracking photovoltaic system and a tracking system with a continuous improvement on horizontal axis and on vertical axis is selected to match the actual generation of the PV panels and to lead to a typical coefficient of performance of 25% . By lack of data upon the actual solar system used in Tamera, typical polycrystalline solar cells with an efficiency of 13%

are considered, the lifetime is set at 25 years and the derating factor at 80% to take into account the ageing effect. The Sunny Boy inverter used is a 5 kW and 48V inverter. As only one inverter can be considered in HOMER simulation, its capacity is set at 10 kW. To match its characteristics, the inverter efficiency is set at 95% while the rectifier efficiency is set at 90% with a relative capacity of 100%. The inverter lifetime is set at 20 years.

6.2.2 The battery system

The solar system of Tamera directly provides the community with electricity during the day and the surplus is stored in two battery banks. The battery storage used is made of two strings of 12 lead-acid batteries and each battery is 2V with 3500 Ah capacity at 100 hour rate. The minimum depletion level allowed on the batteries is 75% and they are charged to 100% from the grid every night during the off-peak period. So there is 168 kWh of nominal capacity but only 168*0.25 = 42 kWh of useable nominal capacity. The efficiency of the batteries is 69%.

6.3 Load assessment

To establish the load profile of Tamera, the same method for extracting data as for the Findhorn ecovillage cannot be applied since the tag list given by the ORIGIN project is erroneous. Consequently, a typical community profile is downloaded from the HOMER database and scaled from data in The Baseline Energy Usage Report (2014) to match the measured annual electricity consumption. The annual average load is scaled to 210 kWh/day with a peak power of 44.4 kW supposed to happen in July due to important amount of electricity required for cooling. The total load is assessed to be 76 650 kWh/year.

The load profile created by HOMER on the basis of the input data is shown in Figure 57.

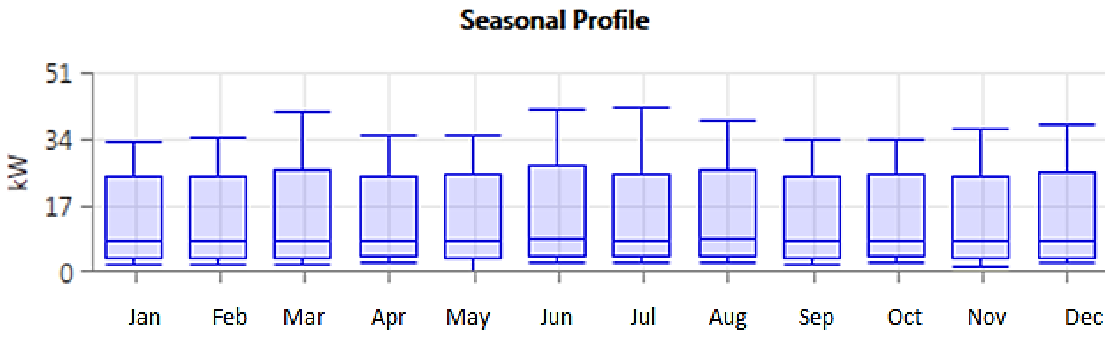

Figure 57: AC primary load monthly average of Tamera

Interestingly, the load profile tends to be similar for each month regardless of the season while it has been seen that there are important variations in electricity demand according to season in Findhorn. This seems realistic as Portugal has a temperate Mediterranean climate and so electricity is required both in winter and summer for heating and cooling, respectively.

Figure 58 shows the average daily load profile of Tamera.

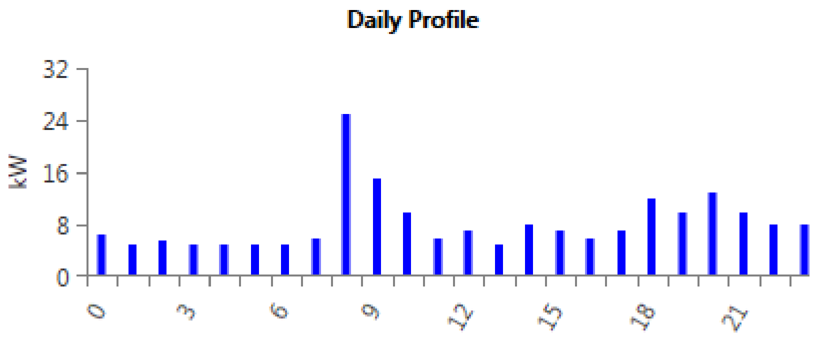

Figure 58: Daily load profile of Tamera

It can be seen that peak hour is around 8am in the morning and around 8pm in the evening and refer to people's activities which use electric appliances. The shape of the load profile is aligned with the data provided by The Baseline Energy Usage Report (2014).

The random day-to-day variability is assessed at 10% by HOMER while the random hourly variability is assessed at 20%.

6.4 System configuration

Figure 59 presents the system configuration used in HOMER to model the original electrical system of the Tamera ecovillage.

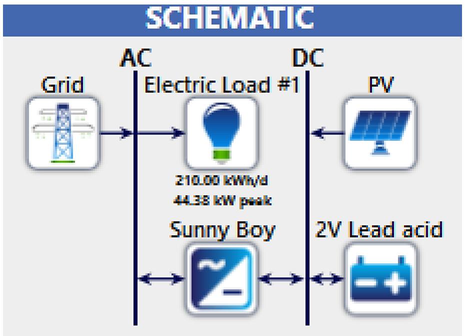

Figure 59: System configuration of the Tamera ecovillage

The energy system is grid-tied but only electricity import is allowed as there is no agreement with the local grid to sell the excess of electricity from renewables. The electric load is met either by the electricity produced from PV panels or coming from the main grid. Both PV panels and battery banks are connected to the DC bus and require the use of converter to meet the AC load.

6.5 Financial input data

Financial data have to be input to conduct HOMER optimisation.

6.5.1 Technology costs

The initial cost of PV panel is set at £3 000/kW, being a total of £60 000 while the replacement cost is set at £2 800/kW, being a total of £56 000. The operation and maintenance cost is set at £800/year. According to the actual commercial price of the Sunny Boy inverter, the initial cost and replacement cost of the converter is set at £2 880, being £5 760 for the double size considered for the simulation. The O&M cost is set at £10/kW/year, being £100/year. The initial cost of the 2V lead-acid batteries is set at £1 000 each while the replacement cost is set at £900 and the O&M cost is set at £10/year.

The financial data of the system components which are used in the simulation are summarised in Table 29.

Component	Size	Initial cost (£)	Replacement cost (£)	O&M cost (£/year)	Lifetime
PV panels	20 kW	60 000	56 000	800	25 years
2V lead-acid	6.7 kWh	1 000	900	10	20 years
Inverter	10 kW	5 760	5 760	100	15 years

Table 29: Component costs for the Tamera energy system

6.5.2 Power prices

A new functionality of HOMER is investigated here. It deals with advanced grid parameters with scheduled rates which allow for defining power prices according to the hour of the day and so to take into account peak power prices and off-peak prices. This is of interest to define when the batteries have to be charged to take financial advantage as the Portuguese electricity sector operates a time of use tariff system with electricity prices increasing in line with peak demand. The timing of grid import therefore has fiscal implications for the Tamera community and opportunities are critical for better matching low tariff periods to grid import timing. The Tamera ecovillage specifies that grid charging usually happens at night when the electricity is cheap and no sun is available.

According to Eurostat, the average price of electricity paid by Portuguese households was £0.223/kWh in 2014. Also, off-peak power prices are installed during 7 hours between 9pm and 4am.Given that, the grid scheduled rates are set as follows:

	Power prices (£)	Grid rate schedule
Rate 1	0.323	4am-9pm
Rate 2	0.023	9pm-4am

Table 30: Grid rate schedule

The grid rate schedule is defined such as grid charging the batteries occurs during Rate 2 schedule.

6.6 Control of the system

As the renewable output of Tamera is significantly lower than the one of Findhorn, the management of the storage system follows a different approach. The cycle-charging strategy is used by HOMER to select the optimal storage technology. A setpoint state of charge can be applied to the cycle charging strategy. If a setpoint state of charge is applied, once the system starts to charge the battery bank, it will not stop until the battery bank reaches the setpoint state of charge. A setpoint of state of charge of 100% is set to model grid charging batteries at night. The batteries are charging between 9pm and 4am until they reach 100% of SoC. Grid charging the batteries is prohibited during Rate 1 schedule as it is defined to be the peak power pricing period. Grid sales are prohibited as there is no arrangement with the local grid for export and the sale capacity is set at 0 kW.

Chapter 7: Simulation results of the Tamera ecovillage

Through this section, the results of the simulation exercise are presented for the original energy system of Tamera and for alternative systems designed by means of the search space of HOMER.

7.1 The Original system of Tamera

7.1.1 Simulation results

The simulation results are presented for the initial system since the point of this simulation exercise is to validate the model used in HOMER by comparing the results with data provided by the community. It also deals with studying how HOMER capabilities can be exploited to model the electrical system of Tamera. Attention is given to the electricity generation from PV panels and the energy balance of the system.

Electricity generation from PV panels

Figure 60 shows the PV power output over the year (x-axis) and according to the time (y-axis).

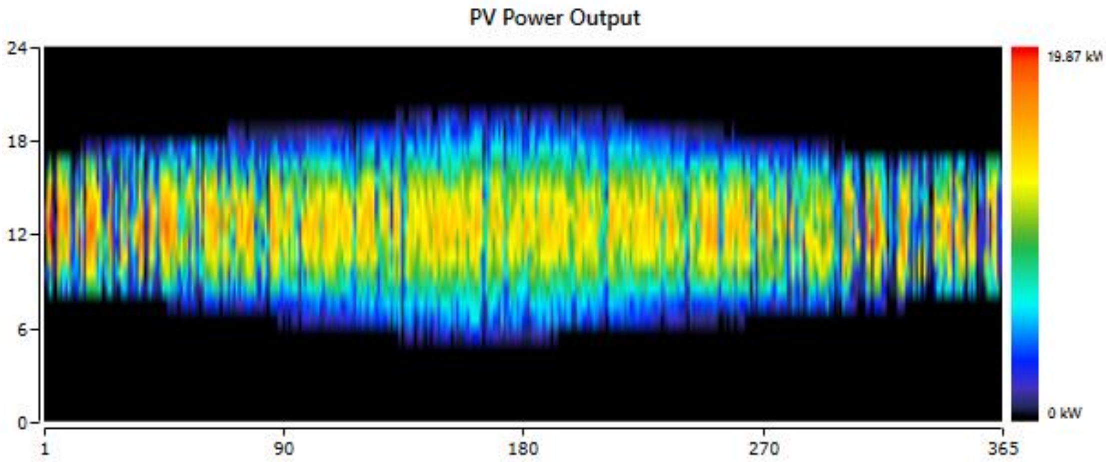

Figure 60: PV power output of Tamera over a year

PV panels operate 4 381 hours per year with a mean output of 4.89 kW and a maximum output of 19.88 kW. They produce 42 879 kWh/year and have a solar penetration around 55.94%. This signifies that almost 55.94% of the electrical load has the ability to be met by solar energy. It can be seen that the power output is stronger in the middle of the day during winter due to cell temperature close to the ambient temperature and so with higher efficiency. However, the PV panels produce power more often in summer due to longer daytime.

Total renewable electricity generation and electric load

Figure 61 illustrates the renewable generation profile compared to the load profile over a year.

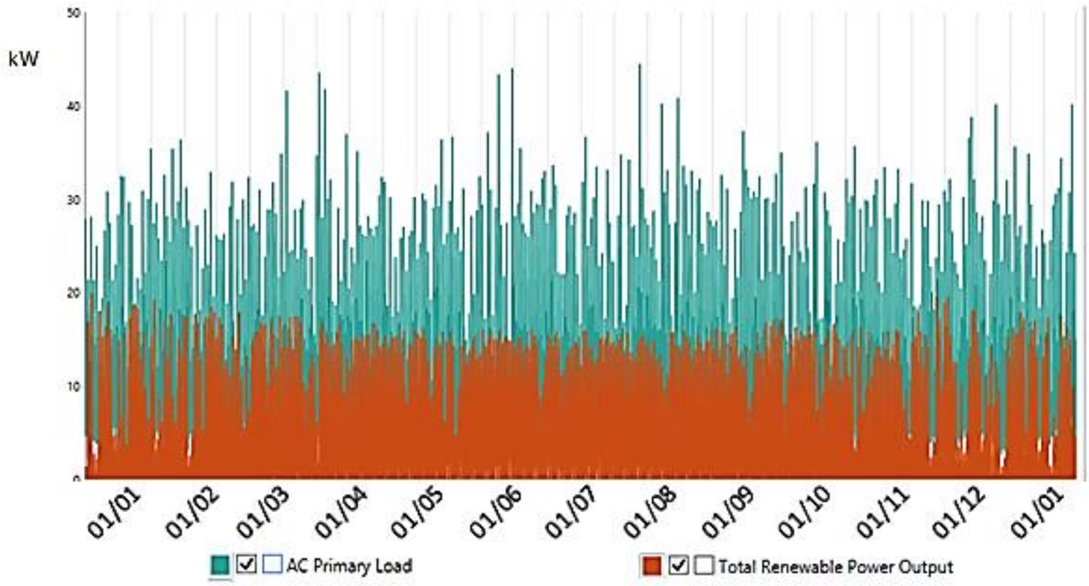

Figure 61: Primary load and renewable generation in Tamera over a year

It can be seen that the load is significantly higher than the renewable output all year round. As it has been seen, it is the contrary for Findhorn which has higher renewable output than demand, hence the matter of matching supply with demand is different for Tamera. However, storage development can avoid renewable power curtailment and so reduce electricity import.

State of charge of the batteries

Figure 62 shows the SoC of the two battery banks over a year and according to the time of the day.

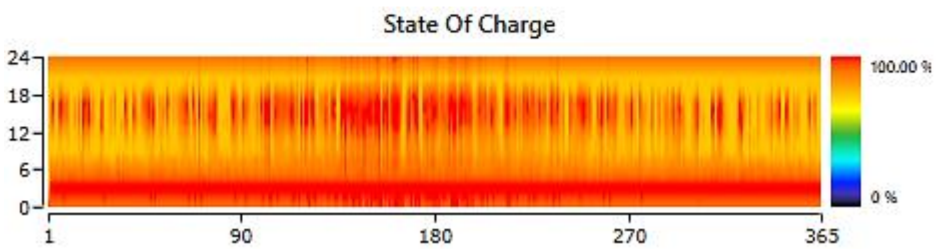

Figure 62: SoC of the Tamera batteries

The SoC of the batteries is always comprised between 75% and 100% which limits the useable nominal capacity. The batteries are charged by the grid at night to reach 100% of SoC at 3am while they are charged during the day by the PV output. The batteries tend to be full quicker and more often during summer due to stronger solar radiation and longer daytime than in winter. The annual throughput of the batteries is 19 573 kWh/year.

Load, renewable output and SoC of batteries in winter

Figure 63 illustrates the load, the renewable output and the SoC of the batteries during a typical day in January.

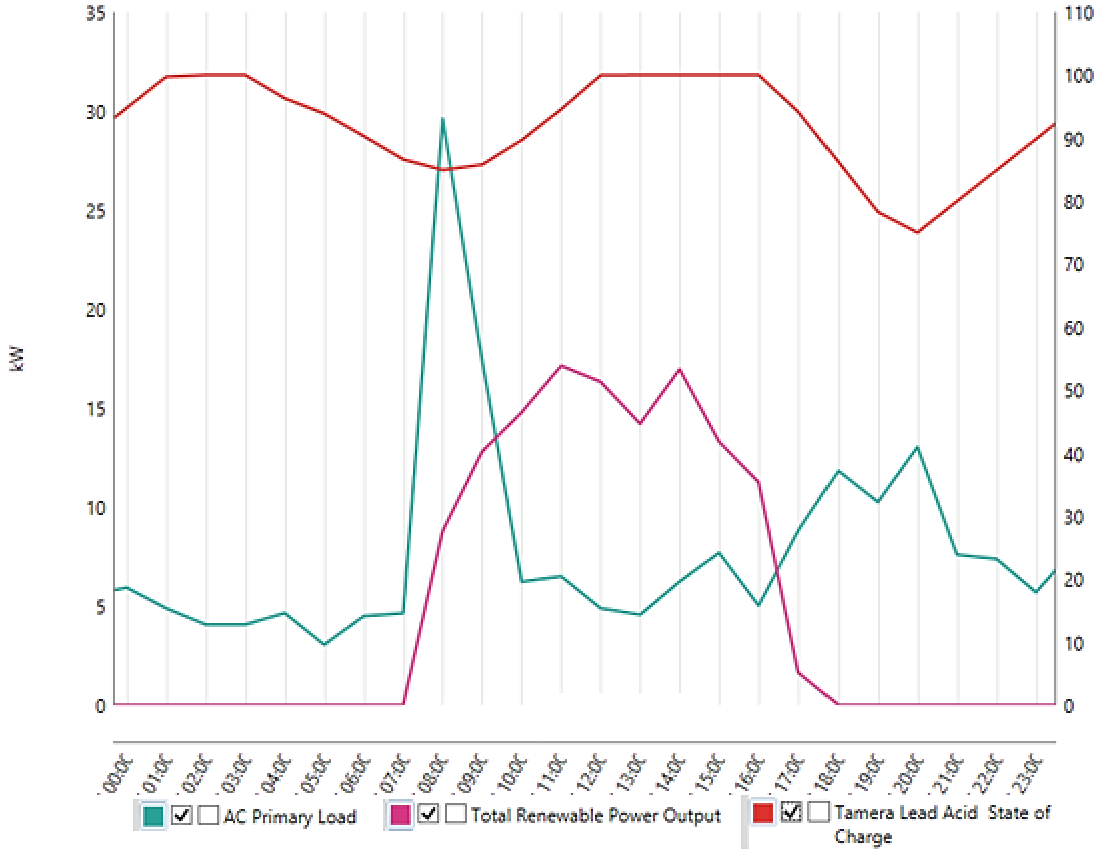

Figure 63: Load, renewable output and SoC of batteries in Tamera the 17th of January

It can be seen in Figure 63 that PV panels produce energy between 7am and 5pm due to the availability of solar radiation. The batteries are fully charged at night, then start releasing power in the early morning to meet the load until the morning peak load around 8am. In the graph above, the generation is greater than the load from 10am and the batteries are fully charged at 12pm so there is an excess of electricity which causes the increase in the microgrid frequency. In practice, the control of the panels is based on the frequency of the voltage in the network. When the frequency exceeds 51 Hz the inverters begin to restrict the output of the PV arrays. Consequently, a large potential of renewable generation is lost as storage capacity is not sufficient or because the batteries are fully charged at night and are not totally discharged after the morning peak load. Batteries are full for 4 hours from 12pm to 4pm which shows the potential benefit of adding storage capacity. Also, they reach their minimum SoC at 8pm as they meet the evening peak load and no renewable power is produced. It is during this period that most of the power is drawn from the grid, hence storage development could minimise import. However, it seems that the PV generation is not sufficient to cover the entire load and adding both storage capacity and solar capacity could significantly increase the energy autonomy of Tamera. Nevertheless, given that the graph presented illustrates the energy system in January, it shows the worst case of PV generation as solar radiation is the lowest over this month.

Electricity balance

Table 31 shows the electricity balance given by HOMER with the CC strategy.

PV generation (kWh/year)	Grid purchases (kWh/year)	load (kWh/ year)	Fraction of load met by green electricity (%)	Battery throughput (kWh/year)	Excess of electricity (kWh/year)	% of load coming from batteries
42 879	55 336	76 650	55.9	19 573	6 870	25.5

Table 31: Electricity balance of the Tamera system with the CC strategy

The percentage of load met with power coming from the batteries is calculated as follows:

$$Load\ met\ by\ batteries\ (\%) = \frac{Battery\ throughput\ \left(\frac{kWh}{year}\right)}{Primary\ load\ \left(\frac{kWh}{year}\right)} \times 100$$

Equation 7: Fraction of load met by the batteries

The excess of electricity is the surplus of electrical energy that must be dumped or curtailed because it cannot be used to serve the load or charge the batteries. It occurs when there is a surplus of power being produced by the renewable source and the batteries are unable to absorb it all. However, the excess of electricity given by the simulation is small compared to grid purchases over a year. It can be seen that the batteries provide one quarter of the load.

7.1.2 Model validation

In order to validate the model of Tamera used in HOMER, the ORIGIN portal is consulted to obtain information on the electricity balance. The following dashboard is obtained:

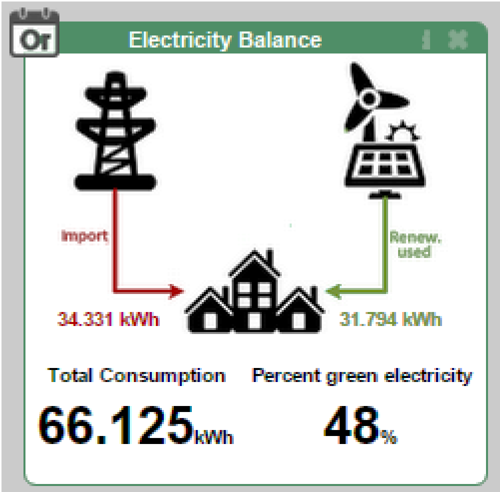

Figure 64: Energy balance of Tamera since the ORIGIN project. Source: ORIGIN Concept.

By linearization, this would lead to import of 41 200 kWh/year, load of 78 522 kWh/year and renewable used of 38 152 kWh/year. By taking into account the imprecision of the data, their variability and the linearization, loads and PV generation are relatively aligned as they have been scaled to match the reality. However, there is a significant discrepancy between the measured data and the results given by HOMER in regards to grid purchases. This might be explained by the CC strategy used by HOMER and which is not appropriate to model the system of battery charging used by Tamera.

The electricity balance given by HOMER with the LF strategy is shown in Table 32.

PV generation (kWh/year)	Grid purchases (kWh/year)	Load (kWh/year)	Fraction of load met by green electricity (%)	Battery throughput (kWh/year)	Excess of electricity (kWh/year)	% of load coming from batteries
42 879	43 121	76 650	55.9	10 082	1 931	13.2

Table 32: Energy balance of the Tamera system with the LF strategy

In this case, grid purchases are more aligned with the data provided by HOMER. However, the batteries are not charged by the grid at night as they are only charged by the surplus of renewable output. Consequently, the percentage of the load met by the batteries is low as this scenario underestimates the battery throughput.

It can be concluded that neither of the two control strategies used by HOMER provide a suitable model for the energy management of the batteries in Tamera. Even if the energy balance given by the LF strategy seems to give consistent overall results, the battery throughput is reduced as batteries are only charged with surplus of renewables. This shows the challenge of modelling battery storage and HOMER limitations. However, both strategies are further investigated and their impact on the energy system is compared.

7.2 Alternative system

As a result of the project scope, increased storage capacity only is investigated as an opportunity to store excess of PV power output and avoid its curtailment by the inverters. Given that HOMER considers only one type of battery per simulation and that the original system comprises 2V lead-acid batteries, increased capacity of this battery type is considered. Consequently, the number of battery string is varied from 1 to 6 and the CC strategy is firstly used for simulation and then replaced by the LF strategy.

7.2.1 Additional storage capacity with the CC strategy

Figure 65 presents the results given by the HOMER simulation.

Architecture					Cost		System		Grid
PV (kW)	2V Lead acid	Grid (kW)	Sunny Boy (kW)	Dispatch	COE (£)	NPC (£)	Ren Frac (%)	Excess Elec (kWh/yr)	Energy Purchased
20.0	24	999 999	10.0	CC	0,196 £	194 649 £	28	6870.673	55 336
20.0	36	999 999	10.0	CC	0,204 £	202 194 £	26	6663.417	56 901
20.0	48	999 999	10.0	CC	0,217 £	214 761 £	26	5928.778	56 557
20.0		999 999	10.0	CC	0,222 £	219 801 £	34	13999.3	50 658
20.0	60	999 999	10.0	CC	0,230 £	228 312 £	26	5651.851	56 548
20.0	72	999 999	10.0	CC	0,245 £	242 304 £	26	5406.519	56 469

Figure 65: HOMER simulation results for increased storage capacity with CC strategy

HOMER calculates the renewable fraction using the following equation:

$$f_{ren} = 1 - \frac{E_{non\,ren}}{E_{served}}$$

Equation 8: Renewable fraction

where:

Enon ren = nonrenewable electrical production (kWh/yr)

Egrid,sales = energy sold to the grid (kWh/yr) (included in E served)

E served = total electrical load served (kWh/yr) which includes the primary load and the energy sold to the grid. However, there is no export in this system configuration so the load served only included the primary load.

It appears that the best scenario in terms of COE and NPC is obtained with 24 batteries which refers to the original system. Indeed, the energy purchased rises with the number of batteries as the battery capacity increases and the simulation continues to charge them to 100% at night. Even if cheap electricity can be bought at night to be used during the day to meet the load, it does not compensate for the costs associated with additional batteries. Also, the renewable fraction decreases as more electricity is purchased from the grid to fully charge the batteries at night, which increases the share of fossil fuel in electricity consumption and so has negative environmental impact.

7.2.2 Additional storage capacity with the LF strategy

Figure 66 presents the results obtained with a load-following strategy, meaning that the batteries are only charged with the excess of renewable output.

Architecture					Cost		System		Grid
PV (kW)	2V Lead acid	Grid (kW)	Sunny Boy (kW)	Dispatch	COE (£)	NPC (£)	Ren Frac (%)	Excess Elec (kWh/yr)	Energy Purchased
20.0		999 999	10.0	LF	0,222 £	219 801 £	34	13999.3	50 658
20.0	24	999 999	10.0	LF	0,225 £	222 550 £	44	1913.142	43 121
20.0	36	999 999	10.0	LF	0,239 £	236 912 £	45	111.6921	41 987
20.0	48	999 999	10.0	LF	0,254 £	251 880 £	45	0.0002255223	41 902
20.0	60	999 999	10.0	LF	0,269 £	266 869 £	45	0.0002231871	41 886
20.0	72	999 999	10.0	LF	0,284 £	281 857 £	45	0.0002234226	41 870

Figure 66: HOMER simulation results for increased storage capacity with LF strategy

It can be seen that adding batteries to the original configuration system does not have a significant effect on the energy purchased as no more renewable energy is available to be stored in the batteries. Adding two more strings of batteries reduces the excess of electricity to 0% and reduces import by 3%. However, the excess of electricity given by the LF strategy is small and would not justify the actual curtailment of PV output.

Chapter 8: Discussion and future work

Two different energy systems have been analysed through the study of two very different communities in terms of load size, location, climate, availability of resources, renewable technologies, tariff regulations and grid arrangement. Shaping renewable supply to match demand is challenging for both locations but requires different approaches. Due to different sizes, different electricity uses (e.g., Tamera uses 30% of its energy consumption to pump water) and different climate locations, the load profile of each community is really different from one another. Also, Findhorn generates important wind power which outstrips demand but does not have storage technologies, and so needs to export important quantity of green electricity. On the contrary, Tamera already uses storage technologies to store excess of PV output but only produces up to 50% of its electricity consumption. Also, the PV output needs to be curtailed for grid stabilisation reasons.

Adding storage devices in Findhorn can allow for diverse services such as wind and solar integration, energy smoothing and load-shifting. In regards to Tamera, the issue is to deal with microgrid stabilisation by means of frequency regulation. Indeed, energy storage has the ability to absorb the excess of renewable output to maintain the grid frequency. This would not lead only to frequency stabilisation but also to increased solar penetration as the PV output would not need to be curtailed. While Findhorn has a renewable generation which can potentially meet 102% of the community's energy needs, the one of Tamera hardly reaches 50% of its load, meaning that there are opportunities for additional batteries to store electricity from the grid during off-peak power prices and so to take advantage of grid rates schedule.

Consequently, both communities show opportunities to improve the performance of their energy system. The results of the simulation exercises are discussed through this section to propose future alternative system designs in order to increase the energy autonomy of communities.

8.1 Discussion of the results for the Findhorn electrical system

8.1.1 Conclusion on adding renewable capacity to the Findhorn energy system

It is important to define the output variable of interest (e.g., costs, renewable use, emissions…) and to base on them the system analysis. Indeed, different objectives to be achieved often lead to different optimal system configurations as output variables might be in conflict. The selection of the system design has to be made according to the project considerations.

In regard to the ORIGIN objective which is to increase local renewable use by 20% by means of demand-side management, developing a solar park of 1.5 MW of capacity or extending the wind park to 1.5 MW of capacity are options to meet his goal. However, they appear to be neither cost-competitive nor feasible in terms of required land and would lead to an over industrialisation of the landscape. More realistic options would be to install a ground mount array of up to 225 kW coupled with the existing PV capacity which has the ability to increase renewable use by 12.8% while adding one V29 wind turbine of 225 kW increases the renewable use by 8%. As a consequence, adding 225 kW of solar capacity results in more use of renewables than adding the same wind capacity. This is especially of interest given that adding 225 kW of wind capacity results in more annual energy generation than adding 225 kW of solar capacity but import is reduced by 9.6% and 14.6%, respectively.

The following graph illustrates the situation for an addition of 225kW of solar capacity leading to a total solar capacity of 250 kW.

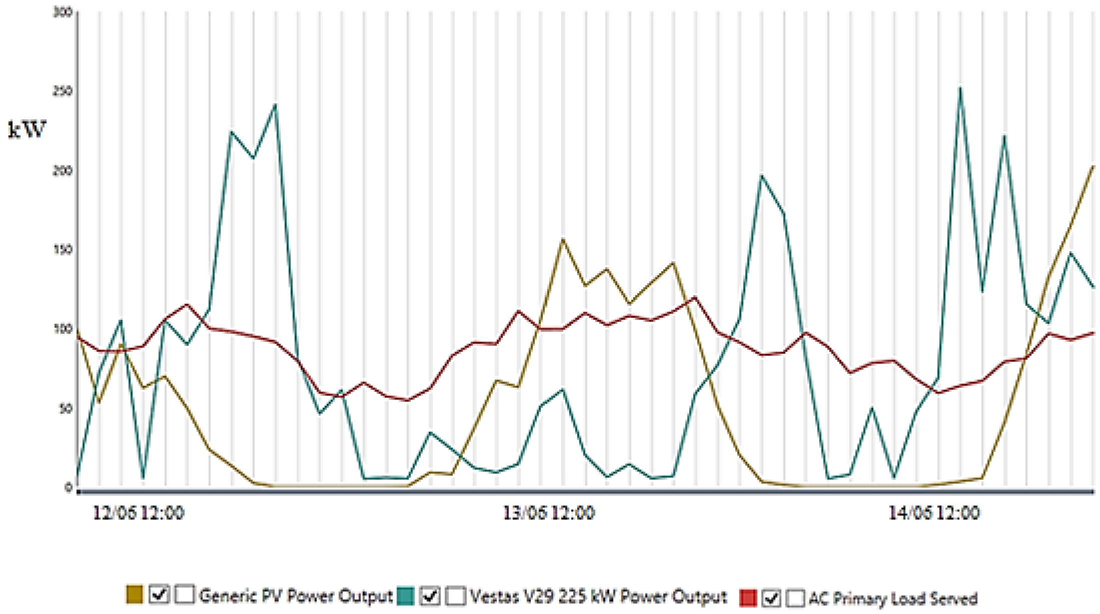

Figure 67: Renewable energy generation for 250kW PV and load

The graph above illustrates the solar output of 250 kW PV panel and the wind power output of the three V29 compared to the AC primary load for two days in June. The wind power output of the V17 wind turbine is neglected due to low values and same trend as the power output of V29. The solar energy output is usually the highest in the middle of the day while the wind power output is the highest in the evening. Although the wind and solar resources seem to be available at different moments throughout the day, their combination only cannot avoid grid purchases, which usually happen at night, while electricity is required to maintain the functioning of electrical equipment.

The same graph can be obtained in typical winter days so is not presented here. However, due to low solar radiation and overcast sky, solar generation is lower in winter but the shape of the solar generation profile is the same and the hours of operation of PV panels complement those of the wind turbine output. Also, given that the installed wind capacity of the Findhorn village is much higher than the solar capacity, it appears more relevant to balance wind and solar renewables by adding more PV capacity. This would have for consequence to increase the renewable electricity consumption as the electricity coming from PV tends to be used locally whereas most of the wind power is usually sold to the grid. Indeed, a great part of wind output is exported to the grid as its penetration into electricity consumption is limited by hours in which wind is available and does not always correspond to hours of high demand. Also, solar power might be more predictable as it can only be generated during daylight, and adding more wind capacity has little effect if the wind speed is low.

Adding PV capacity seems to be the best strategy to reduce grid dependency as both import and export are minimized and the fraction of the load that is met by green electricity increases. Indeed, it reaches 60% with 225 kW additional PV while 53% of the load is met by green electricity for the initial scenario. Consequently, adding solar capacity increases the energy autonomy of the ecovillage. It also has environmental benefit as less electricity coming from fossil fuel is drawn from the grid. Consequently, adding solar capacity expands the generation mix by producing electricity during hours in which little wind power is generated. As it has been seen in the literature review, diversifying the generation mix is a common strategy to increase the use of renewable energy.

In conclusion, hybrid systems made of both wind and solar technologies with more balanced capacity have the ability to increase local renewable electricity use as their renewable outputs tend to be complimentary and allow for a more reliable renewable energy supply which covers a larger part of the load.

8.1.2 Conclusion on adding storage capacity to the Findhorn energy system

The simulation results have shown that lithium-ion batteries provide better energy performance than other battery technologies and that 1 MWh of lithium-ion battery capacity offers the opportunity to reduce electricity import by 32%. This option should be investigated by the Findhorn ecovillage, especially if people plan to increase their solar capacity. However, the Tesla lithium-ion batteries are used for household application and 1MWh would require the combination of 100 batteries which significantly increases the cost of storage.

A more realistic option would be to install a large-scale storage technology such as FB 200kW-1600kWh which reduces the number of charge/discharge cycles and increases the local renewable use by 33.2% while import is decreased by 38% over a year. Also, the combination of two FB 200kW-400kWh batteries has been selected as the optimal financial option while it decreases the electricity purchased by 32% over a year.

The storage technology has to be selected by the community according to the storage application it is designed for (e.g., domestic application for hot water, large-scale storage application for backup…) In sum, the final choice of the energy system design has to be made to suit the most the customer requirements in terms of system size, payback period and grid independence.

8.1.3. Discussion of batteries performance

It has been seen that the lithium-ion battery is the most suitable battery type for renewable integration as a greater share of the load is provided by the renewable energy stored in the batteries. This reduces import due to more energy deficit supplied by the batteries and better renewable use.

Given the minimum SoC of the batteries, 1 MWh of lithium-ion batteries, vanadium batteries and lead-acid batteries refers to 800 kWh, 1 MWh and 400 kWh of useable capacity, respectively. As more energy can be stored in the lithium-ion batteries and the vanadium batteries, it explains why they cover a larger part of the load than the lead-acid batteries. However, the lithium-ion batteries provide better energy performance than the vanadium batteries while they offer less storage capacity. This might be explained by the fact that the round-trip efficiency of the lithium-ion batteries has been set at 93% while that of the vanadium has been set at 65%. Indeed, the round-trip efficiency accounts for energy loss from charging and discharging energy, meaning that for a same amount of energy in, the energy output of batteries with higher efficiency is higher, and so the renewable electricity delivered to the load increases. In addition, the lithium-ion battery is the technology that has the higher power rate, meaning that more power can be drawn from the storage device to meet the load. Also, energy can be charged and discharged more quickly in lithium-ion batteries, making the technology more suitable for renewable back-up application.

Although, the lead-acid and vanadium batteries have almost the same efficiency, 64% and 65% respectively, it can be seen that the vanadium batteries supply a bigger part of the energy deficit although they have the lowest power rate. This might be explained by the fact that the depth of discharge of the vanadium batteries is 100% for an unlimited number of cycles, as specified by the manufacturer website. Consequently, the nominal capacity of the vanadium batteries is considered as the useable nominal capacity while the useable capacity of the lead-acid batteries is reduced by 60% given their minimum state of charge of 60%. Indeed, an important limitation of the lead-acid batteries is that their state of charge should stay above 50% not to prematurely damage the performance of the battery. As the depth of discharge increases, the number of cycles to failure decreases and the lifetime of the battery decreases. Consequently, the depth of charge significantly limits the power that can be drawn and these two parameters have to be balanced to avoid premature depletion of capacity and hence achieve long-term storage.

In sum, lithium-ion batteries have the ability to offer a wide range of storage applications, such as load-following, load-leveling, emergency back-up, uninterruptible power supply and renewable integration due to high efficiency and high charge and discharge rates which make them a flexible technology to supply power.

8.1.4 Conclusion on adding both renewable capacity and storage capacity to the Findhorn energy system

It has been seen previously that additional solar capacity and the new lithium-ion batteries recently developed by Tesla offer promising opportunities to increase the local renewable use of communities. On a same nominal capacity basis, these batteries provide better energy performance than lead-acid and redox flow batteries due to higher efficiency and quicker charge and discharge times. The energy analysis has shown that equipping the ecovillage with 38 lithium-ion batteries of 340 kWh of useable capacity improves the local renewable use by 15.6%, while combining 25 PV panels of 3 kW each with 25 lithium-ion batteries of 200 kWh of useable capacity increases the local renewable use by 15.9%. This signifies that almost the same local renewable use can be achieved with a lower number of batteries if they are combined with additional solar capacity. This observation can be explained by the fact that adding solar capacity results in significant renewable penetration into the load which is directly achieved by PV output and reduces the need for storage capacity.

8.1.5 Conclusion on the HOMER capabilities to model the Findhorn energy system

It has appeared that HOMER is not suitable to fully model a scenario with a two-way grid interaction associated with batteries. Indeed, the special system control required by battery simulation makes impossible to model grid export. In this configuration, the worst financial case analysis only can be conducted and does not refer to the real situation of the system which would financially benefit from the grid connection. This main limitation underlines the inability of the software to model battery scenarios with a multiple approach and to obtain consistent results in regards to both energy system performance and system cost. In sum, the HOMER software is more appropriate to model an islanded energy system using a diesel generator than a typical grid-tied system comprising battery storage.

However, the focus of the study has been put on the energy performance of the system and still generates useful information for the ecovillages. Thus, the resulting costs provided by the HOMER simulation for each scenario can be considered as a way to compare the different system designs in the worst financial case but should not be a barrier to select a system rather than another one as it does not match the reality.

Another limitation in HOMER which can be suggested to model battery system is that not all the batteries which figure in the database use the kinetic storage model. Indeed, some of them consider the idealized storage model to model battery's capacity to be charged and discharged and this does not take into account storage depletion associated with increased discharge current. Consequently, this model tends to overestimate battery capacity and does not match real battery performance which is more addressed by the kinetic model.

It is also interesting to underline that the HOMER database in regards to new battery technologies such as lithium-battery is very poor and comprises a 1kWh lithium-ion model only. This is especially remarkable as the database comprises 16 and 17 models of vanadium flow batteries and lead-acid batteries, respectively. This may be explained by the fact that lithium-ion battery is a new technology which has just been adapted to large-scale application and integration into microgrid system. However, the development of new battery technologies in the next few years might lead to the expansion of the HOMER database and to the development of HOMER capabilities to model batteries in a more realistic way and allow for a battery control mode able to accommodate grid interaction and battery operation.

8.1.6 Future work on the Findhorn electrical system

The investigation of combining additional PV with battery storage, for example by considering the installation of 3 kW PV panels on all Whins building roofs associated with the installation of 200 kWh of lithium-ion batteries centralized in a battery hub, has shown interesting results with an increase in local renewable use by 15.9% compared to the initial scenario. Beyond the scope of this project, this scenario could be furthered by considering PV and battery combinations in all of the community buildings with south facing roofs to maximise PV generation and local use.

It has been underlined that all the financial analysis conducted for scenarios with battery storage only has only depicted the worst financial case. Storing renewable energy during low demand hours and then using electricity from the batteries during peak power prices could lead to financial benefit and significantly reduce the COE. Beyond the scope of this thesis, a future work could be to take into account a grid rates schedule with day and night import and export tariffs and so to conduct a complete financial investigation to determine the system which would lead to the financial optimum. Also, the financial input data have been collected in order to be as accurate as possible to match current market price but some assumptions have had to be made when data have not been available and a refined financial analysis would be necessary for economic minimisation. Also, the complex control of the battery system in HOMER has imposed restrictions which makes the financial results valid for a one-way energy flow system only and does not suit the situation of Findhorn. Some other software like MERIT could be used to further the economic analysis or a financial spreadsheet using useful outputs from HOMER could be developed in excel to fully assess the different energy system designs.

8.2 Discussion of the results for the Tamera electrical system

8.2.1 Conclusion of the Tamera analysis

It has been seen that neither of the two control strategies proposed by the HOMER software have provided satisfactory results to model the energy performance of Tamera. Indeed, the CC strategy has been applied with a setpoint of 100% at night to model the grid fully charging the batteries at night. However, it has resulted in overestimated import of electricity, and adding more storage has resulted in even more grid purchases as storage capacity has increased and the setpoint of 100% at night still has had to be met. However, scenarios with 24, 32 and 48 batteries have resulted in lower COE and lower NPC than a scenario without any battery, even if more electricity has been imported from the grid. This shows the benefit of storage device to store electricity during off-peak period to use it during the day and meet demand during higher peak prices. This is especially of interest for a community like Tamera which relies on solar renewable source which is only available a few hours during the day and whose renewable output has to be limited for microgrid stabilisation reasons. PV power output curtailment usually happens around 10am when PV output outstrips demand, resulting in excess of electricity which can be absorbed by the addition of two more banks of batteries.

However, the addition of storage capacity is not a scenario which appears cost-effective according to the LF strategy as this strategy does not take into account battery charging by the grid at night which could compensate the increased costs of additional batteries by taking advantage of the grid rates schedule. As battery charging does not match the reality with this scenario, battery output is underestimated and does not justify additional capacity. Also, the excess of electricity which has to be curtailed appears to be underestimated in comparison with the data provided by the ORIGIN project.

8.2.2 Explanation for the mismatch of the results

At first, it has been thought that the discrepancy between the simulation results and the measured data comes from the inappropriateness of the battery dispatch strategies which do not reflect the real battery control used in Tamera. However, Figure 64 which illustrates the electrical system with the CC strategy seems to be correct and the orchestration of the energy flows is in agreement with the information provided by the community. Facing the mismatch of the results, further investigation has been conducted and the consultation of the Tamera community have revealed that 12 kW of solar capacity have been added to the electrical system and are probably the origin of the discrepancy between the measured data and the simulation results. However, this piece of information has been released too late due to limited licence required by the HOMER utilisation but future work is suggested in the next section. Even if this analysis has not provided realistic data for the community, the comparison of the two battery dispatch strategies has been conducted and appropriate controls have been set to investigate the possible energy management of storage systems in HOMER.

8.2.3 Future work

Due to software licence restriction and the limited time for the project, the model of the Tamera energy system could not be fixed to further the study. Future work could be to model the system with 32 kW of solar capacity instead of the 20 kW value provided by the community and still not updated in the ORIGIN portal. Also, the demand profile of Tamera has not been input as a time series file but has been synthetized by HOMER according to the annual electricity consumption and the load shape profile. Consequently, the same work as for building the Findhorn load profile should be done to get real data in each time step and so to get a more accurate profile. Associated with PV, the existing storage capacity could be simulated by using the CC strategy and the results could be compared with real data to validate the model. As the generating capacity is increased, grid purchases are expected to decrease and could be more aligned with measured data. Also, the excess of electricity which has to be curtailed would increase. Then, some variations of PV and storage sizes could be run by using both the CC and LF battery controls to define what strategy would result in the best energy management. Adding more storage could offer the opportunity to move away from the CC strategy currently used to control the battery system to progressively move to the LF control as fully charging the batteries at night would not be necessary anymore and would increase the independence from the grid.

Finally, a complete study of Tamera including additional renewable capacity and storage capacity could be a future work to fully investigate opportunities to increase its renewable generation and maximise its integration into the electrical system. To do so, the methodology developed for the Findhorn community could be followed to provide future alternative system design to increase the energy autonomy of Tamera.

8.3 Conclusion on the future energy system

In a society more and more concerned by sustainable and environmental aspects in which electricity demand is likely to escalate, the current focus is put on establishing a clean, reliable and long-term energy supply. Today, the first step to meet challenges in the energy system has been achieved by producing high amount of renewable power. In recent years, the price of photovoltaic technology has relatively decreased and solar cell efficiency has been improved while wind power has been greatly developed. New expectations are also addressed to harness tidal power and wave power. However, this increased amount of renewable-generated electricity raises the matter of matching supply with demand more than ever. All the aforementioned renewable sources have the ability to significantly penetrate electricity consumption by adding diversity to the generation mix and to reduce dependency on fossil fuel.

Also, intelligent resource utilisation is required in distributed system and renewable technologies offer interesting opportunities if they are coupled with storage which allows for better renewable use.

It has been seen that adding renewable capacities to the generation mix associated with large-scale storage technologies undeniably plays a critical role in energy autonomy for communities. However, certain technology combinations might be considered as prohibitively expensive in reality. Indeed, a large capacity of microgrid solar and/or wind power can appear not economically viable even with storage, and this might be the main barrier to the development of decentralised and distributed energy systems. Indeed, the cost of the overall system associated with increased renewable capacity grows rapidly, but not only due to the cost of renewable technologies but also due to the price of increased storage capacity required with higher renewable generation. Consequently, drawing power from the grid can be revealed as a significantly cheaper strategy than producing electricity from a smart grid.

The literature review has shown that even if each storage technology shows limitations and that the ideal renewable technology does not exist yet, intensive research is undergoing towards this goal. Amongst the large-scale energy storage technologies currently available, batteries seem to be of significant interest for communities. Indeed, they can play diverse roles such as providing ancillary services or supporting the integration of large-scale wind and solar power in the existing electrical system. As battery chemistry and design evolve, new battery technologies are no longer seen as a threat for the environment as they contain no heavy metals and can be recycled safely and cheaply. Since there is no 100% clean technology, batteries are still in the race for the integration of renewables into energy systems. Indeed, they are of great help for matching supply with demand and by coping with the intermittency of renewable output. Also, they do not require special landscape features, they require low maintenance and they can be scaled according to needs.

Moreover, the development of certain sustainable technologies can assist the one of others. As a case in point, the increased utilisation of electric vehicles could significantly boost the market of lithium-ion batteries. In addition, there would be opportunities to create a second market for EV batteries by recycling them into home storage. A wider market penetration of battery technologies would increase demand for batteries, leading to increased battery production and finally lower technology prices. This continuous improvement cycle is shown in Figure 68.

Figure 68: Orchestration between market, demand and technology price

As technologies are developed and the price of natural gas and fuel will probably continue to increase due to likely carbon emission charges on electricity generation, the cost of renewable technologies is expected to decrease significantly in future years. However, it is obvious that the integration of renewable energy technologies in the electrical system has to be led by incentives. A market-determined carbon price would create incentives for renewable energy sources without distinction amongst technologies. Indeed, certain projects can appear not economically viable under existing regulations and be aborted even if they could significantly reduce environmental impact. As a case in point, the Findhorn ecovillage finally decided to abandon the idea of expanding its wind park as it would result in a lower FIT under the current regulations, even if it would reduce its carbon footprint.

Chapter 9: Conclusion

The overarching goal of this dissertation has been to study strategies to harness renewables and increase their integration into the electrical system of real ecovillages. To conduct these case studies, a general procedure for auxiliary technology analysis has been developed and tested. This has led to suggestions on future alternative energy system designs to optimize energy management for each community. Through the present study, it has been shown that adding renewable capacity and storage technology help to integrate renewables in the local energy consumption of communities. Also, lithium-ion batteries have shown promising opportunities in the future design of community energy systems. However, the improvement in local renewable use and the decrease in electricity import are limited by the system design which has to balance energy efficiency, environmental aspect, cost and feasibility.

In terms of modelling, it has dealt with testing energy strategies on real systems and an important output of the study has been the evaluation of the HOMER software. To accommodate a great number of variable inputs dependent on the system (e.g., converter size, number of batteries…) and but also variable inputs independent of the system (e.g., power prices and sellback rates), a significant number of sensitivity studies have been conducted to determine the best scenario and provide information for alternative studies. It has been seen how different the optimal system suggested by the HOMER tool can be according to the different input variables and that the control of the system plays a critical role through each simulation. Also, software limitations have been underlined and alternative methods have been suggested to address these gaps. Nevertheless, a general computing methodology has been developed to provide future alternative energy system designs in order to optimize energy management and increase renewable use of ordinary communities.

Thus, other useful project outputs are a modelling methodology, computing models and alternative design suggestions to ecovillages. The optimal energy system design coupled with community energy management presents the best energy opportunities for ecovillages, even if a 100% renewable strategy cannot be achieved and would lead to the over industrialization of the landscape. Also, future work has been suggested according to different community objectives to further maximise the performance of their energy system.

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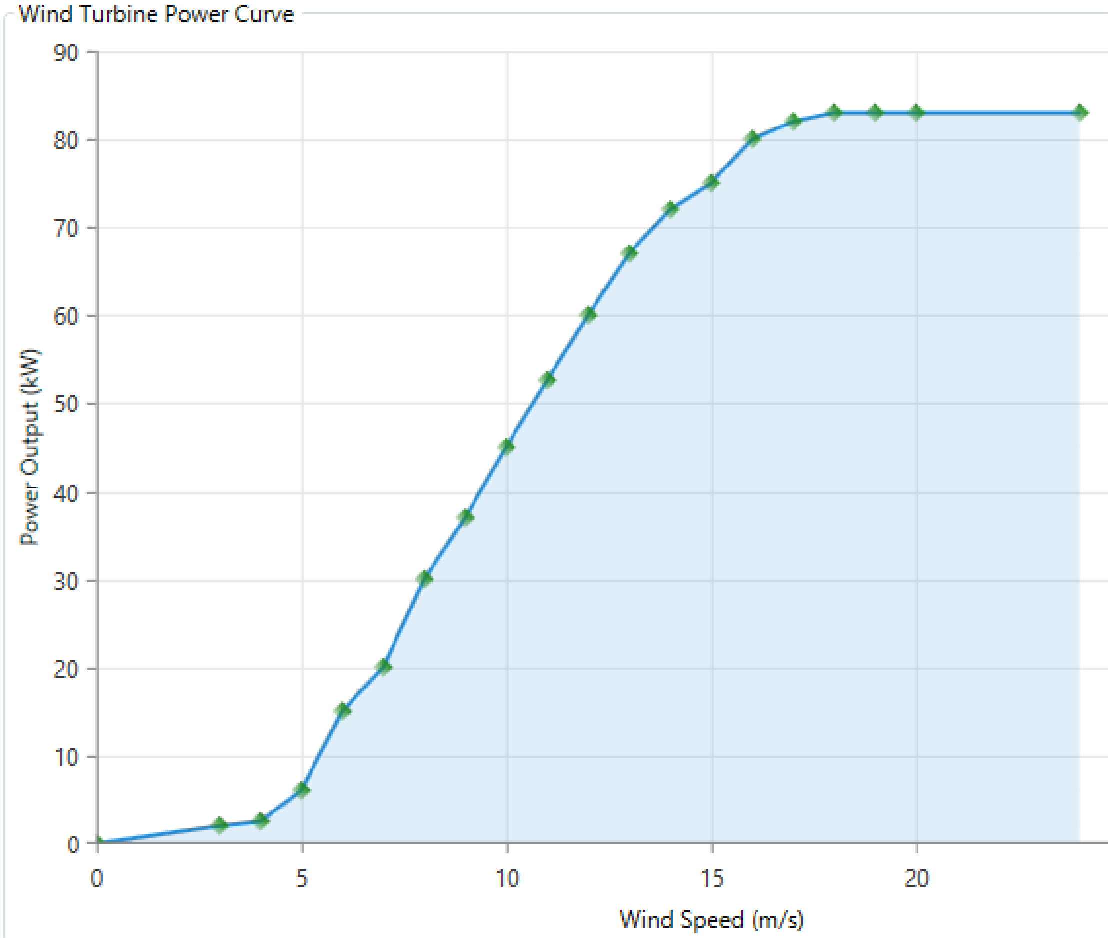
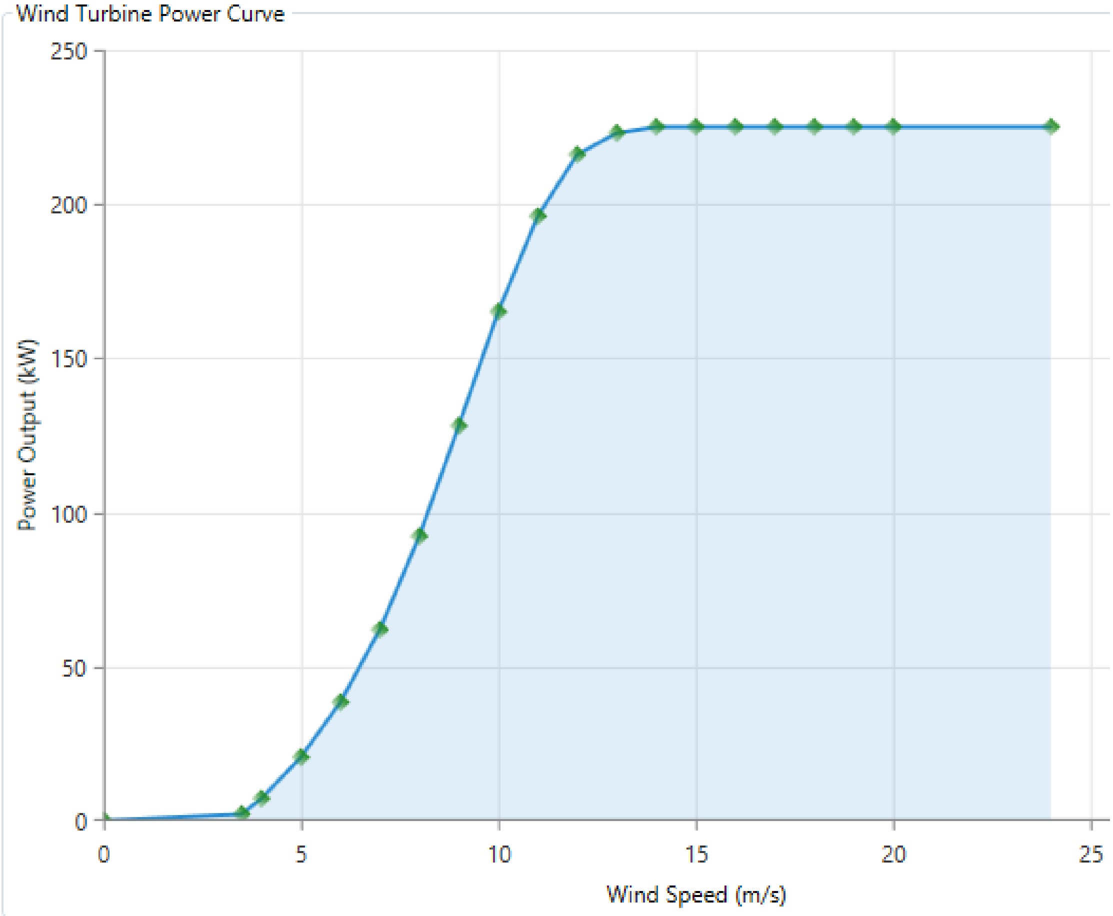
Appendix 1: Vestas V17-75 kW Power Curve



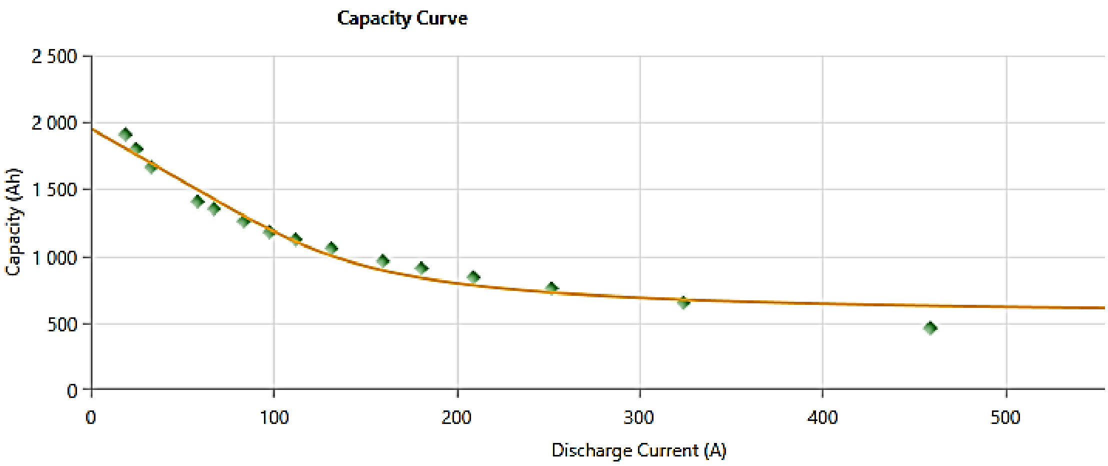
Wind Speed (m/s)	Power Output (kW)
0.00	0.00
3.00	2.00
4.00	2.50
5.00	6.00
6.00	15.00
7.00	20.00
8.00	30.00
9.00	37.00
10.00	45.00
11.00	52.60
12.00	60.00
13.00	67.00
14.00	72.00
15.00	75.00
16.00	80.00
17.00	82.00
18.00	83.00
19.00	83.00

Appendix 2: Vestas V29-225 kW Power Curve



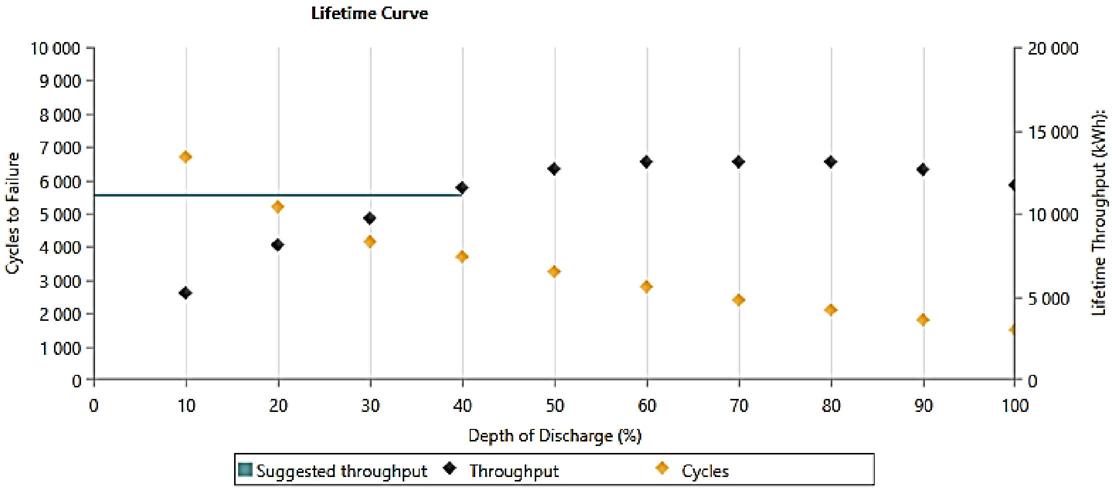
Wind Speed (m/s)	Power Output (kW)
0.00	0.00
3.50	2.10
4.00	7.10
5.00	20.50
6.00	38.30
7.00	61.90
8.00	92.20
9.00	128.00
10.00	165.00
11.00	196.00
12.00	216.00
13.00	223.00
14.00	225.00
15.00	225.00
16.00	225.00
17.00	225.00
18.00	225.00
19.00	225.00

Appendix 3: Capacity curve of 4 KS25P lead-acid battery



HOUR RATE:	SPECIFIC GRAVITY	CAPACITY / AMP HOUR	CURRENT / AMPS
@ 100 HOUR RATE	1.280	1904	19.04
@ 72 HOUR RATE	1.280	1796	24.94
@ 50 HOUR RATE	1.280	1661	33.21
@ 24 HOUR RATE	1.280	1404	58.50
@ 20 HOUR RATE	1.280	1350	67.50
@ 15 HOUR RATE	1.280	1256	83.70
@ 12 HOUR RATE	1.280	1175	97.88
@ 10 HOUR RATE	1.280	1121	112.05
@ 8 HOUR RATE	1.280	1053	131.63
@ 6 HOUR RATE	1.280	959	159.75
@ 5 HOUR RATE	1.280	905	180.90
@ 4 HOUR RATE	1.280	837	209.25
@ 3 HOUR RATE	1.280	756	252.00
@ 2 HOUR RATE	1.280	648	324.00
@ 1 HOUR RATE	1.280	459	459.00

Appendix 4: Lifetime curve of 4 KS25P battery



Appendix 5: Available power and storage capacity of the Cellcube FB technologies

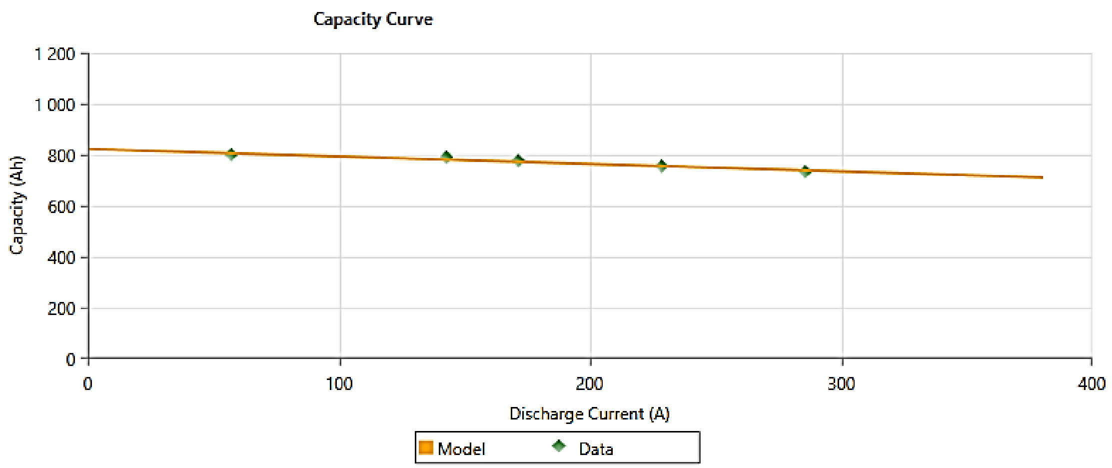
Available power and storage capacity

	Power output (kW)	Storage capacity (kWh)				
CellCube FB 10	10	40	70	100	130	
CellCube FB 20	20	40	70	100	130	
CellCube FB 30	30	40	70	100	130	
CellCube FB 200	200		400	800	1600	

Appendix 6: Cellcule FB technical data

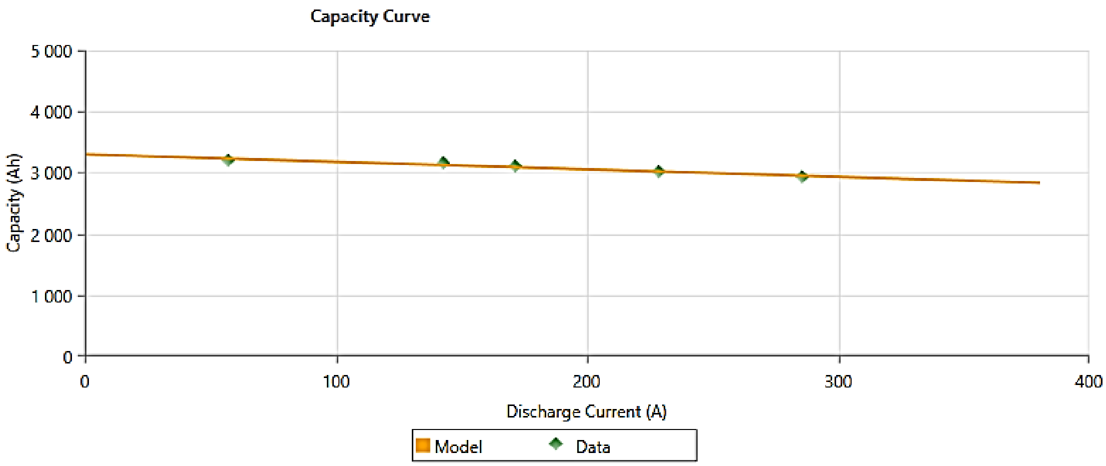
Perfomance and energy	CellCube FB 10/20/30 kW	CellCube FB 200 kW	
Nominal charge output	10/20/30 kW	200 kW	
Nominal discharge output	10/20/30 kW	200 kW	
Capacity of the energy storage system	40/70/100/130 kWh	400/800/1600 kWh	
Battery and system voltage			
Output voltage option	- 48 VDC; 120 VAC; 230 VAC (1-phase); 400 VAC (3-phase)	400 VAC	
Duration of connection / Reaction time	grid-independent: < 20 ms, remote control: < 8 ms		
Control system			
Control via external interfaces	serial, TCP / I P, bus systems		
Monitoring			
Condition detection via remote interrogation by e-mail	State of charge (SOC), available energy, charge / discharge power output, and more		
Efficiency			
Charge / discharge cycle DC	up to 80 %	up to 70 %	
Multi-stage management reduces power losses	3 independent, switchable circuits with energy-efficient pump control system	4 independent, switchable circuits with energy-efficient pump control system	
Discharge time at nominal power output		DC battery power	AC inverter power
Discharge time (autonomy)	Depends on power output and capacity		
1 hour**		220 kW	200 kVa
2 hours**		140 kW	130 kVa
3,5 hours**		110 kW	100 kVa

Appendix 7: Capacity curve of FB 200kW-400kWh battery



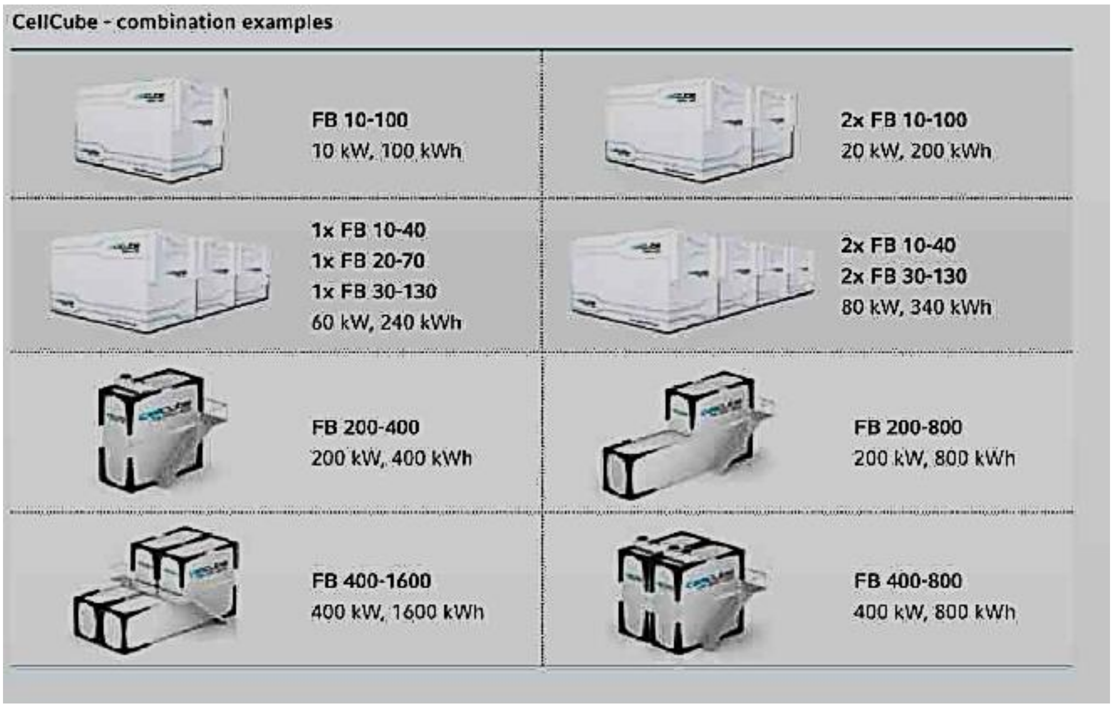
Current (A)	Capacity (Ah)
285.71	732.25
228.57	754.13
171.43	776.01
142.86	789.48
57.14	799.58

Appendix 8: Capacity curve of FB 200kW-1600kWh battery



Current (A)	Capacity (Ah)
285.71	2 928.99
228.57	3 013.16
171.43	3 105.74
142.86	3 156.24
57.14	3 198.32

Appendix 9: Cellcube FB combination examples



Appendix 10: Tesla Powerwall specification

Powerwall specs:

- Mounting: Wall Mounted Indoor/Outdoor
- Inverter: Pairs with growing list of inverters
- Energy: 7 kWh or 10 kWh
- Continuous Power: 2 kW
- Peak Power: 3.3 kW
- Round Trip Efficiency: >92%
- Operating Temperature Range: -20C (-4F) to 43C (110F)
- Warranty: 10 years
- Dimensions: H: 1300mm W: 860mm D:180mm

Appendix 11: Monthly energy deficit and energy surplus of the original system of Findhorn

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Purchases (kWh)	Peak demand (kW)
January	40 379	108 937	-68 558	250
February	43 798	63 706	-19 908	214
March	38 664	70 873	-32 209	177
April	43 470	36 820	6 650	186
May	36 766	58 926	-22 160	192
June	32 886	24 805	8 081	152
July	37 228	17 332	19 897	134
August	38 185	31 897	6 289	147
September	41 291	21 777	19 514	162
October	50 608	27 273	23 336	188
November	59 489	22 308	37 181	226
December	58 282	55 503	2 779	240
Annual	521 046	540 155	-19 109	250