System approach to evaluate economic feasibility of renewable generation for rural communities

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ABSTRACT

Over recent years, severe weather from storms and flooding have damaged electricity networks and caused power cuts substantially for rural communities. With Government targets for increasing the contribution of renewable electricity to energy supplies, it is possible that this contribution could be combined with improvements to the security of energy of rural communities. This research investigates the hypothesis that communities with adjacent land could generate communal electric power economically to substitute grid power for substantial period of time. Excess generated power is made available to the grid thus boosting the availability of renewable energy while at the same generating revenue for the community and increasing security of supply to these communities.

The question for this research is whether community energy schemes can be economically viable and if so what configuration of wind turbines and solar panels would support an optimal solution. An optimal solution is dependent on energy consumption, the dynamics of weather, land availability, lifetime support for generation facilities and changing government policies. The complex nature of the community energy question, with nonlinear and dynamical constraints requires a systems approach to the problem definition and modelling in order to understand the economic feasibility of renewable electricity generation for rural communities in the UK. A comprehensive renewable electricity generation model is developed that combines onshore wind turbine and solar PV panel to generate electricity for community.

The energy generation model combines linear, non-linear and dynamical behavioural variables to develop a novel approach to modelling. Discrete event simulation is applied to analyse the performance of the community energy system together with configuring the optimal combination of technologies. System dynamics modelling is used to assess the impact of feasibility of the renewable generation economics on future investment in the technology.

Overall, this thesis successfully demonstrates the development of the system modelling method for grid connected renewable electricity generation at community level. The results demonstrate viability of these type of renewable electricity generation investments and how economy scale can be improved, aiming to attract more investment in local renewable generation farms. This research applied the new model to a case study, Huntly in Scotland with real data and found that, one 1.5MW turbine generating 2,700,000kWh/year of electricity yielded 72% rate of return on investment (ROR) that makes the scheme feasible.

NOMENCLATURE

°C	Celsius
AC	Alternating Current
BNEF	Bloomberg New Energy Finance
CEGB	Central Electricity Generating Board
CFD	Contract for Difference
CHP	Combined Heating and Power
CM	Capacity Market
CM	Corrective Maintenance
CMS	Conditioning Monitoring System
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
COP21	Conference of the parties which held in Paris in 2015
COP24	Conference of the parties which held in Katowice in December 2018
DCF	Discounted Cash Flow
DES	Discrete Event Simulation
EEA	European Environment Agency
EEC	Energy Efficiency Commitment
EMR	Electricity Market Reform
EU	European Union
EU ETS	European Union Emission Trading System
EUR	Euro
FIT	Feed-in Tariff
GB	Great Britain
GBP	Great Britain Pound Sterling
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GW	Gigawatt
GWh	Gigawatt per hour
GWP	Global Warming Potential
HERS	Hybrid Renewable Energy System
i	Interest Rate
IEA	International Energy Agency
IR	Infrared Radiation
IRR	Internal Rate of Return
kJ/m^2	Kilojoule per square meter
Knot	Knot
kW	Kilowatt
kWh	Kilo Watt per Hour
LCOE	Levelised Cost of Energy
Met Office	Meteorological Office
MIT	Massachusetts Institute of Technology

MW	Mega Watt
NEEAP	National Energy Action Plan
NESEMP	North East Scotland Energy Monitoring Project
NGET	National Grid Electricity Transmission plc
NGO	Non-Governmental Organisations
NPV	Net Present Value
NREL	Renewable Energy Laboratory
O&M	Operation and Maintenance
OECD	Organisation of Economic Co-operation and Development
Ofgem	Office of Gas and Electricity Markets
P	Initial Loan Amount
PM	Preventive Maintenance
PR	Performance Ratio
PV	Photovoltaic
RECs	Regional Electricity Companies
ROI	Return on Investment
ROR	Rate of Return on Investment
SA	Sensitivity Analysis
SD	System Dynamics
U.S.	United State
UK	United Kingdom
UN	United Nation
UNFCCC	United Nation Framework Convention on Climate Change
VAT	Value Added Tax
WeSET	Westmill Sustainable Energy Trust
Wp	Watt Peak

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1 INTRODUCTION

1.1 BACKGROUND

Rural populations are increasing as people choose to leave cities and settle in the English countryside. According to Office of National Statistics (2014) rural population will increase by 6% by 2025. However, rural communities are known to be affected the most by severe weather and power cuts compared to large towns and cities. 17% of UK population lived in rural area in 2016, with a higher proportion of older people compared to the urban areas, but yet it seems that not enough attention has been given to these communities in the UK to secure their electric power supplier (Dominiczak, 2014; Kuenssberg, 2019). In severe weather such as storms, flooding and gales, rural communities are affected the most by power cuts as a result of damaged electricity networks. Therefore, it is essential to secure reliable and sustainable energy production for these communities through local-level power generation plants. In this case a distributed generation approach that employs small-scale technologies to produce electricity close to the end users may be a solution to such a problem.

Average global temperatures have significantly increased over two decades and the main contributors to this increase is related to the nature of human activities. Along with the constant increase in average environmental temperature, environmental policies are becoming more prevalent and stricter in enforcement with the main aim of having no harmful greenhouse emissions by 2100. In order to reach this target, there is a clear need to progressively reduce the emission of greenhouse gases (GHG) over time with aim of reaching zero before 2100. As a result, Governments have targets for increasing renewable energy as part of carbon emissions. There is a target of reducing greenhouse gas emission by at least 40% in comparison with 1990 and to ensure that at least a 32% share for renewable energy followed with a long-term goal for 2050 to cut emissions by 80% compared to 1990 (European Commission, 2019). The majority of these emissions (approximately 70%) originate from the energy sector, which is the main reason to prioritise this sector when it comes to actions that need to be taken (OECD, 2018). In the UK, domestic sector used 29% of energy in 2017, that makes it the second largest energy user after transport at 49% (Jack, 2019). This research therefore, focuses on the energy sector for domestic users in the UK both to cut greenhouse gas emission and to ensure electricity supply to rural communities.

UK as a member of European Environment Agency (EEA) is constantly assessed against targets set for greenhouse emission. In 2014 for instant, European Union countries agreed on a reduction of at least 40% in domestic GHG emission by 2030. During the COP21[1] meeting that took place in Paris in 2015, the UK as a one of the members present agreed to joint efforts to keep the global increase in temperature below 2°C, and to have additional action to limit the increase of the temperature to 1.52°C. (United Nation, 2016; EEA, 2018; Sporer, 2018; European Commission, 2018).

Therefore, in order to achieve greenhouse emission targets of at least 30% of total energy consumption from renewable energy by 2030 and to reduce carbon emission is to encourage individual households to improve the efficiency of their energy applications and to invest in individual household-based Microgeneration[2]. However, this may not be the most efficient method of domestic generation as economics of scale may not be realised.

In order to achieve greenhouse emission targets as well as providing sustainable and more reliable electricity for rural communities, the scheme model of having community electricity generation should be considered as a serious alternative. In this case, a grouping of households can be supplied energy from shared generation resources providing sustainable energy as well as providing a surplus of energy to the grid and thus generating the revenue while reducing greenhouse emissions.

Rural communities are the main focus of this research as they are affected the most by unsustainable energy and usually occupant of these areas is on low income. According to a report by OECD (2017) on linking renewable energy to rural development, local renewable energy generation will help to reduce greenhouse gases and can provide hosting communities with benefits including:

- Affordable energy
- New revenue sources
- New jobs and business opportunities

Therefore, this research investigates the hypothesis of grid-connected distributed communal renewable electricity generation located close to the communities with priority of providing

[1] COP21 is s 21st Conference of the parties which held in Paris in 2015. COP is the supreme decision-making body of convention (United Nation, 2019).
[2] Microgeneration refers to small-scale systems that generates electricity and/or heat for individual households from renewable sources.

electricity to the community and selling any excess of electricity to the grid is a viable solution (see Figure 1-1).

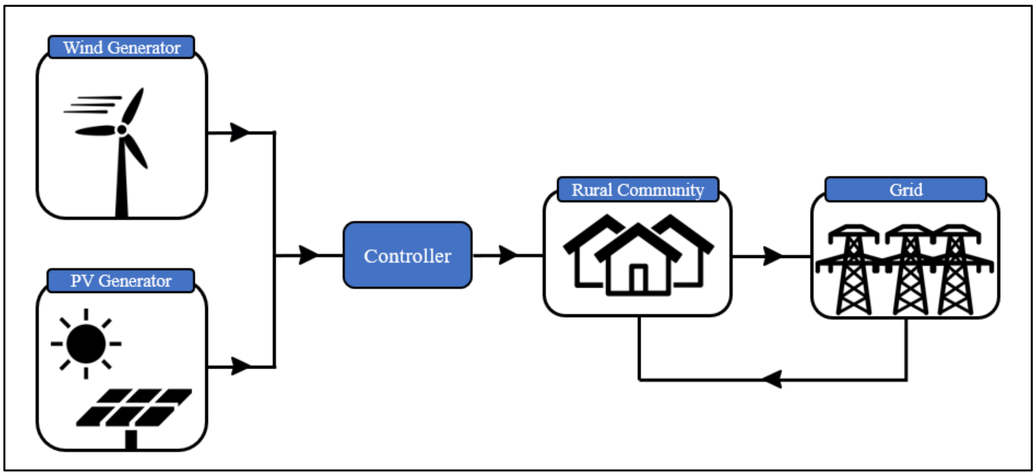

Figure 1-1: Rich Picture of Proposed Model

Since the focus of this research is on rural communities, in order to test the model as community must be selected with available detailed data on household electricity consumption, weather data such as wind speed and solar irradiance, land availability for the renewable farm and associated costs.

As mentioned, selecting the right community to test the hypothesis is essential in order to obtain a clear understanding of the economics of community-centred renewable electricity generation. Part of the choice must be that adjacent land is available to host the shared generation facilities and therefore this will limit the size of community that can be served. Furthermore, to test the research model, a case study (rural community) is selected where good input data is available. Rural areas account for 98% of the land of Scotland and 17% of the population live there. Increased accessibility of rural areas over recent years, led to faster rate of growth in these areas compared to the rest of Scotland, mainly as a result of inward migration (Dominiczak, 2014; Scottish Government, 2018).

Therefore, in this research a case study of a small town in Scotland, Huntly, has been selected as detailed household electricity consumption data together with detailed weather data is available. Huntly is a town in Aberdeenshire Scotland, formally known as Strathbogie, and has a population circa 5,000 with between 2,200 and 2,300 households. The UK Government categorises the area as rural[3] (Scottish Government, 2018). Daily electricity consumption of 140 households from the town has been collected, weather data is available together with land information.

1.1.1 Modelling approach

Fluctuation of wind speed and solar irradiance has a significant effect on the electricity power generation. On the other hand, changes in policies and regulations of renewables, cost and efficiency of technology used have an equally important effect on investment in the renewable systems. Moreover, variations in energy consumption are mainly affected by the seasons and the weather conditions prevailing at the time. Dealing with these variation effects and achieving optimal design for a power plant (renewable energy) requires development of specific modelling and analysis tools as the variables concerned are multifarious, linear and non-linear. To deal with non-linear multifarious variation in the real-world situations this research requires a hybrid modelling approach – deterministic and dynamic.

A deterministic (probabilistic) model is used to evaluate the economic viability of community renewable generation, and to optimise the best combination of wind turbine and solar panel utility for electricity generation; a discrete event simulation (DES) is used. The DES model optimises generation utility considering the effects of the weather. After obtaining an optimised result, a system dynamics (SD) model is used to investigate the relationship between the efficiency of the renewable investment and viability of future investments in renewable energy. In this research both models, DES and SD are integrated to form the test model in order to provide sensible information into a decision process. Modelling activity is thus divided into two groups:

1. Modelling Group I: application of DES to optimise the energy scheme. Optimisation results obtained from DES give the best combination of wind turbine and solar PV panel for a selected region considering its weather data and energy consumption. In this case energy consumption is considered constant with constraints:
    - Land limitation – a limitation of 10 acres applied.
    - Total capacity of renewable installation – installation of 5MW or less applied in order for the energy farm to be eligible for feed-in tariff

   The model is optimised with these constraints.

[3] Aberdeenshire Council Towns

2. Modelling Group II: application of SD to assess the future behaviour of the energy scheme. With application of SD, adding casual loops to the DES model, the effect of results obtained from 1st year investment of renewable generation are applied to the next year and then subsequent years for the lifetime of the project as illustrated in Figure 1-2. In this part of modelling constraints are removed to assess the effect of efficiency of initial investment on future investments. Results from both 'Modelling Groups' are presented in detail in Chapter 6.

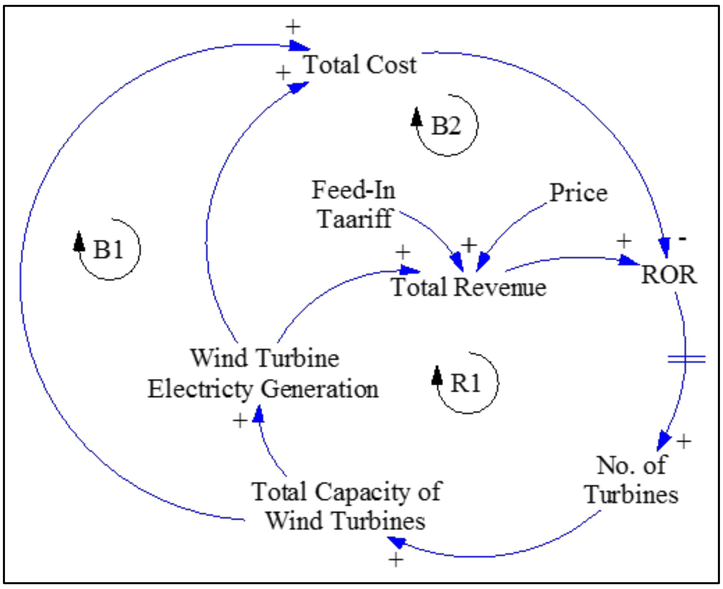

Figure 1-1-2: System Dynamic Approach of the Research Model

In optimization of any system the first step is to model individual components to identify and improve understanding of the modelling environment to clarify the problem and to support decision making. Modelling results are validated by checking results produced by a correct prediction of performance at specific points in time, although it is too complex or extremely time consuming to design a perfect model. The individual component performance is modelled by deterministic or probabilistic approach (Bhandari et al, 2015).

Weather and consumption events are continuous in nature and nonlinear, but data collected to represent these events is discrete. System dynamics modelling relies on the discrete nature of these variables together with verifiable constraints. The constraints are identified under the headings of land availability, upper and lower limit to weather conditions, upper and lower limit to consumption and government regulation. Decision making in a multifarious situation is difficult because any optimisation is not readily available from just viewing the discrete data results. The discrete event simulation (DES) and system dynamics (SD) model present the combination of variations in a readily available format.

The modelling tool selected for this research is Vensim which is a visual modelling tool used to conceptualise, document, simulate, analyse and optimize models of dynamic systems. Vensim provides a simple and flexible way of building simulation models from causal loop or stock and flow diagrams. By connecting words with arrows, relationships among system variables are entered and recorded as causal connections. This information is used by the Equation Editor to help form a complete simulation model.

Discrete event simulation (DES) provides a formal modelling and framework based on dynamical systems theory (Byon et al, 2011). DES is a modelling approach used in decision making and optimisation and recently used to evaluate viability of sustainable energy generation (Paulista et al, 2019).

System Dynamics (SD) was specifically developed by Jay Forrester to understand the nonlinear behaviour of complex system over time using stocks, flow, internal feedback loops and time delays. The system dynamics was founded and developed to simulate the behaviour of social systems by explaining that behaviour and designing effective policies to improve system performance (Forrester, 1990; Lane and Sterman, 2011). Initially SD was applied only on managerial problems, however its application widened to include urban dynamics, socio-economic system and more. In this research, SD approach is used in order to model the community energy proposition (Marquez and Blanchar 2006; Ansari, 2012; Jeon, Lee and Shin, 2015).

Renewable energy generation technologies are impacted by number of factors such as supply and demand, availability of other energy resources, government policies, subsidies, cost of electricity per unit and more. It has been widely reported that SD can be used to present the complex dynamic behaviour of the renewable energy technology providing a rich source of information necessary for modelling purpose (Sterman, 2000; Marquez and Blanchar, 2006; Ansari and Seifi, 2012; Aslani and Wong 2014; Jeon, Lee and Shin, 2016).

1.2 PROJECT SCOPE AND OBJECTIVES

The aim of this research is to assess the economic feasibility of renewable generation at community level. The renewable generation considers the combination of solar and wind farms with grid connection for communities.

Within this primary aim, the following objectives are addressed:

- To show that Discrete Event Simulation (DES) and System Dynamics (SD) modelling are well suitable for this type of problem.
- To design and develop a test model comprising DES and SD elements that is general and can be used at suitable locations anywhere in the world.
- To test the developed model using a specific case study in the UK

1.3 THESIS STRUCTURE

The thesis is arranged into the following chapters:

Chapter 2, is a literature review which is divided into 5 subsections, as follows: Evolving greenhouse gas regulations; the current state of electricity generation from renewables with focus of Europe (Scotland in this case, Huntly town); identified barriers for renewable electricity generation; changes in policies and regulation for wind turbines and solar panels with specific focus on Scotland; and CO_2 emission management. This chapter addresses variance sources but the Department of Energy and Climate Change in Great Britain, International Renewable Energy Agency and Ofgem has mainly influenced this research. The outcome of this literature review sets the foundation for the remainder of this research.

Chapter 3 is a continuation of literature review specifically focused on building the model and understanding systems. This chapter presents and discusses approaches to identify and provide a solution to renewable related problems. Discrete Event Simulation Model (DES) and System Dynamics (SD) are introduced in this chapter.

Chapter 4, Model Development, presents a comprehensive analysis of the problem and the routes to a possible solution. In this chapter details of each input are described and sorted in core Excel model. The Excel model provides data in the correct format for all other modelling tools applied in this research.

Chapter 5, Development of the Model, in this chapter the Vensim software is used to build the test model with both modelling functions. Details of each sub-function are presented and discussed before outlining how each is integrated to form a system dynamic model capable of meeting the principal objective of the research.

Chapter 6, Results and Analysis, analysis and results from the model given in Chapter 5, are analysed and discussed in detail. Social aspect of the wind and solar farm are also presented in this chapter, with the main focus on the policies and regulation of renewable generation farms rather than technology and modelling. Furthermore, this chapter presents a number of scenarios examined by the test model. The chapter then presents a case study of building a renewable (wind and solar) farm in Huntly. Data collected for the case study is used to populate the research model to first test its credibility then to explore how sensitive the renewable farm generation and profitability is to specific parameters including policies, costs of generator, location and cost of buying electricity from Grid and CO_2 management. At the end of the chapter results obtained for each scenario are presented. The answer to the economic question posed by this research is addressed in the conclusion section.

The final chapter (7), conclusions of this research discusses the main emphasis on how certain objectives have been achieved. The recommendation based on findings of this research and directions for the future work are provided. Conclusion, gathers all the conclusions from the research, with particular emphasis on how the objectives have been achieved. The thesis then concludes with recommendation based on the findings of the research and directions for the future work. The final chapter is followed with a reference list and appendices.

1.4 Outcome and Contribution of the Research

The outcome of this research is a model to assess the economic feasibility of renewable generation at community level. The model has been proven against a case study of Huntly in Scotland. Furthermore, the model is shown to be generic and can be applied to suitable locations worldwide. The main contributions of this research are:

- Multidisciplinary application
- Wide application of the model to different renewable energy scenarios

- Uniqueness of the model in that no other current model performs in the community arena
- Hybrid system dynamic modelling employing both dynamical techniques and discrete techniques in an integrated manner
- Social aspect is encompassed for completeness
- Educational aspects to help students learn to test renewable scenarios
- Promotion of renewable energy at community level

This research is multidisciplinary as it encompasses different aspects such as; modelling, technology, economic, social and educational aspects with wide application as it can help to solve global issues such as sustainable energy for rural communities anywhere in the world given the required data are available. Furthermore, the model is unique as it deals with a large number of input data for generating electricity with focus on rural communities, also it considers land availability for the given area and the cost of land, and detailed through-life costs which are usually not considered in detail. In this model, the hybrid system dynamic modelling developed can handle linear, nonlinear and dynamical input data. The model is applicable for optimising and managing the renewable energy generation in community size scenarios.

Application of the model tests the feasibility of renewable generation for selected regions leading to providing sustainable energy at affordable cost for a rural community additionally generating revenue from investment from the renewable generation farm, creating new jobs and developing new business opportunities for the tested area. The model also has an educational aspect as it can raise awareness about economic viability of renewable generation in community size scenarios and can be accessed by any user given the training to work with the model. Last but not least the model can be used to promote the development new technologies in the tested area.

2 Energy Market and Rural Communities in UK

2.1 Chapter Overview

Current regulations on greenhouse gas emissions from electricity generation are recognised as an important factor affecting implementation of renewable energy generation in a national context. In order to ensure successful implementation of these regulations in the UK, it is necessary to give a clear understanding of both complexity and relationship between climate change, electricity generation and policies.

This Chapter provides an overview of climate change and energy market in the UK as well as progress made in renewable generation and CO_2 emission management. Then, brief description of rural communities in the UK and chosen region as a case study for examining the developed research model provided followed by effect of renewable generation on rural communities. Chapter 3, will provide literature review about selected modelling approach for this research.

2.2 Climate Change

Climate change is mainly a result of human activities (anthropogenic) which has risen sharply since the mid-20th century. According to NASA reports and the research conducted by 130,000 independents experts, it is concluded that there is more than 95% probability that anthropogenic activities are the main reason global warming of our planet (NASA, 2019). One of the main contributors whose presence has drastically changed in the global climate is the increase in amount of greenhouse gasses produced from carbon dioxide (CO_2). Greenhouse gases appear naturally in the atmosphere and absorb large amount of infrared radiation (IR) thus providing a supporting layer to keep the surface temperature of the Earth stable. However, increasing emissions of carbon dioxide and methane increases the amount of IR absorbed, which as a result increase the surface temperature on Earth and this phenomenon is well known as greenhouse effect or 'global warming'. According to Sims, Rogner and Gregory (2003), the industrial revolution as well as significant consumption of fossil fuels has caused a major climate change by increasing the level of greenhouse gases such as carbon dioxide (CO_2) in the atmosphere. Climate Scientists state that since 1998 of the ten hottest years recorded nine out of which have been recorded since 2002. As Gavin Schmidt, a climatologist at NASA's Goddard Institute for Space Studies notes: "What matters is, this decade is warmer than the last decade, and that decade was warmer than the decade before," moreover it's estimated by the International panel on climate change that temperature will be increasing in the next 100 years (NASA, 2016).

Therefore, the average temperatures in the UK will keep increasing due to the above-mentioned global climate changes. These climate changes significantly impact agriculture and forestry, businesses, health and wellbeing, health o of buildings and other infrastructure as well as the natural environment (Government, 2012). The main problem with CO_2 is that about one third of CO_2 will be present in the atmosphere for around 50 to 100 years. As a result, it will warm the atmosphere which increases the surface temperature of the earth as well as rising the global sea level by melting ice sheets. Overall rise in global warming is estimated to reach around 2 to 7 degree this century which will have significant consequences for the human.

2.3 KYOTO PROTOCOL 1992

Kyoto Protocol was created in 1992 in Japan, where United Nation Framework Convention on Climate Change (UNFCCC) set the meeting with the main aim to force action on the international community to reduce greenhouse gases.

Participants from more than 170 countries have attended this meeting, involving various non-governmental organisations (NGOs) as well as inter-governmental organisations. China, India and developing countries were excluded from committing to the agreement and as a result, this protocol only applied to the industrialised nations such are European Countries, United States, Canada and Japan (Oberthur and Ott, 1999). Also, the Kyoto agreement considered that poorer economies of developing counties will not be able to bear the costs associated with change of fuel for energy generation, therefore the plan was to bring developing countries into future climate change agreements when cleaner technologies were developed and become more affordable (Henson, 2011).

The main focus of this protocol was to reduce the greenhouse gases by switching from fossil fuel-based systems for energy generation to cleaner fuels and the baseline chosen for measurement of greenhouse gases reduction was 1990 year. Industrialised countries were obliged to cut their emission of carbon dioxide by 5% on average by 2012 compared to 1990 and at least 50% reduction in greenhouse gas emission by 2050. The Kyoto protocol was finalized and adopted by Japan in December 1997. However, in 2002 when George W Bush became president, United States decided to withdraw from the previously agreed protocol and became exempted from obligations that were part of Kyoto protocol. That act left US and China (two largest carbon polluter) free from restrictions. On the other hand, in late 2004 Russia finally signed up to the agreement and as a result Kyoto had 55 members and became a law in February 2005; nearly 7 years after it first adopted in Japan (United Nations Framework Convention on Climate Change, 2014; BBC, 2001; Ed King, 2015).

In 2012, emissions were 22.6% lower than in 1990 and it was way beyond 5% which was initial target proposed by Kyoto reduction agreement. The reason was due to policies that developed countries applied to decarbonise their industrial environment and everyday living. In the UK, the emissions were cut mainly by replacing coal by gas. As a result of this astonishing result, Ed King (2015) described Kyoto as a great success.

Form technical point of view, Kyoto has been a reason of major developments such as:

- Introducing multinational carbon market and providing new rules for emissions
- Offering support for less developed countries
- Setting rules-based architecture that has an influence on countries all around the world to create low carbon legislation, i.e. UK's 2008 Climate Change Act.

According to Craig *et al* (2014) there is a notable positive relationship between carbon footprint and electricity generation. Therefore, European countries proposed regulation under carbon emission in order to change the way energy generates to decrease greenhouse gases emission.

2.4 EUROPEAN UNION CARBON EMISSION

To comply with the Kyoto target, the EU implemented a number of directives aimed at specifically reducing emissions from carbon dioxide and methane. In 2003, Tony Blair proposed the cut of Carbon Dioxide by 60% in UK and stated that by 2016-2018 no household should have a shortage of energy in Britain (TSO, 2003). Moreover, in 2007, EU countries announced that their main focus on reducing carbon dioxide emission would be by proposing a package of binding legalisation to ensure that Europe meets its climate and energy targets for 2020. Main targets for that package are 20% reduction in greenhouse gas in comparison with 1990, 20% of EU countries energies to be generated by renewable and 20% improvement in energy efficiency (Oberthur and Ott, 1999; McLoughlin et al, 2012; Sense about Science, 2016). Meanwhile, UK as a member of the EU supported the mission and Tony Blaire, former prime minister stated, “We will therefore support the proposal for bidding EU-wide 20% target for renewable” (Financial Times, 2007).

UK’s Government in its attempt to reduce carbon emission passed the Climate Change Act 2008 that makes Government responsible for lowering greenhouse gas emission by setting five-yearly carbon budget for the UK from 2008-2012, 2013-2017, and 2018-2022 till 2050. In 2030, the target is to reduce greenhouse gas emissions by at least 40% in comparison with 1990 and to ensure at least 32% share for renewable energy. A long-term goal related to the 2050 the target is to cut emissions by 80% compared to 1990 (Kelly, 2011; Zhang et al, 2011; Committee on Climate Change, 2015; European Commission, 2019).

In December 2015, the Paris Agreement was reached with new policies and changes mainly related to low-carbon energy transition. However, in order to achieve the goal of a 2°C rise in global temperatures, the International Energy Agency (IEA) states that average CO_2 potency of electricity needs to decrease from 114 grams per kilowatt hour (g/kWh) in 2015 to 15 g/kWh by 2050, which is challenging (Baritaud et al., 2016). The upshot of these machinations is that in order to meet the 2020 renewable target, European counties are now mainly focused on use energy generated from renewables such are wind turbines and solar power systems (BBC, 2016; Guardian, 2017).

2.5 Paris Agreement - December 2016

The first ever legally binding global climate deal was adopted by 195 countries in Paris and is well known as ‘Paris Agreement’. During the climate conference that took place in Paris, countries taking part agreed to set out a global action to limit global warming to be below 2°C. This was a historical moment as this deal has united all countries of the world to contribute and agree on the agreements made in the climate change direction. The key element and the achievement of this agreement was that governments from all the countries have sympathised the same goal which was the CO_2 reduction. In order to achieve this goal, several approaches have been adopted, such are: limit the amount of greenhouse gases produced by anthropogenic activities between 2050 to 2100 point to the same level as amount of CO_2 all trees, all oceans and soils can absorb naturally. Aim to limit the rise in temperature to 1.5°C, to take prompt reductions afterward in line with the best available science. Followed by countries to come together every 5 years to set review each country's contribution to the agreement and set more targets as required for cutting emissions and to regularly update each other and the public on how well they are doing to achieve their target (European Commission, 2016; Briggs, 2017).

However, after 18 months after the agreement was reached the United States, the World's second largest carbon emitter, decided to pull out from the agreement after their initial promise of $3Bn contribution towards the agreement (Macguire, 2017). President Trump made his claims on his 100th day in Office on 29th April 2017 stating that the U.S. pays billions of dollars for the agreement while Russia, China and India make no contributions. In addition, he claimed that the Paris agreement would shrink the U.S. GDP by $2.5 trillion over 10 years (Schipani, 2017). This action made the Unites States the only country not taking part in the Paris Agreement. Despite Trump's intention to pull out of the agreement, there was a need to hold to it due to a legally required notice period. In the meantime, all other participants have decided to contribute more in order to reduce the effect of U.S. exit from the agreement (Milman, 2018).

2.6 KATOWICE DECEMBER 2018

At COP24 in Katowice – Poland, on December 2018, parties to the UNFCCC[4] met with a main goal to put the challenging elements of 2015 Paris agreement into practice. The main focus was to agree how government will measure, report and verify their emission-cutting efforts and the Katowice "rulebook" will ensure all countries are held to proper standards and will follow their commitments by 2020 when countries must show they have met their set targets from decade age for cutting their emission and when they set new much tougher targets (Harvey, 2018). The UN's next meeting will be in Chile where final elements of Paris rulebook will be finalised and work on future emission targets begins.

[4]The United Nations Framework Convention on Climate Change is an international environment pact that developed to address the problem of climate change.

2.7 UNITED KINGDOM IMPLEMENTATION OF AGREED WORLD REGULATION

UK government introduced the National Energy Efficiency Action Plan (NEEAP) in 2007 in order to decrease level of emission in comparison with emission levels from 1990 in UK housing by 31% and this target was meant to be achieved by 2020 (Kelly, 2011). There are many organisations responsible for helping government achieve targeted emission such as the Energy Efficiency Commitment (EEC) in the UK which is responsible to oblige energy supplier companies to reduce their customer's carbon emission by providing customer's home efficient energy (Druckman and Jackson, 2008).

2.7.1 Electricity Market Reform

The government is dedicated to meeting the decarbonisation targets given by Climate Change Act 2008, to reduce the carbon emission level from on 1990 to 2050 by 80% and to generate energy from renewable at least 15% by 2020. In order to achieve that, in July 2011, the government introduced a new project named Electricity Market Reform (EMR) in which new investment was introduced in order to meet Britain's long-term energy and climate goals to deliver a secure, sustainable, low carbon electricity at affordable prices. In fact the EMR is a policy introduced by government to increase the motivation in investment in safe low-carbon electricity, to improve the safety of the country's electricity supply and improve the affordability for consumers. There are two main market mechanisms used by National Grid as a System Operator of Electricity Market Reform, and they are Feed-in-Tariffs with Contracts and Capacity Agreements to secure supply of electricity (DECC, 2012; Energy Act, 2013; Ofgem, 2018). According to Nationwide (2018) there are 4 main mechanisms behind EMR and they are provided below:

- Contracts for Difference
- Capacity Market
- Carbon Price Floor
- Emissions Performance Standards.

All four mechanisms are described in more details in this subsection.

2.7.2 Contracts for Differences

The Key Mechanism for Electricity Market Reform is known as Contract for Difference for renewable energy. The Contract for Difference (CFD) is a private contract between the Low Carbon Contracts Company, owned by Department of Business, Energy and Industrial Strategy and a low carbon electricity generation producer. The National Grid has been appointed as the delivery body for contracts for differences, responsible for publishing Contracts for Differences application guidelines and running the CFD allocation process (BEIS, 2017).

2.7.2.1 The CFD Contract

CFD delivers long-term stable price to low-carbon plant, by offering investors a lower cost of capital, resulting in a lower cost to consumers. CFD requires generators to sell energy into the market as usual, however, in order to diminish the fluctuation in electricity prices they offer a variable refill from the market price to a pre-agreed price. When the market price is more than pre-agreed price, the generator has to pay back the difference and protect consumers from over payment (BEIS, 2017)

2.7.3 Capacity Market

As part of Electricity Market Reform programme, Capacity Market was introduced by government through Department of Energy and Climate Change in order to protect the security of Great Britain's electricity supply throughout offering capacity providers predictable, stable revenue in an auction process in return of their delivery of energy at times of system needs. The first auction took place in December 2014 for deliveries beginning in October 2018 (National Grid, 2014; Ofgem, 2018).

All electricity generation technologies have a carbon footprint at some point; Coal and gas generation produces most harmful emission, while nuclear and renewable generation have lower carbon footprint. In renewable case most of the emission is caused indirectly by electricity generation for example during construction of technology (Ashcroft and Singh, 2016).

UK goal is to reduce the CO_2 emission by 80% by 2050 in comparison with the emission in 1990. There is a notable positive relationship between carbon footprint and electricity consumption (Craig et al., 2014). Rise in climate change temperatures, increases in the price of electricity and a rise in population number have made societies and governments more and more concerned with the importance of renewable sources for producing electricity, reduction of CO_2 as well as cost of electricity for consumers (Natarajan et al., 2011; HM Government, 2015). Therefore, renewable generation for domestic consumption is one of the main focuses in the UK and a primary reason for this research.

The Capacity Regulation established in 2014 requires Office of Gas and Electricity Markets (Ofgem) to provide an annual report on the Delivery Body's National Grid Electricity

Transmission plc (NGET) performance in relation to Capacity Market (CM) for the Secretary of State. On 18th June 2018, Ofgem published a report on CM, stating there is an unrealistic rise in complexity of delivering the CM annually due to increase in the number of capacity agreements. In addition to that, each auction has increased demand on NGET in relation to Capacity Market Agreement development (Keijonen, 2018).

2.7.4 Carbon Price Floor

One of the key elements of Electricity Market Reform in United Kingdom is Carbon Price Floor (CPF), which was introduced on 1st April 2013 to support the price of carbon at a level that drives low carbon investment that the European Union Emission Trading System has not achieved so far. In this case, a carbon price refers to the cost applied to carbon pollution. This is a method accepted by many economists for reducing global-warming emission.

The CPF itself imposes tax on fossil fuel used to generate electricity from Carbon Price Support rates that were set under the Climate Change Levy. The price floor paid by energy generators is achieved in two different ways:

i. The European Union Emission Trading System (EU ETS) allowance price
ii. The Carbon Support Price which tops up the EU ETS price

Carbon target price and Carbon support Price rates are confirmed by Treasury 3 years in advance of delivery for each budget and all the revenues from the CPF are reserved by the Treasury. The amount that Treasure earnt from CPF tax receipts in 2017 was approximately £1B (Helm, 2017; Hirst, 2018).

2.7.5 Feed in Tariff

Feed-in Tariff (FIT) scheme, was a subsidy introduced in April 2010 by Department of Energy and Climate Change in Great Britain to encourage people all around Great Britain to get involved in renewable and low-carbon energy. This scheme was introduced with the aim to help UK achieve EU 2020 renewable targets of 20% reduction on green gashouse emission and 2050 decarbonisation targets as well as promoting behaviour changes and help to develop local supply chains and decrease costs of energy (DECC, 2010; DECC, 2015)

The main focus of Feed-in Tariff (FIT) Scheme was to encourage placement of small-scale low-carbon electricity generation such as solar photovoltaic (PV), onshore wind turbine, hydropower of up to 5 megawatts, (micro-combined heat and power for less than 2 kilowatt) for domestic consumers. The FIT would provide cashback to suppliers on green energy produced according to their share in the electricity-market of Great Britain. Also, the European Commission granted state aid approval for Feed-in Tariff scheme for 10 years till March 2020 (DECC, 2018).

When FIT scheme started it had three elements of payments:

- Generation tariff; which paid to individuals, households, communities and businesses for every kilowatt hour (kWh) generated regardless of whether electricity used or exported to the local electricity network.
- Export tariff; that guaranteed market and price for generators export of electricity
- Consumer bill savings; using electricity on site and avoid electricity import for the life span of the equipment (DECC, 2010; DECC, 2018)

As a result of FIT scheme introduction, there was a noticeable increase of 99.7% of PV installation and important rise of wind turbine installation of 8% to capacity growth, which is shown in Figure 2-1.

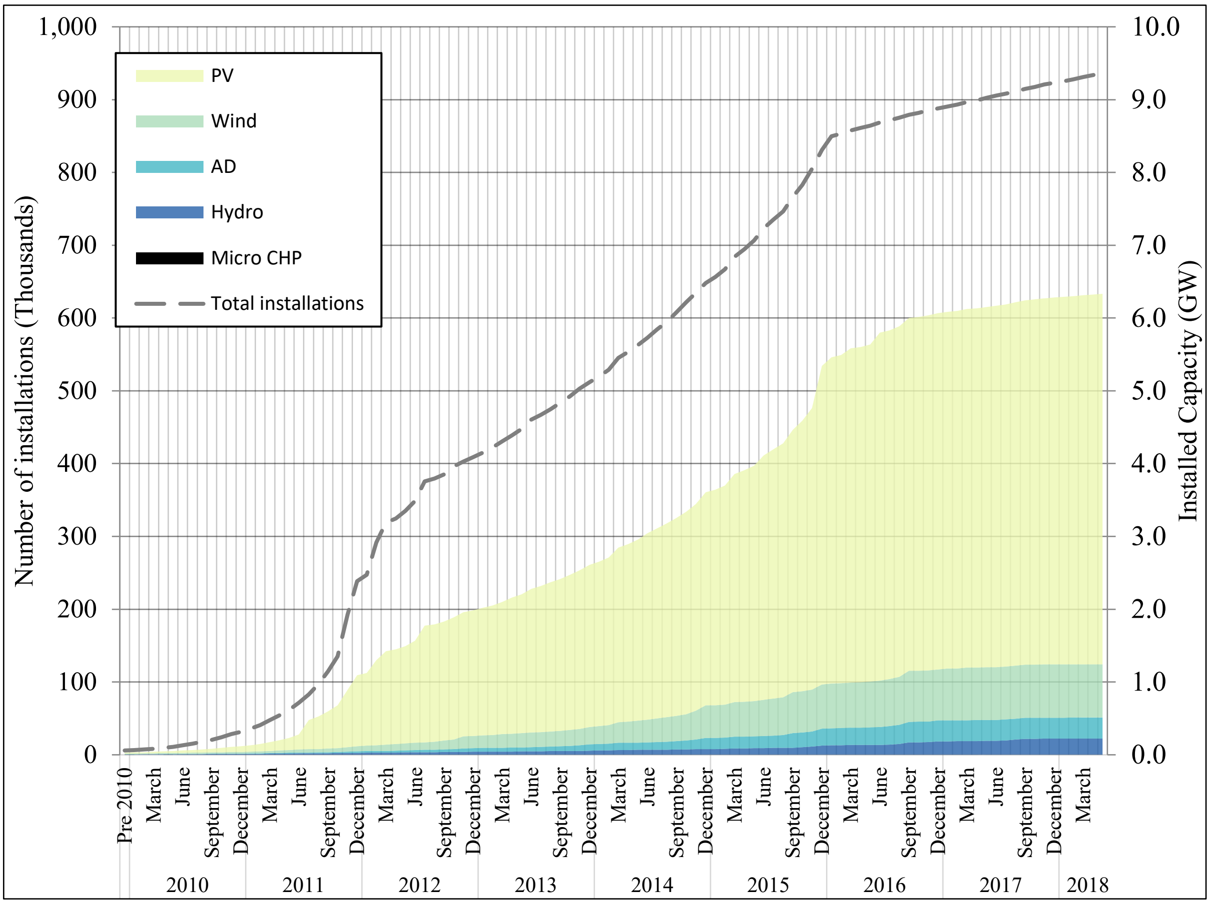

Figure 2-1: Feed-in Tariff Deployment: Calculative Installed Capacity by technology and Cumulative Number of Installation [Source: DECC, 2018]

However, from 2012 following reductions in tariff, the rate of growth slowed down to 83% of total installed (DECC, 2018). By looking at these figures, it is clear that FIT introduction has significantly met its objectives which as a result has increased number of individuals who took part in the low-carbon energy transmission. Alongside, fall in cost of buying and installing most of renewable technologies, specifically in the case of Solar PV has had a great impact for such changes (DECC, 2013).

Government's obligation given by European Commission is to review the Feed-in Tariff scheme every 3 years to make certain that it works along with its initial objectives and Government's goals (DECC, 2013). The most recent revision took place in August 2015. Following the introduction and implementation of FIT over the period of first four years, there has been several legislative and policy changes that made FIT more complex. Majority of these changes occurred in the 3rd year since its introduction and as a result all these changes led to little hesitation whether they helped to stabilise the scheme in long term. However, Ofgem tries to keep updating its guidance and hold events for its stakeholders as well as having an 'open house' policy in which they help licensee in any way they possibly can (Ofgem, 2014).

Figure 2-2 shows the change in average capacity of technology type from 2010 to 2014 (Year One = 2010, Year Two=2011, Year Three=2012 and Year Four=2014). Over this period there has been an increase in average installation size of both wind and photovoltaic technology from the 1st year while micro-CHP had a same level over the four years. Anaerobic Digestion and Hydro had a reduction in average capacity after second year as they tend to be on non-domestic properties (DECC, 2014).

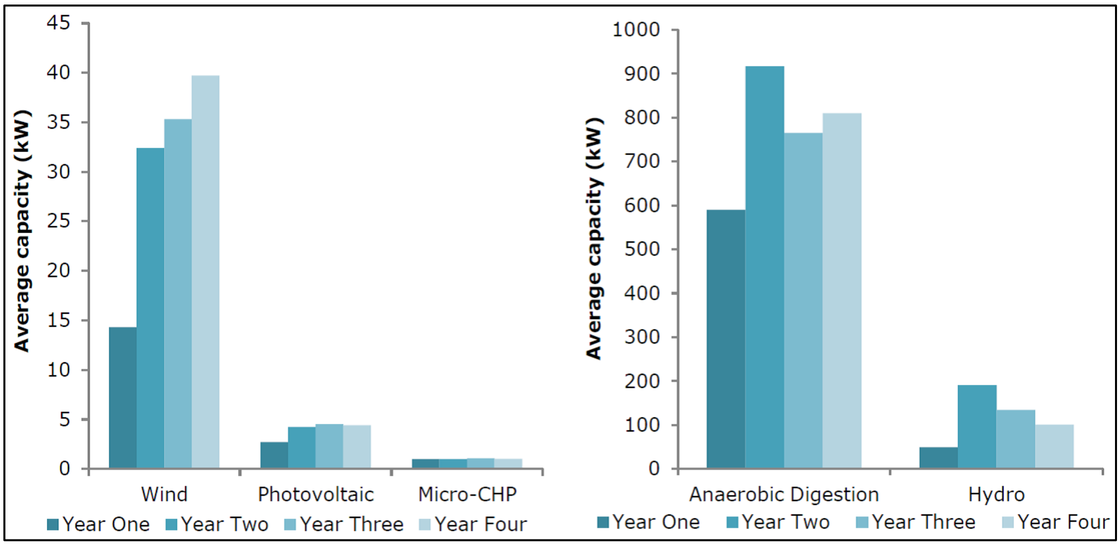

Figure 2-2: Average capacity by technology type after introducing Feed-in Tariff (Year One= 2010) [Source: DECC, 2014]

In January 2016, government decided on cutting around 65% of feed-in tariff to households with rooftop solar panel right after Paris climate conference in 2015 which led to significant fall in solar power. This was covered by media and Guardian published it in February and March 2015. There were 81 megawatts of generated power by small solar panels installed and this number is reduced to 21 MW for the same period in 2016 (Vaughan, 2016). Moreover, according to Department of Energy and Climate Change, it could as a consequence cut jobs related to installation of solar panels by more than half, as well as cause a bankrupt of several solar companies (Macalister, 2015).

Alongside government decided to end the Renewables Obligation that excludes new onshore wind farms from subsidy scheme from 1st April 2016 (BBC, 2015). Taking these changes into account and according to the Department of Energy and Climate Change, Britain is already within its target of 11GW to 13 GW of onshore wind with 13.8GW (Wintour, 2016).

Overall, Feed-in-Tariff had a great impact on renewable energy generation capacity installed from 2010. From introducing the FIT in 2010 there was a substantial increase in the capacity installed specially in the domestic sector. However, after government introduced the deployment caps in 2016 the actual rate of installation of new domestic capacity dropped significantly (Ofgem, 2017). Feed-in Tariffs has overreached its objectives in number of installation and capacity of installation launched back in 2010.

UK already has met its projection for 2020 and by August 2015 UK reached over 730,000 installations. In 2010 impact assessment on Feed-in Tariffs estimated 750,000 installations by

2020. Overall, the UK made a significant progress in building renewables industry with help of the Renewable Obligation and Contract for Difference regime. In addition to that introduction and implementation of the FIT in the UK had a significant influence on low-carbon economy and emission cut.

Figure 2-3 presents the annual carbon dioxide saving and cost of carbon saving from 2010 to 2017, showing a continuous rise in greenhouse gas emission saved due to the scheme with saving of 3.25 million tonnes of carbon dioxide in 2017. The implementation of FIT saved around 10.4 million tonnes of carbon dioxide up to the end of 2017, after 7 years of its introduction. Alongside the average CO_2 saving was 174.4kg per household as a result of the FIT (Ofgem, 2017).
However other objectives such as cost reduction and distribution still requires attentions despite the fact that the cost of buying and installation of most technologies such as solar PV has fallen significantly. The government is still concerned about the value for money and affordability within carbon reduction context (DECC, 2015).

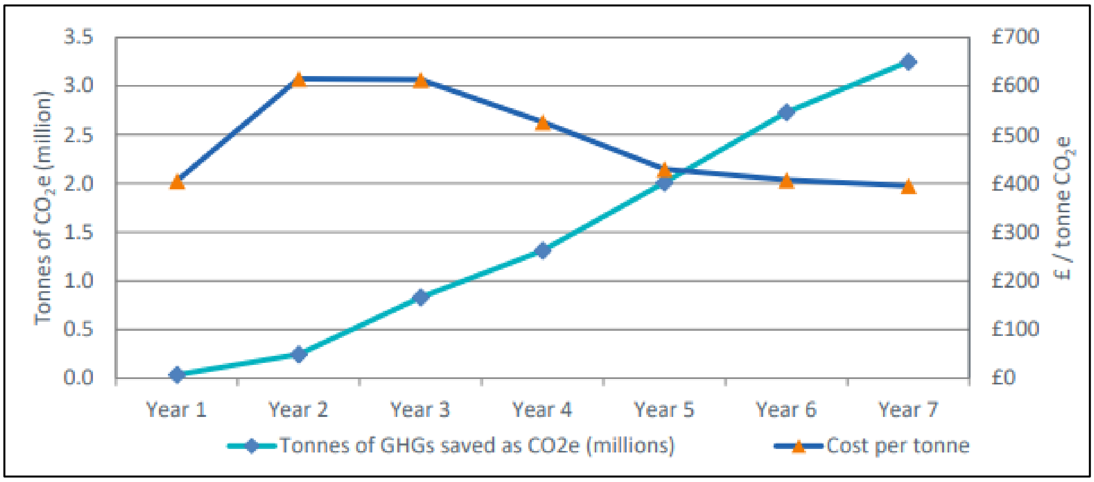

Figure 2-3: Annual CO2 Saving and Cost of CO2 Saving 2010 to 2017. [Source: Ofgem, 2017]

2.7.6 End of Feed in Tariff

On 19th July 2018, Department for Business, Energy and Industrial Strategy published the report called "consultation on the feed-in tariffs scheme" in which the government announced the closure of the scheme to new applications from 1st April 2019. Government explained that this decision is based on the success of the scheme from early years by generous subsidies and continuous fall in renewable generation technology and increase in affordability (DECC, 2018; Cuff, 2018). These changes will affect the capacity of renewables installation as well as the consumer electricity bills which discussed further in this thesis.

In this thesis the installation of renewable farms in 2011 was not affected by the implementation of FIT, however for more up to date results extra scenarios are added to the calculation, for a main purpose to examine how would Rate of Return on Investment (ROR) on renewable investment by community changes if installation is in 2020, after the closure of Fit.

2.7.7 Energy Efficiency

As mentioned earlier in this thesis, there was a significant fall in improvements in global energy efficiency in 2017, mainly due to weakening of efficiency policy and lower energy prices. The energy consumed per unit of economic output (energy intensity) has been decreasing since 1998 but the rate of fall slowed in 2017. Globally the energy intensity decreased by 1.7% less than the 2.3% registered on 2014,2015 and 2016 and it is now half of what was proposed and demanded by Paris Agreement.

The energy intensity is one of the main drivers of carbon emissions and it is necessary to understand the slowdown in the improvement of energy intensity in order to understand the future direction of carbon emissions. One of the key elements is the coverage of policies targeting energy efficiency and it has been steadily increasing from 14% in 2000 to 31.5% in 2016. However, the rate of improvement in energy intensity slowed in 2017 due to extensions to existing policies, rather than new policies in uncovered countries and sectors. Another significant contributing element is the rigidity of these policies. In 2016 the stringency of these policies slowed with increase of just 0.3%, therefore governments have to take a strategic approach to energy efficiency (IEA, 2018).

2.8 Electricity generation in UK

This thesis is focused with community electricity generation for the rural community by renewable sources. In order to make an appropriate evaluation of electricity generation by renewable sources, it is necessary to have a clear understanding of renewable sources and technology used to date. Introduction to electricity generation in the UK is provided in this chapter. Although renewable generation is focus of this work, a brief description of how electricity is generated in the UK and types of organisations who are part of this process is presented including the share in a total production.

This section presents the history and complexity of generating electricity with main sources of gas, nuclear, coal, renewable and oil. The source usage over the years is provided and it is important to be understood in detail. The government plays an important role in seeking the economic benefits and reduction in greenhouse gas emissions while generation electricity. The aim from the government is to ensure low price for customers which will enable them to ensure safe targets set by EU carbon reduction emission.

2.8.1 Electricity

One of the key driving forces of the economic development of societies is electricity generation. In the 1870s and 1880s Thomas Edison and Werner von Siemens had the greatest impact to electrify the world. Electricity from dc systems could power factories and small downtown areas but did not reach, nowhere near 95% of resident's coverage. The solution to power whole cities were to generate the power from one place and transit it to the city. This was done with several main steps;

1. Alternating Current (AC): First developed in Italy and Germany and they quickly proved to be the best method for harnessing electric power
2. Three phase power: Germany was the first country to develop the three phase AC power in 1887 and made its major world launch in 1891 at the International Electro-Technical Exhibition.
3. Transformers: Power voltage is controlled by transformer which are very important part of the system. Austro-Hungary and England were the first to develop the transformer, with the first fully developed design coming from William Stanley in Massachusetts.

2.8.2 Privatisation of Electricity in UK

Transferring public-sector enterprises and other activities and assets to private sector was Thatcher's government principle, which took place in 1990. In late 80s rise in demand for infrastructure services made Government to announce its plan to move the electricity industry from the state to private sector in which the Central Electricity Generating Board (CEGB) split into three generating companies and one Transmission Company.

One of the most complex transformations in public sectors was privatisation of the electricity supply industry in England and Wales, in which major changes in the structure took place as well as its ownership (Green 1991; Chesshire and Surrey 1988; and Ince 1988). The Privatisation of the UK electricity supply industry initially took place to minimize any opportunistic behaviour in the industry and to make the electricity market competitive. The competitive market would productive efficiency and stimulate allocative, improved services and lower prices (Ince 1988; Zhang and Lirkpatrick, 2004; Plane, 1999). In addition, as stated in White Paper 1988, the main purpose of privatisation was reducing cost and price of electricity for consumers (Domah and Pollitt, 2001) and rising market incentives (Caves, 1990). Although competition was not strong enough at the beginning as government hoped (Arrowsmith, 2003), a decade later the result of privatisation experience shown improvement in performance, productive efficiency, as well as profitability and fall in real price of electricity (Nestor and Mahboobi, 2000; Branston, 2002). Currently electricity is provided by a commercial supplier (a 'Generator') through National Grid systems. National Power was a large company that consisted of 60% conventional stations, and PowerGen was a smaller company with the remaining conventional stations. Meanwhile, nuclear assets remained under a new government company called Nuclear Electric. (Domah and Pollitt, 2001) Moreover, CEGB's transmission grid was moved to a company called National Grid Company that provided electricity to 12 areas known as Regional Electricity Companies (RECs) which were responsible for distribution and supply of electricity to customers (Branston, 2011). Price of electricity continuously changes due to change in factors of production and demand. However, there has been an increase in price of electricity over time.

2.8.3 Pricing Electricity in United Kingdom

Electricity is first sold to energy suppliers before getting to consumer's homes. Each of these energy suppliers have their team of energy traders or analysis to monitor price movement in the gas and electricity market throughout each day. As a result of that, price of electricity and gas today will be different from what is bought for delivery next day, and these prices will vary for energy priced for delivery next week, next month or next year. These price variations depend mainly on supply and demand of energy, therefore if it is cooler next week demand for energy rises and as a result prices for energy increases for matter as such electricity or gas that household use today could have been bought by suppliers anytime between now and as far back as five years ago (Essex, 2010).

There is a "time of use" tariffs in which the price of electricity consumption depends on the time at which it was used. In this tariff, the time divided into peak and off-peak time. Filippini (2011) states that pricing policy in long run, is an effective way of shifting consumption of electricity to off-peak from peak time in order to have a conservation consumption through the day.

2.8.3.1 Day ahead Market

Day ahead price is a reasonable tool of the short-time electricity price in the UK. However, suppliers often buy most of their electricity months or even years in advance (Ofgem, 2018). The figure 2-3 presents the Nord Pool day ahead price market. It is clear that the electricity price on 25th September is different from the next day prices due to daily changes in factors such as gas prices, change in weather. The electricity on 1st October 2018 sold for £60.36 to deliver on 2nd October (Nord Pool, 2018).

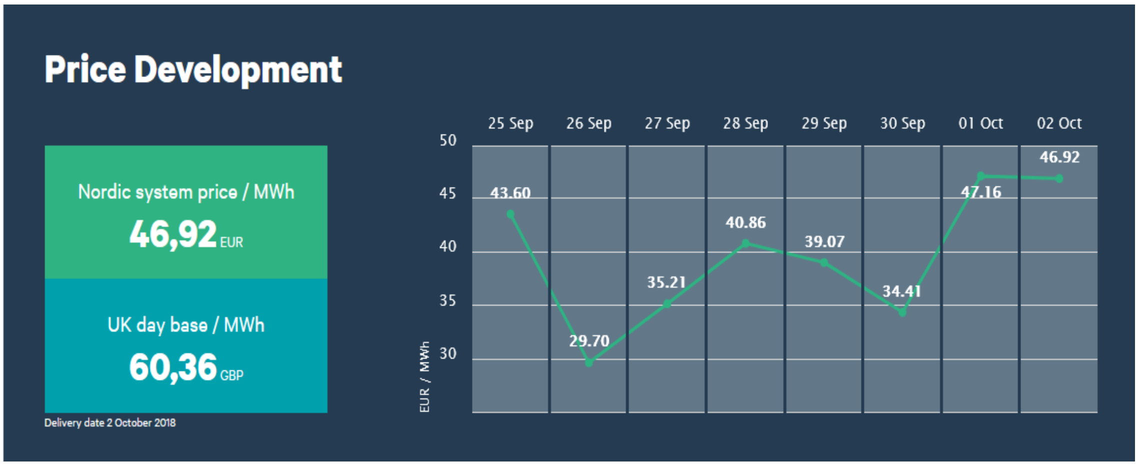

Figure 2-4: Nord Pool Day ahead Market Price [Source: Nord Pool, 2018]

2.8.3.2 The main factor of electricity price in UK

There are many factors that influence electricity prices and one of them is Gas prices. Gas as one of the main sources of producing electricity has a significant effect on price of electricity. Other factors are demand of electricity, change of the season and weather. For instance, in winter as days are shorter electricity consumption would be increasing. Also, during holiday season in (i.e. December) there is a clear sign of increased consumption. On the other hand, in summer as days are longer and weather gets warmer the consumption decreases, but that changes in line with technology used for cooling the air and so on. Overall, in this thesis, gas prices and production, consumption of electricity and weather considered as main influencer on electricity prices.

2.8.3.2.1 Gas

The main influence on Electricity price in the UK is related to the fluctuation of price of gas. Considering that gas-fired generation is usually the main source of the electricity generation, there is no surprise for such strong relationship between gas price and electricity price. The figure below shows the forecast for price of gas in the United Kingdom in which the price of gas is expected to rise from 2017 with 34.6 pence per year to 43.9 in 2018.

However, there would be a steady fluctuation in the prices from 2018 to 2023 from the Statistics. The rise in the price of gas is in line with reduction of gas production in the UK. (Statista, 2018).

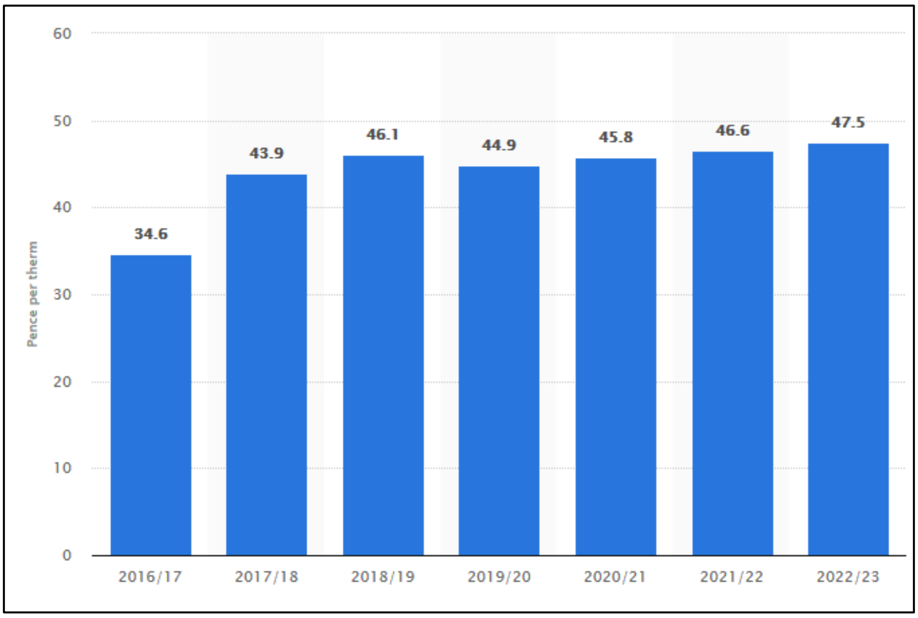

Figure 2-5: Forecasted gas prices in the UK (pence per therm) [Source: Statista, 2018]

Recall, the change in gas prices will have a direct effect on electricity prices as presented in figure 2-6. There has been a general decrease in volatility of gas and power prices in recent years due to closure of old gas, oil-fired plants and low level of investment in new gas plants. However, an increase in gas and power volatility during winter 2016 and 2017 was observed. In March 2018, gas price reached its highest price in 7 years as both demand and supply of gas increased (Ofgem, 2018).

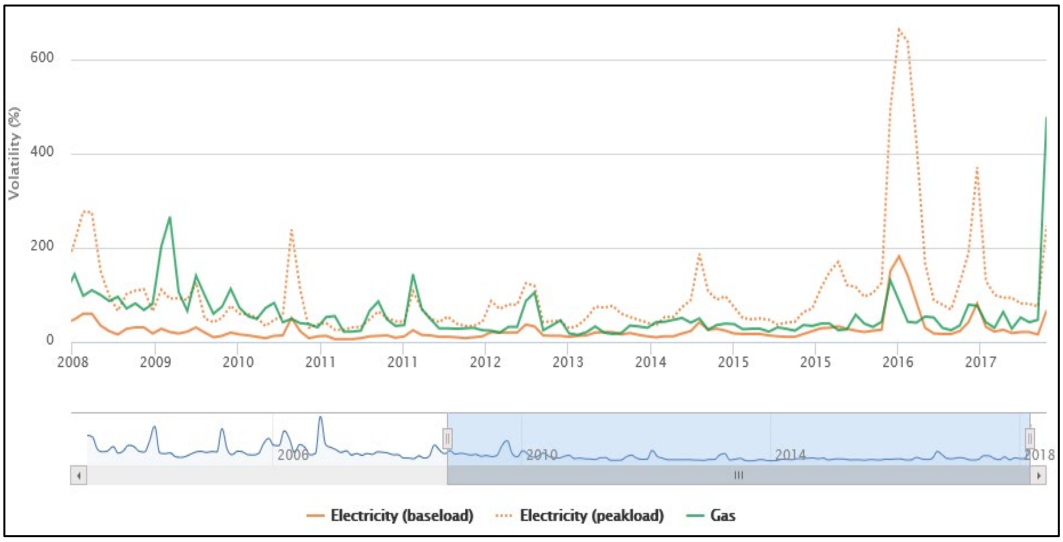

Figure 2-6: Price volatility of gas and electricity: Day-ahead contracts (GB) [Source: Ofgem, 2018]

2.8.3.2.2 Weather

Another factor that affects the electricity price is change of the weather circumstances. Changes in the weather influences the electricity prices mainly via customer demand. In a cold weather electricity consumption may rise and that raises the electricity prices due to significant increase in demand. Similarly, as in summer the ambient temperature is increased, and days are longer electricity demand decreases and that leads to lower electricity prices as a result.

Figure 2-7 shows the monthly average price of electricity in UK's related to wholesale market for delivery the next working day for the period of five years from 2010. The highest price was £62.9 Mw/h on 1st March 2013 which was the coldest march in the UK, since 1962, which was dominated by strong winds, late-season snowfalls and low temperature and dry weather (Met Office, 2013; Ofgem, 2018). One of the lowest prices noted was £35.46 MW/h in 1st July 2014 with mean ambient temperature of 16.3°C which was 1.2°C above the temperature measured in 1981-2010 (Met Office, 2014). Yet the lowest price was £35.07 MW/h in December 2015 that was a record-breaking month according to MetOffice with warm and moist tropical air mass and it became warmest December in Central England (Met Office, 2015).

Figure 2-7: Electricity prices: Day-ahead baseload contracts-monthly average (GB) [Source: Ofgem, 2018]

In comparison to the other European countries for domestic electricity prices, the UK is on 9th place making it in top 10 countries with high electricity price although its gas prices are ranked below average among other European countries.

2.8.4 What will future look like

Global warming will impact electricity market through electricity demand and supply. Considering estimated rise in temperature globally by +2 °C, this will increase cooling electricity demand and reduces heating electricity demand. However, in EU according to a study by Damm, et al. (2017) demand for cooling systems in most of European countries considered in their study is relatively small compared to heating electricity. But for countries such as Italy, Spain, Hungary and Croatia with warm summer's significant fall in heating demand is expected in comparison to a rise in cooling demand. Changes in cooling and heating is likely to decrease the electricity demand in northern Europe compare and increase it in southern Europe. Supply is likely to fall for countries where much of electricity is generated from thermal power. However, it is suggested that energy policy would impact electricity prices far more than climate change (Mideksa and Kallbekken, 2010; Damm, et al. 2017).

Furthermore, due to a fall in gas production, rise in gas prices and increase in the demand of electricity due to larger population it is expected that electricity prices will increase. Also, Perez-Linkenheil (2017) estimates the increase of 25% in EU population by 2050. Moreover, in supporting the prediction of rise in electricity prices in future Statista (2018) presented the figure 2-9 which shows the projected average prices of electricity for the final demand in the UK to increase from 2020 with €115 per MWh to €178 MWh in 2025.

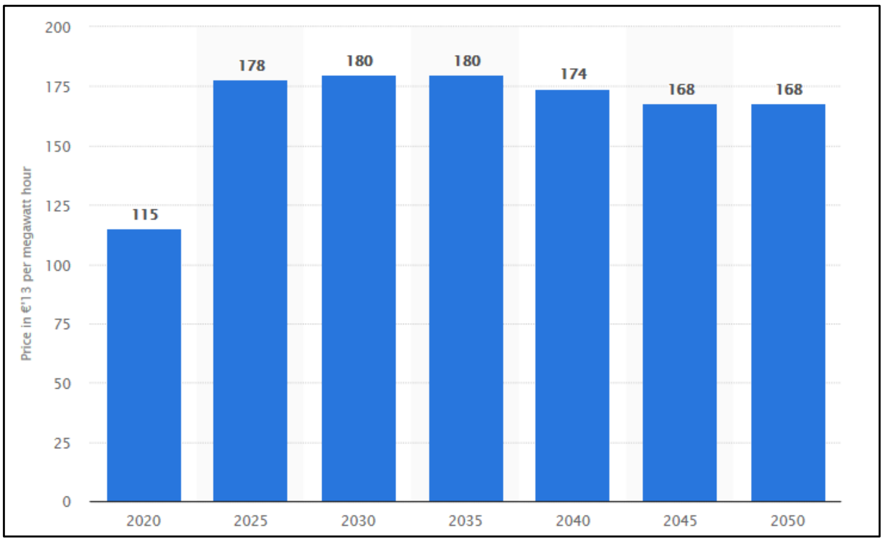

Figure 2-8: Projected Average prices of electricity for final demand in the UK (in €13 per MWh) [Source: Statista, 2018]

2.8.5 National Grid

In England and Wales the National Grid owns and manages the electricity grid that connects energy and is responsible for delivering reliable, efficient and safe electricity and balancing supply with demand on a minute-by-minute basis. Scotland has its own transmission network which works in a similar way.

UK electricity industry contains four main sections:

1. Generators- where electricity is produced from gas, coal, oil, nuclear power plants, solar farms, wind farms or any other sources.
2. Suppliers- who supply and sell electricity to around 50 million homes and businesses in the UK. The big six UK energy suppliers are: British Gas, EDF Energy, E.ON, Npower, Scottish Power, and SSE.
3. National Transmission network- this section is owned and managed by National Grid.
4. Distributors- who are the connection between national grid and consumers. They own and operate the towers and cables that bring electricity to communities. Distributors are different from suppliers, because they aren't involved in sales of the electricity to consumers (BBC, 2015).

2.8.6 Electricity Supplier

Supplying electricity involves buying and selling to customers as well as customer services, billing and collection of customer accounts. There are six major energy suppliers in UK, the “Big-Six”: British Gas, Npower, EDF Energy, and E. ON (PowerGen), SSE and Scottish Power. Each of these suppliers buys and re-sells energy in a bid to secure lower wholesale price to attract customers (DECC, 2015). In addition to the big six, there are more than 60 suppliers in the UK such as, Bristol Energy, and Engie, iSupply, Green Star Energy, Good Energy, Bulb and more. Although the big six supply the most of the energy to domestic households in the UK, but there are many new suppliers such as bulb, which supplies 100% renewable electricity with far cheaper prices than big six suppliers.

Figure 2-9 illustrate the standard electricity deals for households in the UK in 2019, as presented Bulb is cheaper than Bix Six and many other supplier –shown in grey-. British Gas and Scottish Power are the most expensive suppliers with £1249 standard deals followed by npower standards £1173, furthermore, Bulb is £273 cheaper than Big Six standard deals.

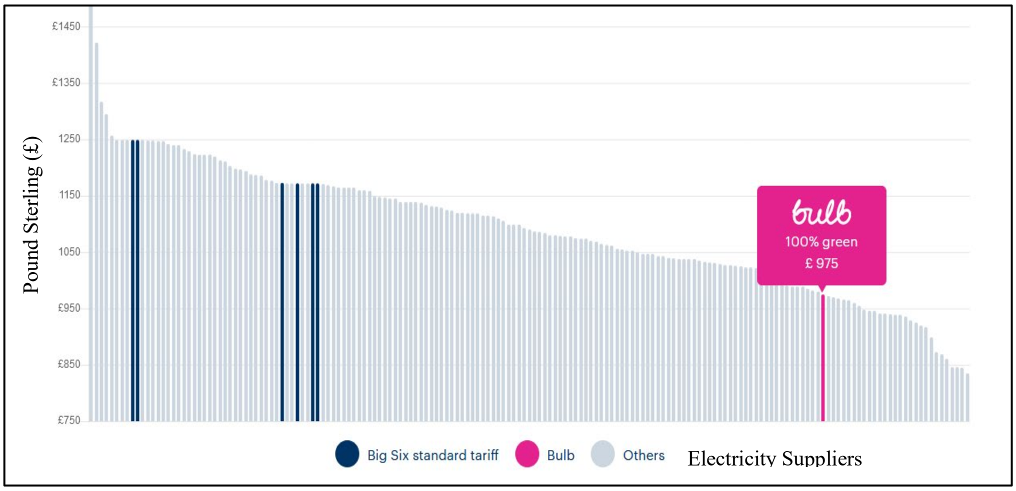

Figure 2-9: Bulb standard deals compare to Big Six [Source: Bulb, 2019]

2.8.7 Diversity of UK’s Electricity Supply

As mentioned in the previous subsections, the UK has many different sources of electricity generation and the main difference between them is in their-capacity. The main capacity sources for 2015 are illustrated in Figures 2-10 and 2-11.

As shown before in Figure 2-10 the coal (black) and gas (blue) sites were distributed evenly while all the nuclear sites were on the coast for easy access to the cooling water. As illustrated Yorkshire area has the most coal sites with three large power stations. Gas site on the other hand are mainly near import terminals and gas pipelines.

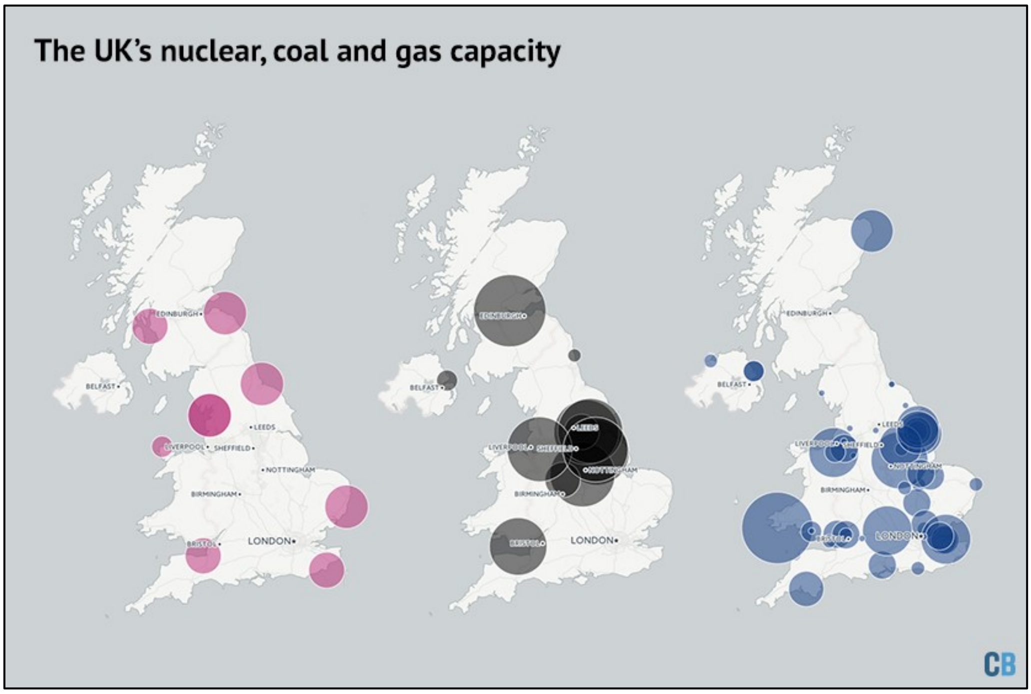

Figure 2-10: UK's nuclear, coal and gas capacity in 2015. [Source: Evans, and Pearce, 2015]

Figure 2-11 presents the UK's hydro, wind and solar capacity. Major hydroelectric generation was in Scotland and Wales where building dams was far more convenient than in any other region. The largest circles are the pumped storage that act like giant batteries for the grid. Windfarms are mainly near coastline and higher ground were wind speeds are higher. On the other hand, solar farms are mostly concentrated in south where irradiance rates are higher. In this map the small rooftop solar generators are not included.

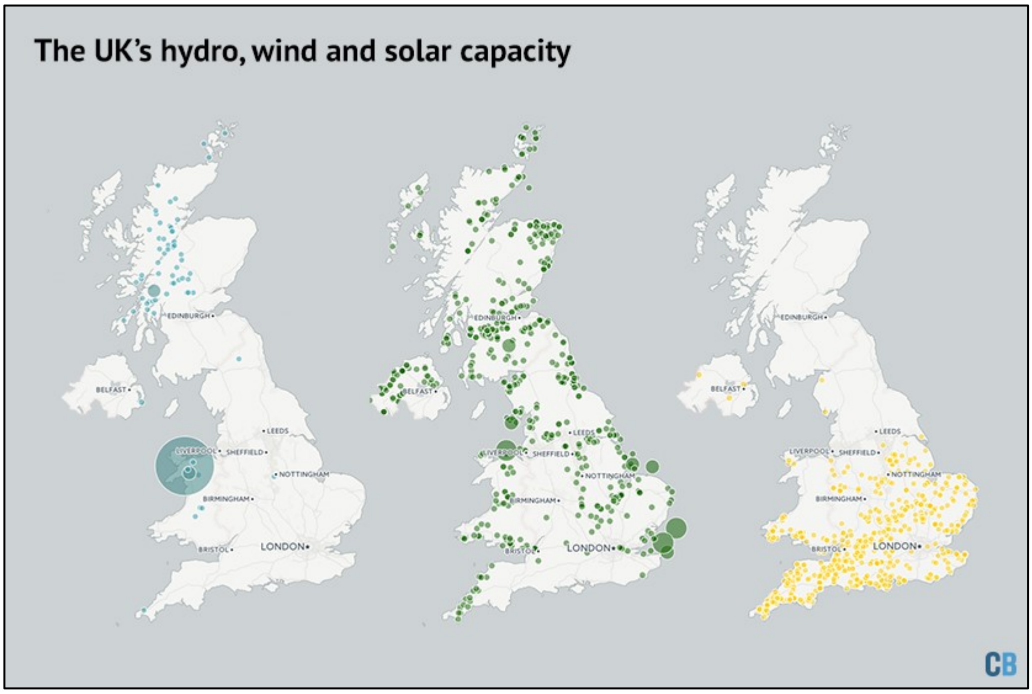

Figure 2-11: The UK's hydro, wind and solar capacity in 2015 (From left to right) [Source: Evans, and Pearce, 2015]

Figure 2-12 presents interesting shift in the type of sources used to generate the UK's electricity. The black bars show the plants of coal built in 1960s. Also, in early 1970s first nuclear sites built in the UK (purple). From 1990s new gas-fired plants were added to the UK's electricity generation (blue) and as it shows in the 4th graph with green bars there was a boom in renewable capacity from2000s. Later in this thesis the research conducted reveals changes in the capacity of these sources by 2018.

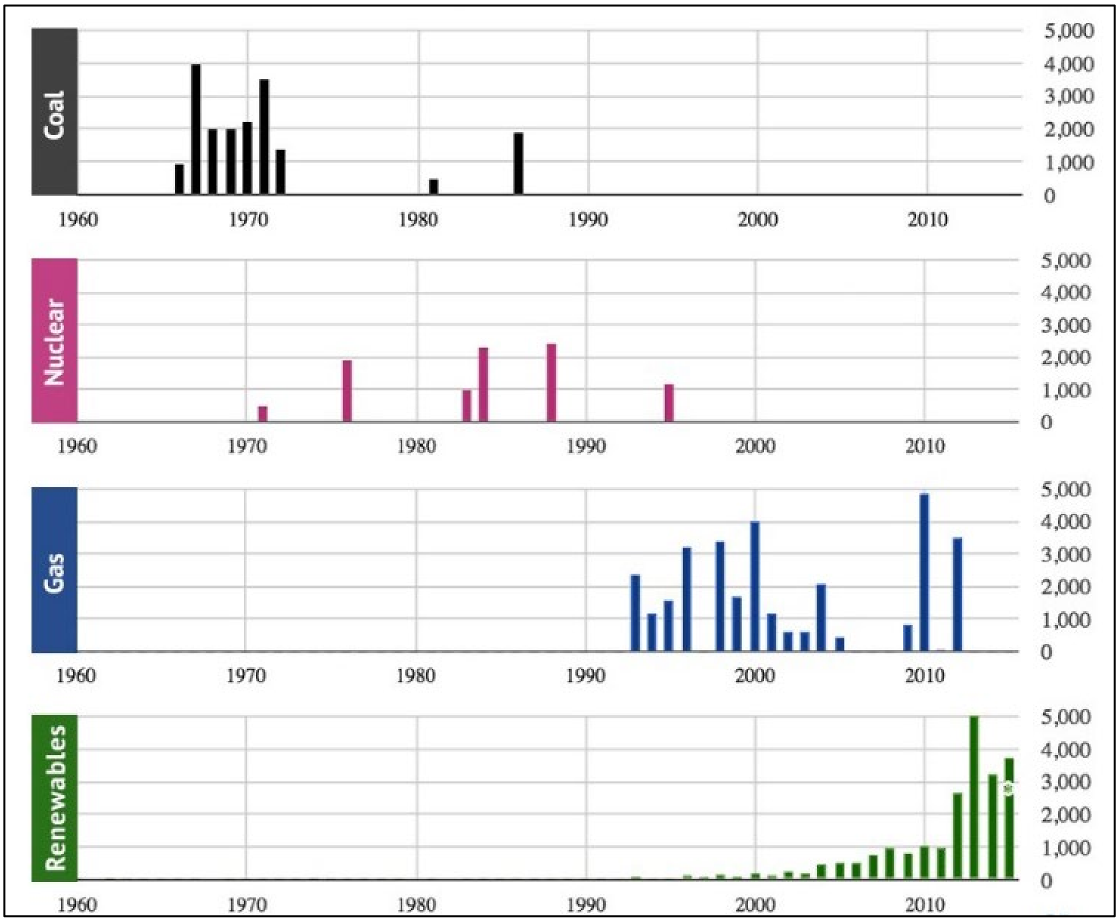

Figure 2-12: UK 's annual capacity in MW from 1960 to 2010 [Source: Evans, and Pearce, 2015]

2.9 PROGRESS IN RENEWABLE ENERGY

Recall, the European Union has set a target of producing 20% of its energy from renewable sources by 2020. In addition to that, an individual target for each EU country has been set with taking their size, their wealth and their renewable energy capacities into account. UK's share of this carbon reduction is to have 15% of energy consumed from renewable sources by 2020. To achieve this target, 30% of electricity, 12% of heat and 10% of transport energy should come from renewable sources to meet overall previously set target (Ashworth-Hayes, 2015). UK has exceeded its third interim target; renewable energy generated in 2015 and 2016 is 8.5% against its target of 7.5%. In UK, renewable electricity represented 25% of total generation. In 2016, nearly 9% of total energy consumption came from renewable sources; there was a 0.07% increase since 2015 (DUKES, 2017). Over the last few years there has been a significant improvement on renewable electricity generation. There are many energy suppliers in the UK such as Bulb, iSaving, Green Energy Supply and Ecotricity that supply 100% renewable electricity (Electricity info, 2019).

2.9.1 United Kingdom

Overall, there has been a significant increase in renewable generation capacity in the United Kingdom since 2010. This growth in electricity generation from renewables varies for difference sources. For example, onshore wind is the main source of electricity generation with significant growth from 2010 with 7.2TW per hour to 29.1 TW per hour in 2017. Even though 2018 was a lowest year for new onshore installation since 2008, the amount of the generated from the wind was much higher than any other power generation method. On average in the UK average power rating for wind turbine in 2018 was 2.2MW. After that, offshore wind stands with 20.9TWh in 2017. In contrast, there is a progress in solar generation to some extent, from 2011 to 2016 solar had a 38% increase in market share and this growth was only 11% in 2017 compare to the previous year with 11.5TWh. Meanwhile, biomass, experienced the same dramatic increase from 2011 especially after former UK's largest coal plant, Drax converted half of its unit to biomass (DUKES, 2018; IRENA, 2018; Komusanac and Fraile, 2018; Timperley, 2018).

2.10 CO2 EMISSION MANAGEMENT

Carbon footprints are sensitive to number of factors including both technology operating conditions and country where it has been manufactured. All electricity generation technologies at some point in their lifetime release greenhouse gases and mainly CO_2 which as a result has presence of carbon footprint. However, some generators have a smaller carbon footprint than others. For instance, fossil fuelled generation emits high greenhouse during its plant operation while nuclear and renewables generation generally have low carbon footprint which is what makes them more acceptable and compatible with number of new policies. Most of emissions in nuclear and renewables case scenarios are caused indirectly, such as during the construction of the technology itself (Jardine et al., 2005).

To calculate the carbon footprint, greenhouse gas emission is converted into standard units based on the relative radiative forcing and global warming potential (GWP) of each gas. The GWP of a gas species is the cumulative radiative forcing that occurs from the instantaneous release of 1kg of a trace gas compared to 1kg of a reference gas (Jardine, Boardman, Osman, Vowles and Palmer, 2005).

There is a notable positive relationship between carbon footprint and electricity consumption (Craig, Polhill, Dent, Galan-Diaz, Heslop, 2014). Rise in climate change, increases the price of electricity. Rise in population have made societies and governments more and more concerned about the importance of renewable sources for producing electricity, reduction of carbon dioxide as well as cost of electricity for consumers (HM Government, 2015).

2.10.1 UK's Current CO_2 Emission Status

The United Kingdom is a global leader in CO_2 emission reduction and ambitions set out in five-year carbon budgets. The carbon price floor has supported coal to gas shift that combined with a significant investment in offshore wind and solar PV, is transforming the UK power sector. As presented in Figure 2-13, CO_2 emission has fallen significantly from 1990 with 549.30 Mt to 371.14Mt in 2016 (IEA, 2018). However, in 2017, the changes in emission trend were noticeable for selected regions. There is a strong warning for global effort for cutting emissions and climate change, and it proves that current efforts are insufficient to meet the Paris Agreement objectives (IEA, 2018).

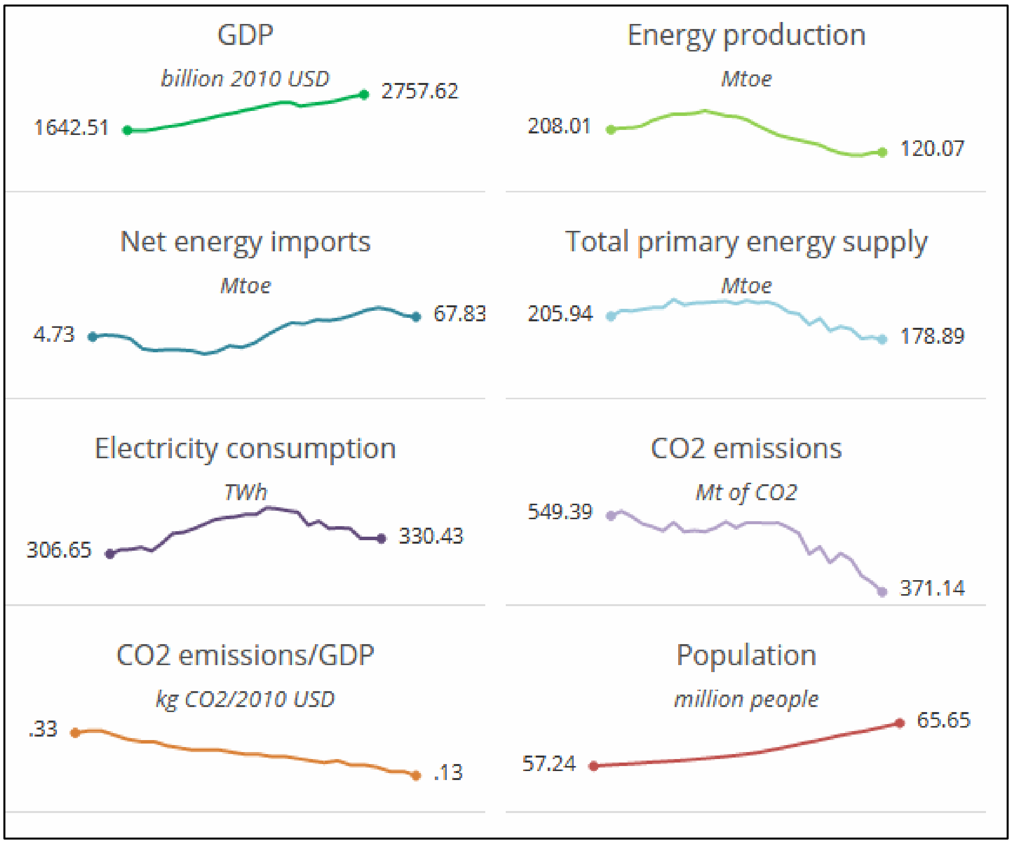

Figure 2-13: Key stats for UK 1990-2016 [Source: IEA, 2018]

The carbon emissions in the UK have decreased since 1990 by 38% and the largest contributor to the fall in CO_2 emission between 2016 and 2017 were energy supply mainly as a result of changes in the mix of fuel being used for electricity generation from coal to gas and more investment on renewables. Lon gannet and Ferrybridge C two coal fired power stations closed in 2016, and in 2017 50% of electricity generated were from low carbon generation[5]. Moreover, in 2017, energy-related CO_2 emission in UK reached the lowest level since 1888. This rapid reduction was achieved as significant investment on renewable generation (IEA, 2019).

2.11 Progress towards 2030

As part of the data monitoring, the European Environment Agency (EEA) is conducting assessment of the progress of all the members in order to inspect the level of achievement of the climate and energy targets. The progress towards international commitments regarding greenhouse gas (GHG) emissions within the EU is presented in the Figure 2-15. The target of 20% reduction in GHG by 2020 is set in comparison with 1990 level which was around 4,573.09 MtCO2e. This is around14% reduction compared with 2005 level. In 2014 UK as one of EU leaders agreed a 2030 target of at least 40% domestic reduction in GHG to emissions that is around 3,429.83 MtCO2e, compared to the 1990 level (European Commission, 2018; EEA, 2018; Sporer, 2018). By 2030, UK expects to increase its share of renewable more than 50% that will have direct impact on UK's CO_2 emission targets for 2030.

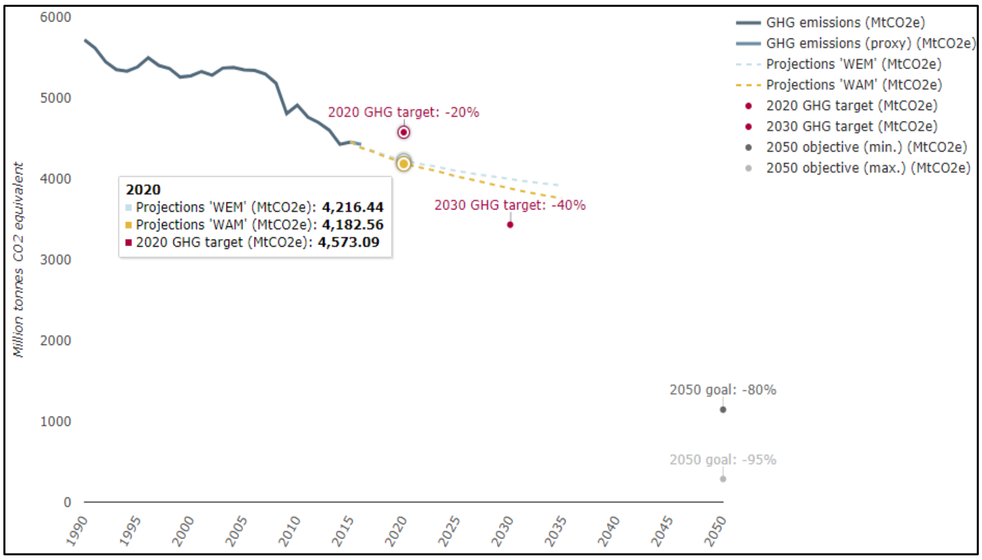

Figure 2-14: Greenhouse gas emission trend, projections and targets in the EU [Source: EEA, 2018]

[5] Low carbon generation are; wind, solar, hydro, bioenergy and nuclear.

UK performance shows a promising future for meeting CO_2 emission targets for 2030 and onward. As presented in the Figure 2-16, renewables are predicted to have the majority capacity of electricity generation, 67 Gigawatt out of 139 Gigawatt in the United Kingdom by 2035. This will significantly help UK to achieve its 2030 targets and more. Moreover, it is predicted that there will be no generation from coal from 2025 and very close to zero for oil around the same time (Statista, 2018). This will make gas and renewables the main sources for generating electricity and renewables will become more in demand. However, these changes will affect the price of renewable technology and associated land and costs with them which will be examined in this research.

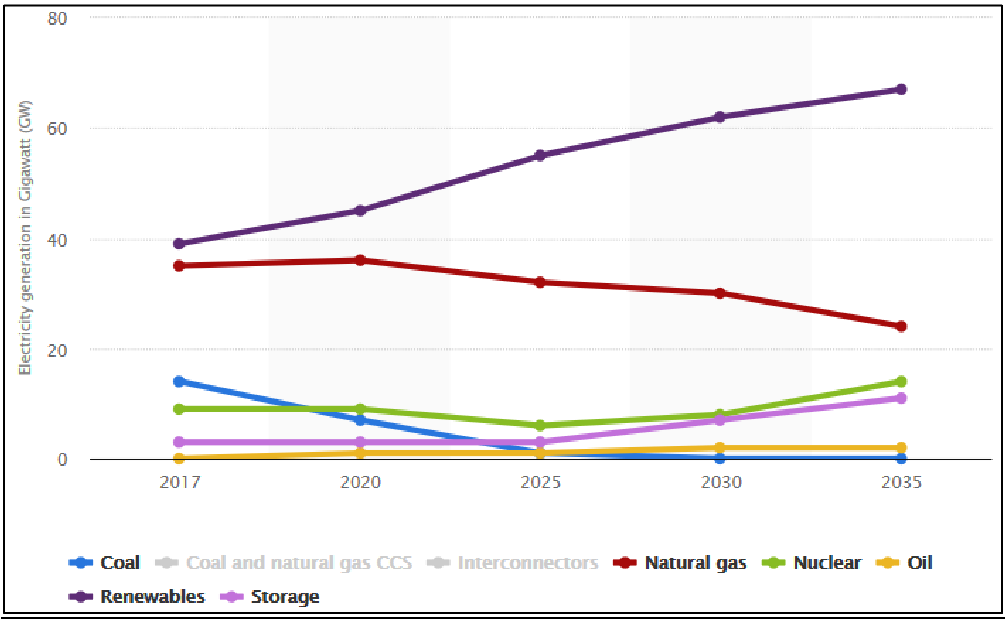

Figure2-15: Total electricity generation capacity projections of main power producers in the UK [Source: Statista, 2018]

2.12 COST OF RENEWABLE TECHNOLOGY

The cost of renewable technology has fallen rapidly since 2000 with soar of solar and wind generation. Nowadays, power generation from renewable sources and technologies become significantly competitive with less cost than fossil fuel or nuclear power. Solar PV experienced module price reduction of around 80% since 2010 and onshore wind turbine price fallen around 35% since 2009 cost reduction followed by increase in performance improvement for both solar PV and wind turbine. The cost reductions result from three key elements: improvement in technology, competitive procurement and increase in project developers (IRENA, 2017; IRENA, 2018).

By 2020, electricity from renewable will be cheaper than from most fossil fuels. Based on latest auction and project-level cost data, global average cost of electricity from solar PV and wind turbine could fall to about $0.05/kWh for onshore wind turbine and $0.06/kWh for solar PV. Fall in total installed costs are driving falls in Levelised cost of energy (LCOE)[6] for solar and wind power technologies to a varying extend (IRENA, 2018).

Furthermore, Bloomberg New Energy Finance (BNEF) analysis reports that the price of PV solar panel is expected to decrease by 34% in 2018 followed by another 10% to 15% reduction in 2019. Fall of PV solar panel prices is mainly driven by sudden withdrawal of support for the nation’s solar PV market which reduced price of PV solar module in China which in return changes the price of PV panels in many parts of the world (Roselund, 2018; UN, 2018).

According to Jack, (2019), wind power has made it possible for the UK to consider a zero carbon target by 2050. As presented in Figure 2-16, both offshore and onshore wind turbines average auction prices reduced over time and expected to fall more by 2022.

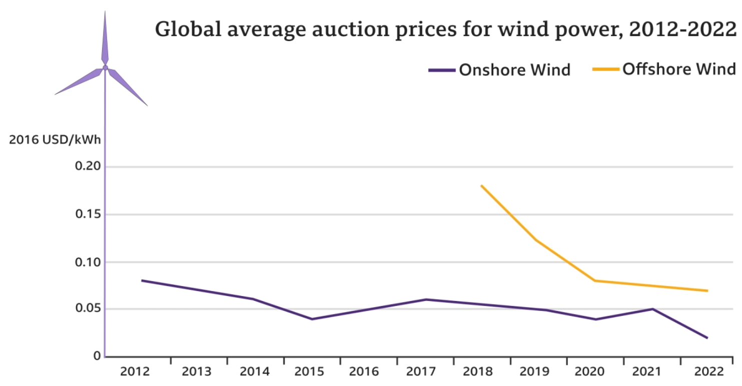

Figure 2-16: Wind Power Global Average Auction Prices, 2012-2020 [Source: Jack, 2019]

[6] LCOE also known as Levelized Energy Cost is the present value of the price of the produced electrical energy considering the economic life of the plant (Ragheb, 2017)

2.12.1 Discount Rate

The investments made in energy sectors are usually long-term projects with uncertainty arising from changes in political and legal environment and rapid technological developments. In the case of discounted cash flow analysis (DCF) used for assessing the economic efficiency of investment, the discount rate is the only parameter showing investors' uncertainty and it increases with the increase in the risk assessment of the project (Saluga and Kaminski, 2018). The discount rate of a project is an important element for all investors as it reflects a fair value for the project, and it influences the economic efficiency of investment projects. Discount rate should be applied for the future although it is estimated on the current data (Zaman, 2017).

In 2018 around $253 billion has been invested in utility-scale renewable energy projects, 10% more than in 2017 with solar and wind in terms of capacity. It is expected that the renewable energy market keeps its high growth in investment as project costs continue to fall. In United Kingdom renewable energy sector grew rapidly between 2010 and 2015 due to energy market reform which offered feed-in-tariff, Renewable Obligation Certificates and other form of incentives which were offered to clean energy projects (Freyman and Tran 2019; Garcia-Gusano and Espegren, 2016). In UK the discount rate fluctuated between 5% and 10% in energy investments and in 2017 it was stable at 6% for solar, 6.5 for onshore wind and 7.5% for offshore wind. In this research effect of change in discount rate of return on investment (ROR) and Levelized cost (LCOE) of electricity from onshore wind and solar is examined. The 5% discount rate for project in 2011 considered and possible changes for future projects tested at 7% and 10% followed by presenting the effect of changes of discount rate on ROR and LCOE.

2.13 CASE STUDY – SCOTLAND

Recall, to test a research model developed (presented in Chapter 5), a case study should be selected. In 2017, Scotland with 7.5% of the total UK population had 68% of its power from renewables with 73% of that coming from wind (Elliott, 2019). Purpose of this research is to evaluate economic viability of renewable generation for rural community and as Scotland is well-known for having large number of rural communities, Scotland were chosen as an area of study of this research. As Figure 2-17 illustrates the majority of lands in Scotland are categorised as very remote rural which have very little services. According to Scottish

Government (2018), rural Scotland is defined as settlements with a population of less than 3,000. Rural communities in Scotland are divided into 2 sections:

1. Accessible rural: those with less than 30 minute drive time to the nearest settlement with population of 10,000 or more.
2. Remote rural: those with a greater than 30 minute drive time to the nearest settlement with a population of 10,000 or more.

These definitions form part of the Scottish Government Urban Rural Classification are presented in the Figure 2-17. North-East of Scotland is mainly rural communities, whether it is accessible or remote community with reasonable sizes of land surrounded.

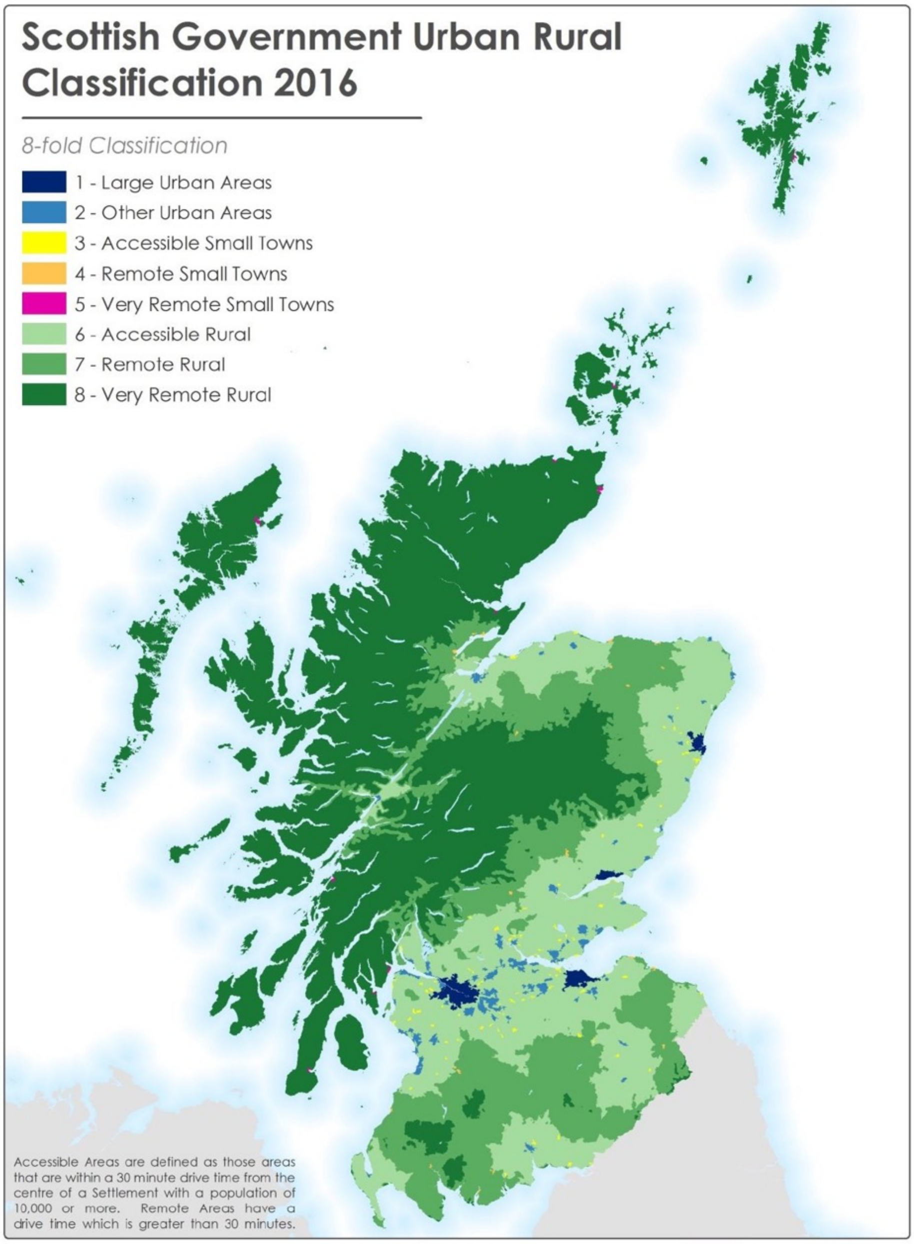

Figure 2-17: Scottish Government Urban Rural Classification 2016 [Source: Gov.scot, 2018]

2.13.1 Electricity Generation in Scotland

Since the case study of this thesis focuses on Scotland, this chapter emphasizes electricity generation in Scotland and share of renewables in this market. Figure 2-18 presents the electricity generation by fuel type (GWh) in Scotland from 2000 to 2016. For more than a decade Nuclear has been a main source of electricity generation. It is important to mention that in 2014 and 2015 renewables became the main fuel for electricity generation. Renewables as an important source have gradually increased over years and reached the highest level in 2015. However, in 2016 it decreased compared to the previous year, but still was one of the main sources of electricity generation. Gas on the other hand, faced fluctuation from 2000 to 2009, however after that time it declined and reached the lowest level in the decade in 2015.

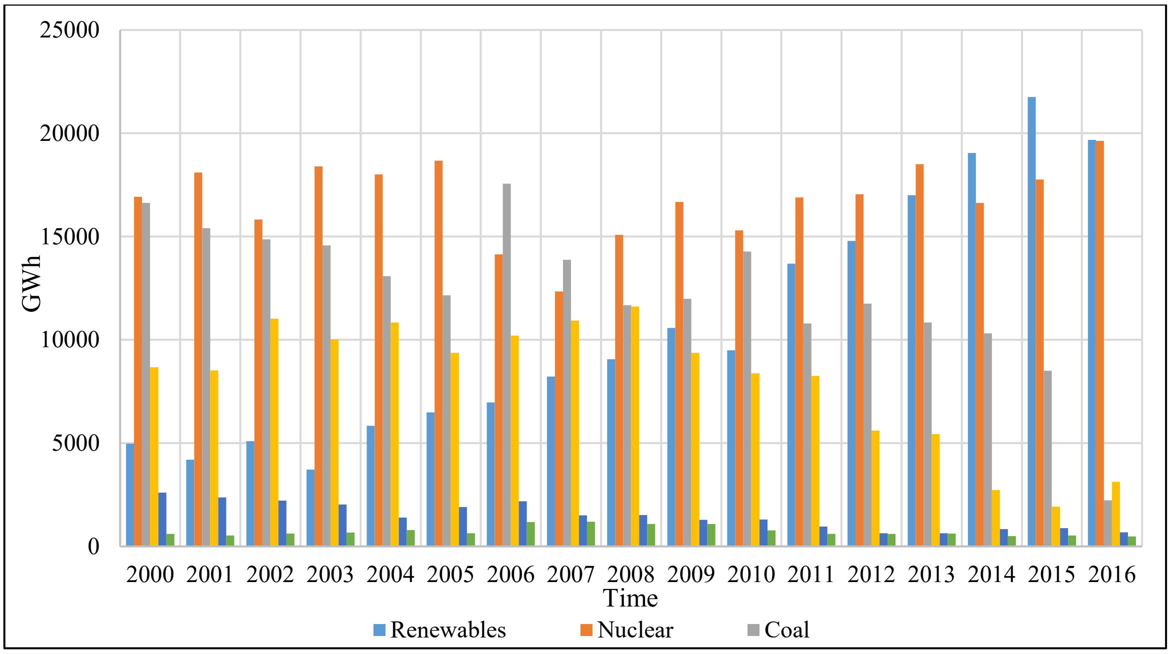

Figure 2-18: Electricity Generation by Fuel in Scotland [Source: Scottish Government, 2018]

2.13.2 Renewable Electricity Generation in Scotland

In renewable generation, wind plays the main role in Scotland. Hydro has been in the market since 2000 with the same amount to 2017 with slight changes through years. Generation from wind on the other hand has increased from 2002 with around 20 GWh and by far have the highest generation capacity in Scotland by nearly 750 GWh in 2017 compared to the other renewable sources. Solar and other bio-fuels have entered the market in 2012 and generation from them increased slightly to 20 GWh in 2017. Capacity of renewables by technology follows the same pattern as renewable generation as presented in Figure 2-19 Wind has the highest capacity of generation by far from any other renewable sources. Hydro has had a same amount over years, while solar PV fluctuated from 2005 to 2014 and then the capacity decreased from 2015 to the lowest level.

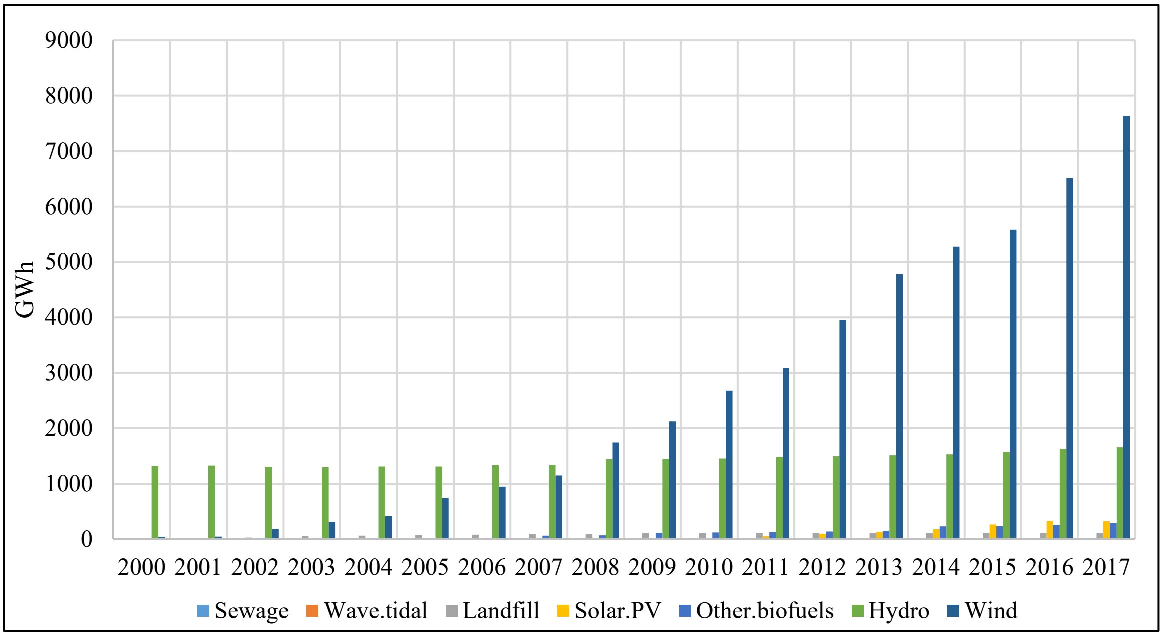

Figure 2-19: Renewable Generation by Technology in Scotland in GWh [Source: Scottish Government, 2018]

2.13.3 Progress in renewable energy in Scotland

Scotland with 7.5% of UK population, have 68% of its power from its 10.5 GW of renewables, 73% of that comes from wind. Moreover, Scotland generated more than 51% of total UK renewable electricity. Therefore, with around 12 GW more installation on its way, Scotland may meet 100% by 2020 power target (Elliot, 2019).

Renewable electricity generation installation in Scotland from 2008 to 2017 is presented in Figure 2-20. As it illustrates, solar PV was nearly zero till end of 2011 and then from 2012 to 2017 there was a slight increase in annual generation reaching to 290 GWh in 2018. Again, generation from onshore wind turbine is far greater than solar and had a significant increase over the years with a decrease in 2016 and then sharp increase in 2017 to the highest record of 17,063 GWh. This large variation between capacity installed for solar and wind turbine is mainly due to Scotland's weather. As Figure 2-20 shows in Scotland between the two renewable technologies, the most popular way of producing electricity from renewables is wind turbine.

The difference in installed capacity of wind turbine and solar PV panel is examined and discussed further in the research model developed later in this thesis.

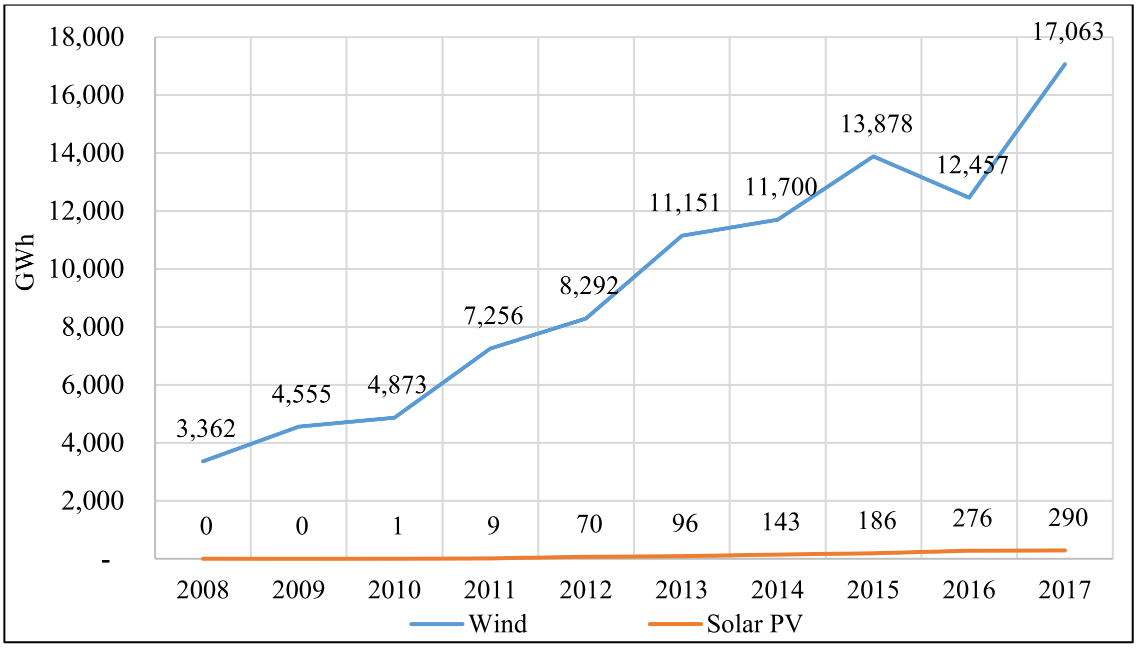

Figure 2-20: Renewable Electricity Generation in Scotland 2008 to 2018 in GWh. [Source: National Statistics, 2018]

According to annual energy statement report by government of Scotland (2019), 75% of Scotland's electricity demand is generated from renewable source in 2018 which was a record year for renewable electricity in Scotland. This progress makes the Scotland's target of 100% electricity demand from renewable sources by 2020 viable (Gov.scot, 2019). Scotland overall energy target is to have 50% of all energy to come from renewable sources by 2030, in 2017 20% of total energy of Scotland came from renewable sources. Also, Scotland is aim to have decarbonised energy system almost completely by 2050. In order to achieve its 2030 and 2050 targets Scotland sets few strategies such as:

- Target for community and locally-owned renewables 1GW of capacity by 2020 (this has been increased from the original target of 0.5GW that was met in 2014) and 2GW by 2030.
- Promoting the development of onshore wind in Scotland
- Obliging suppliers to source more electricity from renewable sources via the renewable obligation.

- Establishing the energy investment fund that will invest £20 million in low-carbon energy infrastructure (Gov.scot., 2019).

2.14 SUMMARY

From data gathered in this chapter can conclude that UK is getting close to meet its 2020 targets set in Paris Agreement and predicted to achieve more than its 2030 targets. These are all mainly as a result of vast investment on renewable energy generation whole across United Kingdom.

To set the foundation of this research the significant points (SPs) from the literature survey are identified as follows:

SP1- (Climate Change, 2.2); In 2009, UK was one of the leading countries in producing greenhouse gases with majority of it coming from burning fossil fuel for producing energy, therefore, an input to this research in change the identify alternative methods for producing energy to positively contribute towards controlling CO_2.

SP2- (European Union Carbon Emission, 2.4); European countries began focusing on reducing the CO_2 by proposing a package of binding legislation to ensure that Europe meets its climate and energy targets. One of the key targets is reducing the greenhouse gas level by 20% in 2020, 32% by 2030 and 80% by 2050 in comparison to greenhouse gas levels in 1990.

SP3- (UK Electricity Market Reform (EMR), 2.7.1); UK government introduced the EMR policy in 2008 to help Britain achieve its long-term energy and climate goals to deliver a secure, sustainable, low carbon electricity at an affordable price. The feed-in-tariff was introduced in EMR policy. This research considers the changes in the tariffs during modelling.

SP4- (Renewable Electricity Generation Incentive –Feed-in-Tariff-, 2.7.5 and 2.7.6); the feed-in-tariff was a government programme introduced in 2010 to promote small-scale (up to 5MW) electricity generation technology. However, the government has closed the feed-in-tariff payment for households/projects that have not installed an eligible system on or before 31^{st} march 2019. This has affected the overall results of this research causing the financial calculations to be reworked.

SP5- (Price of Electricity in UK, 2.8.3); In the UK there has been a significant increase in electricity prices in the last decades due to rise in consumption, more expensive source of generation. There has been an increase in gas prices over decade to 43.9 pence per therm in 2018 and historic weather data considered to be accurate and collected from Met Office which will be used in modelling for this research. Due to rise in electricity prices, finding alternative way of generating electricity can help households with affordable energy and more reliable especially for rural communities. This research examines the internal rate of return and LCOE for community size renewable generation considering these variations in electricity prices over time.

SP6- (Renewable Sources in UK and Scotland- 2.9) Overall there has been a substantial increase in renewable generation capacity annually in the England and Scotland since 2010. Onshore wind turbines are the main source of electricity generation with an increase in installed capacity of 13,436MW in 2018 followed by offshore wind turbines with installed capacity of 8,300MW in the same year. Solar on the other hand has had a huge jump in installed capacity from 95MW in 2010 to 13,108MW in 2018. This research considers onshore wind turbine and solar PV for modelling the renewable generation farm which will discuss in chapter 4.

SP7- (CO_2 Emission Management, 2.10); A major contributor to climate change is the increase in greenhouse gases produced. The literature review found that the largest contributor to CO_2 level in UK was energy supply which had the significant fall in annual total greenhouse gas emission from 794.2 $MtCO_2e$ in 1990 to 455.9 $MtCO_2e$ in 2017. The 42% reduction was mainly due to changes in the fuel mix for electricity generation from coal and gas to renewables and it helps the UK towards achieving its target of 80% reduction in greenhouse gas by 2050. This target was set out in the Climate Change Act 2008 and reducing the CO_2.

SP8- (Cost of Renewable Technology, 2.12); Solar Panel and Wind Turbine costs have reduced significantly over the past 10 years while performance and reliability has improved. Solar PV prices decreased by around 80% since 2009 and wind turbine prices reduced by around 60% compare to 2009. However, this level of reduction in renewable technology might not be achieved in the future. This research examines the changes in cost of technology - increase, decrease and remain the same- and its effect on viability of renewable generation in community size.

SP9- (Discount Rate, 2.12.1); Discount rate is an important criterion affecting investor's decision as it reflects the uncertainty in the project, higher the risk or uncertainty in a project, higher the discount rate. As energy sector are long-term projects which influenced by changes in political and legal environmental changes as well as technological development therefore discount rate plays a significant role in measuring the economic efficiency of investment. Recently over the years the bank rate in the UK has fluctuated between 5% to 10%, since 2009 in has been stable at 7%, therefore the discount rate for this research is safe to be At 5% in 2011 and examine the effect of changes in discount rate on return between 7% to 10% on investment, which is detailed in chapter 6.

SP10- (Rural Communities); Rural communities are known to be affected by power cuts in severe weather conditions. Therefore, providing electricity at local-level for these communities from renewable sources would help with more sustainable energy as well as helping towards CO_2 emission.

SP11- (Case Study- Scotland, 2.13); To test the developed model a small town of Huntly in Scotland is chosen with detailed household electricity consumption data and detailed weather data. Scotland has set a target for community and locally-owned renewable; 1GW of capacity by 2020 and 2GW by 2030.

3 SYSTEM MODELLING

3.1 CHAPTER OVERVIEW

In addition to Chapter 2, a literature review regarding the published materials on how to build the specific models required for this research is given in this chapter. Systems thinking, Discrete Event Simulation (DES) and System Dynamics modelling are used as foundation models for the overall economic models used in this research. The main reason for a need to implement and evaluate dynamic elements in the model is related to the natural changes and behaviours of the weather. The energy generated is dynamic as it reflects the change in generated energy from weather elements. In order to quantify the electricity produced for given solar PV farm and wind farm configurations, it is necessary to have a clear understanding of a modelling technique that can reflect dynamic behaviour.

Discrete Event Simulation (DES) models can handle systems exhibiting dynamic behaviour but only in a limited sense and must be built as arrangement of events in time which provides the modeller the freedom to design and build each part of model independently in order to achieve optimum efficiency. The models can then interact with each other by following well-defined procedures explained by number of authors (Boyn, et al. 2010; Allen, et al. 2015). However, real dynamical behaviour and the resulting emergent properties will often be sacrificed.

System dynamics (SD) modelling was introduced by J. Forrester in the late 1950s, who applied his knowledge of mathematical application in electronics to the dynamic behaviour of complex control system. SD is an approach that provides understanding of behaviour of complex systems overtime which usually includes number of internal feedback loops, both positive and negative feedback as well as time delays that effect the behaviour of the entire system under control. SD provides a unique methodology to understanding complex systems through the complex combination of feedback loops, stocks and flow in displaying nonlinearity (Forrester, 1990; Morecroft, 1997; Hitchin, 2003; Reynold and Holwell, 2010).

This research has adopted a discrete event simulation combined with system dynamics approach to modelling as a core. This chapter will address the concept of DES and SD modelling as a hybrid model, the development of both modelling method for this research will set the overall model in preparation for the research undertaken in Chapter 4.

This chapter comprises four major sections addressing systems approach to problems, system thinking, discrete event simulation, system dynamics and DES and SD applied in electricity generation sector.

3.2 SYSTEMS APPROACH TO PROBLEMS

Many studies define systems as a collection of interrelated parts that function together towards some common objective or purpose in the context of its environment and the system which it interacts with (Forrester 1990; Hitchin 2003). Despite the seeming simplicity of the definition of a system, the system approach generally makes a claim toward analysing, improving and solving the complex situations is more complicated. (Chester 2010; Reynold and Holwell, 2010). Complexity is not necessarily defined in terms of the number of components in a system or the number of possibilities. It usually arises from finding the best solution out of many of possibilities hidden in combinatorial complexity and the behaviour that exists between elements. Most cases of policy resistance emerge from dynamic complexity, which can arise even in a simple system with low combinational complexity but with unpredictable behaviour (Streman, 2001).

Similar to Chester (2010) in this thesis the term 'system approach[7]' is used to cover the sub-disciplines of systems theory, system thinking, and system engineering and system management. In order to put the system approach in context it's important to acknowledge its development over the past century or so.

As Hitchin (1992, p17) explains, *'system' is a concept-so broad, perhaps, that it might seem impossible to find common ground between the various definitions.* System engineering has been recognised as a discipline for over half a century. Systems may be categorised as real, tangible wholes or they may be concepts. A fundamental idea about systems is that they possess some degree of order which leads to notions of structure and architecture (Hitchin, 1992).

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[7] The use of 'system approach' is synonymous with Hitchin's use of 'system engineering' and has adopted thought this thesis.

Systems approach has been introduced during World War II, while engineers looked at the machinery as integrated systems with feedback and dynamics and where behaviour of the whole machine is affected by behaviour of each single part. This approach led to the development of new disciplines in cybernetics, operations research general system theory, system analysis and system dynamics. In all these disciplines, system approach has been used to investigate problem in terms of flows, feedback and interactions by decomposing a system into its component parts, understanding the behaviour of these parts and then recombining them to understand the system as a whole. Understanding a system behaviour via its interactions and emergence is the essence of the system approach (Chester, 2010).

In terms of this research, applying a system approach means understanding how a renewable electricity generation farm functions as well as how legislation and policies, land limitation, technology improvements influence and affect the economic viability of renewable generation. Thus, understanding the influence of the system is essential to get a clear idea of the renewable energy systems which is subject of this research.

3.3 DISCRETE EVENT SIMULATION

As mentioned earlier this research examines the economic viability of wind and solar farm for generating electricity in community size with a limited number of households. First objective of this thesis is to model an optimal combination of wind turbine and solar panel for electricity generation for a chosen community. Considering the discrete nature of the problem, the discrete event simulation (DES) tool is used for this work and that tool requires sensitivity analysis and behavioural measurement of targeted variable. DES is a method of simulating behaviour and performance of real-life process, facility or system. In DES, complex decision logic can be incorporated which is not as convenient to be applied on other types of modelling. Simulation helps decision-makers to validate their ideas and get and better understanding about alternative ways in which a new policy may be met. In this case, it is possible to test number of 'what if' scenarios (Allen et al. 2015).

Moreover, discrete event simulation has been applied widely in energy industry to evaluate and optimise energy management with aim of sustainable development which considers industry's economic, social and environmental performance as well as meeting targets defined by sustainable development (Paulista et al. 2019).

3.4 SYSTEM THINKING

'System thinking' refers to scientific thinking about events and situations from using system methods, systems theory and systems tools. System thinking then looks at wholes as an open system interacting with other systems in their environment. Instead of thinking in the abstract sense, systems thinking had developed into dynamic modelling of open systems, often using smart simulation programs. System thinking has evolved as modelling technique to provide better understanding of the behaviour of system (Hitchin, 2007).

This offers the opportunity to manage highly complex situations, procedures, organisations, etc. by providing modelling with high degree of confidence. In general, system thinking, and behaviour modelling are not used to provide specific numerical answers to complex mathematical problem. Instead, they are used to model the interaction between various systems of interest to explore likely outcomes from such interactions that affect other systems in the model and surrounding the model. In this way, models are used as experimental laboratories to explore possible scenarios of a given future situation and to give an answer to the well-known 'what if' question (Forrester, 1971; Hitchin 2007). 'What if' analysis in this research is undertaken in chapter 6 when 'use case' modelling is performed.

3.5 SYSTEM DYNAMICS

One of the biggest challenges is to be able to tackle how the system reacts to dynamic forces and how those reactions affect the behaviour of the whole system over time. A good example of system dynamics is the domestic central heating, the required temperature is set at thermostat and the system itself is responsible for all possible scenarios. If temperature of the house is lower in comparison to what has been previously set the action is taken by the system itself and thermostat and its controller are used to turn the heating on in order to reach previously set target. The control system has a common feature with system dynamics, in both, the system 'senses' the effect that the external factor has produced on the actual 'state' of the system. It 'compares' the actual state with the 'desired state', and then it assigns 'policies' specifying what actions are going to be performed in certain circumstances. Right after feedback delays, the system will react through 'information feedback' (Coyle 1996).

System Dynamics (SD) is one of the most popular system approaches used worldwide to understand the nonlinear behaviour of complex systems over time using, stocks, flow, internal feedback loops and time delays. SD is a strong tool for analysing behaviour of the system and mainly used tool to examine systems and their current behaviour to what has been expected.

Initial recognition of system dynamics uses to solve number of problems related to various systems and application of control theory for better understanding of problems is first introduced by Professor Jay Forrester, from Massachusetts Institute of Technology in late 1950s (Forrester, 1959). The system dynamics method was founded and developed by Forrester to simulate the behaviour of social system by explaining that behaviour and designing effective policies to improve system performance (Lane and Sterman, 2011). Similar approach has been applied to the energy model for this research.

Jay Forrester established a MIT System Dynamics Group where he started applying his knowledge about systems during his work in electrical engineering to everyday kinds of system. Forrester started work on servo-mechanical devices to control radar and then shifted his focus to the field of industrial reaction and then modelling global resource depletion. Sustainable development involved modelling of the world as a system called 'world system'. System dynamics has been defined by Forrester as an approach of understanding the behaviour of complex system over time (Forrester 1971; Morecraft 1997; Reynold and Holwell 2010).

System dynamics is a strong tool for analysing behaviour of the system. In addition to the previously mentioned applications, strategic point of view can be supported by system dynamics and it was used in wider range such as management and defence (Sterman, 2010). SD offers a methodology to assist decision making organisations such as business and government organisations in strategy development, analysis of policy options and analysis of dynamic processes. Further in this chapter few examples of use of system dynamics in decision and policy making regarding renewable generation are presented. System dynamics model captures factors affecting the behaviour of a complex system in casual loop diagram which presents links and feedback loops between elements in the system. This type of analysis could benefit decision-makers by helping them to understand complex system, adjust parameters of a system, add new links and feedback loops. It also, rearranges components in the system thus models a variety of scenarios and observes performance of the system under different conditions (Sterman 2001; Hitchin 2007).

3.5.1 Casual Loop Diagram

Establishing the casual relation between the variables is the first stage of model development in system dynamics approach. During development of the model variables may have positive or negative effect on each other. It is of crucial importance to identify all the variables that significantly influence the behaviour of the system. Figure 3-1 presents the casual loop for population which is a combination of positive and negative loops. The relationship between net new population and population is represented by the positive loop. However, a negative relationship between effect of population on survival of net new population and population is characterised by a negative loop.

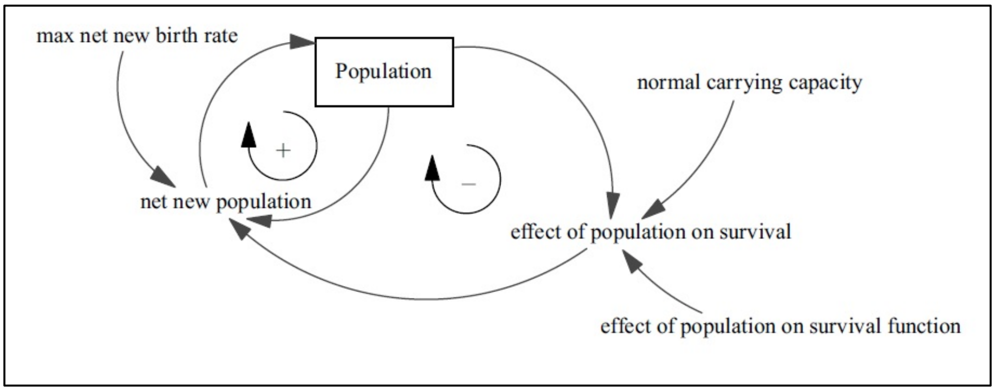


Figure 3-1: Casual Loop Diagram [Source: Forrester 1997]

3.5.2 Stock and Flow Diagram

System Dynamic uniqueness arises from its stock and flow feedback structure which enables modellers to describe the relationship between inputs. Stocks and flows are fundamental to the dynamics of complex systems. Bathtub example presented in figure 3-2 is a representative example of understanding the stock and flow relationship. In this case the bathtub shows the stock of water in the tub which is filled by the inflow and drained by the outflow without any feedback, nonlinearity or any other complexity. This represents one of the simplest case scenarios.

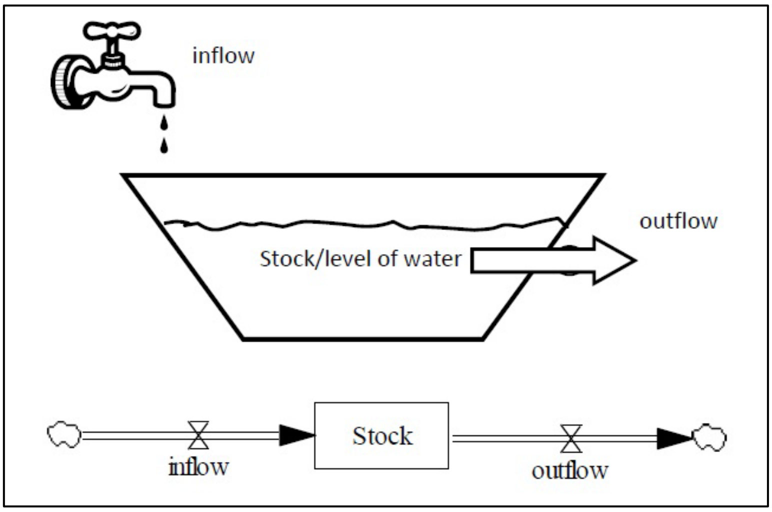


Figure 3-2: The bathtub metaphor for stock and flow [Source: Shepherd, 2014]

Ability of System dynamics to be used for both qualitative and quantitative analysis has made it a powerful tool. For instance, in a qualitative view it can draw working of the system as an instrument to understanding and thinking, while for the quantitative view of system dynamics it can turn the diagram into simulation model and optimization to support policy design (Coyle, 1996).

Initially SD was applied only on managerial problems, however its application widened to include urban dynamics, socio-economic systems and many more. Also, it has become a modelling tools for energy systems with uncertainties, causalities and complex interaction (Marquez and Blanchar 2006; Ansari, 2012; Jeon, Lee and Shin, 2015).

3.6 LITERATURE REVIEW FOR SYSTEM DYNAMICS MODELLING

System dynamics has been used widely in the energy industry to help with resource planning which has a unique capacity to observe and evaluate the feedback "at work in power systems. The work is proven to be useful to both small as well as large power companies and government agencies (Ford 1996). Furthermore, Ford (1997) presented that system dynamics' ability to simulate the information feedback is a unique feature that can be applied in electric power industry. System dynamics modelling is also a powerful tool for quantify social and political impacts on studied system although quantitative energy models usually limit their focus on techno-economic factors while political, social and behavioural aspect frames exogenously (Gravelsins et al. 2018).

There are numerous examples focused on the way that systems methods have been used to analyse renewable generation options in many countries across the world to determine the most suitable option or mix of options necessary to meet legislative targets or to drive the direction of policy. There are many different techniques available to model systems, however in this thesis discrete event simulation (DES) and system dynamics (SD) approach used for modelling the renewable electricity generation.

3.7 OVERVIEW OF SOME EXISTING LITERATURE

As explained, discrete event simulation (DES) and system dynamics (SD) modelling are proven to be suitable tool for modelling complex systems. Below are examples from existing literature on applying DES and SD in renewable generation.

3.7.1 Discrete Event Simulation Example

Byon et al (2010) applied DES modeling and simulation framework based on dynamical systems theory for insights into wind farm operations under two different maintenance strategies. DES result from comparing scheduled maintenance and conditional-based maintenance shows that condition-based maintenance provides more wind generation by decreasing the failure rate of wind turbine and thus increasing wind turbine availability. For building the simulation model of a wind farm, all critical components associated with operation and maintenance considered such as power generation model, wind speed model, wind turbine components with degradation model, sensor model and maintenance model.

Paulista, et al. (2019) applied DES to analyze the behavior of consumption and generation of electrical energy in combination with other variables of the process. DES used to model and simulate part of the production process of plant, focusing on electrical energy consumption and PV generation with some financial considerations related to the current energy contract.

3.7.2 System Dynamic example

Ford (1997) presented collection of articles which used system dynamics in energy sector and mainly for electric power industry. He believes that system dynamics practitioners have been successful in this industry by letting the investigators to focus on feedback loops in the energy system. In supporting that, he began by going through history of electric power in United State from 1880s followed by main historical developments which helped this sector to survive the “energy crisis” in 1970s. He presented 33 articles on system dynamics applications to electric power from 1970s to 1990s and one of the articles was listed as Roger Nail 's teamwork and well known as *System Dynamics Review* in 1970s, 1980s and 1990s. This provided an excellent description of the system dynamics model used at the Department of Energy in the United States. In conclusion he stated that his experience with energy industry modeling convinced him that the ability to simulate the information feedback in the system is a truly unique feature of the system dynamics approach (Ford, 1997. P. 21).

Reddi, Li, Wang and Moon (2013) presented the results from comprehensive system dynamic model of hybrid renewable energy system (HERS) and combined heating and power (CHP) generator. The HRES model includes micro-turbine-based CHP system, wind turbines and solar panel modules in which micro-turbine, wind turbine and solar panel generate power while the heat exchanger manages the waste heat. A model was developed with the main goal of evaluating possible options for planning and operating a hybrid energy system to meet energy demand. The model itself has the capability of calculating the economic and environmental impact for every possible combination of energy source. Modelling with system dynamics is useful in choosing the energy system parameters given different constraints such as cost, climate, environmental commitments and more. With applying system dynamics modelling this study indicates that the components of HERS can have conflicting effect on cost and environmental benefits, therefore there is a need for an organization to make trade-off decision.

Decision making plays a significant role in developing policies to promote photovoltaic (PV) energy market. Movilla, Miguel and Blazquez (2013) used system dynamics model to analyses PV energy market in Spain. System dynamics has proven to be an adequate tool to perform the modelling and simulation to such a problem to help decision makers by giving a better understanding of the behavior of the main variables. In this case with help of system dynamics modelling, dynamic behavior of PV energy market explained to help design optimal policies. The recognized weakness of this sector is dependency of PV energy market on subsidies for it to be profitable.

Securing energy supply is one of the today's important factors in developed economic with considering threats of carbon dioxide emission and global warming for developed countries. Aslani and Wong (2014) used system dynamics to evaluate different costs of renewable energy utilization during 2010-2030 in the United States. The focus of this study is to analyze the role of renewable portfolio in the United States energy action plan with system dynamics modelling to evaluate different costs of renewable energy utilization. The study indicates that while renewables create a market worth around $10 billion in 2030, the total value of renewable energy promotion and utilization in the US will be more than $170 billion during 2010 to 2030 which raises the concern about economic viability of this approach.

Management of energy supply is a complex topic due to number of various effective factors. Effective management of energy supply have become important mainly for import-dependent countries. Aslani et al. (2014) proposed system dynamics model approach to evaluate role of renewable energy policies in energy dependency in Finland which helps decision makers to test their scenarios related to renewable energy policies as well as implementing by other countries. Applied system dynamics modelling and causal loop diagram are used to evaluate different Finish scenarios of renewable energy policies by 2020. As presented in the Figure 3-3, each renewable electricity source presented in stock and flow diagram with relevant policy that effects the number of systems. Then the output of each stock combined in the "Renewable Electricity" variable which is the total renewable electricity generated in Finland. The analysis has demonstrated that despite 7% increase in energy consumption by 2020 in Finland, dependency on imported sources will decrease depending on the policies introduced.

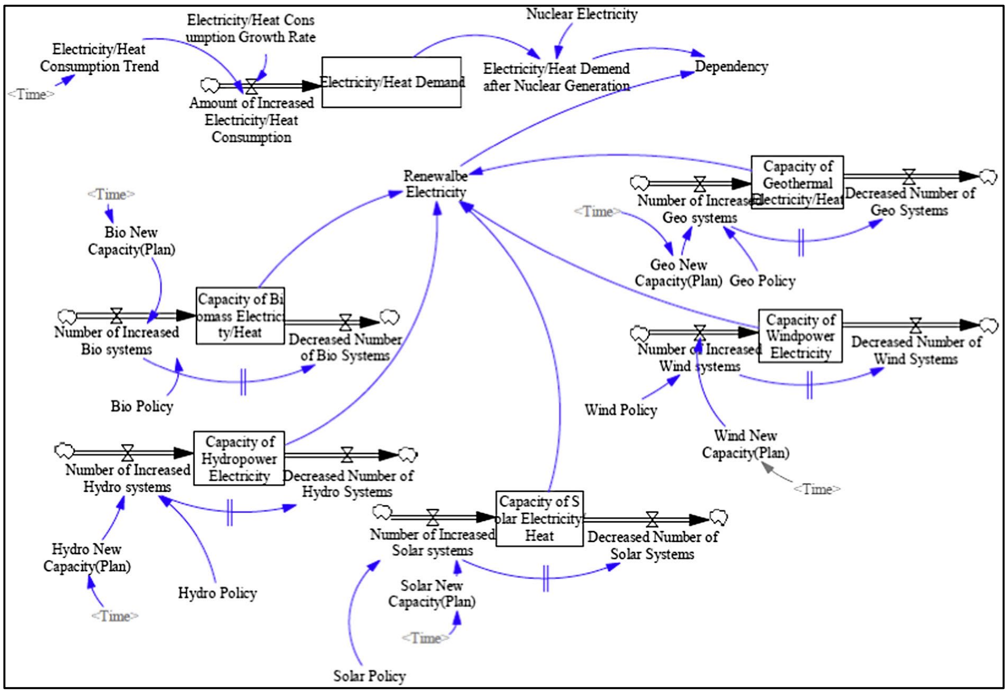


Figure 3-3: System Dynamic model of application policies in Finland [Source: Aslani et al, 2014]

An example of applying system dynamics in energy policy making is reported by Mutingi et al. (2017) and the purpose of their work was to present system dynamic approach for capacity management of energy system with main emphasis on investigating the effects of capacity inadequacy on system behaviour. The study demonstrates the importance of taking a system thinking approach when managing the capacity of complex energy systems. In this research a limit to growth, growth and underinvestment were identified and modelled in casual loops. In addition to that, stock flow analysis models are presented followed by 'what if' simulation experiments that illustrated the main effect of limited capacity growth and growth with underinvestment in the presence of time delays. Figure 3-4 illustrates the stock and flow analysis model for the 'limit to growth' section of the modelling. Rise in demand was modelled as a function of growth factor, industrial activity and the following investment activities. On the other side there is an unfilled demand which is a product of failure rate and the current demand.

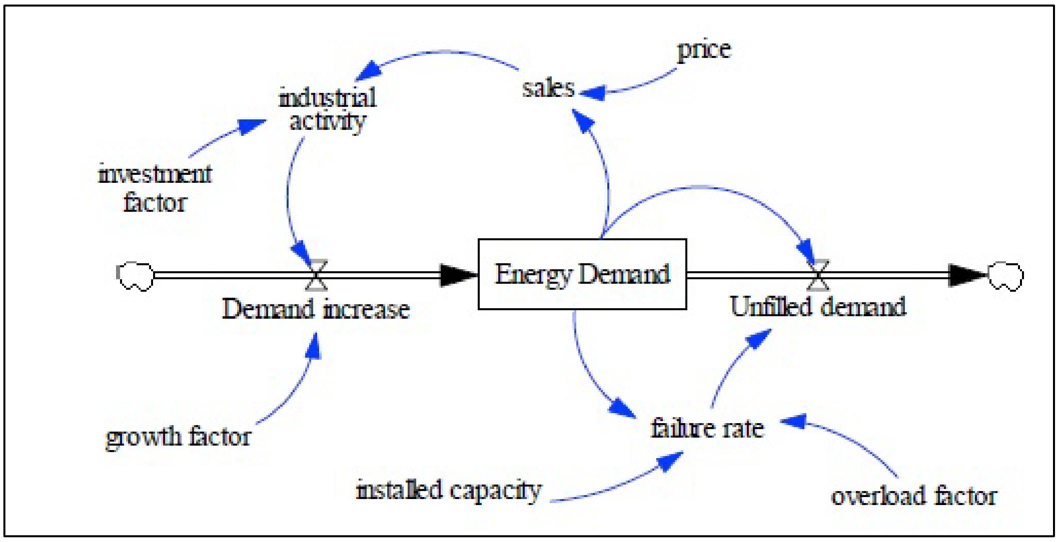


Figure 3-4: Stock and flow analysis model: Limit to growth [Source: Mutigni et al., 2017]

This study shows that capacity inadequacy causes unpredictable system behaviour which can make it challenging for the energy policy makers to realise the actual source of unwanted demand fluctuations in the capacity and its management. Unpredictable system fluctuations can be avoided through proper capacity adjustment decisions.

Gravelsins et al. (2018) presents another example of system dynamic approach for energy policy maker in which the SD was used for modelling of the energy transition towards low carbon energy system (integration of photovoltaics and wind turbines) by combining techno-economic and socio-technical analysis. This study looks at flexibility issues related to integration of renewable energy sources (RES) by presenting simplified model to illustrate the flexibility and socio-technical aspects can be modelled with system dynamics. In their study, the growth to electricity demand, unit costs of electricity production with fossil fuels are assumed to happen as a result of exogenous factors. It is assumed that economic growth, electrification and energy efficiency measures could change electricity demand. Results from modelling demonstrated that RES increases due to decrease unit costs of production of RES power technologies and increase of flexibility limit is resulting from potential disruption in power system.

3.8 Modelling and Analysis Method

This research uses system dynamics approach to build a simulation for dealing with a complex system with feedback and long-time horizons. The validity of a model is tested by reproducing historical data and different policies and changes that can be expected in future. The process of using system dynamics follows the steps below.

- First critical step of any modelling is to define the problem. Analysing the economic viability of renewable generation for rural communities; i.e. profitability of the renewable generation in community size. Moreover, identifying variables that affect profitability of renewable generation such as, cost of renewable technology, subsidies, electricity prices, cost of land and more. Furthermore, it is essential to analyse proposed government policies and results of any changes in new policies introduced.
- Following problem definition, the hypothesis about the model should be clearly defined. System evaluation is presented by stock and flow in system dynamics modelling, therefore, it is necessary to identify the key stocks and flows and influences between these elements. After defining the link between main elements, depending on the influences, the formal model is developed through a computing program. The model contains the most significant variables involved in renewable generation. Also, the evaluation of stock and flow links the parameters with appropriate formula.
- The next step is to check the validity of the simulation model. In modelling, it’s critical to ensure that structure of the model is correct, and no important factors are forgotten. Later some part of the formulation might need to be recalculated for the

purpose of validation and this process repeats again and again in a loop as it's an important part of modelling. The loop will end when the model is validated. For simplicity of the validation, the model can be divided into subsystems which eases identifying the different structures or behaviors.

- When the model works in an equilibrium point, the simulation is tested under extreme condition to check the structure's behavior. Moreover, sensitivity of the key parameters is analysed to get better understanding in terms of their effect on the system (Movilla, Miguel and Blazquez, 2013).

3.9 SOFTWARE

The considered wind and solar PV farm used as part of this research is based in Huntly, a town in North-East of Scotland with a limited number of households. The research aim is to find the most economically viable combination of wind turbine and solar PV panels for this particular place using the simulation and optimization method proposed as part of this research. Considering the nature of the problem being discrete, the model requires both a sensitivity analysis and behavioral analysis of the target variables. Both Excel and Vensim software are used for this simulation. Vensim software, is mainly used for a dynamic analysis of the system that is capable of simulating a system, and it can be used to see the causal relationship between the variables. Vensim's capability and compatibility with Excel led to this selection to ensure successful simulation required for this research.

3.9.1 Vensim Software

Vensim is a simulation software developed by Ventana Systems. It is used for developing, analysing and packaging dynamic feedback models. Vensim has many built-in functions including user defined lookups, test input patterns, logical operators, random number generators, continuous and discrete delays, smooth and forecasts, scientific functions and customised macros and external functions. The gaming simulation model allows the user to step forward at discrete intervals and make changes to model variable at each step. Vensim can use external data series as exogenous input to drive a model to compare against data from simulation runs (Vensim, 2019).

In this research Vensim is used for modelling discrete event simulation to evaluate economic viability of renewable generation farm in community size as well as developing system dynamic model.

3.9.1.1 Optimization

Getting the most out of models and data requires a good model and sophisticated algorithms for calibration, and Vensim provides tools for both. A model can be automatically calibrated to fit historical data series. External data series are loaded, and specified parameters are adjusted which is followed by Vensim's automatically adjustment of the parameters to get the best fit. Vensim's optimizing engine is capable of searching through complex multi-dimensional surfaces to look for optimal solutions. Payoff functions provide model-data comparison with a variety of error models, including Normal, robust, Poisson and Binomial distributions. Kalman filtering provides state estimation. Markov Chain Monte Carlo permits estimation of confidence bounds and joint (Bayesian) posterior distributions of parameters. Vensim also provides policy optimization, even for worst-case situations with multiple optima, discrete or rough surfaces, and stochastic objective functions (Vensim, 2019).

3.9.1.2 Sensitivity testing

Sensitivity testing involves changing the assumptions about the value of inputs to the model while performing multiple simulation the examining the uncertainty in selected output variables. Vensim automates multivariate Monte Carlo simulation and a variety of vector and grid search methods. Output can be displayed as graphs with confidence bounds, individual simulation traces and histogram (Vensim, 2019).

3.10 LESSON LEARNED FROM THIS RESEARCH

From published model papers this research identifies following:

- Discrete Event Simulation and System Dynamics are strong tools for modelling renewable energy market with its qualitative and quantitative features can help with policy design.
- Simulation optimisation is another feature of DES and SD which this research has applied.

- This study looks at economic viability of renewable generation by using DES and SD in Vensim which can run simulation optimisation and presents the best results of running.

3.11 Chapter Summary

As mentioned earlier, in this research, the feasibility and sensitivity analysis of the construction of renewable power plants including wind turbines and solar panels has been discussed. Renewable energy generator technologies are affected by different factors such as supply and demand, availability of other energy resources, government policies, subsidies, cost of electricity per unit and more. Many researches have applied DES and SD modelling tool to understand the complex dynamic behaviour of the renewable energy technology (Steman, 2000; Marquez and Blanchar, 2006; Ansari and Seifi, 2012; Aslani and Wong 2014; Jeon, Lee and Shin, 2016).

In order to evaluate an economic viability of renewables, it is important to understand the interaction between managed elements with each other considering flow of legislation, pollution, energy and finances. Understanding the viability of renewable energy generation and its associated carbon footprint requires identification of all interactions in and between community renewable generations. After all these considerations, an appropriate model can be developed. The conclusions made are only based on the assumptions associated with the formulation of the model itself. Credibility and confidence in any model are mainly gained if it can recreate history and would be more useful in understanding the community renewable generation.

The research directions taken in the development of this work comprises use of discrete event simulation and dynamic approach to model the evaluation of an economic viability of community renewable generation. It is necessary to take this approach due to the historical nature of legislative targets and uncertainty of renewable generation itself. The main focus of the next chapter is to report on the progress of the adopted approach and to provide more details of the research model itself.

4 MODEL DEVELOPMENT

4.1 CHAPTER OVERVIEW

Intuitively there should be a relationship between the economic feasibility of an investment on renewable energy generation and capacity of renewable technology used to achieve it. An increase in the quantity of feasibility of a renewable energy generation investment should require better cost-benefit (more revenue generated from the investment and less cost) over lifetime of the project. This research focuses on optimising wind generation and solar generation together in order to identify an optimised combination with the main goal to determine the most viable economic solution. This solution will also consider buying/selling electricity from/to grid to cover shortfall or excess generation.

Chapter 4 presents a detailed description of the research model used in this thesis. Data from each input is logged daily and stored in database; Total community electricity consumption over a 12-month period from December 2010 to January 2012 is presented in Appendix A. wind speed and sun irradiance over a 7 year period from 2011 to 2018 is presented in Appendix B, cost of buying electricity from Grid for the same period as weather data is presented in Appendix C followed by cost of technology in Appendix D and cost of land in Appendix E. The regression tool in Microsoft Excel 's Data Analysis toolbox was used to undertake the regression analysis, the result of which are discussed in this chapter.

This chapter presents a detailed analysis of the types of input data, such are, electricity demands, weather, land availability, technology type, cost and government policies for renewable generation, and the core excel model. Section 4.2 presents the model overview, followed by detailed description of input data reported in section 4.3 and section 4.4 explaining the core excel model used to store and manipulate the data. DES and SD model are described in more detail in next chapter (Chapter 5).

4.2 RESEARCH MODEL RENEWABLES

A high-level view of the overall renewable research model is shown graphically in Figure 4-1 which shows the qualitative approach and quantitative approaches with interfaces between Vensim (DES and SD model) and Excel. As the figure presents, first approach to this research model as any other research model, is qualitative approach. Problem first identified as explained in Chapter 1 with identifying barriers following with mapping the structure which is presented in Chapter 3 in which research model introduced. After finalising the qualitative approach, data collected for the selected case study, Huntly in this case. Then quantitative approach begins after formatting data in Excel and defining mathematical relation between inputs. After that the research model developed in Vensim. Results obtained from Vensim and Excel are presented in Chapter 6 with analysis. In this research, Excel serves two purposes, first as a background database of constants used in Vensim and second, as a user interface in which renewable farm data is entered to develop scenarios and control the level at which the renewable farm boundary is drawn.

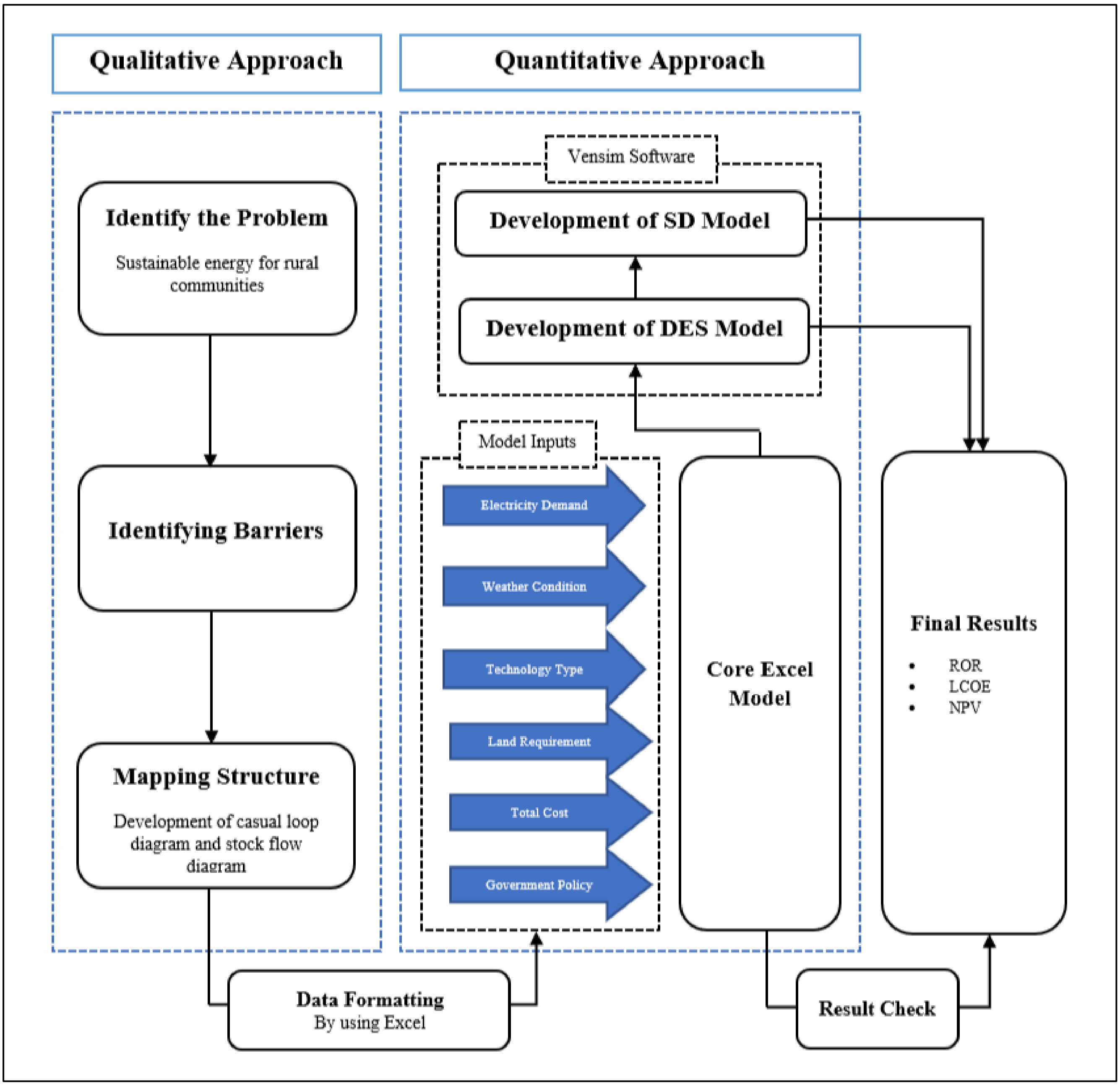


Figure 4-1: Schematic of the Research Model

4.3 INPUT DATA FOR THE RESEARCH MODEL – CASE STUDY

Recall, to test the developed model, input data for a specific region required to evaluate the model. In this case Huntly is selected for testing the model. This section addresses the input data for the research model starting with electricity demand data, then weather data collection, renewable technology type chosen for this research, cost of renewable technology and data regarding amount of land required for the renewable farm and its cost and government policy data.

As discussed earlier in Chapter 2, a small town of Huntly in North-East of Scotland is selected as a case study of this research.

4.3.1 Electricity demand

Electricity demand by household is a key input for this research as it is a primary indicator for the size of any renewable farm. One of the challenges was to collect an accurate data on household consumption due to the limitation on availability of data for each house. Research conducted by Craig T. *et al* (2014) and inputs from his research provided representative data sample for North East Scotland electricity consumption by number of households between 2010 and 2012. For this specific area, study presents findings from Phase 1 of the three-phase and well know North East Scotland Energy Monitoring Project (NESEMP). This project has examined a relationship between different types of energy feedback, psycho-social measures including environmental attitudes, household characteristics and everyday behaviour. Electricity usage of several households was recorded at a 5-minute time interval using smart current cost monitors and this is provided in the official report of the project.

The authors, Craig and Dent (2017) reported missing of some of the data at a 5-minute interval due to the technology challenges. These missing points were removed from the recording tables. Also, partial days of readings at the beginning or end of the dataset were deleted to ensure all readings in data comprised a full set (Craig et al. 2014).

The data became available on September 2017 via UK Data Service archive under name of "Study Number 8122 - North East Scotland Energy Monitoring Project, 2010-2012". The original data for this study comprised three sets of data as shown below:

- A base questionnaire data which is a carbon footprint calculator questionnaire,
- "Raw data" - a raw reading of electricity meter and temperature at the point of meter
- "Drive data" –cleaned readings of data- in .csv files.

"Drive data" used for this research consists of 217 excel files for each individual household, where there is a one separate file for each household. This data presents the core of this research. In order to understand the format of the raw data, Table 1 is given below, where column 1 shows the timestamp in a format of YYYY/MM/DDHH: SSZ[8], Column 2 shows the electricity meter reading in Watts for every 5-minute period counted in milliseconds and column 3 presents the room temperature in degree centigrade. Data in this table is direct input from the original file reported by Craig *et al* (2014).

Date	Reading (W/5min)	Temperature (Centigrade)
2010-11-03T00:04:16Z	142	16.3
2010-11-03T00:09:17Z	141.3543	16.3
2010-11-03T00:14:18Z	139.0728	16.3
2010-11-03T00:19:20Z	100.952	16.3
2010-11-03T00:24:21Z	80	16.17363
2010-11-03T00:29:22Z	80	16.1
2010-11-03T00:34:23Z	80	16.03742
2010-11-03T00:39:25Z	80	16
2010-11-03T00:49:26Z	80	16
2010-11-03T00:54:27Z	80	16
2010-11-03T00:59:29Z	96.44682	16
2010-11-03T01:04:30Z	132.2761	15.87816
2010-11-03T01:09:31Z	143.398	15.8
2010-11-03T01:14:32Z	142.4007	15.8
2010-11-03T01:19:33Z	141.404	15.7404
2010-11-03T01:24:34Z	141	15.7
2010-11-03T01:29:36Z	133.3377	15.7
2010-11-03T01:34:37Z	100.448	15.7
2010-11-03T01:39:38Z	80.42123	15.7
2010-11-03T01:44:39Z	80.57616	15.58477
2010-11-03T01:49:40Z	82.1457	15.5

Table 1: Raw data [Source: Craig and Dent 2017]

Derived data used for this research is given in Table 2 and it consists of four columns, where column 1 presents the date of reading in the format of YYYY/MM/DD (i.e. 20111003 presents the 3rd October 2011), column 2 shows the timesheet presented in seconds, column 3 presents the electricity usage in the format of real number without the decimal points and is presented in Watts and finally the column 4, presents the room temperature in degree

[8] Although the timestamp includes the Z code to designate UTC, the time is actually the local UK time.

centigrade. Data in this table is direct imported from the original file with additional column used for timestamp; derived_data <household_1.csv (Craig et al 2014). The full data is presented in Appendix A.

Date	Time	Reading (W/5min)	Temperature (Centigrade)
20101103	0	142	16.3
20101103	500	141.3543	16.3
20101103	1000	139.0728	16.3
20101103	1500	100.952	16.3
20101103	2000	80	16.17363
20101103	2500	80	16.1
20101103	3000	80	16.03742
20101103	3500	80	16
20101103	4000	80	16
20101103	4500	80	16
20101103	5000	96.44682	16
20101103	5500	132.2761	15.87816
20101103	10000	143.398	15.8
20101103	10500	142.4007	15.8
20101103	11000	141.404	15.7404
20101103	11500	141	15.7
20101103	12000	133.3377	15.7

Table 2: Household 1 Electricity Consumption Derived Data [Source: Craig et al. (2014)]

For the purpose of this research 140 files that represent number of households are combined into one file to calculate the total community consumption. Due to missing data from 75 households, these households were excluded from the analysis as it would cause significant errors. Table 3 presents short example of adding 140 households in one file that comprises 5 columns as follows, column 1 presents date YYYY-MM-DD, column 2 shows timesheet presented in format of HH:MM: SS, column 3 presents electricity consumption by household 1, column 4 shows electricity consumption by household 2 and column 5 presents electricity consumption by household 3, end etc. for the remaining 137 households (detailed Figure presented in Appendix A).

Date	Time	Household 1	Household 2	Household 3	Household 4
20101103	0	142	27.48584	120.1954	279.3924
20101103	500	141.3543	12.13853	118.2781	259.0648
20101103	1000	139.0728	25.57098	118.904	241.45
20101103	1500	100.952	12.74595	125.3046	241.1067
20101103	2000	80	9.446797	126	247.5367
20101103	2500	80	30.27815	126	267.1368
20101103	3000	80	29.30857	125.1161	254.9083
20101103	3500	80	34.53566	111.5875	215.55
20101103	4000	80	28.30034	86.712	166.4667
20101103	4500	80	19	81	107.7667
20101103	5000	96.44682	16.5894	81.7947	112.08
20101103	5500	132.2761	12.00325	119.1954	117.25
20101103	10000	143.398	37.82895	126.8148	103.7579
20101103	10500	142.4007	48.80431	125.4936	102.406
20101103	11000	141.404	23.18543	125	95.74
20101103	11500	141	9	125	83
20101103	12000	133.3377	9	125	87.23

Table 3: Household Electricity Consumption - 5Minutes interval [Source: Craig et al. (2014)]

Total community consumptions are calculated by adding the consumption from each household together and it is presented as part of Table 4. 24-hour (daily) time frame has been chosen for all calculation as 24 hours period was sufficient to presents changes/fluctuations in consumption, weather and electricity generation over 25 years period. Therefore, consumption time changed from 5-minute interval to 24 hours interval which referred to as daily consumption which is a period of 00:00 to 23:55. The chosen time interval still presents the variation in sun irradiance over year as well as wind speed, seasonal changes in consumption and generation from renewable.

As a result, as shown in Table 4, the final consumption data used in the calculation has two columns; column 1 presents date of the reading (day) and column 2 presents the community consumption per day in Kilowatt per hour.

Date	Community Consumption (kWh)
01/01/2011	1698.32
02/01/2011	1700.53
03/01/2011	1689.42
04/01/2011	1698.12
05/01/2011	1666.30
06/01/2011	1679.45
07/01/2011	1701.77
08/01/2011	1680.20
09/01/2011	1678.17
10/01/2011	1675.57
11/01/2011	1674.08
12/01/2011	1667.47
13/01/2011	1680.19
14/01/2011	1675.35
15/01/2011	1674.39
16/01/2011	1675.57
17/01/2011	1620.68
18/01/2011	1678.64
19/01/2011	1669.58
20/01/2011	1644.24

Table 4: Community (140 households) Electricity Consumption kWh per day

As available consumption data was for two years period (2010 to 2012) changes in consumption data from 2013 and assumptions are made by Scottish Government reports on domestic electricity consumption which are presented below:

- The report by Department of Energy and Climate Change (DECC) Scotland on 25th June 2015 reported a 1% fall in electricity consumption by household in 2013 compared to 2012.
- Report by Energy in Scotland (2016) presented 1.4% increase in total domestic electricity consumption in 2014 compared to 2013.
- Paper by DECC in July 2018 discussed the changes in domestic electricity consumption in more details; rise in population by 19% from 1970 to 2017 and increase in number of households in the UK by 49% resulted in reduction of number of residences per household. As a result of reduction of number of residents, household with fewer occupants has less electricity consumption, however rise in number of households will increase the overall consumption. Between 2016 and 2017 number of occupants per household remained stable but there was a fall of electricity

consumption per household by 4.7% which is likely to be as a result of increase in efficiency of electronic products. This research applied these changes for each household from the data from Craig *et al* (2014) and calculated the consumption in the following years.

- Household electricity consumption fell by 1.0% in 2018 compare to 2017 (DECC. 2018).
- Domestic consumption decreased by 2% in 2019 compare to 2018 (Roberts and Frankland, 2019).
- The same report suggested a 12% decrease in domestic electricity consumption by 2020 from baseline 2005 to 2007. These changes applied on electricity consumption data from 2013 to 2035.

Overall decrease in household consumption could be as a result of change in occupant's behaviour and more awareness of efficient time of use electricity through the day, fewer residence per household, warmer temperature and increase in efficiency of electrical equipment.

Having new technology, such as 'smart meters', would significantly contribute to more controlled energy consumption inside the household. Smart meters are new generation meter for gas and electricity that give real-time information on the energy use. Ofgem and Department for Business Energy and Industrial Strategy are working together to secure cheap and clean energy in which smart technologies and services will play a vital role in decarbonising the energy sector. At national level smart meters are key for Britain to shift to cleaner and more flexible energy system (DBEIS, 2018; Ofgem, 2018).

In June 2019, total of 21.2 million gas meter and 25.7 million electricity meters operated by large energy suppliers in domestic properties across UK. The number of smart meters operating expected to continue to increase by 4% compare to the previous quarter (DBEIS, 2019).

4.3.2 Weather

A further key input data for this research is weather data collected from Met Office; UK's national weather service. Met Office provides weather and climate services to government departments, armed forces, civil aviation, shipping, industry, agriculture and the public (Gov.uk, 2019). Table 5 presents a sample of daily weather data for this research and selected geographical region, Huntly, Aberdeenshire, Scotland. Column 1 presents the date (from 1st

January 2011), Column 2 shows daily mean wind speed in knots (kn)[9], Column 3 presents daily total sunshine over 24 hours period and column 4 shows daily total global radiation presented with kilojoule per square meter (kJ/m2).

Date	Daily Mean Wind speed (0100-2400) (kn)	Daily Maximum Gust (0100-2400) (kn)	Daily Total Sunshine (0100-2400) (hrs)	Daily Total Global Radiation (kJ/m2)
01/01/2011	5	23	0.0	1154
02/01/2011	6	20	0.0	733
03/01/2011	12	15	0.0	115
04/01/2011	13	26	0.9	832
05/01/2011	6	20	3.8	1344
06/01/2011	8	31	5.3	2408
07/01/2011	4	19	3.9	1328
08/01/2011	7	22	0.3	2352
09/01/2011	8	21	2.6	2009
10/01/2011	8	26	0.0	963
11/01/2011	8	22	5.2	2792
12/01/2011	4	22	2.3	1002
13/01/2011	5	9	1.8	2148
14/01/2011	11	21	4.3	2475
15/01/2011	17	41	0.1	415
16/01/2011	20	37	5.5	2040
17/01/2011	13	22	3.3	2570
18/01/2011	8	19	5.0	2389

Table 5: Weather Data [Source: Met Office (2019)]

Data from Table 6 is direct input from Aberdeen Dyce Daily 1_1_2011_6_2018.xlsx file received from Met Office Library and Archive on 10th September 2018 via email which contains daily mean wind speed, daily maximum gust, daily sunshine and daily total global radiation from 1st January 2011 to the 30th June 2018 for Dyce. The email contacting data is given in Appendix A. The Aberdeen Dyce is the closest weather station to Huntly, which is approximately within 44.2km distance the place that has been selected for this research.

The weather data presented in table 7, is an example of Huntly's wind speed (meter/second/day) and daily total global radiation (kilowatt per hour/square meter) in which the data provided from Met Office presented in Table 6 converted wind speed from kn to

[9] All carabiners come with a kn (knot) or KiloNewton, 1 kn equals to 0.5144 meter/second.

m/s/day[10] and sun irradiation from kJ/m2 to kWh/m2[11] . Those units have been selected for output calculation from wind turbine and PV solar panel. More details for this selection are presented in subsections 4.4.2.1 and 4.4.2.2 where equations for each output renewable electricity generation are discussed in detail.

Date	Daily Mean Windspeed (kWh)	Daily Total Sunshine (hrs)	Daily Total Global Radiation (kWh/m2)
01/01/2011	3	0.3	0.321
02/01/2011	3	0.0	0.204
03/01/2011	6	0.0	0.320
04/01/2011	7	0.0	0.231
05/01/2011	3	0.8	0.373
06/01/2011	4	5.6	0.669
07/01/2011	2	0.2	0.369
08/01/2011	4	4.4	0.653
09/01/2011	4	3.3	0.558
10/01/2011	4	0.0	0.268
11/01/2011	4	5.8	0.776
12/01/2011	2	0.0	0.278
13/01/2011	3	2.3	0.597
14/01/2011	6	3.9	0.688
15/01/2011	9	0.0	0.115
16/01/2011	10	2.9	0.567
17/01/2011	7	4.1	0.714
18/01/2011	4	4.0	0.664
19/01/2011	4	0.6	0.597
20/01/2011	4	6.7	0.953
21/01/2011	4	1.0	0.643

Table 6: Huntly Wind Speed and Sun Irradiation [Source: Met Office (2018)]

According to the wind speed data for the region presented in figure 4-2, the average wind speed has increased by 1% annually. Influencing this increase to estimate the wind speed, the normal distribution function is used. As the average wind speed increases in 2011 to 2018 as shown in the following diagram. The following relationship is derived if we estimate the daily mean wind speed for these years by linear regression shown in Equation 4-1. In this research the wind speed calculated from Equation 4-1 for predicting future changes to the wind speed.

$$Wind\ Speed = 0.03885 \times\ Year + 4.3794$$

Equation 4-1

[10] To convert kn to meter/second the wins speed value is divided by 1.944

[11] kJ/m2 divided by 3600 to get kWh/m2

$Year: 0,1,2, \dots ,25$

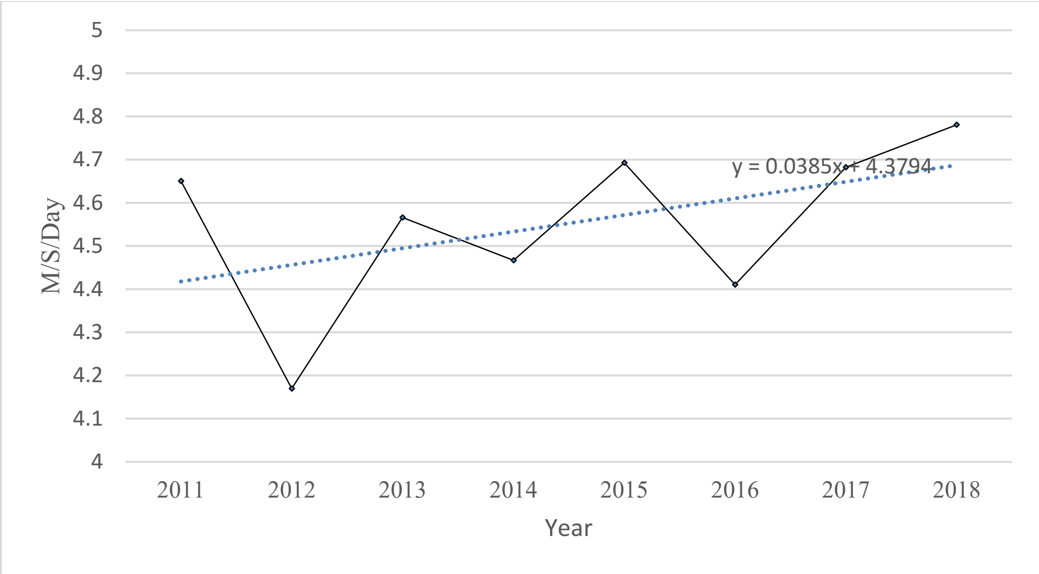


Figure 4-2: Huntly annual wind speed (m/s)

4.3.3 Renewable technology type

Two types of renewable energy source are used for this research;

1. Onshore wind turbine (WT)
2. Photovoltaic (PV) solar panel.

The reasons for this selection of source of electricity generation are described in 4.3.3.1 and 4.3.3.2 respectively.

4.3.3.1 Onshore Wind Turbine

Wind Turbine models considered for this research are detailed in Table 7. The choice of five was selected mainly due to its generation capacity and the availability of valid technical data. An important consideration is the amount of land required for installation as cost and availability of land adds to the importance of economic viability. One key constraint is the availability of land adjacent to the Huntly community.

Model	Power Rate (kW)	Rotor Diameter (m)	Blade Length (m)	Swept Area (m2)	Air Density (kg/m3)	Power Coefficient
Enercon E-28	2000	82	41	5281	1.23	0.5
GE 1.5sle	1500	77	38	4657	1.23	0.5
EWT DW61	900	61	24	1810	1.23	0.5
Enercon E-53	800	58	22	1521	1.23	0.5
Endurance E-31	55	19	8	201	1.23	0.5

Table 7: Types of Wind Turbine [Source: GE; Endurance Enercon; EWT (2019)]

The data presented in Table 8 are direct input from the wind turbine data specification sheets (GE, 2019; Endurance, 2019; Enercon, 2019; EWT, 2019). This table comprises six columns, where following data is provided via different columns; column 1 presents model of each wind turbine, column 2 shows power rate in kilowatt, column 3 shows rotor diameter in meter, column 4 presents blade length in meter, column 5 shows swept area in square meter and column 6 presents air density in kilogram on cubic meter. Air Density chosen for this calculation is 1.225 kg/m3, it's a value at the sea level at 15-degree C (Emerging Technology, 2011).

4.3.3.2 Photovoltaic Panel

Likewise, for PV four options are considered, in this case Sharp NU-RC300 is chosen due to its characteristics, as follows: type of its silicon (monocrystalline silicon solar), highest efficiency as well as availability of data in regards to panel cost. Table 8, presents data of panel types that are used and meaning of each column is given as follows; column 1 present the model name, column 2 presents the maximum output of the panel (Wp)[12], Column 3 shows the module efficiency in percentage and columns 4, 5 and 6 present size of panel in millimetre.

Model	Max Output (Wp)	Module Efficiency (%)	Length (mm)	Width (mm)	Depth (mm)
Bosch c-Si M	285	17	1674	990	46
LG X Plus A5	300	17.3	1686	1016	40
Q-Cells	280	17.4	1650	991	35
Sharp NU-RC300	300	18.3	1660	990	50

Table 8: Types of Photovoltaic Panels [Source: Bosch; LG; Q-Cells; Sharp (2019)]

[12] Wp stands for watt peak capacity. Wp is not presenting the regular power output, but instead in presents the maximum capacity of the model under optimal condition (Bacia, 2017)

In this research monocrystalline silicon solar cells are chosen in order to make a comparison with polycrystalline silicon solar cells due to their highest efficiency rates (15-20%). They are made of the highest-grade silicon and they are space efficient, so they have longer life time of approximately 30 years compare with polycrystalline silicon with life time of 25 years (NREL, 2018).

4.3.4 Cost

Another key element for this research is cost of capital which in this case is cost of renewable technology, cost of land as well as cost of electricity purchased from the grid.

4.3.4.1 Cost of renewable technology

Collecting data about the cost of wind turbine and solar panel was very challenging due to lack of or insufficient information on detailed costs. None of the suppliers contacted – Enercon, 2016 and Vestas, 2016- would provide information on final cost of their product. Full email provided in Appendix C. Most of available data was general cost information on turbines and panels which was in accordance with size rather than investment cost or technology cost itself. This limited the number of turbines and panels to be selected for this research.

4.3.4.1.1 Wind Turbine Unit Cost

A report by Renewable First (engineering consultants and project delivery experts specialising in Hydropower, Wind power and Water Source Heat Pumps), provided a necessary information of the installation cost of different scales of wind turbines and this information is presented in Table 9, reporting maximum output power, turbine type and capital cost per unit. The original data provided the cost of project and indicated that 69% of cost of project is cost of turbine, therefore in Table 9 the capital cost per turbine is calculated and presented.

Maximum Power Output	Turbine Type	Capital Cost per Turbine (£)
55 kW	Endurance E-3120	220.80
800 kW	Enercon E53/48/44	966,000.00
900 kW	EWT DW61	966,000.00
1.5 MW	GE 1.5sle	1,863,000.00
2 - 3 MW	Enercon E82	2,139,000.00

Table 9: installed Cost for different scales wind turbine [Source: Renewable first (2018)]

Response from Westmill Sustainable Energy Trust (WeSET) Wind and Solar farm co-ops via email (Appendix D) supported the data shown in Table 9. Westmill Wind and Solar farm co-ops started as a small group of local people and it has grown now to more than 4,000 members with an energy project that generates over 15GWh/year of renewable energy and 100% of which is owned by community. WeSET is a charity set up with main activities in educational work, supporting local energy conservation and renewable energy initiatives and arts project. In order to have a better understanding of wind and solar farms and their operation a visit was made to Westmill and with help of volunteer's better information was gathered regarding cost of wind and solar farm.

This wind farm has a capacity of 6MW up to 1 hectare of land with overall installation cost of £7.7M investment made in 2008. The farm consists of 5 wind turbines that are widely spread out. Wind turbine separation (tower to tower) is approximately 150 meters and each tower foundation takes approximately an area about 6.75 square meters (Appendix E).

4.3.4.1.2 Operation and Maintenance cost (O&M)

Operation and maintenance cost are associated with cost of servicing and repairing wind turbine during its lifetime. Maintenance cost of turbine for the first two years of operation is covered by the manufacturer and the maintenance cost is assumed to start from the 3rd year of operation. Turbines generally have both fixed and variable costs for maintenance. The model used for the calculation variable cost is reported by Puglia (2013). In her work, operation and maintenance cost of wind turbine has been evaluated as a very important part of the wind turbine life cycle cost or ownership cost.

Research reported by Puglia (2013), compares the cost of two different types of maintenance strategies; preventive maintenance (PM) which is carried out before a failure and corrective maintenance (CM) that carried out after fault occurs. Furthermore, two models have been investigated;

i. Base model with constant failure rate
ii. Ageing model with increase failure rate over the life time of wind turbine

The effect of conditioning monitoring system (CMS)[13] on the maintenance and life cycle cost studied for two introduced models was the considered. Use of CMS gives an opportunity to plan maintenance before failure occurs and carry out preventing maintenance (PM) which can save spare parts, crane usage and man hours leading to total a reduced maintenance cost.

Use of CMS with 80% efficiency for 3MW onshore wind turbine ensures a profit of 1.36% (Puglia 2013). This agreement is accepted, and, in this research, data provided for cost of maintenance and lost production for using CMS with 80% efficiency on wind turbine chosen (Appendix D).

This research uses ageing model when applying CMS with 80% efficiency for its calculation, Table 10 illustrates the operation and maintenance cost for this model. The table contains two columns; column 1 shows the year of operation of the turbine starting with 0 and column 2 shows the presentation maintenance cost in pound sterling (£). First 3 years of operation are considered as free of charge due to company assurance of the turbine performance and reliability. Data presented in the Table 12 is taken from Puglia (2013) and conversion from euros to pounds have been made with exchange rate from July 2013 of GBP/EUR = 0.8703.

[13] CMS is a process that monitors the condition of an equipment through its life time in order to check its functioning to report any failure for maintenance (Janie and Zaharia, 2011).

Operation Year	PM [£]
0	0
1	0
2	0
3	12,128
4	16,170
5	20,213
6	24,255
7	28,298
8	32,340
9	36,383
10	40,425
11	44,468
12	48,510
13	52,552
14	56,595
15	60,637
16	64,680
17	68,722
18	72,765
19	76,807
20	80,850

Table 10: Onshore Wind Turbine CMS, PM Operation and Maintenance Cost [Source: Puglia, 2013]

Despite numerous contacts of number of companies who use wind turbines, getting information on maintenance cost was almost impossible due to confidentiality of the information. James (2018), WeSET volunteer coordinator in her email on 2nd August 2018 stated that: “for wind turbines maintenance is done every 6 months, servicing all 5 turbines in a week. Generally, they are shut down one after another” (Appendix D). But no information on maintenance cost were available.

4.3.4.1.3 Photovoltaic Panel Unit Cost

A report by Energy news provided information unit cost of Sharp NU-RC300 panels which is presented in Table 11, reporting price of the PV model per watt.

Model	Power (Watt)	Price (£/W)
Sharp NU-RC300	300	£80.00

Table 11: Cost of Sharp PV Panel [Source: energynews, 2018]

4.3.4.2 Cost of buying electricity from the grid

Domestic electricity prices vary depending on different suppliers, seasons, time of the day and etc. As mentioned in Chapter 2, in Section 2.4.1., there are 6 major energy suppliers in Great Britain which are; British Gas, Npower, EDF, E. ON (PowerGen), SSE and Scottish

Power. Since the case study used in this research is Huntly, the Scottish Power domestic electricity prices are used for calculating price of electricity for domestic customers from 2011. Almost all these companies offer different options, such as:

- Pay monthly by direct debit or standing order
- Pay quarterly by direct debit, cash, cheque or postal order
- Pay weekly by payment book or card
- Pay as you use with a prepayment meter.

This research used to pay monthly by direct debit or standing order due to availability of valid data.

Table 14 presents the data available from Scottish Power archive of electricity prices in 2011. In this research, 2011 has been chosen as the baseline or so-called reference year. As shown in the Table below, there are three main columns; Electricity prices, excluding VAT and including VAT and each column is divided into three more columns. In electricity prices section there are three columns such as; supply area code, supply area and meter type.

In the "excluding VAT" and "including VAT" columns, there are three columns providing information about daily service charge, all day consumption and night consumption. This research used the daily service charge and all-day price inclusive of VAT for calculating consumer's electricity price from gird. Data in table 12 and Figure 4-2 are direct inputs from the original file; Scottish Power.m201212_standardv2.pdf (Scottish Power 2012).

Electricity Prices			excluding VAT			including VAT		
Supply Area Code	Supply Area	Meter Type	Daily Service Charge	All/Day kWh	Night kWh	Daily Service Charge	All/Day kWh	Night kWh
10	Eastern	Single Rate	26.09p	13.440p	---	27.39p	14.112p	---
10	Eastern	Two Rate	26.09p	15.596p	7.475p	27.39p	16.376p	7.849p
11	East Midlands	Single Rate	26.09p	13.315p	---	27.39p	13.981p	---
11	East Midlands	Two Rate	26.09p	15.775p	7.339p	27.39p	16.564p	7.706p
12	London	Single Rate	26.09p	14.175p	---	27.39p	14.884p	---
12	London	Two Rate	26.09p	16.210p	7.380p	27.39p	17.021p	7.749p
13	Manweb	Domestic 'S'	26.09p	14.780p	---	27.39p	15.519p	---
13	Manweb	Economy 7	26.09p	17.047p	7.586p	27.39p	17.899p	7.965p
14	Midlands	Single Rate	26.09p	13.900p	---	27.39p	14.595p	---
14	Midlands	Two Rate	26.09p	15.956p	7.207p	27.39p	16.754p	7.567p
15	Northern	Single Rate	26.09p	13.833p	---	27.39p	14.525p	---
15	Northern	Two Rate	26.09p	16.099p	7.439p	27.39p	16.904p	7.811p
16	Norweb	Single Rate	26.09p	14.194p	---	27.39p	14.904p	---
16	Norweb	Two Rate	26.09p	16.571p	7.031p	27.39p	17.400p	7.383p
17	Scottish Hydro	Single Rate	26.09p	14.946p	---	27.39p	15.693p	---
17	Scottish Hydro	Two Rate	26.09p	16.903p	8.080p	27.39p	17.748p	8.484p
18	ScottishPower	Domestic	26.09p	13.182p	---	27.39p	13.841p	---
18	ScottishPower	White Meter No.1¥	26.09p	15.935p	7.775p	27.39p	16.732p	8.164p
19	SEEBOARD	Single Rate	26.09p	14.150p	---	27.39p	14.858p	---
19	SEEBOARD	Two Rate	26.09p	16.319p	7.097p	27.39p	17.135p	7.452p
20	Southern	Single Rate	26.09p	13.885p	---	27.39p	14.579p	---
20	Southern	Two Rate	26.09p	16.143p	7.295p	27.39p	16.950p	7.660p
21	SWALEC	Single Rate	26.09p	14.843p	---	27.39p	15.585p	---
21	SWALEC	Two Rate	26.09p	17.216p	7.204p	27.39p	18.077p	7.564p
22	SWEB	Single Rate	26.09p	14.966p	---	27.39p	15.714p	---
22	SWEB	Two Rate	26.09p	16.926p	7.905p	27.39p	17.772p	8.300p
23	Yorkshire	Single Rate	26.09p	13.718p	---	27.39p	14.404p	---
23	Yorkshire	Two Rate	26.09p	16.020p	7.345p	27.39p	16.821p	7.712p

Table 12: Scottish Power Electricity Domestic Prices [Source: Scottish Power (2012)]

Figure 4-2 illustrates the supply area map provided by Scottish power. The main area selected for this research is related to north Scotland with single rate meter type and this area is marked with code 17 in figure 4-2 shown below (Scottish Power 2012).

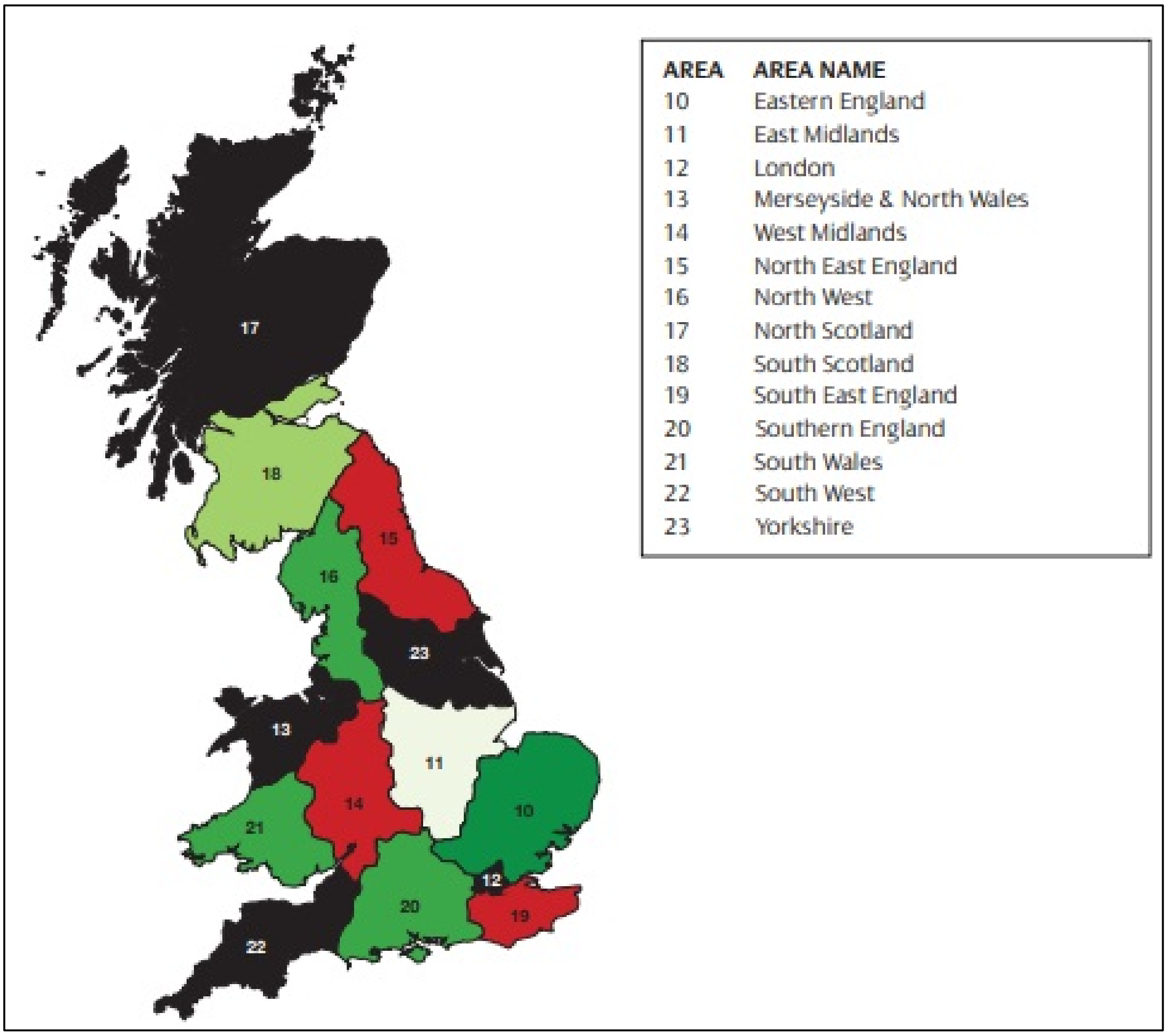


Figure 4-2: Scottish Power Supply Area [Source: Scottish Power, 2018]

Table 13 presents an example of "price of electricity" for domestic customers after taking the data from Table 13 for north Scotland with the addition of a daily service charge and an all-day kWh price of electricity; Column 1 presents the date (daily) and the column 2 presents the price including VAT in £ per kWh which is combination of daily service charge and all-day price kWh.

Data for domestic electricity prices was collected from Scottish power from 2011 to 2019 and this data has been used in this research for all calculations made. After 2019, a 5% increase of prices is used as a price escalator (BBC, 2018; Williams, 2018). Table of domestic electricity prices from 2011 to 2035 presented in Appendix C.

Date	Price + VAT (£/kWh)
01/01/2011	0.3380
02/01/2011	0.3380
03/01/2011	0.3380
04/01/2011	0.3380
05/01/2011	0.3380
06/01/2011	0.3380
07/01/2011	0.3380
08/01/2011	0.3380
09/01/2011	0.3380
10/01/2011	0.3380
11/01/2011	0.3380
12/01/2011	0.3380
13/01/2011	0.3380
14/01/2011	0.3380
15/01/2011	0.3380
16/01/2011	0.3380

Table 13: Scottish Power Domestic Electricity Price January 2011 [Source: Scottish Power (2012)]

4.3.4.3 Cost of Land

Cost of land is another important input data for this research, which has a significant influence on the results produced as part of this research. The importance arises from different types of land and different prices. One of the challenges for this research is associated with collection of data on land in Scotland, Table 14 presents the Knight Frank Scottish Farmland Index from 2007 to 2017 by head of rural research (Shirley, 2018).

Table 14 is comprised of six columns; column 1 presents the quarter, column 2 shows price of good arable land, column 3 presents the cost of average arable land, column 4 shows cost of arable/grass land, column 5 presents price of hill land and column 6 presents cost of unweighted average land. All prices presented in pound sterling (inclusive VAT) per acres (£/acres). This table is a direct input from Knight Frank; Scot Farm H2 2017_WEB.pdf file received from Shirley (2018) via email on 29th March 2018.

Quarter	Good arable (£/acres)	Average arable (£/acres)	Arable/Grases (£/acres)	Hill (£/acres)	Unweighted average (£/acres)
2007 Q4	3,700	3,300	3,000	375	2,305
2008 Q2	4,100	3,650	3,125	400	2,535
2008 Q4	4,500	4,000	3,250	425	2,765
2009 Q2	4,875	4,125	3,375	450	2,940
2009 Q4	5,250	4,250	3,500	475	3,115
2010 Q2	5,700	4,255	3,500	500	3,305
2010 Q4	5,850	4,450	3,475	515	3,348
2011 Q2	634	4,475	3,500	571	3,472
2011 Q4	6,825	4,501	3,500	600	3,585
2012 Q2	7,053	4,633	3,603	614	3,687
2012 Q4	7,258	4,786	3,783	659	3,829
2013 Q2	7,698	5,057	3,846	692	3,994
2013 Q4	8,468	5,394	3,974	704	4,265
2014 Q2	8,612	5,502	4,054	704	4,331
2014 Q4	8,956	5,612	4,013	718	4,417
2015 Q2	9,046	5,612	4,013	732	4,437
2015 Q4	9,046	5,425	3,946	673	4,366
2016 Q2	9,046	5,154	3,920	673	4,357
2016 Q4	9,046	5,154	3,659	673	4,223
2017 Q2	9,200	5,154	3,622	707	4,253
2017 Q4	9,319	5,139	3,622	719	4,271

Table 14: Scottish Farmland Index [Source: Knight Frank Research (2018)]

This research has chosen the unweighted average land prices (the last column in table 14) for calculating the cost of land for renewable farm as arable land would not be an ideal land for farm purpose for area such as Scotland where it can be used for agriculture purposes. Arable land characterised by the production of crops for food or feed supply purposes therefore would not be used for renewable farm land (Benchman, 2006). One of the important assumptions made for this research is that land would be used exclusively for renewable energy generation and not in combination with agriculture.

4.3.5 Land Availability

Land availability is another key input data in this research as it is one of the main constraints. It directly affects the type of technology which can be used in the available space. However, sufficient information on land availability in the chosen area was not available. Data, Statistics and Outcomes in Scottish Government, UK Land and Farms and Knight Frank Agency in Scotland were contacted on several occasion via email and phone but these types of data were not hold by the agency. As initial idea of contacting agencies and land organisation in Scotland did not work due to lack of available information on land availability. Estimation of 230 acres land limit is made in the calculation according to unweighted average land advertised in rightmove.com and onthemarket.com (Right move, 2018, onthemarket, 2018)

4.3.5.1 Size of the system

System size varies for different types of technology options. Table 15 illustrates the land requirement for different sizes of solar photovoltaic system and wind energy. There are two columns in the table; column 1 presents the technology type and column 2 presents the size of land required in acres per Megawatt generated. This data is taken from the National Renewable Energy Laboratory (NREL) research and last time it was updated was on February 2016 full table presented in Appendix E. NREL is specialised in renewable energy and energy efficiency research and development (NREL, 2019).

Technology Type	Size (acrez/MW)
PV<10 kW	3.2
PV 10-100 kW	5.5
PV 100-1000 kW	5.5
PV 1 10 MW	6.1
Wind <10 kW	30
Wind 10-100 kW	30
Wind 100-1000 kW	30
Wind 1-10 MW	44.7

Table 15: Size of renewable system [Source: NREL (2019)]

This research uses the PV panel 300 kW, wind turbine sizes of; 55kW, 800kW, 900kW, 1.5MW and 2MW, therefore, the system size chosen is in accordance with Table 18.

4.3.6 Government policy

As discussed in chapter 2, section 2.3, Government policies are introduced to help boost of the investment on renewable technology and they were successful with rise of investment in solar and wind energy systems over decades. In UK one of the main schemes were feed-in tariff (FIT) which was introduced in 2010 to encourage placement of small scale, low carbon electricity generation of up to 5 megawatts.

FIT would provide additional revenue on electricity generated by the system and excess of electricity generated. Payments are made based on meter reading submitted to the energy supplier. Table 16 presents the price of tariff on electricity exported to the grid given in pence per kilowatt per hour, the table comprises three columns; column 1 shows description which is the type of technology, column 2 shows application date that is where the system applied for the tariff and column 3presents tariff price in pence/kWh. This data was published by Ofgem (2018) report on feed in tariff rates. However, this scheme closed to new applicants from 1st April 2019 and the reasons behind this were discussed in detail in chapter 2.

Description	Applicable Date	Tariff (p/kWh)
Non-Solar Panel	01/04/2010 - 30/11/2012	3.82
	01/12/2012 - Present date	5.38
Solar Panel	01/04/2010 - 31/07/2012	3.82
	01/08/2012 - Present date	5.38

Table 16: Feed-in Tariff - Export [Source: Ofgem (2019)]

As mentioned earlier in the FIT scheme applicants would receive money for every kWh electricity produced by the system (as long as system is 5 MW or smaller). Table 17 illustrates the feed in tariff for stand-alone solar PV system between 0 to 5MW, where column 1 presents the Applicable date as price of tariff changed over time and column 2 presents the tariff price in pence per kilowatt per hour. As illustrated, in the same table, there was a significant fall in tariff price since it introduced in April 2010 from 38.043 pence/kWh to 0.15 pence/kWh (Ofgem, 2018).

The biggest observed decrease happened a year after introducing the scheme and this decrease mainly related to the increase of number of applicants, especially for solar PV. According to Ofgem 2016, solar PV had 75% of the total installation in a year one, followed by 94% in the second year of introducing the scheme. 83% was measured in its 3rd year, followed by 79% in the 4th year and 74% of renewable installation belonged to solar PV installation on the 5th Year of introducing FIT. Significant rise in solar PV installation led to quite noticeable fall in price of electricity generated by solar PV. From 2010 to 2018 more than 50% of total installed capacity belonged to domestic installations. The South West of England had the highest number of installations with 115,848 followed by South East with 106,507 installations (Ofgem, 2018).

Applicable Date	Tariff (p/kWh)
1 April 2010 - 31 July 2011	38.43
1 Aug 2011 - 31 July 2012	10.62
1 Aug 2012 - 31 Oct 2012	8.47
1 Nov 2012 - 30 April 2013	8.22
1 May 2013 - 31 March 2014	7.92
1 April 2014 - 30 Sept 2014	7.45
1 Oct 2014 - 31 March 2015	7.19
1 April 2015 - 30 June 2015	6.83
1 July 2015 - 31 Dec 2015	6.59
1 Jan 2016 - 7 Feb 2016	6.28
8 Feb 2016 - 31 March 2016	0.95
1 April 2016 - 30 June 2016	0.81
1 July 2016 - 31 Dec 2016	0.67
1 Jan 2017 - 31 March 2017	0.45
1 April 2017 - 30 June 2017	0.37
1 July 2017 - 30 Set 2017	0.31
1 Oct 2017 - 31 Dec 2017	0.25
1 Jan 2018 - 31 March 2018	0.2
1 April 2018 - 30 June 2018	0.15

Table 17: Feed in Tariff Stand-alone Solar Photovoltaic 0-5000kW [Source: Ofgem (2019)]

Another renewable technology installation eligible for the FIT scheme is onshore wind turbine for installations of maximum power of 5 MW. Table 18 presents the FIT price for generated electricity by wind turbine and this table consist of three column; column 1 presents the applicable date which refers to the date FIT scheme introduced and each changes made to the scheme over years, column 2 shows total installed capacity of wind turbine in kilowatt per hour that is divided into installation capacity of 500 to 1000 kW and 1500 to 5000 kW and column 3 presents the tariff price in pence per kilowatt per hour (p/kWh).

Wind turbine case is very similar to solar PV as it also suffered a dramatic decrease in the price of tariff due to significant rise in the number of installed systems. Wind system after Photovoltaic had the highest number of installations with 13% in the first year (2010), 4% in the second year (2011), 11% on the third year, 14% on the fourth year and 17% in the fifth year (2015). Comparing the number of installations between 2010 and 2013, there is a very small difference, however it is very noticeable that there is a rise of installations in 3rd year which as a result had drop in tariff. Scotland had the highest number of wind system installations in 2018 with 3,159, followed by East of England with 833 wind system installations (Ofgem, 2018).

Applicale Date	Total Installed Capacity (kW)	Tariff (p/kWh)
1 April 2010 - 30 Nov 2012	500-1500	12.4
	1500-5000	5.84
1 Dec 2012 - 30 March 2012	500-1500	11.32
	1500-5000	5.35
1 April 2012 - 31 March 2014	500-1500	11.32
	1500-5000	4.8
1 April 2014 - 30 Sept 2014	500-1500	9.07
	1500-5000	3.84
1 Oct 2014 - 31 March 2015	500-1500	8.16
	1500-5000	3.46
1 April 2015 - 30 Sept 2015	500-1500	7.26
	1500-5000	3.07
1 Oct 2015 - 7 Feb 2016	500-1500	6.53
	1500-5000	2.76
8 Feb 2016 - 31 March 2016	500-1500	5.98
	1500-5000	0.94
1 April 2016 - 30 June 2016	500-1500	5.36
	1500-5000	0.93
1 July 2016 - 31 Dec 2016	500-1500	4.82
	1500-5000	0.93
1 Jan 2017 - 31 March 2017	500-1500	3.75
	1500-5000	0.88
1 April 2017 - 30 June 2017	500-1500	3.44
	1500-5000	0.89
1 July 2017 - 30 Set 2017	500-1500	3.08
	1500-5000	0.87
1 Oct 2017 - 31 Dec 2017	500-1500	2.76
	1500-5000	0.86
1 Jan 2018 - 31 March 2018	500-1500	2.37
	1500-5000	0.73
1 April 2018 - 30 June 2018		2.21
		0.68

Table 18: Feed in Tariff Onshore Wind Turbine [Source: Ofgem (2019)]

4.4 CORE EXCEL MODEL

This section recalls the overall system model for this research, as mentioned where the feasibility and sensitivity analysis of the construction of renewable power plants including wind turbines and solar panels has been discussed. The considered wind and solar PV farm is for Huntly with a limited number of households and the reason explained for that are explained above.

The current issue is to find the most economically viable combination of wind turbine and solar PV panels considering their type using the simulation and optimization method. Considering a discrete nature of the problem and the fact that model requires a sensitivity analysis and behavioral analysis of the target variables, both Excel and Vensim software are used for the simulation and this research overall. This section provides an overview of modelling assumptions for this research and mathematics formula used to define the relationship between components followed by creation of spread sheets in excel.
As mentioned, Excel serves two purposes, first as a background database of constants used in Vensim and second, as a user interface in which renewable farm data is entered to develop scenarios and control the level at which the renewable farm boundary is drawn.

4.4.1 Modelling Assumptions

The modeling assumptions for this research are as follows:

1. Project costs includes the cost of purchasing wind turbines and solar panels, components operation cost, maintenance costs (O&M cost) and land costs.
2. Operation and maintenance cost of wind turbine are calculated based on the failure time per year as well as production lost due to turbine failure.
3. The cost of buying wind turbines, solar panels and land is met through a loan.
4. Each of the solar panels and wind turbines have their own installations cost as well as operation and maintenance costs (O&M), which are included in the modeling. Chosen wind turbines have 5 different capacity types.
5. Project revenues include incomes from saving on not buying electricity from the grid, revenues from electricity sales to the grid and revenue from tariffs introduced by the government.
6. Electricity produced from the renewable farm will initially be used to supply electricity for the community. If the amount of production is more that community consumption, it will be sold to the grid at the price approved by the network. Also, any shortfall of electricity will be supplied from the grid.
7. The government considers tariffs with respect to farm capacity (less than and including 5 MW) in support of renewable energy development (For application made between January 2010 and April 2019)

The present modeling structure includes several sectors of renewable energy; renewable electricity sales to the grid, renewable electricity generation, and financial aspect of the generation and CO_2 savings.

4.4.2 Spread sheets

The spread sheet is created for the mathematical calculation of the model and it has seven sheets (Renewable Generation, Renewable Consumption, Financial Cal, Power Coefficient Data, Feed-in-Tariff, Sensitivity Analysis and Formula). These sheets are described together with the mathematical expression and formulas used.

4.4.2.1 Wind Turbine Electricity Generation

The renewable generation sheet consists of two main sections such are, solar panel electricity generation and wind turbine electricity generation. The wind turbine electricity generation is presented in Table 19, the first column presents the wind turbine electricity generation in kWh with relevant factors; date, mean wind speed (meter/second/day), power coefficient[14], generation from each 5 different type of wind turbine described in Table 8 with energy calculation which is explained in details in equation 4.4-1, air density and total turbine generation in kilo watt per hour.

The following columns contains the number of wind turbines used and each of their turbine blade length in meter units and swept area in square meters. Further sections belong to associated cost of wind turbine such as; price of wind turbine in sterling pound per unit and operation and maintenance cost (O&M) per day. This section of the renewable generation sheet calculates the energy generation as well as cost of turbine calculation based on the optimised number of wind turbines required for given wind speed per day and identified constraints are explained further in detail.

[14] Power coefficient is a measurement of how efficiently wind turbine converts the energy in the wind into electricity (Dodson, Busawon and Jovanovic, 2005).

Wind Turbine Electricty Generation																							
			Wind Turbine Electricty Generation (kW)						No. of Turbines					Turbin blade Length					Swept Area				
Date	Mean Wind Speed (m/s/day)	Power Coeffiecient Cp	2MW (kW/h)	1.5 MW (kW/h)	900 KW (kW/h)	800 KW (kW/h)	55 KW (kW/h)	Total Turbine Generation (kWh)	2MW	1.5 MW	900 kW	800 kW	55 kW	2MW (m)	1.5 MW (m)	900 kW (m)	800 kW (m)	55 KW (m)	2MW (m2)	1.5 MW (m2)	900 kW (m2)	800 kW (m2)	55 kW (m2)
01/01/2011	6.17	0.46	16871335	7438291.8	0	0	0	24309.62728	2	1	0	0	0	41	38.5	22	24	8	5281	4656.6	1520.53	1809.56	201.06
02/01/2011	4.63	0.4	6189212.7	2728721.2	0	0	0	8917.933921	Price of Turbines (£/Unit)														
03/01/2011	3.09	0.29	1329534.6	586169.73	0	0	0	1915.704324	2139000	1863000	966000	966000	220800										
04/01/2011	3.60	0.29	2111251.7	930815.83	0	0	0	3042.067514	O&M cost (per day)														
05/01/2011	4.12	0.4	4346881.9	1916468.1	0	0	0	6263.350024	361.64384	135.61644	0	0	0	Source in Infomration									
06/01/2011	6.69	0.46	21450419	9457133.7	0	0	0	30907.55274		Air density (Kg/m3)		Power Coeficiant											
07/01/2011	3.09	0.29	1329534.6	586169.73	0	0	0	1915.704324		1.23		0.5	Bets Law/Netz Limit										
08/01/2011	3.60	0.29	2111251.7	930815.83	0	0	0	3042.067514															
09/01/2011	4.12	0.4	4346881.9	1916468.1	0	0	0	6263.350024		O&M Cost £/kWh		Reference Irena - information											
10/01/2011	4.12	0.4	4346881.9	1916468.1	0	0	0	6263.350024		£1.32	£0.01												
11/01/2011	4.63	0.4	6189212.7	2728721.2	0	0	0	8917.933921															
12/01/2011	3.09	0.29	1329534.6	586169.73	0	0	0	1915.704324		Or	20% total Levelised Cost per kWh												
13/01/2011	1.03	0	0	0	0	0	0	0		Total Capacity of wind turbins													
14/01/2011	3.60	0.29	2111251.7	930815.83	0	0	0	3042.067514		5.5													
15/01/2011	7.20	0.48	27955884	12325285	0	0	0	40281.16984															
16/01/2011	7.72	0.48	34384515	15159562	0	0	0	49544.07734	cost (per day)	0.090411	9E-05												
17/01/2011	3.60	0.29	2111251.7	930815.83	0	0	0	3042.067514		33000	90.411	£/MW/Day											
18/01/2011	3.60	0.29	2111251.7	930815.83	0	0	0	3042.067514															
19/01/2011	3.60	0.29	2111251.7	930815.83	0	0	0	3042.067514															
20/01/2011	1.03	0	0	0	0	0	0	0															

Table 19: Wind Turbine Electricity Generation (kWh)

The expression for the amount of the power(P_T), that wind turbine is capable of generating is given by the equation 4.4-1, where the u is a wind speed in meter/second, ρ is the air density[15] in kilogram/m3, A is the area swept by the rotor in m2 and power coefficient, $C\rho$ which is a ratio of power extracted by the turbine to the total power of wind $C_P = P_T/P_{Wind}$ (Gourieres, 1982; Letcher, 2017).

$$P_T = \frac{1}{2}\rho A u^3 Cp$$

Equation 4-2

The power coefficient is a nonlinear function of the top speed ratio which changes with wind velocity (Dodson et al, 2005; James, 2005). Table 20 and Figure 4-3 present 2 MW turbine power coefficient used in this study which is always smaller than wind speed,P_{Wind}, and is known as Betz Limit which is the theoretical maximum coefficient of power for any wind turbine. Albert Betz a well-known German physicist calculated that wind turbine cannot convert more than 59% of the kinetic energy of the wind into mechanical energy by turning a rotor which is known as Betz Limit. This is known as the theoretical maximum coefficient of power for any wind turbine (Blackwood, 2016; Letcher, 2017).

Power Coefficient		Wind Speed	Power Coefficient		Wind Speed
0	←	0	0.29	←	13
0	←	1	0.23	←	14
0.12	←	2	0.19	←	15
0.29	←	3	0.15	←	16
0.4	←	4	0.13	←	17
0.43	←	5	0.11	←	18
0.46	←	6	0.09	←	19
0.48	←	7	0.08	←	20
0.49	←	8	0.07	←	21
0.5	←	9	0.06	←	22
0.49	←	10	0.05	←	23
0.42	←	11	0.05	←	24
0.35	←	12	0.04	←	25

Table 20: Power Coefficient for 2MW Enercon E28 Wind Turbine [Source: Enercon, 2018]

[15] Air Density chosen for this calculation is 1.225 kg/m3, it’s a value at the sea level at 15 degree C (Emerging Technology, 2011)

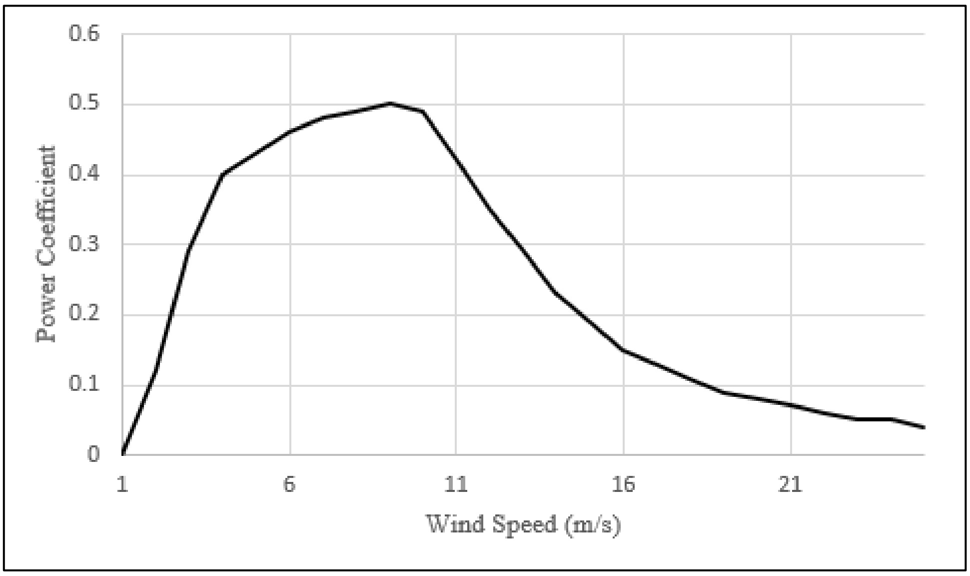


Figure 4-3: Power Coefficient (Cp) vs Wind Speed (m/s) for 2MW Enercon E28 Wind Turbine

4.4.2.2 Total cost of wind turbine

Cost of wind turbine is calculated by number of wind turbines multiplied by the price of relevant turbine which shown in equation 4.4-2.

$$Cost\ of\ \ Wind\ Turbines = \sum_i No.of\ Turbines_i \times Price\ of\ Turbines_i\ \ i = 55kW, 800kW, 900kW, 1.5MW, 2MW$$

Equation 4-3

4.4.2.3 Operation and Maintenance Cost of Turbine and Panels

Equation 4.4-4 presents the fixed operation and maintenance cost of wind turbine and solar panels in which a fixed amount assigned to each turbine size and panels.

$$O\&M\ Cost = \sum_i No.of\ Turbines_i \times Unit\ O\&M\ Cost\ of\ each\ Turbines_i + No.of\ Pannels \times Unint\ O\&M\ cost\ of\ each\ Pannels$$

Equation 4-4

$i = 55kW, 800kW, 900kW, 1.5MW, 2MW$

4.4.2.4 Solar Panel Electricity Generation

Electricity generation from solar panel is presented in Table 21 with generation section which contains different components for generating electricity from panel such as Date, starting from 1st January 2011, Daily total global radiation (kWh/m2) the data for which is taken from MetOffice which explained in table 7, daily total global radiation (kWh/m2), total solar panel area (m2), performance ratio[16], solar panel efficiency (%), and relevant information in regards to cost of panel.

Solar Pannel Electricty Generation

Date	Daily Total Global Radiation (kWh/m2)	Total Solar Panel Area (m2)	Performance Ratio (%)	Number of Panel (Module) (Unit)	Solar Pannel efficiancy (%)	Total PV Solar Panel Electricty Generation (kWh)
01/01/2011	0.14	0.000	0.75		0.18	-
02/01/2011	0.21	Price of each Sharp PV Panel (Module) (£/300W)	Price of 12 Solar Panels Pack Including VAT(£) each Module 300W			-
03/01/2011	0.14	238.5	2,862	Source in Information Sheet		-
04/01/2011	0.25					-
05/01/2011	0.48	O&M cost of Solar Panels (£/day)	1% of total Cost of the system			-
06/01/2011	0.64	35.8	2011 to 2017 1.5%	2017 to 2022 1%	2022 to 2035 0.7%	-
07/01/2011	0.57	300 Wp / Mono: NURC300 Sharp				-
08/01/2011	0.32	Each Cell Dimention (m2)	Each Panel (Module) Area (m2)		Total Number of Solar Pannels	-
09/01/2011	0.49	0.0000565	1.6434		0	-
10/01/2011	0.30	Each Panel (Module) Dimention	Dimensions (LxHxB) (mm)	1660 x 990 x 50		-
11/01/2011	0.70					-
12/01/2011	0.42	Every 1MW requires 3334 Panles		1MW = 1,000,000 W		-
13/01/2011	0.52	3334		Each Panel 300 W		-
14/01/2011	0.80			Always Round UP number of Panels	3333.333333	-
15/01/2011	0.32					-
16/01/2011	0.77	Inverter for PV Solar Farm				-
17/01/2011	0.63	ABB Inverter 1MW	ABB Inverter 500kW			-
18/01/2011	0.78	£135,500.00	£67,750.00			-
19/01/2011	0.45					-

Table 21: Solar Panel Electricity Generation

[16] The performance ratio measures the quality factor of PV panel in percentage, usually ranging between 50%-90% depending on type of the panel.

The components taken into account for electricty generation from solar panel are presented in Table 22. Equation 4.4-5 presents the mathematic formula used for calculating electritcy generated from solar panel. Constants that have been used in the equation are given in the table 26 and they solar panel efficnecty for the particualr panel is 18% with performance ratio of 75%. The area selected is 1.64 square meter. The energy generated from panel (P) is calculated from, total solar panel area (A) in m2, solar panel efficiency(r) in %, sun radiation (H) in kWh/m2 and performance ratio of solar panel (PR) in % which is presented in equation 4.4-5.

$$P = ArHPR$$

Equation 4-5

Capacity of each panel (W)	O&M cost of Solar Panel (£/day)	Solar Panel Efficiency (%)	Each Panle (Module) Area (m2)	Performance Ratio (%)
300	35.8	0.18	1.64	0.75

Table 22: Solar Panel Characteristics

4.4.2.5 Daily Feed-in-Tariff Charges

As discussed in Chapter 2, subchapter 2.3.4. FIT scheme introduced from 2010 to help increasing investment on renewable energy generation, but over time due to viability of renewable technologies government decided to end the tariff in April 2019. As this research looks at renewable farm in 2011 FIT charges applied in this research calculation with considering changes made over time. Table 23, presents daily FIT changes in 6 columns; column 1 shows date, column 2 shows price feed-in-tariff for electricity generation from onshore wind turbine with install capacity of 500 to 1500 kWh , column 3 presents price of feed-in-tariff for electricity generation from onshore wind turbine with install capacity of 1500 to 5000 kWh, column 4 presents price of feed-in-tariff for electricity generation from standalone solar system with install capacity of 0 to 5000kWh, column 5 shows price of exporting electricity from onshore wind turbine to the grid and column 6 presents price of exporting electricity from solar system to the grid.

Date	Feed-in-Tariff for Electricity Generation from Onshore Wind Turbine - Total Install Capacity of 500-1500 kW (£/kWh)	Feed-in-Tariff for Electricity Generation from Onshore Wind Turbine Totall install capacity of 1500-5000 kW (£/kWh)	Feed-in-Tariffs for Electricity Generation from Stand Alone Solar System Total install capacity of 0-5000 kW (£/kWh)	Exporting Electricty to the Grid from Onshore Wind Turbine System (£/kWh)	Exporting Electricity from Solar System (£/kWh)
01/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
02/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
03/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
04/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
05/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
06/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
07/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
08/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
09/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
10/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
11/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
12/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
13/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
14/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
15/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372

Table 23: Daily Feed-in-Tariff Charges (£/kWh) [Source: Ofgem, 2019]

4.4.2.6 Community Daily electricity bill with electricity generation

Community daily electricity bill is calculated from Scottish Power electricity prices for the relevant time (discussed in details in subsection 4.3.4.2). Table 24 presents community bill from grid, as presented this table has 3 columns; column 1 shows the date, column 2 shows the price of electricity +VAT from Scottish Power and column 3 presents community electricity bill in pound per kilowatt per hour. Community electricity bill calculated from community electricity consumption multiplied by electricity price.

Date	Price + VAT (£/kWh)	Community Electricty bill (£/kWh)
01/01/2011	0.33795	£574.85
02/01/2011	0.33795	£574.52
03/01/2011	0.33795	£198.10
04/01/2011	0.33795	£314.57
05/01/2011	0.33795	£567.08
06/01/2011	0.33795	£567.42
07/01/2011	0.33795	£198.10
08/01/2011	0.33795	£314.57
09/01/2011	0.33795	£567.08
10/01/2011	0.33795	£566.07
11/01/2011	0.33795	£565.73
12/01/2011	0.33795	£198.10
13/01/2011	0.33795	£0.00
14/01/2011	0.33795	£314.57
15/01/2011	0.33795	£565.73

Table 24: Community daily Electricity bill (£/kWh)

4.4.2.7 Community Electricity Consumption, Generation and Grid Connection

Community electricity consumption and optimised renewable energy generation are key elements for evaluating economic viability of renewable farm. This research is considered grid connected renewable farm in which excess electricity generated by renewable farm is sold to grid and community shortfall is purchased from grid. Table 25 comprise 5 columns; column 1 presents date, column 2 shows daily community consumption in kilowatt per hour, column 3 presents daily renewable electricity generation from optimised wind and solar combination in kilowatt per hour, column 4 shows selling/buying electricity to/from grid in electricity excess/shortfall in kilowatt per hour and column 5 presents the amount of electricity bought from the grid in kWh. Data presented in Table 27 is sample of optimisation results which will be reported in details in Chapter 6.

Date	Community Consumption (kWh)	Renewable Generation (kWh)	Grid (kWh)	Buying Electricty from the Grid (kWh)
01/01/2011	1698.32	7438.26	5739.94	0.00
02/01/2011	1700.53	2728.72	1028.19	0.00
03/01/2011	1689.42	586.17	-1103.25	1102.83
04/01/2011	1698.12	930.82	-767.30	767.18
05/01/2011	1666.31	1916.47	250.16	0.00
06/01/2011	1679.45	9457.13	7777.68	0.00
07/01/2011	1701.77	586.17	-1115.60	1093.83
08/01/2011	1680.21	930.82	-749.39	749.18
09/01/2011	1678.17	1916.47	238.30	0.00
10/01/2011	1675.57	1865.23	189.66	0.00
11/01/2011	1674.08	2728.72	1054.64	0.00
12/01/2011	1667.47	586.17	-1081.30	1080.83
13/01/2011	1679.32	0.00	-1680.00	1680.00
14/01/2011	1702.58	930.82	-744.18	744.18
15/01/2011	1674.63	12325.29	10651.29	0.00

Table 25: Community Electricity Consumption, Renewable Electricity Generation and Grid Connection kWh

4.5 SUMMARY

Recall, the function of this research model is to evaluate the economic viability of renewable electricity generation for a rural community. For this renewable generation farm five types of onshore wind turbine and one type of PV solar panel is selected. This chapter identified the modelling approach used and described mathematical equations for the modelling.

In general, only limited household electricity consumption data is available across the UK; however, it was found that detailed data for household consumption was identified for North-East Scotland from research by Craig et al (2012) which is used extensively for this research.

All data required for this research has been recorded in an Excel model. Using this data Excel was used to build a discrete simulation model for this research. All mathematical equations required for the modelling exercise have been incorporated in Excel. The model will be used to calculate ROR and LCOE result of which presented in Chapter 6.

5 DEVELOPMENT OF THE MODEL

5.1 CHAPTER OVERVIEW

The main emphasis of this research is the economic viability of wind and solar farm for generating electricity at the community level rather than for individual household. One objective of this thesis is to model the optimal combination of onshore wind turbine and solar panel systems for electricity generation for a chosen community. Considering a discrete nature of the problem, the discrete event simulation (DES) tool is used which requires sensitivity analysis and behavioural measurement of targeted variable. DES is a method of simulating behaviour and performance of real-life process, facility or system.

After completing the excel core model with all the variables, constrains and defining relationships between variables, data is fed into Vensim software for optimisation simulation. Building the model started with building a DES model to test the economic viability of renewable farm for Huntly, town in North East Scotland. Recall, DES is the "Group Modelling I" in which the developed model optimises and then optimised outcomes are evaluated with SD, "Group Modelling II" which shows system reaction to changes in circumstances over time.

This chapter presents detailed development of the model in the Vensim software and discrete event simulation (DES) followed with illustrating system dynamics. The DES and SD are core engine developments built on techniques reported in Chapter 3 and based on constraints and assumptions given as part of the Chapter2.

5.2 MODELING IN VENSIM

The proposed Vensim software model presented in Figure 5-3 is defined, such that that all the parameters and all the variables used in Excel software are defined, and the simulation results are in line with the Excel results, which are detailed in Chapter 6. Vensim simulation-optimization capacity has made a suitable software for this research modelling. In this way, the model is simulated at each stage using the parameters introduced as decision parameters. Defined time period is 25 years (9135 days) and the output is calculated after that period due to lifetime of wind turbines. The value of the parameters selected is changed using the Kalman filtering algorithm, after which the simulation is executed again. Kalman filter is a mathematically powerful tool that have significant role in computer graphics as sensing of real world includes in the developed system (Maybeck, 1990).

In this research, Kalman Filtering is used to specify the method of searching between values of decision variables. The Kalman algorithm is a filtering algorithm that estimates the state of a dynamic system using a set of measurements involving errors over time. This filter usually provides more accurate estimation than a single measurement based on Bayesian inference and estimates the probability distribution of a common random variable over a period of time. This algorithm is implemented in two steps. In the prediction step, the Kalman filter provides an estimate of the current state of the variables under uncertainty (Kalman, 1960; Grewal and Andrews, 2001).

Figure 5-1, presents the structure of the developed and tested model from system analysis to the final stage (results). It gives an overall view of the whole process of developing the model from start to an end. As presented first the qualitative approach takes place which is the analysis of the system. After that hypothesis of the system developed followed by development of DES model first then model validates and results from DES presented. After that SD model developed, validates and results presented.

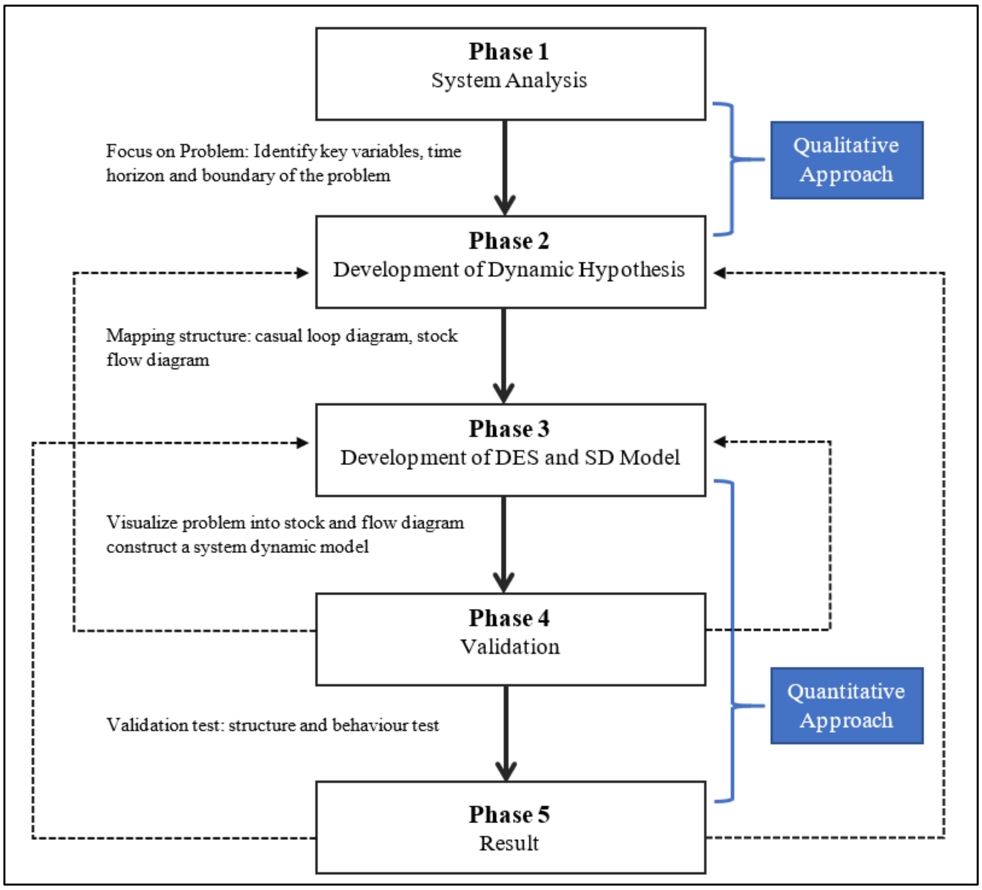


Figure 5-1: Model Structure

5.2.1 Optimising the Research Model

In this research, Kalman Filtering is used to specify the method of searching between values of decision variables. The Kalman algorithm is a filtering algorithm that estimates the state of a dynamic system using a set of measurements involving errors over time. This filter usually provides more accurate estimation than a single measurement based on Bayesian inference and estimates of the probability distribution of a common random variable over a period of time. The filter is taken from the name of Rudolf E. Kalman, one of the founders of the theory. This algorithm is implemented in two steps. In the prediction step, the Kalman filter provides an estimate of the current state of the variables under uncertainty (Kalman, 1960; Grewal and Andrews, 2001). In system dynamics with unobserved variables it is desirable, but impossible to know, the state of all variables at all times. However, if values for some of the variables are known good estimate of the values of other variables can be made. Kalman filtering combines data measurement and model output to make indirect measurement of the model variables (Coyle, 1996; Vensim, 2019).

The developed model runs the DES in step which is defined in the software and the model is designed in step by step simulation. Figure 5-2 illustrates the model structure, where input variables will be simulated and given output compared to goal variables. N presents number of steps in the simulation. Each step consists of a number of steps that can be adjusted using the software. The method used to simulate each step is known as Euler method. This method approximates and simulates discrete equations using the differential equations present in the model.

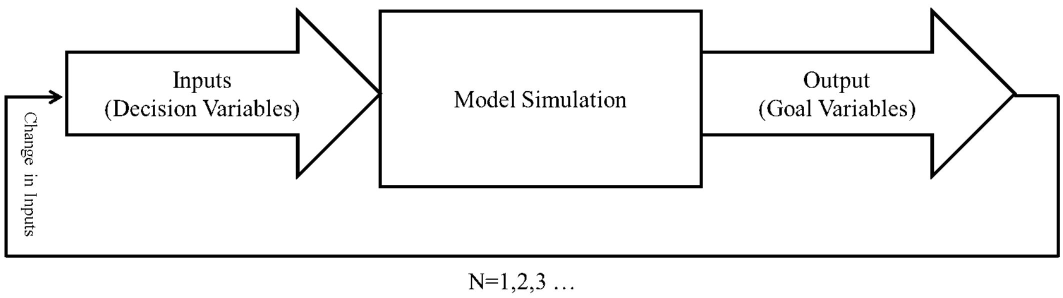


Figure 5-2: DES Model Structure

5.3 Research Model

Research Model developed is divided into 15 sections presented in Figure 5-3. The presented modeling structure includes several sectors of renewable energy; renewable electricity generation, consumption, renewable electricity sales to the grid and financial aspect of the generation and environmental aspect. As presented in Figure 5-3, the research model has three main outcomes:

1. Production: Total Capacity Installed
2. Costs: Levelised Cost of Electricity (LCOE)
3. Incomes/Revenue: Rate of Return on Investment (ROR)

In order to achieve outcomes listed, 12 other sections defined, starting from generation of electricity from wind turbine, solar PV panel electricity generation, cost of buying wind turbine and solar panel with associated operation and maintenance (O&M) cost, income from government feed-in tariff; income from electricity generated and selling the excess of electricity to the grid, cost of buying land and total electricity generated from renewable farm.

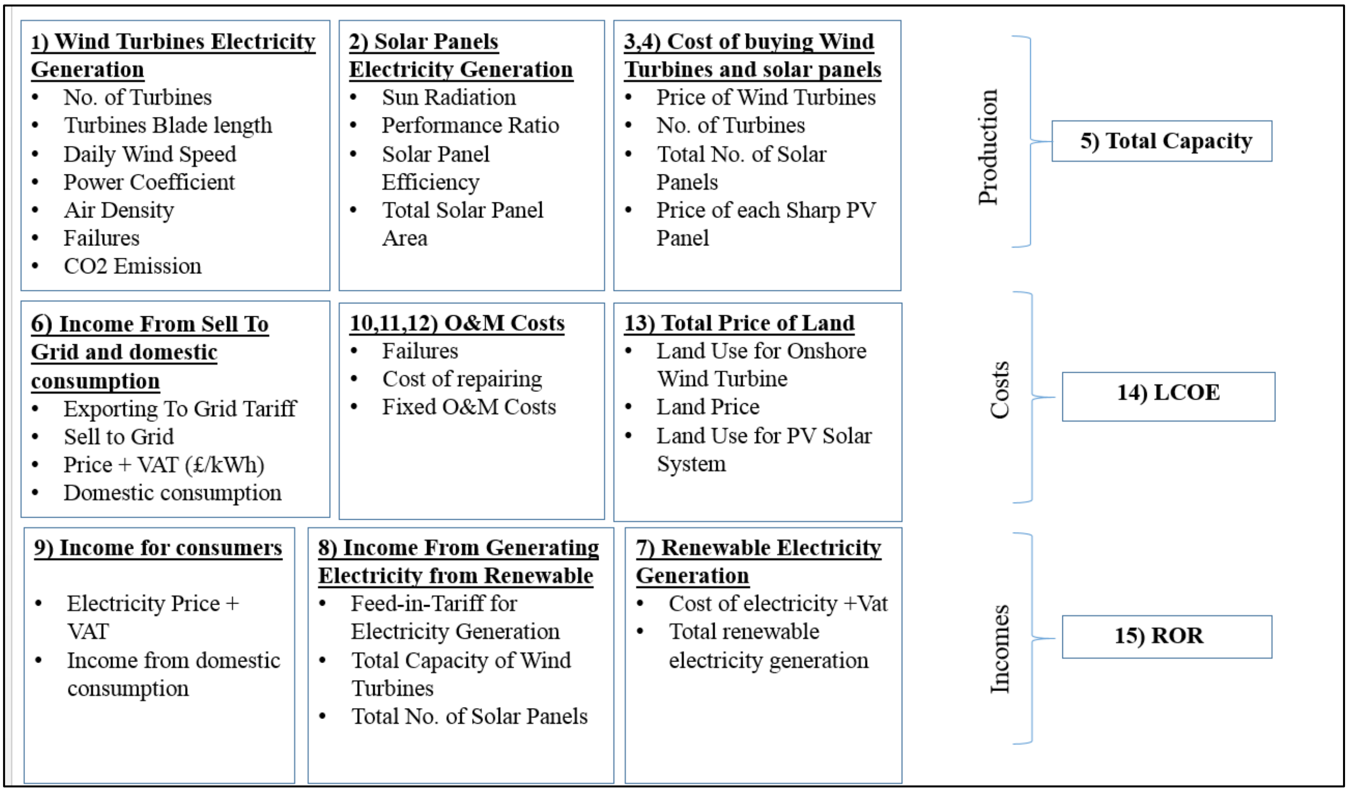


Figure 5-3: Different Sections of the Research Model

5.4 DES MODEL

This section describes each stage of the modelling by presenting the whole developed model presented in Figure 5-4 is divided in smaller chunks which are explained separately in this chapter. The developed model consists of casual loops, stock and flow. In the developed model that is built in Vensim all data for input variables are taken from the Excel sheets presented in Chapter 4.

In this research the developed model runs the DES simulation in step which is defined in the software and the model is designed in step by step simulation. The method used to simulate each step is known as Euler method. This method approximates and simulates discrete equations using the differential equations present in the model. Therefore, the developed model first optimises with DES (group modelling I) then SD model (Group Modelling II) is developed to define the relationship between defined components with optimised result gained from DES.

As presented in figure 5-4, diagramming the system provides clear visualisation of the structure and behavior of the system. Developed model is a simplification of reality and daily time step chosen for DES modelling and yearly time step for SD modeling which is explained in more details in the next section. There are two main types of diagrams used for DES and SD;

- Casual Loop Diagram: which is used to capture the individual components within the system and qualitatively document how they interact to each other. Feedback loops are revealed as the diagram evolves. There are two types of feedback loops; positive feedback and negative feedback. Compering feedback loops drive system behavior.
- Stock and Flow Diagram: Stock (Levels), illustrates within a box and requires an initial value at the start of a simulation. It accumulates of inflows less outflows over time. Flow (Rates), determine how stock values change over time and constants which is a fixed value simulation period that initialises stock values or constrain flow values (See Appendix F).

Adding all of components interactions together illustrates the overall system structure. Frequently, DES and SD models combine the two approaches. In this research the developed model combined both types of diagram. Time base chosen for the model is daily in DES model for optimising the model and yearly time base is chosen for SD as system dynamics illustrates the relationship between rate of return on investment and future investment in capacity of renewable generation yearly.

Step by step development of the research model is described in more details in the next section.

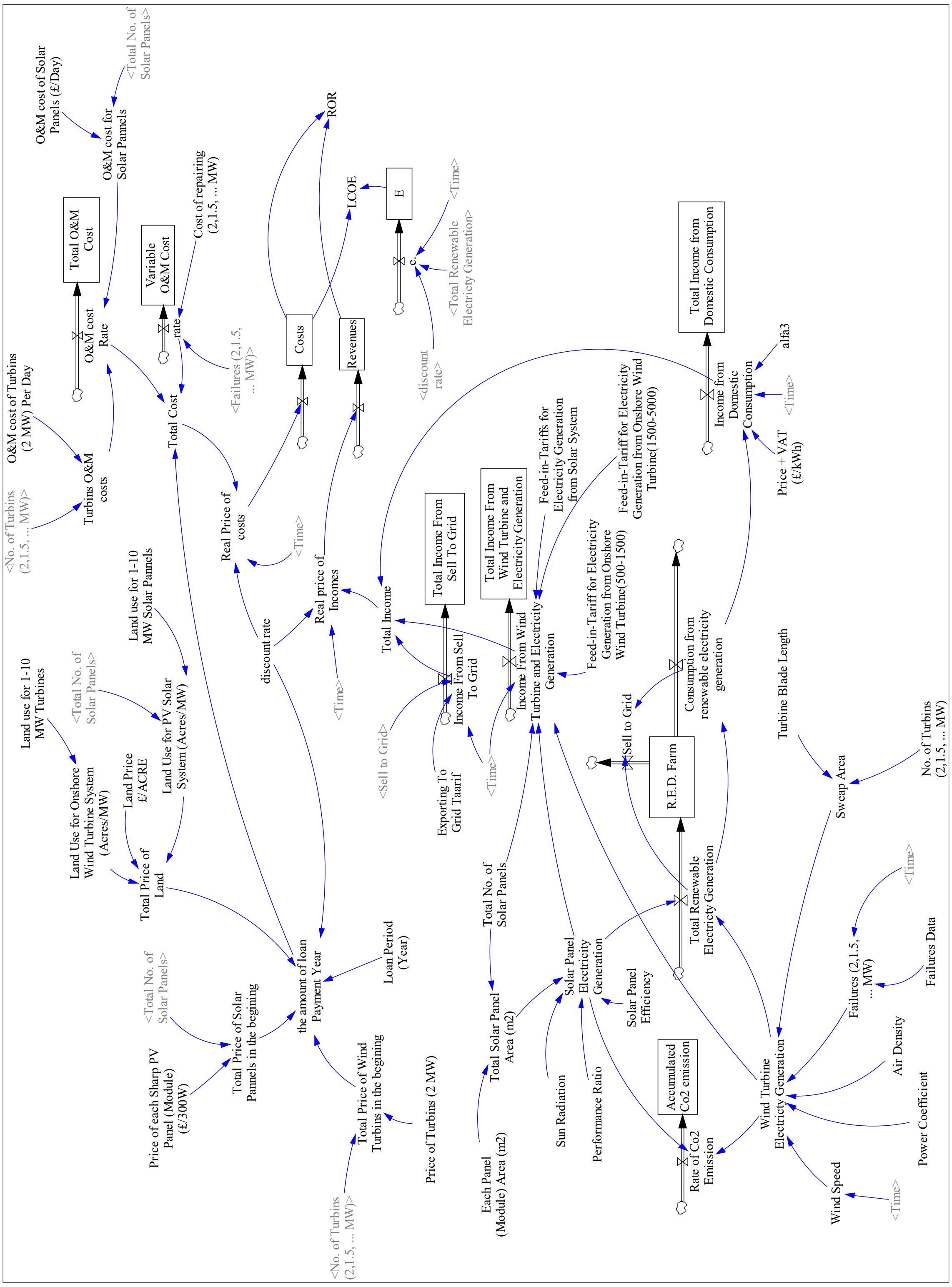


Figure 5-4: DES Research Mode

5.4.1 Wind Turbine Electricity Generation

First part of the modelling starts with developing the electricity generation from onshore wind turbine which is presented in Figure 5-5. In this figure, all components affecting the electricity generation from an onshore wind turbine are considered. As Equation 4-1 from subsection 4.4.2.1 presented, wind turbine power generation (P_T), depends on;

- Wind speed (*u)* which is given in meter per second
- Air Density (ρ) given in kilogram per cubic meter
- Power Coefficient (C_P)– presented in Table 22, subsection 4.4.2.1
- Swept Area (A) which depends on Turbine Blade Length (meter)
- Failure of wind turbine – explained in subsection 4.3.4.1.2

Components considered in the generation of electricity from wind turbine are listed and blue arrows are links that make values of variables available to other elements. As presented in Figure 5-5, Wind Turbine Electricity Generation is the outcome of this section. Air density is a constant, power coefficient, wind speed and sweep area and associated failure of turbines are variables affecting the outcome. Recall, there are 5 different turbines selected for this research (see Table 7) with capacities of 55kW to 2 MW each with different blade length and associated sweep area also each turbine has its own failure time. All of mentioned variables are presented in the model as Figure 5-5 shows and their effect is presented by the blue arrow from one component to the other.

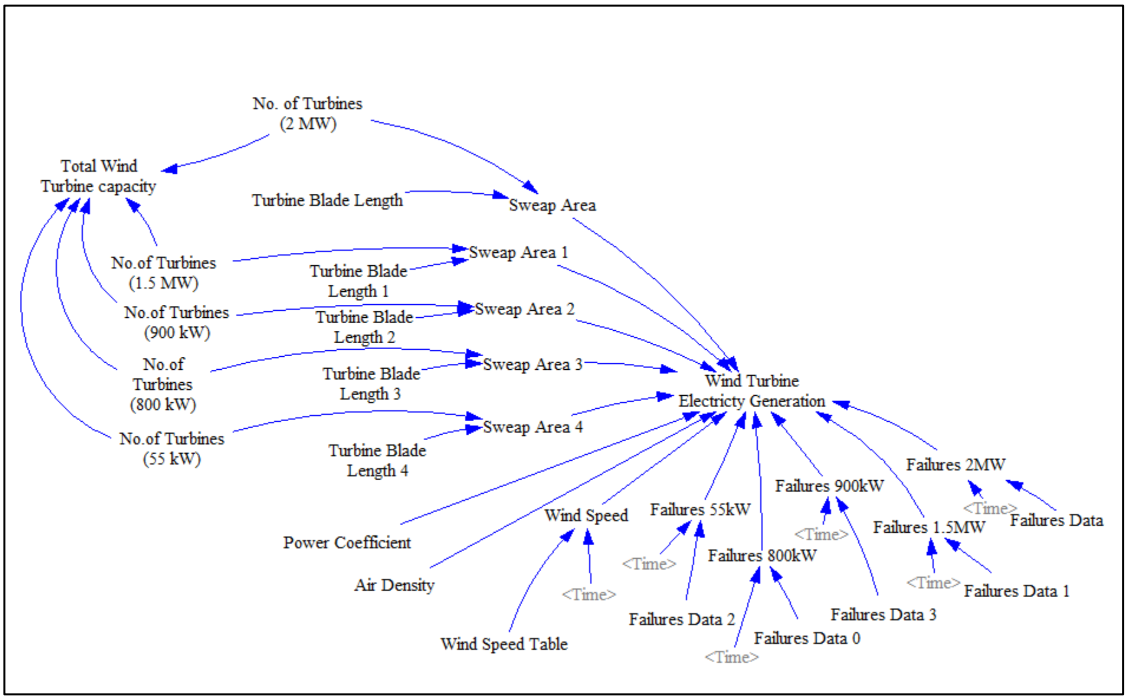


Figure 5-5: Wind Turbine Electricity Generation

5.4.2 Solar Panel Electricity Generation

Recall, in this research Solar PV panel and onshore wind turbine are selected for renewable energy generation. Figure 5-6 shows components effecting amount of electricity generated from solar PV panel. As mentioned in previous chapter electricity generation from solar panel can be calculated from;

- Sun Radiation (H) in kilowatt per hour per square metre
- Solar Panel Efficiency (r) in percentage
- Solar Panel Performance Ratio (PR) in percentage
- Total Solar Panel Area (A) in square meter

Therefore, all variables affecting Solar Panel Electricity Generation are listed in the developed model as Figure 5-6 presents. Total solar panel area in square meter is determined by size of each panel area (m2) and total number of solar panels selected. Then all variables (total solar panel are and sun radiation) and constants (solar panel efficiency and performance ratio) affecting the outcome (total electricity from solar panel) are defined and connected to the outcome by blue arrows.

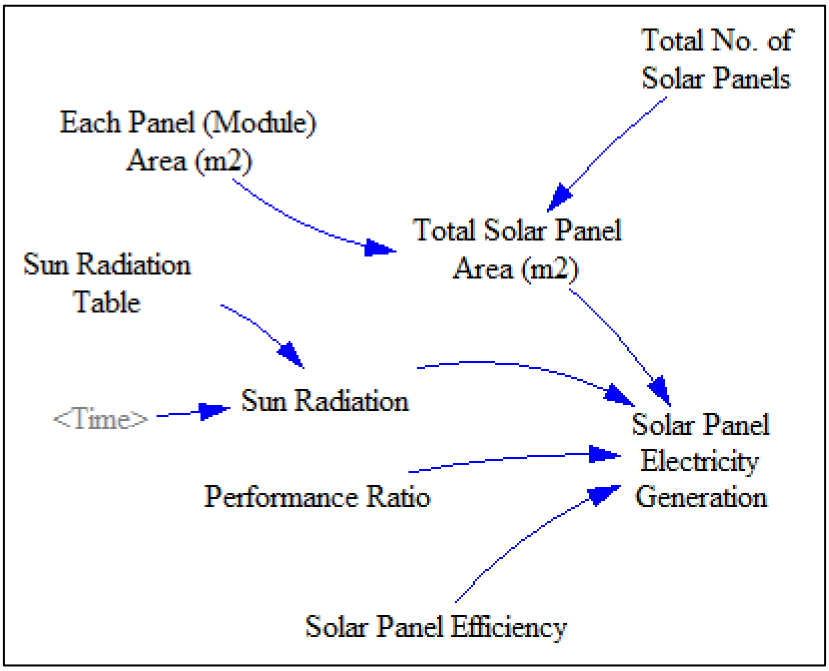


Figure 5-6: Solar Panel Electricity Generation

5.4.3 R.E.D. Farm Electricity Generation

R.E.D is a given name to the renewable farm which in presented in Figure 5-7. The R.E.D (Renewable) farm is shown as a stock with inflow of total renewable electricity generation and outflow of consumption from renewable electricity generation. General equation used for Stock and Flow diagram is presented in Appendix F. As amount of electricity generated from solar panel and/or wind turbine increase, inflow is directly increasing which will result in feeding the community via outflow.

In the event of any excess, the electricity would be sold to the Grid and any shortfall will be bought from the Grid that is presented with blue arrows from total renewable electricity generation to sell to grid and consumption. These relationships are presented by blue arrows in figure 5-7. The equation for this relationship between Grid and excess and shortfall of renewable electricity generation presented in equation 5-1.

$$R.E.D\ Farm = Toral\ renewable\ electricty\ generation \\ - Consumption\ from\ renewable\ electricty\ generation$$

Equation 5-1

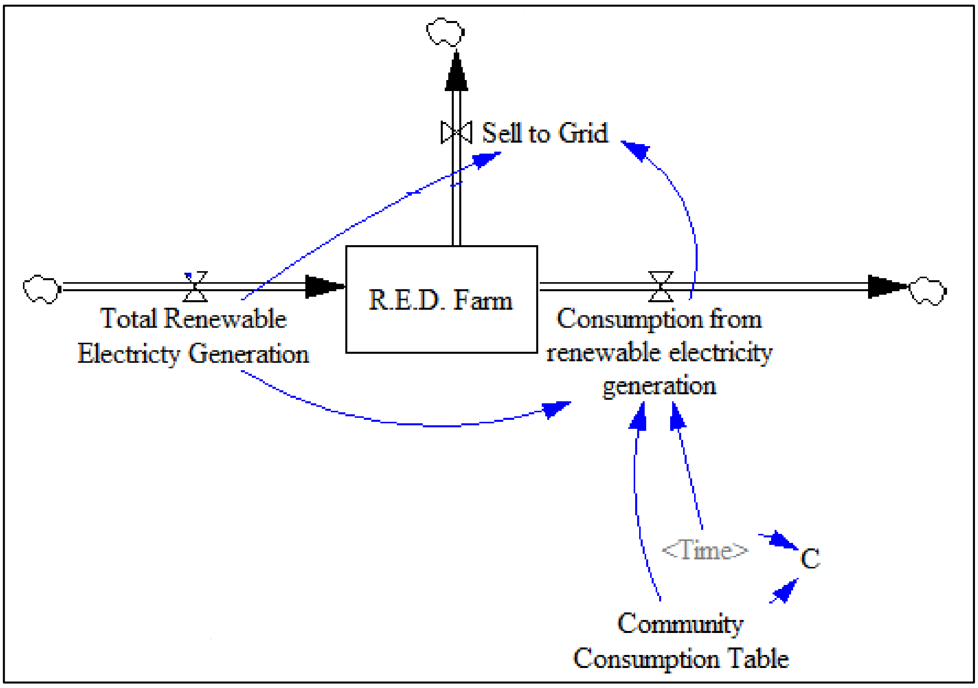


Figure 5-7: R.E.D Farm Electricity Generation

5.4.4 Total Capital Cost of Wind Turbines

Total capital cost of wind turbine is calculated by Equation 5-2, Figure 5-8 presents the total capacity of turbines and total capital cost of wind turbine.

$$Total\ Capital\ Cost\ of\ Wind\ Turbine\ = \sum_i No.of\ Turbines_i \times Price\ of\ Turbines_i$$

$$i = 55kW, 800kW, 900kW, 1.5MW, 2MW$$

Equation 5-2

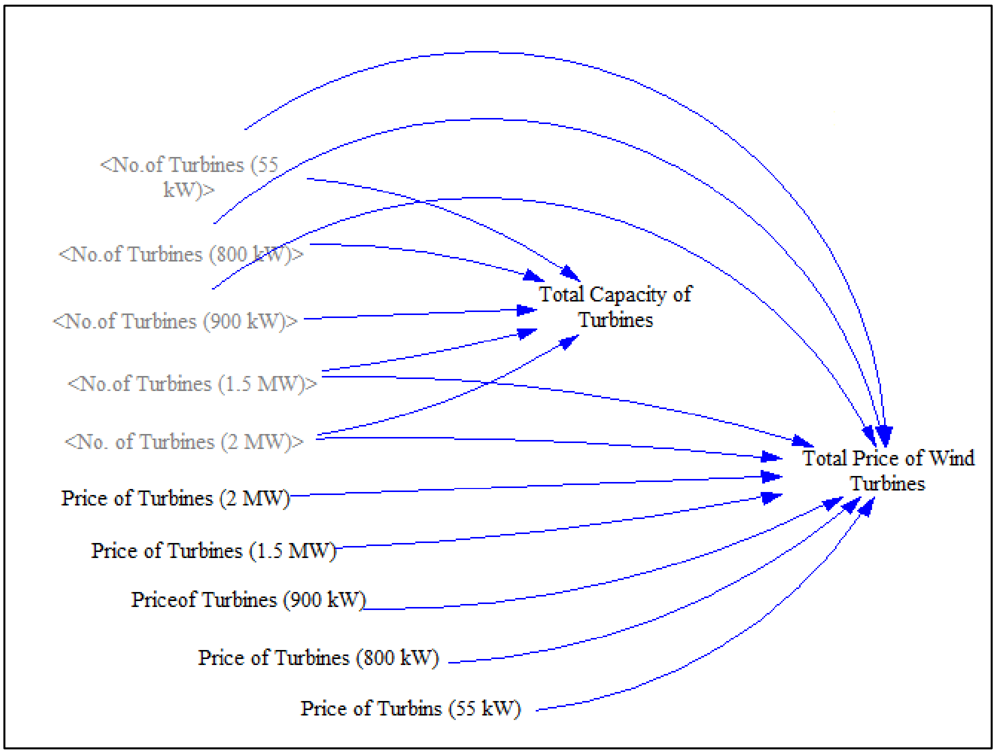


Figure 5-8: Total Cost of Wind Turbines

5.4.5 Total Capital Cost of Solar Panel

Total capital cost of solar panel presented in Figure 5-9 is combination of total number of solar panels and price of each solar panel (as stated in subsection 4.3.3.2, Sharp NU-RC300 used for this research). Total capital cost of solar panel is based on the equation 5-3 given bellow:

$$Total\ Capital\ Cost\ of\ Solar\ Panel$$
$$= Price\ of\ each\ Sharp\ NU - RC300\ Panel\ \times Total\ Number\ of\ Panels$$

Equation 5-3

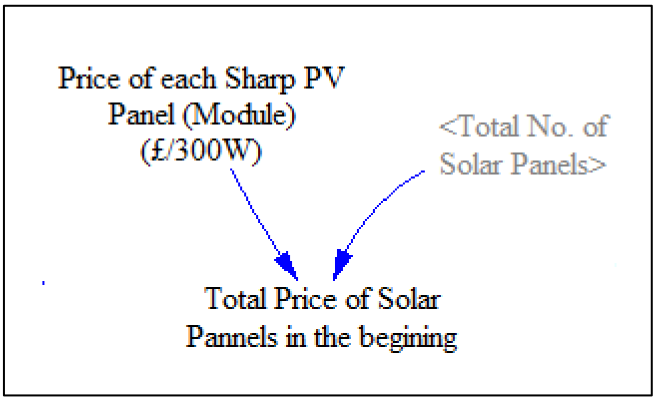


Figure 5-9: Total Capital Cost of Solar Panels

5.4.6 Total Cost of Land

Total cost of land used for renewable generation farm is calculated using following:

- Total land used for onshore wind turbine system (Acres/MW)
    - Total capacity of turbines
    - Land used for 1 to 5 MW turbines
- Land Price (£/Acres)
- Total land used for PV solar panel system (Acres/MW)
    - Total number of solar panels
    - Land used for 1 to 5 MW solar panels

$$Total\ Cost\ of\ Land$$
$$= (Land\ Price\ \times Total\ land\ used\ for\ onshore\ wind\ turbine\ )$$
$$+ (Land\ price\ \times Total\ land\ used\ for\ solar\ PV\ panel)$$

Equation 5-4

Equation 5-4 presents the total cost of land calculation shown in Figure 5-10.

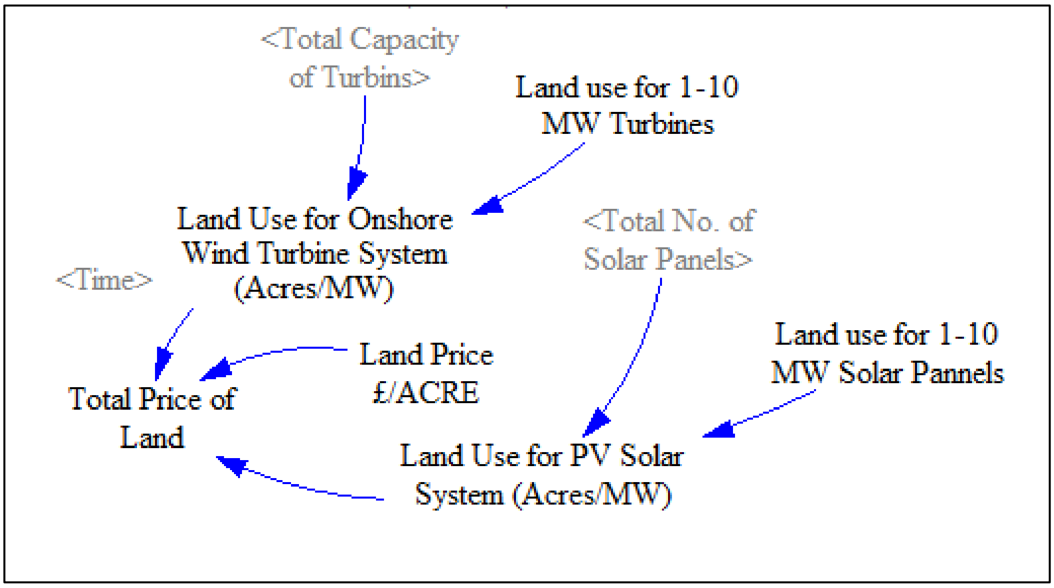


Figure 5-10: Daily Loan Payment and Discount Rate

5.4.7 Daily Loan Payment and Discount Rate

The research assumes that the cost of purchasing wind turbines, solar panels and land are usually financed by a loan. Daily loan payment calculated is presented in Figure 5-11 in which daily loan payment (A) is calculated by the given equation 5-5. In this equation, P is initial loan amount (£), i is a discount rate (%) and n is number of payments for a given period (McFedries, 2007).

$$A = P \times \left(\frac{i \times (1+i)^n}{(1+i)^n - 1}\right)$$

Equation 5-5

As mentioned earlier in Chapter 2, subsection 2.5.4, 10% discount rate for modelling the project in 2011is considered and possible changes for future projects tested at 5% and 7% are implemented by presenting the effect of changes of discount rate on ROR and LCOE all results presented in Chapter 6.

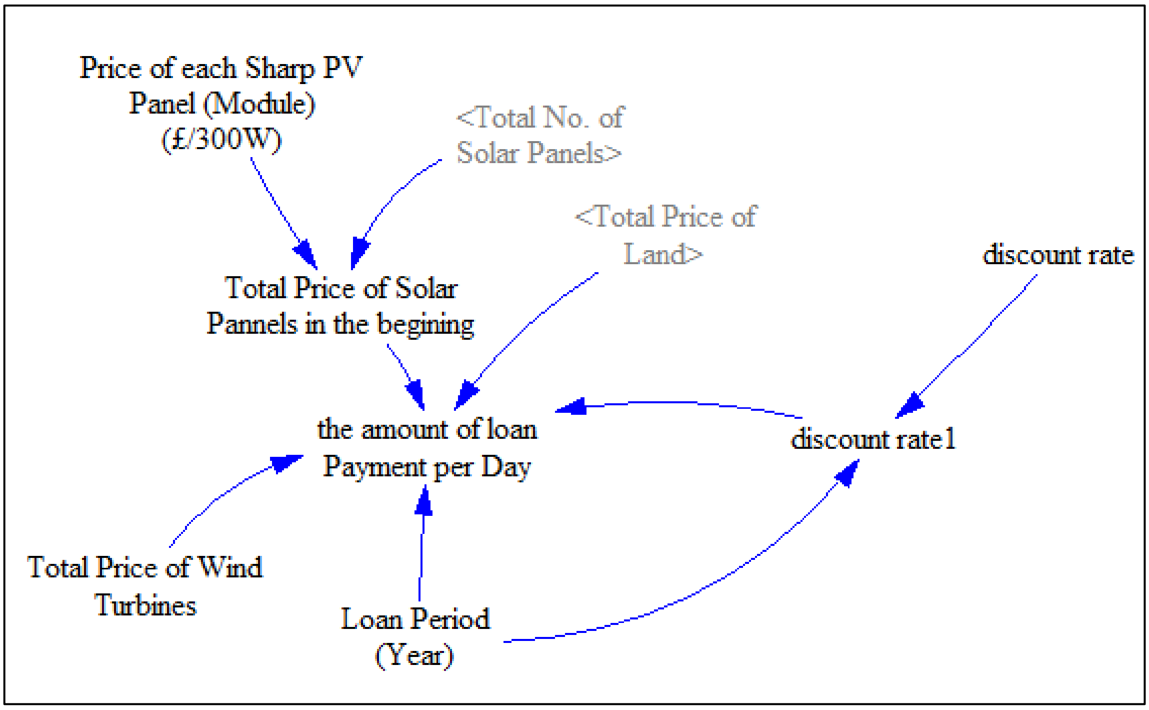


Figure 5-11: Total Cost of Land

5.4.8 Operation and Maintenance Cost

There are two type of Operation and Maintenance costs considered in modelling implemented as part of this research and they are given as follows;

- Fixed Operation and Maintenance (O&M) Cost
- Variable Operation and Maintenance (O&M) Cost

As mentioned in Chapter 4, subsection 4.3.4.1., variable O&M Cost are calculated from Puglia (2013) work with assumption of:

i. Base model with constant failure rate
ii. Ageing model with increase failure rate over the life time of wind turbine

Equation 5-6 presents the total O&M cost for onshore wind turbine and solar panel.

$$O\&M\ Cost = \sum_i No.of\ Turbines_i \times Unit\ O\&M\ Cost\ of\ each\ Turbines_i + No.of\ Pannels \times Unit\ O\&M\ cost\ of\ each\ Pannels$$

$$i = 55kW, 800kW, 900kW, 1.5MW, 2MW$$

Equation 5-6

Total O&M cost is presented in Figure 5-12 which is a combination of operation and maintenance cost of wind turbines and solar panels.

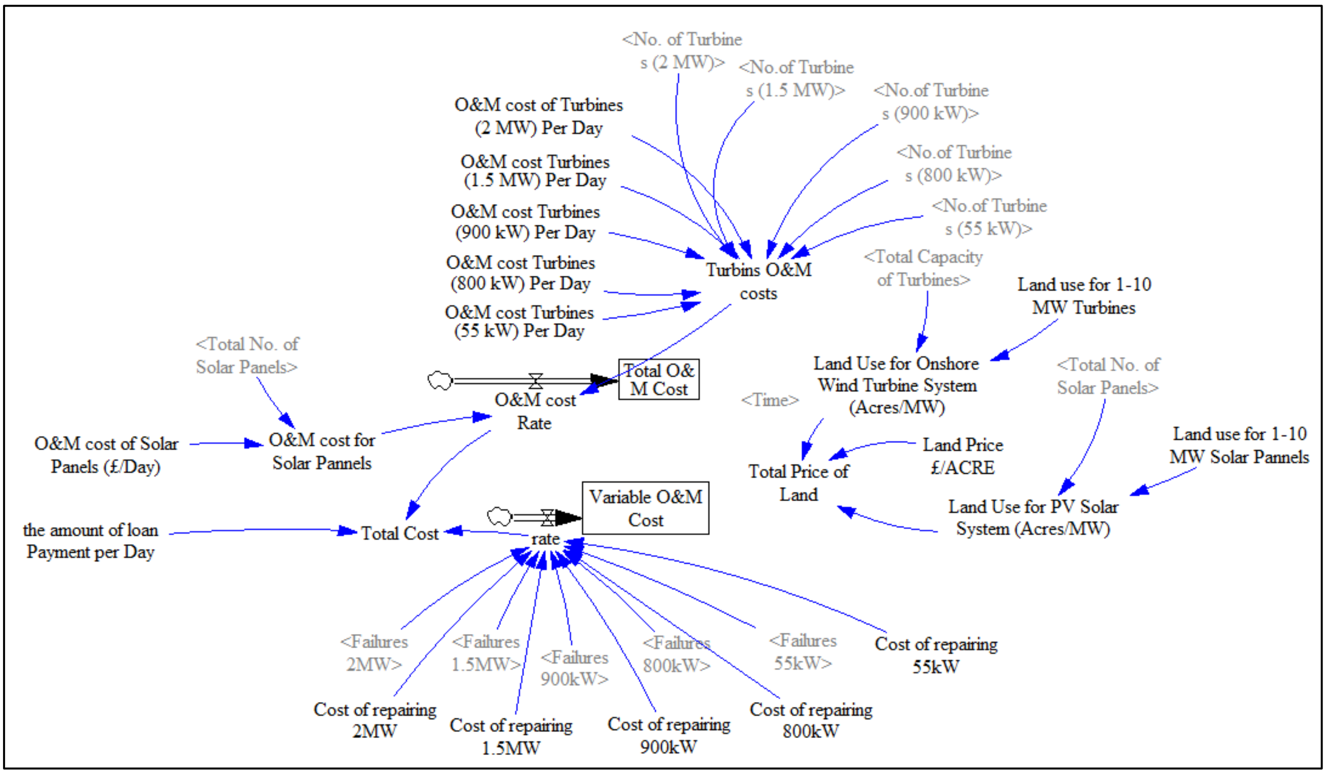


Figure 5-12: Operation and Maintenance (O&M) Cost

5.4.9 Income from Grid

Income from the grid is calculated from equation 5-7 that is presented in Figure 5-13 in which export to grid tariff price multiplied by excess of electricity generation from renewables.

$$Income\ From\ Sale\ To\ Grid = (Total\ Electricity\ Generation - Consumption) \times Sell\ To\ Grid\ Tarrif$$

Equation 5-7

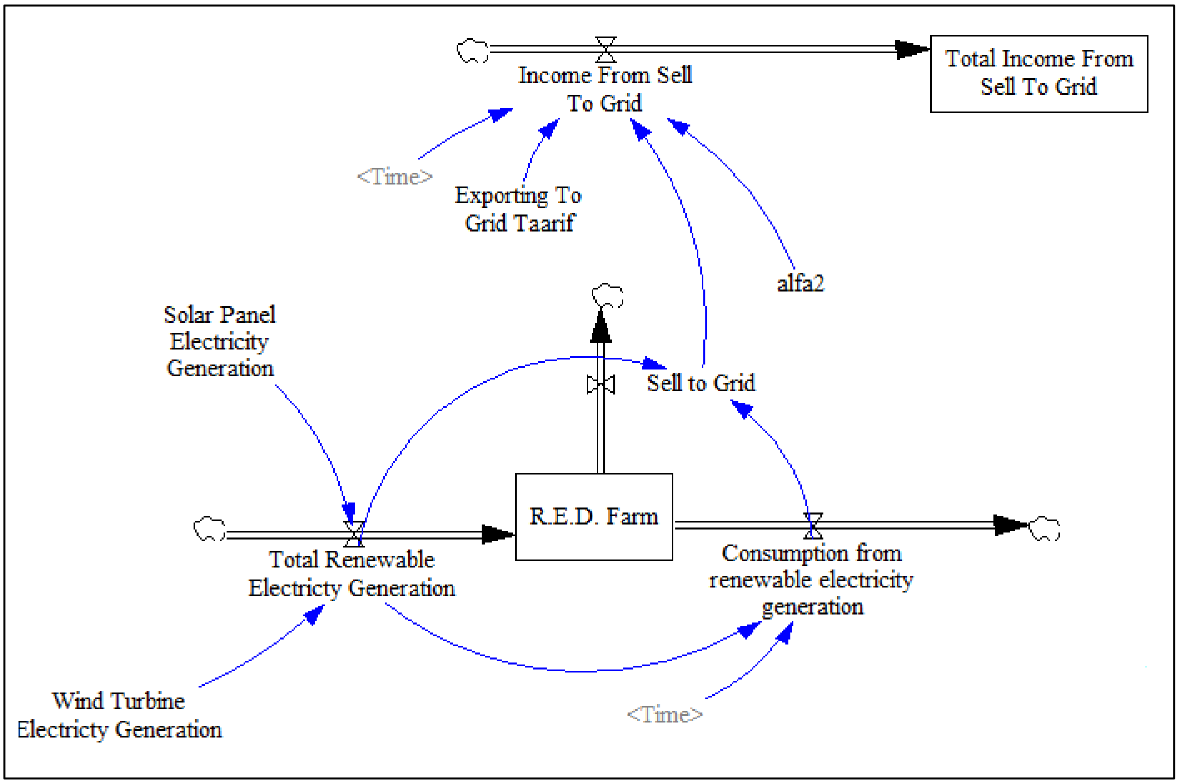


Figure 5-13: Selling Electricity to the Grid

5.4.10 Feed-in-Tariff (FiT)

In this research total income from feed-in tariff calculated using followings:

- Electricity generation from solar system (kWh)
- Electricity generation from onshore wind turbine (kWh)
- Number of solar panels
- Number of wind turbines
- FiT for electricity generation from solar system 0 to 5000 kWh
- Fit for electricity generation from onshore wind turbine 500 to 1500 kWh
- Fit for electricity generation from onshore wind turbine 1500 to 5000 kWh

Equation 5-8 presents the total cost of income from FiT calculation which is presented in Figure 5-14.

$$\begin{aligned} Total\ Income\ from\ Fit \\ &= (FiT\ price\ for\ wind\ turbine\ turbine\ capacity \\ &\times Electricty\ generation\ from\ wind\ turbine\ ) \\ &+ (FiT\ price\ for\ solar\ system \\ &\times Electricty\ generation\ form\ solar\ system) \end{aligned}$$

Equation 5-8

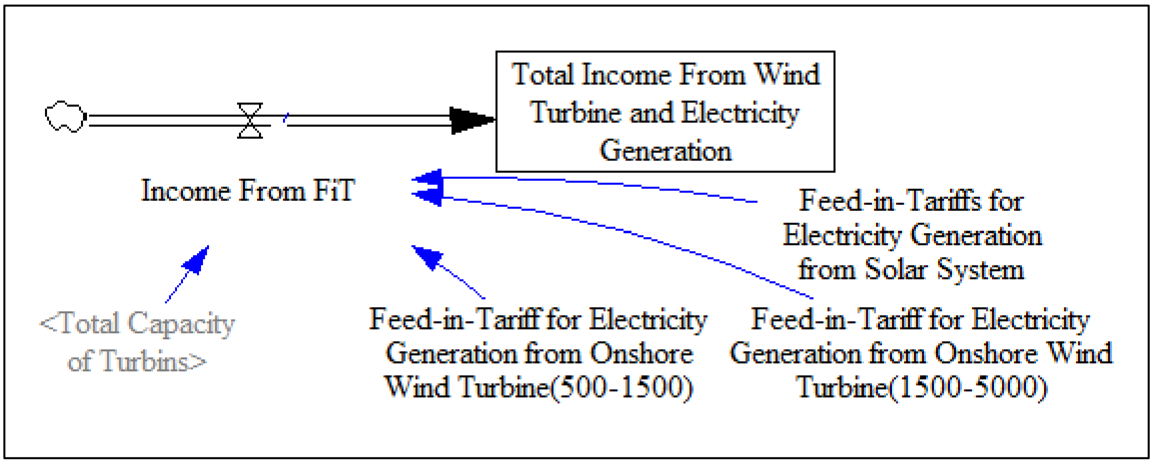


Figure 5-14: Feed-in-Tariff

5.4.11 Total Income

Total income presented in Figure 5-15 shows the calculation of total income for community considering following:

- Income from Fit
- Income from selling electricity to grid
- Saving from not buying electricity from grid (income from domestic consumption)

$$\begin{aligned} Total\ income = \ Income\ from\ FiT + Income\ from\ selling\ electricty\ to\ grid \\ + Income\ from\ domestic\ consumption \end{aligned}$$

Equation 5-9

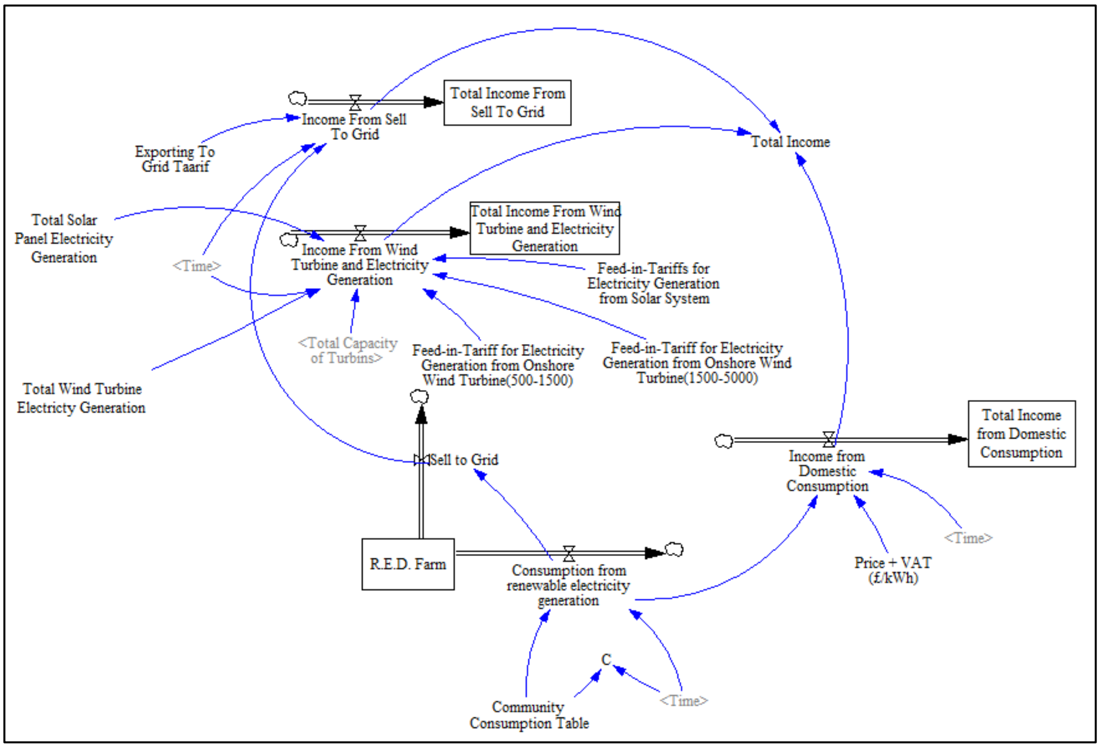


Figure 5-15: Total Income

5.4.12 Rate of Return on Investment (ROR) and Levelised Cost of Electricity (LCOE)

This subsection presents calculation of net present value, rate of return on investment and Levelised cost of electricity. As mentioned earlier, this research aims to evaluate the viability of community renewable generation for rural communities with case study of Huntly.

In order to evaluate the economic viability of a project, rate of return on investment (ROR) is calculated which presents the gain or loss compared to the cost of an initial investment over a certain period (25 years in this research), mainly expressed in the form of percentage. Positive ROR considered a gain and negative ROR reflects a loss on the investment.

5.4.12.1 Rate of Return on Investment (ROR):

This research model objective is to optimise the rate of return on investment (ROR)[17]. ROR is the percentage of net gain or net loss on investment during a certain time period compared to the initial investment Equation 5-10 presents the calculation of ROR (Mueller and Reardon, 1993).

$$ROR = \frac{Gain\ from\ investment - Initial\ Cost\ of\ investment}{Initial\ Cost\ of\ investment}\ X\ 100\%$$

[17] ROR also known as return on investment (ROI)

Equation 5-10

5.4.12.2 Net Present Value (NPV) and Internal Rate of Return (IRR):

In this research all calculations are done in present value, therefore inflation is not considered. Net present value (NPV) in an investment term that illustrates the difference between the present value of cash flow and value of investment in the future. Net present value is calculated using equation 5-11 (Mueller and Reardon, 1993; Shank, 1996; Wetekamp, 2011).

$$0 = NPV = \sum_{t=1}^{n} \frac{C_t}{(1 + IRR)^t} - C_0$$

Equation 5-11

C_0: Net initial investment expenditure
C_t : Total cash inflow for period t (Cash inflow is generated from investment in period$t$)
IRR: Internal Rate of Return
t: Each period
n: Holding Period

5.4.12.3 Levelised Cost of Electricity (LCOE):

Levelised cost of energy (LCOE) is the lifetime cost-benefit for a system and it is a fundamental calculation used in the assessment of an energy producing project. LCOE calculated applying equation 5-12 is an important metric in determining whether or not to move forward with a project (Singh et al, 2015; Obi et al. 2017).

$$LCOE = \frac{\sum_{t=1}^{t=n} \frac{(I + M)}{(1 + r)^t}}{\sum_{t=1}^{t=n} \frac{E}{(1 + r)^t}}$$

Equation 5-12

Where;

I: Initial cost of investment expenditure
M: Maintenance and operations expenditure
E: Total electricity generated
r: Discount rate
n: Expected lifetime of renewable farm

LCOE can be observed as the average minimum price at which electricity must be sold in order to break-even over the lifetime of the project (IRENA, 2018; Branker et al, 2011). In this research LCOE of electricity generation compared to the price of selling electricity to Grid. All equations mentioned above and relevant components are presented in Figure 5-16.

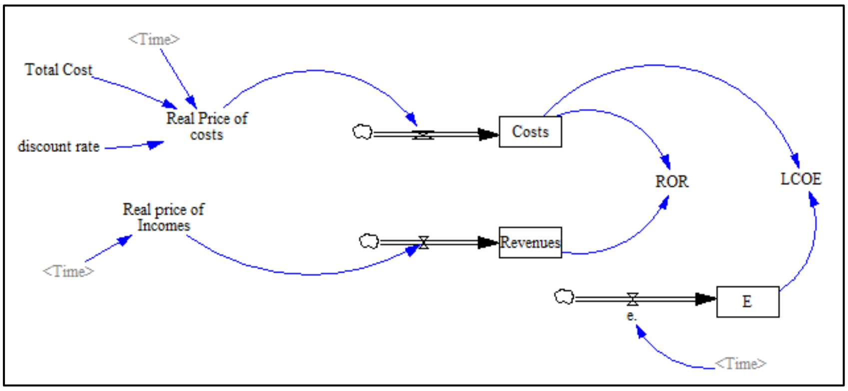


Figure 5-16: ROR and LCOE

5.5 SYSTEM DYNAMICS MODEL

After optimizing the model with discrete event simulation (DES), feedback loop is added at the end of the project to calculate the future economic viability and potential profits of renewable projects on capital utilization and borrowing for renewable farm development. In system dynamics (SD) modelling, adding feedback to the model adds the significant complexity and only software's with made system dynamic modeling features can be applied. One of the most convenient and suitable software solutions is Vensim.

In order to provide an analysis of selected variables that are examined and presented in Figure 5-17, the model is simulated on an annual basis to provide necessary and satisfactory system dynamics analysis.

As shown in Figure 5-17, the feedback related to the profitability of renewable farm (ROR) is added to number of wind turbines. Feedback loop is added to number of wind turbines as wind turbine is an optimised source of energy generation for this research (full details in Chapter 6). When ROR increases, number of wind turbines will increase and as a result, this increase in number of wind turbines will soar the cost generation and increase the revenue from generation. If feed-in-tariff increases and price of electricity rises, the loop will be reinforcing feedback loop[18] and it would lead to development of wind farm. However, if feed-in tariff and price of electricity fall the loop becomes balancing feedback loop[19].

[18] Reinforcing feedback Loop also called positive feedback loop is an effect of an action that produces a result which influences more of the same action.

[19] Balancing feedback Loop also known as negative feedback loop is a circle of cause and effect that counter a change with a push in the opposite direction (Coyle, 1996)

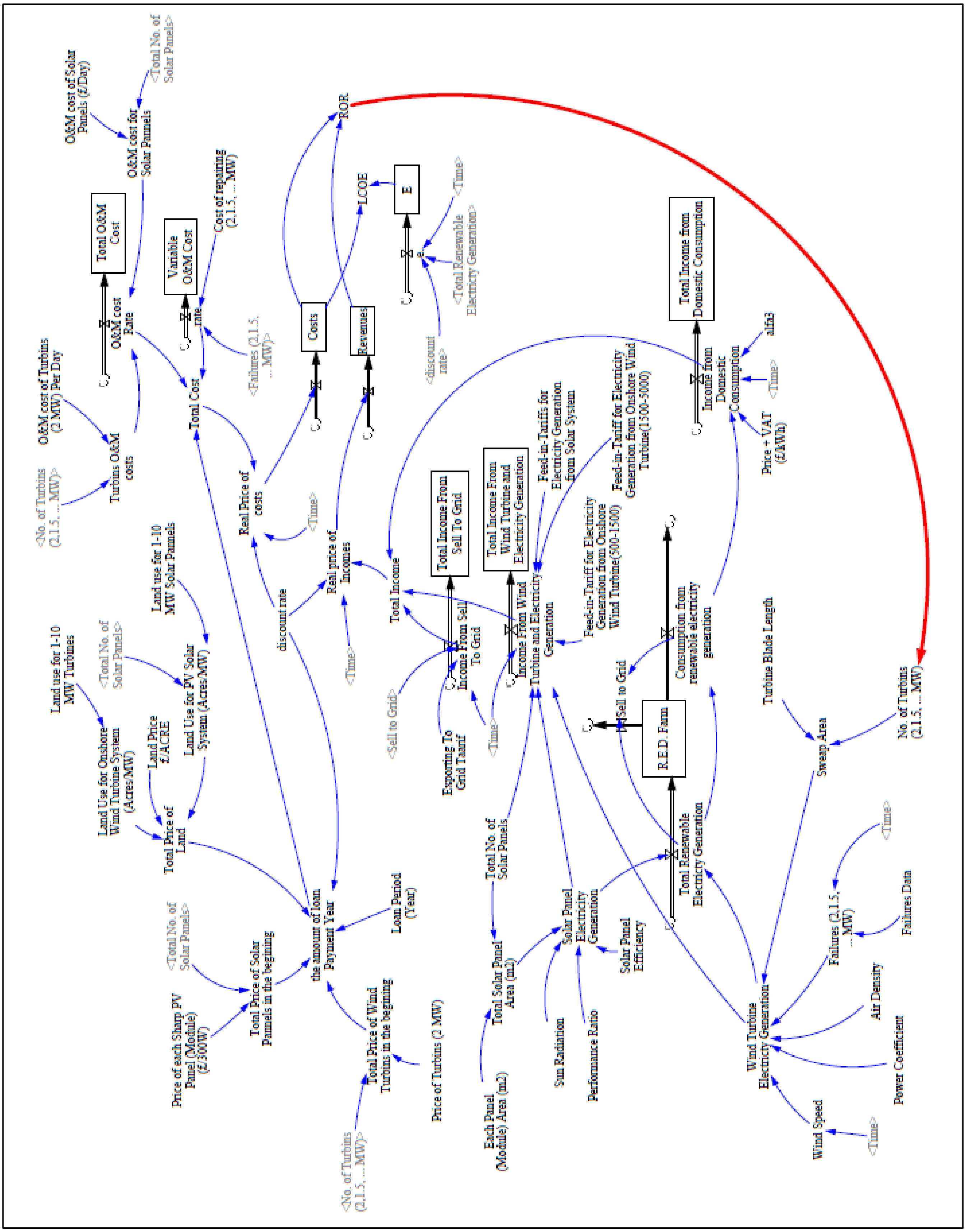


Figure 5-17: System Dynamic Model

5.6 Model Validation

In order to demonstrate that model is a reasonable demonstration of the actual system, it is necessary to have a well-known model validation in place.

However, in practice it is very challenging to achieve a full validation of the model, especially when the system under modelling is not existing in reality. This research suggests use of three different tests for validation and they are given as follows; extreme condition test, sensitivity test and comparison test.

5.6.1 Extreme Condition Test

Extreme condition test is one of the validation methods used for necessary model validation. In this method the input values of the model are changed to their maximum and minimum values and the model must be able to show the correct results.

5.6.1.1 Minimum values

In this extreme testing, number of solar panels and wind turbines is set to zero. In this condition, the model is expected to correctly represent the value of the output variable. By testing these values, the model results show that the ROR value will be zero.

5.6.1.2 Maximum Values

In another extreme test, it is assumed that all wind turbines and solar panels are used for generating electricity from the renewable farm and price of each component is increased by 100 times. It is expected that ROR decreases to its lowest level. As expected, ROR reached its lowest level at -1 and the results from this test are presented in Figure 5-19 which is in line with what was expected.

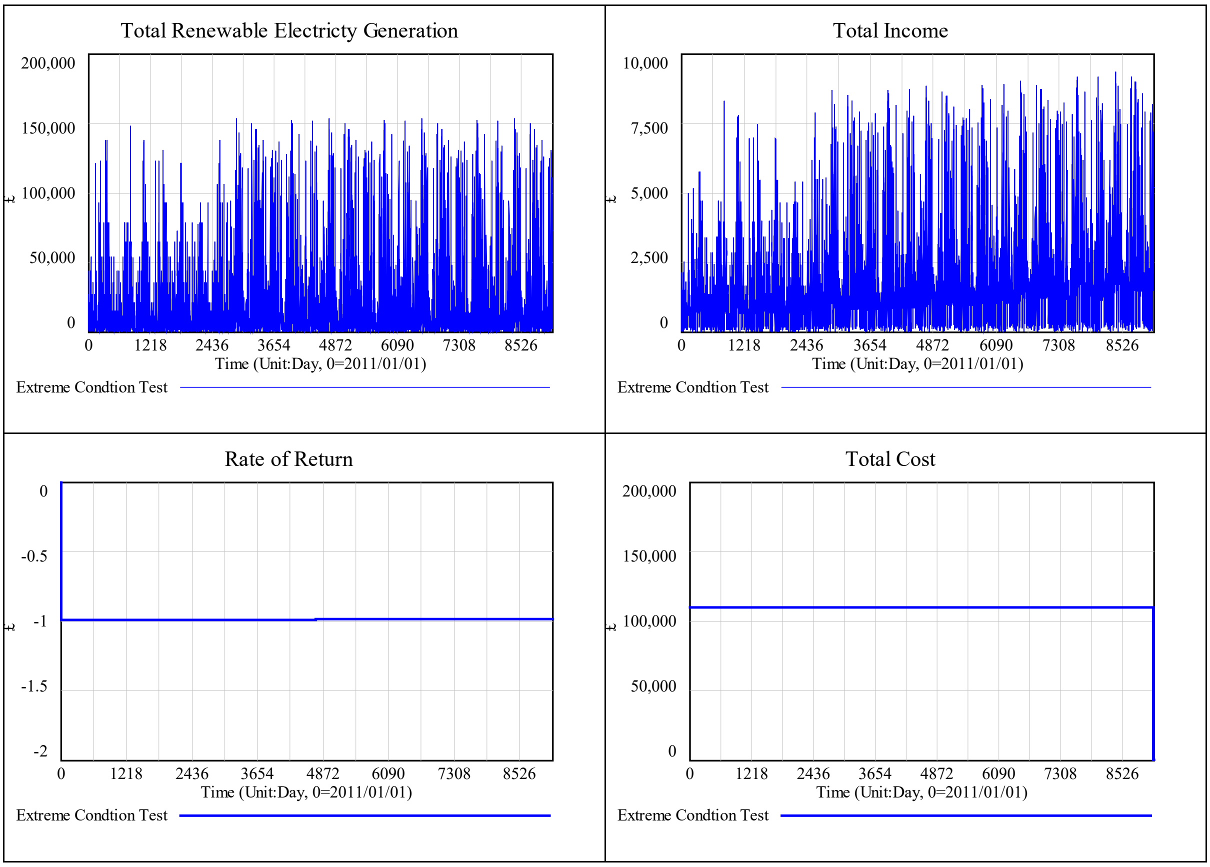


Figure 5-18: Extreme Condition Test II

5.6.1.3 Sensitivity Analysis

Another validation method used in this study is sensitivity analysis (SA), which is a typical measure to quantify the impact of parameter uncertainty on overall simulation uncertainty (Saltelli et al, 2000; Zheng et al, 2014). In system analysis inputs are changed slightly to examine the changes in the output. For example, by increasing the cost of each turbine, price of the land and O&M cost, the output results for this scenario (current 1) are provided in Figure 5-20.

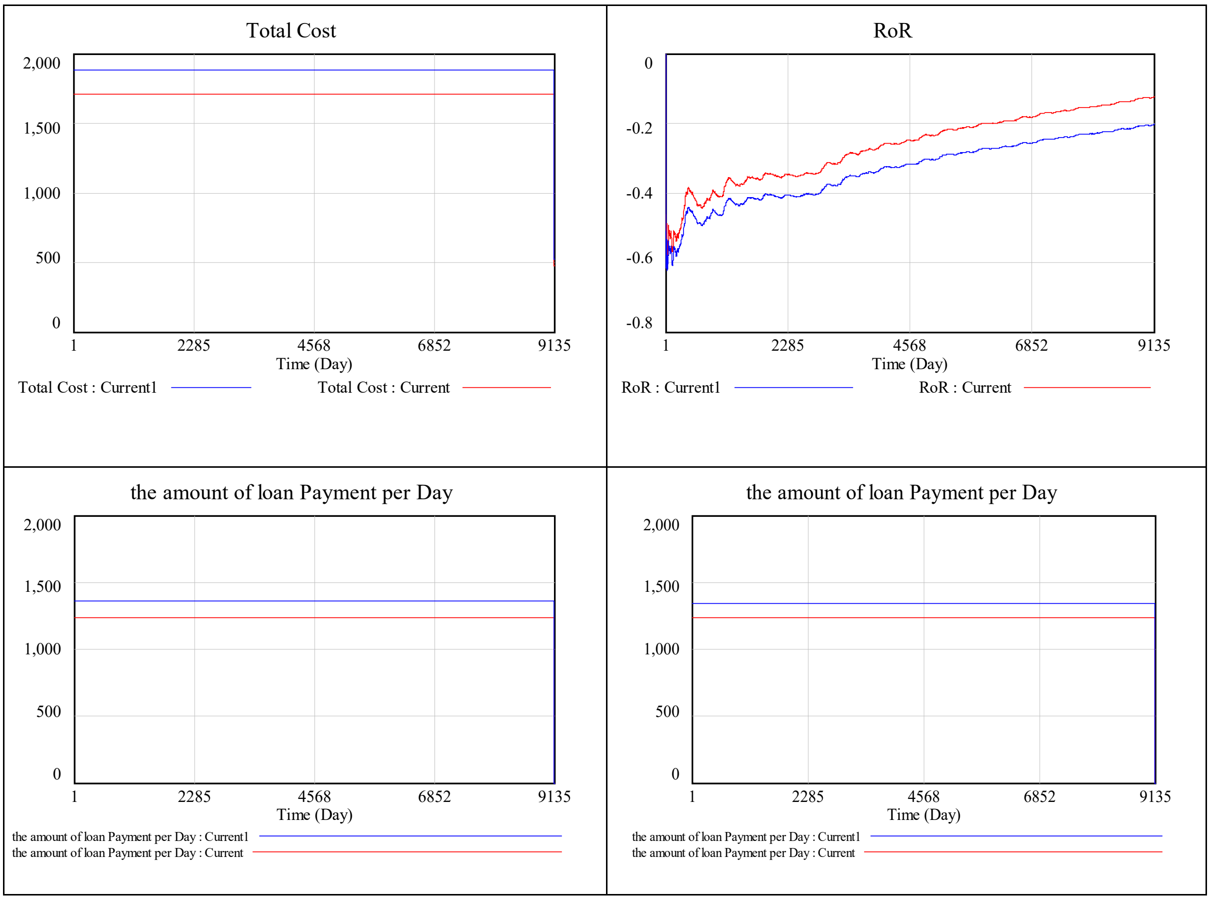


Figure 5-19: Sensitivity Test

5.6.1.4 Comparison between Excel model and DES model

This section presents results of rate of ROR and total income for the second-year of renewable farm operation. First the comparison between results for ROR in Excel and Vensim are presented. Then comparison between the total incomes for the second-year of operation is presented for two chosen models.

5.6.1.4.1 ROR Comparison

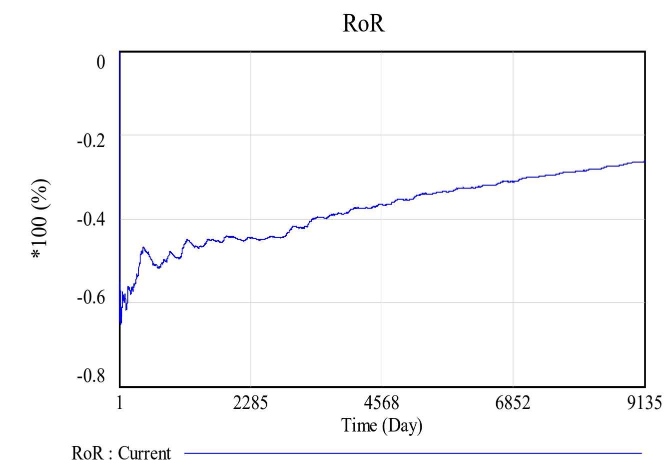
This test compares the results of the proposed model, which was derived from use of both Excel and Vensim software. To do this, the model inputs set in the following conditions.

- Turbine number of 2 MW: 1 pc
- Turbine number of 1.5 MW: 1 pc
- Turbine Number 900 kW: 1 pc
- Turbine Number 800 kW: 1 pc
- Turbine number of 55 kilowatts: 1 pc

- Number of solar panels: 10 pcs

In this situation, the results for the ROR calculated using the Vensim software are presented in the following figure and the result shows that at the end of the project period (25 years), the ROR reaches -0.271. The results of the simulation using Excel software produces results with a very small discrepancy in comparison with Vensim software (-0.2637).

To compare simulation results in more detail, the comparison done between the incomes variable results from both Excel and Vensim software is presented in Figure 5-21. The graphical representation is result from Vensim software and results from Excel is given in a table below the plot.



						OutPut			
Total Number of solar Pannels	Number of wind turbin 2MW	Number of wind turbin 1.5 MW	Number of wind turbin 900 KW	Number of wind turbin 800 KW	Number of wind turbin 55 KW	LandUse	RoR	Total NPV	NPV per Year
10	1	1	1	1	1	231	-0.2637004	(2,821,525.72)	(112,861.03)

Figure 5-20: Simulation result applying Vensim software compared to Excel

5.6.1.4.2 Total Income in 2nd year of the project

Another comparison between two proposed models presented in Figure 5-22 clearly shows the total income for the second year of the project is very similar for those two-software used. The top graph presents the outcome from DES model and the bottom graph shows the result from Excel model. As presented in this case total income is very similar in both models presented.

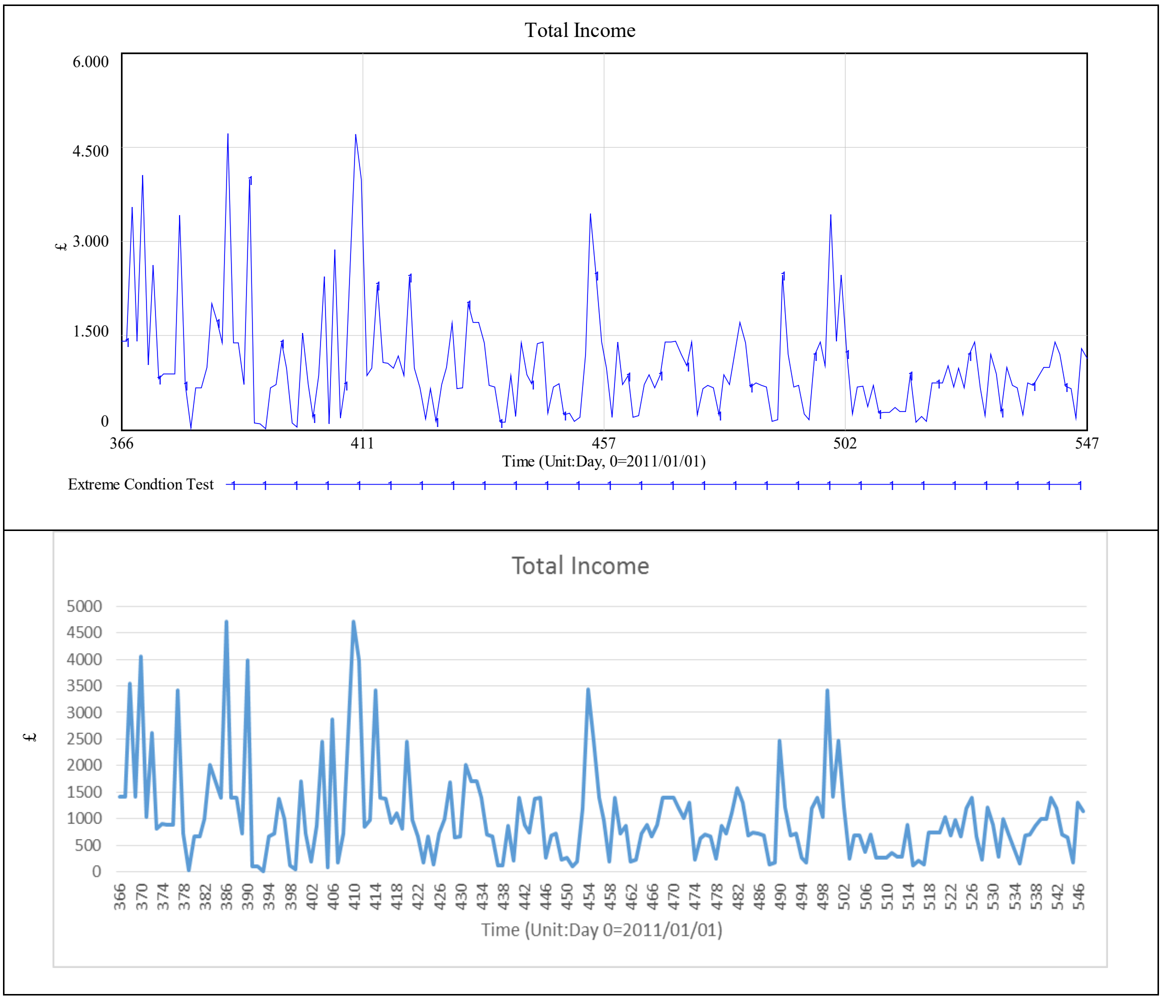


Figure 5-21: Model Simulation Result from comparing daily total income – the top graph presents results from Vensim and the bottom graph presents results from Excel.

5.7 Chapter Summary

This chapter presented a step by step DES and SD modelling in Vensim and detailed the model validation procedure for this research. As discussed earlier in this research, objective of the model is to evaluate the economic viability of renewable generation farm. The model first chooses the best combination of wind turbine and solar PV panel capacity for electricity generation which would maximise the ROR and then illustrates the LCOE and CO_2 for the optimised renewable generation capacity.

This research is based on simulation in both Excel and Vensim software for modelling renewable generation farm which was discussed in more details in this chapter and Chapter 4. The Excel is used for input data, for description of mathematical equations and relationship between inputs. The Excel file was created is used in Vensim for discrete event simulation and system dynamics modelling. In this research and for modelling purposes, Kalman Filtering is used as an algorithm for simulation in

Vensim. The model is validated with extreme testing, sensitivity analysis and the results from DES model and excel model are cross-compared. Optimisation results from illustrated model are presented in the next chapter where various scenarios have been analysed.

6 ANALYSIS OF RESULTS

6.1 OVERVIEW

This chapter presents a full analysis of results derived in Chapter 5 and further analysis of additional model runs with alternative generation schemes to illustrate the impact on the economic viability for the renewable generation at Huntly.

Recall, two Modelling Groups are used:

1. Modelling Group I; in which the model is optimised with Discrete Event Simulation (DES) with constraints to present the best combination of renewable technology and capacity for generating electricity for Huntly. The model uses scenarios to evaluate the sensitivity of results.
2. Modelling Group II; in which system dynamics modelling applied to the optimised result obtained from DES model. The feedback loop of SD is used to explore the relationship between profitability of the renewable investment and future investment using a number of renewable technologies but without considering certain constraints for Huntly.

Both tested models are described in more details in this chapter. The final tested model can be used to evaluate community electricity generating scheme anywhere where enough adjacent land is available to support the generation infrastructure. Thus, supporting the posed hypothesis for the outset of this research, "the tested model can be applied anywhere as long as relevant data for the region is available". First in subsections 6.2, 6.3 and 6.4 the Group Modelling I introduced with optimisation results for the tested scenario followed with sensitivity test in subsection 6.5. In following subsections (6.6 and 6.7) Modelling Group II is described with results from tested scenarios. Then subsection 6.8 supports the hypothesis that the developed model is able to evaluate a community electricity generating scheme anywhere where enough adjacent land is available to support the generation infrastructure. Finally, subsection 6.9 presents the summary of this chapter.

6.2 Modelling Group I: Discrete Event Simulation

The DES model is developed in Vensim software with inputs from Microsoft Excel files is optimised to find the best distributed generation (in this case combination of solar PV panels and wind turbines) for Huntly.

In system optimisation, the first step is to model individual components in order to provide a better understanding of the overall situation to support decision making. The validation of the modelling is validated by its correct prediction of performance. (Bhandari et al, 2015). In this research the performance of individual components is modelled by using deterministic modelling technique. The first modelling step considers, weather conditions for the chosen region to determine the number wind turbines and their capacity together with the number of solar PV panels needed to achieve highest value of the ROR at the end of the 25-year period.

The optimisation suite in Vensim software is used (Ventana, 2018). The ROR function is taken as a target function after that the decision variables are set. As discussed in Chapter 5, the objective of the built model is to optimise the ROR, with defined constraints which are:

- Total renewable electricity installation of less than or equal to 5MW
- Size of the land – limitation of 230 acres

In Chapter 4, it was reiterated in the UK, a renewable electricity installation of 5MW or less is eligible for the feed-in tariff. Therefore, one of the constraints selected for optimisation is the size of the renewable electricity installation. Another constraint selected for optimising the model is area of the land which is considered an important indicator in planning renewable generation farms. Recall from Chapter 5, in the examined case study a land limitation of 5 Acres is applied to the optimisation calculation. Therefore, this research has in the Group Modelling I, applied land limitation and an installation size limitation in the design of the research model of the Huntly case study as part of examining the viability of renewable electricity generation investment for rural communities.

6.3 Optimisation Results from Modelling Group I

6.3.1 Wind and Solar Farm

The "optimisation setup" function in Vensim is used to determine the optimised ROR (see Appendix F). In the first modelling run, solar PV panels and wind turbines were selected as decision variables in optimization with defined constraints (land limitation and installation size limitation) with the aim to optimise the rate of return on investment. Results from the modelling show that installing one 1.5MW is the most cost-benefit option for the farm. The result obtained from the model is what was expected due to weather condition in Huntly and it is in line with report presented in Chapter 2 (see Figure 2-11) which shows that there are mainly windfarms installation in North-East of Scotland with no solar farms installation (Evans and Pears, 2013).

Figure 6-1 presents the total electricity generation for optimised capacity with one 1.5MW wind turbine for Huntly, given its daily wind speed in meter per second (see Appendix B) and associated power coefficient (see Table 22). Fluctuations in the electricity generation figure is an indicator of wind speed changes over time. As presented in Chapter 4, weather data logged for this research is daily over a 7-year period from 2011 to 2018 and the prediction of the future weather, in this case wind speed, is done using the Equation 4-1 which indicates 3.5% increase in wind speed every year which is in line with the prediction by Carrington (2017) and Met Office (2018). As presented in Figure 6-1, 2012 had the lowest electricity generated from the wind turbines which is in accordance with Huntly wind speed (see Figure 4-2) in which 2012 had the lowest average wind speed with 4.18 meters per second (m/s). Overall due to prediction of increase in wind speed over time the electricity generation from wind turbine is expected to increase which is presented in Figure 6-1.

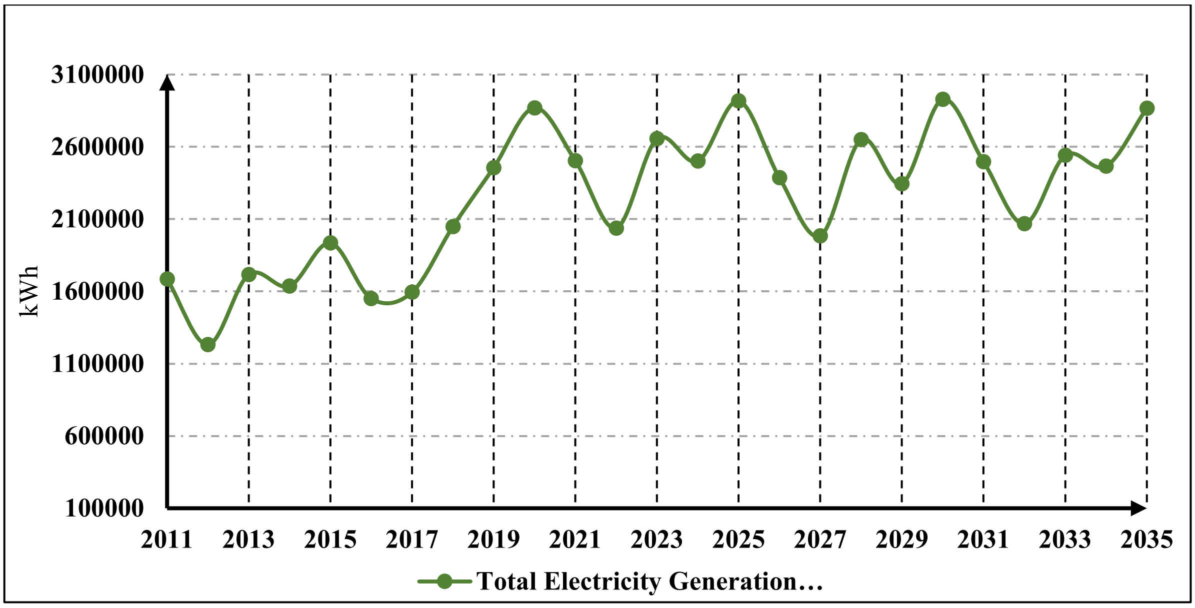


Figure 6-1: Total electricity generation from one 1.5MW wind turbine (kWh/Year)

Wind speed has a significant effect on amount of electricity generated from wind turbine. Figure 6-2 presents electricity generated from 1.5MW turbine for Huntly versus community electricity consumption in January 2011. As presented in the figure on average community consumption is around 1700 kWh per day with small changes. However, electricity generated from 1.5MW wind turbine changes dramatically due to changes in wind speed for that time. Average daily wind speed (m/s) is presented in figure 6-3 which gives a clear view of electricity generated from wind speed.

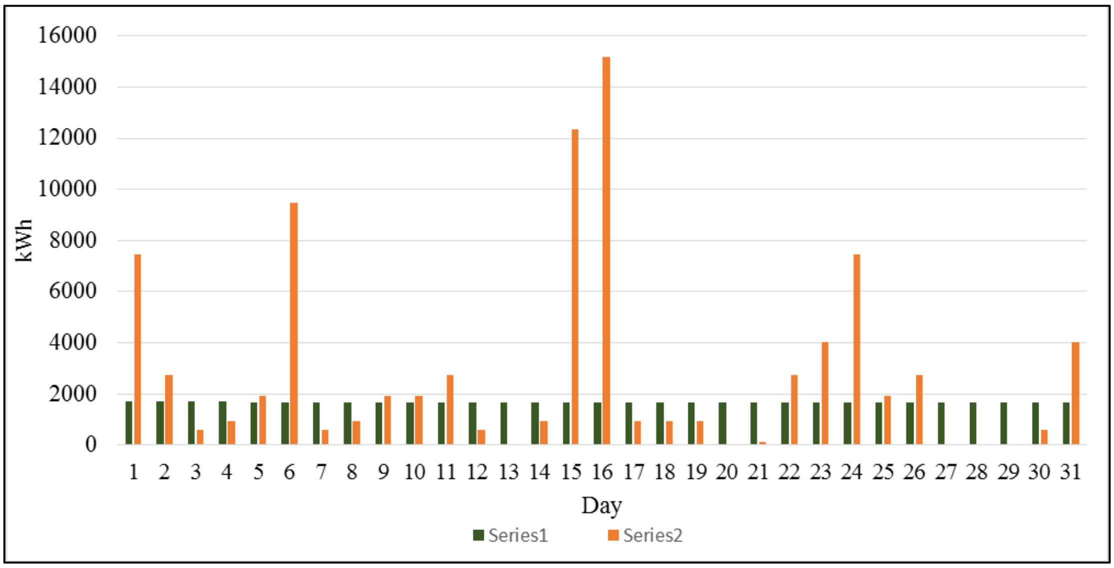


Figure 6-2 Average Daily Electricity Consumption vs Renewable Electricity Generation (kWh/day) in January 2011 for Huntly

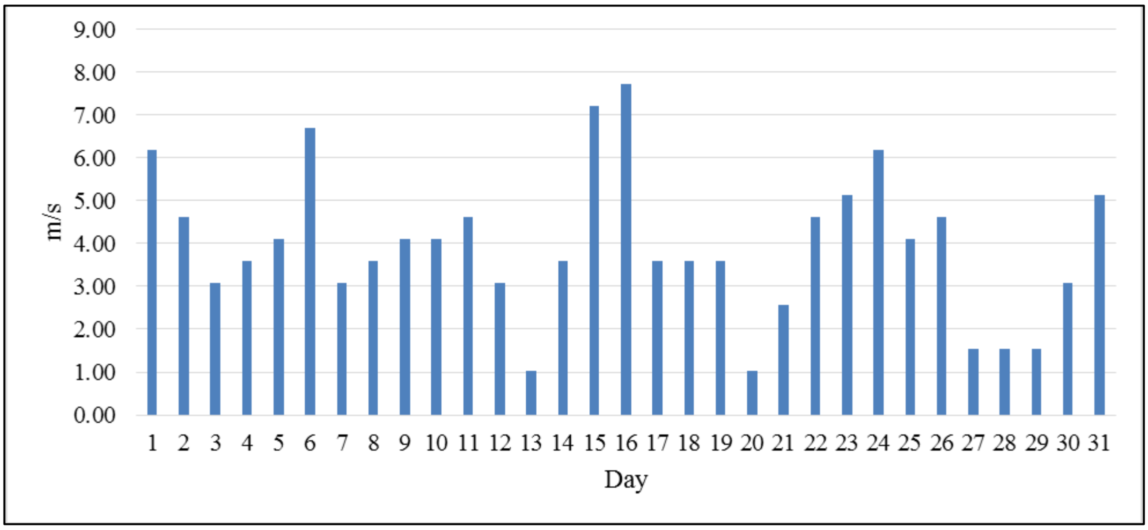


Figure 6-3: Average Daily Wind Speed in January 2011 for Huntly

The rate of return on investment (ROR) for optimised model is presented in Figure 6-4. In this model, investment in wind renewable generation is efficient which is presented with 72% ROR. In ROR calculation, changes in feed-in tariff over time is applied, however results show that feed-in-tariff on generating electricity from wind turbine does not affect the overall revenue and efficiency of an investment as much as expected. On average, ROR for period of 2011 to 2019 with feed-in tariff is 35%. However, the average daily ROR at the end of feed-in tariff for the period of 2020 to 2028 is 43% which indicates that the changes in feed-in tariff changes the profitability/efficiency of the developed model around 8%. In this case wind speed is the main influence variable which dictates the amount of electricity generated and relevant revenue generated. Increase in ROR to 72% over time is due to the increase in the scheme generated revenue from generating electricity and constant initial investment cost.

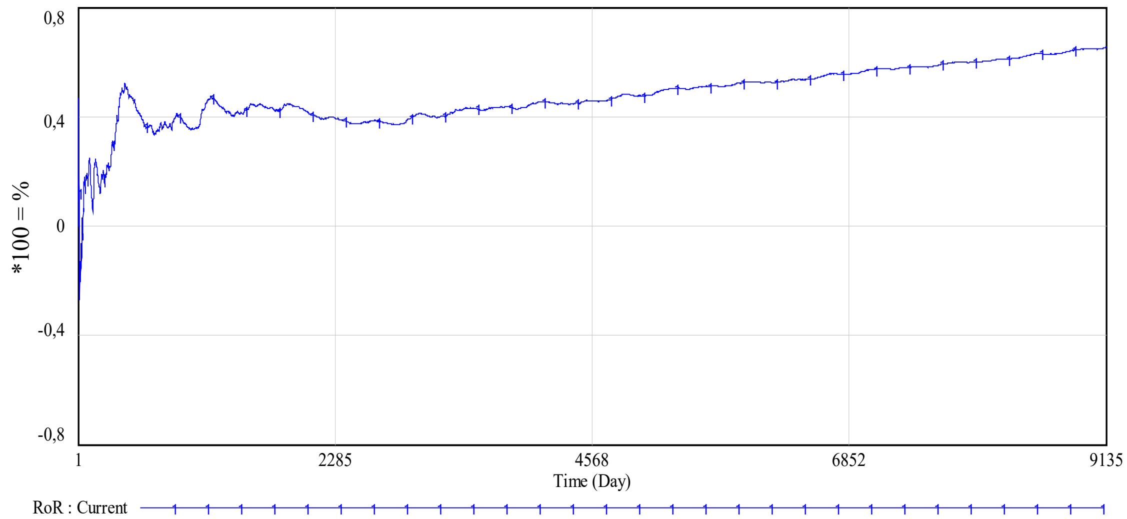


Figure 6-4: Optimised ROR

Figure 6-5 shows, at the beginning of the project, as expected, ROR is less than zero because the initial cost of investment is more than the gain from the investment which makes the ROR less than zero. The negative ROR (less than zero) presents the amount of loss the investment is making, or how inefficient investment in the examined scheme is. However, as generation of electricity increases, ROR increases as a result of rise in revenue generated from feed-in tariff for generating electricity and exporting excess of generated electricity to the grid (see Equation 5-10).

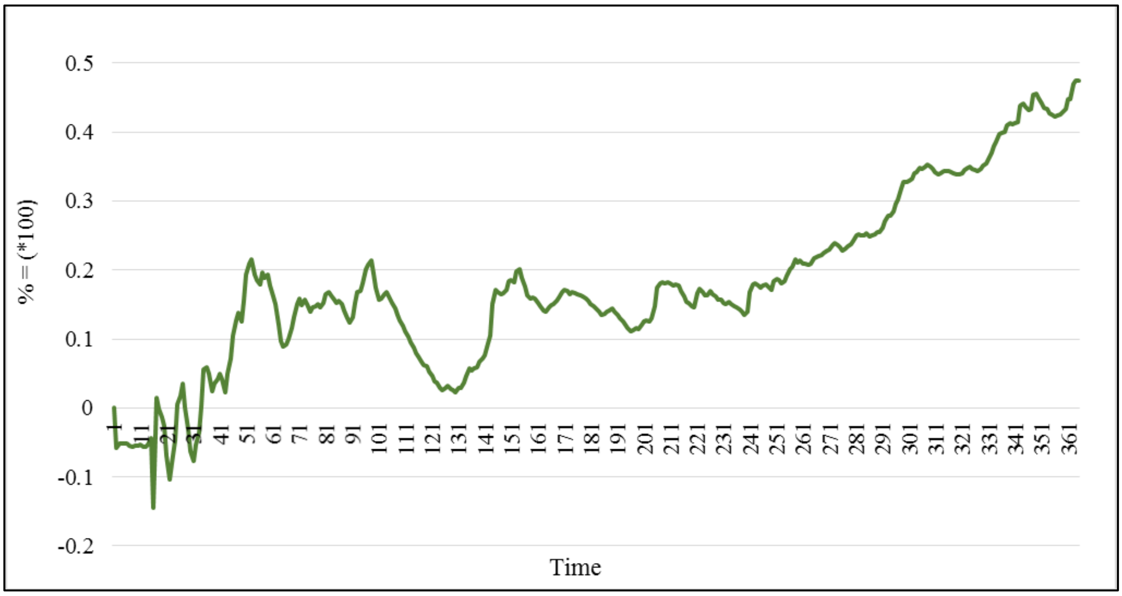


Figure 6-5: Average Daily ROR for 2011

Figure 6.6 shows changes in daily electricity generated from one 1.5MW wind turbine in 2011 in kilowatt per hour. As mentioned in Chapter 2, wind speed changes dynamically over time, therefore electricity generated follows the similar pattern as wind speed, the relationship between wind speed and amount of electricity generated is presented in equation 4-1.

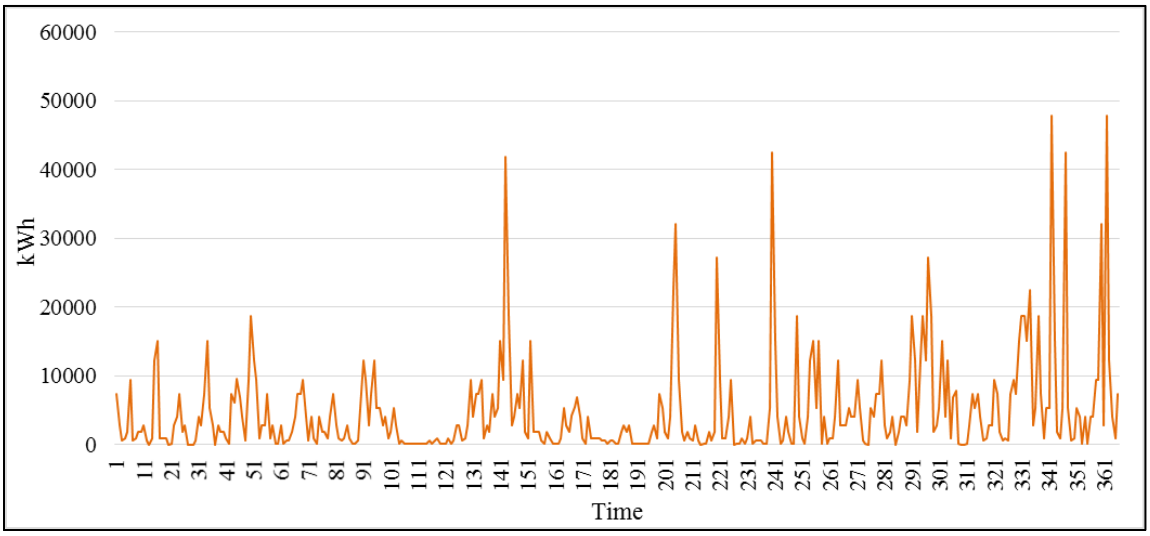


Figure 6-6: Average Daily Electricity Generation from 1.5MW Turbine in 2011

A further economic assessment of renewable generation investment is by way of a levelised cost of energy (LCOE) which is an essential consideration for the cost of electricity generated from power plant during its lifetime (Duan, 2017). LCOE calculated for electricity generated from 1.5MW turbine is presented in Figure 6-7 and Table 26. The graph and table show that LCOE has decreased over years due to the increase in generation of electricity from the turbine due to increase in wind speed and having constant initial cost of investment over time (see Equation 5-12).

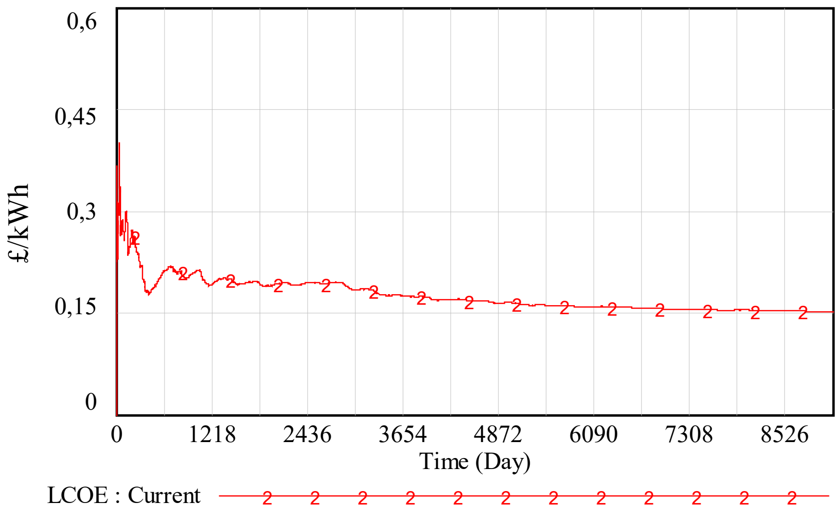


Figure 6-7: LCOE for Optimised Model (£/kWh/Day)

Table 26 shows that the, LCOE is between £0.254 kWh and £0.1517 kWh from 2011 to 2035 is less than cost of buying electricity from grid. For instance, the average cost of buying electricity from grid in 2011 is £0.41 kWh (see Appendix C) for the same period

Year	LCOE	Year	LCOE	Year	LCOE
2011	0.2547	2019	0.1852	2027	0.1592
2012	0.1994	2020	0.1772	2028	0.1588
2013	0.2082	2021	0.1741	2029	0.1572
2014	0.1973	2022	0.1698	2030	0.1554
2015	0.1949	2023	0.1684	2031	0.1551
2016	0.1921	2024	0.1652	2032	0.1543
2017	0.1932	2025	0.1621	2033	0.1537
2018	0.1941	2026	0.1609	2034	0.1517

Table 26: Average Yearly LCOE

Recall, LCOE is another indicator of viability of investment on renewable electricity generation in this research model. Figure 6-8 presents cost of buying electricity, price of selling electricity and Levelised cost of producing electricity from 1.5MW wind turbine. As illustrated, LCOE for the wind turbine is between £0.255 and £0.152 over the lifetime of the project (green line). On the other hand, the price of exporting electricity from the renewable farm to the grid can be considered to be constant from 2012 till end of the project lifetime at £0.054 kWh[20] (blue line). The daily average cost of buying electricity from the grid increases by 5% annually after 2019 as presented in Chapter 4 due to the increase in demand and scarce sources for generating electricity (see Appendix C). Even without the 5% annual increase the cost of buying electricity from the grid was £0.338 in 2011 which is 8% more than the LCOE. The difference between LCOE and Price of buying electricity from the grid illustrates the economic viability of investment on 1.5MW wind farm for generating electricity for Huntly.

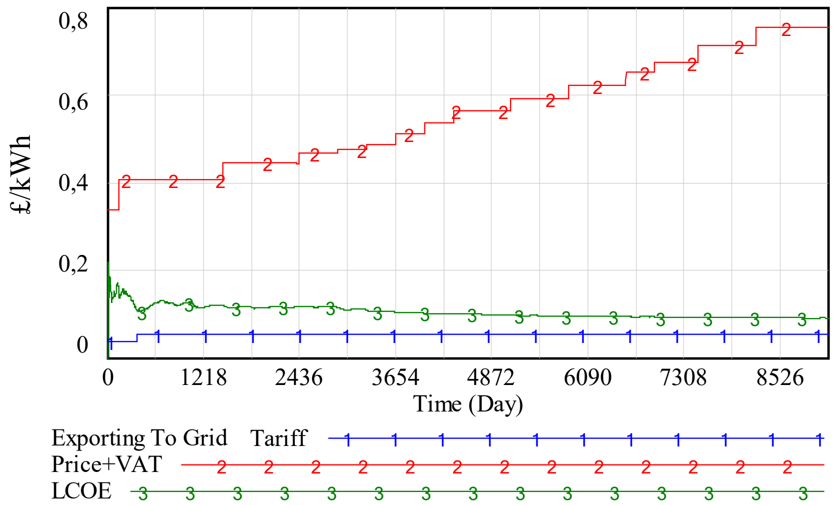


Figure 6-8: LCOE, Price of Export and Price of Buying Electricity from Grid from 2011 to 2035

Recall from Chapter 5, the internal rate of return (IRR) is another indicator for evaluating viability of an investment. IRR for different capacity size for each wind turbine and solar panel calculated which is presented in Table 27. As the table shows, again that one 1.5MW has the highest internal rate of return on investment, and this illustrates the correctness of the result obtained from optimising the research model.

[20] Feed-in tariff for exporting electricity from 2012 to 2019, when this research has taken place were £0.054, therefore the same price considered for the rest of the project.

IRR	No of Solar Panel	No of 55kW WT	No of 800kW WT	No of 900kW WT	No of 1.5MW WT	No of 2MW WT
0.6909						1
0.2609						2
-0.0279						3
0.8241					1	
0.4504					2	
0.2231					3	
-0.0198					4	
1.0011				1		
0.0673				2		
-0.0111				3		
-0.0747				4		
-0.2134				5		
1.1964			1			
0.1959			2			
0.0957			3			
0.0349			4			
-0.0121			5			
0.2311		1				
0.3582		2				
0.3535		3				
0.3085		4				
0.2594		5				
0.2143		6				
-0.8115	10					

Table 27: IRR calculation for different renewable generation capacity

6.3.2 Wind Farm

The first optimisation modelling run (subsection 6.2.1) indicates that one 1.5MW wind turbine is suitable for Huntly. Therefore, in the second run, only wind turbines were selected as a decision variable to check whether simulation gives different results. After the second model execution, the results demonstrate that application of 0.98 (nearly one) 1.5MW of power from wind will maximize the ROR which is almost the same as the first modelling run previous simulation result presented in sub-section 6.2.1.

The next section gives modelling result for different scenarios tested for illustrating the effects of selected input variables on viability of the model renewable investment.

6.4 SCENARIOS

In this section, four different scenarios are examined to illustrate the effect of changes on input parameters and profitability of the scheme.

From the results presented in sub-section 6.2, the use of one 1.5MW wind turbine already achieves viable economic investment. Therefore, the first scenario considers the effect of changes in capacity of the wind turbine on ROR and LCOE. The second scenario illustrates the investment in 2025 with possible changes that might take effect in that time. The third scenario examines effect of a reduction in cost of technology on future investment profitability. The final scenario focuses on possible changes required to make the use of solar PV panels viable.

6.4.1 Different Capacity of Renewable Farm

This sub-section covers details about the effect of changes in capacity and type of wind turbine on the economic viability of the scheme. Table 28 presents, the four different scenarios that are examined.

Scenario	Name
One 1.5 MW wind turbine	Scenario 1 (Base)
One 2 MW wind turbine	Scenario 2
Two 2 MW wind turbine	Scenario 3
Two 1.5 MW wind	Scenario 4

Table 28: Scenario I, Different Capacity of Wind Turbines

Modelling outputs from the different scenarios from Table 29 is presented in Figure 6-9. Scenario 1, clearly provides the optimal scenario in terms of the results. Several conclusions can be drawn:

- Debt service per day is lowest
- Lowest O&M cost
- lowest cost of land – directly affects the size of the area needed for the installation

The electricity generated from scenario 2, 3 and 4 is higher in comparison with application of one 1.5MW wind turbine which is due to increase in capacity of wind turbines applied. However, that does not necessarily mean higher ROR as presented in Figure 6-9. It should be noted that electricity generated is not an indicator of economic viability of the scheme, so higher capacity of wind turbine installed does not mean more feasible investment. Therefore, although scenarios 2, 3 and 4 have more electricity generated in comparison with the scenario 1, but applying one 1.5MW turbine (scenarios 1) is the optimal capacity for electricity generation for this region.

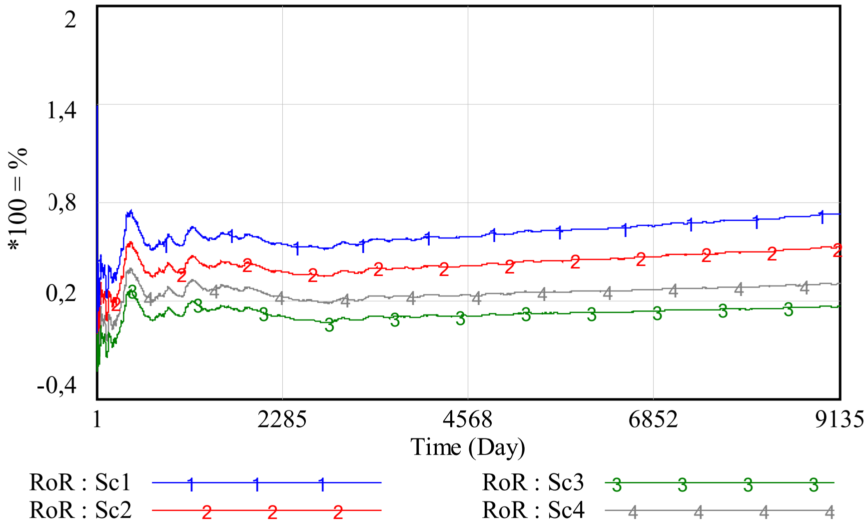


Figure 6-9: ROR for Different Capacity of Wind Turbine Electricity Generation

6.4.2 Discount Rate

Based on ROR analysis, three scenarios were developed and analysed to explore the effect the discount rate has on investment efficiency on the 1.5MW turbine keeping all other variables constant. Figure 6-10 shows the first scenario with 5% discount rate; the second scenario shows a 7% discount rate on ROR and LCOE and finally the third scenario considers a 10% discount rate.

Figure 6-10 shows in the first 10 years of operation of wind turbine the changes in discount rate had no significant impact on ROR as all three scenarios followed similar changes over time with difference of below 1% between first and second scenario and less than 2% between first and third scenario. However, after 10 years (3700 days) the difference between scenarios began to increase where at the end of scheme the difference between scenario one and two reaches nearly 4% and difference between scenario one and three reached 9%. Variation in changes between different scenarios is mainly due to the way Vensim software operates. As there is a large number of data to deal with, it takes time for the software to presents the accurate values. Therefore, what is presented in Figure 6-10 after 10 years is considered as the difference between three scenarios with different discount rates, in which the lowest interest rate, 5% (blue line) gives the highest ROR.

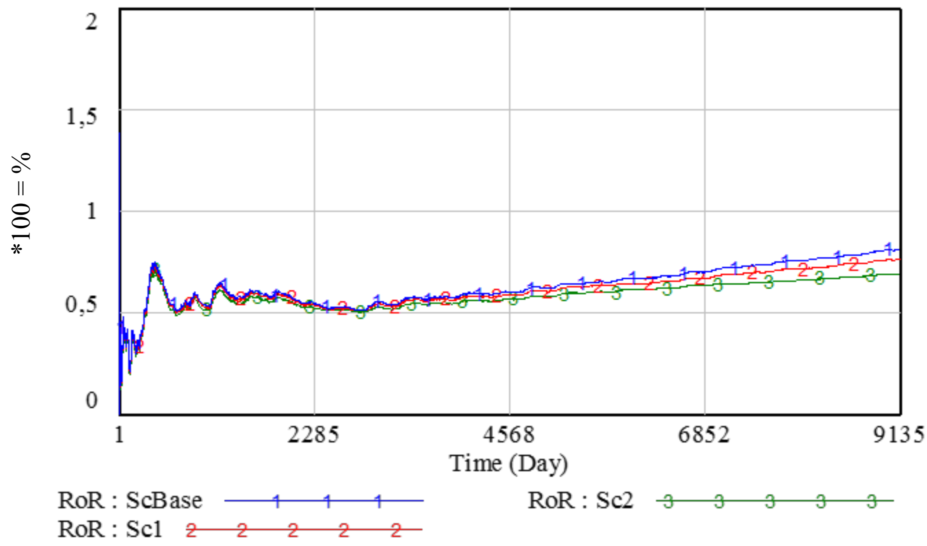


Figure 6-10: ROR for Different Discount Rate

The discount rate as expected has little effect on LCOE as presented in Figure 6-11. In this case the lowest discount rate is presented in scenario 3 (green line) which shows the lowest LCOE over lifetime of the project. So, lower the discount rate, lower the Levelised cost of generating electricity which is clearly presented in the Figure 6-11.

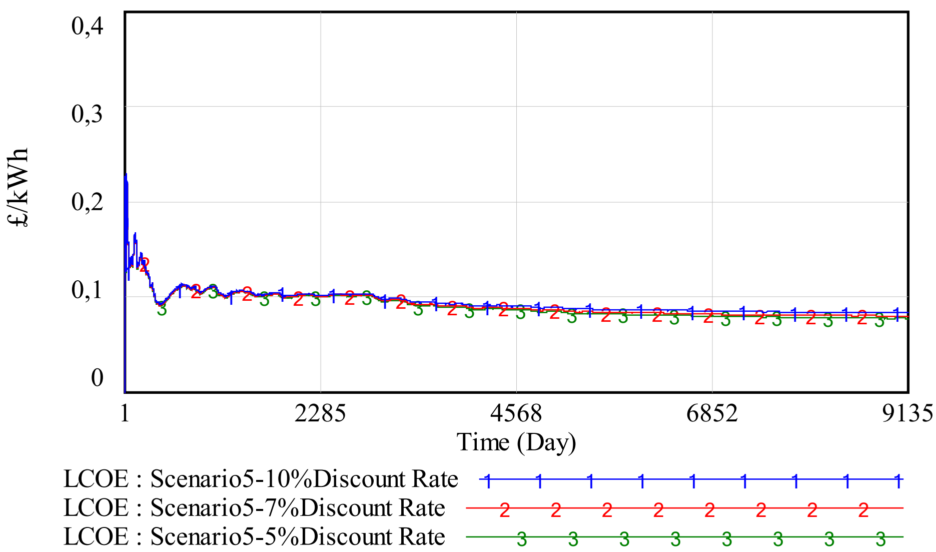


Figure 6-11: LCOE for Different Discount Rate

6.4.3 Investment in 2025

In addition to above, the model evaluates the investment in a community renewable farm in 2011 and the best solution is obtained by using one 1.5MW wind turbine for the chosen community. In this sub-section, viability of an investment from 2020 to 2045 is tested and evaluated in more details. In this scenario, effect of changes, on the inputs which were explained in more detail in Chapter 2, are examined while household electricity consumption, wind speed and sun irradiance are considered to be constant. Applied changes to the scenario are from Chapter2, subsection 2.7 and they are given below:

- Reduction in cost for wind turbine technology and PV panels by 20% in comparison to the base model, SP7.
- Mean time to failure to reduce from 2.83 times a year to 2 times per year
- Turbine repair time reduction from 3 days to 2 days
- Land cost rise by 6% -in comparison with the base model.
- No feed-in-tariff for generation from wind turbine. SP4.
- Price of buying electricity increase by 5% every year, SP5.

The results from simulation clearly indicates that again applying one 1.5MW wind turbine makes the project economically viable and maximizes the ROR. Figure 6-12 presents the ROR for 1.5MW turbine with 20% cost reduction in which ROR reaches 76% with LCOE of £0.081 per kWh. In this case the lower cost of technology a lower failure rate and a lower repair time leads to a higher rate of ROR over time compared to the base model tested for 2011 (see sub-section 6.2). Also, as initial cost of investment is lower than base model, increase in electricity generated increases the ROR in a faster rate than base model.

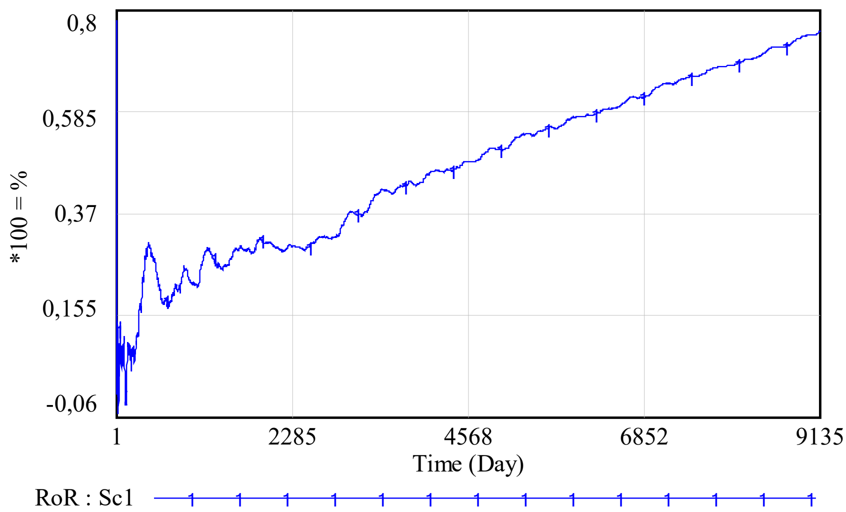


Figure 6-12: ROR (%) for Optimised Model

As discussed, investment in 2025 with changes applied has a higher ROR on investment as well as lower LCOE compare to the base model tested for 2011 as shown in Figure 6-13. Although the cost of land is considered to be higher and no feed-in tariff implemented in this scenario, but the reduction in cost of technology by 20% and lower failure rate and the lower mean time to repair leads to a lower LCOE of LCOE, £0.081 compare to 2011 model with £0.152 (see Figure 6-7).

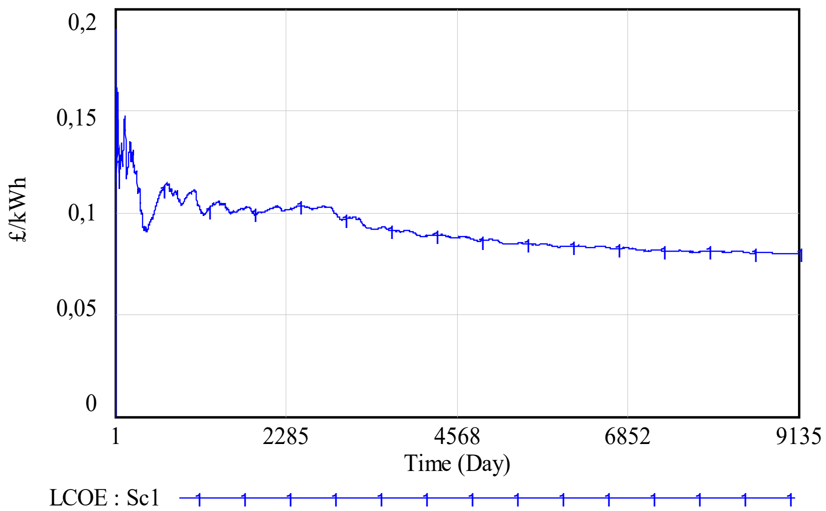


Figure 6-13: LCOE (£kWh) for Optimised Model

6.4.4 Reduction in cost of wind turbine – Investment in 2025

As discussed in Chapter 2, 2.12, SP8 (Cost of Renewable Technology), the cost of renewable technology has fallen dramatically since the renewable technology was introduced and it is expected to decrease still further (Gabbatiss, 2018; IRENA, 2018; Jack, 2019). This section presents the effect of cost reduction on future investment on wind turbine technology as illustrated in subsection 6.3.2.

Three different scenarios are considered:

- First scenario; 20% reduction in the cost of wind turbines in comparison with the cost in 2011
- Second scenario; 30% reduction in the cost of wind turbines in comparison with the cost in 2011
- Third scenario; 40% reduction in the cost of wind turbines in comparison with the cost in 2011

As simulation runs from 2020, 20% reduction of the cost of wind turbine is considered as a first scenario and other two scenarios are compared with that.

RORs for all three scenarios are presented in Figure 6-14. ROR is affected by initial cost of investment which includes the cost of technology (equation 5-11). Therefore, a reduction in renewable technology cost has a significant effect on economic feasibility of renewable investment. The difference between scenario 1 and 2 starts with 10% in the early years of the scheme, however, by the end of the scheme this difference increases to nearly 13%. The difference in ROR for Scenario 1 and 3 starts with 20%, however by the end of the project this number increases to 30%. Therefore, from results presented in Figure 6-14, the cost of technology has a significant effect on efficiency of the renewable investment. In this case, 40% reduction in technology cost increases the ROR from 72% (with 20% reduction) to %110.

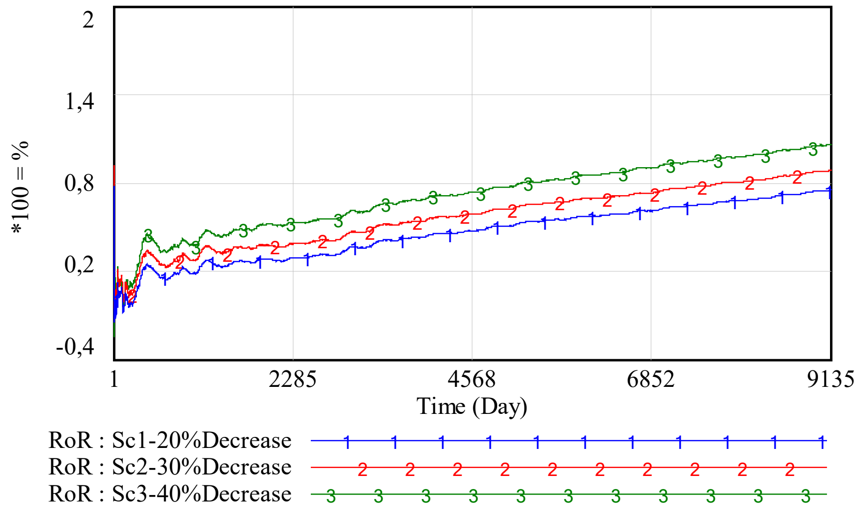


Figure 6-14: ROR for Reduction in Cost of Wind Turbine investment in 2025

As illustrated from Figure 6-15, a reduction in cost of technology has a positive effect on the LCOE as the scenario with 40% reduction in cost of technology has the lowest LCOE comparing to the other two which is due to the direct effect of investment on technology on LCOE (Equation 5-12). Reduction of 40% in technology cost reduces the LCOE from £0.081 (with 20% reduction) to £0.073. Therefore, as expected technology cost can be considered as a significant variable, impacting the LCOE and efficiency of the renewable generation investment. A survey by Hawley (2018) shows that in the near future a reduction in the cost of wind turbines and a higher generating efficiency, will result in wind turbines becoming the most cost-effective source of electricity generation.

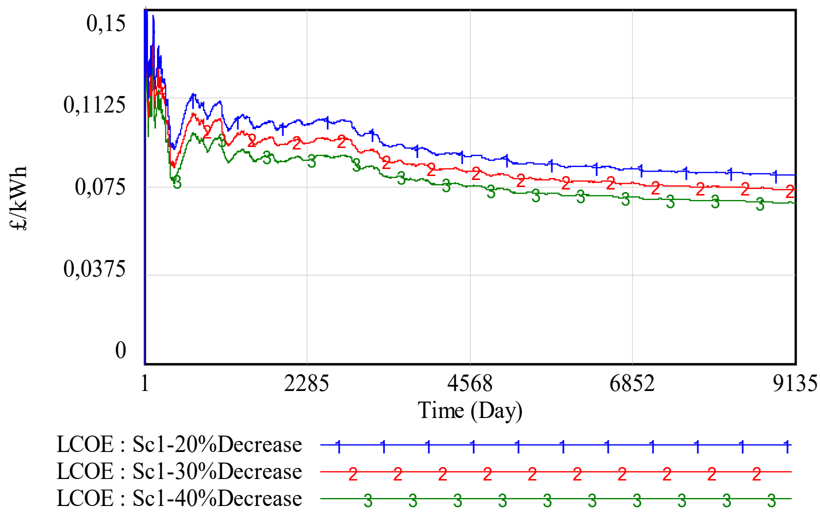


Figure 6-15: LCOE for Reduction in Cost of Wind Turbine from 2020 (£/kWh)

6.4.5 Solar PV panel

So far results from the modelling have focused on wind scenarios, to be specific one 1.5MW turbine is suitable for Huntly. However, this sub-section calculates the changes required for solar panels to be used in the modelling to optimise the ROR.

This scenario illustrates the increase in sun irradiance needed for one solar PV panel to be selected for the model to makes ROR equal to zero. The model is run with base model conditions as described, in sub-section 6.2.1. Results show that sun irradiance must increase by 10 times in order for one solar PV panel to be economically viable for Huntly.

Figure 6-16 shows the ROR for selecting one PV solar panel with an irradiance increase of 10 times. The run of the model is shown by the blue curve; ROR would mainly be less than zero which indicates an inefficient investment for the scheme. Therefore, the ROR for using the one solar panel in the renewable generation demonstrates a loss in the investment over its lifetime. For the region such as Huntly solar panels can only be viable if the sun irradiance increases by at least a factor of 10.

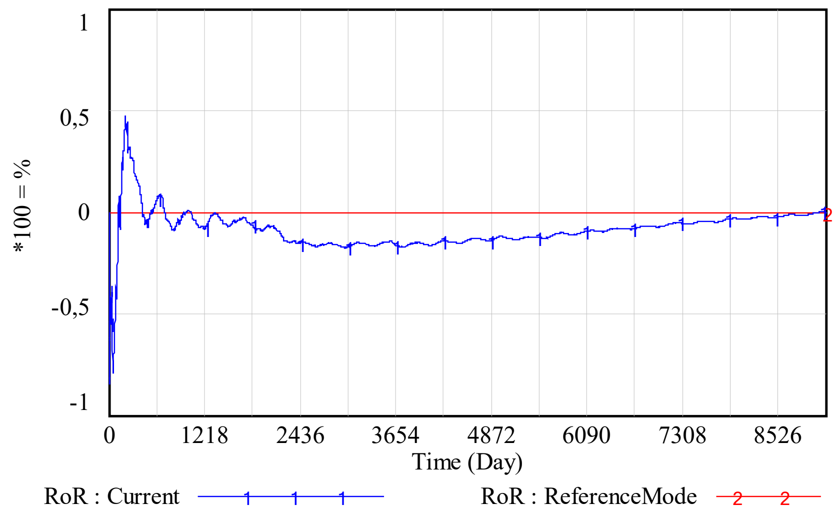


Figure 6-16: ROR for One Solar Panel to be selected by the model (%)

6.5 SENSITIVITY ANALYSIS

This section presents the sensitivity analysis to measure the most sensitivity of examined outputs to the changes in the input variables. From results obtained from previous sections in this chapter (6.4.4), Change in cost of technology (wind turbine) has the most effect on ROR, which is because of initial cost of investment reduces which leads to higher ROR as scheme starts and electricity generates. Moreover, selling price of exporting electricity to the grid effect the efficiency of the investment on the 1.5MW wind farm project significantly. This can be because of continuous generation of electricity and effect of selling price of the total revenue obtained from the investment as well as length of the project. Over lifetime of the project (25 years in this case) initial investment on the project remain the same with small changes due to rise in operation and maintenance cost. However, gain from the investment continuously increase as it predicted that weather would be windier and as a result more electricity would be generated.

In this section sensitivity of ROR with changes in feed-in tariff, price of exporting electricity to the grid, cost of land and discount rate examined which are presented Figures below. In each case, tested parameter is changed between -20% and +20% to assess the effects it has on the ROR. The width of the curve presents how much changes in the selected input variable will change ROR over life time of the project. The 9135 in all four figures refer to number of days farm operates (25 years).

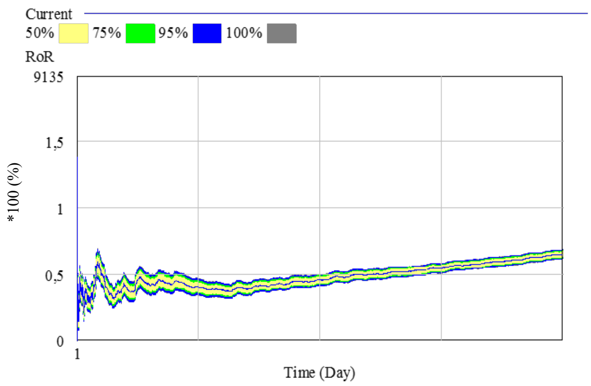


Figure 6-17: ROR vs Feed-in Tariff

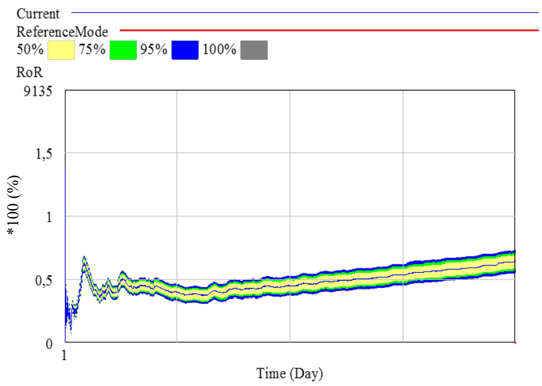


Figure 6-18: ROR vs Price of Exporting Electricity to the grid

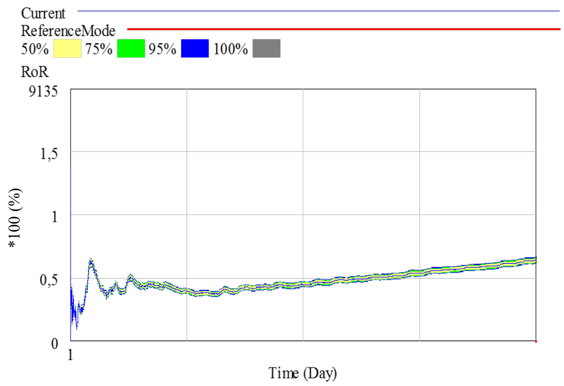


Figure 6-19: ROR vs Cost of Land

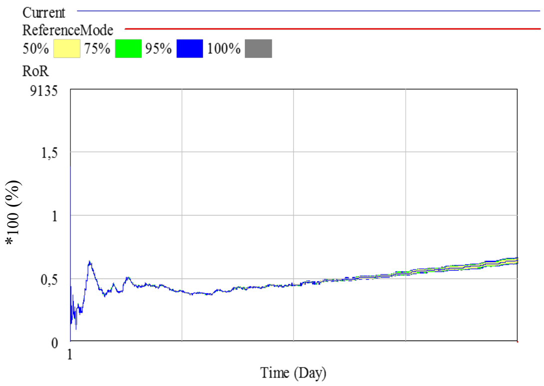


Figure 6-20: ROR vs Discount Rate

As presented in the figures above, ROR is the most sensitive towards changes in price of exporting electricity to the grid (see Figure 6-18) and feed-in tariff (see Figure 6-17). This is because of the way ROR is calculated in which the total net profit (grain from investment) over lifetime of the project effects the efficiency of the ROR. However, still cost of technology is the main influencer of the ROR as it indicates the initial cost of project which is one of the key elements in efficiency of the project.

6.6 MODELLING GROUP II: SYSTEM DYNAMICS

This sub-section presents the 'Modelling Group II' with application of System Dynamics modelling which is a methodology for studying and managing complex feedback systems. SD modelling is used to develop a system simulation by linking a number of feedback mechanisms to provide formal analytical model. This way of modelling allows the relationship between components and overall system behaviour be explored and gives a better understanding of the interactions and impacts among different system components (Sušnik et al., 2013).

The relationship between ROR from the optimised scheme and effect of that on future investment in the number of wind turbines is presented with application of SD. The SD model simulates the system on a yearly basis under different scenarios, a schematic of the functional model is presented in Figure 6-21. As shown, ROR is selected as a starting point to indicate the number of turbines for future investment based on optimised results obtained from DES model. The number of turbines effect the total capacity of wind turbines which effects the amount of electricity generated from wind turbines. The amount of electricity generated from wind turbines effect total revenue and total cost of the scheme. Moreover, the total cost and the total revenue of the scheme will affect the ROR which again effects the number of turbines used.

Recall, the SD model simulates the scheme on a yearly basis under optimised scenario obtained from DES modelling (sub-section 6.2). Characteristics for the system dynamic modelling presented are as follow:

- Household electricity consumption are assumed to be constant
- Weather is assumed to be constant
- Land limitation is removed

- Total capacity installation limitation is removed

Results from system dynamic modelling of future renewable electricity generation investment for Huntly is presented below as well as different scenarios examined.

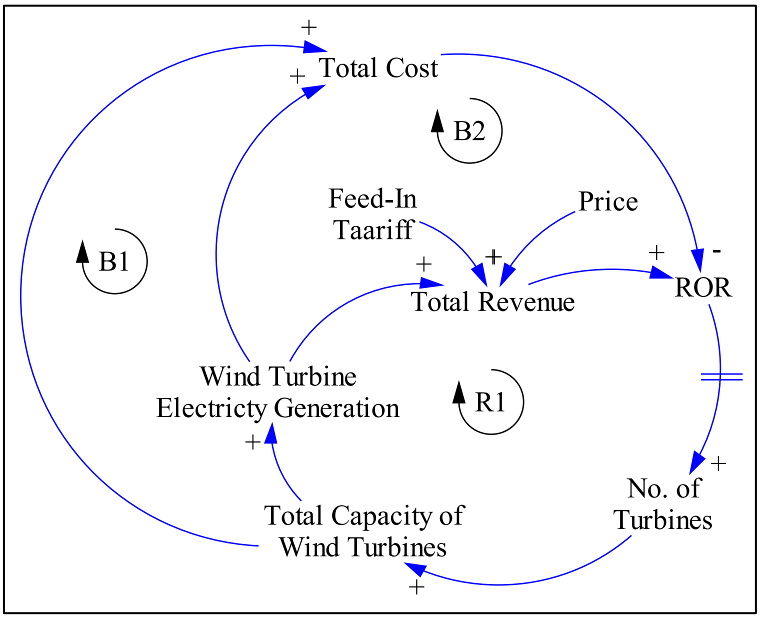


Figure 6-21: System Dynamics Model

6.7 Group Modelling II, Results

The effect of adding feedback from ROR to number of wind turbine is presented in Figure 6-21 in which land limitation and total installed capacity limitation is removed. As Figure 6-22 shows, the installed capacity is 1.5MW at the start of the scheme, then after first year of operation, in 2012 it increases from 1.5MW to 3MW, then in 2013 the capacity increases to 4.5MW which is applying three 1.5MW turbine. The capacity of turbine shows an increasing trend through the lifetime of the project to nearly 6MW by end of the scheme.

On the other hand, as Figure 6-23 illustrates, there is a significant increase in ROR from 2011 to 2014 as capacity increases the ROR has increased significantly to 220% in 2014 this increase is due to effect of system dynamics and increase in revenue generated as installation capacity increases. Moreover, imposing feed-in tariff, higher rate of excess electricity and increase in price of electricity effect the ROR and then again effect the total capacity from wind turbines. However, after 2015 there is a slight increase due to less effect from other variables in the feedback loop such as sharp reduction of feed-in tariffs in 2015 compare to 2012 which reduces rate of increase of the revenue and therefore, reduces the rate of increase in ROR which effects the rate of increase in total capacity of wind turbine applied in the research model.

It should be noted that in system dynamics modelling the limitation of 5MW for total capacity installation of renewable and land limitation have been removed to assess the maximum increase in total capacity of wind turbine and maximum ROR that can be achieved. Therefore, by adding feedback loop to the developed model, the installation capacity of wind turbine increases to nearly 6MW with 300% ROR.

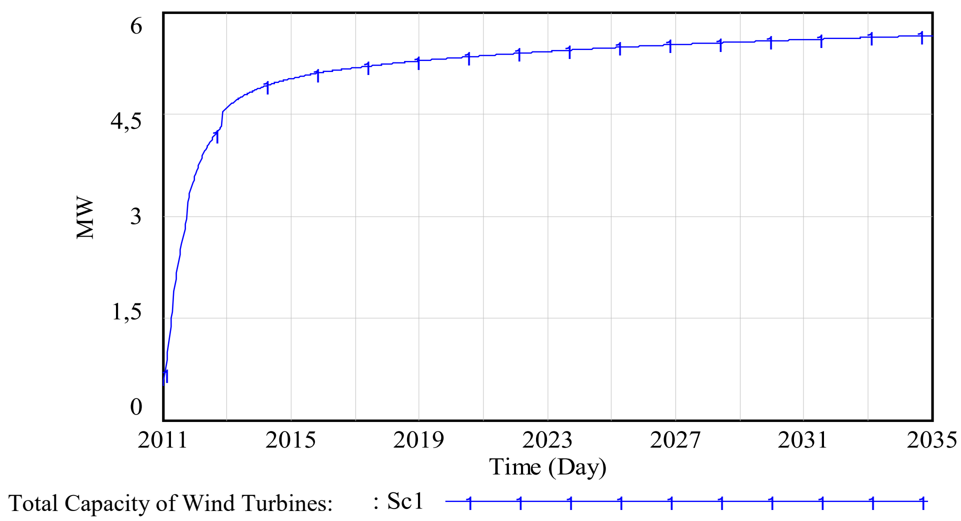


Figure 6-22: Total Capacity of Wind Turbines with Feedback Loops

Adding feedback to the research model changes the number of wind turbine applied which changes the ROR significantly compared to the model without feedback. As illustrates in Figure 6-23, ROR increases significantly from 2011 to 2014 due to increase in number of wind turbine from one 1.5MW turbine to three 1.5MW turbines in 2014. However, ROR doesn't change as much from 2020 meaning tested components do not change as much as the beginning of the project and that leads to reduction in the effects they have on ROR. Even with all changes still rate of return on renewable investment is significantly high, 300%, which means that investment on the scheme is profitable.

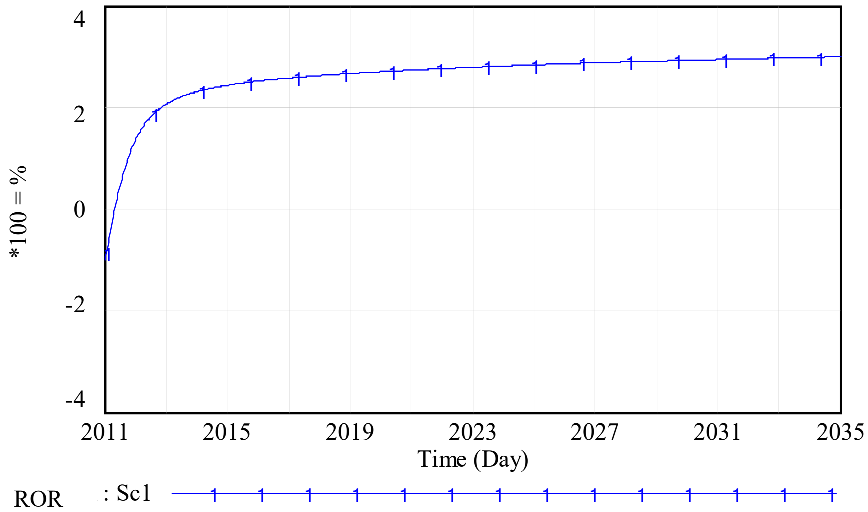


Figure 6-23: ROR with Feedback Loop

The next sub-section examines different scenarios and effect of changes in input on viability of the investment.

6.7.1 System Dynamics Scenarios

As presented in subsection 6.2.1, base model runs from 2011 which considers changes in feed-in tariff, changes in price of buying electricity from the grid and price of exporting electricity to the grid. These changes are detailed in the Table 29. Recall, column in this Table presents the key points reported in detail in Chapter2 and effect of changes on model simulation.

This sub-section presents different scenarios to evaluate the effect of changes in components on ROR and total capacity of wind turbine. It should be noted that in this case limitation of land and total capacity installation of 5MW has been removed to test the maximum increase in capacity of wind farm.

There are five different scenarios that are tested and compared to the base model (see sub-section 6.2.1). Therefore, first scenario considered the base model scenario, then scenarios 2 presents the effect of zero feed-in-tariff on generated renewable electricity, scenarios 3 looks at changes considering 50% increase in feed-in tariff compare to base model, scenario 4 shows 50% fall in price of renewable electricity exported to the grid, scenario 5 presents 50 % rise in price of renewable electricity exported to the grid and scenario 6 presents 40% rise in cost of land compare to 2011 model (base model).

As discussed, in system dynamics modelling, the effect of efficiency of ROR on investment on wind farm examined. In this section different scenarios are tested which effect the feedback loop between ROR and number of turbines applied in the renewable electricity generation farm. In this part of the modelling land limitation and total capacity installation limitation are removed to assess the maximum ROR are Total Capacity on wind turbines installed.

Changes in total capacity of wind turbine installed and ROR with effect from different scenarios are presented in Figure 6-24 which are discussed in more details. Different colour and associated numbers to each curve represents the scenario tested. As it illustrates from the figure, scenario 5 (black line) which is 50% rise in selling renewable electricity to the grid has the highest ROR with more than 550% from 2014 to the end the of the lifetime of the project which leads to the highest increase in number of turbines applied, nearly 10MW (see Figure 6-25). That shows the effect of selling price of electricity to the grid is higher than other changes due to the effect it has on total revenue generated from electricity generation and direct effect of revenue to the ROR and effect of that on the rest of the components on the feedback loop. 550% ROR shows that overtime the investment becomes more and more profitable as the initial cost of investment stays constant and electricity generated from wind turbine increases due to rise in the installation capacity as Figure 6-26 shows Total capacity stays quite constant with nearly 10MW from 2014 to 2035 and same effect applied in ROR as both total installed capacity and wind turbine and ROR follow similar changes.

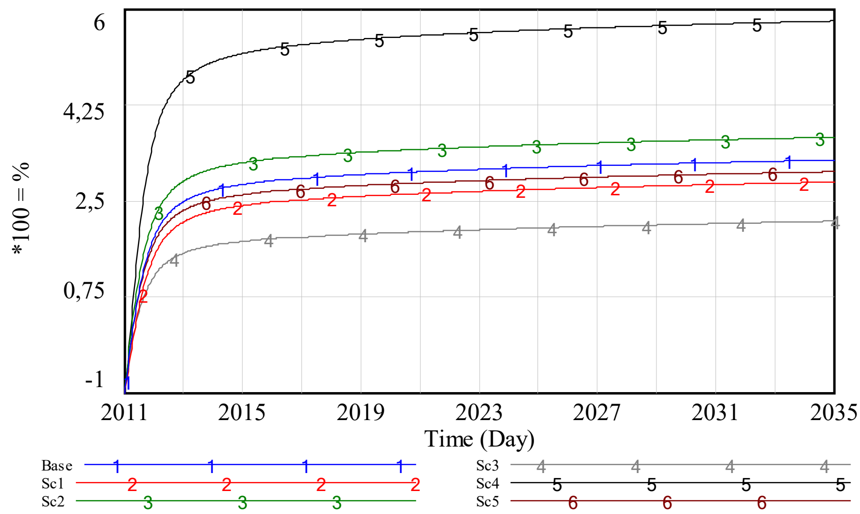


Figure 6-24: ROR with feedback loop – 6 Scenarios

Scenario 6, which is 50% increase in cost of land however, does not affect the output as expected by effecting the overall output the least. Increase in price of land has reduced the ROR and as a result the total capacity of wind turbine by small amount compare to the percentage of changes in cost of land. This can be due to the fact that cost of land considered as initial investment cost in the calculation which increase in total initial cost of investment leads to lower ROR if gain from investment increases (see Equation 5-10). Also, as electricity generated from wind turbine increases the effect of increased revenue from selling the electricity back to the grid and saving from not spending electricity overtakes the initial investment cost.

Scenario 2 is implementation of no feed-in tariff on generated renewable electricity in the research model. As expected removing incentives as such will reduces the efficiency of the ROR simply due to reduction in the revenue generated from the investment. Scenario 3 is used to compare the results of no government incentives with 50% increase in the incentives as well as testing the model. Presented results in Figure 6-20 and 6-21 are as expected. Scenario 4 however, reduces both selected output the most as 50% reduction in selling price of electricity to the grid will reduces the total revenue from the investment.

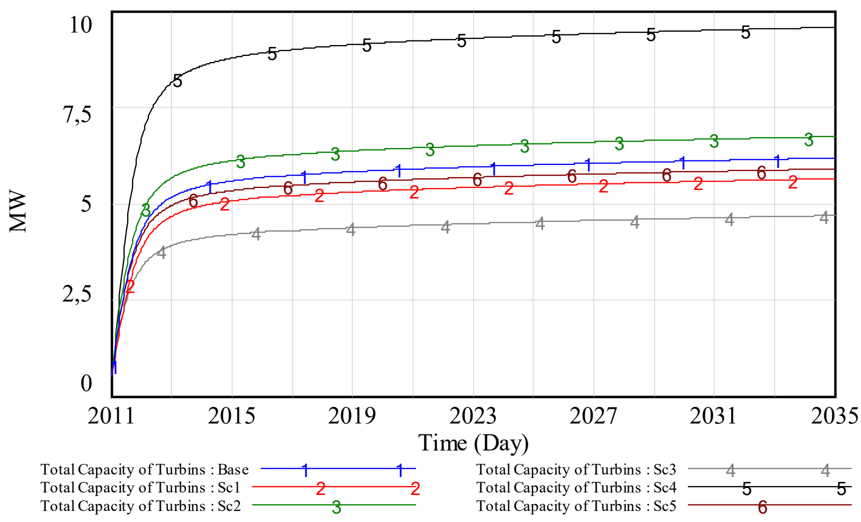


Figure 6-25: Total Capacity of Wind Turbine Installation with feedback loop - 6 Scenarios

Overall effect of examined scenario on LCOE is presented in Figure 6-26. As it demonstrates changes in all scenarios have small effect on LCOE in comparison to the base model (scenario 1, in blue). However, in this case, increase in price of land increase the LCOE which is due to it's the calculation (see Equation 5-12). In this case rise in price of land increase the initial investment of the project while the electricity generated from the project reduces due to feedback loop effect, therefore, LCOE for increase in price of land increase the cost of generation every kilo watt of electricity from wind turbine compare to other scenarios.

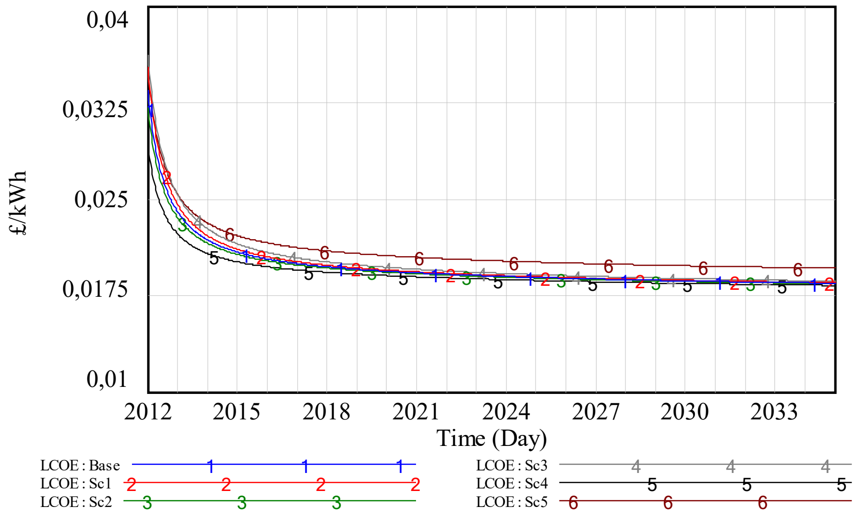


Figure 6-26: LCOE with feedback loop - 6Scenarios

6.8 RESEARCH HYPOTHESIS

To address the hypothesis "the developed model is able to evaluate a community electricity generation scheme anywhere where enough adjacent land is available to support the renewable generation infrastructure" the model is considered in more general sense. To support the hypothesis the case study of Huntly is selected which presented the expected results in accordance with its weather condition and land availability (one 1.5MW turbine to optimise the electricity generation for community of 140 households). Therefore, the developed model is considered to be applicable to any community as long as constrains are defined for a particular area. The main inputs for the model are:

- Community Electricity consumption (It can be in any time interval, this research selected daily time interval)
- Wind Speed and Sun Irradiance
- Land availability for the renewable farm generation
- Cost of renewable technology

- Cost of land
- Government subsidies
- Discount rate
- Lifetime of the scheme

The model will optimise the renewable electricity generation for any selected region based on the constraints defined and input data. Changes in wind speed, sun irradiance, land availability and electricity consumption will change the results obtained from the model. Therefore, the model, although specific in the case of Huntly, is quite generic as the constraints used are 'vanilla' in nature.

6.9 Chapter Summary

In this chapter the developed research model tested for the chosen case study applying the region's average daily household electricity consumption and daily weather as well as land availability and associated costs for the land and renewable technology. Findings from optimisation results obtained from group modelling I run, illustrates that one 1.5MW onshore wind turbine is the most suitable technology and capacity for generating electricity for Huntly, considering the household consumption, weather condition, land availability, cost of technology, price of land and government subsidies. In all scenarios examined in this research wind turbine was the most suitable technology for renewable electricity production. Result for testing for solar PV panels feasibility shows that for the first solar panel to be selected by the model for this region, the sun irradiance has to be 10 times more comparing to the period of 2011 to 2018. In optimisation simulation model, ROR has set as an indicator of feasibility of renewable investment. The model with application of DES runs the simulation to optimise the ROR over 25 year's lifetimes of the project.

Optimisation result for Huntly illustrates that application of one 1.5MW turbine maximises the scheme for Huntly with 72% rate of return on the investment (ROR) with LCOE of £0.15 which on average produces 2,700,000 kWh of electricity per year. After that different scenarios tested to evaluate the best investment options as well as illustrating the biggest influencer of the ROR in the scheme. One of the components that influences the decision making in renewable generation investment is cost of renewable technology. As presented in sub-section 6.4, Figure 6-15, highest ROR and lowest LCOE is for 40% cost reduction of wind turbine, where ROR reaches nearly 110% at the end of the project lifetime even though the assumption of no feed-in tariff or subsidy for electricity generated by wind turbine applied.

Future investment in renewable provides the similar result in terms of technology selection but with higher ROR and lower LCOE due to improvement in efficiency of technology, lower cost of technology and lower operation and maintenance cost. These results obtained from running the model for 2025 considering reduction in cost of technology and improvement in performance of technology despite the rise in price of land and no government incentives on renewable investment.

Furthermore, after optimising the model with Modelling Group I, feedback loop is added to the model to run the model with Modelling Group II, to present the future relationship between optimisation outcome (ROR) and variables affecting it. In this case, only wind turbine considered for modelling as optimisation results show that wind turbine is suitable for the selected region. With application of SD modelling the relationship between ROR and future investment in number of wind turbines described which presented in Figure 6-17. Constrains defined in the Group Modelling I removed to assess the maximum ROR and maximum total capacity of wind turbine generation that can be achieved in future from the wind farm. The model starts from ROR optimisation result obtained after the 1st year of operation to indicate the number of turbine applicable with associated ROR rate and then total capacity of wind turbine and so on. With application of system dynamics (SD) modelling to the optimisation result obtained from discrete event simulation (DES) model and with removal of constraints, it is concluded that in Huntly the renewable electricity generation farm can expand to nearly 6MW over 25 year with secure ROR (around 29%).

As presented in Chapter 2, Government policies and subsidies can significantly influence the feasibility of renewable investment via changes to exporting price of electricity to the Grid. As presented the sub-section 6.4.1. Figure 6-24, if exporting price of electricity to the grid doubled, ROR reaches the highest level, around 585% at the end of the project lifetime. In the same figure, it presented that if feed-in tariff or price of buying electricity from the grid doubled, ROR reaches to nearly 380% at the end of lifetime of the project compare to the base scenario which has ROR of 300%. Therefore, effect of changes in feed-in tariff for generated electricity from the wind turbine is considered to be miner compare to the changes in price of exporting electricity to the grid which generates the most revenue for the scheme.

The model is shown to be generic and can be applied to any world-wide region subject to sufficient land area being available and weather and consumption data being readily available. The data point being important as for remote districts, where the scheme is most beneficial, the data is difficult to find.

7 SUMMARY AND CONCLUSION

7.1 OVERVIEW

A summary is provided from the key points from each chapter presented with concluding remarks. The stated aim and objectives from Chapter 1 is revisited with statements on how this aim and objectives have been met. Finally, future research is identified based on the work undertaken for this research.

7.2 SUMMARY OF CHAPTERS

Chapter 1, presented the introduction of the research in which problem of sustainable energy for rural communities and government's target for greenhouse reduction was briefly explained together with the research hypothesis; 'the developed model is able to evaluate a community electricity generation scheme anywhere where enough adjacent land is available to support the renewable generation infrastructure'. The hypothesis was followed by a clearly defined aim and associated objectives. The renewable generation considers the combination of solar and wind farms with grid connection for rural communities.

Chapter 2 presented the literature review for the research that identified that in the UK rural populations are rising as more people choose to move to countryside. It is expected that rural population will increase by 6% by 2025. Although the population of rural communities is increasing the services provided for these communities is not increasing with the same speed. Still there are many areas which have difficulties with basic needs such as electric power. In case of severe weather conditions, rural communities are considered to be one of the most affected areas from power cuts as a result of damage to the electricity distribution network. Therefore, it is important to secure reliable energy supplies to these communities possibly through local power generation plants. On the other hand, UK as a member of European Union passed the Climate Change Act 2008 which makes Government responsible for lowering greenhouse gas emissions by 80% in 2050 compare to 1990. With domestic sector accounting for second largest energy user with 49%, one of the UK Government's solutions to achieve 2050 greenhouse target would be to generate electricity from renewable sources for domestic sector. Therefore, in order to provide sustainable electricity for rural communities and to achieve greenhouse emission targets, the model of community electricity generation should be considered in which a group of household use shared renewable energy generation resources providing sustainable energy. If households invest in locally generated energy, it could become a source of revenue for them as any excess of electricity could be sold to the national grid, therefore, households could have sustainable energy, could save on their electricity bills and with energy consumption management could benefit from revenue by selling the excess electricity to the grid. As a result, this research investigated the hypothesis of grid-connected distributed communal renewable electricity generation for rural communities with priority of providing electricity to the community and selling any excess of electricity to the grid. For such an investigation, selecting a right community to test the hypothesis was essential, and part of the selection is that adjacent land is available for the shared generation facilities as well as detailed consumption, weather and land availability data. Therefore, to test a model a case study must be selected where detailed input data is available. This research chose a small town of Huntly in North-East of Scotland, as rural area are account for 98% of the land in Scotland with 17% of the total population. Huntly has a population of 5,000 with nearly 2,300 households. This research obtained daily electricity consumption of 140 households with the weather data and land availability for the region from 2011. From data gathered in this chapter it can be concluded that UK would achieve more reduction in greenhouse gas emission than its target for 2030. To set the foundation for this research the following significant points (SPs) were identified from the Literature Review:

- **SP1**- (Climate Change); over decade ago, the UK was one of the leading countries in producing greenhouse gases with majority of it coming from burning fossil fuel for producing energy, therefore, an input to this research is to identify alternative methods for producing energy.
- **SP2**- (European Union Carbon Emission); European countries proposed a package of binding legislation to ensure that Europe meets its climate and energy targets. One of the key targets is reducing the greenhouse gas level by 20% in 2020, 32% by 2030 and 80% by 2050 in comparison to greenhouse gas levels in 1990.
- **SP3**- (UK Electricity Market Reform (EMR)); UK government introduced the EMR policy in 2008 to help in delivering secure, sustainable, low carbon electricity at an affordable price. The feed-in-tariff was introduced in EMR policy. This research considered the changes in the tariffs during modelling.
- **SP4**- (Renewable Electricity Generation Incentive, Feed-in Tariff); the feed-in tariff is a government programme introduced in 2010 to promote small-scale (up to 5MW) electricity generation technology. However, the government has closed the feed-in-

tariff payment for households/projects that have not installed an eligible system on or before 31st march 2019. This has affected the overall results of this research causing the financial calculations to be reworked.

- **SP5**- (Price of Electricity in UK); In the UK there has been a significant increase in electricity prices in the last decades due to rise in consumption and more expensive source of generation. Therefore, finding an alternative way of generating electricity can help households with affordable energy and more reliable especially for rural communities. The research examines the internal rate of return (ROR) and LCOE for community size renewable generation considering these variations in electricity prices over time.
- **SP6-** (Renewable Sources in UK and Scotland) Overall there had been a substantial increase in renewable generation capacity annually in the England and Scotland since 2010. Onshore wind turbines are the main source of electricity renewable generation with an increase in installed capacity of 13,436MW in 2018 followed by offshore wind turbines with installed capacity of 8,300MW in the same year. Solar on the other hand has had a huge jump in installed capacity from 95MW in 2010 to 13,108MW in 2018. This research considered onshore wind turbines and solar PV for modelling the renewable generation farm discussed in chapter 4.
- **SP7**- (CO_2 Emission Management); A major contributor to climate change is the increase in greenhouse gases produced. The literature review found that the largest contributor to CO_2 level in UK was energy supply which had the significant fall in annual total greenhouse gas emission from 794.2 $MtCO_2e$ in 1990 to 455.9 $MtCO_2e$ in 2017. The 42% reduction was mainly due to changes in the fuel mix for electricity generation from coal and gas to renewables and it helped the UK towards achieving its target of 80% reduction in greenhouse gas by 2050. This target was set out in the Climate Change Act 2008 and reducing the CO_2.
- **SP8**- (Cost of Renewable Technology); Solar Panel and Wind Turbine costs have reduced significantly over the past 10 years while performance and reliability has improved. Solar PV prices decreased by around 80% since 2009 and wind turbine prices reduced by around 60% compare to 2009. However, this level of reduction in renewable technology might not be achieved in the future. This research examined the changes in cost of technology – increase, decrease and remain the same – and its effect on viability of renewable generation in community size.

- **SP9**- (Discount Rate); Discount rate is an important criterion affecting investor's decision as it reflects the uncertainty in the project, higher the risk or uncertainty in a project, the higher the discount rate.
- **SP10-** (Rural Communities); Rural communities are known to be affected by power cuts in severe weather conditions. Therefore, providing electricity at local-level for these communities from renewable sources would help with more sustainable energy as well as helping towards CO_2 emission.
- **SP11**- (Case Study- Scotland); To test the developed model a small town of Huntly in Scotland was chosen with detailed household electricity consumption data and detailed weather data. Scotland has set a target for community and locally-owned renewable; 1GW of capacity by 2020 and 2GW by 2030.

Chapter 3, developed an appropriate model that can be applied for identifying economic feasibility of renewable energy generation. To overcome non-linear diverse variation in the real-world situation, a hybrid modelling approach (combining deterministic and dynamical modelling) was adopted. Weather and consumption events are continuous in nature and nonlinear, but data collected to present these events was discrete. A deterministic model was used to evaluate the viability of community renewable generation, and to optimise the best combination of wind turbine and solar panel utility for electricity generation, a discrete event simulation (DES) was used. After the optimisation, a System Dynamics (SD) model was applied to present a clear understanding of the relationship between outcome and relative components. Both modelling methods introduced were used in the decision making and the handling of complex models with dynamical behaviour. The application of this hybrid modelling approach is novel and contributes to the discovery element of this research.

Chapter 4 presents the core Excel model applied in this research. All data required for this research was recorded in an Excel model. Using this data Excel was used to build a discrete simulation model for this research. All mathematical equations required for the modelling exercise were incorporated in Excel. Data from each input logged daily and sorted in database, the key input for the developed model was community consumption data which obtained from research conducted by Craig et al., (2014) in which household electricity consumption recorded from 2nd November 2010 to 31st December 2011. Another important data collected for this research are wind speed and sun irradiance, type of renewable technology (this research applied onshore wind turbine and solar PV panel), cost of technology for the examined period, cost of buying electricity from the grid and any government subsidies (feed-in tariff) for the examined period and cost of land. Then regression tool in Microsoft Excel's Data Analysis toolbox was used to undertake the regression analysis.

Chapter 5 began with building the test model with DES in Vensim to test the economic viability of renewable farm for Huntly. The DES model objective was set to optimise the rate of return on investment (ROR) given defined constraints. After obtaining optimised results, a SD model was used to investigate the relationship between ROR and future investment in renewable farm. The outcome of this chapter is a fully described developed DES and SD models in Vensim which tested with case study of Huntly and results are presented in the next chapter.

Chapter 6 presented analysis of results from testing the model for Huntly. The optimisation result from DES model shows that application of one 1.5MW wind turbine optimises the scheme for Huntly with 72% ROR with LCOE of £0.15 that produces around 2,700,000 kWh electricity per year towards the end of the lifetime of the scheme. These results confirm the feasibility of an investment on grid-connected renewable electricity generation in local-community level. The developed model then tested different scenarios to evaluate the changes in cost of technology, policy changing, changes in discount rate, change in cost of land, change in price of selling electricity to the grid and price of buying electricity from the grid, while keeping consumption and weather data constant. It concluded that changes in price of technology affects the outcome of the model most for instance, 40% reduction in price of wind turbine increases the ROR by 110%. After optimising the developed model with DES, the SD element of the model was used to illustrate the relationship between efficiency of ROR and future investment. In SD modelling the constraints were removed to assess the relationship between outcome (ROR) and input variables (for example: number of wind turbine applied, total capacity of wind turbine, and more).

7.2.1 Conclusion

Overall, the research shows that it can be concluded that providing local-community electricity for rural communities is beneficial both for the community and for the government as it can provide sustainable energy and contribute towards the greenhouse gas emission. Below is brief overview of results obtained from testing the Huntly model that shows the test model is generic and can be applied anywhere worldwide if the required data was available.

In all cases presented, only application of wind turbine was efficient (maximum ROR) for Huntly, the test model result shows that application of one 1.5MW wind turbine would maximises the ROR to 72%. The most influence on ROR was the cost of technology as this directly affects the initial cost of investment. In the scenario with 40% reduction in cost of technology, the ROR increased by110%. Sensitivity analysis was applied to the ROR with changes in feed-in tariff, the price of exporting electricity to the grid, the discount rate used and cost of land measured. The results of this analysis show that ROR is affected most with changes in exporting price of electricity to the grid.

Furthermore, in the system dynamics modelling element, the model runs with yearly time interval and no constraints in order to present the relationship between outcome of the model and input variables. Results show that without land limitation and installation capacity limitation, the farm can be expanded to nearly 6 MW with ROR of around 300%. The significant increase in ROR is as a result of increase in electricity generation from wind turbine while keeping consumption constant which leads to increase in revenue generated from the scheme.

To conclude, the research test model developed is shown to be generic and can be applied to anywhere world-wide subject to availability of consumption and weather data as well as availability of land. The data point being important as for remote district, where the scheme is most beneficial, the data is difficult to find.

7.3 How Objectives met

The aim of the research was to assess the economic feasibility of renewable generation at community level with focus on onshore wind turbine and solar PV panel for a renewable grid-connected generation for rural communities. It was shown in Chapter 6 that the tested model is viable when one 1.5MW wind turbine applied for Huntly generating 2,700,000kWh/year of electricity yield a 72% rate of return on investment which makes the scheme viable.

Below following objectives and brief explanation of how they met presented:

- To show that Discrete Event Simulation (DES) and System Dynamics (SD) modelling are suitable for such problems. This has been presented in Chapter 3 and 5 in detail where application of two model on other renewable management project discussed in literature review and shown that due to complexity of the model and dynamical behaviour of variables (such as weather) the most suitable tools are DES and SD which could be applied to present the complex relationship between components of the model as well as optimise the model with behavioural management.

- To design and develop a model comprising DES and SD elements that is general and can be used at suitable location anywhere in the world. This objective was addressed in Chapter 5 where detailed development of the research model presented step by step as the model developed in the Vensim software with inputs from the Excel core model which presented in Chapter 4.
- To test the developed model with a specific case study in the UK to present the generic nature of the developed model. The developed model was tested with a case study of Huntly in North-East of Scotland, due to availability of detailed household electricity consumption data. The result obtained from testing the model shows that the model is functional as results obtained are similar to the real-life experience of investment in renewable generation in North-East of Scotland (Large number of investments on onshore wind turbine and small number of investments on solar PV panels). Also, the model is generic and can be applied anywhere worldwide where required data are available.

7.4 FUTURE WORK

The research work done has shown that the developed model is suitable for assessing the economic viability of grid-connected renewable generation at community level for Huntly. By extension and by considering the data needed to run the model it has been shown a generic model can be applied worldwide if required detailed data was available. Thus, an area where future work in this field could be identified as:

- On-going work to extend the model with adding water-based electricity generation to the model; some communities would have fast moving water courses available for generation. The work done suggests that this should be relatively straight forward but power generation from this source would need to be studied in depth to understand the efficiency of water turbines.

- Application of scaling factor for community consumption data. As collecting data, especially household consumption data, has been challenging and time consuming, it is suggested to take a sample consumption data, use Huntly data for instance, and then scale it for other regions/communities. It is suggested that only consumption data would require scaling as data related to weather, land prices, government policies and technology costs should be quite straight forward to collect although time consuming.

8 APPENDIX

8.1 APPENDIX A: HOUSEHOLD ELECTRICITY CONSUMPTION

8.1.1 Craig et al. (2014) Household Electricity Data

Below is an extended example of household's electricity consumption in North-East Scotland in 5 minutes interval. Due to large number of data's only an extended example provided. There are 215 household's electricity consumption from 2nd November 2010. Below 24 hours electricity consumption of 65 household in 5 minutes-interval from 2nd November 2010 presented in Figure 8-1 to 8-5.

Time	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	H12	H13	H14	H15
2010-11-02T11:31:39Z	142	27.4858	120.1954	279.3924	11	20.40435	114.1656	423.2833	263	681.4243	107	358.8218	950.5733	180.8676	410.6356
2010-11-02T18:07:47Z	141.354	12.1385	118.2781	259.0648	11	47.01667	111.0596	378.9733	260.1202	625.8398	107	395.5695	764.4103	164.8245	419.8222
2010-11-02T18:12:49Z	139.073	25.571	118.904	241.45	11	74.86	119.3013	228.99	148.028	606.0066	106.1358	2800.008	575.8236	149.6289	494.3878
2010-11-02T18:17:50Z	100.952	12.746	125.3046	241.1067	11.27	60.57	118.3038	227.8769	143	809.9113	106	3459.166	552.9667	147.5895	578.4067
2010-11-02T18:22:51Z	80	9.4468	126	247.5367	12	30.63576	118	191	150.5755	936.99	106	115.2438	521.36	145.55	594.72
2010-11-02T18:27:52Z	80	30.2782	126	267.1368	11.73667	15.36213	118	240.8344	241.8715	657	117.9603	109.1814	482.1533	143.8387	590.4167
2010-11-02T18:32:54Z	80	29.3086	125.1161	254.9083	38.04	15.64	117.3113	213.2759	163.2522	648.198	142.9212	108	428.4533	143.3442	562.8733
2010-11-02T18:37:55Z	80	34.5357	111.5875	215.55	76.11504	24.66189	97.80795	193.2653	144.8823	644.7512	145.3118	115.6633	363.7917	142.7929	502.56
2010-11-02T18:42:56Z	80	28.3003	86.712	166.4667	88.83111	49.94693	79.45033	248.8769	144	667.7	144.1589	140.6226	439.6613	142.2768	482.6267
2010-11-02T18:47:57Z	80	19	81	107.7667	88	64.65667	152.3841	264.6517	144	673.61	144	155.8951	653.16	142.4065	482.2921
2010-11-02T18:52:58Z	96.4468	16.5894	81.7947	112.08	88	135.0872	102.004	258.1854	144.9237	694.1333	122.3046	132.79	486.6633	151.4431	535.1333
2010-11-02T18:58:00Z	132.276	12.0033	119.1954	117.25	87.35147	169.0021	102.004	239.5662	144.0795	746.14	108.8576	109	266	166.4947	618.36
2010-11-02T19:03:01Z	143.398	37.829	126.8148	103.7579	86.3374	169.5522	102.004	250.6026	144	731.0333	107	109.3833	265.65	168.7115	610.2514
2010-11-02T19:08:02Z	142.401	48.8043	125.4936	102.406	85.83982	170.1024	102.004	233.7094	144	678.82	107	110	265	153.0281	586.6652
2010-11-02T19:13:03Z	141.404	23.1854	125	95.74	85	170.6525	102.004	201.4229	144	673.56	107	118.2867	265	148.897	518.7241
2010-11-02T19:18:04Z	141	9	125	83	73.56667	171.2027	102.004	180.9272	245.6159	670.6433	107	136.1067	265	144.8187	471.5267
2010-11-02T19:23:06Z	133.338	9	125	80	30.48	171.7528	102.004	188.553	182.5726	661.5341	107	130.7698	291.26	142.5155	471.7
2010-11-02T19:28:07Z	100.448	9	124.4603	80	12	172.303	102.004	177.6699	146.0677	630.7814	107	115.441	478	140.9689	497.26
2010-11-02T19:33:08Z	80.4212	9	107.3709	80	11.77667	172.8531	102.004	181.7015	143.9007	613.5	107	138.32	722.5479	140.1311	590.1067
2010-11-02T19:38:09Z	80.5762	42.5323	134.0497	80	11	173.4033	102.004	221.3576	144	646.52	107	159.86	563.1857	141.614	605.5
2010-11-02T19:43:11Z	82.1457	68.4437	183.7748	80	11	173.9534	102.004	247.2759	144	676.4633	136.0101	140.1	336.36	141.8002	535.6
2010-11-02T19:48:12Z	83	37.0111	196.5265	80	11	174.5036	102.004	261.9784	143.1117	802.98	145.5599	111	318.2167	141.9863	371.53
2010-11-02T19:53:13Z	83	30.9673	197	89.95555	11	175.0537	102.004	192.7881	143	909.3212	144.4511	110.6572	276.6733	162.255	249.4
2010-11-02T19:58:14Z	83	30.9674	196.4801	97.19764	11	175.6039	102.004	188.8358	143	652.8365	144.7701	110	264.69	168.6683	195.8097
2010-11-02T20:03:16Z	109.111	30.9674	196	100.735	11	176.2993	102.004	178.9486	142.1316	616.6667	141.1842	110	264.3067	169	178.1556
2010-11-02T20:08:17Z	143.272	30.9675	153.2338	102.6406	11	171.9933	102.004	244.4735	192.1128	600.66	114.99	110	275.3133	168.0894	213.04
2010-11-02T20:13:18Z	154	30.9676	120.6126	102	11	135.1319	102.004	242.8571	204.3046	602.98	106.245	110	414.8	147.549	336.52
2010-11-02T20:18:19Z	154	30.9676	137.0658	101.6467	11	123.58	102.004	231.2237	151.8278	624.0767	106	110	655.9267	141.5954	367.8833
2010-11-02T20:23:21Z	153.457	30.9677	143.5051	96.8	11	135.9435	102.004	197.8209	143	668.16	106	112.91	492.39	141.7397	363.3389
2010-11-02T20:28:22Z	153	30.9677	136.2191	89	11	199.5333	102.004	186.8933	143.851	677	106	132.7828	265	141.8027	327.08
2010-11-02T20:33:23Z	140.205	30.9678	128.5724	89	11	421.5	102.004	213.4013	126.1987	703.9019	106	173.5741	265	141.8658	197.0482
2010-11-02T20:38:25Z	105.689	30.9678	125.1067	89	11	577.7933	102.004	253.9934	82.4702	762.0584	106	180.09	265	141.9288	178
2010-11-02T20:43:26Z	100.795	30.9679	122.53	88.66277	13.34388	116	102.004	258.1225	75	758.4475	106.728	129.72	265	141.9918	185.8
2010-11-02T20:48:27Z	98.7815	30.968	121.0667	87.67055	38.53581	125.1502	102.004	221.3792	75	749.8519	107.7252	111	264.7267	150.7511	247.2867
2010-11-02T20:53:28Z	102.739	30.968	119.5367	84.71333	75.36725	156.5216	102.004	184.7761	75	713.4	108	111	289.65	159.7414	370.0301
2010-11-02T20:58:29Z	101.552	30.9681	118.54	80	86.88654	164.5467	102.004	187.7781	126.0051	651.2533	120.9163	111	458.7333	166.6704	365.0879
2010-11-02T21:03:31Z	83.4901	30.9681	117.5433	80	85.77778	151.3867	102.004	195.0265	124.7363	629.44	141.6517	110.7067	697.45	167.1457	343.5544
2010-11-02T21:08:32Z	83	30.9682	117	87.28333	85.18584	105.9316	102.004	420.9973	83.71523	604	147.2923	110	530.2879	167.851	250.16
2010-11-02T21:13:34Z	83	30.9682	116.55	103	84.80809	88	102.004	476.0149	75	595.1133	147	110	336.9883	168.8456	177.6467
2010-11-02T21:18:35Z	107.541	30.9683	116	102.6938	84.29488	88	102.004	361.4545	74.19205	568.4667	146.3051	110	333.75	154.7065	175.8267
2010-11-02T21:23:36Z	142.835	30.9683	116	103.82	84.1352	82.62667	102.004	250.0348	74.80464	556.16	134.2351	111.8372	315.4867	142.7848	201.86
2010-11-02T21:28:37Z	153.509	30.9684	116	101.4	81.23771	61.39	102.004	275.6258	75	567.28	114.5364	127.92	258.8367	141.8344	338
2010-11-02T21:33:39Z	152.518	30.9685	115.5617	84.22	42.6	58.8	102.004	265.7214	75	609.6533	107.3146	158.7433	249	140.3415	362.51
2010-11-02T21:38:40Z	151.52	30.9685	115	80	12	67.84964	102.004	270.2781	107.5174	630.8086	107.6815	147.6133	275.27	140.8242	355.192
2010-11-02T21:43:41Z	147.187	30.9686	115	80	11.86047	249.17	102.004	266.2285	144.3582	640.5851	108	115.25	429.5333	139.3576	306.732
2010-11-02T21:48:42Z	115.975	30.9686	115	80	11	714.6432	102.004	238.7219	178.6821	674.6706	108	110	627.87	139.8179	177.85
2010-11-02T21:53:43Z	85.0682	30.9687	115	80	11	105.46	102.004	198.724	219.6026	690.3425	108	116.48	464.1092	140	176.7067
2010-11-02T21:58:45Z	84.4633	30.9687	115	79.72333	11	93.46	102.004	182.8906	162.8576	624.7375	108	136.5341	255.4909	177.1509	186.8967
2010-11-02T22:03:46Z	84.54	30.9688	115	79.27333	11	53.34052	102.004	189.8874	143.2252	636.479	108	128.7797	269.3667	171.5166	273.4
2010-11-02T22:08:47Z	84	30.9688	115	80	11	76.66224	102.004	183.149	142.2285	671	108	108.2233	248.7867	168	367.7267
2010-11-02T22:13:48Z	83.5459	30.9689	114.68	80.53333	11	86.08	102.004	190.6159	142	619.0067	108	109	248	166.404	365.6
2010-11-02T22:18:50Z	83	30.969	114	91.75949	11.11667	59.12	102.004	204.9458	143.5298	547.6167	108	109	248.2067	158.8477	347.92
2010-11-02T22:23:51Z	83	30.969	114	122.5874	12	22.84333	102.004	314	144	455.6	136.2388	109	266.08	142.755	238.26
2010-11-02T22:28:52Z	83	30.9691	114	131.2267	12	21.53924	102.004	325.4827	143.2417	288.6633	149.4437	110.4467	398.8	139.7881	178.2467
2010-11-02T22:33:53Z	131.47	30.9691	110.9667	125.5	12	18.85358	102.004	318.6567	142.245	262.9	146.7285	124.3367	643.2857	139.2168	179.76
2010-11-02T22:38:55Z	175.367	30.9692	93.71598	115.6133	12	18.86	102.004	216.254	142	255.77	146	156.8	520.1478	139.7778	201.1
2010-11-02T22:43:56Z	151.431	30.9692	70	89.51333	12	31.84	102.004	192.398	145.7417	255	146	148.7233	319.8133	140	374.4133
2010-11-02T22:48:57Z	151.577	30.9693	71.38333	86.56	12	79.59	102.004	191.6954	222.2483	248.3112	134.262	117.0635	318.45	139.2285	361.34
2010-11-02T22:53:58Z	151	30.9694	86.79225	81.52588	12	110.1215	102.004	184.8808	176.7947	218.9599	114.7632	109	316	138.2318	346.3095
2010-11-02T22:59:00Z	133.917	30.9694	117.4751	80	14.43	321.8386	102.004	191.3629	144.6159	198.44	107	108.8167	306.99	158.6523	255.7046
2010-11-02T23:04:01Z	99.2533	30.9695	116	79.77333	43.35482	270.03	102.004	184.1907	142	199.5667	107	108	261.5333	165.7616	177.7933
2010-11-02T23:09:02Z	83.59	30.9695	116	79.22333	88.70813	57.6	102.004	190.0199	142.7318	198	107	108.1767	266.9664	166.7583	176
2010-11-02T23:14:03Z	83	30.9696	116	80	86.62308	60.01338	102.004	219.9404	143	205.98	107	113.1738	419.3314	165.4926	193.7193
2010-11-02T23:19:05Z	82.6007	30.9696	116	80.86667	86	42.03493	102.004	257.2662	141.5497	245.0933	107	133.4884	626.56	159.0166	359.8087
2010-11-02T23:24:06Z	82	30.9697	107.8265	83.57333	85.92667	17.68	102.004	258.8947	141.7219	299.8935	106.4269	131.5126	452.11	145.0795	369.5652
2010-11-02T23:29:07Z	82	30.9697	89.9468	86.41731	85	15.20667	102.004	217.2388	141.2815	376.9816	106	108	232	140.2583	381.6517
2010-11-02T23:34:09Z	82	30.9698	124.7569	102.797	77.21333	17	102.0039	240.0988	140.2848	372.2	106	108	232	140	317.1737
2010-11-02T23:39:10Z	82	30.9699	184.5824	102	24.24516	58.37333	102.0039	241.7363	129.3742	368.6067	106	108.1476	232	140	186.0793
2010-11-02T23:44:11Z	82	30.9699	225.95	101.6067	20.08956	443.5954	102.0039	246.2809	91.02568	363.1269	106	111.8459	231.8567	140	264.6392
2010-11-02T23:49:12Z	105.873	30.97	253.5571	101.16	15.93397	406.4117	102.0039	208.9727	102.9608	304.9194	106.5249	134.3245	231.1402	140	291.3813
2010-11-02T23:54:13Z	175.393	30.97	250.8706	120.25	12	149.1252	102.0039	193.0702	122.534	224.2178	112.755	157.76	251.1682	145.0762	393.4533
2010-11-02T23:59:15Z	234.56	30.9701	250.1231	181	12	239.4612	102.0039	184.4651	149.8742	209.5583	133.636	150.6333	394.7715	161.4172	463.8267

Figure 8- 1: Household 1-15 Electricity Consumption - [Source: Craig et al. (2014)]

Time	H16	H17	H18	H19	H20	H21	H22	H23	H24	H25	H26	H27
2010-11-02T11:31:39Z	124.7555	249.5075	80	406.3887	132.5695	329.5	280.75	173.9468	242.4106	248.3146	120.0331	141.5576
2010-11-02T18:07:47Z	162.5512	216.5629	79.1755	529.9633	194.7483	300.0167	262.52	167.5464	117.1854	325.1987	120.9801	141.002
2010-11-02T18:12:49Z	208.8005	256.8046	79	463.81	185.255	233.68	220.9667	145.0066	284.6987	280.7914	121	140.4463
2010-11-02T18:17:50Z	190.8667	515.3907	79	403.3333	113.9338	187.2733	331.6133	143.245	130.1722	175.1523	118.0795	139.8907
2010-11-02T18:22:51Z	145.5541	481.5712	78.19079	497.3067	112	193.0467	218.46	141.5762	292.2649	121	117.0298	139.335
2010-11-02T18:27:52Z	128.9266	446.8806	102.1294	253.32	109.0893	185.579	290	213.4172	194.0927	148.8	117	138.7794
2010-11-02T18:32:54Z	126.5416	259.053	85.56291	258.29	107.0662	199.1837	271.7567	186.1258	202.2682	197.2533	117	138.2237
2010-11-02T18:37:55Z	156.6693	213.3344	80	286.2733	111.8179	188.9733	216.98	168.6159	236.0596	179.25	117	137.6681
2010-11-02T18:42:56Z	217.58	209.3179	80	358.15	191.702	190.61	333.7404	165.4106	153.3576	158.0333	117	137.1124
2010-11-02T18:47:57Z	241.93	209	79.20861	438.4267	192.1379	178.94	202.641	165	275	174.0603	116.0498	136.5567
2010-11-02T18:52:58Z	217.2	318.3113	162.5364	372.46	123.7895	192.87	304.7333	183.8769	124.5232	255.9744	116	136.0011
2010-11-02T18:58:00Z	137.9656	430.3862	86.39498	171.3	112.4511	184	157.85	253.8308	236.4967	342.48	116	135.4454
2010-11-02T19:03:01Z	129.6128	446.5274	85.79196	167.1367	110.1192	194.57	154.9533	153.7219	121.0166	1050.8	116	134.8898
2010-11-02T19:08:02Z	129.1285	348.2781	85.18895	174.4	101.5911	187.4393	154.0433	136.2715	258.894	1107.361	116	134.3341
2010-11-02T19:13:03Z	128.6443	282.8344	84.58593	216.39	99.15008	277.8714	155.0434	139.457	128.3013	1112.907	116	133.7785
2010-11-02T19:18:04Z	128.16	267.3103	83.98292	220.9	167.2984	313.34	155.92	136.6954	255.5232	1118.453	115.0695	133.2228
2010-11-02T19:23:06Z	127.6757	245.8093	83.3799	228.82	186.7318	331.76	154	117.6424	128.202	1123.999	115	132.6671
2010-11-02T19:28:07Z	127.1914	224.1026	82.77688	194.16	144.1807	302.9167	153.9667	110.4768	241.3974	1129.545	115	132.1115
2010-11-02T19:33:08Z	126.7071	406.7086	82.17387	206.0333	112.6777	333.1133	153.0599	112.2709	169.6887	1135.091	115.9146	131.5558
2010-11-02T19:38:09Z	126.2229	447.4139	81.57085	173.62	109.0927	264.87	154.97	142.2985	201.3179	1140.637	116	131.0002
2010-11-02T19:43:11Z	125.7386	436.4636	80.96784	163.14	105.3941	213.4267	154	150.5033	226.043	1146.183	116	130.4445
2010-11-02T19:48:12Z	125.2543	258.3113	80.36482	242.5467	101.4307	161.21	153.1367	138.8245	163.3974	1151.728	115.096	132.5621
2010-11-02T19:53:13Z	124.77	208.0596	79.76181	340.7067	137.3688	196	116.74	136.4834	249.0166	1157.274	115	136.5893
2010-11-02T19:58:14Z	124.2857	207.7848	79.15879	202.6	185.4374	155.9633	104	237.4238	128.649	1162.82	115	136.8523
2010-11-02T20:03:16Z	123.3556	208	83.57221	156.03	165.4891	196.7867	104.0167	249.4768	278.0298	1101.015	142.7152	137.1154
2010-11-02T20:08:17Z	136.9933	262.3681	83.60927	171.92	115.5692	157.005	104.9867	227.8278	140.1589	215.3045	167.3775	137.3784
2010-11-02T20:13:18Z	197.8133	455.3632	153.3907	141.19	109	199.6563	104	181.4768	248.2881	301.705	169.1126	137.6414
2010-11-02T20:18:19Z	186.0832	538.7285	176.3742	138.2867	105.5481	145.56	103.9667	165.2748	134.4702	345.168	166.3477	137.9044
2010-11-02T20:23:21Z	127.4273	469.2152	174.2781	195.3333	105	204.9	98.96007	138.2914	229.7715	343.1747	165.1192	138.1674
2010-11-02T20:28:22Z	138.5133	266.0265	172.5629	207.76	116.9603	148.28	87	122.2517	129.298	340.7579	164.1225	138.4305
2010-11-02T20:33:23Z	118.3933	210	114.7815	177.3233	180.2715	213.84	87	116.4238	216.0099	272.99	163.1258	138.6935
2010-11-02T20:38:25Z	131.09	209.245	84.16887	123.4933	183.3522	156.76	2160.113	116.4238	126.6556	155.6333	162.1291	138.9565
2010-11-02T20:43:26Z	193.3067	208.2496	81	157.45	116.0191	290.69	2355.742	116.2914	252.6854	121.788	162	139.2195
2010-11-02T20:48:27Z	266.2167	344.2637	129.6656	190.2	103.1592	290.6667	2330.268	136.4536	144.9603	132.2763	161.1358	139.4825
2010-11-02T20:53:28Z	249.82	431.053	145.7931	192.8733	102.1603	356.9733	2348.748	137.9801	225.5099	177.7467	160.1391	139.7456
2010-11-02T20:58:29Z	221.401	442.0464	166.9304	192.02	103.676	285.4925	2350.967	131.5066	212.8808	207.7088	160	140.0086
2010-11-02T21:03:31Z	258.1284	314.5629	194.9934	204.09	104	359.5912	2339.2	118.8742	167.9702	186.087	160	140.2716
2010-11-02T21:08:32Z	285.16	223.6291	238.8146	141.24	162.7546	271.5167	2331.159	111.9238	239.227	179.2346	159.1472	140.5346
2010-11-02T21:13:34Z	254.61	209.9139	234.4371	178.6	187.3128	292.6533	2355.421	151.5931	138.3682	180.2762	159.8512	140.7976
2010-11-02T21:18:35Z	224.6333	247.2583	225	135.8933	141.0547	139	2349.185	148.8706	244.0662	245.2818	142.1987	141.0607
2010-11-02T21:23:36Z	222.91	261	225.6788	192.53	110.4429	217.6467	2348.027	138.3212	142.7143	308.4027	131.4007	141.3237
2010-11-02T21:28:37Z	188.6	327.106	225.3245	139.3623	106.8095	153.0633	2352.851	163.6689	222.1574	222.5123	130	141.5867
2010-11-02T21:33:39Z	130.6433	435.2517	280.7914	172.0666	104.5871	209.64	2354.934	234.4801	137.6316	206.4542	125.8113	141.8497
2010-11-02T21:38:40Z	123.6295	517.7704	307.3311	172.95	104	157.8567	2344.401	251.6291	235.7894	260.9783	116.6556	142.1127
2010-11-02T21:43:41Z	111.3078	440.7363	307	140.6533	130.3344	198.0333	2367.046	241.3411	185.6093	229.7633	115	142.3758
2010-11-02T21:48:42Z	119.6133	300.3179	306.3377	201.1633	177.5298	166.83	2377.57	209.8609	215.3874	144.64	115	142.6388
2010-11-02T21:53:43Z	129.16	255.904	268.4404	207.1	167.4238	185.2667	2357.912	173.255	234.755	126.5733	114.1755	142.9018
2010-11-02T21:58:45Z	110.6556	243.192	233.2649	163.15	116.2914	187.8633	1293.603	131.1854	196.6656	124	114	181.3473
2010-11-02T22:03:46Z	116.7679	217.3532	224.3477	173.3067	103.2152	177.48	583.4205	116.957	269.3113	184.55	114	135.9216
2010-11-02T22:08:47Z	156.3333	338.9172	221.404	269.15	99.87417	192.3195	340.6556	114.106	152.7185	282.44	114	135.6713
2010-11-02T22:13:48Z	200.0084	431.0596	219.3543	184.8133	98.22185	165.4089	728.1887	111.3543	232.8013	229.9367	113.1887	135.421
2010-11-02T22:18:50Z	172.1762	496.2318	220.2848	157.06	98	228.04	570.8981	111	146.5629	180.3	113.8062	135.1707
2010-11-02T22:23:51Z	116.72	408.543	221	175	168.9801	281.51	501.6892	160.8477	237.4636	176.6633	114	134.9204
2010-11-02T22:28:52Z	117.1667	269.0355	236.2583	136.1291	186.1519	358.5467	677.9205	198.5364	150.1556	227.3333	113.2093	134.6701
2010-11-02T22:33:53Z	120.5533	234.3151	229.8212	163.8146	130.4296	285.06	636.7748	212.2219	244.2384	334.62	113	134.4197
2010-11-02T22:38:55Z	125.4	218.1325	222.8874	137.2682	106.3645	363.8	1190.348	252.2187	154.4172	305.1267	112.2152	134.1694
2010-11-02T22:43:56Z	175.1166	208	229.0066	252.4503	102.4868	269.09	1603.953	190.2886	231.3775	198.8536	112	133.9191
2010-11-02T22:48:57Z	240.2746	294.543	232.622	132.053	99.74627	347.2213	1753.473	138.7616	166.3146	136.2271	112	133.6688
2010-11-02T22:53:58Z	276.5933	409.1457	263.3667	188.8079	98.25166	179.9465	3299.348	139.8477	201.106	119.6795	112	133.4185
2010-11-02T22:59:00Z	279.4667	443.4056	306.0265	195.8609	127.8013	232.79	3655.212	132.4223	239.4073	152.103	112	133.1682
2010-11-02T23:04:01Z	276.91	365.6678	318.5894	196.9704	174.2876	134.24	3783.232	124.5471	184.6026	205.8549	112	132.9178
2010-11-02T23:09:02Z	291.5756	250.592	315.202	151.5589	168.6335	237.5833	3652.771	154.0693	249.8675	158.42	111.2351	132.6675
2010-11-02T23:14:03Z	371.7089	209	305.0596	149.0364	119.5563	138.72	4891.335	266.7065	155.7285	154.8933	111	132.4172
2010-11-02T23:19:05Z	447.3767	224.0993	260.4735	201.8146	103.2715	239.9133	5354.116	356.7681	236.2417	174.09	111	132.1669
2010-11-02T23:24:06Z	630.6641	251.7748	232.8212	293.9536	99.37929	144.4933	6142.861	282.9993	159.404	197.2	111	131.9166
2010-11-02T23:29:07Z	626.8082	310.9338	232.5861	330.4238	96.56385	227.62	5504.053	187.0265	218.7781	275.58	111.7554	131.6663
2010-11-02T23:34:09Z	397.8029	406.2237	233	263.5762	100.2914	161.3333	4539.947	162.8146	162.3483	298.24	112	131.416
2010-11-02T23:39:10Z	386.28	379.9656	232.4205	244.8477	165.3609	291.73	3686.14	133.7086	220.2881	703.55	108.2583	131.1656
2010-11-02T23:44:11Z	290.0265	358.7635	232	267.5927	190.2923	243.1351	3463.287	111.0689	229.4437	1518.66	96.56954	130.9153
2010-11-02T23:49:12Z	244.7178	287.0288	241.7423	300.0331	122.91	284.1979	3570.375	144.3051	171.4225	622.75	93	130.665
2010-11-02T23:54:13Z	250.8436	222.404	243.9104	351.6656	114.3893	251.3764	3233.395	149.8344	245.5587	310.32	93	130.4147
2010-11-02T23:59:15Z	267.9033	266.1887	237.1854	333.5232	105.8686	290.3577	3262.831	135	167.2337	192.19	93	130.1644

Figure 8- 2: Household 16-27 Electricity Consumption - [Source: Craig et al. (2014)]

Time	H28	H29	H30	H31	H32	H33	H34	H35	H36	H37	H38	H39	H40
2010-11-02T11:31:39Z	113.0498	152.67	482.12	515.0132	30	153.1987	123	336.8554	65.04667	255.044	237.7815	364.9867	113.9068
2010-11-02T18:07:47Z	113	133	486.0818	655.1391	30	293.1589	146.04	313.3582	66.98	238.5473	232.9934	331.5467	76.80667
2010-11-02T18:12:49Z	113	133	481.2945	527.4638	29.58	425.5695	154.3167	319.9272	66	238.4901	237.5861	482.9	76.77627
2010-11-02T18:17:50Z	112.0596	132.9432	489.0933	356.25	29	428.298	129.8569	348.0051	65.96	234.2417	236.6159	627.8167	93.56667
2010-11-02T18:22:51Z	112	132.0533	531.8	284.9818	29.41333	426.1258	123	358.3615	63	249.4369	234.4203	793.9866	89.15973
2010-11-02T18:27:52Z	112.9303	133	482.1669	276.9669	55.01	423.1987	130.99	358.6358	63	238.6915	233.2156	792.8667	92.30333
2010-11-02T18:32:54Z	123.1987	133	468.3044	238.9242	138.9867	420.2003	155.8667	347.6159	63	236.6921	230.6556	773	105.4291
2010-11-02T18:37:55Z	150.7143	133	374.3933	262.2985	215.05	319.4974	151.797	350.4303	62.00331	229.9261	229.2219	384.5724	73
2010-11-02T18:42:56Z	191.5174	133	275.4776	292.7308	201.6	97.82781	126	352.2923	62	214.6236	229.7748	382.9868	72.61937
2010-11-02T18:47:57Z	152.9603	134.4	222.8536	317.0099	135.8167	21.87417	125.54	349.3841	62	202.7483	230.7715	214.8358	68.47089
2010-11-02T18:52:58Z	148.092	168.33	222.1433	251.2848	65.58557	17	149.66	325.7255	62	207.2185	233.3046	349.2185	93.64
2010-11-02T18:58:00Z	119.9818	176.7333	232.8163	214.9568	31.61333	17.91722	173.0969	306.7628	62	220.0596	208.0393	365.6755	105.3005
2010-11-02T19:03:01Z	113.3974	169.495	289.9384	200.7945	87.61538	17.08609	133.0239	303.3974	62.98013	220.4285	194.6949	366.9735	110.6972
2010-11-02T19:08:02Z	112.1051	177.2872	270	198.7641	105.3172	17	128.8332	303.5994	65.93046	211.2106	193	361.1788	103.96
2010-11-02T19:13:03Z	160.9801	177.3585	269.6194	163.6088	105.8505	17	128.5658	304	66	215.053	194.5033	461.5563	102.1185
2010-11-02T19:18:04Z	120.9769	177.4298	266.8802	147	106.3837	17	128.2983	304.5861	65.0298	210.2781	194.2517	324.3179	78.34109
2010-11-02T19:23:06Z	112.3651	177.5011	266	143.6584	106.917	17	128.0309	337.6441	65	252.4139	194	346.7619	57.4808
2010-11-02T19:28:07Z	112.874	177.5724	265.66	160.6208	107.4503	17	127.7634	386.8955	65.96358	215.0439	195.4834	446.2172	75.03993
2010-11-02T19:33:08Z	112.1314	177.6437	262.7796	233.1579	107.9835	17	127.496	404.2815	114.0132	205.8292	194.5254	450.0497	76.66611
2010-11-02T19:38:09Z	112	177.715	269.3561	217.8026	108.5168	155.5762	127.2285	401.2898	130.3543	218.4834	193.2686	448.1117	57
2010-11-02T19:43:11Z	112.8609	177.7863	326.1	176.5263	109.05	254.8377	126.961	357.0229	128.1391	210.0861	194.457	324.25	57
2010-11-02T19:48:12Z	112.1424	177.8576	178.9333	214.6086	109.5833	263.2252	126.6936	312.9868	126.0993	197.5402	195.7252	234.7711	56.99666
2010-11-02T19:53:13Z	112	177.9289	140.1913	207.5243	110.1166	261.2318	126.4261	305.5534	124.106	201.3881	200.3311	87.56954	56.00328
2010-11-02T19:58:14Z	112	178.0006	130.0067	181.0536	110.6498	260.1192	126.1587	325.6418	123.0563	197.6424	199.1258	179.9139	75.86733
2010-11-02T20:03:16Z	132.2649	179	109	220.9604	114.0108	321.586	129.3159	1005.603	122.0596	201.9868	194.4286	360.7583	76
2010-11-02T20:08:17Z	148.6159	162.0563	109	276.5157	188.06	295.7702	167.7067	1659.711	120.1258	204.0132	192.2919	374.0821	57.31509
2010-11-02T20:13:18Z	149.3284	133.1921	108.8533	306.546	219.2567	175.6093	140.6	1363.946	124.6552	199.0492	192.7053	289.9337	57
2010-11-02T20:18:19Z	147.3383	132.0099	107	265.2709	165	159	125	922.8717	125	202.2139	191.596	235.6896	57
2010-11-02T20:23:21Z	142.0331	132	107	170.1138	69.51	159.8675	125	611.4146	124.0762	198.5099	191.6987	338.5539	89.01493
2010-11-02T20:28:22Z	117.9654	133.9736	109.8153	138.1098	34	160	145.4533	853.58	124	201.457	192.6954	449.9735	224.9426
2010-11-02T20:33:23Z	112.1824	133.0197	151.3933	155.27	33.68053	156.5563	161.79	838.5025	123.0828	199.2185	191.6159	478.947	5770.348
2010-11-02T20:38:25Z	111.1854	133	107.9466	159.2667	32.68333	158.5728	133.3677	408.9735	123	199.1938	191	631.2844	5929.402
2010-11-02T20:43:26Z	111.8113	133	109.1897	155.2436	32	159	126	406.505	123	202.8955	192.3709	695.0698	3994.144
2010-11-02T20:48:27Z	140.2185	133	154.4333	158.0432	34.48	157.2951	140.5667	408	115.7417	197.7086	193.6821	547.7417	5769.069
2010-11-02T20:53:28Z	118.9652	133	163.8	149.444	37.24	145.9565	170.84	374.2228	77.93709	210.8974	198.7472	487.5132	4289.015
2010-11-02T20:58:29Z	112	135.8896	158.6695	164.68	31	60.90232	165.4267	344.72	74	204.1969	198.3134	398.9536	5278.768
2010-11-02T21:03:31Z	112	143.6827	149.9401	159.6539	30.7	45.15563	133.1547	347.71	73.10265	200.7678	193.6556	349.6485	3642.619
2010-11-02T21:08:32Z	112	180.3642	148.1867	129.7867	30	217.4172	124.6261	347.749	71.21192	219.0894	191.3344	349.1841	3733.852
2010-11-02T21:13:34Z	112	172.4636	153.9015	117.5667	30	263.404	130.3004	374.3133	64.7649	209.7219	192.3245	347.4172	4490.073
2010-11-02T21:18:35Z	112	149.1921	108	171.472	30	262.6623	151.8819	390.4152	66.66225	202.2417	191.6821	344.4272	4798.833
2010-11-02T21:23:36Z	150.7417	133.7947	108	181.6953	30	257.8444	154.08	840.35	68.76821	198.9737	191.6556	232.9404	2821.862
2010-11-02T21:28:37Z	123.4238	133	108	137.66	44.16667	257.8278	124	1560.673	68.11921	201.5489	192.6523	204.6391	2940.867
2010-11-02T21:33:39Z	112.7668	134.8876	108	134.7231	88.12	258	124	1640.986	67.12252	199.4801	192.351	377.6225	2272.55
2010-11-02T21:38:40Z	146.4925	133.1192	108	205.89	120.3433	134.2807	132.1402	979.1003	64.37748	201.4834	217.1821	484.149	2354.801
2010-11-02T21:43:41Z	152.4503	133	108.9967	290.6669	170.2267	49.69536	152.6	315.9333	64	208.3449	236.1363	498.8411	2043.098
2010-11-02T21:48:42Z	148.7389	133	109	192.3609	223.1887	41.0894	149.1333	340.5057	64	224.4693	239.6352	533.1893	2678.182
2010-11-02T21:53:43Z	147.2521	133	109	175.8487	178.4107	37.92715	123.3439	361.8467	64	214.2583	243.7947	597.9071	1659.752
2010-11-02T21:58:45Z	141.7848	132.073	109	223.33	52.76	36.18874	122.9934	361.3333	64	196.1358	242.8543	530.0232	2991.744
2010-11-02T22:03:46Z	119.2318	132.9212	109	258.1867	34.74333	42.46358	130.1052	362.2746	63.14238	200.8344	236.6192	415.2781	2137.63
2010-11-02T22:08:47Z	111.2627	133	109	274.1435	33.74667	37.56291	150.3333	361.7133	63	208.2649	233.3775	142.0927	2430.612
2010-11-02T22:13:48Z	111	150.3642	150.8609	264.0698	33	43.21192	144.44	351.98	63	204.931	233	78.66887	2491.952
2010-11-02T22:18:50Z	111.7285	178.4825	111.3793	220.1733	33	92.18037	122.3467	342.6639	63	203.7778	231.7762	83.49007	1787.653
2010-11-02T22:23:51Z	112	173.714	109.0365	255.28	32.51333	146.3125	121.3233	321.5556	63	199.9172	260.245	150.3057	2724.206
2010-11-02T22:28:52Z	112	146.6887	109	261.1595	31	154.6159	130.9451	304	63	201.0464	249.3079	195.5757	1424.974
2010-11-02T22:33:53Z	112	134.9603	108.046	112.1248	31	157.957	151.2821	303.62	63	212.5563	228.1921	201.4113	2474.222
2010-11-02T22:38:55Z	112	134	108.9502	118.0567	30.76667	374.1457	142.9167	303	63	218	227	208.1225	1691.433
2010-11-02T22:43:56Z	111.2923	134	109	153.9	30.23	427.2914	119	303	63	296.8747	306.8675	255.7086	2700.715
2010-11-02T22:48:57Z	111	134	109	162.3158	31	458.0397	120.24	302.6361	63	467.2736	330.7715	433.5861	3908.259
2010-11-02T22:53:58Z	111	133.1058	109	145.2867	30.78036	442.8775	138.3588	303.07	63	496.543	255.7748	508.6954	4536.318
2010-11-02T22:59:00Z	111	133	109	164.153	30	422.803	168.807	331.2065	63	312.4834	212.724	584.6987	1496.48
2010-11-02T23:04:01Z	111	133	108.0695	131.6667	44.50667	426.7521	148.3378	386.9333	63	201.2318	255.8806	663.552	2795.871
2010-11-02T23:09:02Z	111	133	108.9272	164.22	100.31	192.9139	122.7029	400	63	208.6027	291.7285	518.2206	1582.864
2010-11-02T23:14:03Z	111	133	109	157.224	108.5867	66.92053	122	396.2538	63	206.3881	290.7086	449.1126	2584.963
2010-11-02T23:19:05Z	116.9702	133	108.0829	91.20796	115.9467	45.4106	129.25	363.0431	63	207.6093	279.3179	544.2914	1665.443
2010-11-02T23:24:06Z	141.1921	133	108.9139	106.65	165	35.62252	150.7205	308.6862	63	551.4238	270.8675	430.4106	2287.37
2010-11-02T23:29:07Z	186.24	213.1192	109	165.1333	195.8267	39.8245	149.3757	304.3233	63	572.9735	271.6887	449.6821	1162.239
2010-11-02T23:34:09Z	181.1891	289.1987	109	153.0586	81.59333	35.96026	122.7167	304.6833	64.59603	248.9668	320.0351	400.3444	2592.162
2010-11-02T23:39:10Z	152.7748	280.8047	109	134.6208	33.81	48.30553	122	304.3095	66.5894	237.5652	311.7164	266.9934	1364.279
2010-11-02T23:44:11Z	122.7486	219.2164	109	184.5	49.05333	43.97518	128.0867	312.6667	66.21018	240.4973	280.4967	129.4205	880.352
2010-11-02T23:49:12Z	111	209.1391	109	215.2367	122.1167	49.23179	149.1933	343.3688	69.92205	237.6375	309.4317	81.6903	879.2675
2010-11-02T23:54:13Z	111	209	109	277.154	132.4	37.09934	152.4875	386.1432	105.3175	227.5333	317.2658	76.2691	2195.197
2010-11-02T23:59:15Z	111	209	109	188.4243	114.5867	47.57616	123.4591	420.8764	115.5453	216.3433	307.588	136.4636	1870.512

Figure 8- 3: Household 28-40 Electricity Consumption - [Source: Craig et al. (2014)]

Time	H39	H40	H41	H42	H43	H44	H45	H46	H47	H48	H49	H50	H51	H52	H53
2010-11-02T11:31:39Z	364.9867	113.9068	263.3907	131.8146	197.76	165.1904	320.3212	324.0962	128.1159	193.4702	131	80.8222	151.2239	93.7	226.4533
2010-11-02T18:07:47Z	331.5467	76.80667	230.245	108.8146	212.26	160.0763	346.7152	293.3775	128	428.7881	129.6	80.81416	202.2781	178.3644	225.1333
2010-11-02T18:12:49Z	482.9	76.77627	253.7715	108	277.7333	159.0795	373.6411	279.2318	127.1248	153.5844	165.53	80.80613	229.2682	258.9666	237.57
2010-11-02T18:17:50Z	627.8167	93.56667	262.7616	108.5862	289	187.4338	339.9998	281.5762	127	249.5821	226.48	80.79809	208.5364	255.48	221.2978
2010-11-02T18:22:51Z	793.9866	89.15973	262.2417	108.4212	271.14	162.6601	506.2384	317.6291	126.141	193.5242	247	80.79005	171.9503	142.5	170.813
2010-11-02T18:27:52Z	792.8667	92.30333	259.7351	112.6093	252.4733	159.0929	682.7152	375.245	126	192.9141	213.4533	80.78202	140.5762	93.12667	142
2010-11-02T18:32:54Z	773	105.4291	257.4967	163.5464	264.5633	159.904	641.404	375.8113	126	192.0464	127.1	80.77398	126.8839	112.3667	149.32
2010-11-02T18:37:55Z	384.5724	73	213.596	173.9404	250.28	160.8982	594.4107	296.6093	126	172.1034	71.44667	80.76594	126.5795	222	201.7167
2010-11-02T18:42:56Z	382.9868	72.61937	125.9868	158.3974	248.8833	213.738	674.4037	286	125.1729	219.1244	71.55667	80.75791	126.9536	224	188.1467
2010-11-02T18:47:57Z	214.8358	68.47089	100.2571	141.2871	263.5	197.7318	664.4768	286.8662	125	233.3189	70.56	80.74987	156.6722	201.076	159.43
2010-11-02T18:52:58Z	349.2185	93.64	99.25901	136	354.37	182.6092	674.3808	286.1395	207.2405	384.0332	70	80.74183	159.1375	133.4503	178.8802
2010-11-02T18:58:00Z	365.6755	105.3005	98.26421	147.8709	415.6267	163.3881	699.8808	285.1445	238.9801	377.194	70.43333	80.7338	146.7098	130.0298	243.3973
2010-11-02T19:03:01Z	366.9735	110.6972	97.26446	144.404	373.29	158.3744	637.7384	284.1492	238.775	280.1623	70.14	80.72576	144.3212	215.8477	221.7333
2010-11-02T19:08:02Z	361.1788	103.96	96.26821	155.3907	312.9	182.3781	403.5828	348.2695	205.1592	187.702	68.57333	80.71772	126.4702	224.8675	149.9
2010-11-02T19:13:03Z	461.5563	102.1185	96	171.1722	245.0152	163.4437	343.0695	373.4527	141.1391	223.6211	104.1747	80.70968	125	193.5342	155.96
2010-11-02T19:18:04Z	324.3179	78.34109	96	202.6854	243.5757	160.8621	404.5043	349.2544	125.4106	360.0514	111.1401	80.70165	161.3319	107.9966	222.584
2010-11-02T19:23:06Z	346.7619	57.4808	159.5232	202.7632	242.1363	161	483.4366	291.0666	125	281.9637	111.5886	80.69361	195	107.9532	231.7363
2010-11-02T19:28:07Z	446.2172	75.03993	189.7483	169.8905	240.6969	177.2318	459.0397	276.7249	123.4312	209.1227	112.037	80.68557	189.6467	230.6678	168.8364
2010-11-02T19:33:08Z	450.0497	76.66611	189.8543	149.4702	239.2575	168.9638	471.2914	275.1857	121.4371	634.6225	112.4855	80.67754	209.1333	266.0166	149.7454
2010-11-02T19:38:09Z	448.1117	57	186.1523	138.9536	237.8181	175.4411	378.1026	274.1887	121	280.5166	112.934	80.6695	244.16	225.4238	178.24
2010-11-02T19:43:11Z	324.25	57	180.0397	138	236.3786	190.4253	285.4106	274	121	211.0728	113.3825	80.66146	266.3467	108.3709	156.0833
2010-11-02T19:48:12Z	234.7711	56.99666	172.3576	125.7015	234.9392	201.3416	257.3874	292.5066	120.2359	189.9868	113.831	80.65343	251.6533	104	130.5067
2010-11-02T19:53:13Z	87.56954	56.00328	107.5232	126.2384	233.4998	252.0364	283.6478	349.8874	120.7616	145.8245	114.2794	80.64539	223.23	183.7075	98.93012
2010-11-02T19:58:14Z	179.9139	75.86733	81	145.5993	232.0604	240.5254	283.2148	343.8477	121	149.9404	114.7279	80.63735	196.6815	223.3642	102.207
2010-11-02T20:03:16Z	360.7583	76	79.60927	163.5695	231.9655	207.2686	309.2152	292.9073	121	148.3278	113.4262	80.62932	177.9918	218.3245	157.6667
2010-11-02T20:08:17Z	374.0821	57.31509	78.30795	150	259.24	166.649	401.0795	284.957	128.4834	262.4768	84.03	80.62128	202.5667	137.2219	149.7067
2010-11-02T20:13:18Z	289.9337	57	78	127.49	274.4333	157.3744	386.0894	312.0066	150.34	255.7815	68.84	80.61324	198.9333	127.3005	100.94
2010-11-02T20:18:19Z	235.6896	57	78	396.9411	268.7733	158.4463	316.0662	351.8967	152.5721	235.3841	66.61667	80.6052	194.75	186.6678	102.1533
2010-11-02T20:23:21Z	338.5539	89.01493	78	400.5837	275.25	158.8763	313.4934	333	148.064	209.3079	66	80.59717	169.0533	221.1424	138.96
2010-11-02T20:28:22Z	449.9735	224.9426	77.31788	400.6056	274.8067	157.8397	290.894	284.7086	133.1675	127.3245	66.37667	80.58913	146.0633	200.4305	154.4027
2010-11-02T20:33:23Z	478.947	5770.348	93.29139	400.6276	258.8367	161.2862	287.6457	273.7715	122.1987	245.7583	66.62667	80.58109	182.32	113.7252	122.5977
2010-11-02T20:38:25Z	631.2844	5929.402	153.6887	400.6495	251.16	180.0954	339.0686	280.9139	120	189.5232	66	80.57306	192.3139	100.5298	96.4207
2010-11-02T20:43:26Z	695.0698	3994.144	177.6556	400.6714	258	161.9943	513.7843	283.7649	120	178.8642	82.5	80.56502	182.4243	191.4558	106.9967
2010-11-02T20:48:27Z	547.7417	5769.069	176.3311	400.6933	266.6333	156.4202	389.3642	285.5232	120	215.2504	116.45	80.55698	175.5867	259.4182	154.7062
2010-11-02T20:53:28Z	487.5132	4289.015	175.3344	400.7152	285.11	155	283.0331	291.3079	120	387.6504	166.68	80.54895	162.11	251.0199	145.5324
2010-11-02T20:58:29Z	398.9536	5278.768	173.6755	400.7371	251.7733	156.798	263.0828	361.702	120	185.257	231.8667	80.54091	145.38	126.2053	98.08
2010-11-02T21:03:31Z	349.6485	3642.619	153.8907	400.759	246.5333	175.2859	265.3311	374.2285	119.298	207.2715	187.5533	80.53287	135.6667	105.8742	102.0284
2010-11-02T21:08:32Z	349.1841	3733.852	100.7285	400.781	239.8	171.1045	251.9949	326.8477	119.6979	245.9735	128.95	80.52484	126.4533	152.6954	145.7155
2010-11-02T21:13:34Z	347.4172	4490.073	77.34768	400.8029	287.0333	160.5862	247.388	291.9161	129.6816	180.9172	126.6533	80.5168	123.28	220.9735	187.7333
2010-11-02T21:18:35Z	344.4272	4798.833	77	400.8248	344.36	161.5788	326.4815	285	134.6887	191.5497	126	80.50876	129.222	196.9503	167.8097
2010-11-02T21:23:36Z	232.9404	2821.862	77	400.8467	345.57	163.1523	323.2252	280.5894	124.7185	111.3874	125.32	80.50073	140.1847	133.04	149.1133
2010-11-02T21:28:37Z	204.6391	2940.867	77.64238	400.8686	362.3067	174.3113	262.2152	275.3465	138.3992	117.5298	123.6633	80.49269	140.1167	126.0926	182.8882
2010-11-02T21:33:39Z	377.6225	2272.55	77.36093	400.8905	381.3033	184.8489	233.1921	274	151.0497	110.3642	110	80.48465	118.2133	195.606	240.6153
2010-11-02T21:38:40Z	484.149	2354.801	77	400.9124	394.4	190.3731	231.755	303.596	149.6391	123.7285	79.05	80.47661	125.58	220.1126	241
2010-11-02T21:43:41Z	498.8411	2043.098	77	400.9343	330.3	176.7715	235.8681	344.4603	141.9852	110.5099	68.34667	80.46858	149.44	191.4901	258.8215
2010-11-02T21:48:42Z	533.1893	2678.182	110.3444	400.9563	235.38	162.8866	236.3769	318.8079	127.0987	107	66.67667	80.46054	170.6	110.2185	280.7086
2010-11-02T21:53:43Z	597.9071	1659.752	159.4139	400.9782	136.82	172.4295	313.4007	279.7947	120.3454	129.9007	66	80.4525	181.8063	96.54636	402.947
2010-11-02T21:58:45Z	530.0232	2991.744	177	401.0001	132.0883	168.9703	357.3046	272.1258	120	175.7285	76.57757	80.44447	185.7637	176.9733	361.0345
2010-11-02T22:03:46Z	415.2781	2137.63	176.3769	401.022	215.7755	159	296.1921	302.5864	120	216.6391	107.8667	80.43643	181.26	257.1208	270.4411
2010-11-02T22:08:47Z	142.0927	2430.612	174.7616	401.0439	325.9867	159	234.0199	340.8325	120	126.2384	126.6867	80.42839	176.7	205.8808	241.8867
2010-11-02T22:13:48Z	78.66887	2491.952	173.3841	401.0658	265.4933	164.3367	219.2119	319.3179	120	146.4503	126	80.42036	166.64	123.1325	295.1271
2010-11-02T22:18:50Z	83.49007	1787.653	141.7583	401.0877	250.12	173.2057	210.9603	275.2417	120	352.5232	108.7387	80.41232	148.92	99.83775	290.2545
2010-11-02T22:23:51Z	150.3057	2724.206	100.0662	401.1097	277.5	167.0596	228.9735	263.3775	120	247.7815	81	80.40428	128.86	187.1656	236.2252
2010-11-02T22:28:52Z	195.5757	1424.974	90.84768	401.1316	264.1833	160.6026	361.2191	264	120	304.3642	115.23	80.39625	123.9382	219.1589	167.0132
2010-11-02T22:33:53Z	201.4113	2474.222	94	401.1535	261.44	178.3731	360.0424	263.3179	139.2925	305.2103	167.5467	80.38821	119.9235	144.5893	167.8146
2010-11-02T22:38:55Z	208.1225	1691.433	94	401.1754	252.3933	200.1391	265.1026	263.6788	131.927	232.6255	258.29	80.38017	114.2833	114.7768	223.8999
2010-11-02T22:43:56Z	255.7086	2700.715	93.40397	401.1973	156.56	191.8013	232.8742	266.702	124.2881	342.859	258.14	80.37213	111.34	139.6556	234.5263
2010-11-02T22:48:57Z	433.5861	3908.259	92.40728	401.2192	136.15	203.718	224.7252	327.1523	145.2781	277.7795	255.15	80.3641	120.08	247.3113	219.9632
2010-11-02T22:53:58Z	508.6954	4536.318	92.58932	401.2411	229.3333	240.4127	223.9139	356	153.3645	275.8001	246.28	80.35606	131.3333	224.5497	168.3917
2010-11-02T22:59:00Z	584.6987	1496.48	93.59009	401.2631	272	257.9067	256.1237	320.5788	148.6053	150.7152	228.17	80.34802	119.03	113.5158	169.6689
2010-11-02T23:04:01Z	663.552	2795.871	137.957	401.285	269.48	291.013	336.017	278.0032	135.0795	101.3775	211.5374	80.33999	117.2467	92.58181	232.3411
2010-11-02T23:09:02Z	518.2206	1582.864	184.1523	401.3069	269.99	294.8385	322.1126	263.6887	122.851	116.5166	166.1553	80.33195	135.0533	134.5497	233.2914
2010-11-02T23:14:03Z	449.1126	2584.963	194.4205	401.3288	355	268.0768	244.3377	264.3046	119.4105	150.4238	147.7296	80.32391	143.12	214.053	234.8477
2010-11-02T23:19:05Z	544.2914	1665.443	239.5166	401.3507	250.87	228.1961	260.8543	265	119	287.5033	168.5216	80.31588	122.2203	227	186.2119
2010-11-02T23:24:06Z	430.4106	2287.37	231.1821	401.3726	246.4533	173.78	254.3642	264.3582	119	179.2517	207.8633	80.30784	123.5957	212.702	176.4808
2010-11-02T23:29:07Z	449.6821	1162.239	243.2848	401.3945	212.6267	187.1116	292.1126	268.4735	119.5762	150.4404	148.4875	80.2998	124.28	180.6788	234.7108
2010-11-02T23:34:09Z	400.3444	2592.162	264.6755	401.4164	159.32	242.84	318.1391	273.5419	120	315.298	141.68	80.29177	159.6833	234.384	235.4305
2010-11-02T23:39:10Z	266.9934	1364.279	256	401.4384	256.7667	246.5714	281.3483	258.0362	119.4345	247.6009	115.25	80.28373	196.8	275.2149	233.1788
2010-11-02T23:44:11Z	129.4205	880.352	256.5596	401.4603	251.8267	235.2212	276.3267	217.5273	119	211.6947	82.75374	80.27569	217.0054	230.3013	172.2119
2010-11-02T23:49:12Z	81.6903	879.2675	257.5563	401.4822	225.9	229.7149	261.4423	196.5232	119	193.0824	82.49415	80.26766	242.8283	167.8477	198.6344
2010-11-02T23:54:13Z	76.2691	2195.197	253.0232	401.5041	222.9733	214.8966	253.7947	196.2318	119	127.8113	93.49	80.25962	248.7308	172.6656	853.8801
2010-11-02T23:59:15Z	136.4636	1870.512	158.8543	401.526	278.0633	179.6471	239.0397	250.2947	119	181.5166	129	80.25158	231.0715	300.8212	523.106

Figure 8- 4:: Household 39-53 Electricity Consumption - [Source: Craig et al. (2014)]

Time	H54	H55	H56	H57	H58	H59	H60	H61	H62	H63	H64	H65
2010-11-02T11:31:39Z	502.1523	365.3742	568.5265	212.5333	118.7344	200.93	611.1493	201.005	276	1894.299	1267.017	298.9867
2010-11-02T18:07:47Z	503.6887	362.0596	636.2252	218	115.3351	250.2	599.5695	197.5541	273.9733	1891.468	1268.413	240.66
2010-11-02T18:12:49Z	505.6821	323.3311	542.043	217.6944	99.79207	221.04	596.156	159.4733	238.8	1888.878	1291	160.87
2010-11-02T18:17:50Z	339.2881	223.9139	386.7431	214.8498	128.1549	195.68	596.4096	122.4841	253.3477	1894.836	1291.373	57.81333
2010-11-02T18:22:51Z	182.1227	269.0331	305.9171	227.8967	152.1169	165.98	597	120.6206	239.5793	1899.397	1285.85	57
2010-11-02T18:27:52Z	115.6235	265.755	258.3411	277.7	149.0749	207.4105	605.2924	121.7929	230.74	1874.965	1177.32	57
2010-11-02T18:32:54Z	97.93046	216.6435	233.665	288.21	117.64	396.556	702.4746	162.8055	226	1856.043	808.39	76.96333
2010-11-02T18:37:55Z	96	152.7778	246.4577	263.5333	76.97667	318.6207	921.5588	204.0733	252.0167	1855.99	714.5733	173.8133
2010-11-02T18:42:56Z	96	140.8079	283.1159	260.58	71	347.76	927.2023	195.6278	305.6	1857.005	703	174.15
2010-11-02T18:47:57Z	82.96689	248.9172	299	263.1486	89.28296	329.2	768.8642	158.0348	322.88	1858.52	703	82
2010-11-02T18:52:58Z	68.64238	316.9735	298.394	266.8386	122.64	264.9933	722.2349	123.9	317.0267	1702.011	696.2911	57
2010-11-02T18:58:00Z	66	376.0265	296.7947	268.7233	117.4588	310.8267	705.4179	122.763	244.4867	1332.243	659.59	57
2010-11-02T19:03:01Z	66	392.7446	307.3874	262.26	118.4288	214.97	681.9106	127.92	223.04	1133.531	657.8267	57
2010-11-02T19:08:02Z	66	393	293.543	235.4093	150.1467	247.1667	597.4702	167.8504	225.1333	1127.114	689.1	56.84667
2010-11-02T19:13:03Z	66	408.5066	251.7351	204.5409	148.1505	274.75	435.6805	205.28	233.04	1172.66	683.7067	56
2010-11-02T19:18:04Z	66	291.9735	232.4106	231.8667	139.9849	324.2	345.8869	193.1704	236.05	884.8141	695.416	56
2010-11-02T19:23:06Z	66	226.7781	230.2413	299.05	106.0465	288.3261	328.8377	169.0981	241.3267	840.4687	729.1922	56
2010-11-02T19:28:07Z	66	219	228.4211	266.42	71	235.1687	330.1445	143.1487	289.95	835.0051	729.8018	56
2010-11-02T19:33:08Z	66	219	228	207.0533	71.39601	124.82	333.2434	120.2229	275	829.5415	730.4114	56
2010-11-02T19:38:09Z	66.7734	219	228.5698	213.2529	83.0316	72.84	362.9112	117.54	275	824.0779	731.021	56
2010-11-02T19:43:11Z	67	219	271.7264	213.4925	113.5333	84.66667	373.6966	155.0481	276.9868	818.6143	731.6306	56
2010-11-02T19:48:12Z	67.75748	219	301.6424	211.25	132.3444	95.26877	365.9704	190.812	235.2805	813.1507	732.2403	56
2010-11-02T19:53:13Z	68	218.2914	317.9264	207.52	137.7933	112.9251	358.0133	177.9684	227.0793	807.6871	732.8499	56
2010-11-02T19:58:14Z	68	215.1788	359.9178	205.92	152.1333	95.21333	297.9735	145.559	221.1173	802.2235	733.4595	56
2010-11-02T20:03:16Z	67.25166	213.298	351.0896	245.72	148.26	100.75	252.2947	120.2321	221.9767	795.4682	733.2293	56
2010-11-02T20:08:17Z	67	203.9172	273.7252	349.8633	121.6162	132.6912	247	116.3677	222.9766	751.9734	697.8	56
2010-11-02T20:13:18Z	95.18543	125.6793	230	356.3927	68.40189	105.7604	244.069	116.1135	306.7256	937.5171	679.7867	56
2010-11-02T20:18:19Z	121.245	92.31177	231.5993	293.7814	51	99.81667	242.5788	148.9902	324.5232	848.2042	674.6933	56
2010-11-02T20:23:21Z	127	91.31457	230.8808	251.02	51	94.23333	243.5762	194.7267	284.3907	486.5435	644.6	56
2010-11-02T20:28:22Z	125.5364	91	229	224.6533	51	72.99	243.4266	189.8699	273.3642	743.2757	632	56
2010-11-02T20:33:23Z	122.8146	91.67881	227.9536	202.7767	76.5	104.5467	241.8765	157.4824	238.4305	441.7097	632	56
2010-11-02T20:38:25Z	120.5497	92	227.5199	201.78	154.28	89.05	267.1283	118.7	241.7848	402.2375	632	56
2010-11-02T20:43:26Z	120	92	261.0596	201	185.6667	132.54	284.1575	117.9166	246.7682	616.2239	631.9133	56
2010-11-02T20:48:27Z	122.1443	92	331.5199	204.9065	135.6778	110.3827	279.9073	111.6239	243.2102	460.3185	634.3333	56
2010-11-02T20:53:28Z	189.2086	91.33775	362.3515	235.8533	128.8036	132.2821	277.9129	132.9663	231.6766	660.9218	673.08	56
2010-11-02T20:58:29Z	150.8079	91.65894	335.0695	296.3172	120.64	89.53333	334.9079	185.9767	243.2252	581.1978	699.4533	56
2010-11-02T21:03:31Z	118.3576	105.7682	304.0502	289.39	125.4833	55.22	379.6981	187.7133	296.4768	417.0962	728.8533	56
2010-11-02T21:08:32Z	115.298	98.64901	270.97	299.7621	129.5533	76.79333	372.9269	161.6246	311.2387	393.074	726.93	56
2010-11-02T21:13:34Z	114.3013	91	238.7562	366.5	118.2677	46.01667	370.482	115.7354	318.4992	637.8352	721.8	56
2010-11-02T21:18:35Z	114	91	229.5324	427	110.2995	51	337.6312	112.3723	279.4003	549.3543	661.1	56
2010-11-02T21:23:36Z	113.3079	91	229	437.2497	126.84	80.90066	255.5	110.6938	224.6434	430.28	633.06	56
2010-11-02T21:28:37Z	113	91	228.0718	478.3278	191.3733	88.94702	229.1733	137.6491	219.0861	323.1109	634	56
2010-11-02T21:33:39Z	112.3153	91	227	420.4591	244.7004	92.96026	249.1414	198.3344	219	639.678	633.9467	56
2010-11-02T21:38:40Z	112	90.37086	242.4133	276.3491	191.1071	66.35762	243.515	191.4133	235.2857	725.4282	633.05	56
2010-11-02T21:43:41Z	112	90	293.4537	379.5025	123.4875	52.23179	257.6248	168.5044	232.4975	226.5257	633.9067	56
2010-11-02T21:48:42Z	112	90	323.2628	361.6323	83.53333	77.48344	279.1871	116.5657	261.5321	381.5271	633.69	56
2010-11-02T21:53:43Z	111.335	90	309.68	307.604	51.73667	50.64901	283.6223	115.76	280.1393	625.1055	671.4	56
2010-11-02T21:58:45Z	111.6613	90	304.0634	294.2154	51	59.7351	280.64	109.1686	274.0132	238.088	685.2533	56
2010-11-02T22:03:46Z	97.03299	90	297.7122	281.4642	51	59.03284	275.8785	119.3994	295.9868	477.5216	797.5667	56
2010-11-02T22:08:47Z	75.45273	90	281.0667	228.0133	51	58.03648	256.4833	162.6159	242.6291	634.1005	812.71	56
2010-11-02T22:13:48Z	69.92715	90.60265	247.8767	199	55.19333	53.19868	237.8815	188.7404	227.9801	184.4409	770.9733	56
2010-11-02T22:18:50Z	104.2318	90.40066	230	199.7011	99.63333	99.74716	238.5674	174.14	221.755	305.6916	770.0233	56
2010-11-02T22:23:51Z	99.48746	90	230	204.6656	218.9146	102	238.4315	129.6862	221	515.5812	770.6	56
2010-11-02T22:28:52Z	74.05804	90	237.0267	209.5191	263.8019	167.3444	239	116.2612	217.5157	360.3968	750.5333	56
2010-11-02T22:33:53Z	67	90	260.12	219.3806	162.95	99.27815	239	112.2938	227.4106	624.77	723.0133	56
2010-11-02T22:38:55Z	66.37748	96.44702	261.5133	267.4467	62.4	53.62252	239.406	117.6323	316.2881	180.7462	724.09	56
2010-11-02T22:43:56Z	66	202.404	248.5033	298.5867	87.42222	82.86093	239.596	161.8163	310.1987	198.2231	733.2933	56
2010-11-02T22:48:57Z	66	292.3894	281.4	251.9218	131.6206	74.72848	256.0848	193.0948	276.9834	322.7338	776.9833	56
2010-11-02T22:53:58Z	66	286.6915	360.5167	245.5626	121.9333	91.62728	281.614	183.7467	253.2053	451.6501	772	56
2010-11-02T22:59:00Z	66	171.6225	525.6151	258.1667	116.3172	59.74627	278.7238	152.5243	225.3212	179	774.9901	56
2010-11-02T23:04:01Z	66	110.8543	650.4044	267	110.609	63.44371	275	118.574	234.5629	218.3746	753.1457	56
2010-11-02T23:09:02Z	66	168.596	558.5667	266.78	117.8	65.83444	272.4143	115.9483	235.3113	314.2993	729.2384	56
2010-11-02T23:14:03Z	66	212.3991	364.2658	261.6988	146.0467	52.29139	258.0836	111.188	227.4305	239.4845	751.6954	56
2010-11-02T23:19:05Z	66	219.5522	300.5467	232.5017	202.14	47.35762	241	122	219.298	398.2533	767.7351	56
2010-11-02T23:24:06Z	66	218.351	315.5792	225.7	247.3627	53.35099	240.6433	180.5609	238.0735	322.5711	775.8411	56
2010-11-02T23:29:07Z	66	216.4536	360.01	286.0383	98.53576	54	239.6467	190.4309	275.2364	692.0525	776.9768	56
2010-11-02T23:34:09Z	65.41722	183.4172	336.48	382.37	93.44	54	239	174.9333	307.5999	173.7997	776.0265	56
2010-11-02T23:39:10Z	65.57947	121.8053	331.6433	457.9867	98.76333	51.32836	238.6572	117.8149	309.7082	173.386	803.1656	56
2010-11-02T23:44:11Z	74.64543	92.33186	328.5226	362.9167	93.69448	63.42384	238.4546	116.1987	245.906	203.7376	855.245	56
2010-11-02T23:49:12Z	89.53234	92.11208	322.96	362	97.33278	49.08609	238.8513	111.4719	221.3636	376.8821	810.7483	56
2010-11-02T23:54:13Z	96	92	317.26	390.4433	109.6343	54.92715	239	113.32	217.3709	527.0125	804.1987	56
2010-11-02T23:59:15Z	96	92	307.005	794.2779	174.4967	86.71192	253.5458	155.0316	222.6788	178.5574	795.3874	56

Figure 8- 5: Figure 8 5: Household 54-65 Electricity Consumption - [Source: Craig et al. (2014)]

8.1.2 24hours total community consumption – November 2010

Figure 8-6 presents the total community with 215 household ‘s electricity consumption in 24 hours in Watt per 5 minutes interval starting from 00:00 on 3rd November 2010.

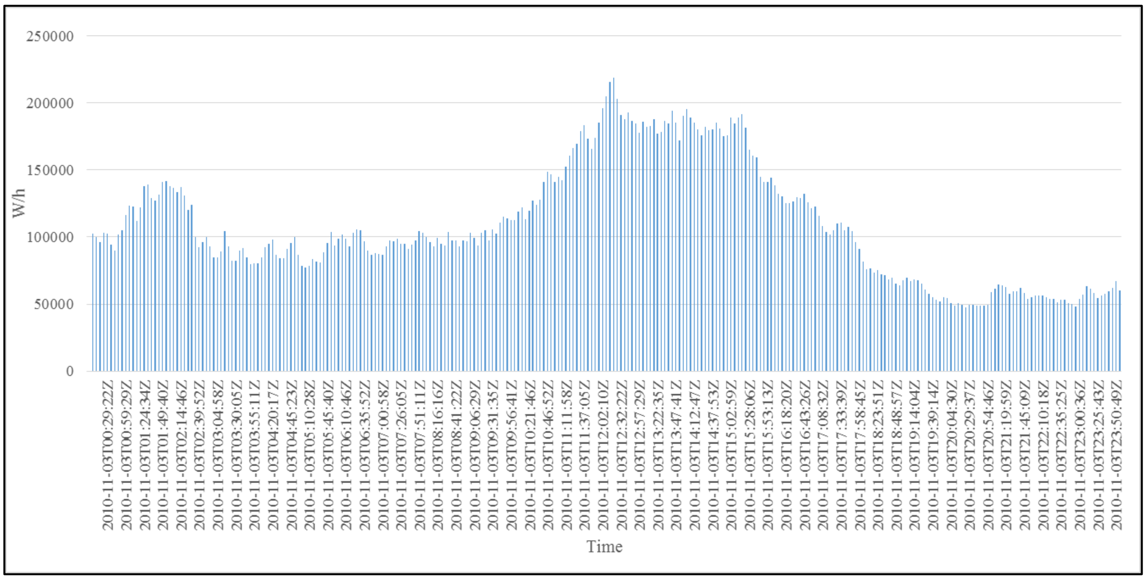


Figure 8- 6: 24 hour’s community electricity consumption - 3rd November 2010 [Source: Craig, et al. (2014)

8.1.3 Household Input Data for this research

Table 29 shows the electricity consumption for 140 households used in the developed model for this research. In Kilowatt per hour per day.

Date	Community Consumption (kWh)
01/01/2011	1552.938564
02/01/2011	1552.025608
03/01/2011	1541.983089
04/01/2011	1550.199696
05/01/2011	1531.940571
06/01/2011	1532.853527
07/01/2011	1533.766483
08/01/2011	1533.766483
09/01/2011	1531.940571
10/01/2011	1529.201702
11/01/2011	1528.288746
12/01/2011	1521.898052
13/01/2011	1533.766483
14/01/2011	1529.201702
15/01/2011	1528.288746
16/01/2011	1529.201702
17/01/2011	1528.288746
18/01/2011	1531.940571
19/01/2011	1532.853527
20/01/2011	1528.288746
21/01/2011	1531.940571
22/01/2011	1528.288746
23/01/2011	1529.201702
24/01/2011	1524.636921
25/01/2011	1526.462833
26/01/2011	1526.462833
27/01/2011	1527.37579
28/01/2011	1530.114658

29/01/2011	1530.114658
30/01/2011	1529.201702
31/01/2011	1528.288746
01/02/2011	1524.636921
02/02/2011	1522.811008
03/02/2011	1523.723965
04/02/2011	1521.898052
05/02/2011	1522.811008
06/02/2011	1524.636921
07/02/2011	1520.07214
08/02/2011	1520.985096
09/02/2011	1518.246227
10/02/2011	1523.723965
11/02/2011	1525.549877
12/02/2011	1520.07214
13/02/2011	1519.159183
14/02/2011	1515.507358
15/02/2011	1501.813015
16/02/2011	1498.16119
17/02/2011	1501.813015
18/02/2011	1502.725971
19/02/2011	1500.900059
20/02/2011	1497.248234
21/02/2011	1499.074146
22/02/2011	1501.813015
23/02/2011	1501.813015
24/02/2011	1499.987102
25/02/2011	1500.900059
26/02/2011	1503.638927
27/02/2011	1481.727978
28/02/2011	1506.377796

Table 29: 140 households Electricity consumption - applied in the developed model for this research

8.2 APPENDIX B: WEATHER DATA

Table 30 presents the extended example of weather data collected from MetOffice for Huntly. As the table shows, there are 5 columns in the table; column 1; shows date (daily from 1st January 2011), column 2; presents daily mean wind speed in 24 hours in knot, column 3 shows daily maximum gust in 24 hours in knot, column 4presents daily total sunshine in 24 hours in hours of sunshine available, and column 5 shows the daily total global radiation in kilojoules per square meter.

Date	Daily Mean Wind speed (0100-2400) (kn)	Daily Maximum Gust (0100-2400) (kn)	Daily Total Sunshine (0100-2400) (hrs)	Daily Total Global Radiation (KJ/m2)
01/01/2011	12	23	0.0	512
02/01/2011	9	20	0.0	770
03/01/2011	6	15	0.0	493
04/01/2011	7	26	0.9	889
05/01/2011	8	20	3.8	1718
06/01/2011	13	31	5.3	2309
07/01/2011	6	19	3.9	2065
08/01/2011	7	22	0.3	1160
09/01/2011	8	21	2.6	1759
10/01/2011	8	26	0.0	1066
11/01/2011	9	22	5.2	2518
12/01/2011	6	22	2.3	1509
13/01/2011	2	9	1.8	1886
14/01/2011	7	21	4.3	2869
15/01/2011	14	41	0.1	1149
16/01/2011	15	37	5.5	2772
17/01/2011	7	22	3.3	2265
18/01/2011	7	19	5.0	2799
19/01/2011	7	17	0.1	1624
20/01/2011	2	9	6.3	4383
21/01/2011	5	20	0.1	1537
22/01/2011	9	18	4.1	2751
23/01/2011	10	20	0.0	1108
24/01/2011	12	26	0.3	1445
25/01/2011	8	24	0.0	1439
26/01/2011	9	27	0.3	2006
27/01/2011	3	10	1.3	1848
28/01/2011	3	11	3.3	3084
29/01/2011	3	13	2.0	2674
30/01/2011	6	23	4.7	3668
31/01/2011	10	31	0.0	985
01/02/2011	9	27	6.7	4423
02/02/2011	12	30	0.3	1593
03/02/2011	15	50	4.1	3592
04/02/2011	11	35	0.0	960

05/02/2011	9	30	3.7	4204
06/02/2011	2	11	0.0	1762
07/02/2011	9	28	0.0	1198
08/02/2011	8	23	0.3	3170
09/02/2011	8	23	0.0	1501
10/02/2011	7	24	7.7	6061
11/02/2011	5	27	0.0	2545
12/02/2011	12	29	0.0	1124
13/02/2011	5	n/a	0.0	686
14/02/2011	7	n/a	0.3	2460
15/02/2011	8	n/a	1.2	2554
16/02/2011	10	29	0.0	1043
17/02/2011	6	17	1.4	3743
18/02/2011	13	31	0.0	739
19/02/2011	16	33	0.0	908
20/02/2011	14	26	0.0	758
21/02/2011	13	26	0.0	453
22/02/2011	7	17	6.3	7598
23/02/2011	9	24	0.2	2845
24/02/2011	9	21	1.3	3757
25/02/2011	12	31	5.4	6498
26/02/2011	7	20	1.4	4784
27/02/2011	9	28	6.6	8257
28/02/2011	5	15	8.2	8752
01/03/2011	5	19	9.2	9434
02/03/2011	9	25	8.1	9138
03/03/2011	4	14	0.0	3751
04/03/2011	6	15	0.9	5569
05/03/2011	6	19	2.8	7330
06/03/2011	8	18	9.4	10927
07/03/2011	10	24	9.8	10795
08/03/2011	12	35	2.8	5813
09/03/2011	12	36	9.2	11268
10/03/2011	13	49	5.7	9261
11/03/2011	10	30	8.8	11585
12/03/2011	6	21	0.0	1778
13/03/2011	10	34	0.0	2812
14/03/2011	7	26	0.0	3524
15/03/2011	5	20	0.0	1861
16/03/2011	10	25	3.5	9241
17/03/2011	8	19	0.8	5739
18/03/2011	8	25	8.6	12799
19/03/2011	7	20	9.2	13460
20/03/2011	10	26	8.8	13643
21/03/2011	12	28	9.8	13054
22/03/2011	9	27	0.0	4316

23/03/2011	7	19	2.7	8668
24/03/2011	6	19	4.9	10836
25/03/2011	7	19	2.3	8448
26/03/2011	9	21	0.0	4866
27/03/2011	7	23	2.9	10891
28/03/2011	5	15	1.8	7410
29/03/2011	5	13	0.0	5930
30/03/2011	6	17	0.0	2057
31/03/2011	11	37	0.7	4617
01/04/2011	14	33	3.1	10583
02/04/2011	13	41	4.7	11055
03/04/2011	9	26	7.8	14014
04/04/2011	12	31	2.1	6454
05/04/2011	14	31	7.7	15700
06/04/2011	11	34	2.3	10370
07/04/2011	11	30	4.8	13638
08/04/2011	9	26	4.3	13682
09/04/2011	10	27	9.4	16756
10/04/2011	7	22	9.5	17305
11/04/2011	8	33	1.2	6957
12/04/2011	11	26	9.2	16989
13/04/2011	9	23	1.8	10659
14/04/2011	5	16	1.5	10986
15/04/2011	6	22	4.5	14174
16/04/2011	5	17	2.9	11405
17/04/2011	4	19	10.5	20220
18/04/2011	5	20	4.9	15693
19/04/2011	5	13	2.1	11382
20/04/2011	5	21	4.7	15692
21/04/2011	4	14	2.3	13150
22/04/2011	5	19	8.1	18424
23/04/2011	5	19	0.3	10125
24/04/2011	5	17	6.1	16017
25/04/2011	6	17	4.5	14971
26/04/2011	4	16	10.0	20166
27/04/2011	6	20	13.8	24328
28/04/2011	7	22	13.9	24493
29/04/2011	4	14	10.9	20474
30/04/2011	4	17	14.0	24720

Table 30: Extended example of original weather data [source: MetOffice, 2018]

8.2.1 Example of Huntly wind speed

Huntly 24 hours wind speed in 1st January 2011 is presented in Figure 8-9.

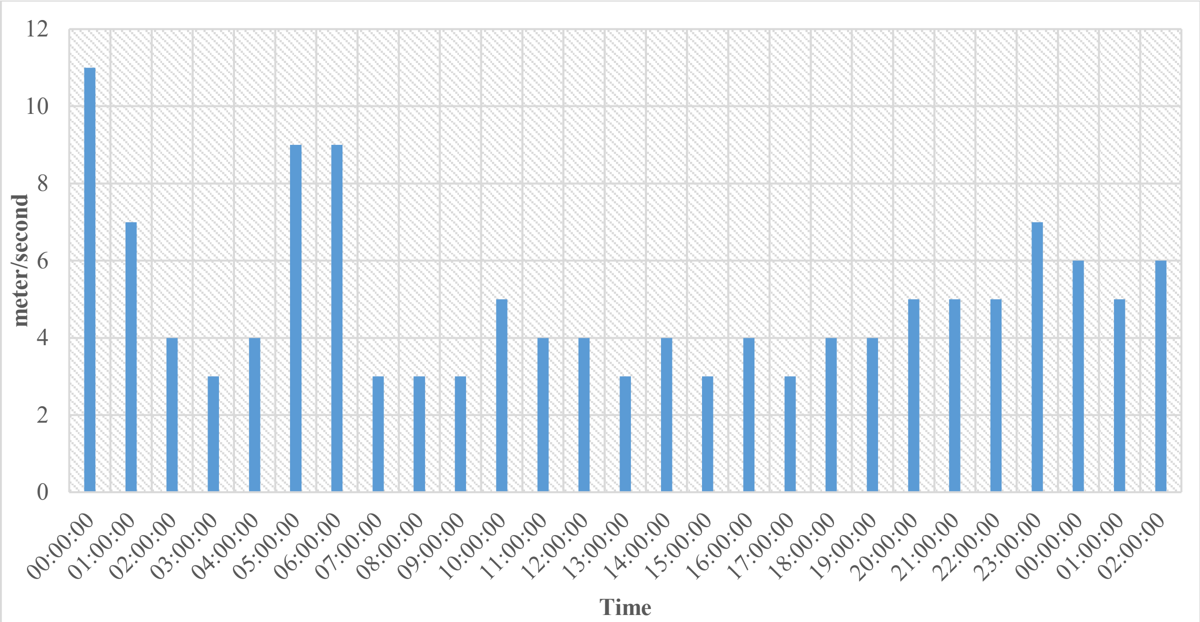


Figure 8- 7: Huntly 24 hours wind speed meter/second [Source: MetOffice, 2018]

8.2.2 Sun Irradiation – MetOffice 2018

Figure 8-10 shows the 24 hours sun irradiance for Huntly in 1st January 2011.

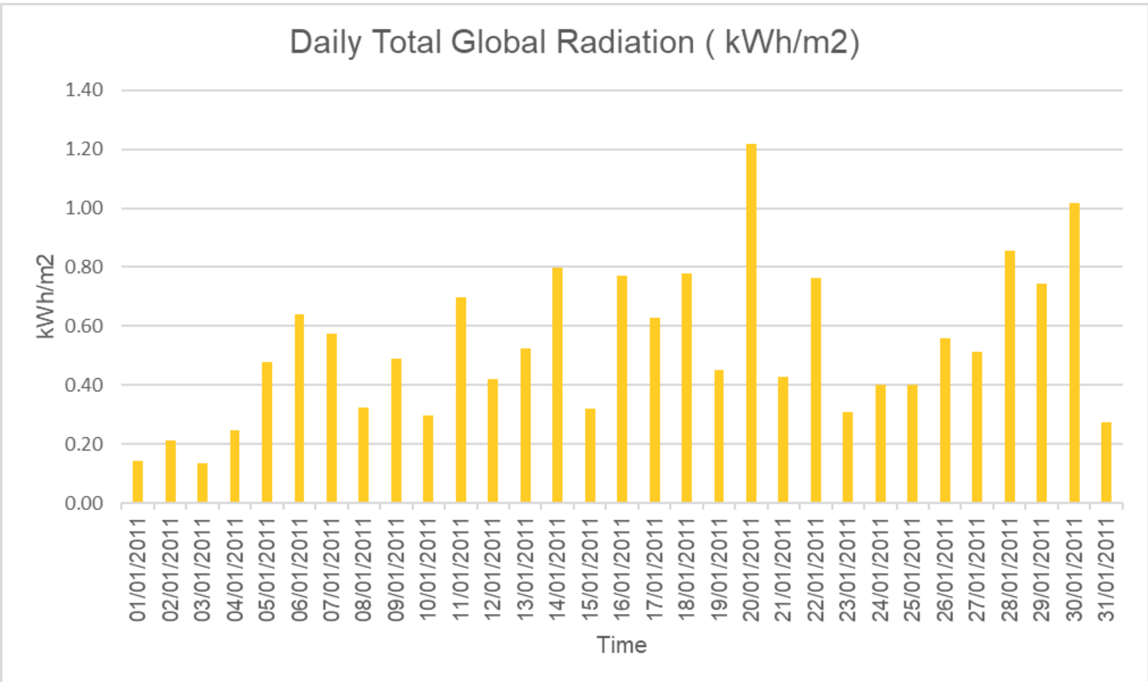


Figure 8- 8: 24 Hours sun irradiance 1st January 2011

8.3 Appendix C: Technology Type

8.3.1 Wind Turbine

Output (kW)(Wind Speed (m/s)), created by Plot Digitizer, 2.6.8
Date: 16/02/18, 19:02:31

Wind Speed (m/s)	Output (kW)
3.01471	10.4762
3.19853	41.9048
3.52941	83.8095
3.86029	130.952
4.11765	172.857
4.48529	220
4.70588	272.381
4.85294	309.048
5.18382	350.952
5.36765	387.619
5.625	450.476
5.91912	497.619
6.10294	550
6.21324	602.381
6.39706	644.286
6.58088	722.857
6.76471	796.19
6.91176	864.286
7.09559	942.857
7.16912	969.048
7.31618	1031.9
7.46324	1094.76
7.57353	1141.9
7.57353	1168.1
7.68382	1199.52
7.72059	1225.71
7.79412	1272.86
7.90441	1299.05
7.94118	1325.24
8.08823	1388.1
8.30882	1456.19
8.38235	1503.33
8.45588	1550.48
8.56618	1592.38
8.67647	1608.1
8.75	1655.24
8.82353	1686.67
9.04412	1765.24
9.26471	1828.1
9.41177	1859.52
9.55882	1890.95
9.70588	1911.9
9.77941	1948.57
10.0735	1964.29
10.2941	1980
11.2132	1995.71
11.9853	2000.95
12.2794	2000.95
12.6103	2000.95
12.9044	2000.95
13.3456	2000.95
14.0074	2000.95
14.3382	2000.95
15.0735	2000.95
15.5882	2000.95
16.2132	2000.95
16.9853	2000.95
18.0515	2000.95
18.6029	2000.95
22.7941	1995.71
20	1995.71
20.5882	1995.71
20.6985	1995.71
20.8824	1995.71
21.1765	1995.71
21.4338	1995.71
22.0588	1995.71
22.3162	1995.71
23.4926	1995.71
23.7132	1995.71
23.8235	1990.48
24.4853	2000.95

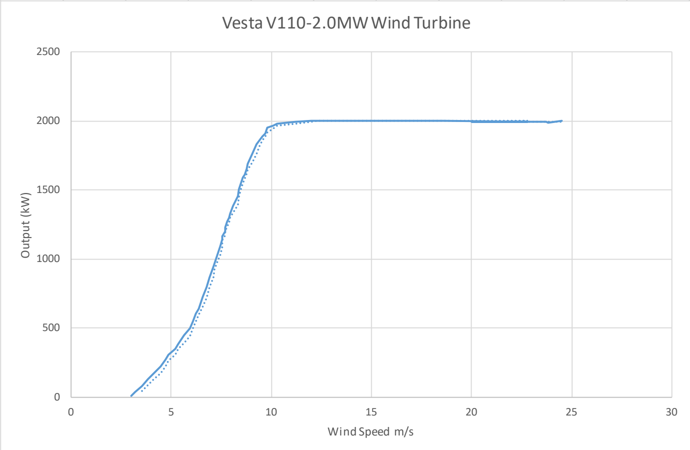


Table 31: Vesta 2MW wind turbine

8.4 APPENDIX D: COST OF ELECTRICITY

Date	Feed-in-Tariff for Electricity Generation from Onshore Wind Turbine - Total Install Capacity of 500-1500 kW (£/kWh)	Feed-in-Tariff for Electricity Generation from Onshore Wind Turbine Total install capacity of 1500-5000 kW (£/kWh)	Feed-in-Tariffs for Electricity Generation from Stand Alone Solar System Total install capacity of 0-5000 kW (£/kWh)	Exporting Electricity to the Grid from Onshore Wind Turbine System (£/kWh)	Exporting Electricity from Solar System (£/kWh)
01/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
02/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
03/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
04/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
05/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
06/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
07/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
08/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
09/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
10/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
11/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
12/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
13/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
14/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
15/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
16/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
17/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
18/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
19/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
20/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
21/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
22/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
23/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
24/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
25/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
26/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
27/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
28/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
29/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
30/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372
31/01/2011	0.1208	0.0568	0.3742	0.0372	0.0372

Table 32: Feed-in-tariff 2011

Feed-in-Tariff for Electricity Generation from Onshore Wind Turbine - Total Install Capacity of 500-1500 kW (£/kWh)	**Feed-in-Tariff for Electricity Generation from Onshore Wind Turbine Total install capacity of 1500-5000 kW** (£/kWh)	**Feed-in-Tariffs for Electricity Generation from Stand Alone Solar System Total install capacity of 0-5000 kW (£/kWh)**
01/01/2011 - 31/03/2011	01/01/2011 - 31/03/2011	01/01/2011 - 31/03/2011
0.1208	0.0568	0.3742
01/04/2011 - 31/07/2011	01/04/2011 - 31/07/2011	01/04/2011 - 31/07/2011
0.1208	0.0568	0.3742
01/08/2011 - 29/09/2011	01/08/2011 - 29/09/2011	01/08/2011 - 29/09/2011
0.1208	0.0568	0.1034
30/09/2011 - 02/03/2012	30/09/2011 - 02/03/2012	30/09/2011 - 02/03/2012
0.1208	0.0568	0.1034
03/03/2012 - 31/03/2012	03/03/2012 - 31/03/2012	03/03/2012 - 31/03/2012
0.1208	0.0568	0.1034
01/04/2012 - 31/07/2012	01/04/2012 - 31/07/2012	01/04/2012 - 31/07/2012
0.1208	0.0568	0.1034
01/08/2012 - 30/11/2012	01/08/2012 - 30/11/2012	01/08/2012 - 30/11/2012
0.1208	0.0568	0.0825
01/12/2012 - 14/03/2013	01/12/2012 - 14/03/2013	01/12/2012 - 14/03/2013
0.1103	0.0521	0.0801
15/03/2013 - 30/04/2013	15/03/2013 - 30/04/2013	15/03/2013 - 30/04/2013
0.1103	0.0468	0.0801
01/05/2013 - 31/12/2013	01/05/2013 - 31/12/2013	01/05/2013 - 31/12/2013
0.1103	0.0468	0.0771
01/01/2014 - 31/03/2014	01/01/2014 - 31/03/2014	01/01/2014 - 31/03/2014
0.1103	0.0468	0.0725
01/04/2014 - 30/06/2014	01/04/2014 - 30/06/2014	01/04/2014 - 30/06/2014
0.0883	0.0373	0.0725
01/07/2014 - 30/09/2014	01/07/2014 - 30/09/2014	01/07/2014 - 30/09/2014
0.0883	0.0373	0.07

01/10/2014 - 31/03/2014	01/10/2014 - 31/03/2014	01/10/2014 - 31/03/2014
0.0795	0.0337	0.07
01/01/2015 - 31/03/2015	01/01/2015 - 31/03/2015	01/01/2015 - 31/03/2015
0.0795	0.0337	0.0689
01/04/2015 - 31/06/2015	01/04/2015 - 31/06/2015	01/04/2015 - 31/06/2015
0.0707	0.0299	0.0665
01/07/2015 - 30/09/2015	01/07/2015 - 30/09/2015	01/07/2015 - 30/09/2015
0.0707	0.0299	0.0479
01/01/2016 - 14/01/2014	01/01/2016 - 14/01/2014	01/01/2016 - 14/01/2014
0.0636	0.0269	0.0329
15/01/2016 - 31/03/2016	15/01/2016 - 31/03/2016	15/01/2016 - 31/03/2016
0.0583	0.0092	0.0093
01/04/2016 - 30/06/2016	01/04/2016 - 30/06/2016	01/04/2016 - 30/06/2016
0.0522	0.0091	0.0079
01/07/2016 - 30/09/2016	01/07/2016 - 30/09/2016	01/07/2016 - 30/09/2016
0.0469	0.0091	0.0065
01/10./2016 - 31/12/2016	01/10./2016 - 31/12/2016	01/10./2016 - 31/12/2016
0.0418	0.0089	0.0054
01/01/2017 - 31/03/2017	01/01/2017 - 31/03/2017	01/01/2017 - 31/03/2017
0.0365	0.0085	0.0044
01/04/2017 - 30/06/2017	01/04/2017 - 30/06/2017	01/04/2017 - 30/06/2017
0.0335	0.0086	0.0036
01/07/2017 - 30/09/2017	01/07/2017 - 30/09/2017	01/07/2017 - 30/09/2017
0.03	0.0084	0.003
01/10/2017 - 31/12/2017	01/10/2017 - 31/12/2017	01/10/2017 - 31/12/2017
0.0269	0.0083	0.0024
01/01/2018 - 31/03/2018	01/01/2018 - 31/03/2018	01/01/2018 - 31/03/2018
0.0231	0.0071	0.0019
01/04/2018 - 30/06/2018	01/04/2018 - 30/06/2018	01/04/2018 - 30/06/2018
0.0215	0.0066	0.0015

01/07/2018 - 30/09/2018	01/07/2018 - 30/09/2018	01/07/2018 - 30/09/2018
0.0213	0.0065	0.0013
01/10/2018 - 31/12/2018	01/10/2018 - 31/12/2018	01/10/2018 - 31/12/2018
0.0212	0.0064	0.0001
01/01/2019 - 31/03/2019	01/01/2019 - 31/03/2019	01/01/2019 - 31/03/2019
0.0212	0.0064	0.0007

Table 33: Feed-in-tariff for generated electricity

8.4.1 Wind Turbine Feed-in Tariff – Generation

Date	**Feed-in-Tariff for Electricity Generation from Onshore Wind Turbine - Total Install Capacity of 500-1500 kW** (£/kWh)	**Feed-in-Tariff for Electricity Generation from Onshore Wind Turbine Total install capacity of 1500-5000 kW** (£/kWh)
01/01/2011	0.1208	0.0568
30/11/2012	0.1208	0.0568
12/01/2012	0.1103	0.0468
31/03/2014	0.1103	0.0468
04/01/2014	0.0883	0.0373
30/09/2014	0.0883	0.0373
10/01/2014	0.0795	0.0373
31/03/2015	0.0795	0.0373
04/01/2015	0.0707	0.0299
30/09/2015	0.0707	0.0299
01/01/2016	0.0636	0.0269
14/01/2016	0.0636	0.0269
15/01/2016	0.0583	0.0092
31/03/2016	0.0583	0.0092
04/01/2016	0.0522	0.0091
30/06/2016	0.0522	0.0091
07/01/2016	0.0469	0.0091
30/09/2016	0.0469	0.0091
10/01/2016	0.0418	0.0089
31/12/2016	0.0418	0.0089
01/01/2017	0.0365	0.0085
30/06/2017	0.0365	0.0085
07/01/2017	0.03	0.0086
30/09/2017	0.03	0.0086
10/01/2017	0.0269	0.0084

31/12/2017	0.0269	0.0084
01/01/2018	0.0231	0.0083
31/03/2018	0.0231	0.0083
04/01/2018	0.0215	0.0071
30/06/2018	0.0215	0.0071
07/01/2018	0.0213	0.0066
30/09/2018	0.0213	0.0066
10/01/2018	0.0212	0.0065
31/03/2019	0.0212	0.0065

Table 34: Feed-in-tariff Wind Turbine

8.4.2 Wind Turbine and Solar PV Feed-in tariff – Export to Grid

Date	**Exporting** Electricity to the Grid from Onshore Wind Turbine System (£/kWh)	**Date**	**Exporting** Electricity from Solar System (£/kWh)
04/01/2010	0.0372	04/01/2010	0.0372
30/11/2012	0.0372	31/07/2012	0.0372
12/01/2012	0.0524	08/01/2012	0.0524
31/12/2018	0.0524	31/12/2018	0.0524
01/01/2019	0.0524	01/01/2019	0.0524
31/12/2019	0.0524	31/12/2019	0.0524

Table 35: Wind Turbine and Solar Panel Export to the grid

Exporting Electricity to the Grid from Onshore Wind Turbine System (£/kWh)	**Exporting** Electricity from Solar System (£/kWh)
01/04/2010 - 30/11/2012	01/04/2010 - 31/07/2012
0.0372	0.0372
01/12/2012 - 31/12/2018	01/08/2012 - 31/12/2018
0.0524	0.0524
01/01/2019 - 31/12/2019	01/01/2019 - 31/12/2019
0.0524	0.0524

Table 36: Exporting to the grid

8.4.3 Solar PV Panel feed-in tariff – Generation

Date	Feed-in-Tariffs for Electricity Generation from Stand Alone Solar System Total install capacity of 0-5000 kW (£/kWh)
01/01/2011	0.3742
31/07/2011	0.3742
08/01/2011	0.1034
29/09/2011	0.1034
30/09/2011	0.1034
02/03/2012	0.1034
03/03/2012	0.1034
31/03/2012	0.1034
04/01/2012	0.1034
31/07/2012	0.1034
08/01/2012	0.0825
30/11/2012	0.0825
12/01/2012	0.0801
14/03/2013	0.0801
15/03/2013	0.0801
30/04/2013	0.0801
05/01/2013	0.0771
31/12/2013	0.0771
01/01/2014	0.0725
31/03/2014	0.0725
04/01/2014	0.0725
30/06/2014	0.0725
07/01/2014	0.07
30/09/2014	0.07
10/01/2014	0.07
31/03/2014	0.07
01/01/2015	0.0689
31/03/2015	0.0689
04/01/2015	0.0665
31/06/2015	0.0665
07/01/2015	0.0479
30/09/2015	0.0479
01/01/2016	0.0329
14/01/2014	0.0329

Table 37: Feed-in tariff for solar PV

8.5 APPENDIX E: LAND REQUIREMENT

8.5.1 NREL – Land Requirement for Different Technology

Technology Type	Size (acres / MW)	Size Std. Dev. (acres / MW)
Photovoltaics <10 kW	3.2	2.2
Photovoltaics 10 100 kW	5.5	0.7
Photovoltaics 100 1,000 kW	5.5	0.7
Photovoltaics 1 10 MW	6.1	1.7
Wind <10 kW	30	n/a
Wind 10 100 kW	30	n/a
Wind 100- 1000 kW	30	n/a
Wind 1 10 MW	44.7	25.0
Biomass Combustion Combined Heat & Power	3.5	1.9
Technology Type	**Size (Btu/ft2/ day)**	**Size Std. Dev. (Btu/ft2/ day)**
Solar Water Heat, flat plate & evacuated tube	774	320
Solar Water Heat, plastic collector	n/a	n/a
Solar Vent Preheat	n/a	n/a
	Size (acres /MW)	**Size Std. Dev. (acres /MW)**
Biomass Wood Heat	0.3	0.3
Technology Type	**Size (Btu/ft2/ day)**	**Size Std. Dev. (Btu/ft2/ day)**
Ground Source Heat Pump	n/a	n/a

Figure 8- 9: NREL-Land

8.5.2 Knight Frank communication for land availability and Cost of land

RURAL RESEARCH

SCOTTISH FARMLAND INDEX H2 2017

Knight Frank

SCOTTISH FARMLAND VALUES REMAIN IN THE BLACK IN 2017

A drop in supply helps balance out political and economic uncertainty

Farmland performance
(average all types, unweighted)

6 months	0.4%
12 months	1%
5 years	12%
10 years	85%
20 years	157%

Source of buyers

Scotland	83%
England/Wales	8%
Northern Ireland	7%
Europe	2%

The average value of Scottish farmland nudged up 1% during 2017, according to the latest results of the Knight Frank Scottish Farmland Index.

Across the board, prices ended the year at £4,271/acre. However, performance varied depending on land type. Good arable land and hill land were the strongest performers with values for each rising by around 3% to £9,319/ace and £719/acre, respectively. The best arable land in sought after locations can command premiums of up to 20%.

Poorer quality and smaller blocks of arable and grazing land is less in demand – prices remained static or fell slightly in 2017 – although improved farm-gate milk prices are helping to support the value of good dairy units.

The continuing dearth of land and farms for sale is the main reason agricultural land values are holding their own, despite the uncertainty surrounding Brexit. Last year, Knight Frank's analysis of the open market revealed that just 61 farms – totalling fewer than 30,000 acres – guided at over £1m were launched publicly. This compares with 72 farms in 2016 and 75 in 2015.

A number of vendors opted to sell their farms privately in 2017 and they achieved strong prices, but overall the pattern is still one of falling volumes.

This trend looks set to continue throughout 2018 with no signs so far of a significant increase in the amount of land that is set to come up for sale. This seems slightly counterintuitive given that the outlook for farming post Brexit remains unclear – now would actually appear to be a good time for anybody thinking of retiring or quitting farming to sell while values remain firm.

However, a lack of clarity in any property market always makes potential vendors nervous. The fact that Defra Minister Michael Gove has committed to maintaining UK farm support at levels equivalent to current CAP spending until 2024 has probably helped to delay many decisions. The weakness of sterling following the vote to leave the EU has also boosted subsidy cheques and commodity prices.

It seems increasingly certain that future support payments will be very much linked to the environment and the delivery of public goods – something Scottish farmers could be well placed to deliver.

ctricity from
ic Land Prices in

res rise in the

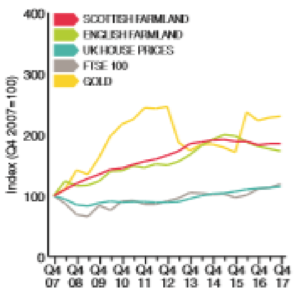
ence.

ANDREW SHIRLEY
Head of Rural Research

"Overall the pattern is still one of falling volumes."

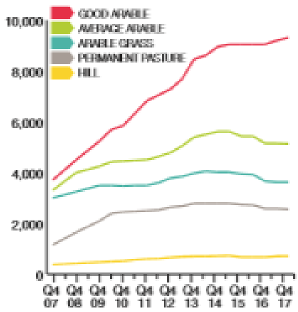
Follow Andrew at @kfandrewshirley

Capital value growth of Scottish farmland v other assets



Source: Knight Frank Research

Scottish farmland values by type
£/acre



Source: Knight Frank Research

Figure 8- 10: Knight Frank Scottish Land Values 2017

DATA DIGEST

The Knight Frank Scottish Farmland Index tracks the average price of bare (no residential property or buildings) commercial (productive arable and pasture) agricultural land in Scotland. The quarterly index is based on the opinions of Knight Frank's expert valuers and negotiators across the country, that take into account the results of actual sales conducted by both the firm and its competitors, local market knowledge and client and industry sentiment.

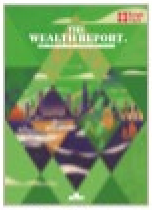
Knight Frank Scottish Farmland Index

Average value £/acre

Quarter	Good arable	Average arable	Arable/ Grass	Permanent Pasture	Hill	Unweighted average
2007 Q4	3,700	3,300	3,000	1,150	375	2,305
2008 Q2	4,100	3,650	3,125	1,400	400	2,535
2008 Q4	4,500	4,000	3,250	1,650	425	2,765
2009 Q2	4,875	4,125	3,375	1,875	450	2,940
2009 Q4	5,250	4,250	3,500	2,100	475	3,115
2010 Q2	5,700	4,425	3,500	2,400	500	3,305
2010 Q4	5,850	4,450	3,475	2,450	515	3,348
2011 Q2	6,340	4,475	3,500	2,475	571	3,472
2011 Q4	6,825	4,501	3,500	2,500	600	3,585
2012 Q2	7,053	4,633	3,603	2,531	614	3,687
2012 Q4	7,285	4,786	3,783	2,633	659	3,829
2013 Q2	7,698	5,057	3,846	2,676	692	3,994
2013 Q4	8,468	5,394	3,974	2,783	704	4,265
2014 Q2	8,612	5,502	4,054	2,783	704	4,331
2014 Q4	8,956	5,612	4,013	2,783	718	4,417
2015 Q2	9,046	5,612	4,013	2,783	732	4,437
2015 Q4	9,046	5,425	3,946	2,737	673	4,366
2016 Q2	9,046	5,425	3,920	2,719	673	4,357
2016 Q4	9,046	5,154	3,659	2,583	673	4,223
2017 Q2	9,200	5,154	3,622	2,583	707	4,253
2017 Q4	9,319	5,139	3,622	2,557	719	4,271

Source: Knight Frank Research

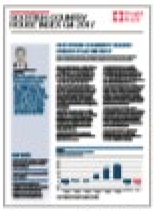
RECENT MARKET-LEADING RESEARCH PUBLICATIONS



The Wealth Report - 2017

The Rural Report - Spring 2017

Edinburgh City Index - Q4 2017



Prime Scottish Index - Q4 2017

Knight Frank Research Reports are available at KnightFrank.com/Research

Key agricultural indicators*

Commodity prices	Latest	12-month change
Outputs		
Feedwheat (£/t)	136	-4%
Oilseed rape (£/t)	288	-17%
Beef (p/kg dw)	370	2%
Lamb (p/kg dw)	419	10%
Milk (p/litre)	31.7	21%
Input prices		
Red diesel (p/litre)	56	11%
Oil (£/brl)	46	12%

For more detailed information on the issues affecting UK landowners and farmers, including the latest on agricultural commodity and input markets, please visit our blog www.knightfrankblog.com/ruralbulletin

*Sources: www.fwi.co.uk www.dairyco.net

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Knight Frank

Figure 8- 11: Knight Frank Scottish Land 2017 II

8.6 Appendix F: Modelling Steps

8.6.1 Stock and Flow

All stock equations have the same equation format:

$$Stock_t = Stock\ (t-\Delta t) + \Delta t \times \sum_{i=1,j=1}^{I,J}(\text{Inflows}_i - \text{Outflows}_j)$$

8.6.2 Example of some equations

8.6.2.1 Total Electricity Generation from Wind Turbine

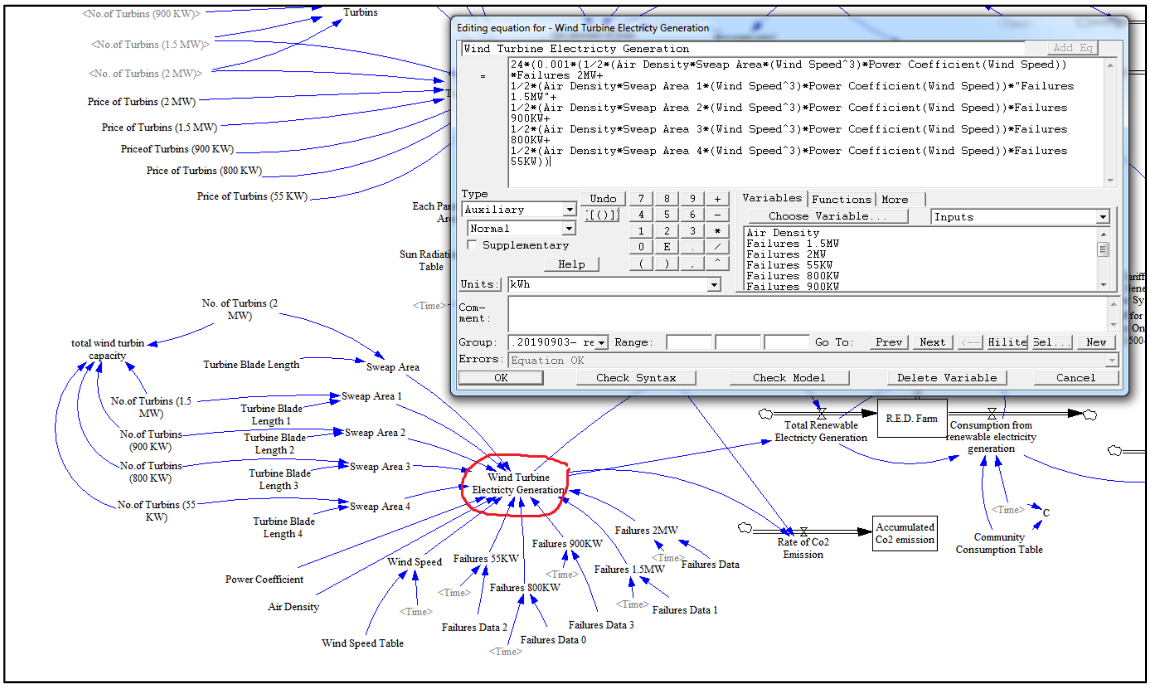

Figure 8- 12:Total Electricity Generation from Wind Turbine

8.6.2.2 Total Cost of Wind Turbine

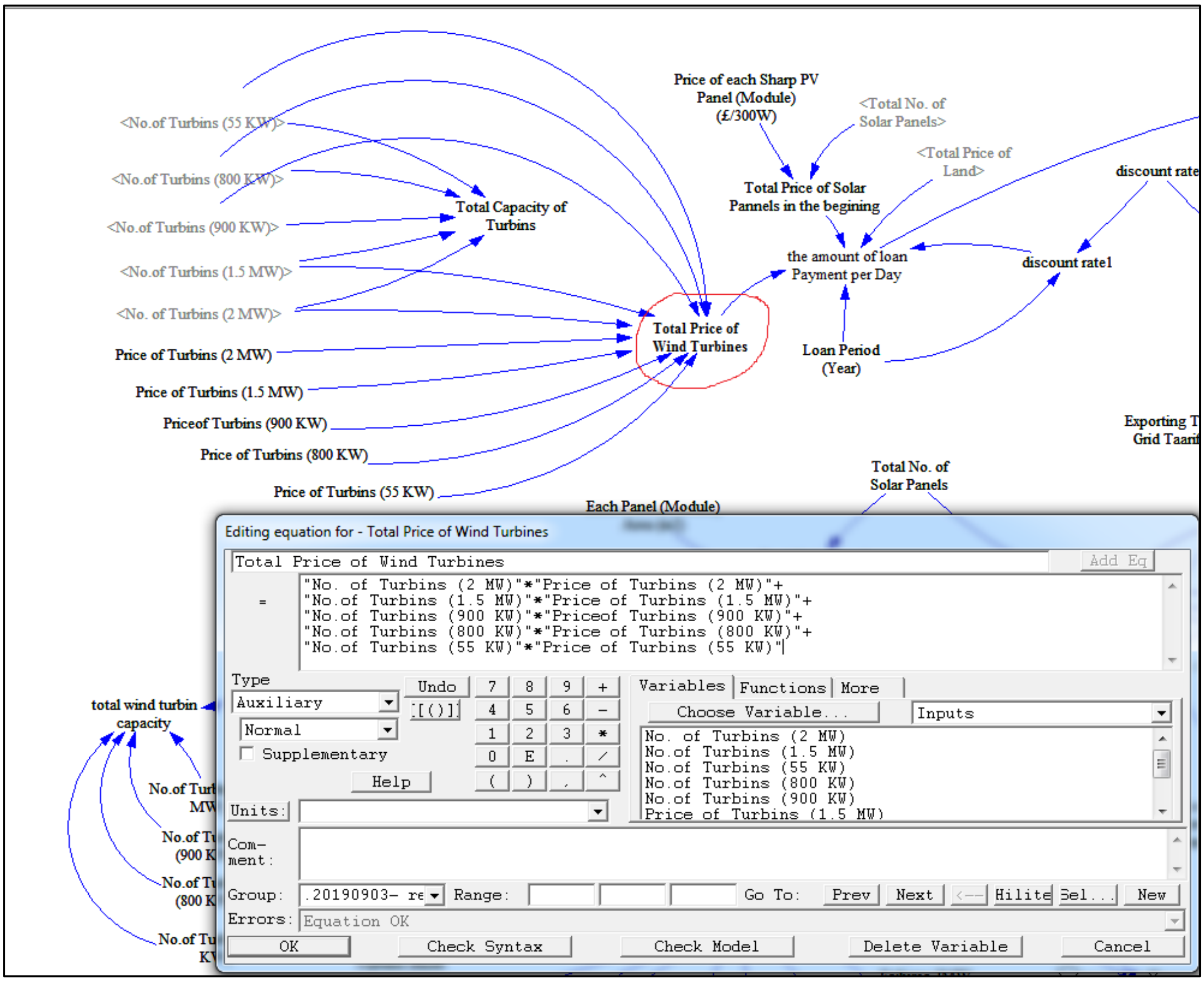

Figure 8- 13: Total Cost of Wind Turbine

8.6.2.3 Daily Loan Payment

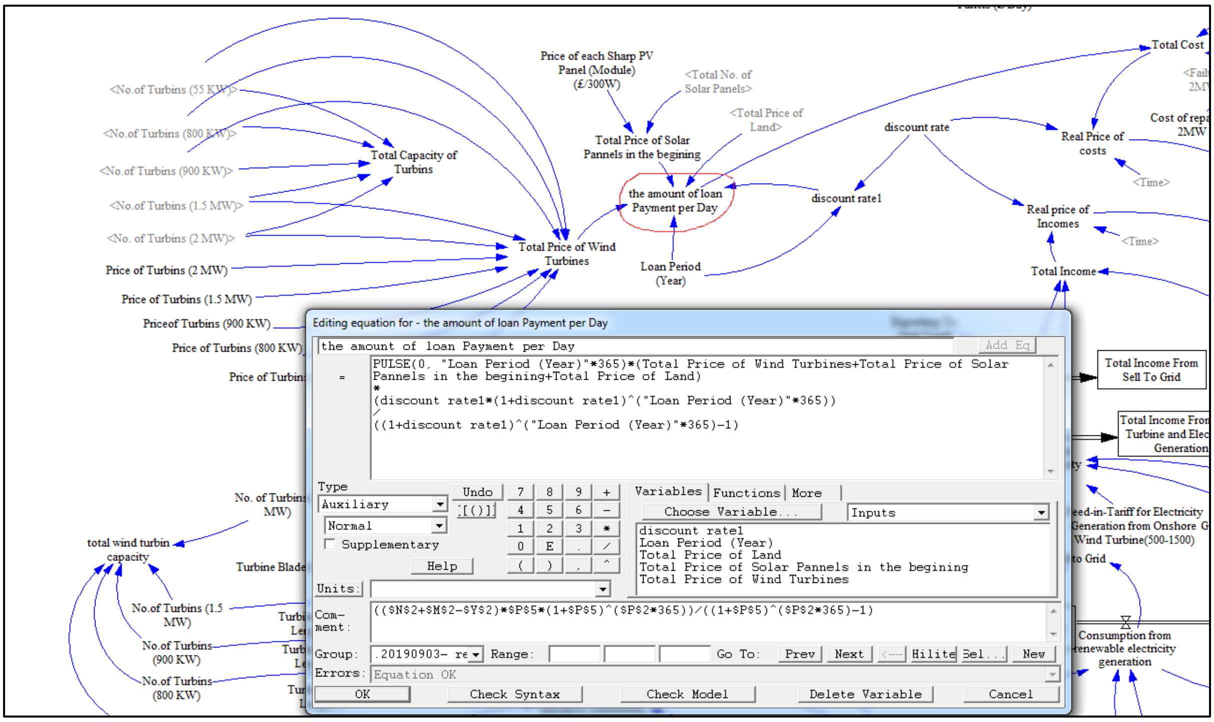

Figure 8- 14:Daily Loan Payment

8.6.3 Optimisation

In this subsection an example of selecting optimisation model in Vensim is presented. In order to perform the simulation-optimization, the desired variable is first used for optimization. In this research, rate of return on investment (ROR) is selected as a target variable to be optimised, presented in Figure 8-*.

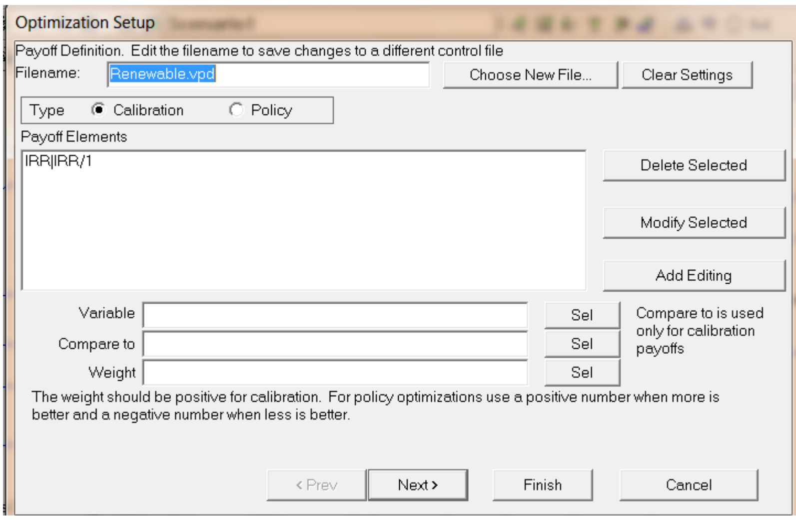

Figure 8- 15: Optimisation Setup

After that, decision parameters or variables are selected. The number of wind turbines and solar panels are selected as the target variables. Decision variables oscillation intervals are also specified and this step is shown in Figure 8-*

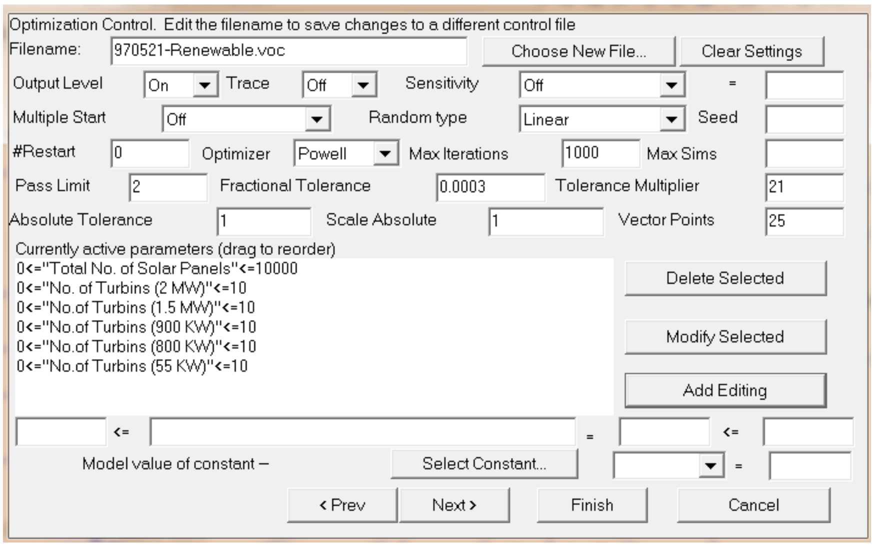

Figure 8- 16: Optimisation Control

After that, when the next measurement results obtained, the previous estimate is updated with the weighted average. That way, the weight of information that is more certain will be greater. The algorithm is recursive and executes immediately using new inputs and previous calculated states that is presented in Figure 8-*.

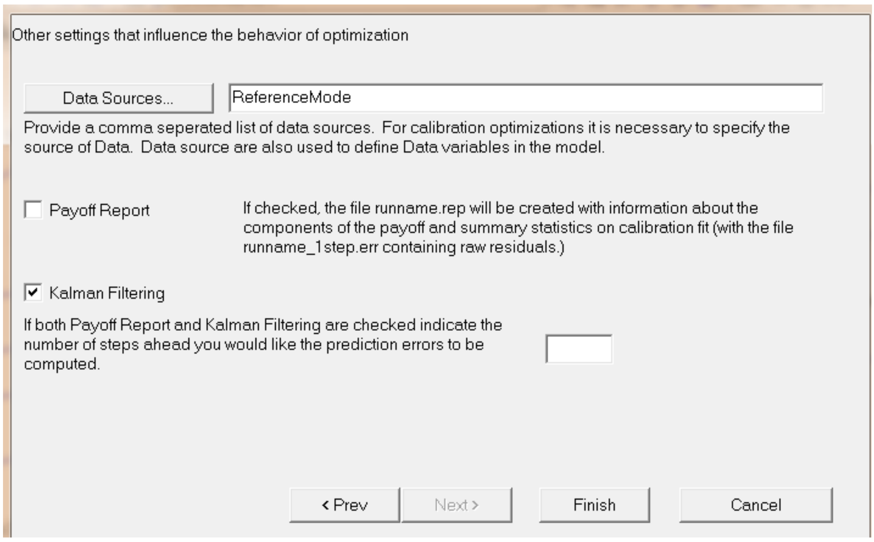

Figure 8- 17: Other Setting that Influence the Behaviour of Optimisation

8.6.4 Results of optimising the model considering wind turbine and solar panel

```
Initial point of search
"No. of Turbines (2 MW)" = 4
"No. of Turbines (1.5 MW)" = 4
"No. of Turbines (900 KW)" = 4
"No. of Turbines (800 KW)" = 4
"No. of Turbines (55 KW)" = 4
"Total No. of Solar Panels" = 500
Simulations = 1
Pass = 0
Payoff = -3.26292
-----------------------------------------------
Maximum payoff found at:
"No. of Turbines (2 MW)" = 0
"No. of Turbines (1.5 MW)" = 0.913968
"No. of Turbines (900 KW)" = 0
"No. of Turbines (800 KW)" = 0
"No. of Turbines (55 KW)" = 0
*"Total No. of Solar Panels" = 0
Simulations = 233
Pass = 3
Payoff = -1.00702e-007
```

8.6.5 Result of optimising the model only for Wind Turbine

```
Initial point of search
  "No. of Turbines (2 MW)" = 4
  "No. of Turbines (1.5 MW)" = 4
  "No. of Turbines (900 KW)" = 4
  "No. of Turbines (800 KW)" = 4
  "No. of Turbines (55 KW)" = 4
Simulations = 1
Pass = 0
Payoff = -2.02424
-----------------------------------------------------
Maximum payoff found at:
  "No. of Turbines (2 MW)" = 0.0131556
  "No. of Turbines (1.5 MW)" = 0.980401
  "No. of Turbines (900 KW)" = 0
  "No. of Turbines (800 KW)" = 0
 *"No. of Turbines (55 KW)" = 0
Simulations = 173
Pass = 3
Payoff = -0.619386
----------------------------------------------------
```

8.6.6 Optimised Discount Rate

Initial point of search.
 Discount rate = 0.05.
Simulations = 1.
Pass = 0.
Payoff = -0.855756.
.--------------------------------
Maximum payoff found at.:
* discount rate = 0.823936.
Simulations = 17.
Pass = 3.
Payoff = -9.74652e-009.

8.6.7 Investment in 2020

Initial point of search.
"No. of Turbins (2 MW)" = 4.
"No.of Turbins (1.5 MW)" = 4.
"No.of Turbins (900 KW)" = 4.
"No.of Turbins (800 KW)" = 4.
"No.of Turbins (55 KW)" = 4.
"Total No. of Solar Panels" = 500
Simulations = 1.
Pass = 0.
Payoff = -18.5512.

Maximum payoff found at:
"No. of Turbins (2 MW)" = 0.
"No.of Turbins (1.5 MW)" = 0.998283.
"No.of Turbins (900 KW)" = 0.
"No.of Turbins (800 KW)" = 0.
"No.of Turbins (55 KW)" = 0.
*"Total No. of Solar Panels" = 0
Simulations = 284.
Pass = 3.
Payoff = -1.791.

8.6.8 PV Solar Panel

Below is the simulation for making the 1st solar PV panel to be selected by the model.

Initial point of search.
ALFA = 1.
Simulations = 1.
Pass = 0.
Payoff = -0.812019.
.--------------------------------
Maximum payoff found at:
ALFA = 10.1134.
Simulations = 11.
Pass = 3.
Payoff = -2.25152e-013.

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