An assessment of the technical and economic feasibility of a renewable microgrid on a New Zealand dairy farm

---

A dissertation
submitted in partial fulfilment
of the requirements for the Degree of
Master of Planning

at
Lincoln University
by
Portia King

Lincoln University
2020

Abstract of a Dissertation submitted in partial fulfilment of the requirements for the Degree of Master of Planning.

An Asessment of the Technical and Economic Feasibility of a Renewable Microgrid on a New Zealand Dairy Farm

by

Portia King

One-hundred per cent renewable electricity generation is an ambitious target that will require significant investment and innovation to increase the nation's renewable capacity. This study investigates the potential for renewable microgrid electricity systems to increase the proportion of renewable electricity, and whether microgrids are relatively less expensive than a typical grid connection for New Zealand dairy farms facing rising grid electricity prices. The Lincoln University Research Dairy Farm was used as a case study to model an optimal microgrid. Several microgrid scenarios were modelled, and the system configurations and economic analyses were examined. The results indicated that microgrids are not yet cheaper than a typical grid connection. Additionally, a sensitivity analysis established that increases in sell back rates and wind turbine heights may have a more significant impact on improving the economic viability of a microgrid in comparison to rising electricity prices. Despite microgrids lacking the economic feasibility required to encourage widespread investment, renewable microgrids increase the proportion of renewable electricity generation, which has environmental benefits. Furthermore, microgrids also ease pressure on the national grid and may reduce or delay the need for costly grid upgrades and maintenance in the future.

Keywords: Renewable Energy, Microgrid, Distributed Generation, Agriculture, Energy Planning, Dairy Farm, Techno-Economic Assessment

Acknowledgements

Firstly, I would like to thank my supervisors, Shannon Page and Wim de Koning, who have been immensely supportive and have generously given up hours of their time to help me conduct this research. Thank you for sharing your knowledge and valuable feedback to keep my research on track.

Secondly, I am grateful for my classmates who have made the last two years an enjoyable journey full of insightful discussions. I would also like to thank our MPlan tutor, Ashley Rudkevitch, for her endless guidance through the dissertation process.

Finally, I would like to thank my family for all their support, especially mother. Thank you for spoiling me whilst also ingraining in me the values of hard work and striving for excellence in all my endeavours.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

CCC	Christchurch City Council
COE	Levelised cost of energy
EA	Electricity Authority
EECA	Energy Efficiency & Conservation Authority
ICCC	Interim Climate Change Committee
kW	kilowatt
kWh	kilowatt-hour
LEDF	Lincoln Energy Demonstration Farm
LURDF	Lincoln University Research Demonstration Farm
MBIE	Ministry of Business, Innovation and Employment
MfE	Ministry for the Environment
NIWA	National Institute of Water and Atmospheric Research
NPC	Net present cost
NPS-REG	National Policy Statement on Renewable Energy Generation
O&M Costs	Operational and maintenance costs
RMA	Resource Management Act
SDC	Selwyn District Council
TPM	Transmission Pricing Methodology

Chapter 1
Introduction

In New Zealand, a high proportion of electricity is already generated from renewable sources, fluctuating between 80-85% over the last five years (Ministry of Business, Innovation & Employment [MBIE], 2020a). Nevertheless, the government's goal of reaching 90% renewable electricity generation by 2025, and 100% by 2035 requires a significant investment in order to transition away from fossil fuels (New Zealand Government, 2011, 2019). Diesel has traditionally been the cheapest form of energy, but prices have risen as oil fields continue to deplete (Frisk, 2017). Simultaneously, advances in renewable energy technology are driving down the price of such investments and increasing the energy return on investment (Bardi et al., 2013; Datta et al., 2018). There has been an increasing number of studies regarding all aspects of renewable energy as the effects of climate change become more apparent. Microgrids have been particularly advantageous in developing countries to fast-track rural electrification. At the same time, there is potential for microgrids to assist in reducing electricity prices and increasing the proportion of renewable electricity generation in New Zealand.

1.1 Microgrids

Microgrids are a local-scale electricity system that is designed to meet a particular electrical load to supplement the national grid connection or to operate autonomously as an alternative to a grid connection. In this research, the term 'electrical load' refers to the electricity consumed from the national grid by an energy user such as a household or farm. Microgrids can consist of one generation source or a hybrid of sources which may be renewable (e.g. wind, solar, biomass) or non-renewable (e.g. diesel). Previous studies of renewable microgrids demonstrate that they can be cost-competitive in comparison to electricity from the national grid while ensuring security of supply (Campiotti et al., 2010; Powell et al., 2019; Uski et al., 2018). Microgrids can relieve pressure on the national grid, thereby reducing the severity of peaks in demand, and reducing or delaying the requirement for line upgrades and maintenance. Overall, microgrids potentially offer a way to increase the capacity of renewable electricity generation towards New Zealand's 100% renewable target.

Private investments in microgrids are becoming more common with homeowners installing solar panels for residential use. However, the supply of intermittent renewable sources such as solar is not well-matched to residential demands in New Zealand which peak in the early morning and evening. As a result, energy storage is required to ensure a consistent and reliable supply for residential applications. In contrast, the supply of renewables may be better-suited to agricultural or commercial loads which operate during the day. However, there have been no agricultural microgrid studies in New Zealand to validate these assumptions. Farms have the land area to accommodate larger microgrid systems with a hybrid of generation sources, and the rural landscape is conducive to wind speeds and the turbine's output. Furthermore, the seasonal demand for irrigation matches the seasonal supply of solar generation.

1.2 Traditional Electricity Market

In New Zealand, the electricity market consists of electricity generators, the transmission company, distribution companies and retailers. In the traditional market, electricity is generated at one point and transported to the end-user via the high voltage transmission and distribution lines. The introduction of microgrids has disrupted this linear one-way system (Electricity Authority [EA], 2018). Microgrid owners can be both the consumer and producer of electricity, and these electricity purchases and sales at the distribution level have created bi-directional electricity flows. Thus, the introduction of microgrids has decentralised the electricity market, and distribution networks have been forced to evolve from a passive to an active system to manage these electricity flows. As microgrids only interact with the electricity network at the distribution level, they bypass the costs imposed by the generation and transmission companies which form part of the retail price of electricity. Instead, the cost of electricity from a microgrid depends on a combination of the investment costs, generation output and the revenue earned from selling excess electricity back to the national grid.

Transpower is the system operator responsible for managing the transmission line infrastructure and ensuring security of supply (Electricity Industry Act 2010). The Transmission Pricing Methodology (TPM) is the pricing mechanism set by the EA to recover Transpower's operational, maintenance and investment costs. The TPM, along with other charges imposed by the generation, distribution and retailer companies, is reflected in the retail electricity price paid by consumers. The TPM is updated as required by the EA to recover these costs more accurately.

As a result of the evolving and decentralising electricity market, the EA updated the TPM in June 2020 (EA, 2020). The update introduces a beneficiary-pays approach in which consumers that utilise longer distances of transmission lines are charged higher prices to reflect the real cost of Transpowers services to each user (EA, 2020). This update is a transition away from the previous 'postage stamp' method in which all users pay the same rate regardless of distance travelled. The EA justifies variable pricing to reflect the true cost of transmission (EA, 2020). The update also removes charges imposed on South Island generators for transporting electricity to the North Island.

Farms and communities in rural and remote areas where electricity must travel further along transmission lines will be disproportionately affected by the updated TPM. Consequently, these individuals may be motivated to invest in alternative electricity solutions such as microgrids.

1.3 This research

This research aims to investigate the applicability of microgrids in an agricultural context. This will involve exploring the technical and economic feasibility of a microgrid as an alternative solution to rising grid electricity prices as a result of the updated TPM. This research is particulraly significant as agricultural microgrids are a relatively unexplored field in a New Zealand context. The Lincoln University Research Dairy Farm (LURDF) is used as a case study to design and optimise a suitable microgrid. Additionally, the results of this research will provide insight for the design of a microgrid for the Lincoln Energy Demonstration Farm.

Lincoln Energy Demonstration Farm

The Lincoln Energy Demonstration Farm is a new venture that will incorporate renewable energy and low emission concepts into farming practices for livestock and crops. The Energy Farm will be established adjacent to the LURDF on a 6-hectare site. A range of industry stakeholders are collaborating to set up a successful zero emission farm to provide proof of concept to farmers interested in similar investments.

1.4 Research Questions & Methods

The purpose of this research is to explore the feasibility of a renewable microgrid in an agricultural context in New Zealand. The following research questions will be addressed:

1. Are microgrids a technically and economically feasible electricity solution for farms in New Zealand?

2. What are the key characteristics of a typical dairy farm microgrid configuration?

3. Which variables increase the economic feasibility of the microgrid?

4. Are there scenarios in which an off-grid system is a feasible solution for farms?

The following research objectives will be used to answer the research questions:

1. Using the LURDF as a case study, determine the current electricity costs of the farm.

2. Using the HOMER Pro software, determine the configuration and system costs of grid-connected and off-grid scenarios. Investigate different combinations of components for the grid-connected scenarios (i.e. solar-wind-supercapacitor, wind-supercapacitor, solar-supercapacitor and solar-wind).

3. Conduct a sensitivity analysis to identify how specific variables may influence the economic feasibility of a microgrid.

4. Evaluate scenarios in which the cost of an off-grid system may be relatively cheaper than a grid-connection given the increased transmission pricing.

1.5 Outline of Dissertation

This dissertation has been dividied into seven chapters. Following on from this introduction, Chapter 2 provides a background on the state of renewable energy technology, the electricity system and the regulatory environment in New Zealand. A review of the literature is presented in Chapter 3 which examines the broader literature on microgrids and specific case studies in an agricultural context. Chapter 4 describes the methodology of this research and the microgrid system design. The results of the microgrid modelling and sensitivity analysis are explained in Chapter 5. In Chapter 6, the research questions are answered and the findings of this research are related to the literature and planning. Chapter 7 concludes this research by summarising the key findings and opportunities for further research.

Chapter 2

Background

2.1 Electricity in New Zealand

New Zealand has a diverse energy mix; hydroelectricity and geothermal are the predominant sources representing 59% and 17% of the total electricity generation respectively, followed closely by thermal at 16%. Wind and solar represent 5.1% and 0.3% of generation, respectively (EA, 2018; MBIE, 2020a). Electricity generation is responsible for 4 million tonnes of carbon dioxide equivalents annually, which is 5% of the nation's total greenhouse gas emissions (Interim Climate Change Committee [ICCC], 2019).

Renewable Energy Technology

Hydroelectric generation can be easily ramped up or down as necessary to meet demand, but the hydro lakes have a low storage capacity and are vulnerable to low inflow levels during dry years which limits generation capacity. Geothermal energy provides a steady baseline of supply but is not strictly zero-emission as there are relatively low levels of greenhouse gas emissions. Technology has been developed to reinject greenhouse gases produced from geothermal generation back into the gas field rather than being emitted into the atmosphere (Kaya & Zarrouk, 2017). This technology is used by countries such as Iceland and the US but is yet to be introduced in New Zealand (Matter et al., 2009). Therefore, geothermal energy has the potential to become zero-emission in New Zealand subject to future technology investments. Hydropower and geothermal generation are more suited to larger utility-scale applications due to the infrastructure requirements and higher capital costs.

Wind and solar are intermittent renewable energy sources that are becoming more common in New Zealand. After the initial investment capital costs, there are low operational and maintenance costs associated with harnessing these free and abundant natural resources (Datta et al., 2018). Solar panel technology is already well developed and efficient; meanwhile, turbine technology continues to advance. The height and generation capacity of wind turbines has increased as advanced engineering and design enables taller turbines with a larger rotor diameter to increase the generation output (Harvey, 2010). Small-scale turbines have rated capacities of 2-5 kilowatts (kW) meanwhile utility-scale turbines have capacities in the range of 500 kilowatts to 5 megawatts (MW). Wind and solar generation technology is commercially available and can be easily scaled to fit specific electrical loads for a range of applications.

Energy storage increases the reliability of a system and compensates for intermittent renewable sources during periods of insufficient wind or solar resources. Energy storage technology comes in various forms such as batteries, flywheels and supercapacitors, and each technology has advantages and disadvantages. Lithium-ion batteries are a developed technology that is commonly used in microgrids as they are lightweight and relatively cheap. However, they have a shorter lifespan and discharge at a faster rate hence they are less suitable for large-scale and long term storage (Gao, 2015). Batteries must maintain a charge of between 20% and 80% to maximise the lifetime of the battery. In contrast, supercapacitors are a more recent technology development; they have a higher power density, longer lifetime, fast response time, high charge and discharge rate, maintain charge over extended periods and are more resilient to heat (Tan et al., 2013). The disadvantage of supercapacitors is their lower energy density which makes them heavier and less portable than lithium-ion batteries (Gao, 2015).

Technology Pricing Trends

Overall, solar panels and turbines are well-developed technologies (Hussain et al., 2017), whereas further developments are expected for energy storage and supercapacitor technology. As these technologies continue to advance, prices are expected to continue dropping and become a more economical investment than their fossil fuel counterparts (EA, 2018). In the United States, commercial-scale solar panel prices (10 kW-2 MW in capacity) dropped by two-thirds between 2011 and 2018 (Fu et al., 2018). The International Renewable Energy Arena (IRENA, 2019) published even lower panel prices of US$1,210 per kilowatt in 2018, which was a 75% drop from 2010 prices. The IRENA (2019) predicts prices will drop below US$834 per kilowatt by 2030 and below US$481 by 2050.

In New Zealand, the price of solar panels dropped by over 75% in the last decade (EA, 2018), and are approximately NZ$1,880 per kilowatt as of 2020 (Harrison Energy Solutions, personal communication, June 25, 2020). Although small-scale wind turbines are less common in New Zealand, a 2011 study (Reuther & Thull, 2011) estimated a price of NZ$25,000 for a 1.9 kW turbine. There have been evident price drops and the current price of the commercially available 2 kW ThinAir 102 turbine is NZ$17,100 (Powerhouse Wind, n.d.). This is significantly lower than current price estimates advertised by Energywise (n.d.) of NZ$20,000-30,000 for an equivalent 2 kW turbine.

2.2 New Zealand's Regulatory Environment

There are several groups involved in managing the energy and electricity sector in New Zealand. The Electricity Authority (EA) is the independent market regulator of the electricity sector (Electricity Industry Act 2010); Ministry of Business, Innovation and Employment (MBIE) who advise the government on energy-related policy and the Energy Efficiency and Conservation Authority (EECA) whose role is to promote energy efficiency, energy conservation and the uptake of renewable energy.

Renewable Energy Policy

At present, New Zealand does not have policies that provide financial incentives for investment in renewable energy or microgrids. In contrast, a range of policies exist across Europe, the US and China (Ali et al., 2017). Subsidies, feed-in tariffs and tradeable green certificates are policies that have proven effective at increasing renewable generation capacity (Nicolini & Tavoni, 2017). However, these policies are criticised for increasing socio-economic inequalities amongst end users of energy as only those who can afford the capital investment cost of microgrids will benefit from the cheaper microgrid electricity in small-scale private applications (Farrell & Lyons, 2016) .For this reason, microgrid incentives aimed at agricultural or commercial microgrid applications may be a more equitable solution compared to a private residential application because the microgrid can be oversized with a greater amount of excess electricity sold to the grid for public consumption at competitive prices.

Zero Carbon Future

While it has been argued that reaching 100% renewable electricity in New Zealand would be too costly (ICCC, 2019), particularly the last few percent, there are already countries proving that it is achievable and sustainable. Iceland, Paraguay and Albania all produce 100% renewable electricity; meanwhile, numerous countries maintain levels above 95% (IEA, 2020; IRENA, 2015; Orkustofnun, 2015).

Feasible and realistic scenarios of 100% renewable generation in New Zealand have already been modelled (Mason et al., 2013). The main barrier to further investment in hydropower is the shortfall of supply during years of low inflow (Kelly, 2011; EA, 2018), which results in thermal energy sources being used to compensate. One possible solution to increase the proportion of renewable generation is investment in wind energy. Approximately 2,500 MW of wind capacity has been consented across the country but is yet to be built (New Zealand Wind Energy Association, n.d.).

Statutory Framework

Legislative targets to decarbonise the energy sector are a priority outlined in the National Policy Statement on Renewable Electricity Generation (NPS-REG, 2011). In 2011, the preliminary target was to generate 90% of electricity from renewable sources by 2025, but this has been hastened by the Climate Change Response (Zero Carbon) Amendment Act 2019 (ZCA) which has set new emission reduction requirements with the ultimate goal of the nation becoming net carbon zero by 2050 (excluding methane). In light of the ZCA (2019) and the ICCC's *Accelerated Electrification* report, the New Zealand Government (2019) has indicated a more ambitious goal of reaching 100% renewable electricity generation by 2035. International commitments such as the Paris Agreement and Kyoto Protocol also oblige New Zealand to meet emission reduction targets (MfE, 2018).

The Resource Management Act 1991 (RMA) gives national direction for the management of natural resources. The RMA is generally supportive of renewable generation activities as it must give effect to the policies and objectives of the NPS-REG (2011). The RMA (1991) also states that all those exercising functions and duties under the RMA must have 'particular regard to the efficiency of the end use of energy' (s7(ba)) and consider 'the benefits to be derived from the use and development of renewable energy' (s7(j)).

Although the NPS-REG (2011) requires regional and district plans to provide provisions for the development of wind and solar generation as well as other less common renewable generation sources, there remain district plans which are yet to provide for these technologies explicitly. For example, the Christchurch District Plan (Christchurch City Council [CCC], 2018) contains explicit rules for solar and wind generation in contrast to the Selwyn District Plan (Selwyn District Council [SDC], 2018) which mentions only the broader activity of electricity generation. Resource consents are required for any electricity utility infrastructure that does not meet the provisions of a permitted activity under the relevant district plan.

In addition to resource consent requirements, the EA (2014) sets out the guidelines and application process for those wishing to install and connect a microgrid (referred to as distributed generation) to the distribution lines. This is required to ensure the national grid remains secure and safe. A streamlined application process is followed for residential microgrids of less than 10 kW capacity. Meanwhile, microgrids greater than 10 kW follow a more complex application process because residential lines are not typically designed for such capacity.

Chapter 3
Literature Review

The literature review begins by discussing the various forms of microgrids and the characteristics of microgrid case studies in developing and developed countries. Next, energy use in the agricultural sector before focusing on agricultural applications of microgrids. The literature review identifies gaps within the microgrid literature and relates this to the purposes of this research and the research questions.

3.1 Defining Microgrids

Within the literature, there are a range of definitions for microgrids because the term encapsulates a broad range of energy sources and storage options. Microgrids can service thermal and/or electrical loads, and are established at a variety of scales, from servicing an individual home to an entire community. Bevrani et al. (2017) defined microgrids as a configuration of several distributed generation sources servicing multiple consumers that are particularly useful in remote areas where national grid access is uneconomical.

Schwaegerl and Tao (2014) simplified the components that comprise a microgrid as *supply*, *storage* and *demand*. A microgrid is therefore the combination of 'microgenerators' with storage capabilities that serves a specific local load. A similar concept is the term 'distributed generation' which represents any form of small-scale generation that bypasses transmission lines and connects to the distribution lines, or bypasses all transmission and distribution lines and connects directly to a microgrid. Therefore, a microgrid is a form of distributed generation. The distinguishing feature is that microgrids have the additional aspect of local control and coordination for a specific load (Schwaegerl & Tao, 2014).

Grid-Connected or Off-Grid

Microgrids can operate either grid-connected or in an autonomous off-grid mode. Grid-connected microgrids provide two important advantages over off-grid systems. Electricity can be purchased from the national grid when renewable generation or storage capacity is insufficient, and, excess electricity can be sold to the national grid creating an additional revenue stream. Electricity retailers pay the microgrid owner the wholesale price, which is lower than the retail price at which they on-sell the electricity. Depending on the size of the system, the revenue can be a payment or credit to offset any grid purchases.

Grid-connected systems can disconnect and run autonomously when required, such as during power outages or when grid issues arise. Power outages are uncommon in New Zealand, so this aspect is more beneficial in countries with less reliable national grids. However, an increase in natural disasters such as the 2019 wildfires in California and Australia has resulted in more frequent and longer-lasting power outages in developed countries. The severity of these events is predicted to worsen as a result of climate change (Neale & May, 2020).

Many case studies in developing countries focus on off-grid systems. In New Zealand and other developed countries where most farms are already grid-connected, there is no benefit of disconnecting. However, as new farms are established in New Zealand, the installation of new electricity lines to reach these locations will cost up to $25,000 per kilometre in addition to connection fees, making off-grid systems a more cost-competitive solution (EECA, 2019).

A disadvantage of off-grid systems is that there are times of the day when renewable supply exceeds demand, and this excess electricity cannot be sold to the grid, resulting in a loss of potential revenue. Insufficient supply can also be an issue, leading to a capacity shortage and power outages. An off-grid system must be oversized to deal with the occasional peak loads and overcome any capacity shortages, which is both inefficient and expensive. This highlights the importance of weighing up the unique circumstances of each electrical load and considering the cost of connecting to the grid versus the cost of an off-grid system.

3.2 Microgrid Case Studies

There is a large body of literature addressing case studies of microgrids. The case study approach is a common research method that enables an in-depth analysis that acknowledges the sensitivity of the input and output variables, and the significance of geography and climate within each unique study.

Farming techniques vary between regions, and even within regions, due to traditional farming practises and the available technology. Each farm is unique in its scale and various irrigation, milking and/or harvesting schedules. Microgrids must be tailored to each farm’s electrical load profile and is heavily dependent on the geographic location and climate which influences the design of a microgrid to best harness the available renewable resources. The availability of components and technology also varies between regions and impacts the resulting microgrid configurations. Datta et al. (2018) compared single-component and hybrid microgrids and concluded that a hybrid system results in a lower system cost as multiple generation components increase reliability and reduce the capacity required to service an electrical load.

Some studies consider grid-connected systems to supplement the national grid supply (Chel & Kaushik, 2011; Houston et al., 2014); meanwhile, other studies consider off-grid systems (Campiotti et al., 2010; Nacer et al., 2016; Querikiol & Taboada, 2018; Shoeb & Shafiullah, 2018). The most frequent microgrid applications include rural electrification in developing regions to meet residential, community and agricultural demands. Case studies in developed countries are predominantly focused on residential loads and few focus on agricultural loads.

The characteristics of microgrid case studies in developing and developed countries will be discussed briefly meanwhile agricultural applications of microgrids will be discussed in more detail in Section 3.4.

Developing Countries

Several case studies recognise that national grid infrastructure in developing countries are less extensive and reliable in rural and remote areas, with future expansions and upgrades being less of a national priority (Bardi et al., 2013; Bańkowska & Gradziuk, 2017; Chel & Kaushik, 2011; Querikiol & Taboada, 2018; Shoeb & Shafiullah, 2018). Therefore, off-grid systems are promoted as a method of fast-tracking rural electrification in developing regions where there has previously been no electricity. Case studies based in developing countries are generally more supportive of microgrids because it is often the first time that an area receives electricity. Rural electrification to meet residential needs improves the general standards of living, however expanding the microgrid to power agricultural and commercial activities significantly increases productivity and economic growth (Shoeb & Shafiullah, 2018).

Shoeb and Shafiullah (2018) modelled an off-grid system to power irrigation pumps on a farm in Bangladesh and the optimal microgrid consisted of solar, diesel generators and batteries. Querikiol and Taboada (2018) also retained a diesel generator in the energy mix of their agricultural microgrid in the Philippines. These results suggest that for developing countries, electricity access is more important than sourcing from renewables. Diesel generators require constant fuel which is an ongoing operational cost that may be hard to source at times, in contrast to wind turbines and solar panels which have a higher capital cost but lower operational cost.

Developed Countries

Despite developed countries being underrepresented in the literature, the US Department of Agriculture reported that 57,000 US farms (2.7% of all US farms) generate some type of renewable energy (Hitaj & Suttles, 2016). Additionally, a range of policies exist across the US, European Union and China to encourage investment in renewable energy (Ali et al., 2017).

Studies based in developed countries are more focused on increasing the proportion of renewable energy and are concerned with juggling the economic viability, statutory environmental targets and ensuring a technically viable microgrid (Uski et al., 2018; Houston et al., 2014). In comparison to developing countries, a transition from national grid electricity to a microgrid will have little noticeable impact on reliability to consumers in developed countries with reliable infrastructure. For this reason, developed countries should not expect benefits to the same degree as found in developing countries.

Several studies have noted incentives implemented by governments for private investment in off-grid systems (Chel & Kaushik, 2011; Houston et al., 2014; Shoeb & Shafiullah, 2018). It is a sensible investment for transmission and distribution line companies to financially assist individuals and communities to invest in autonomous microgrids if those costs are less than the cost of equivalent network extensions. Case studies show that this theory applies to both developed and developing countries (Chel & Kaushik, 2011; Shoeb & Shafiullah, 2018; Uski et al., 2018). Uski et al. (2018) compared the investment costs of a microgrid versus installing underground distribution lines and found microgrids to be the cheaper option.

3.3 Energy Use in Agriculture

New Zealand is heavily dependent on the agriculture sector, which makes up approximately 70% of primary industry export earnings (Ministry for Primary Industries, 2017; Verma et al., 2018). Fossil fuels are used in vehicles and machinery, and electricity is used to power irrigation, dairy sheds, refrigeration, lighting and greenhouses. With growing awareness of the causes and effects of climate change, previous studies have considered the potential for farms to transition away from fossil fuels towards electrification and using renewable energy sources in order to reduce their greenhouse gas emissions. The impact of these emission-reduction efforts varies between countries with different dependencies on fossil fuels. At over 80% (MBIE, 2020a), New Zealand has a significant proportion of electricity generated from renewable sources in contrast to countries such as the USA and Australia where less than 20% of electricity was generated from renewable sources in 2019 (Australian Government, 2020; United States Energy Information Administration, 2020).

Several previous studies have considered the suitability of renewable energy to specific agricultural activities such as greenhouses, irrigation and water pumps (Bayrakcı & Koçar 2012; Campiotti et al., 2010; Chel & Kaushik, 2011; Shoeb & Shafiullah, 2018).

A study of agricultural greenhouses (Campiotti et al., 2010) found renewable electricity sourced from solar and biomass to be a cost-effective alternative compared to traditional grid prices, and the installation of a microgrid lowered carbon emissions associated with electricity consumption. Chel and Kaushik (2011) highlighted the compatibility between solar generation and specific activities such as drying grains, heating greenhouses and pumping water. Bayrakcı and Koçar (2012) expanded on the compatibility of a broader range of renewables including solar, biomass, geothermal and wind in common Turkish agricultural activities. In addition to confirming the findings of Campiotti et al. (2010), Bayrakcı and Koçar (2012) found that electricity from wind energy could also assist in warming greenhouses and powering irrigation. The discussion of geothermal energy focused on its thermal abilities to warm soil and greenhouses rather than electricity generation. Overall, these studies were consistent in finding that renewable energy generation is well matched to specific agricultural activities.

3.4 Agricultural Applicatons of Microgrids

As previously discussed, microgrids are predominantly an energy solution for farms in developing countries. However, there have been a few case studies in developed countries which demonstrate their feasibility for farmers facing increasing electricity prices, expensive upgrades, or where new grid connections are uneconomical. These case studies reiterate that farms operate at different scales, with varying technologies and different farming practices which influences the design of the optimal microgrid. This section discusses case studies of farms in Finland (Uski et al., 2018), Australia (Australian Government, 2018; Powell et al., 2019), the Netherlands (Friesland Campina, 2019) and Canada (Houston et al., 2014).

A Finnish study (Uski et al., 2018) considered the microgrid design for two case studies, a rural household and a dairy farm. As studies generally focus on one microgrid application, this approach was unique in examining microgrid designs of two different sizes and applications. Off-grid systems were determined to be uneconomical; instead, the study compared distribution line upgrade costs to improve security of supply against the cost of establishing a microgrid as a substitution for the upgrades. This study found that the upgrade costs to the distribution company were higher than the cost of a private microgrid investment. The study concluded that distribution companies would benefit from financially assisting the cost of the microgrid.

A study of renewable microgrids to power irrigation pumps in Queensland, Australia, found the microgrid system cost to be cheaper than the farm sourcing electricity from the grid (Powell et al., 2019). A sensitivity analysis was also conducted to identify variables that improved the economic viability of the project. Irrigation operation hours were adjusted to match renewable supply and this increased the microgrids economic feasibility. Distribution regulations prohibited microgrids greater than 30 kW capacity from exporting electricity to the grid, and a microgrid was found to be uneconomical if electricity could not be sold back to the grid for revenue. Therefore, the optimal microgrid configurations had capacities of less than 30 kW. In New Zealand, regulations do not stipulate a restriction on the export capacity of a microgrid, although the application process to connect to the distribution network is streamlined for microgrids of less than 10 kW capacity. Additionally, this study calculated the emissions saving of 1303 tonnes of carbon dioxide equivalents over the lifetime of the renewable microgrid project which is an insightful measurement of the environmental benefits.

An innovative microgrid is in progress in Australia, a country with a high reliance on fossil fuels. In 2018, a project in the Latrobe Valley, Australia, received funding to establish a local energy market with a virtual network. The microgrid will connect approximately 200 farms selling excess electricity from their solar microgrids to 100 local homes (Australian Government, 2018). This method of distributed generation removes the high voltage transmission charges and lowers electricity prices. This Australian study goes beyond the feasibility of one generation point in an agricultural context, and considers a medium-scale network with multiple farms generating electricity on-site and selling to many local consumers. A similar concept to the Latrobe Valley microgrid exists in the Netherlands where a co-operative of dairy farms has begun investing in wind turbines as part of their 2050 carbon neutral goals (Friesland Campina, 2019). The first turbine was placed in 2019 as they aim to increase their self-sufficiency and reduce emissions. Additional energy efficiency goals have been indicated as part of the long-term project (Friesland Campina, 2019).

In a review of renewable technologies, Hussain et al. (2017) considered the supply of renewable energy to fit small-scale rural farm loads. Although the literature generally supports the agricultural application of microgrids, a study by Bardi et al. (2013) provided an interesting argument against farmers' investing in microgrids. It is argued that farmers do not benefit from owning their own microgrid or by being off-grid because they are not trained in the operation or maintenance of the system. Instead, the study recommends national-level investment in generation and maintaining the traditional electricity system. This overlooks the lack of resources in developing countries, and also overlooks the simplicity of microgrid technology and ability for farmers to conduct basic maintenance such as clearing solar panels of dust to maintain optimal generation output. Other studies do not explicitly expect the owners to conduct maintenance themselves. It also highlights the need for long term planning to manage any required maintenance and replacement throughout the lifetime of the project. This study by Bardi et al. (2013) was not specific to a region, hence it does not consider the proximity of farms to the national grid and the grid connection costs. Ultimately, these are the variables that dictate whether a grid connection is economically viable, in addition to the unique electrical load and location-specific climate data. It also ignores the situation in many developing countries where national grids do not have a wide coverage and lack reliability. Indeed, it may be suitable for farmers in populated areas with grid access to remain connected, but this conclusion cannot be broadly applied to all farms.

Demand-side management is a field of energy research that may improve the economic viability of a microgrid by reducing the microgrid capacity requirements and system costs. Demand-side management involves incorporating energy efficiency and load shifting measures to reduce or adapt electricity consumption. Energy efficiency measures include updating outdated equipment that is less energy-efficient, and performing regular maintenance on equipment. Load shifting requires consumers to adapt their daily consumption behaviour to coincide better with supply from renewables which smooths out peak demands. A recent study based on New Zealand dairy farms (Dew et al., 2021) found that irrigation can be timed to coincide with off-peak consumption to smooth the farm's demand curve without negatively impacting the operation of the farm or soil moisture.

A Canadian case study of a dairy farm on Prince Edward Island focused on a renewable microgrid and improving energy efficiency on the farm (Houston et al., 2014). The motivation to install a microgrid was in response to increasing electricity prices to the remote island, which is a similar issue that will soon face rural New Zealanders when the updated TPM comes into force. The study concluded that energy efficiency opportunities were limited. Lighting could be made 75% more efficient, however improvements in refrigeration efficiency through regular maintenance were marginal at best. Installing a renewable microgrid was the best option to reduce electricity costs.

3.5 Summary of Literature

This literature review has covered the broader field of microgrid case studies before narrowing in on case studies specific to the agricultural context. More recent studies have incorporated microgrids into agricultural research, but the historical focus of microgrids has been on rural electrification for residential or community use in developing countries. This literature review identified a gap in the literature on the suitability of microgrids in an agricultural context in developed countries. The literature review found agricultural-based microgrid studies in Canada, Scotland, Finland and Australia. These studies concluded that renewable microgrids were technically suitable, and in some cases economically feasible, for meeting the farms' load profiles. As renewable technologies continue to develop and become more cost-competitive, microgrids will continue to become a more appealing electricity solution. In comparing grid-connected and off-grid microgrids, studies have generally found off-grid systems to be uneconomical in developed countries where there is a reliable and expansive national grid (Uski et al., 2018). However, it is suggested that off-grid systems may be justified if the system costs are relatively lower than the price of a new grid connection in a rural location.

There has been little research specific to microgrids in New Zealand, and no studies that focus on agricultural applications. Country-specific research provides greater certainty about the economic and environmental benefits of renewable microgrids and will build confidence amongst local farmers considering an investment in renewable energy solutions in response to increasingly higher electricity prices. The high number of input variables which are unique to each electrical load and location mean that results from one region cannot be applied to another region with accuracy. Therefore, this research aims to fill the gap in agricultural microgrid literature based in the New Zealand context by asking the following research questions which were posed in Chapter 1:

1. Are microgrids a technically and economically feasible electricity solution for farms in New Zealand?
2. What are the key characteristics of a typical dairy farm microgrid configuration?
3. Which variables increase the economic feasibility of the microgrid?
4. Are there scenarios in which an off-grid system is a feasible solution for farms?

The following chapter outlines the methodology taken to conduct the microgrid case study in order to answer these research questions.

Chapter 4
Methodology

4.1 Introduction

This chapter discusses the research methods adopted for this research, followed by a discussion of the software tool and the microgrid system design components. This research uses a case study approach to simulate a microgrid in a real-life context.

The scope of this research is limited to electricity demand. One purpose of the microgrid installation is to increase the proportion of renewable electricity generation, therefore only renewable sources were considered as components for this microgrid. The components considered are solar panels, wind turbines and supercapacitors as these technologies are developed and commercially available in New Zealand.

4.1.1 Case Study

The literature review in Chapter 3 identified numerous case studies of microgrids. Case studies are an important method of applied research as it enables an in-depth examination of one case. The case study method is often criticised for having limited external validity because the results' specific nature cannot be generalised (Glifford, 2016). However, researchers argue that this is the motivating objective of the research to identify in detail the unique features of a particular case (Bryman, 2016).

Microgrid case studies are quantitative and utilise an extensive range of data inputs in order to model a realistic microgrid to suit a particular purpose such as a farm's electrical load. The climate data and electrical load data are obtained as primary data and the technical specifications of components are obtained as secondary data from the manufacturer.

Lincoln University Research Dairy Farm

Lincoln University operates several farms in the Lincoln area which are shown in **Figure 4-1**. The Lincoln University Research Dairy Farm (LURDF) was chosen as the case study for this research due to the accessible data and its location next to the proposed Lincoln Energy Demonstration Farm (LEDF). The results from the LURDF case study will contribute to the design of the microgrid on the LEDF as their close proximity means that location-specific weather data will apply to both farms.

The LURDF, shown in **Figure 4-1**, is a 72-hectare irrigated farm located on Weedons Road, Lincoln, New Zealand (43.6 S, 172.4 E) and has a herd size of approximately 200 cows (Lincoln University, n.d.). The LURDF electricity consumption data for the 2019 calendar year was obtained from the farm's retail company, Meridian Energy, and compared against the 2018 data to ensure that it was representative of a typical year.

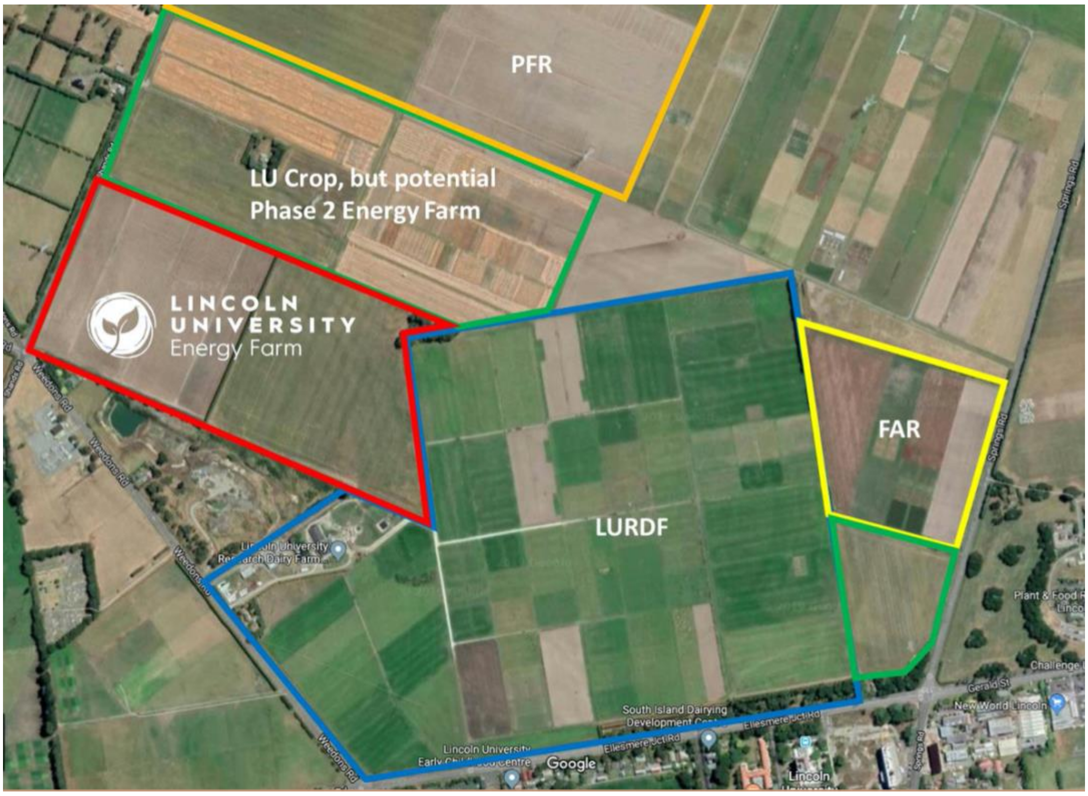

Figure 4-1. Map of the LURDF and surrounding Lincoln University farms.

Note. LU Crop, PFR and FAR are Lincoln University farms that are not part of this research.

Image source: Google (n.d.).

The Lincoln University Dairy Farm was also considered to be a case study. However, it recently had a biomass boiler installed which has reduced electricity consumption from the national grid and therefore gives an unrealistic representation of the farm's electricity consumption.

The LURDF data was compared with the Ashley Dene Farm, operated by Lincoln University, and one farm not affiliated with Lincoln University, to ensure it was representative of a typical dairy farm in the Selwyn District (Meridian Energy, personal communication, July 13, 2020; Platinum Energy, personal communication, August 27, 2020). All three farms were found to have similar electricity consumption patterns, although a sample size of three farms is too small to be representative of New Zealand farms in general. Further research would be required to assess regional variations in consumption as well as the consumption patterns of other types of farming such as cropping, arable and sheep and beef farming before these findings could be applied more broadly.

4.1.2 Design Tools

Microgrid modelling is a critical component of microgrid design to ensure the final microgrid design will meet the needs of the farm efficiently, cost effectively and reliably. There are several software products available to support microgrid design. The premise of the software tool is that it analyses input data resulting in output metrics that guide the microgrid design. The critical success factor however, is getting accurate and relevant input data.

The software simulates thousands of results before conducting economic analyses of the solutions to identify the optimal configuration. **Figure 4-2** outlines the data input requirements to model a microgrid and the resulting outputs provided by the software. These inputs and outputs are discussed in detail in Section 4.2.

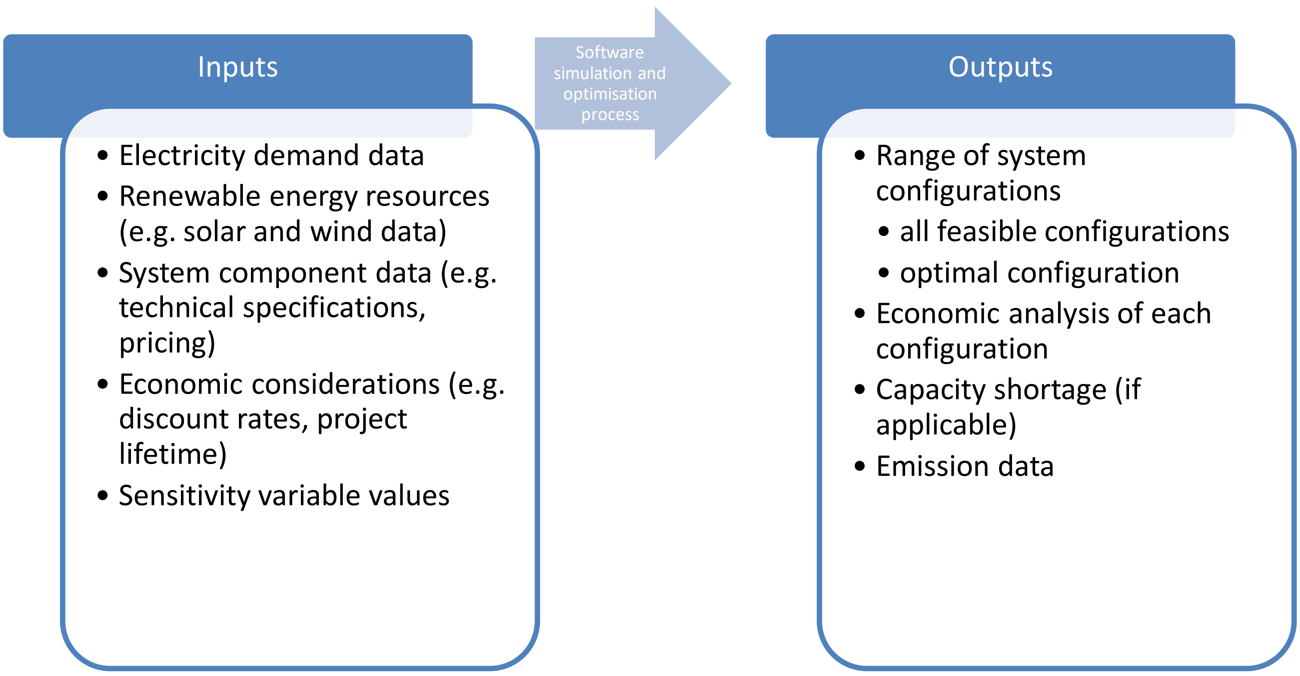

Figure 4-2. Microgrid software simulation and optimisation process.

HOMER Pro Modelling Software

HOMER Pro 3.14.2 (Hybrid Optimisation of Multiple Energy Resources) is the software modelling tool chosen for this research. HOMER Pro was developed in 1993 by the National Renewable Energy Laboratory (US Department of Energy) for internal use before it was commercialised in 2009. In a comparative study of 19 microgrid optimisation products with similar features, HOMER Pro was most widely used (Sinha & Chandel, 2014). HOMER Pro is regularly updated, and additional features are added to reflect advances in the field of energy systems and improve on the limitations identified by Sinha and Chandel (2014) based on the previous 2010 version of HOMER Pro.

HOMER Pro is a well-established product that is frequently used by professionals and academics (Frisk, 2017; Nacer et al., 2016; Querikiol & Taboada, 2018). HOMER Pro lists the results of different combinations of possible components by lowest cost. A full economic analysis is provided for each configuration which includes a breakdown of the total system cost over the lifetime of the project (net present cost), the initial investment cost, annual operational costs, and the cost per unit of useful electricity produced (COE). The components that HOMER Pro supports are solar, wind, hydroelectric, biofuel, generators and energy storage. Additionally, HOMER Pro enables sensitivity analyses to be conducted, allowing a range of values to be entered for each input variable, and the simulation process considers how different values influence the overall configuration and economics of the microgrid.

4.2 LURDF Microgrid System Design

This section will discuss the full range of input data required by HOMER Pro to design the microgrid (see Appendix A for list of values). The following scenarios will be modelled using HOMER Pro:

- Grid-Only Scenario
- Grid-Connected Microgrid Scenarios
- Off-Grid Scenario

The Grid-Only Scenario will demonstrate the farm’s existing electricity costs. Multiple Grid-Connected Microgrid Scenarios will be modelled with different combinations of components. One Off-Grid Scenario will model the configuration and cost of an off-grid system.

4.2.1 Load Profile

There are three electricity meters on the LURDF which service the irrigation, milk shed and woolshed. The data from the three meters were merged to represent the farm's load profile for 2019. **Figure 4-3** depicts the load profile as a heat map (referred to as a data map within HOMER Pro) in which each pixel represents one hour of the day across each day of the year. Heat maps enable daily and seasonal patterns to be visualised.

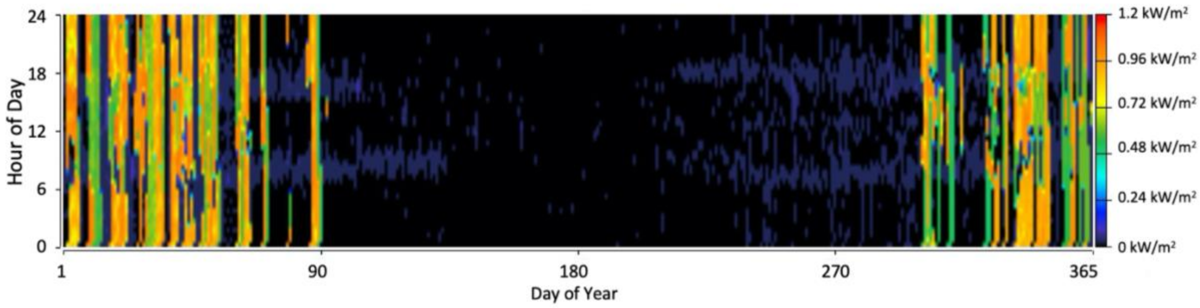

Figure 4-3. Yearly electrical load profile for the LURDF.

Data source: Meridian Energy (personal communication, April 23, 2020).

The LURDF's average daily consumption is 63 kilowatt-hours (kWh) with a peak demand of 15 kW. There is high temporal variability in consumption from hour to hour (97%) and day to day (82%). Daily milking times are visible between April and October, identified in **Figure 4-3** as the blue areas at approximately 07:00H and 18:00H. Milking stops for three months between May and July. Milking continues over the summer months, but the daily pattern is masked by higher irrigation and refrigeration requirements throughout the entire day which are the green and orange areas in **Figure 4-3**. There are clear seasonal trends attributed to the increased use of irrigation and refrigeration during warm and dry summer months and low consumption in winter when less irrigation and refrigeration are required. These daily and seasonal patterns are consistent with those of a typical dairy farm (Back, 2017).

4.2.2 Renewable Energy Resources

Solar radiation and wind speed data are required for the HOMER Pro software to evaluate the renewable generation potential at a specific location. This data was obtained as raw data from CliFlo, New Zealand's National Climate Database operated by the National Institute of Water and Atmospheric Research (NIWA). This data was taken from the Lincoln climate station (station number: 17603, coordinates -43.62622, 172.4704) which is approximately 1.75 kilometres from the LURDF and therefore fairly represents the climate of the farm. The data was imported into HOMER Pro as an hourly time series file containing 8,760 cells for 2019. This data is provided as monthly averages in Appendix B.

Solar Resource

HOMER Pro requires the hourly solar radiation data in order to calculate the output of the solar panels. CliFlo measures solar radiation in the unit megajoules per square meter (MJ/m^2) which must be converted to kilowatt-hours per square meter (kWh/m^2)to match the input unit used in HOMER Pro. This is calculated by the equation: $kWh/m^2 = MJ/m^2 \times 0.277$.

Figure 4-4 shows the average monthly solar radiation from the Lincoln climate station and the clearness index is calculated by HOMER Pro. The annual average solar radiation is 3.77 $kWh/m^2/day$; however, there is a high monthly variation in solar radiation.

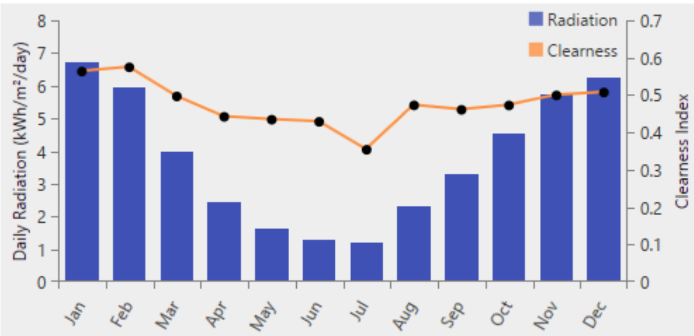

Figure 4-4. Solar radiation and clearness index for Lincoln.

Data source: CliFlo (NIWA, 2019).

The heat map in **Figure 4-5** illustrates the seasonal variation in sunlight hours and generation output.

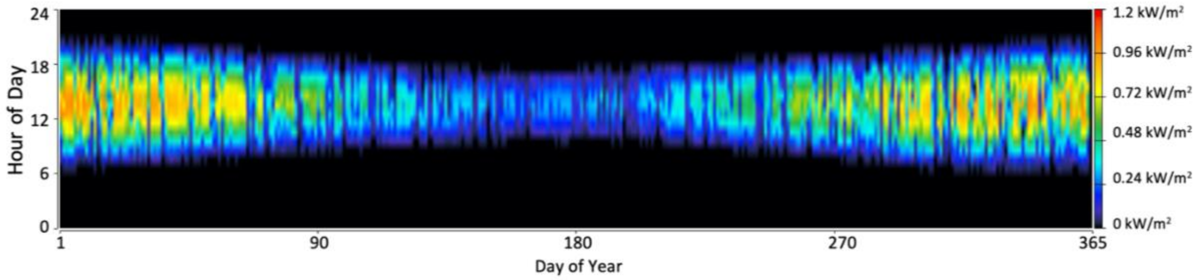

Figure 4-5. Heat map of solar radiation over one year in Lincoln.

Data source: CliFlo (NIWA, 2019).

Wind Resource

The hourly surface wind speed data is required in order to calculate the output of the wind turbines. The annual average speed is 3.89 metres per second (m/s) and **Figure 4-6** shows that wind speeds are more consistent throughout the year compared to solar radiation. Wind speeds peak during the summer months between December and February; however, the average monthly fluctuations are marginal at less than 1 m/s.

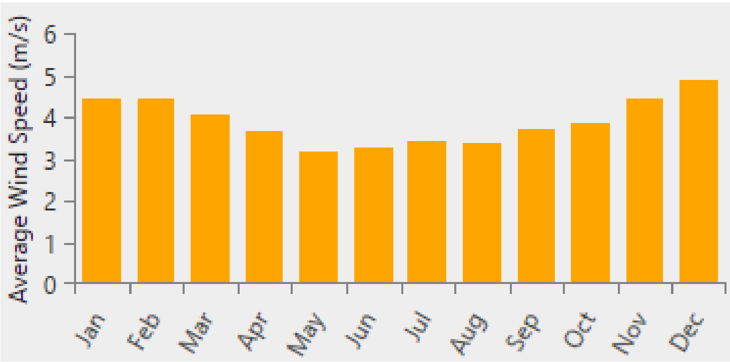

Figure 4-6. Average monthly wind speeds in Lincoln.

Data source: CliFlo (NIWA, 2019).

Since wind speeds increase with height, the height of the anemometer (wind speed measurement device) at the climate station is an important parameter. The altitude of the Lincoln climate station is 18 metres above sea level and the anemometer height is 10 metres. Wind speeds are influenced by friction against the surface of the earth; obstacles and rough terrain slow down wind speeds. The farm has a surface roughness length of 0.01 metres corresponding to the 'rough pasture' surface of the farm.

Temperature

Warmer temperatures reduce the output potential of solar panels, hence temperature data is a necessary input variable in HOMER Pro. **Figure 4-7** shows the average daily temperature by month which is consistent with New Zealand's seasonal climate.

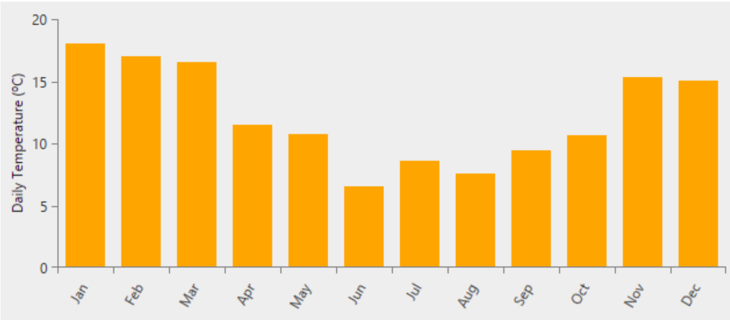

Figure 4-7. Average daily temperature by month in Lincoln.

Data source: CliFlo (NIWA, 2019).

4.2.3 System Components

A schematic of the microgrid configuration is shown in **Figure 4-8**, which comprises of the farm's electrical load, wind turbines, solar panels, supercapacitors, inverters and a grid connection. In addition, one off-grid scenario is conducted which excludes the grid connection. This section discusses each component in more detail and the full list of microgrid input values is in Appendix A.

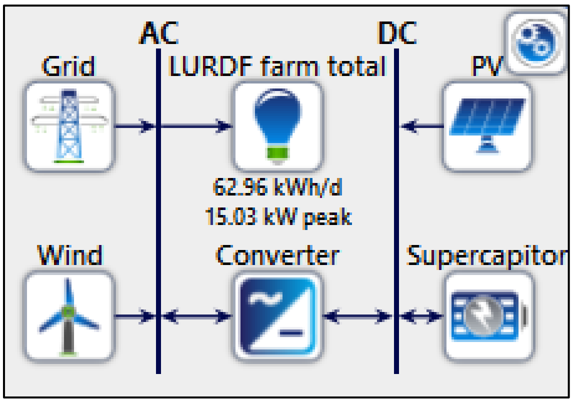

Figure 4-8. Schematic of microgrid components.

Solar Panels

The solar panel specifications are based on the LG Neon 2 panel with a 355 watt capacity which has a longer lifetime of 25 years in comparison to standard models with a lifetime of 15 years, and higher efficiency of 90.08% in comparison to standard models of 80%. This model is available in New Zealand and prices were obtained from Harrison Energy Solutions (personal communication, June 25, 2020). The slope of the panel is equal to the degrees of latitude which is 43° for maximum generation.

Wind Turbines

The majority of commercially available wind turbines are large utility-scale of greater than 1 MW which is larger and more expensive than what is required for the LURDF. The turbine specifications used in this research are based on the small-scale 2 kW ThinAir 102 turbine produced by Powerhouse Wind in New Zealand. The rural zone rules of the Selwyn District Plan apply to the location of the LURDF. The turbine height is set to the highest permitted height of 25 metres.

Grid

The EA is responsible for ensuring that electricity prices remain reasonable (EA, 2018) and this is monitored by MBIE. MBIE publishes data on the national average prices for each sector, and regional averages for retail prices. **Figure 4-9** shows that national agricultural prices have remained stable over the past 15 years, in contrast to relatively higher residential prices which gradually increased until 2015, before prices stagnated and have since declined marginally (MBIE, 2020b).

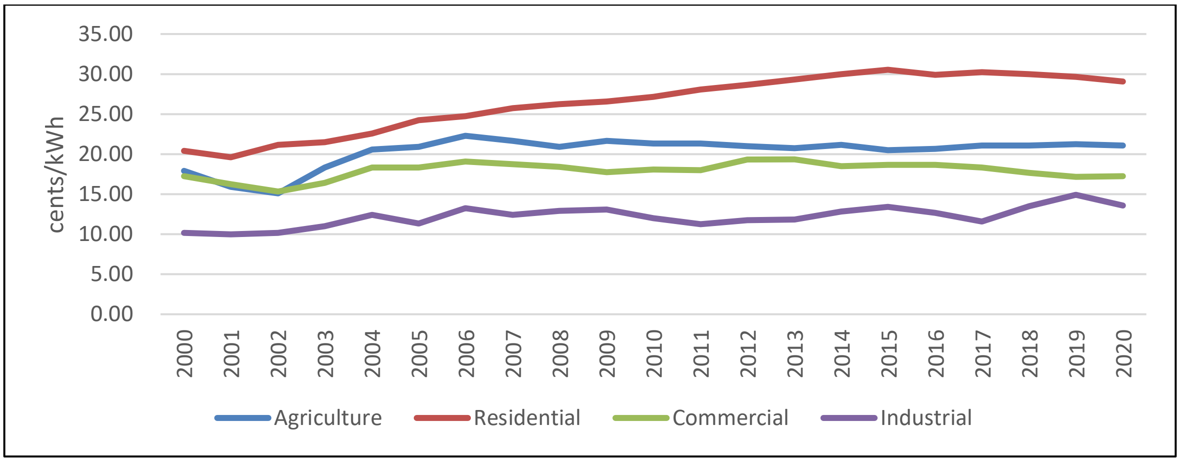

Figure 4-9. Real annual average electricity prices by sector.

Data source: MBIE (2020b).

The price of \$0.21 per kilowatt-hour (kWh) is used as an input variable of the price paid by the LURDF which is representative of the national average agricultural price (MBIE, 2020b). This price does not take into consideration any lower price agreements or contracts between Lincoln University and their retail company as the purpose of this research is to apply the findings to dairy farms that are not affiliated with Lincoln University.

Electricity prices vary between regions but this is not monitored by MBIE for the agricultural sector. However, MBIE releases data on the regional variations in retail electricity prices (MBIE, 2020b). Retail electricity prices range from \$0.28 to \$0.42/kWh across New Zealand, and the Canterbury region is on the lower end of the range at an average \$0.29/kWh. If agricultural pricing follows the same trends as retail pricing, it can be assumed that agricultural electricity prices in Canterbury would be no higher than the national average agricultural price of \$0.21/kWh.

Electricity sell back prices are set by each retailer and range from \$0.07 to \$0.12/kWh (My Solar Quotes, 2020). As the retailer for the LURDF, Meridian Energy's sell back rate of \$0.08/kWh is entered as an input variable in HOMER Pro. This rate applies to domestic microgrids up to 10kW in size, and there is no indication of the sell back prices for larger or non-domestic systems.

In addition to pricing, HOMER Pro takes into consideration the emissions factor of electricity purchased from the grid which is measured in grams of carbon dioxide equivalent per kilowatt hour (g CO_2–e/kWh). An emissions factor quantifies the amount of greenhouse gas emissions associated with each unit of electricity generated. The grid emissions factor in New Zealand is 97.7g CO_2–e/kWh, which is relatively low in comparison to other countries due to the high renewable share of electricity generation (MfE, 2019).

Energy Storage

Energy storage components are often present in microgrids with renewable generation sources due to their intermittency and the ability to use stored energy when supply is insufficient. The benefits of supercapacitors as an energy storage technology within microgrids were outlined in Chapter 2. The supercapacitor input values in this research are based on the Sirius 3.55 kW supercapacitor which is commercially available in New Zealand.

Inverter

An inverter (referred to as a converter within HOMER Pro) is required to convert the direct current power generated by the solar panels into alternating current for use on the farm. This study uses the 8 kW Victron Quattro inverter, which is commercially available in New Zealand and compatible with the other system components.

Table 4-1. Summary of technical and economic component input values.

Component	Capacity per unit (kW)	Capital Cost per kW	Replacement Cost per kW	O&M costs	Lifetime (years)
Solar panel	0.355 kW	$1,971	$1,971	0	25
Wind turbine	2 kW	$8,550	$6,840	0	20
Supercapacitor	3.55 kW	$1,267	$1,267	0	45

Table 4-1 summarises the technical specifications and pricing of the system components (see full list in Appendix A).The replacement cost of solar panels and supercapacitors are identical to their initial capital cost because the whole component is replaced at the end of its lifetime (Frisk, 2017). In contrast, at the end of the wind turbines lifetime, only some parts may need to be replaced which results in a lower replacement cost. Some studies reduce the replacement cost as it is likely that the current technology will become relatively cheaper by the time it needs replacing, although a counter argument is that technology will be outdated and replaced by newer technology of a similar price.

In this research, the initial capital cost was reduced by 20% to represent the turbine replacement cost. This is a common approach within the literature although the degree of price reductions varies. For example, Sinha and Chandel (2014) considered replacement costs for turbines to be 42% lower than the initial investment costs, meanwhile Nacer et al. (2016) discounted the price by 10% and Frisk (2017) discounted the price by 15%.

The operation and maintenance (O&M) costs of each component are not factored into these scenarios because system faults cannot be predicted and the cost of repair varies upon the fault, so these costs have been omitted rather than including unpredictable figures. Some previous studies have also excluded O&M costs (Sinha & Chandel, 2014), meanwhile others have frequently reported O&M costs of less than $20 per year which is a small value that will not significantly affect the results (Frisk, 2017; Harvey, 2010; Nacer et al., 2016; Shoeb & Shafiullah, 2018).

4.2.4 System Search Space

The search space defines the parameters of the capacity or quantity of each component which can be either manually chosen or optimised by the software. The range of values for the search space of each component is listed in **Table 4-2**. The converter and grid purchase capacity have been set manually meanwhile the optimisation feature was selected to size the solar array, number of turbines and number of supercapacitors.

Table 4-2. Search space.

Converter Capacity (kW) ☐ Optimizer	Grid Purchase Capacity (kW)	PV Size (kW) ☑ Optimizer	Sirius Strings ☑ Optimizer	Wind Quantity (#) ☑ Optimizer
8	0	0	0	0
16	10	63	30	32
	15			

The converter capacity is manually set to multiples of eight as each unit has a capacity of 8-kW. The grid purchase capacity sets a limit on how much electricity can be sourced from the grid at any time. Taking into consideration the LURDF’s peak demand of 15 kW, the grid capacity is manually set to 10 kW for the grid-connected microgrid scenarios. This enables some electricity to be sourced from the grid when necessary, while still encouraging a moderately sized microgrid to make the project worthwhile. In contrast, the Grid-Only

Scenario has a capacity limit of 15 kW as all electricity is sourced from the grid; meanwhile, for the Off-Grid Scenario, the limit is set to zero as no electricity is sourced from the grid.

HOMER Pro optimised the capacity of solar panels which increase in increments of 355 watts; meanwhile, the supercapacitor and wind turbine were optimised by quantity rather than capacity. In this process, HOMER Pro identified the upper limit for solar capacity at 63-kW, and a maximum of 30 supercapacitors and 32 turbines.

4.2.5 Economic Inputs

All microgrid simulations in this research are based on a project lifetime of 25 years which is the standard period for microgrids of all applications (Querikiol & Taboada, 2018; Sen & Bhattacharyya, 2014; Shoeb & Shafiullah, 2018). All costs are in New Zealand Dollars. Discount rates are used to evaluate the present value of future cash flows in an economic analysis. HOMER Pro uses the real discount rate in simulations to remove the effects of inflation from the analysis. The real discount rate is calculated as the nominal discount rate minus the expected inflation rate. A real discount rate of 4% was used for this case study, based on the nominal discount rate of 6% recommended by New Zealand Treasury (2020) minus inflation of 2%. Real discount rates ranging from 2 to 8% have been commonly used in previous studies (Chmiel & Bhattacharyya, 2015; McHenry, 2012; Uski et al., 2018; Pasonen & Hoang, 2014; Prodromidis & Coutelieris, 2011).

4.2.6 Economic Outputs

The system cost of a microgrid, referred to as net present cost (NPC) within HOMER Pro, is the primary economic output used to rank and compare results. This value represents the total lifetime cost of the microgrid system, calculated as the present value of all costs incurred minus the revenue earned over the lifetime of the project. Costs include capital costs, replacement costs, operational and maintenance (O&M) costs and grid purchases. Revenues include the salvage value and grid sales revenue (HOMER Energy, n.d.).

The other economic outputs calculated by HOMER Pro include the levelized cost of energy (COE), annual operating costs and the initial capital costs. The COE is a measure of the average cost per kWh of useful electricity produced by the system. The COE is a useful indicator which can be compared between results and grid prices to evaluate whether a microgrid system is economically feasible per unit of electricity. A low NPC doesn’t necessarily correspond to a low COE as a large capacity microgrid will have a high NPC due to higher initial investment costs, but it will have a low COE if a high quantity of electricity is sold to the grid to earn revenue.

The annual operating cost is the annualised value of the total system cost (NPC) which smooths out the capital and operational costs evenly over the lifetime of the project. This removes the effect of components with varying initial and operational costs. The operating cost can be negative which indicates an annual net revenue resulting from grid sales.

4.2.7 Sensitivity Analysis

There is a high variability and uncertainty within the input variables used to simulate microgrid scenarios in HOMER Pro. For example, values such as the electricity prices and sell back rates are set externally and subject to change at any time throughout the lifetime of the project. Discount rates and turbine heights are determined internally with regulatory guidance. Small changes in one or more of the inputs can have a significant effect on the overall configuration and economic analysis of the results. For this reason, a sensitivity analysis is conducted to assess how changes to these variables impact the resulting microgrid configurations, and assess the risk and dependency of the scenario results on particular input variables.

The sensitivity values for each variable are listed in **Table 4-3**. The choice of sensitivity values are justified in Chapter 5 in the discussion of the sensitivity analysis results.

Table 4-3. Sensitivity analysis input values.

Power Price ($/kWh)	Sellback Rate ($/kWh)	Nominal Discount Rate (%)	Wind Hub Height (m)
0.210	0.06	2	15
0.230	0.08	4	25
0.25	0.10	6	30

Chapter 5

Results

This chapter outlines the results of the microgrid configurations modelled using HOMER Pro and a sensitivity analysis is conducted to consider how the lowest cost scenario is impacted by several variables considered to have planning implications.

5.1 Scenarios

Five microgrid scenarios were explored for the LURDF using HOMER Pro. **Table 5-1** provides a summary of these microgrid configurations and their economic analyses. The results are ranked in order of lowest system cost (NPC). The Grid-Only Scenario shows the present situation on the LURDF in which all electricity is sourced from the grid and enables an economic comparison with the microgrid scenarios. Scenarios 1-4 represent the optimal grid-connected microgrid system for each possible combination of components. The Off-Grid Scenario demonstrates the lowest-cost configuration that enables the farm to operate entirely off-grid. Each of these scenarios is discussed in further detail below.

Table 5-1. Results of the microgrid configuration and economic analysis.

Scenarios	PV (kW)	WT (#)	Supercapacitor (#)	Grid (kW)	Inverter (kW)	System Cost (NPC)	COE	Operating Cost/Year	Initial Capital	Microgrid Autonomy	kWh Sold	kWh Purchased
Grid-Only	-	-	-	15	-	$ 75,396.00	$ 0.21	$ 4,826.00	-	-	-	22982
1	4.55	3	2	10	16	$103,415.00	$ 0.155	$ 1,545.00	$ 79,272	72%	20,338	12,063
2	-	8	3	10	8	$109,845.00	$ 0.116	$ -1,487.00	$ 155,300	91%	50,569	6,376
3	26.2	11	-	10	16	$163,647.00	$ 0.083	$ -5,417.00	$ 249,861	96%	104,760	4,774
4	24.2	-	26	10	8	$174,999.00	$ 0.324	$ 490.04	$ 169,638	65%	12,713	12,467
Off-Grid	61	-	53	0	16	$329,633.00	$ 0.954	$ 2,270.00	$ 368,843	100%	-	-

Grid-Only Scenario: Grid-connected

The Grid-Only Scenario or status quo represents the present electricity consumption of the LURDF which is sourced entirely from the grid. The system cost of $75,396 is relatively lower than that of the microgrid scenarios as there are no capital costs associated with purchases from the grid, however the farm has an annual electricity bill of $4,826. The electricity price of $0.21/kWh is relatively higher than the COE in Scenarios 1-3 in which the system components and proportion of grid purchases contribute to the overall COE.

Scenario 1: Grid-connected solar, wind and supercapacitor system

Scenario 1 is the lowest cost microgrid with a configuration that has been optimised to meet the electrical load of the LURDF. The system cost at $103,415 is $28,000 higher than that of the status quo. The COE of $0.155 is 25% lower than the grid price of $0.21. The system cost and initial capital cost of this grid-connected scenario is two thirds cheaper than that of the Off-Grid Scenario.

Scenario 1 has a generation capacity of 10.55kW which consists of solar and wind generation components and is supplemented by electricity purchases from the national grid. **Figure 5-1** distinguishes the contribution of each source to the monthly electricity consumption. Grid purchases are concentrated in the summer months when electricity demand peaks. The microgrid produces 30,972 kWh per year and 39% is sold back to the grid.

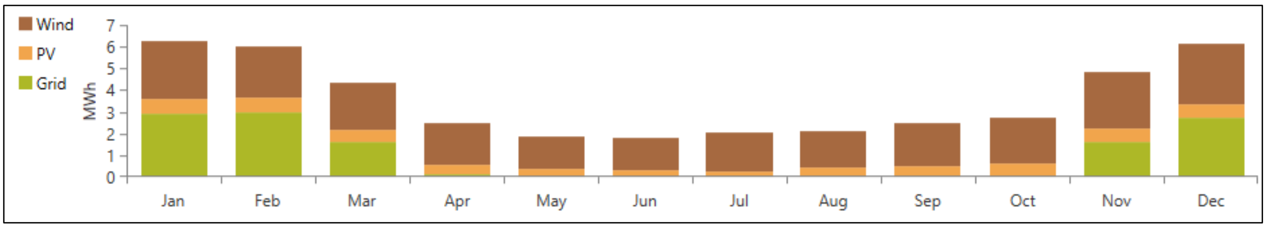

Figure 5-1. Monthly electricity production by source.

Scenario 2: Grid-connected wind and supercapacitor system

The next cheapest solution is Scenario 2, a 16 kW capacity microgrid consisting of wind turbines as the sole generation component and accompanied by three supercapacitors. Scenario 2 has a higher fraction of autonomy than Scenario 1 with 91% of the electricity consumed being sourced from the microgrid. In addition, a high proportion of the electricity generated is excess that is sold back to the grid which results in an annual net revenue of $1,487. The COE of $0.116 is lower than the COE in Scenario 1 and 45% lower than the grid price of $0.21.

Scenario 3: Grid-connected solar and wind system

The system configuration in Scenario 3 is vastly different to Scenarios 1 and 2. The microgrid has a capacity of 48.2 kW, comprising of a large solar array, eleven turbines and no supercapacitors. The high system cost is due to the initial capital costs associated with such a large capacity microgrid, but this is compensated by having the lowest COE and highest annual net revenue of all scenarios. The COE of $0.083 is only marginally higher than Meridian's sell back price of $0.08 which incentivises the system to be significantly oversized to take advantage of profits from grid sales. This results in an annual net revenue of $5,417.

It would be expected that the lack of energy storage would require more electricity to be purchased from the grid, but this microgrid has the highest level of autonomy of the grid-connected scenarios at 96%.

Scenario 4: Grid-connected solar and supercapacitor system

Scenario 4 is the most expensive grid-connected scenario consisting of a 24.2 kW solar array and 26 supercapacitors. This scenario is representative of a typical residential configuration consisting of solar panels and some form of energy storage, although that is usually batteries as opposed to supercapacitors. Scenario 4 has a high system cost due to the large number of supercapacitors.

Scenarios 2 and 4 both have a single generation source. A larger number of supercapacitors are required in Scenario 4 in comparison to in Scenario 2 which consists of turbines. This demonstrates that solar generation is less consistent and reliable, thereby requiring more storage capacity than if wind turbines were included in the configuration.

Although this configuration has been optimised to meet the LURDF's electricity requirements, the scenario is not economically feasible as the COE of $0.32 is relatively more expensive than the grid electricity price. Overall, the high costs and the low fraction of autonomy of 65% do not support the economic or environmental goals of a microgrid investment.

Off-Grid Scenario: Islanded system with solar and supercapacitors

An off-grid scenario was explored to enable a comparison of the economic analysis and configuration between the grid-connected and off-grid systems. The Off-Grid Scenario is the consists of a 61 kW solar array as the sole generation component and is accompanied by a large number of supercapacitors to maintain supply when there is insufficient solar resources.

The Off-Grid Scenario configuration is similar to that of Scenario 4, although the capacity is much larger in the Off-Grid Scenario. It is interesting that this configuration is the lowest cost feasible off-grid system, yet the same configuration of components in a grid-connected system was found to have the highest system cost.

Overall, the system is oversized to meet peak demand, but only 27% of the electricity produced is consumed by the farm, which results in an annual excess production of 58,834 kWh that is discarded. At the same time, there is an annual capacity shortage of 5% (1,171 kWh/year) in which electricity demand is not met. The system cost and initial capital cost of this scenario are triple that of Scenario 1, and the COE of $0.954 also discourages investment.

5.2 Sensitivity Analysis

Microgrids are configured based on an extensive range of input variables that have a high temporal and spatial variability. A sensitivity analysis was conducted on four variables deemed to have implications for planning and the uptake in microgrid investment; electricity purchase prices, sell back rates, discount rates and wind turbine heights. This section discusses how these variables influenced the optimal configuration and economic feasibility in the HOMER analysis.

There are a large range of possible values for each input which combine to create hundreds of thousands of results. In this sensitivity analysis, three values were chosen for each variable and each variable was tested in isolation in order to see its influence on the configuration and economic analysis. However, in reality, these variables could change simultaneously. Scenario 1 is used as a base case for the sensitivity analysis and is indicated in bold in **Table 5-2**.

Table 5-2. Sensitivity analysis results.

Sensitivity Variables		PV (kW)	WT (#)	Supercapacitor (#)	Grid (kW)	Converter (kW)	NPC	COE	Operating Cost/Year	Initial Capital	Ren Fraction	kWh Sold	kWh Purchased
Purchase Price (cents/kWh)	**21**	**4.55**	**3**	**2**	**10**	**16**	**$ 103,415.00**	**$ 0.155**	**$ 1,545.00**	**$ 79,272**	**72%**	**20,338**	**12,063**
	23	4.54	3	2	10	16	$ 107,186.00	$ 0.161	$ 1,788.00	$ 79,254	72%	20,330	12,066
	25	9.36	4	1	10	8	$ 103,297.00	$ 0.122	$ 443.86	$ 96,363	83%	31,795	9,139
Sell Back Rate (cents/kWh)	6	0.65	4	2	10	8	$ 109,532.00	$ 0.154	$ 1,654.00	$ 83,691	75%	23,121	11,365
	8	**4.55**	**3**	**2**	**10**	**16**	**$ 103,415.00**	**$ 0.155**	**$ 1,545.00**	**$ 79,272**	**72%**	**20,338**	**12,063**
	10	10	4	1	10	8	$ 87,558.00	$ 0.102	$ -649.83	$ 97,710	84%	32,498	9,034
Discount Rate	2%	10.4	4	1	10	8	$ 97,263.00	$ 0.090	$ -61.11	$ 98,456	84%	32,858	8,985
	4%	**4.55**	**3**	**2**	**10**	**16**	**$ 103,415.00**	**$ 0.155**	**$ 1,545.00**	**$ 79,272**	**72%**	**20,338**	**12,063**
	6%	6.89	4	1	10	16	$ 102,858.00	$ 0.156	$ 498.21	$ 96,489	81%	29,184	9,605
Wind Turbine Height (metres)	15	17.7	4	1	10	16	$ 110,363.00	$ 0.115	$ -473.53	$ 117,760	86%	39,015	8,606
	25	**4.55**	**3**	**2**	**10**	**16**	**$ 103,415.00**	**$ 0.155**	**$ 1,545.00**	**$ 79,272**	**72%**	**20,338**	**12,063**
	30	7.27	4	1	10	8	$ 96,328.00	$ 0.117	$ 262.47	$ 92,228	82%	30,268	9,434

Electricity Purchase Price

Electricity prices are expected to increase as the updated TPM disproportionately impacts rural and remote areas of New Zealand where electricity must travel further along the transmission lines (EA, 2020). The variables of $0.23 and $0.25 were chosen to consider how marginal increases in price would impact the overall configuration and economic analysis.

An increase to $0.23 did not change the optimal configuration, however a larger increase to $0.25 resulted in the lowest system cost and was significant enough to double the solar capacity and increase the number of turbines by one.

Both configurations at $0.21 and $0.25 have similar system costs. As expected, the larger configuration has a higher initial investment cost, however the annual operating cost is much lower as the microgrid generates more electricity and sells a greater proportion back to the grid which lowers the COE.

Sell Back Rate

Sell back rates are set by each retail company and range from $0.07 to $0.12 and are subject to change at any time (Canstar Blue, 2018; My Solar Quotes, 2020). Scenario 1 is based on Meridian Energy's sell back rate of $0.08. The values of $0.06 and $0.10 have been chosen for the sensitivity analysis to reflect the impact of a small increase or decrease in sell back rates which may result from small market fluctuations or a switch between retail companies.

Each of the three variables results in vastly different system configurations. The economic analysis are similar at $0.06 and $0.08, however there is a more noticeable difference at $0.10. A sell back rate of $0.10 resulted in the lowest-cost scenario of all sensitivity variable scenarios in **Table 5-2**. A higher sell back rate reduces the system cost and encourages a larger capacity system as revenue increases. This leads to a system cost of $87,558 which is 15% lower than Scenario 1 and 16% higher than the Grid-Only Scenario.

Discount Rate

In the economic analysis of the lifetime of this 25-year project, the discount rate is used to calculate the present value of future cash flows. Discount rates are recommended within government policy but can ultimately be decided internally and manipulated to achieve the desired outcome for a project. Discount rates generally fluctuate with inflation by 1-2%. The discount rate can be a deciding factor in whether or not a project is approved, so although it does not directly impact planning, it does influence the share of renewable electricity generation. In previous microgrid studies using HOMER Pro, discount rates range from 2% (Uski et al., 2018) to 16% (Querikiol & Taboada, 2018), although rates of between 2 and 8% are most common (Chmiel & Bhattacharyya, 2015; McHenry, 2012; Prodromidis & Coutelieris, 2011). It is also common in other studies for a sensitivity analysis to be conducted on discount rates, for example, Pasonen and Hoang (2014) considered rates of 2, 3, 4, 5 and 6%.

Scenario 1 is based on a real discount rate of 4% which is justified as the recommended rate by New Zealand Treasury (2020). This scenario has the highest system cost and operating costs but a low initial capital cost. The sensitivity variables of 2% and 6% demonstrate how discount rates influence the system configuration and economic analysis. There are no linear patterns in the economic results or configuration as the discount rates increase. The system is a similar size at both 2% and 6% although the system cost and COE are lowest at 2%.

Wind Turbine Height

The height of a turbine influences the generation potential which will dictate whether wind resources are an economical investment. As wind speeds increase and turbulence decreases with elevation, the goal is to maximise the generation capacity of the turbine whilst remaining within the height restrictions prescribed in District Plan rules.

The Selwyn District Plan rules set a height restriction of 25 metres in the rural zone where the LURDF is located and a restriction of 15 metres in the township zone (SDC, 2018). The values of 15 and 30 metres were used to consider the impact of a turbine within the township zone, and the impact if restrictions were eased to 30 metres.

The system costs of the scenarios decreased with increasing turbine heights. Both scenarios at 15 and 30 metres had a lower COE of $0.11 compared to $0.15 at 25 metres. Overall, the scenario at 30 metres had the lowest system cost although it remains relatively more expensive than the Off-Grid Scenario.

Chapter 6

Discussion

In this chapter, the four research questions that were posed in Chapter 1 are answered by considering the results of this research and what has been found in previous literature. Additionally, the implications of these findings are related to the policy and planning context. This chapter concludes by identifying opportunities for future research

6.1 Research Questions

1. Are microgrids a technically and economically feasible electricity solution for farms in New Zealand?

A microgrid would be considered economically feasible if it has a relatively lower system cost compared to the farms existing electricity bill. Although previous international case studies have found microgrids to be economically feasible for farms, the results in Chapter 5 suggest that a microgrid is not yet a cheaper solution for dairy farms in New Zealand. In the LURDF case study, the lowest-cost microgrid, Scenario 1, was $28,000 more expensive than the Grid-Only Scenario which represented the farms existing electricity costs. It is therefore cheaper for the farm to continue sourcing electricity from the national grid. This was demonstrated when no grid capacity limit was set within HOMER Pro, the optimal result was to continue sourcing electricity entirely from the grid. As discussed in Section 4.2.4, a grid capacity limit of 10 kW was set to optimise microgrid scenarios that encouraged the design of a reasonable capacity microgrid while also enabling some electricity to be sourced from the grid.

In this research, microgrids have proven to be well-suited to the agricultural application. The smooth ground surface of the rural farms is conducive to higher wind generation potential. The demand for irrigation coincides with renewable energy supply from the microgrid, as irrigation demand increases on warmer and drier days when solar resources are in abundance; meanwhile, less irrigation is required during wet and colder weather. These findings are consistent with the literature that considered the suitability of microgrids to specific farming activities (Bayrakcı & Koçar, 2012; Chel & Kaushik, 2011). However, these studies focussed on the particular energy sources and not the farm’s consumption behaviour.

An interesting finding was that the three-month winter period (May to July) when the LURDF ceases milking coincides with a period of high residential demand for heating (Andersen et al., 2017). This time of year has the greatest strain on the national grid to meet peak loads, meanwhile the farm's consumption is negligible, and the surplus electricity generated from the farm is needed most across the distribution network. Therefore, it may benefit the electricity retailers to offer seasonal sell back rates that are higher in winter.

There are additional benefits which somewhat compensate for the unfavourable economic results of the microgrid. Despite Scenario 1 having a higher investment cost, farmers benefit from lower electricity prices in this microgrid scenario. Security of supply is increased as the microgrid provides a backup supply in the event of a power outage. The high levels of microgrid autonomy relieves pressure on the national grid and reduces the need for generators to resort to fossil fuels to meet peak demands on the national grid. This also benefits the electricity market long-term as microgrids reduce or delay the need for grid maintenance or upgrades.

Further research is required to quantify the environmental benefits of emissions abatement within renewable microgrid scenarios. If the environmental benefits outweigh the economic investment costs, renewable policies and incentives should be explored to identify the most effective method of assisting microgrid investment. The purpose of these policies is to increase the proportion of renewable electricity, reduce carbon emissions and decrease electricity prices for farmers.

2. What are the key characteristics of a typical dairy farm microgrid configuration?

Scenario 1, the lowest cost microgrid scenario, is a hybrid configuration of solar and wind generation with supercapacitors for energy storage. This configuration supports the idea that hybrid microgrids are relatively less expensive and more reliable than single-source microgrids (Datta et al., 2018). Scenario 1 benefits from the diversity of having all components to increase reliability and energy storage can compensate in times of unfavourable weather.

Despite turbines being four times more expensive than solar per kW, Scenario 1 validates turbines as a worthwhile investment due to their high operational rate that outweighs the relatively higher investment cost. The benefit of turbines is further validated by the configuration of wind turbines in Scenario 2 being the next lowest cost microgrid. At the

LURDF site, wind generation operates 7,994 hours per year (91% of the year) which is twice as frequent as solar. This is an important finding which demonstrates that the cheapest generation source will not necessarily have the greatest output, a factor which is dependent on the location-specific climatic conditions. The solar microgrid in Scenario 4 is the most expensive grid-connected configuration, despite being a cheaper investment per kilowatt than wind turbines, which further demonstrates that wind resources have a higher generation output than solar resources in the Lincoln area.

3. Which variables increase the economic feasibility of the microgrid?

The sensitivity analysis in Chapter 5 considered the impact of changes in grid electricity prices, sell back rates, discount rates, and turbine heights on the system costs of Scenario 1. Increased sell back rates and turbine heights were found to be beneficial in the economic analysis of the sensitivity analysis results, although neither was sufficient in reaching a lower system cost than the Grid-Only Scenario. Increases in the grid electricity prices and discount rates showed similar system costs which indicated these systems were more resilient and robust.

A sell back rate of 10 cents/kWh resulted in the lowest system cost of the sensitivity scenarios. The system cost was $87,558 which is approximately $16,000 lower than Scenario 1 at 8 cents/kWh, and $12,000 higher than the system cost of the Grid-Only Scenario. A net revenue is earned at the rate of 10 cents/kWh, whereas the lower sell back rates maintain annual operating costs.

As discussed by Reuther and Thull (2011), it must be recognised that sell back rates are not regulated in New Zealand, hence relying on sell back rates to make a project economically viable is risky because the electricity retailers may change or revoke sell back rates at any time and compromise the viability of the microgrid. Several European countries have implemented feed-in tariffs which regulate sell back rates which provides confidence for the long-term economic viability of a project (Ali et al., 2017). The introduction of feed-in tariffs in New Zealand would provide more certainty to investors.

An increase in turbine height from 25 to 30 metres had the next greatest positive impact on the system cost. This reduced the system cost to $96,328 which is $21,000 more than the current system. Wind speeds increase with height relative to the roughness of the ground surface. A smoother surface such as farm pasture reduces turbulence, so wind speed increases at a higher rate with height. In contrast, rough surfaces such as urban environments cause more significant turbulence and result in a lower rate of wind speed increase with height (Harvey, 2010). This research reinforced that rural agricultural areas are an ideal location for harnessing wind energy, consistent with Reuther and Thull's (2011) previous findings. Therefore, relaxing the height restrictions for wind turbines in rural areas would further increase the generation potential and economic feasibility of microgrids.

An increase in grid electricity prices had little impact on the microgrid system costs. The negligible impact suggests that the microgrid system is resilient and robust to changes in grid pricing. As discussed in Chapter 2, the updated TPM will result in more significant regional electricity pricing variations and will disproportionately affect communities and farms in locations where electricity must travel further on the transmission lines (EA, 2020). The EA (2020) has indicated how electricity charges are expected to be redistributed among different regions. Although they do not provide an indication for the agricultural sector specifically, cost and benefit estimates are distinguished for industrial, residential and non-residential electricity users. Net benefits are expected for industrial and residential users in most regions, with national averages of 2.2% for industrial users and 2.4% for residential users. In contrast, a net cost of 0.6% is expected for non-residential users which is likely to include agricultural users. In addition to cost and benefit estimates, real price changes are provided for residential users; the most extreme regional change estimates include an annual price drop per household of $80 in Southland and an increase of $40 in Waitaki.

Further research could explore if these findings apply to different regions and different microgrid applications. When considering the electricity prices paid by each sector, the residential sector pays the highest prices. Therefore, residential applications would be expected to experience a larger financial saving from microgrids. As the residential sector faces grid prices of up to $0.42/kWh, homeowners are likely to continue the trend of investing in solar panels (Canstar Blue, 2018). This is primarily a private benefit to the residential microgrid owner and has a lower environmental benefit because small residential microgrids sell back less electricity. Therefore, agricultural microgrids remain a more equitable sector for investment as systems can be oversized to supply additional electricity to the grid, particularly over winter when residential demand is highest.

All microgrid investments will increase the proportion of renewable generation capacity in New Zealand and reduce pressure on the national grid. A well-planned microgrid will ensure efficiency and a high level of autonomy. The lowest cost scenario had a moderate level of autonomy at 72%; meanwhile, Scenarios 2 and 3 offer levels above 90%. In addition, these larger capacity microgrids have a greater public benefit as more electricity is sold back to the grid, while also economically benefiting the farmer with a lower COE, and having a more significant impact on the environmental by reducing the need for fossil fuels to supplement electricity generation.

Although this was not investigated further in this case study, system costs may decrease if farmers are willing to invest in energy efficiency measures to reduce their electricity consumption, and adapt their consumption habits to coincide better with supply. This demand-side management actions have been investigated in previous studies (Dew et al., 2021; Houston et al., 2014; Powell et al., 2019) and found to successfully reduce and shift dairy farm electrical loads to be more cost-effective.

There are various factors beyond the control of microgrid technology and pricing trends that will influence future microgrid investment. One such example is the announced closure of Tiwai Point Aluminium Smelter, in Southland, New Zealand. The closure of the smelter has been debated for years, and it was recently announced that the smelter will close in 2021 (Hickey, 2020). The closure will free up 13% of the country's electricity generation sourced from the neighbouring Manapouri Dam. It has not been confirmed whether the electricity will be redirected and distributed across the country or if another energy-intensive industry will replace the smelter. Significant and extensive line upgrades will be required to increase the capacity of the lines before the electricity can be transported elsewhere but this would reduce the need for microgrids or any additional renewable infrastructure as well as further reducing the need for electricity generation from fossil fuels.

4. Are there scenarios in which an off-grid system is a feasible solution for farms?

Microgrid autonomy is a factor that some investors may value over minimising costs, despite the economic feasibility of the microgrid. The results of the Off-Grid Scenario in Chapter 5 confirm that this is not an economically sensible investment for the LURDF. The Off-Grid Scenario is 4.4 times more expensive than the Grid-Only Scenario, and triple the system cost of Scenario 1. In comparison, Scenario 3 reaches the next highest level of autonomy at 96% while maintaining a system cost 50% lower than the Off-Grid Scenario. Therefore, unless the situation required an off-grid system, Scenario 3 would be considered a more economically sensible compromise that lowers the system cost while maintaining a high level of autonomy with the backup of a grid connection.

Another factor that will influence the decision to connect to the grid is the presence and proximity to grid connection points. For the LURDF case study, there was no benefit to having an off-grid system as there is an existing connection on site. Although New Zealand's national grid is generally reliable, there are rural and remote locations where there is no grid infrastructure, or it is outdated and needs upgrading. In these cases, an off-grid system may be relatively cheaper considering that establishing a new grid connection can cost the landowner up to $25,000 per kilometre (EECA, 2019) from the nearest connection, and in some cases a long distance would surpass the $330,000 cost of the Off-Grid Scenario. Therefore, investors should weigh up the costs of connecting to the grid and an off-grid system.

Off-grid systems are required to be significantly oversized to meet infrequent peak demands and avoid any electricity shortages. This investment in such a large capacity system contributes to the higher system cost. Another disadvantage of off-grid systems is that excess electricity cannot be sold back to the grid, so there is no potential to earn revenue, and the electricity goes to waste if energy storage is at capacity. A further argument against off-grid systems suggest that it is unnecessary to aim for 100% autonomy at such a high price when over 80% of New Zealand's grid electricity is sourced from renewables (MBIE, 2020a).

6.2 Implications for Policy and Planning

In regards to microgrids, land use planning is concerned with the footprint and scale of the project; meanwhile, energy planning is concerned with the efficiency, safety and reliability of the microgrid. As discussed in Chapter 2, the NPS-REG outlines the broader strategies for future investment in renewable energy in New Zealand. Furthermore, the NPS-REG requires that regional and district plans contain explicit provisions for renewable generation. Chapter 2 compared the renewable infrastructure provisions within the Christchurch District Plan and Selwyn District Plan which showed inconsistencies in their efforts to implement the NPS-REG. The results of this research demonstrated that a hybrid of renewable sources was the optimal solution. Therefore, plans should explicitly state provisions for a range of generation components as required by the NPS-REG.

Renewable Microgrid Provisions

Solar panels are a popular component of residential microgrids because they blend into rooftops and have less of a visual impact on the surrounding landscape. Wind turbines have a more significant visual impact. As a result, district plan rules are more enabling of solar panel installations than wind turbines. District plans set lower height restrictions for turbines in urban areas to reduce the visual impact (CCC, 2018; SDC, 2018), but in fact, turbines operate more optimally in rural landscapes with a smoother ground surface, and at greater heights to increase the generation potential. If a landowner applied for consent to install a turbine surpassing 25 metres in the rural zone of the Selwyn District in order to make the project more economically viable as demonstrated in the sensitivity analysis, the Council's discretion to grant consent takes into consideration the visual impact of the structure on neighbouring dwellings and visual obtrusion in regard to the surrounding environment.

The efficiency of different renewable policies and incentives were discussed in Chapter 2 (Ali et al., 2017; Nicolini & Tavoni, 2017). If microgrids are to be incentivised by feed-in tariffs and subsidies, it has been suggested that this occurs at an agricultural, industrial or commercial scale to maximise public gain (Nicolini & Tavoni, 2017). Subsidies to lower microgrid investment costs will contribute to a lower COE, and encourage microgrids to be oversized to benefit from higher electricity generation and sell back revenue.

In Queensland, Australia, electricity distribution regulations prohibit microgrids larger than 30 kW from exporting electricity to the grid which makes larger microgrids an uneconomical investment as no revenue can be earned (Powell et al., 2019). In New Zealand, clarity within the regulations on permitted sizing of microgrids would provide investors with greater certainty for long-term microgrid investments and secure the ability to earn revenue.

6.3 Future Research

Further agricultural microgrid studies could investigate the electrical loads of different agricultural activities such as crop, sheep and beef farming. Additionally, exploring the regional variations in loads may determine the applicability of these results to other areas of New Zealand. Economically viable applications of microgrids may be identified as the body of agricultural microgrid research grows. One promising application identified in the literature that could be further explored in New Zealand was medium-scale community microgrids that connect multiple consumers to one microgrid (Australian Government, 2018: Friesland Campina, 2019).

Further sensitivity variables can be explored to identify which factors may increase the economic viability of microgrids. Microgrids potentially have more favourable economic outcomes if combined with demand-side management such as shifting or reducing peak loads, thereby reducing the microgrid capacity requirements and minimising investment costs (Powell et al., 2019). This was beyond the scope of this study, but future research should focus on economic analyses of microgrids that incorporate increasing energy efficiencies, and altering farming practices to smooth electricity demand and better coincide with renewable supply (Dew et al., 2021).

Chapter 7
Conclusion

This research considered the technical and economic feasibility of microgrids in an agricultural context which had not been previously studied in the New Zealand context. The literature review covered an extensive range of microgrid studies from developed and developing countries both broadly and in an agricultural context.

The decision to invest in microgrids will take into consideration the economic costs and environmental benefits. If financial incentives are to be provided to encourage these investments, further research will be required to determine the most effective and efficient policy instruments specific to New Zealand.

The findings of this research suggest that grid-connected microgrids are not yet an economically viable alternative to traditional grid connections. These findings are significant as they do not support previous international findings that found microgrids to be a cheaper alternative to national grid connections. This highlights the importance of case studies to accurately assess each unique location and electrical load. This research did however agree that rural farms are well-situated for renewable technology. The patterns of renewable supply match consumption patterns on dairy farms, and low consumption over winter enables excess electricity to be sold to the grid when residential demand is highest. These peak demands would otherwise trigger the use of fossil fuels; hence microgrid investments increase the proportion of renewable energy in New Zealand.

Off-grid systems were ruled out as an unnecessarily expensive investment when there is a pre-existing grid connection, but Chapter 6 discussed that off-grid systems may be justified in remote areas where the alternative option of line upgrades or establishing a new grid connection is relatively more expensive.

The primary motivation of this research was the updated TPM which will increase regional variations in electricity prices, especially in rural and remote areas of New Zealand. The sensitivity analysis results in Chapter 5 suggests that microgrid economics are more resilient and robust to increases in electricity prices, meanwhile increased sell back rates are expected to make the greatest impact on the economic analysis. However, sell back rates are unregulated in New Zealand which could compromise the economic viability of a microgrid if rates were changed by the retailer. An introduction of policy instruments such as feed-in tariffs in New Zealand would reduce risk and provide greater certainty to microgrid investors.

References

Ali, A., Li, W., Hussain, R., He, X., Williams, B. W., & Memon, A. H. (2017). Overview of current microgrid policies, incentives and barriers in the European Union, United States and China. *Sustainability*, *9*(7), 1146.

Andersen, F. M., Baldini, M., Hansen, L. G., & Jensen, C. L. (2017). Households' hourly electricity consumption and peak demand in Denmark. *Applied energy*, *208*, 607-619.

Australian Government. (2018). *Latrobe Valley virtual microgrid could allow dairy farms to trade energy via blockchain.* https://arena.gov.au/news/latrobe-valley-virtual-microgrid-allow-dairy-farms-trade-energy-via-blockchain/

Australian Government. (2020, May 27). 2020 Australian energy statistics [Press release]. https://www.minister.industry.gov.au/ministers/taylor/media-releases/2020-australian-energy-statistics

Back, P. (2017). Dairy production. In K. Stafford (Ed.), Livestock production in New Zealand (pp. 12-53). Massey University Press.

Bardi, U., El Asmar, T., & Lavacchi, A. (2013). Turning electricity into food: the role of renewable energy in the future of agriculture. Journal of Cleaner Production, 53, 224-231.

Bańkowska, K., & Gradziuk, P. (2017). Renewable Energy–Implications for Agriculture and Rural Development in Poland. Village and Agriculture (Wieś i Rolnictwo), 3(1229-2018-3771), 121-141.

Bayrakcı, A. G., & Koçar, G. (2012). Utilization of renewable energies in Turkey's agriculture. Renewable and Sustainable Energy Reviews, 16(1), 618-633.

Bevrani, H., François, B., & Ise, T. (2017). Microgrid dynamics and control. John Wiley & Sons.

Bryman, A. (2016). Social research methods. Oxford university press.

Campiotti, C., Belmonte, A., Catanese, V., Dicarlo, F., Dondi, F., Scoccianti, M., & Lucerti, G. (2010). Renewable energy for greenhouse agriculture. Journal of sustainable energy, 1(2).

Canstar Blue. (2018). Compare power plans for homes with solar. https://www.canstarblue.co.nz/energy/solar-power-plans/

Chel, A., & Kaushik, G. (2011). Renewable energy for sustainable agriculture. Agronomy *for Sustainable Development*, *31*(1), 91-118.

Chmiel, Z., & Bhattacharyya, S. C. (2015). Analysis of off-grid electricity system at Isle of Eigg (Scotland): Lessons for developing countries. *Renewable Energy*, *81*, 578-588.

Christchurch City Council [CCC]. (2018). Christchurch district plan. http://districtplan.ccc.govt.nz

Climate Change Response (Zero Carbon) Amendment Act 2019. http://www.legislation.govt.nz/act/public/2019/0061/latest/LMS183736.html#LMS183848

Datta, U., Kalam, A., & Shi, J. (2018). Hybrid PV-wind renewable energy sources for microgrid application: An overview. In H. Fathima, N. Prabaharan, K. Palanisamy, A. Kalam, S. Mekhilef & J. Justo (Eds.), Hybrid-renewable energy systems in microgrids: Integration, developments and control (pp. 1-22). Woodhead Publishing.

Dew, J. J., Jack, M. W., Stephenson, J., & Walton, S. (2021). Reducing electricity demand peaks on large-scale dairy farms. Sustainable Production and Consumption, 25, 248-258. https://doi.org/10.1016/j.spc.2020.08.014

Energy Efficiency & Conservation Authority [EECA]. (2019). Small wind turbines. https://www.energywise.govt.nz/at-home/generating-energy/small-wind-turbines/

Electricity Authority [EA]. (2014). Connection of small scale distributed generation (equal to or less than 10 kW) to a local network. https://www.ea.govt.nz/assets/dms-assets/24/24762Guideline-for-the-connection-of-DG-equal-or-less-than-equal-to-10kW.PDF

Electricity Authority [EA]. (2018). Electricity in New Zealand. https://www.ea.govt.nz/assets/dms-assets/20/20410Electricity-in-NZ-2018.pdf

Electricity Authority [EA]. (2020). Transmission pricing methodology 2020 guidelines and process for development of a proposed TPM. https://ea.govt.nz/assets/dms-assets/26/26851TPM-Decision-paper-10-June-2020.pdf

Electricity Industry Act 2010. http://www.legislation.govt.nz/act/public/2010/0116/latest/whole.html

Energywise. (n.d.). Wind energy. https://www.energywise.govt.nz/at-home/generating-energy/small-wind-turbines/

Farrell, N., & Lyons, S. (2016). Equity impacts of energy and climate policy: Who is shouldering the burden?. *Wiley Interdisciplinary Reviews: Energy and Environment*, *5*(5), 492-509.

Friesland Campina. (2019). *Installation of the first small windmill after collaboration.* https://www.frieslandcampina.com/news/installation-first-small-windmill-collaboration/

Frisk, M. (2017). Simulation and Optimization of a Hybrid Renewable Energy System for application on a Cuban farm.

Fu, R., Feldman, D., & Margolis, R. (2018). *U.S. solar photovoltaic system cost benchmark: Q1 2018*. United States. https://www.nrel.gov/docs/fy19osti/72399.pdf

Gao, D. W. (2015). *Energy storage for sustainable microgrid*. Academic Press.

Glifford, R. (2016). *Research methods for environmental psychology*. Wiley-Blackwell.

Google. (n.d.). [Google Maps location of LURDF in Lincoln area]. Retrieved June 16, 2020, from https://www.google.com/maps/@-43.6398914,172.462173,1273m/data=!3m1!1e3

Harvey, L. D. (2010). *Energy and the new reality 2: carbon-free energy supply*. Routledge.

Hickey, B. (July 9, 2020). Tiwai Point closure to hit 2,600 jobs. *Newsroom.* https://www.newsroom.co.nz/tiwai-point-closure-to-hit-2600-jobs

Hitaj, C., & Suttles, S. (2016). *Trends in US Agriculture's Consumption and Production of Energy: Renewable Power, Shale Energy, and Cellulosic Biomass.* EIA-159, U.S. Department of Agriculture, Economic Research Service.

Houston, C., Gyamfi, S., & Whale, J. (2014). Evaluation of energy efficiency and renewable energy generation opportunities for small scale dairy farms: A case study in Prince Edward Island, Canada. *Renewable energy*, *67*, 20-29.

HOMER Energy. (n.d.). *HOMER Pro glossary.* https://www.homerenergy.com/products/pro/docs/latest/glossary.html

Hussain, A., Arif, S. M., & Aslam, M. (2017). Emerging renewable and sustainable energy technologies: State of the art. *Renewable and Sustainable Energy Reviews*, *71*, 12-28.

Interim Climate Change Committee [ICCC]. (2019). Accelerated electrification. https://www.iccc.mfe.govt.nz/assets/PDF_Library/daed426432/FINAL-ICCC-Electricity-report.pdf

International Energy Agency. (2020). Electricity statistics. https://www.iea.org/subscribe-to-data-services/electricity-statistics

International Renewable Energy Agency [IRENA]. (2015). Renewable energy policy brief: Paraguay. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2015/IRENA_RE_Latin_America_Policies/IRENA_RE_Latin_America_Policies_2015_Country_Paraguay.pdf?la=en&hash=9DD71986E5F6998AE3F782C3AEDBA3EFC9F32E2D

International Renewable Energy Agency [IRENA]. (2019). Future of solar photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation: paper), International Renewable Energy Agency, Abu Dhabi.

Kaya, E., & Zarrouk, S. J. (2017). Reinjection of greenhouse gases into geothermal reservoirs. *International Journal of Greenhouse Gas Control, 67*, 111-129.

Kelly, G. (2011). History and potential of renewable energy development in New Zealand. *Renewable and Sustainable Energy Reviews*, *15*(5), 2501-2509.

Kilowattlabs. (n.d.). *Sirius energy storage.* https://kilowattlabs.com/product/sirius

LG Energy. (n.d.). *LG neon 2*. https://www.harrisonsenergy.co.nz/Downloads/Assets/80285/1/

Lincoln University. (n.d.). *Lincoln university research dairy farm*. https://www.lincoln.ac.nz/about-lincoln/lincoln-university-farms/lurdf/?sti=1

Mason, I. G., Page, S. C., & Williamson, A. G. (2013). Security of supply, energy spillage control and peaking options within a 100% renewable electricity system for New Zealand. *Energy Policy*, *60*, 324-333.

Matter, J. M., Broecker, W. S., Stute, M., Gislason, S. R., Oelkers, E. H., Stefánsson, A., Wolff-Boenisch, E., Gunnlaugsson, E., Axelsson, G., & Björnsson, G. (2009). Permanent carbon dioxide storage into basalt: The CarbFix pilot project, Iceland. *Energy Procedia*, *1*(1), 3641-3646.

McHenry, M. P. (2012). A technical, economic, and greenhouse gas emission analysis of a homestead-scale grid-connected and stand-alone photovoltaic and diesel systems, against electricity network extension. *Renewable energy*, *38*(1), 126-135.

Meridian Energy. (n.d.). Solar for your home. https://www.meridianenergy.co.nz/your-home/sustainability/solar

Ministry for Primary Industries. (2017). New Zealand agriculture: A policy perspective. https://www.mpi.govt.nz/dmsdocument/27282/direct

Ministry for the Environment [MfE]. (2018). About the Paris agreement. https://www.mfe.govt.nz/climate-change/why-climate-change-matters/global-response/paris-agreement

Ministry for the Environment [MfE]. (2019). Measuring emissions: A guide for organisations. https://www.mfe.govt.nz/sites/default/files/media/Climate%20Change/2019-detailed-guide.pdf

Ministry of Business, Innovation & Employment [MBIE]. (2020a). Electricity statistics [Data set]. https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-statistics-and-modelling/energy-statistics/electricity-statistics/

Ministry of Business, Innovation & Employment [MBIE]. (2020b). Energy prices [Data set]. https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-statistics-and-modelling/energy-statistics/energy-prices/

My Solar Quotes. (2020). Solar power buy-back rates. https://www.mysolarquotes.co.nz/about-solar-power/residential/solar-power-buy-back-rates-nz/

Nacer, T., Hamidat, A., & Nadjemi, O. (2016). A comprehensive method to assess the feasibility of renewable energy on Algerian dairy farms. Journal of Cleaner Production, 112, 3631-3642.

National Institute of Water & Atmospheric Research [NIWA]. (2019). CliFlo [Data set]. https://cliflo.niwa.co.nz

Neale, T., & May, D. (2020). Fuzzy boundaries: Simulation and expertise in bushfire prediction. Social Studies of Science, 50(6), 837-859.

New Zealand Government. (2011). National Policy Statement for Renewable Energy Generation. https://www.mfe.govt.nz/publications/rma/nps-renewable-electricity-generation-2011

New Zealand Government. (2019, July 16). NZ embracing renewable electricity future [Press release]. https://www.beehive.govt.nz/release/nz-embracing-renewable-electricity-future

New Zealand Treasury. (2020). Discount rates. Retrieved May 17, 2020, from https://www.treasury.govt.nz/information-and-services/state-sector-leadership/guidance/financial-reporting-policies-and-guidance/discount-rates

New Zealand Wind Energy Association. (n.d.). New Zealand's wind farms. http://www.windenergy.org.nz/wind-energy/nz-windfarms

Nicolini, M., & Tavoni, M. (2017). Are renewable energy subsidies effective? Evidence from Europe. *Renewable and Sustainable Energy Reviews*, *74*, 412-423.

Orkustofnun. (n.d.). *Hydro power plants in Iceland.* https://nea.is/hydro-power/electric-power/hydro-power-plants/

Orkustofnun. (2015). Energy statistics in Iceland 2015. https://orkustofnun.is/gogn/os-onnur-rit/Orkutolur_2015-enska-utfaersla2.pdf

Pasonen, R. & Hoang, H. (2014). Microgrids and DER in community planning: Practices, permits and profitability. VTT Technology 189.

Powell, J. W., Welsh, J. M., Pannell, D., & Kingwell, R. (2019). Can applying renewable energy for Australian sugarcane irrigation reduce energy cost and environmental impacts? A case study approach. Journal of Cleaner Production, 240, 118177.

Powerhouse Wind. (n.d.). *ThinAir 102 specifications*. https://www.powerhousewind.co.nz/thinair-wind-turbine/thinair-specs/

Prodromidis, G. N., & Coutelieris, F. A. (2011). A comparative feasibility study of stand-alone and grid connected RES-based systems in several Greek Islands. Renewable Energy, 36(7), 1957-1963.

Querikiol, E. M., & Taboada, E. B. (2018). Performance Evaluation of a Micro Off-Grid Solar Energy Generator for Islandic Agricultural Farm Operations Using HOMER. Journal of Renewable Energy, 2018.

Resource Management Act [RMA] 1991. http://www.legislation.govt.nz/act/public/1991/0069/latest/DLM230265.html?src=qs

Reuther, N., & Thull, J.-P. (2011). Feasibility study of small and micro wind turbines for residential use in New Zealand (LEaP research report No. 30). Lincoln University. https://researcharchive.lincoln.ac.nz/bitstream/handle/10182/4141/LEaP_rr_30.pdf?sequence=3&isAllowed=y

Schwaegerl, C., & Tao, L. (2014). The microgrids concept. In N. Hatziargyriou (Ed.), Microgrid: Architectures and control (pp. 1-24). Wiley.

Selwyn District Council [SDC]. (2018). Selwyn district plan. https://eplan.selwyn.govt.nz/eplan

Sen, R., & Bhattacharyya, S. (2014). Off-grid electricity generation with renewable energy technologies in India: An application of HOMER. Renewable Energy, 62(C), 388-398.

Shoeb, M. A., & Shafiullah, G. M. (2018). Renewable energy integrated islanded microgrid for sustainable irrigation—A Bangladesh perspective. Energies, 11(5), 1283.

Sinha, S., & Chandel, S. S. (2014). Review of software tools for hybrid renewable energy systems. *Renewable and Sustainable Energy Reviews*, *32*, 192-205.

Tan, X., Li, Q., & Wang, H. (2013). Advances and trends of energy storage technology in microgrid. International Journal of Electrical Power & Energy Systems, 44(1), 179-191.

United States Energy Information Administration. (2020). Electricity in the United States. https://www.eia.gov/energyexplained/electricity/electricity-in-the-us.php

Uski, S., Rinne, E., & Sarsama, J. (2018). Microgrid as a cost-effective alternative to rural network underground cabling for adequate reliability. Energies, 11(8), 1978.

Victron Energy. (n.d.). Quattro inverter. https://www.victronenergy.com/upload/documents/Datasheet-Quattro-3-10kVA-120V-EN.pdf

Verma, P., Patel, N., Nair, N. K. C., & Brent, A. C. (2018). Improving the energy efficiency of the New Zealand economy: A policy comparison with other renewable-rich countries. Energy Policy, 122, 506-51.

Appendix A

HOMER Input Variables

Table A.1 HOMER input variables.

Component	Value	Source
Solar Panel (LG Neon 2 355W)		
Capital cost (per kW)	$1,971	Harrison Energy Solutions (personal communication, June 25, 2020)
Replacement cost	$1,971	
O&M cost	$0	
Lifetime (years)	25	
Derating factor (%)	90.08	
Effect on power (%/C)	-0.3	LG Energy (n.d.)
Nominal operating temp (°C)	42	
Efficiency (%)	20.7	
Wind Turbine (ThinAir 102 2kW)		
Capital cost (per unit)	$17,100	
Replacement cost	$13,680	Powerhouse Wind (n.d.)
O&M cost	$0	
Lifetime (years)	20	
Hub Height (metres)	25	Selwyn District Council (2018)
Supercapacitor (Sirius 3.55kW)		
Capital cost (per unit)	$4,500	Platinum Energy (personal communication, June 22, 2020)
Replacement cost	$4,500	
O&M cost	$0	
Lifetime (years)	45	
Nominal voltage (V)	48	
Round trip efficiency (%)	99	Kilowattlabs (n.d.)
Minimum and maximum charge (%)	0-100	
Maximum charge and discharge rate (A)	125	
Inverter (Victron Quattro 8kW)		
Capital cost (per unit)	$5,000	Platinum Energy (personal communication, June 22, 2020)
Replacement cost	$5,000	
O&M	$0	
Lifetime (years)	15	Victron Energy (n.d.)
Maximum efficiency (%)	96	
Grid		
Grid power price ($/kWh)	0.21	MBIE (2020b)
Grid sell back price ($/kWh)	0.08	Meridian Energy (n.d.)
Grid emissions (grams of CO2-e/kWh)	97.7	MfE (2019)
Economics		
Nominal discount rate	6%	
Expected inflation rate	2%	New Zealand Treasury (2020)
Real discount rate	4%	
Project lifetime (years)	25	
system fixed capital	0	
system fixed O&M	0	
Capacity shortage penalty	0	
Currency	NZD	

Appendix B

Climate Data

Table A.1 Average monthly wind speed in Lincoln.

Month	Average wind speed (m/s)
January	4.462
February	4.440
March	4.035
April	3.655
May	3.188
June	3.254
July	3.421
August	3.346
September	3.692
October	3.858
November	4.447
December	4.883

Data source: CliFlo (NIWA, 2019).

Table A.2 Average daily solar radiation and clearness index in Lincoln.

Month	Average daily radiation (kWh/m2/day)	Clearness index
January	6.710	0.563
February	5.940	0.574
March	3.978	0.496
April	2.458	0.441
May	1.630	0.434
June	1.282	0.428
July	1.195	0.353
August	2.311	0.472
September	3.307	0.460
October	4.549	0.472
November	5.754	0.499
December	6.259	0.506

Data source: CliFlo (NIWA, 2019).