POWER SYSTEMS FOR DAIRY SHEDS

- an investigation into the right mix of energy efficiency, load shifting and energy supply technologies

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Abstract
This study investigated the potential for using stand-alone power systems for dairy milking sheds in New Zealand.

The study was in two parts:

- designing a typical load profile for a dairy shed and evaluating changes that could be made to the dairy shed to improve energy efficiency or shift load, using a mechanistic modelling approach.
- using the optimisation modelling tool HOMER Pro to find the best configuration of power system, energy efficiency and/or load shifting improvements of a solar-diesel hybrid power system and a solar-diesel-biogas hybrid power system.

The study found that milk vat insulation, variable speed drives and generator heat recovery were good investments to reduce power system costs. The high capital cost of ice banks made them less attractive for herds less than 370 cows. Superheat heat pumps and biogas systems were poor investments and increased costs in most cases when compared with the base scenario. While there was variation within the regions, overall the optimal system, when sensitivity scenarios were accounted for, was found to be similar between the three regions studied with the Bay of Plenty having the lowest overall costs followed by Taranaki and Manawatu. Sensitivity scenarios showed bias against deferrable loads such as ice bank refrigeration systems, hot water storage systems and the pumping of effluent. Diesel prices had a greater effect where the renewable fraction was low. Increasing diesel prices resulted in larger PV arrays and batteries.

Acknowledgements

Thanks to Sam and Ken from PowerCo for providing an interesting topic for this thesis. Thanks to my supervisor Ralph for prompt response and feedback regardless of where he was in the world. Special thanks to my mum, Jenny, for helping fix the many spelling and grammatical errors and to my wife Heather for support and tolerance particularly in the final few months

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1 Introduction

Reliable electricity supply is essential for dairy farming in New Zealand. Much of the electricity infrastructure in remote rural areas, which includes some dairy farms, is at the end of its useful life. People in these areas experience more network outages and the network requires higher levels of maintenance. New Zealand's electricity infrastructure was expanded into increasingly remote areas in the post-war period between the 1950s into the late 1970s. This infrastructure was constructed with funding assistance from landowners and government rural development subsidies under the "Rural Electrification Scheme" that is no longer available to farmers. Since this infrastructure was constructed new technologies have advanced so that, in some instances, stand–alone power systems (SAPS) are competitive financially with grid electricity (Whaley and Pattie, 2012).

Electricity distribution networks have been privatised which has created natural monopolies that serve different regions throughout New Zealand. PowerCo is an electricity distributor that operates in the Manawatu, Taranaki and Bay of Plenty regions of New Zealand. These regions cover some remote rural networks with challenging topography in sparsely populated areas and typically less than one customer per kilometre of line. These customers have a much higher marginal cost than in more densely populated areas (Whaley and Pattie, 2012). New Zealand law requires that if a property was connected to the grid before 1993 it must be able to retain electricity supply regardless of the economics of supplying electricity for the transmission and distribution system. Although the customer was protected, as of 2010 electricity does not necessarily have to be provided through the national electricity grid (MBIE, 2010).

Since 2008, PowerCo has been using SAPS in areas where line replacement is uneconomic. To date, conversions have been focused on private residences and shearing sheds. PowerCo provides customers with a "hassle free" power system specified to meet the customer's energy requirements using a PV array, a battery bank and a diesel generator (Whaley and Pattie, 2012). So far, the expectation has been that the customer would fund the costs of diesel and continue to pay the line charge whilst PowerCo would provide the capital equipment and the maintenance.

As a major and growing rural energy consumer, dairy sheds have been of interest to PowerCo. They have considerably different characteristics from the SAPS that PowerCo has undertaken so far.

SAPS for dairy sheds constructed in areas that do not have existing grid connections would be important to farm owners particularly where the costs of accessing the national electricity network would be high. Customers needing new grid connections have to bear the costs of installation. For new dairy farms in remote areas this cost could range from \$100,000-\$400,000 (Parshotam *et al.*, 2011).

The cost of solar photovoltaic (PV) panels and battery costs for stand-alone power systems has declined steadily in recent years. This has changed the economics of stand-alone power systems and has allowed them to be competitive in an increasingly larger number of applications. PV panels and battery costs are likely to continue to decline as manufacturing capacity increases and knowledge improves due to greater experience (Nykvist and Nilsson, 2015).

Studies of the electricity consumption of New Zealand dairy farms have focused on technologies characterising total electricity demand on an annual basis and identifying ways to improve energy efficiency (Sims *et al.*, 2004; Miller and Glenn, 2011). The characteristics of SAPS have made these studies of limited use because the cost to produce energy in stand-alone power system depends on the source of generation much more than is experienced by the typical user supplied by grid electricity. Electricity from the grid has a relatively static price. In SAPS, electricity from PV panels would have a marginal cost close to zero whereas electricity from the generator would be at a much higher marginal cost with greater price fluctuations than grid-sourced electricity.

Energy efficiency and peak load shifting would be of importance in SAPS. Investment in energy efficiency would allow SAPS to be smaller by reducing the total electricity demand. Load shifting would allow the unit cost of electricity to be lower by shifting it to a time where low marginal cost energy was available.

Most farms have anaerobic digestion ponds to treat effluent from the milking shed and any wintering or feeding pads on the farm. Anaerobic digestion produces methane gas that is usually released to the atmosphere but could be available to be used as a fuel for a power source if captured. This approach would be particularly attractive if farmers were incentivised to reduce their greenhouse gas emissions. This could be achieved through the inclusion of on-farm agricultural emissions in the Emissions Trading Scheme (ETS) or other regulatory framework.

Solar energy was chosen because PowerCo have existing experience with its provision, it has been low maintenance and hasn't required specialist skills to maintain. Biogas is a dispatchable source of energy available on dairy farms that could provide significant benefits. Other renewable energy sources such as wind and micro-hydro would be worth investigating but time constraints made them impractical for this study.

1.1 Problem statement, research question, aims and objectives

PowerCo's ageing remote rural distribution infrastructure is reaching the end of its life. Replacing this infrastructure with like-for-like is unlikely to bring any future returns and will increase the overall network costs. To date, PowerCo has focused on converting customers with relatively low or intermittent electricity demand, to SAPS. Dairy farms by comparison, based on the conversions from other land uses that PowerCo has undertaken to date, have a relatively large and continuous electricity demand. Given the high number of dairy customers using their rural infrastructure, there has been interest in developing a better understanding of the optimal manner of supplying dairy sheds with a SAPS.

The aim of this thesis was, to model dairy farm electricity load profiles for various technologies and to then use these modelled loads in a power system model to simulate how these technology combinations performed in various regions under various oil pricing regimes.

The objectives of this research addressed the following:

- Develop load profiles models using Microsoft excel software
- Build a series of regional and technological change scenarios that modify the load profile
- Validate these load profiles against the published literature.
- Use these load profiles in a system simulation model utilising sensitivity analyses around key variables
- Assess results for optimum combination of technology.

Section 2 defined and examined the load characteristics of a "typical" dairy shed by using the existing literature on dairy shed electricity consumption. This was then used as the 'base farm model' and the other regional and technology scenarios. It also considered the technical performance of the efficiency, load shifting and biogas technologies and their costs

In Section 3 a half hourly load profile was developed using mechanistic modelling techniques for each of the individual components of the shed to create a model of electricity use for dairy farms. Load profiles were developed for the Manawatu region and as part of the regional scenario for Taranaki and Bay of Plenty. The technology scenario was deveveloped to assess the impact of efficiency measures and load shifting measures on the electricity load profile for a range of farm sizes. The efficiency measures assessed were superheat heat pumps, insulation and variable speed drive vacuum pumps .The load shifting technology assessed was an ice bank. Load profiles for the alternative energy supplies of biogas and hot water heat recovery from the generator were developed which were not included in the "technology scenario". The reason for this is discussed in Section 3.1

Section 4 assessed the validity of the modelling approach. This was done by comparing the base farm model from Section 3 with a range of data sources from the literature including two case study farms;

the Massey University number 4 dairy farm in the Manawatu and a farm near Waipawa in the Central Hawke's Bay.

Section 5 examined a stand-alone power system able to meet the load profile as specified in section 3. It compared the net present cost of the different scenarios using the HOMER Pro SAPS modelling tool. The study focused on the Manawatu; all the simulations were performed using the farm model of the Manawatu region. The best performing "technology scenario" options for each farm size were applied to the regional scenario, the oil price sensitivity scenarios, the capital price sensitivity, storage sensitivity, biogas supply option and hot water heat recovery from the generator option. The power systems investigated were solar-diesel hybrid systems and solar-diesel biogas systems. The solar-diesel hybrid systems were modelled around PowerCo's modular energy storage unit(ESU) power system that is designed for quick deployment, and low maintenance requirements.

Section 6 discussed the findings of the research and presented the conclusions.

2 Dairy shed electricity loads

2.1 The New Zealand dairy farm

Dairy farming in New Zealand is pastoral; most herds spend the whole year outside and cows are only brought inside to be milked. Cows must be milked at least once a day to remain healthy and productive. Unlike beef cattle or sheep farming dairy farms need reliable continuous electricity supplies to operate the milking machinery and keep the milk refrigeration system operating. To gain an understanding of the electricity demand of dairy sheds it was critical to first outline the nature of dairy farming in New Zealand and the seasonal fluctuations in milk production which drive the changes in electricity consumption.

Since the 1980s, dairy farming in New Zealand has grown steadily and has become increasingly intensive and productive as the total number of herds has decreased.The average New Zealand dairy herd size has increased steadily. In the 2014/15 season average herd size was 419 cows having grown from 251 in the 2000/01 season (DairyNZ, 2015d). Land intensity, milk volume and milk solids have also increased. Regionally most of the growth in cow numbers has occurred in the South Island to 40% of total New Zealand population in 2015 from 22% in 2000. Most of the South Island's growth in cow numbers occurred in North Canterbury, South Canterbury and Southland which together accounted for 30% of New Zealand's dairy cows. North Island cow numbers have remained relatively stable. Intensity has tended to be lower in the North Island, 2.78 cows per hectare compared with

3.03 cows per hectare in the South Island (DairyNZ, 2015d). The North Island has a greater number of smaller herds with 74% of herds in the North Island but only 60% of total cows (DairyNZ, 2015d). In the South Island dairy farms have increased in number and size. The South Island average is 634 cows per farm compared to the North Island average of 343.

Production per cow is regionally dependent. The average milk solids per cow for the 2014/2015 season in Manawatu and Taranaki was an average of 395 kg/cow/per annum. In the Bay of Plenty this was lower at 363 kg (DairyNZ, 2015d). Inside the study region the increase in cow numbers has been relatively slow although productivity increased markedly on a per cow basis (DairyNZ, 2015d).

An individual cow's milk production varies throughout the milking season. Peak production occurred around one month after calving which occurred typically in the months of September/October however it varied between seasons depending on climatic conditions (University of Illinois, 1999).

The month of peak production in the Bay of Plenty was August which was a month earlier than peak production for Taranaki and the Manawatu (Fig. 1). The Manawatu had the highest overall per cow production with a seasonal average of 20l per cow/per day. This was followed by Taranaki with 19l per cow/per day then the Bay of Plenty with 18l per cow/per day.

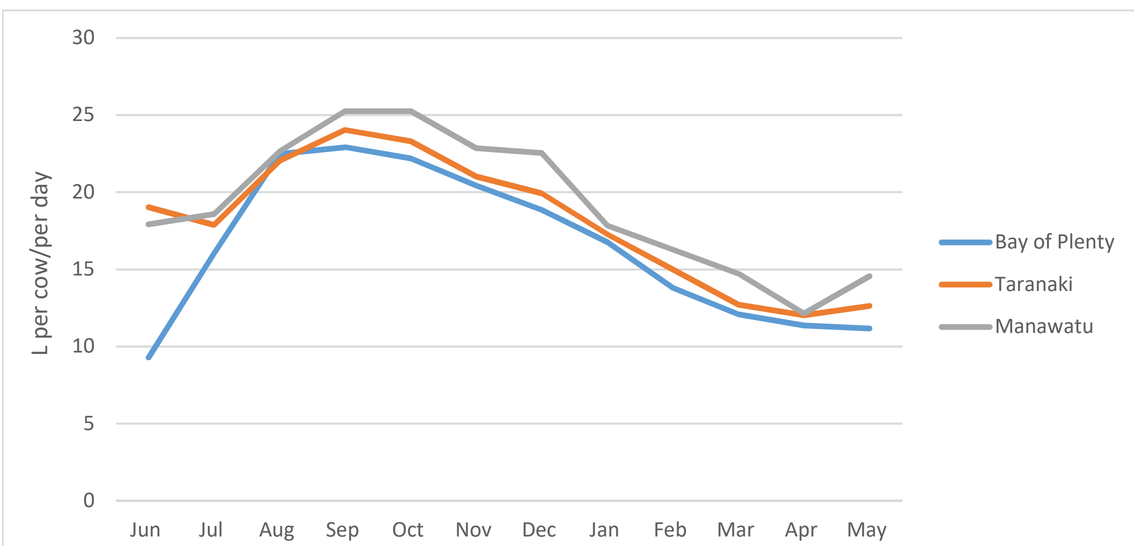

Figure 1: Seasonal trends in daily milk production per cow after calving for three regions (DairyNZ, 2015d)

Calving in New Zealand begins mid-way through July in the upper North Island and generally occurs progressively later travelling south. Calving in all regions is finished by the end of September. The start of calving is controlled by the mating time of cows. The planned start of calving date is 282 days after mating (DairyNZ, 2015d). The median calving date is 4 to 6 weeks after the planned start (Appendix 1). Within the study region calving begins with the Bay of Plenty followed by Taranaki and the Manawatu respectively. The planned start of calving date has little variation between milking seasons. Manawatu had the longest period of lactation with 176 days in milk for the 2014/15 season, Bay of Plenty had a slightly shorter lactation period (173 days in milk) and Taranaki had the shortest overall period (170 days in milk). Overall lactation periods for New Zealand between the 2001/02 season and the 2014/15 season were 152 to 275 days with an average of 165 days. There was no detectable trend in lactation periods but it is in part dependent on weather conditions supporting pasture growth.

Regional milk production data at the farm gate was not available, however the data from Dairy New Zealand provided a basis to model the regional milk production for the study regions (Section 3.2). This was the basis upon which the electricity load profile was developed and linked with available data on annual electricity consumption of dairy farms.

The two most common types of dairy sheds used in New Zealand are herringbone milking sheds and Rotary dairy sheds representing 72% and 27% of dairy sheds with the New Zealand respectively (DairyNZ, 2017a). Rotary milking farms have a higher utilisation with 44% of dairy cows being milked in a rotary milking shed (DairyNZ, 2017d).

2.2 Electricity consumption

Several studies by various New Zealand government agencies and industry groups along with international studies from Australia and Ireland have examined electricity consumption of dairy sheds (Fig. 2). Within the studies of dairy farms focused on New Zealand non-irrigated land, annual electricity use per cow ranged from 150 kWh/cow to 173 kWh/cow (Sims *et al.*, 2004; Barber and Pellow, 2005; Miller and Glenn, 2011). The lower figure of 150 kWh/cow was taken from a small study of new farms in the Southland region (Morison, Gregory and Hooper, 2007). As dairy herds in the South Island are on average larger than the North Island and dairy shed equipment tends to be newer this is unlikely to be representative of the typical farm in the study region of Manawatu (Sims *et al.*, 2004). Barber & Pellow (2005) did not state their selection methodology.

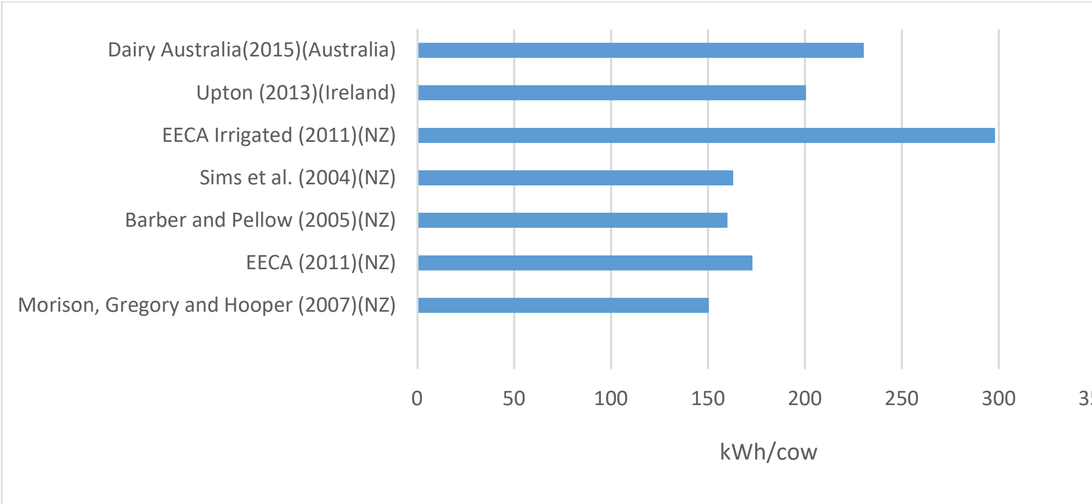

Figure 2: Average electricity consumption per cow per year for New Zealand and International dairy farms

In the two largest studies surveyed, 62 farms in the 2003/4 milking season and 150 farms in the 2010/2011 milking season (Sims *et al*. 2004; Miller & Glenn 2011; Fig 2), the average annual energy use per cow varied by 10 kWh/cow. If only the study region of the lower North Island was considered the variation between the two studies was substantially lower at 165 kWh/cow compared with 162 kWh/cow respectively. The methodology of sample selection between the two studies differed considerably. Sims *et al*., (2004) selected a representative sample of farms from each of the Taranaki, Waikato, Northland, Canterbury, South Canterbury/North Otago and Southland regions. Miller & Glenn (2011) selected only farms supplying the Fonterra Cooperative representing the regions of Waikato, Lower North Island (Taranaki, Manawatu, & Wairarapa), Canterbury, & Otago/Southland. A random selection of 500 farms was taken and farms were contacted until 150 farms had agreed to participate. The group selected by Sims *et al*. (2004) were selected from regions that represented approximately 70% of the dairy farms in New Zealand whereas the Miller & Glenn, (2011) study included farms from regions that represented 82% of all dairy farms (Livestock Improvement Corporation Limited, 2004; DairyNZ, 2011).

2.3 Herd size and electricity consumption

Electricity use in the 2010/2011 season increased with herd size (Fig 3). The 2004 series excluded irrigation and the fit of the trend line was good at R^2 = 0.92. The 2011 series included 22 farms that used irrigation and showed a poorer correlation of R^2 =0.80. This created a greater spread in the sample. Irrigation typically made up 50% of a farm's total electricity consumption. If irrigation was excluded cow number became a reliable indicator of shed electricity consumption.

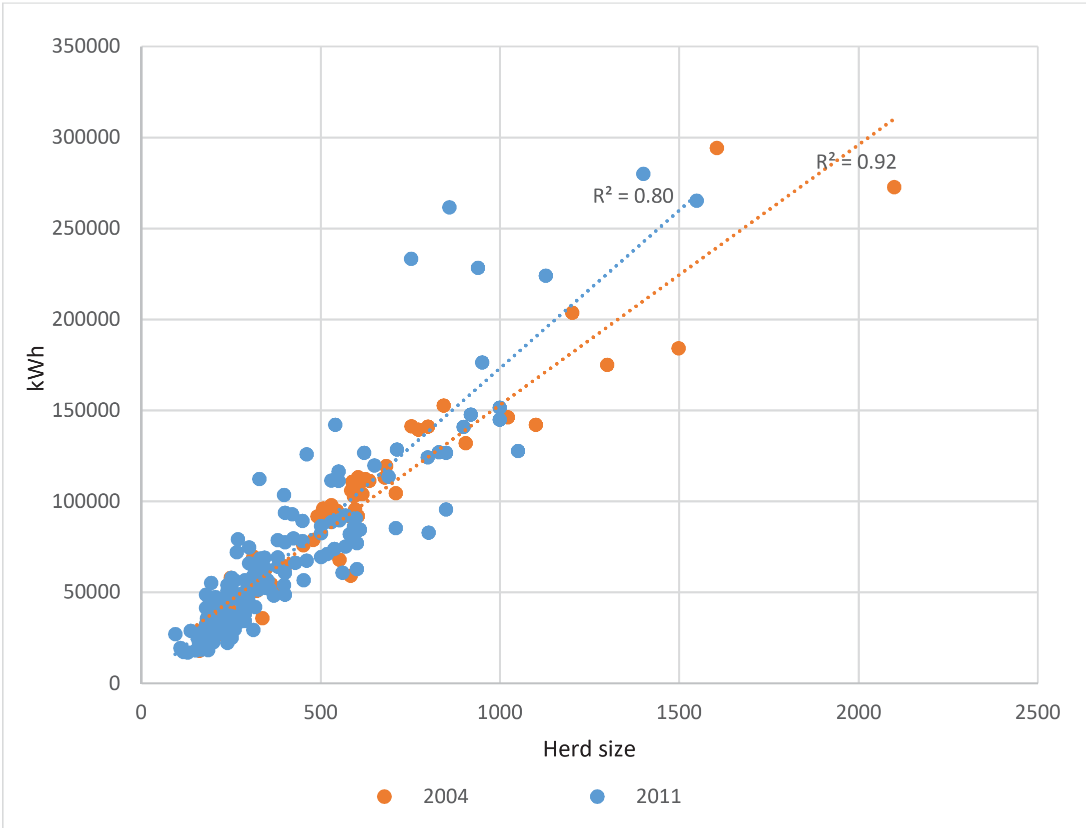

Figure 3: Electricity consumption of different herd sizes (Sims *et al.*, 2004; Miller and Glenn, 2011)

There was no correlation between electrical efficiency per cow and herd size (Fig 4). The effect of the inclusion of irrigation was evident in the 2011 series (Fig 4) where 11 farms had electricity consumption greater than 250 kWh/cow.

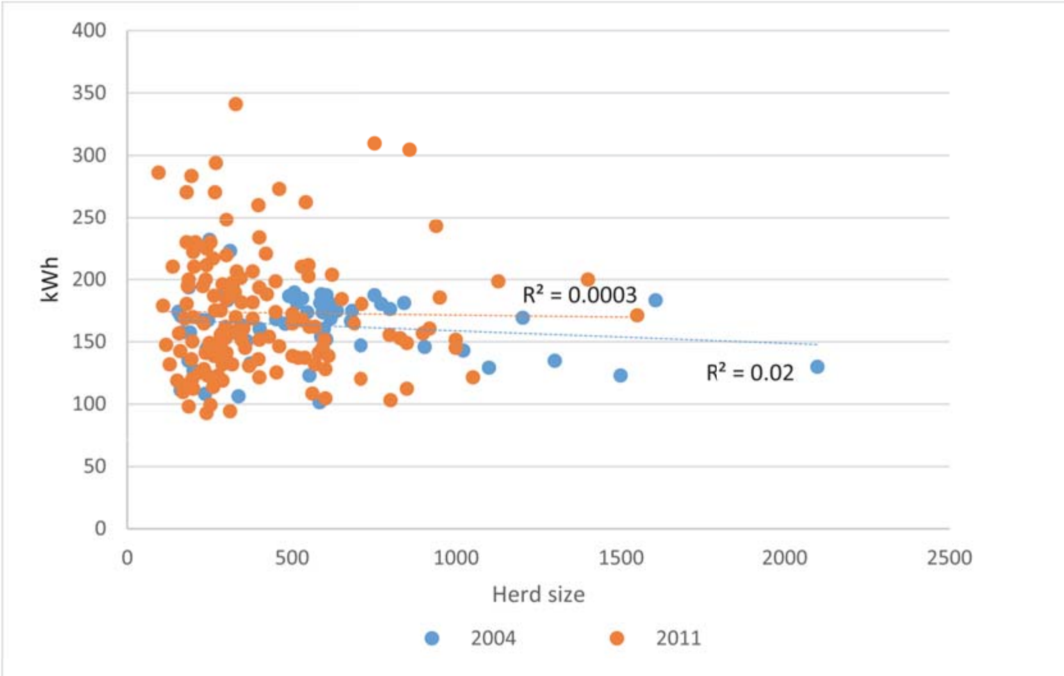

Figure 4: Annual dairy shed electricity consumption per cow for varying herd sizes for years 2004 and 2011 (Sims *et al.*, 2004; Miller and Glenn, 2011)

Electricity consumption was not normally distributed around the mean within the farms (Fig 5). The two most common electricity consumptions were 190 to 199 kWh/cow in 13% of the samples and 170 to 179 kWh/cow in 12.6%. Between 130 and 209 kWh/cow represented 77% of farms surveyed. 13% of farms were above 210 kWh/cow and 10% below 129 kWh/cow.

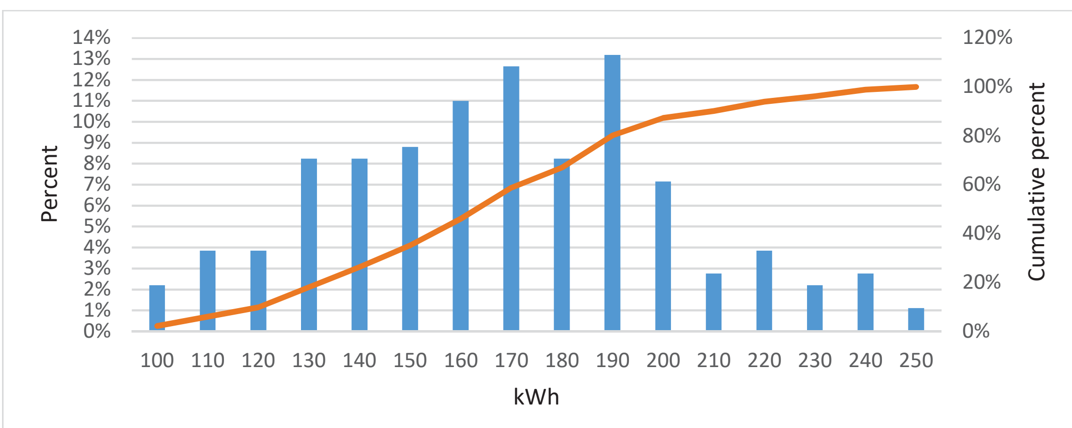

Figure 5: Distribution of herd average electricity consumption. The percentage of herds in each bin is shown by the columns on the left axis and the cumulative percentage by the line on the right axis (Sims *et al.*, 2004; Miller and Glenn, 2011)

2.4 Dairy shed equipment

The equipment used for milking tends to be older in the North Island (Fig 6). The median age of North Island herringbone milking equipment was ten years with 35% of the sheds installed more than 16 years ago. North Island rotary sheds were larger and newer than herringbone shed designs with an average age of 8.5 years. In the South Island, the median age of equipment in dairy sheds was six years with none older than 10 years old. The data used in this study was more than 10 years out of date. However, given the trends discussed in Section 2.1, it was unlikely that the age structure of dairy equipment in the North Island has changed substantially. Farms within the study region tended to have smaller herds with older equipment than the national average, but productivity was higher than the national average. None of the studies correlated the age of equipment with efficiency. However comparison between Miller & Glenn (2011) and Sims *et al*. (2004) gave an indication of efficiency changes over time. The two studies conducted in the 2004 milking season and the 2011 milking seasons found similar overall per cow energy consumption. Overall there was a 42% increase in the use of energy efficient equipment between 2004 and 2011 (Table 1). The Miller & Glenn (2011) study considered a wider array of technologies.

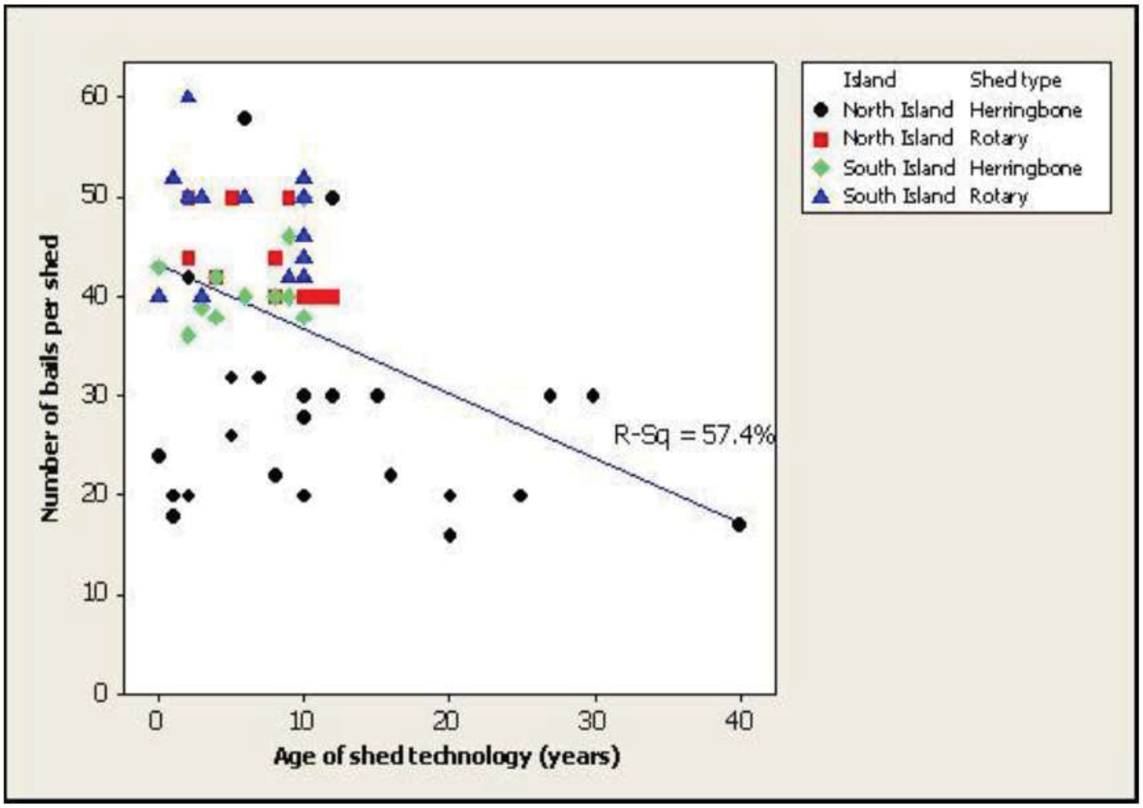

Figure 6: Milking shed age and type with number of milking bails in both North and South Island (Sims *et al.*, 2004)

Table 1: Energy efficient technology adoption in dairy sheds in 2004 and 2011 as shares of total number of sheds in the study (Miller & Glenn, 2011; Sims et al., 2004).

	2004	2011
Change from twice per day hot wash to once per day	5%	68%
Refrigeration heat recovery/heat pump	12%	25%
Other hot water preheats (solar/wastewater heat recovery)		5%
VSD vacuum pump		29%
Milk vat insulation	10%	19%

During the seven years between the two studies there was a major change from twice a day washing of the milking plant to once per day (Table 1). For the farms that continued with two hot washes the primary reason was to maintain milk quality due to concerns about their milking plant (Miller and Glenn, 2011).

Both studies found milking machines consumed 18% of total electricity demand in the shed. Sims *et al*. (2004) found water heating and refrigeration to make up a large percentage whereas Miller & Glenn (2011) found effluent and water pumping to be higher. The difference between the studies may be due to increasing usage of energy efficient technologies in refrigeration and water heating over the seven years as more new sheds were constructed (Table 1).

Based on the literature, there was no evidence of a trend towards dairy sheds reducing their total energy consumption although the limited number of studies of varying power and methodologies means that no significance can be attached to the changes in total energy consumption. In New Zealand however, between 2004 and 2011, there was a notable uptake of energy efficiency technologies such as in vat insulation, variable speed drive vacuum pumps, refrigerant waste heat recovery as well as changes in practice such as reducing the number of hot washes performed per day. While no reduction in overall energy consumption per cow occurred the composition of this consumption changed (Table 2).

Table 2: Electricity consumption by milking shed equipment as a percentage of total electricity consumption

Study	Milking machine	Refrigeration	Water heating	Water pumping	Effluent pumping	Other
Sims et al (2004)*	18%	21%	31%	18%	12%	0%
Miller & Glenn (2011)*	18%	17%	24%	22%	9%	10%
Morison et al. (2007)*	17%	20%	29%	34%		
EECA (2000)*	26%	21%	32%	10%		11%
Upton et al. (2013)**	20%	31%	23%	5%		21%

From farms in: *New Zealand and **Ireland

2.5 Comparison of Irish and New Zealand farming systems

In 2015 the average Irish dairy farm had 68 cows with each cow producing 393 tonnes of milk solids at a stocking rate of 2.03 cows per hectare (Teagasc, 2015). The use of winter housing is common practice (Teagasc, 2015).

The study average energy consumption was 249.13 kWh/cow of which 80% was used for milk extraction and the remaining 20% for other purposes such as winter housing and filling drinking troughs (Upton *et al*., 2013). There were 22 farms surveyed as part of the study. None of the farms in the survey used a variable speed drive (VSD), 21 of the farms used water pre-cooling, 20 farms used a standard electric water heating system and the others used oil fired boilers; four farms used an ice bank milk cooling system and the other 18 farms used a direct expansion system also commonly used in NZ (Miller and Glenn, 2011; Upton *et al.*, 2013).

When comparing New Zealand studies to a study conducted in Ireland by Upton *et al*. (2013), there was a notable increase in the electricity consumption of the refrigeration systems. Regulation for milking requires vats to be cooled to below 4℃ within 30 minutes of milking completion (Murphy *et al*. 2013). In New Zealand cooling temperature target is to reach 6℃ within 2 hours (Barker, 2015).

The effect of the different regulations between New Zealand and Ireland meant that on a per unit basis, Irish refrigeration systems required a higher capacity. The use of water for pre-cooling milk before it reached the vat was also less common in Ireland than it is in New Zealand where it was ubiquitous (Miller and Glenn, 2011; Upton and O'Brien, 2013)

Irish dairy farms in this study used more electricity per cow than non-irrigated dairy farms in New Zealand.

2.6 Seasonality in electricity demand

The average electricity demand of 22 Irish dairy farms monitored over one milking season was linked to the seasonal milk production curve (Fig 7). Milk cooling showed the highest correlation with the production curve (R=0.99). All but four farms used a direct expansion cooling system in which the cooling requirement is dependent on the inlet temperature of the milk, the milk volume and other environmental factors such as ambient temperature, solar radiation and wind speed (Morison, Gregory and Hooper, 2007).

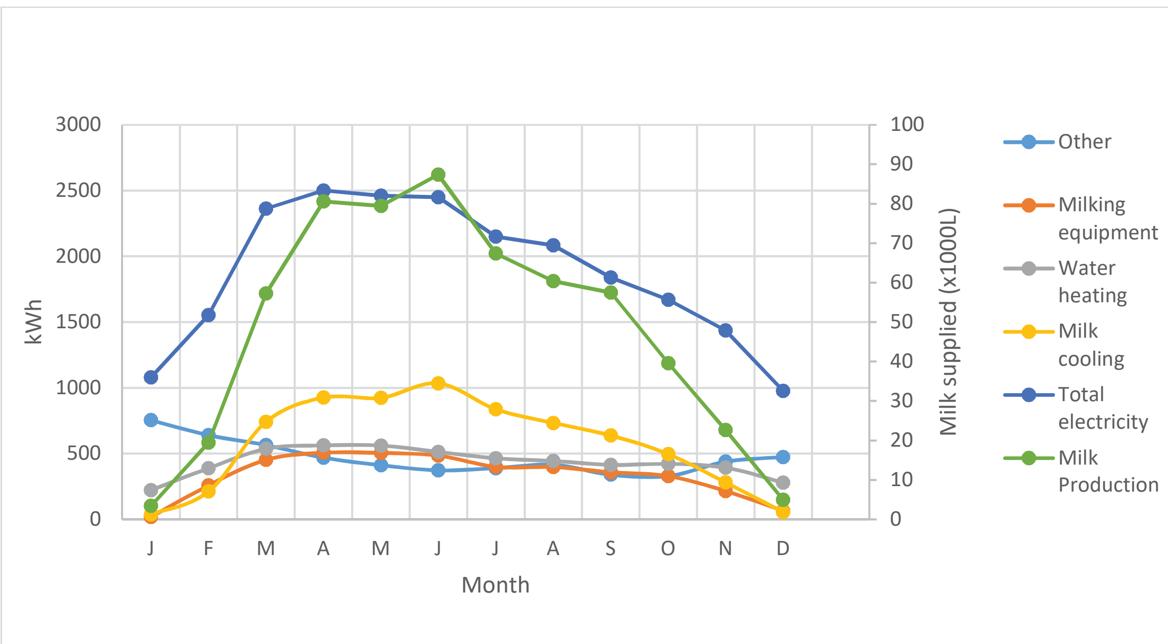

Figure 7: Seasonal trends in milk production and electricity consumption for 22 Irish dairy farms (Upton *et al.*, 2013)

Milking equipment was highly correlated with the production volume (R= 0.95). Electricity consumption at each milking was dependent on the number of cows, average milking cluster cycle time and milking machine size (Upton *et al.*, 2014). In a conventional milking system with a fixed speed milking pump the electricity consumption will depend on the time taken to milk the cows. A variable speed drive vacuum pump allows electricity demand to vary in response to the instantaneous demand, thus reducing the overall energy consumption whilst coupling it more closely to production (Sims *et al*., 2004; Upton *et al*., 2015). Water heating was also correlated with the milk production curve (0.90) though this is not well represented in the literature. Hot water is required to clean the milking plant. The amount used was fixed based on the number of units in the milking plant, water cylinder inlet temperature and environmental conditions (Upton *et al.*, 2015a). Other electricity consumption was not correlated with the production curve (R=-0.57). Other consumption includes high-pressure pumping for washing down the shed, water pumping, lighting, effluent pumping and motorised manure scrapers. The lack of correlation between the production curve in this category was due to using winter housing of dairy cattle in the Irish dairy sector. Winter housing is not commonly used in New Zealand and therefore this trend is not relevant to New Zealand dairy electricity demand. In New Zealand the national milk production curve (Fig 8) and the seasonal trends in production and electricity consumption are similar with peak demand occurring in the December/January period although the 2012 seasonal peak occurred in October and November (Fig 8).

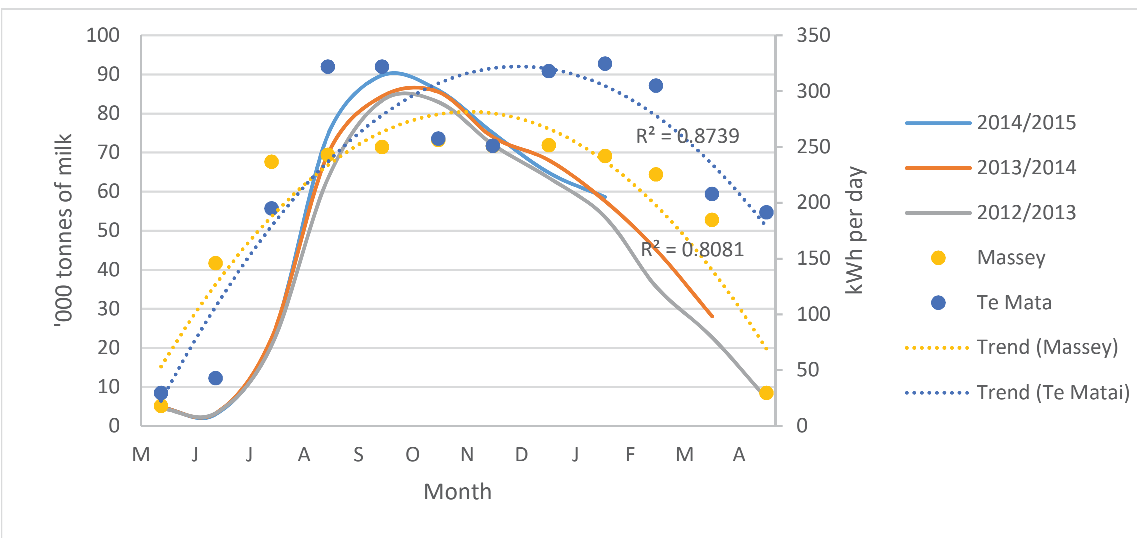

Figure 8: New Zealand milk production for three milking seasons beginning in May (solid line) and electricity consumption on two dairy farms at Massey University and on Te Matai road, Palmerston North (points)

The limited data for New Zealand has shown that electricity demand does follow milk production broadly (Fig 8). The more detailed Irish data showed a strong correlation between the production curve and milk refrigeration, water heating and vacuum pump but no correlation between other types of electricity consumption (Fig 7). Milk refrigeration, water heating and vacuum pump technology were also used in New Zealand.

2.7 Daily load profile

The daily load profile of a New Zealand dairy farm has been characterised by a period in the morning and afternoon of high electricity consumption. The morning peak typically began between 5:30 a.m. and 7 a.m. The afternoon milking typically began between 3:30 p.m. and 4:30 p.m. Milking took between two and three hours in the morning and one and a half to two and a half in the afternoon, depending on the number of cows and size of shed (Process Developments Limited, 2004). The major loads during this time were the milking machine, vat refrigeration unit, water pumping and lighting (Upton *et al.*, 2013). In three case study farms from Sims *et al*. (2004) peak consumption occurred when milking was complete and plant clean-up was occurring. During this time extra pumps were turned on to run the wash down hose and hot water was being consumed meaning that often the hot water element would be on unless on a timer or under ripple control. When the plant had been cleaned, most of the loads were turned off and typically the only remaining devices running were the chiller and the hot water cylinder. Overnight electricity consumption was very low unless the farm had a means of load deferral such as a time-clock on the hot water cylinder or an ice bank system which builds ice overnight for cooling milk after milking.

2.8 Daily milk production

Most farms milk twice per day. The volume of milk produced is typically split on a 6/4 ratio between the morning and night milking (Woods, 2007). This ratio depends on the amount of time in between each milking. If milking time is changed significantly from the typical ranges discussed in Section 2.7 this ratio would be affected. The frequency and time of milking also affect the volume of milk produced (Davis, Farr and Stelwagen, 1999).

2.9 The refrigeration and milk storage system

All the New Zealand dairy farms surveyed used a direct expansion cooling system combined with a heat exchanger (Miller and Glenn, 2011). In these systems, the evaporation plate of the system is in direct contact with the bottom of the milk tank. The refrigerant absorbs the heat from the milk and expands. The heat exchanger uses water to bring the temperature of the milk down before it enters the milk vat and is cooled by the direct expansion cooling system. Some farms supplement their direct expansion cooling system with additional pre-cooling systems.

These add a second stage heat exchanger to cool the milk to a lower temperature than can be achieved with ground water before it reaches the milk vat and therefore reduce the load on the direct expansion cooling system. Precooling can include some form of energy storage such as the use of an ice bank. This allows the electricity used to be deferred to a cheaper night rate so that it does not have to occur at time of milking. This has benefits in a grid connected farm because it reduces the peak demand. This is also of interest for off-grid farms because it allows the cooling load to be shifted into times when solar energy is available while still cooling milk at time of extraction, meeting regulatory requirements. Inside the milk tank there is some form of agitation to prevent freezing of the milk to ensure even milk temperature. The typical milking system is shown in Fig 9.

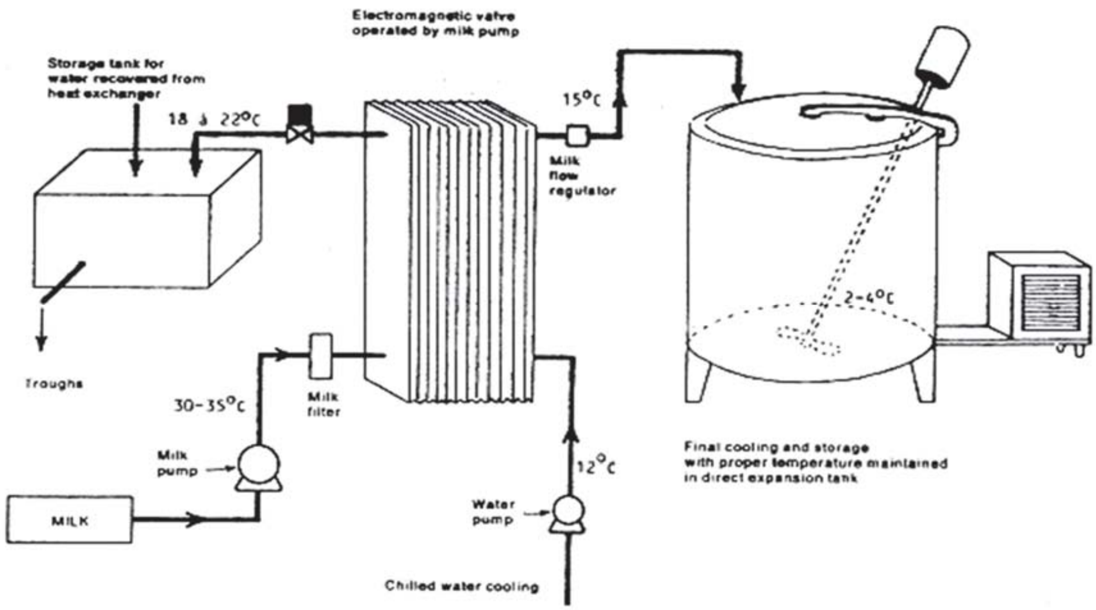

Figure 9: Typical direct expansion milk cooling system (Belloin, 1988)

Milk is harvested at 38°C and is collected in the milk transfer jar. The warm milk is then passed through a plate cooler, which cools the milk to within 5 degrees of the source water temperature. The cooled milk is passed into the milk vat, which cools it further (Madoumier *et al.*, 2015). Assuming a supply of cooling water with a lower temperature than the milk some of this energy can be transferred through a heat exchanger. Whatever remains must be supplied by a refrigeration unit.

New regulations came into force in August 2016 that apply to all new farms and any refrigeration equipment upgrades. The old regulation for milk cooling in the milk vat was:

1. cool to 18℃ at the completion of milking;
2. not to exceed 13℃ at subsequent milkings; and

3. cool and maintain at 7℃ or below 2 hours after milking completion.

In the new regulations milk must be

1. cooled below 10℃ within four hours of milking commencement;
2. cooled to 6℃ within the sooner of;
    a. six hours of milking commencement;
    b. two hours of milking completion;
3. cooled and maintained at 6℃ or below;
4. not exceed 10℃ at subsequent milkings; and
5. for continuous milking systems milk must enter the milk vat at 6℃ or below (defined as any milking system that operates for more than six hours from the time when milk first enters that vat) (Barker, 2015).

The new regulations will be extended to all farms in 2018. This will require more energy to be expended to a lower temperature for a longer period thus increasing the cooling demand.

Heat gains in milk are dependent on the R-value[1] of the milk vat, the surface area of milk vat, the ambient temperature, the incident radiation and the wind speed (Morison, Gregory and Hooper, 2007). Insulating the milk vat increases the R-value and therefore decreases heat gain from the environment. Housing the milk vat inside typically reduces the heat from the environment as well. Heat gain is reported in the literature either as a percentage of the total refrigeration load, an average heat gain in kilowatts or as a daily heat gain in degrees centigrade.

Two studies from outdoor milk vats in the South Island found heat gains of 20% of total refrigeration energy in one case and 13% in another (Morison, Gregory and Hooper, 2007). In the first farm this equated to a heat gain of up to 6 kW. Heat gain in lower North Island farms was found to be 11% in one case study and 1% in two case studies (Sims *et al.*, 2004).

The use of insulation can reduce the heat gain from the milk vat by between 46% and 80% (Sims *et al.*, 2004; Morison, Gregory and Hooper, 2007). 75% of North Island farms in the 2011 survey had no insulation on their milk vat. Most these milk vats were located inside. In most cases milk vat insulation makes financial sense and has a payback of less than five years (Wilson *et al.*, 2004).

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[1] R Value describes a material's ability to transfer heat. A high R Value indicates poor heat transfer. The SI unit is $1\ K \cdot m^2/W$ (Kreith, Manglik and Bohn, 2012)

2.9.1 Direct expansion cooling system

The standard value for COP (coefficient of performance) of a direct expansion cooling system in the literature is 3 (Morison, Gregory and Hooper, 2007; Sapali *et al.*, 2014; Rajaniemi, Turunen and Ahokas, 2015). This was dependent on the average ambient temperature at the farm, the quality of equipment, installation and maintenance and the target milk vat temperature. In a study of three large South Island farms' average COP there was large variation. One of the farms had a COP[2] between 3.8 and 1.4 with an average COP of 2.7. The other two recorded considerably lower COP averaging 1.86 and 1.55 (Morison, Gregory and Hooper, 2007). These were both considerably lower than the recommended COP standard accepted value of three. The causes related to lack of maintenance of the refrigeration subsystem. Chiller capacity did not vary substantially. The average size of chillers was 4.95 kW across both North and South Islands (Sims *et al.*, 2004).

2.9.2 Heat exchanger

Dairy farms use heat exchangers to cool milk before it reaches the milk vat. Most farms surveyed used plate heat exchangers (Miller and Glenn, 2011). These are a series of staked stainless steel plates with grooves cut in each plate in such a way that two streams of fluid can pass through the heat exchanger taking the longest path without contact. The water most commonly used as the source of the cooling water was ground water. The milk and coolant flow through the heat exchanger in opposite directions. The temperature difference between the water in and the milk out is referred to as the temperature approach. The temperature approach is dependent on the flow ratio of the two fluids and the heat exchanger surface area between the two fluids (Murphy, Upton and O'Mahony, 2013). Manufacturers claim temperature approaches of 2-4°C (Morison, Gregory and Hooper, 2007). The instantaneous flow of milk and water are extremely important in achieving low temperature approaches. The heat exchanger does not consume any energy itself. Its load is related to water and milk pumping. The size in terms of number of plates and milk flow ratios of the heat exchanger will cause the pumping requirements to be greater due to the increased resistance to flow that comes of increasing fluid flow over increasing area.

[2] Coefficient of performance (COP) is a ratio of the amount of useful work done by a refrigeration system with the amount of input work required (Stachowiak and Batchelor, 2013).

2.9.3 Milk vat insulation

There are a large range of products available for insulating milk vats offering different performance or R values. A midrange product such as Thermo wrap insulation yielded savings between 11 and 17% (Genesis Energy, 2013). The installation cost was estimated to be $900 for smaller farms and up to $1700 for larger farms. Simple payback times for this technology were estimated to range from between 7.6 years in the case of the small farm down to 3.4 years for the large farm (Genesis Energy, 2013). Based on the price increases between the different sized farms, there was a fixed cost of $877.85. The cost rose at $0.8741 per additional cow on the farm (Genesis Energy, 2013).

2.9.4 Storage of cold thermal energy

Cooling systems that use a secondary heat transfer fluid to cool the milk were of interest within the study because they allow the storage of cold thermal energy. This allows the electricity demand to be decoupled from the milking cycle, which allows the cooling system to replenish the thermal storage with solar energy. The most common types of cooling system used on dairy farms are ice banks and cool water storage (Morison, Gregory and Hooper, 2007).

Ice banks build ice within an insulated container using a dedicated compressor, a pump and a heat exchanger with a heat transfer fluid such as ethylene glycol. This cools the milk during milking before it reaches the milk vat. Ice banks use the latent heat of fusion of water along with a small amount of sensible heat to store energy. This means that they can store a relatively large amount of energy within a compact space. One cubic metre of ice can store 85 kWh of energy at a temperature of 0°C. In an actual ice bank system, much of the volume within the insulated container is taken up with the transfer pipes to allow ice to be generated quickly and efficiently. Ice banks are reported to be less reliable than chilled water systems and to remain efficient, need to be fully discharged after each cycle. Ice generation requires an evaporator temperature of less than 0°C. This means that ice banks have a lower Carnot efficiency[3] when compared with conventional direct expansion cooling systems and water-cooled systems (Murphy, O'Mahony and Upton, 2012).

Water bead systems use encapsulated water or other fluid with a high latent heat of fusion within a plastic shell. These are then put into a tank and surrounded with ethylene glycol. The system is a hybrid of the ice bank and the cold-water storage systems. The primary means of energy storage is latent heat. A tank is filled with liquid and this liquid is circulated through the heat exchanger when

[3] Carnot efficiency is a theoretical maximum efficiency of a heat engine (Kreith, Manglik and Bohn, 2012).

required for cooling. These systems do not have the same reliability issues as ice banks and do not need to be fully discharged every cycle but have a similar efficiency.

The coefficient of performance of an ice bank would be expected to be lower than the performance of a direct expansion cooling system due to the lower evaporator temperature (Upton *et al.*, 2015b). Many of the tests performed on ice bank systems have been based around load shifting between daytime hours and night-time hours. This has two benefits; firstly, many electricity companies offer low rate night-time electricity, secondly night-time temperatures tend to be lower than daytime temperatures which results in a higher coefficient of performance. Some manufacturers have used a water-based cooling system for the condenser which reduces the impact of the ambient temperature on the coefficient of performance.

Public information was extremely limited on the costs of these systems. The only manufacturer willing to give an approximate cost for comparison for an ice bank system being used in the Lower North Island was SnapChill Ltd. A SnapChill Ltd ice bank could supply 75% of the daily cooling load on farms with up to 600 cows at a cost of $4500 excluding GST this includes the cost of a superheat heat pump (Stone, 2016).

2.10 Groundwater temperature

The temperature of the water used affects the performance of the dairy shed. The temperature of ground, roof or river water is important because it is used to cool milk and is also heated to supply the hot water system. The ground water temperature of an aquifer system approximates the temperature of the recharge water or the recharge area atmospheric temperatures. Shallow aquifers will vary seasonally due to seasonal changes in recharge temperature. The temperature of aquifers throughout New Zealand are not routinely monitored and there were no available long-term datasets on aquifer temperature in the study regions. It was assumed that the temperature of groundwater is consistent with the 1 m depth earth temperature measurement that was available at all three study regions. The earth temperature fluctuates throughout the year. The study used the annual average 1m depth earth between 2000 and 2015 which for the Manawatu region was 14.0°C, for Taranaki 14.9°C and for the Bay of Plenty 15.6°C (NIWA, 2016b).

2.11 Milking machine

The milking machine uses a vacuum pump supply suction that is used in the milking process. The varying pressure supplied by the vacuum pump and a pulsator is used to massage the cow's teats, to draw milk from the cow and to transport it to the milking pump via the milk receiving can. The milk pump then pushes the milk through the plate heat exchanger to the vat (Fig 10). To avoid harming the cows the vacuum must be maintained at a constant level. In most conventional milking systems a vacuum regulating valve is used to maintain a constant vacuum level. Vacuum regulators waste a large amount of energy because their means of regulation is to allow air into the system thus reducing the level of vacuum.

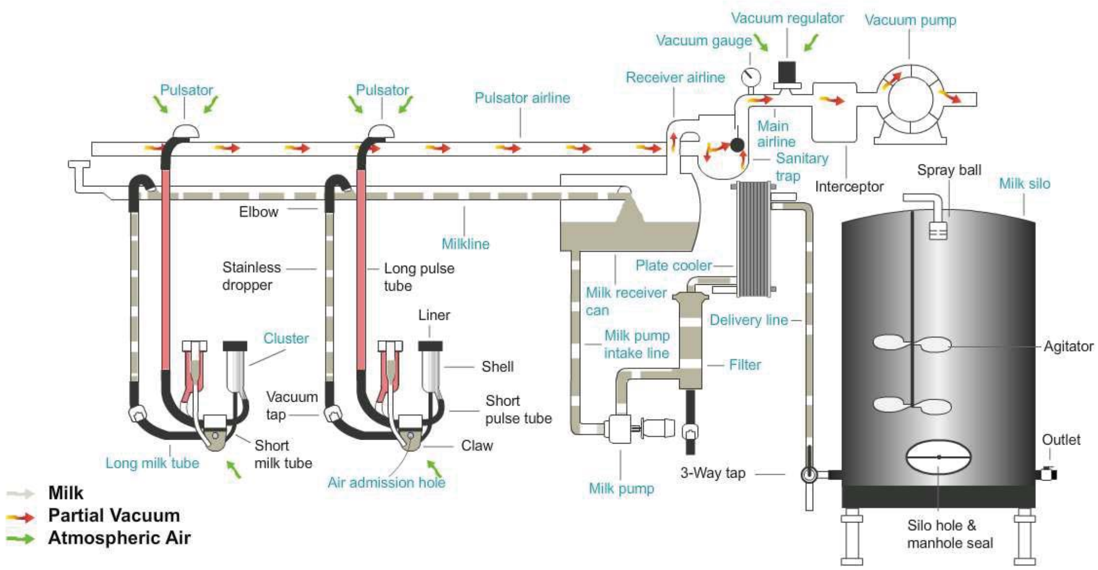

Figure 10: Diagram of milking machine (DairyNZ, 2017b)

One means to improve energy efficiency is by using a VSD vacuum pump which can regulate vacuum without the need for a regulator.

The relationship between milk production and milking time was weaker than milk chilling as discussed in Section 2.5. Overall time taken by milking was most influenced by dairy shed work practice. There was a fixed time component associated with milking each cow. This was required to allow the cows to enter and exit the milking area, to apply pre- and post-treatments to the cow's udders before beginning milking and time lost due to machine downtime whilst transferring clusters between cows or due to inefficient working practices. The work practices chosen by farmers determined the amount of time used by each of these components. This remained relatively fixed throughout the milking season and the only aspect that influenced it substantially is the number of cows within the herd.

There was also a variable component associated with the actual extraction of milk. However, decisions about working systems could also have influence on this. Farmers could influence the amount of time spent milking by using pre-treatment (O'Brien *et al.*, 2012) and by changing the amount of suction provided by the milking machine however this could affect cow-health which was more important to the farmer's livelihood than milking times (Besier and Bruckmaier, 2016).

'Max T' is a system promoted by Dairy NZ. It sets a maximum limit on time of milking. This can substantially reduce the milking rotation time because it minimises operator idle time waiting for the slowest 20% of cows to complete their milking (DairyNZ, 2015c). The Max T data from Dairy NZ fits a linear trend line with a R2 =0.99 (Fig 11).

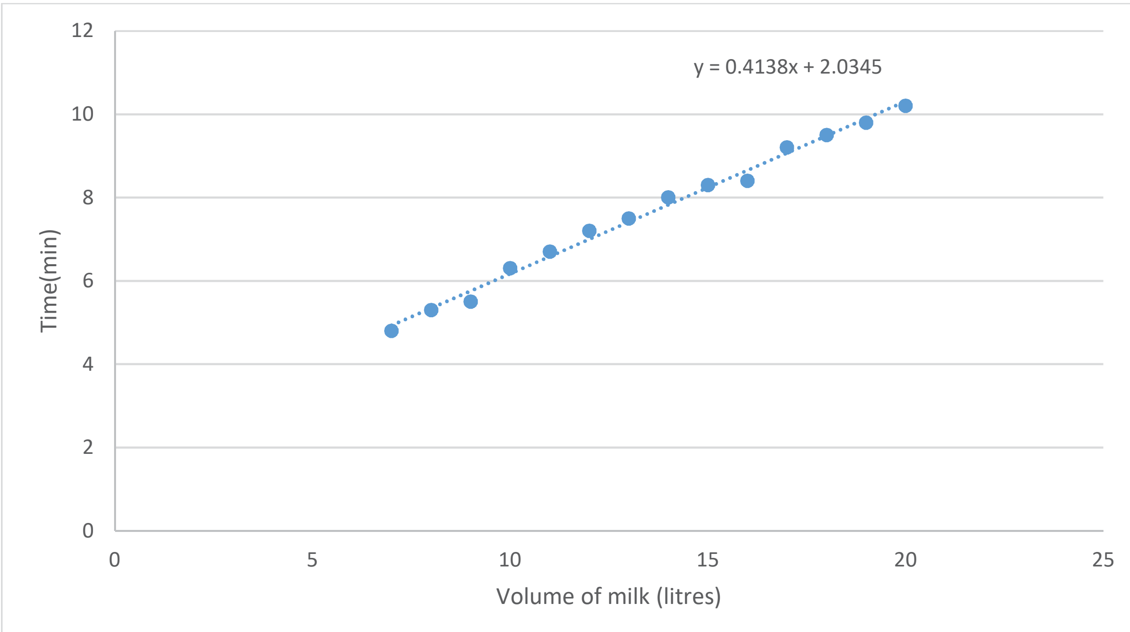

Figure 11: Maximum time to milk a cow based on its milk production using the 'MAX T' milking time system (DairyNZ, 2015c)

The Max T system only accounts for time spent when milking is taking place. There is also time associated with preparing cows for milking for example the time it takes to move cows into place and wash udders. In rotary sheds of between 14 and 30 clusters this took between 0.7 and 2.0 minutes (O'Brien *et al.*, 2012) depending on the pre- and post-milking routine, number of clusters in the shed, season and the amount of idle time.

Variable speed drive vacuum pumps have been shown to reduce electricity consumption. The amount of reduction varied widely between sources (Table 3). Variable speed drive milking pumps were installed in more than a quarter of farms. These tended to be the larger new farms because the payback on investing in variable speed drive technology was better as pump size increased (Miller and Glenn, 2011).

Table 3. A variable speed drive vacuum pump's effect on reducing electricity consumption

Study	Reduction range	Notes
Upton *et al*. (2015)	52-65%	
Sims *et al*. (2004)	45-73%	In comparison with similar farms
Morison *et al*. (2007)	34-55%	
DairyNZ (2014)	10-15%	Of total electricity consumption

Costs of VSD vacuum pumps did not correlate well on a per cow basis and fitted better to a per kilowatt of pump size (Fig 12). The high initial cost of VSD vacuum pumps showed why the savings for larger farms were disproportionately greater than for smaller farms.

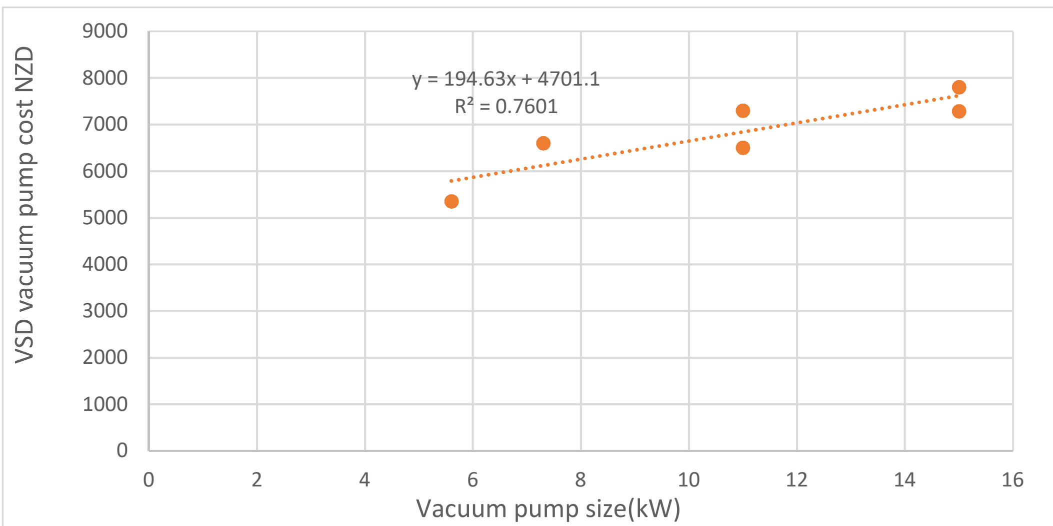

Figure 12: The installed cost of a VSD vacuum pump on 6 farms (Morison, Gregory and Hooper, 2007; Genesis Energy, 2013)

2.12 Hot water system

The milking machine and milking vat require thorough cleaning with hot water at least once per day during the milking season. Around 10l of hot water per set of cups and 2% of milk vat volume for cleaning is recommended (DairyNZ, 2017e). The plant needs to be pre-heated before the hot wash can occur.

Most farms use a conventional electric hot water cylinder with a resistive element. Water is typically sourced from ground water. Refrigerant superheat heat pumps can be used to improve the efficiency of heating hot water. These systems are connected to the condenser of the refrigeration system and use the ejected waste heat to heat hot water. This has been shown to dramatically reduce hot water related energy consumption (Miller and Glenn, 2011).

The coefficient of performance of the superheat heat pump in part depends on the evaporator temperature used. An ice bank evaporator temperature will be lower than direct expansion systems and therefore the amount of superheated refrigerant available at the condenser will be greater than direct expansion systems.

Few studies have looked at the coefficient of performance of superheat heat pumps in applications like dairying. One study showed reductions in heating electricity used from 88 kWh/day to 39 kWh/day which is a saving of 56% and would indicate a coefficient of performance of 2.2 (Morison *et al.*, 2007). SnapChill Limited indicated a coefficient of performance of 4.2 (Stone, 2016).

2.13 Water pumping

The amount of energy required for pumping is highly dependent on the source of water for the farm. In some cases, water can be sourced from gravity fed systems which means pumping requirements would either be very low or zero. Most commonly water is sourced from ground water which requires pumping into the dairy shed. Water is used for cooling milk, cleaning, and drinking water for stock. The volume of cooling water required depends on the configuration of the heat exchanger (Section 2.9.2). The cleaning water can be sourced from the cooling water. Lactating cows drink 70 litres per day and dry cows drink 45 litres per day (DairyNZ, 2012).

2.14 Effluent pumping

The effluent pump is only used during the time of the year when the shed is operating. Effluent is pumped from the storage pond onto the paddocks. This adds back some of the nutrients lost and adds to soil moisture. Effluent can only be applied to the paddocks when there is a soil moisture deficit and the volume cannot exceed the soil's field capacity (DairyNZ 2015a). This is to avoid run-off occurring from land (DairyNZ, 2015b). Most councils require a certain amount of storage which is determined by a farm's location and soil conditions (DairyNZ, 2015b).

This operation is concentrated in the summer months. Effluent application begins in October and finishes in May. The irrigation effect of applying effluent to land has no benefit in terms of pasture growth. The loss of water due to evaporation due to application in the middle of the day has no effect on the farm's productivity (Goold, 1980).

Effluent pumps operate for three hours per day on average during the milking season (Process Developments Limited, 2004) which on average consumes 15.6kWh/cow/year (Miller and Glenn, 2011). Reducing the volume of effluent and water entering the pond were the only mechanisms identified to reduce effluent pumping energy (Miller and Glenn, 2011).

2.15 Biogas

Biogas can be produced from the anaerobic digestion of dairy effluent. The use of effluent to produce biogas is relatively uncommon on New Zealand farms (Milet *et al.*, 2015). Internationally, biogas production has been growing rapidly particularly in Europe where by the end of 2014 there were over 17,000 active biogas plants. These were a mix of landfill gas, sewage, sludge gas and agricultural gas plants (Capodaglio, Callegari and Lopez, 2016). Greenhouse gas emissions associated with effluent ponds made up 6% of the on-farm methane emissions (MfE, 2016a). This could be higher considering recent findings that estimates of methane emissions used in the New Zealand greenhouse gas inventory were low (Laubach *et al*. 2015).

The mechanism used to produce biogas is selected based on what feedstocks are available, volume of feedstocks available, climatic conditions and aim of production. The highest yield of biogas is derived from thermophilic biogas reactors which operate at high temperatures. Biogas on dairy farms is produced in low temperature systems that are primarily designed for the treatment of effluent so that it can be discharged. These are an example of mesophilic reactors. Mesophilic reactors tend to produce less gas at a lower rate.

77% of New Zealand dairy farms use anaerobic ponds to treat waste water which is then expelled onto land (Laubach, Heubeck, Pratt, K. B. Woodward, *et al.*, 2015). It is expected that almost all dairy farms in New Zealand will use anaerobic ponds for wastewater treatment in the future (Laubach, Heubeck, Pratt, K. B. Woodward, *et al.*, 2015). A by-product of this treatment process is biogas which in most cases is released directly into the atmosphere.

The areas where cows spend enough time for effluent to be collected are the milking shed and can also include feed pads and winter housing. While usage of winter housing remains relatively low, feed pads are becoming increasingly common as dairy farming intensifies. Luo *et al*. (2013) found that 27% of New Zealand farms used feed pads. The milking shed generated 0.36 kg total solids (TS)/cow/day and 0.25 kg volatile solids (VS)/cow/day based on an assumed 6% of total excretions occurring in the wash down area of the dairy shed (Vanderholm, 1984). Other studies have estimated that cows spent between 5% and 10% of the day in areas where the manure was able to be captured resulting in a range of 0.175 to 0.35 kg VS/cow/day (Longhurst, Roberts and O'Connor, 2000; Ledgard and Brier, 2004; Stewart and Trangmar, 2008).

The amount of digestible material entering anaerobic digestion ponds in two locations, one in Southland New Zealand and the other in Northland New Zealand, found production rates of 0.18 and 0.16 kg VS/cow/day between the two sites. A site using more intensive farming methods with a feed pad found 0.82 kg VS/cow/day (Heubeck, Nagels and Craggs, 2014).

The technology of an anaerobic pond has been described by Craggs & Heubeck, (2008) and Heubeck & Craggs, (2010). The amount of gas produced from ponds was dependent on the number of volatile solids added into the system and pond temperature and bacterial type (Table 4). The annual production was highest during the summer months and dropped through the winter months (Heubeck & Craggs (2010); Park & Craggs (2007). The purpose of anaerobic ponds on dairy farms is to remove volatile solids and biochemical oxygen demand through sedimentation of solids in the wastewater stream and not to maximise production of methane.

Table 4: Studies of biogas production from effluent ponds from New Zealand (NZ) and International sources (IN)

Study	$m^3 m^{-2} day^{-1}$	$m^3 kgVS^{-1}$	*Notes*	
McGrath & Mason, (2004)	0.012–0.06			IN
Park & Craggs, (2007)	0.03	0.7[a] 0.54[b]	Biogas[a] Methane[b]	NZ
Miranda *et al*., (2015)		0.25-0.45	Mean of meta-analysis	IN
Heubeck *et al*., (2014)		0.21,0.22,0.29	Southland, Waikato and Northland	NZ
Stewart & Trangmar, (2008)		0.24	IPCC Default	IN

Agricultural GHG are not currently included in the Emissions Trading Scheme (ETS) (MfE, 2016b). Agriculture was originally scheduled for introduction by government in 2015 but an Amendment in 2012 removed the scheduled introduction date stating that until there was an economically viable means to reduce GHG biological emissions agriculture would be exempt. However, farmers are required to account for and report on GHG (MfE, 2016b). There is currently no time frame for agriculture's participation in the ETS. If methane GHG is captured and combusted either by flaring or used to produce electricity, overall GHG are reduced when compared to the same gas being released directly into the atmosphere.

Methane has a 100-year direct global warming potential of 25 therefore by combustion of methane before release into the atmosphere there is a 25-fold reduction in GHG emission from the source (Forster *et al.*, 2007).

Biogas will not undergo compression ignition in a diesel generator but in dual fuel systems a small amount of diesel can be injected into the generator to provide an ignition source. This is referred to as the pilot fuel. Pilot fuel volumes are a low 2-3% of total combustion volume (Bedoya, Arrieta and Cadavid, 2009). The combustion products of the dual fuel system result in lower NOx and CO production under load but typically result in higher hydrocarbon emissions especially under partial loading conditions. However, with changes to the inlet system of the generator this could be mitigated (Bedoya, Arrieta and Cadavid, 2009). Yoon & Lee (2011) found that dual fuels systems had a 5% lower efficiency when compared to conventional single fuel systems. This was due to biogas residuals, combusted residual gas, low combustion temperatures, higher total fuel flow rate during the combustion process and a lower flame rate. The system performed best under full loading with dual fuel efficiency decreasing faster than single fuel under partial loading (Mustafi, Raine and Verhelst, 2013).

Covering the existing anaerobic lagoon on a dairy farm reduced the capital costs of capturing biogas significantly when compared to the use of a dedicated bio digester although the former technology comes with disadvantages relating to the size of the collector, its reliability and the volume of production (Table 5). The two studies show a general agreement of capital costs for the installation of the system; however the maintenance costs were considerably different between the two studies (Table 5).

Table 5: Capital costs for a biogas collection cover over a lagoon including gas collection, rain water removal, piping and installation and maintenance costs for biogas systems

Capital costs	$	Life time	Source
Biogas collection cover ($/m2 installed)	20 - 25	20	(Craggs and Heubeck, 2008)
Biogas collection cover ($/m2 installed)	29	20	(Stewart and Trangmar, 2008)
Operational and maintenance costs ($/year)			
All costs	8800		(Craggs and Heubeck, 2008)
All costs	14,000		(Stewart and Trangmar, 2008)

2.16 Fuel prices

While international oil price is a key influence over the oil price paid by consumers there are also factors such as levies and local market competition that determine the oil price. All fossil fuels are included in the Emissions Trading Scheme (ETS). This represents a significant uncertainty in fossil fuel prices. New Zealand's participation in international agreements to address climate change such as the Paris climate change agreement ratified in October 2016 (Ministry for the Environment, 2016) indicated that New Zealand would continue to implement policies to reduce greenhouse gas emissions. The IEA 2040 price projections for the international oil market contain four scenarios (Table 6). These prices would not necessarily be reflective of the price paid at the pump. The price paid by New Zealand diesel consumers depends on future changes within the world market participants and actions by the New Zealand government and oil retail companies operating within New Zealand.

Table 6: IEA oil and carbon priced scenarios to 2040 in USD (IEA, 2015)

IEA price scenarios	Oil price (USD/barrel)			Carbon price(USD/t)		
	2020	2030	2040	2020	2030	2040
Current	83	130	150	20	30	40
New	80	113	128	22	37	50
450	77	97	95	22	100	140
Low oil	55	70	85	22	37	50

Currently, New Zealand purchases its crude oil for import from the Dubai exchange. The trends in price between the Dubai exchange and the IEA price vary slightly. Between 2000 and 2015 the Dubai price has been 11% higher on average than the IEA scenario price (MBIE 2015). Taxes on these have all been relatively stable over the past 15 years (MBIE 2015). The introduction of the ETS in 2008 with participants to begin surrendering credits in 2010 was the only change within that period. Carbon prices were capped at NZD25 per tonne of CO_2.

The importer's gross margin is a major variable in the short-term price difference between the oil market and the price paid by consumers. Some literature has suggested that market participants are faster to respond to price increases in the international price than decreases (Liu, Margaritis and Tourani-Rad, 2010). However, government agencies contend that the New Zealand oil market is competitive and that the market responds evenly for both price increases and price decreases (MBIE, 2016). There is inherent uncertainty in future commodity prices. Oil and carbon prices (Table 6) give a range of possiblities to guide the development of a New Zealand fuel price scenario that will be used in the fuel price sensitivity analysis in Section 5.

3 Dairy farm model

A dairy farm model was developed to assess the electricity consumption of a dairy shed on a half-hourly basis for one year. The dairy farm model used a mechanistic approach to modelling the electricity consumption of individual components and processes. While there were many options for modelling such as regression modelling and artificial neural networks; these were better applied as generalisation tools linking variables and making predictions, for example predicting electricity consumption based on milk yield. The mechanistic approach was used in this study because it allowed for the analysis of the effects of different technologies on electricity consumption with relatively few data points. This allowed new technologies to be modelled without the need to undertake a large data gathering campaign. Effluent and water pumping was not modelled mechanistically because of the lack of reliable data and the dependence of these processes on very site specific inputs such as ground water bore depth and soil type. The methodology was adapted from Upton *et al*. (2014) and Process Developments Limited, (2004). The farm model was regionally dependent meaning that each of the three regions covered in the study had a distinct electricity consumption curve based on the milk production curve.

The subsections detailed the methodology used to model the dairy shed components: direct expansion refrigeration system, heat exchanger, vacuum pump. Each subsection has detailed the methodology used in each component. Electricity consumption was determined for standard equipment used by most dairy sheds and for equipment that could be used to improve efficiency or to shift electricity demand. Milking was assumed to start at 6:30 am and afternoon milking at 4:30 pm (Section 2.7).

This model only considered herringbone milking sheds. Herringbone milking sheds are the most common type of milking shed used in New Zealand (Section 2.1). Other types of milking shed such as rotary milking sheds can be modelled; however, there was no data available on the energy consumption of the rotary platform.

3.1 Description of scenarios

The base farm model scenario represented a typical grid connected dairy shed in the North Island in terms of, milk production, energy consumption and system components. The milk production component of the model was constructed to reflect regional averages. The model used energy efficiency measures that have been adopted by the majority of farms in New Zealand (Table 1). The system component sizes were taken from (Process Developments Limited, 2004) who presented these as representing a typical New Zealand farm. The result of this process was then benchmarked in Section 4 to ensure that system electricity consumption was close to the North Island average. Where possible, loads such as pumping and hot water had been shifted into the daytime so that they utilised solar energy, but these represented very small investments that were not accounted for in the model. The base farm model scenario was then modified by adding one component at a time to evaluate its effectiveness at improving energy efficiency or shifting a load. Six technologies were considered that modified the electricity demand or changed the energy source of the base farm model scenario. These were:

1. Milk vat insulation
2. Variable speed drive vacuum pump
3. Superheat heat pump
4. Ice bank
5. Hot water heat recovery from the generator
6. Biogas

These technologies have been discussed individually in Section 2.

The “technology scenario” considers how a selection of these technologies individually and in combination affect the NPC of the whole system. The “technology scenarios” only consider, milk vat insulation, variable speed drive vacuum pumps, superheat heat pumps ,ice banks. Hot water heat recovery was not included in this first round of simulation because it requires a large amount of post simulation processing to determine whether the system is technically feasible.

The technology scenario tried all possible combinations of milk vat insulation, variable speed drive vacuum pump, superheat heat pump and ice bank to find best mix of technology for a dairy shed supplied by a stand-alone power system for the three farm sizes(Appendix 2). Other technologies; biogas and generator heat recovery, were tested with a limited selection of the best performing components from the technology scenario to limit the simulation time and amount of post simulation processing requirements(Appendix 3;Appendix 4).

The regional and fuel price sensitivity scenarios were conducted on the best performing component combinations from the technology scenario for each of the three farm sizes (Appendix 5). Storage sensitivity scenarios tested the effects of modelling a component with the storage associated with it treated as a deferrable load in the HOMER Pro model. The deferrable load model in HOMER Pro allowed greater flexibility in dispatch time. Ice bank, hot water and effluent loads were modelled as deferrable loads. The periods of storage trialled was one and two days for hot water and ice banks., and was seven and 14 days for the effluent pump to reflect the larger storage volume in an effluent pond (Appendix 6). The capital price sensitivity scenario was applied by varying all costs of all the stand-alone power system components; battery, inverter, PV and generator. Capital prices of all these components was varied between 80% and 120% in 10% increments (Appendix 7)

Biogas production from the effluent pond was also examined for cost effectiveness as an energy source to supplement the running of the diesel generator. It would not affect the electricity load of the dairy farm but could offset the cost of diesel (Appendix 6).

3.2 Herd sizes and milk production

The model considered small, medium and large dairy farms in the North Island corresponding with 150, 343 and 700 cow numbers per herd. The range of 150 to 700 cows represents 77% of all North Island dairy herds. Of the remaining 23% of dairy herds, 7% are below the range and 14% above. The medium size represents the average size dairy herd in the North Island (Section 2.1). A herd size of 700 cows and above represents the large size North Island dairy herd.

The production curves for each study region were based on a weekly time step. It was assumed that calving begins on the planned calving date[4] and that weekly calving is evenly distributed around the median calving date[5]. It was assumed that calf births are also evenly distributed throughout that week. Cows are brought back into milk production one week after calving. It was assumed that cows are dried off at the same rate as they are calved. The period that cows were dried off was determined by the number of weeks in milk. Milk production per cow was calculated based on herd testing during the 2014/2015 season (Appendix 1; DairyNZ 2015d).

This approach yielded milk production approximately 10% higher than the average for the region. The differences were likely to be due to cows not remaining productive due to sickness. The scaling factor

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[4] The planned start of calving date is 282 days from the date that mating is started in the herd (DairyNZ, 2015d).
[5] The median calving date is used as an indicator of actual calving spread (DairyNZ, 2015d).

was applied to each of the regions such that the total production was close to the average production. The scaling factor used in the Manawatu is 87%, Bay of Plenty 89% and Taranaki 90%.

3.3 Refrigeration

The on farm refrigeration system electricity consumption was based on Equation 1 (Upton *et al.*, 2014)

$$Q_{mc} = \frac{C_m \cdot \Delta T \cdot V_m \cdot \rho_m}{3600 \cdot COP} \qquad \text{Equation 1}$$

where:

Q_{mc} is the energy required to cool the milk (kWh),

C_m is the heat capacity of milk (J/Kg °C),

ΔT is the temperature difference between the milk as it exits the heat exchanger and temperature setpoint (°C),

V_m is the volume of milk (l),

ρ_m is the density of milk from Madoumier *et al*. (2015) (kg/l), and

COP is the coefficient of performance of the refrigeration system.

To account for the discrepancies between the standard accepted value and the values measured in the field, a COP value of 2.5 was used in the model (Section 2.9).

Vat heat gain was specified in degrees centigrade. The vat was assumed to gain 4°C per day. Fitting insulation reduces heat gain by 75% to 1°C. Equation 1 was used to calculate the operation of the refrigeration system used to counteract the daily heat gain, using the COP of the direct expansion cooling. The operating schedule that maintained the vat temperature was assumed to operate every second half hour and that it was empty at 1 o'clock every day and it restarted during the afternoon milking. The refrigeration system power was 8.74 W per cow, a conservative figure that also still meets the MPI standards on cooling times. To supply sufficient water to run the heat exchanger, the water pump for the whole shed runs continuously during milking. The milk pump operation is linked to the operation of the milking machine. A temperature approach of 4°C for the heat exchanger was used (Murphy *et al*. 2013).

3.3.1 Thermal storage

In this application, a cold-water storage cooling system would not be feasible due to the volume of cold water required to meet the cooling load. Therefore, the study only considered ice banks and glycol bead storage systems. The similarities between these systems meant that the model covered both systems.

An ice bank system is sized such that it can meet the daily milk cooling demand during peak season. Sufficient ice is built to cool all milk produced plus an additional 10% to account for day-to-day variability in milk production. The transfer fluid circulation pump was assumed to be twice the size of the milk pump to account for the higher fluid flow required of coolant to achieve a temperature approach through the heat exchanger to cool the milk to its set point temperature before it reached the milk vat. It operates at the same time as the milk pump.

This COP was assumed to only include the ice generating system and not the water circulation system. A COP of 1.5 was chosen. This was a very conservative value when compared to the values presented in Table 7 but was chosen because of the daytime operating schedule which would result in higher ambient temperature than would tend to reduce the COP compared to systems that operated during the night-time.

Table 7: Coefficient of performance of ice banks

Source	Coefficient of performance	Notes
Upton et al.(2014)	1.1 to 2.7	Modelling study
Murphy et al. (2012)	1.7 to 3.3	Temperature ranges of 0°C to the 22°C
Stone, (2016)	2.5	Datasheet specification
Murphy et al. (2013)	2.6	Average ambient of 8.3°C

The ice banks were scheduled to be charged once per day beginning at 9 am. The time it took to charge the ice bank would depend on the volume of milk that was produced in any one day. In the storage sensitivity scenarios, there was no operating schedule and the ice bank was treated as a completely deferrable load. The power consumption of the ice bank of 20 W per cow was chosen so that the ice bank could fully recharge between morning and afternoon milking during the milking season. In this model ice bank cost was assumed to be a fixed cost of $15,000 for the ice bank and an incremental increase of $57 per cow (Stone, 2016).

3.4 Vacuum pump

The milking machine model was developed based on the methodology used by Upton *et al*. 2014. The present study extended and amended the model by separating the morning and afternoon milkings and by accounting for the variation in milking time dependent on milk production (O'Brien *et al.*, 2012; Upton *et al.*, 2013; Besier and Bruckmaier, 2016). This is presented in Equation 2

$$\boldsymbol{Q_{mm/cow} = \left(t_{cow} + t_v * V_m * R_{\frac{morning}{afternon}}\right) * R_{\frac{cow}{cluster}} + t_{on} * P_{cow}} \qquad \text{Equation 2}$$

where:

$Q_{mm/cow}$ is the energy used by the milking machine per cow in kWh,

t_{cow} the time component of milking that's independent of the volume of milk produced (min)

t_v time to extract 1 L of milk (min/l)

t_{on} is the time that's independent of the number of cows or milk volume and is typically the time associated with washing the plant but can include things like machine on time before cows begin to be milked for example. A value of 30 min was used,

V_m is the total volume of milk extracted per day for any given week (l),

$R_{\frac{morning}{afternon}}$ is the ratio of milk production between morning and afternoon,

P_{cow} is the power used per cow (kW). 22.46 kw/cow was used as the milk pump power (Process Developments Limited, 2004), and

$R_{\frac{cow}{cluster}}$ is the number of cows to each cluster.

The farm model used 'Max T' as a basis for the milking time with an additional 100 seconds added to account for the rotation time. t_{cow} was taken to be 3.66 min and t_v is 0.41 min/l (DairyNZ, 2015c)

A cows per bail ratio of 11.5 was assumed (Process Developments Limited, 2004).

3.4.1 VSD vacuum pump

When a VSD was used, a factor of 40% was applied to Equation 2 which was a conservative reduction (Table 4). A fixed cost of $4700 was assumed to install a VSD vacuum pump for an incremental increase of $195 per kilowatt installed (Fig 12).

3.5 Milk pump

The milking pump runs at the same time as the vacuum pump. Equation 2 has been applied to the milk pump by using the milk pump power instead of the vacuum pump power. 3.6kW/cow was used as the milk pump power (Process Developments Limited, 2004).

3.6 Hot water

Hot water use in a farm performing one hot wash per day was 1.8l/cow based on an assumed extra 3l for each plant wash, another 0.5% for the vat wash for preheating and a further 5% loss due to uses relating to hot water being used in other areas or wasted. The model farm used one hot wash per day (Table 1). The hot water cylinder size was not explicitly modelled, but it was assumed that the size of the hot water cylinder was appropriate for the daily hot water use. The hot water cylinder was assumed to be filled to the appropriate level on a once daily basis.

All stand-alone power systems considered in this study included a diesel generator. These could use waste heat recovery to capture excess heat from the diesel generator and use it to supply hot water. However, running the diesel generator only to generate hot water would be inefficient. The study used a simple approach to model heat recovery from the diesel generator. It assumed that all the hot water load was met through heat recovery then analysed the validity of this assumption by examining generator runtime and the possibilities for heat capture.

The model conventional hot water system used the methodology presented by Upton *et al*. (2014) but converted to a volume basis rather than using a mass basis therefore a water density was included. An additional factor was introduced to allow for the use of heat pumps (Equation 3).

$$Q_{WH} = \frac{C_w \times \rho_w \times \Delta T \times V_w}{\varepsilon \times 3600 \times COP} \qquad \text{Equation 3}$$

where:

$\Delta T = T_{hot} - T_{cold}$ is the temperature difference between hot water set point and the ground water temperature (° C). Target temperature for the hot water system is 85°C (DairyNZ, 2017c),

C_w is the specific heat capacity of water in kJ/kg ° C,

ρ_w is the density of water in L/kg,

$V_w$is based on the volume (l),

ε is the efficiency of the heating system taken to be 0.90. The efficiency factor is assumed to account for the heat loss that occurs from the hot water system, and

COP is the coefficient of performance for the system used to heat the hot water. In a conventional hot water cylinder the COP would be set to 1. When a heat pump system is used, this factor can be greater than 1. Hot water begins heating at 9:30 AM and completes based on Equation 4.

$$T = \frac{Q_{WH}}{P_{WH}} \qquad \text{Equation 4}$$

T is the time taken to heat water in hours,

Q_{WH} is the energy required to heat the volume of hot water from Equation 3 (kWh), and

P_{WH} is the power output of the hot water element. This is taken to be 12.1 W per cow (Process Developments Limited, 2004).

3.6.1 Refrigerant superheat heat pump COP

The study used a COP of 3 for the superheat heat pump. Superheat heat pumps use refrigerant gases as a heat source. Hot water heating must take place during refrigeration operation. Therefore, the operation of these heat pumps is linked to the operating schedule of the refrigeration device to which they are connected. The hot water heat pump was assumed to use 10 W/cow.

The cost of hot water heat pumps did not vary with the size of unit installed. Cost estimates for farms ranging from 170 cows to 1000 cows were NZD$8200 including installation. Others estimated the cost at NZD$6700 for the unit plus an install cost of NZD$3000 bringing the total to NZD$9700 (Genesis Energy, 2013).

3.6.2 Heat recovery from a diesel generator

Heat recovery from the generator produces hot water at a temperature close to T_{ho} . Recovery of between 30 and 40% of the total input energy from the generator is possible. It was assumed that heat recovered from the generator would be transferred to the hot water cylinder for storage until required. The HOMER Pro model output was analysed to determine the volume of hot water produced through heat recovery.

3.7 Water pumping

There were assumed to be two water pumping systems on the farm; the primary system supplied water from a bore to the surface for animal drinking water, milk cooling, and hot water. The secondary system was the wash down pump. This was used to clean the shed and holding area. The farm model assumed a ground water supplied farm. Lack of high-quality data for water pumping meant that the mechanistic modelling approach couldn't be applied to the water pumping component of the model using a bottom-up approach. The model instead was based on the total energy demand of 38.1kWh from Miller & Glenn (2011). The total energy demand is assumed to be determined by Equation 5. The distribution of this demand was split by the use case and a flowrate was assumed such that total annual pumping energy matched the total annual volume. Electricity demand for drinking was assumed to be deferrable whereas cooling water must operate at the same time as the milking machine to supply water to the plate heat exchanger. The pump was assumed to be a size such that its maximum flow rate was appropriate for the plate heat exchanger and therefore was on fully during the whole milking period.

Using the assumed milk/water flow rate ratio during peak season, the pump's capacity in litres per hour was estimated to be 9.8 l per cow. Drinking water was assumed to be less time-dependent and evenly spread throughout the day. The water pump was turned on for the morning milking and was turned off after the afternoon milking. The water troughs in each paddock were assumed to hold sufficient water that the cows did not run out of water overnight.

$$Q_{wp} = \frac{(V_{he}+V_{mc}+V_{dc}+V_{hw}+V_{w})}{p_c} \times P_{wp} \qquad \text{Equation 5}$$

where:

Q_{wp} is the total energy consumed by the water pump per day in kilowatt-hours

V_{he} is the volume of water passed through the heat exchanger (l),

V_{hw} is the volume of water required for hot washing (l),

V_w is the volume of hot water used in other washing processes excluding wash-down (l),

p_c is the pump capacity in litres per hour, and

P_{wp} is the water pump power (W).

Cooling water was delivered at 3.5 times the maximum milk volume as discussed in Section 2.9.2 . It was assumed for the purposes of the farm model that this was all consumed by the stock.

3.7.1 Schedule

Water power consumption was divided into two categories, peak and off-peak. The water used in the heat exchanger was required over the whole milking period with the pump running at full capacity. The water used for washing the milking machine and plant, excluding that used by the wash down pump, was assumed to be used within the time allocated to washing which occurs at the end of each milking. Drinking water and hot water were assumed to be used only when the water pump was not being used for peak consumption related activities. The off-peak demand was spread evenly throughout the day and occurred at any time in which the pump was not already operating to supply peak demands. The total energy used for off-peak pumping and each time step is shown in Equation 6.

$$Q_{wp\,off\,peak} = \frac{H_{offpeak}}{(H_{p\,on} - H_{p\,peak})} \times P_{wp} \qquad \text{Equation 6}$$

where:

$H_{p\,offpeak}$ is the number of hours of pumping required to supply the off-peak load,

$H_{p\,on}$ is the number of hours that the pump is on,

$H_{p\,peak}$ is the number of hours in which the pump is required to supply peak loads, and

P_{wp} is the pump power per cow (W/cow).

3.7.2 Wash down pump

The wash down pump is a large pump used for cleaning the yard and the exterior of the milking plant. Wash down occurs at the end of each milking. Water used in the wash down process is drawn from the water used by the heat exchanger and is stored until required by the wash down pump. Water from wash down needs to be pumped from the yard sump into the effluent pond. The wash down pump electricity consumption consists of two pumps, one for pumping water used in cleaning and the second for pumping wastewater from the yard into the effluent pond. When the yard is clean and not being used any rainwater from the dairy shed is diverted away from the sump so therefore the sump pump is only required to operate during wash down. The two pumps together have a power of 18W/cow and it was assumed that they would operate for 30 minutes at full power at the end of each milking(Process Developments Limited, 2004). No studies found discussed energy consumption relating to the wash down pump specifically.

3.8 Lighting

Lighting is a key part of work place health and safety but a minor contributor to the overall electricity consumption of dairy sheds especially with ever more efficient lighting technologies becoming cheaper. Lighting levels for the milking area are recommended to be 500 – 538 lux (DairyNZ, 2012). Assuming a shed size of $4.4m^2$ per bail with standard open fluorescent lighting with a coefficient of utilisation of 0.88 and a loss factor from dirt build-up on the lamp of 0.86 (GE Lighting, no date; DairyNZ, 2012). Luminous efficiency was assumed to be 82Lm/W (Lighting Research Center, 2015). The power density and power consumption per cow is determined by Equation 7 and Equation 8 respectively

$$\boldsymbol{P_d = \frac{l}{L_E * C_U * L_f}} \qquad \text{Equation 7}$$

where:

L_E is the luminous efficiency (lm/W),

C_u is the coefficient of utilisation,

L_f is the loss factor,

l is the lux (lx), and

P_d is the power density (W/m^2)

The power density was used in Equation 8 to calculate P_{cow} the power consumed for lighting per cow.

$$\boldsymbol{P_{cow}} = \frac{\boldsymbol{P_d \times A_B}}{(\mathbf{R}_{\frac{\mathbf{cow}}{\mathbf{cluster}}} \times \mathbf{2})} \qquad \text{Equation 8}$$

where:

P_d is from Equation 7,

A_B is the area of dairy shed per bail, and

$R_{\frac{cow}{cluster}}$ is the number of cows per cluster multiplied by 2 to give the number of bails in the dairy shed.

The dairy shed was assumed to require lighting any time it was in use. Lighting was assumed to be the first thing to be turned on and the last thing to be turned off. Lighting was assumed to operate half-an-hour before the vacuum pump was switched on and switched off at the same time the vacuum pump was switched off.

3.9 Effluent pumping

Effluent pump operation was assumed to be distributed evenly to the land for disposal throughout each month, beginning at 9 AM and completed at different times based on the time of year. The total annual effluent pumping energy was taken to be 16.4kWh per cow per year. This was chosen as a value that was between the values found by Miller & Glenn (2011) and Process Developments Limited (2004). The model assumed effluent application was distributed based on the number of days of soil moisture deficit within each month (Table 8).

This operation regime was a simplification and did not reflect the actual operation of an effluent irrigation system. Farmers do not operate their effluent pumps on such a regular basis. Operation is determined based on soil nutrient requirements and effluent storage volume. These make the determination of the time to effluent application complex and highly site specific.

While this model could not accurately simulate times when it was appropriate to apply effluent, it could use the deferrable load functionality in HOMER Pro to investigate how including storage in the model affected the overall power system. Deferrable effluent load was investigated as part of the storage sensitivity scenarios (Appendix 6). The effluent pump size used in the farm model is 18W/cow (Process Developments Limited, 2004)

Table 8: Effluent pumping that occurred in each month of the year based on days of moisture deficit (NIWA, 2016b)

Month	Manawatu	Taranaki	Bay of Plenty
Jan	17%	17%	25%
Feb	19%	36%	20%
Mar	19%	25%	15%
Apr	15%	4%	7%
May	8%	0%	1%
Jun	0%	0%	0%
Jul	0%	0%	0%
Aug	0%	0%	0%
Sep	0%	0%	0%
Oct	2%	0%	2%
Nov	8%	9%	20%
Dec	13%	8%	21%

In the deferrable case the storage available allowed two months of storage which was assumed to be sufficient to account for the periods where effluent disposal was not possible, but the dairy shed was in operation

3.10 Gate drive and vat stirrer

The gate driver controls the flow of cows into the milking area. Where installed, it operates on the same schedule as the vacuum pump (Section 3.4).

The vat stirrer is used to ensure that the milk is cooled consistently and to stop milk freezing around the vat and contact with the direct expansion cooling pad. The vat stirrer operates continuously between from 16:30 and 14:00 with a gap allowing for when the milk vat is empty. The gate driver and vat stirrer use 0.6W/cow and 1.5W/cow respectively (Process Developments Limited, 2004).

3.11 Biogas production

A figure of 0.20 kgVS/cow/day was used for the effluent entering the anaerobic pond (Table 4). The anaerobic digestion pond produced 0.22m^3 of methane per kgVS. There was no variation in production between study locations based on the lack of variation between the North and South Island study sites (Heubeck *et al*. 2014). The biogas resource was based on a monthly average production. The storage volume required was not explicitly modelled in the farm model. It was also assumed that the anaerobic pond cover allowed sufficient storage to manage the difference between biogas production and consumption.

4 Model validation and results

This Section compares the individual farm model components and the whole model described in Section 3 with data gathered from real dairy farms. The effect of milk vat insulation, ice bank, superheat heat pump, and variable speed drive vacuum pump and the three regions Manawatu, Taranaki and Bay of Plenty are presented. The Monthly and daily variations are compared with the available data. The farm model was also applied to two case study dairy farms Massey University number 4 research dairy farm and a farm near Waipawa in the Central Hawke's Bay to investigate how well it functioned when compared to the real data gathered from these farms.

Manawatu, Bay of Plenty and Taranaki showed very similar seasonal trends with each other (Fig 13) and to the national average (Fig 14). The national average peaks in October which was approximately one month later than the peak of the three regions. It was likely that the difference in peak month was driven by peak production within the South Island. Up until February the regional average curves followed a similar trend gradually declining at a similar rate. After February, the national and regional curves began to decline dropping off to near zero in May. The regional curves continued their gradual decline reaching zero in mid-May.

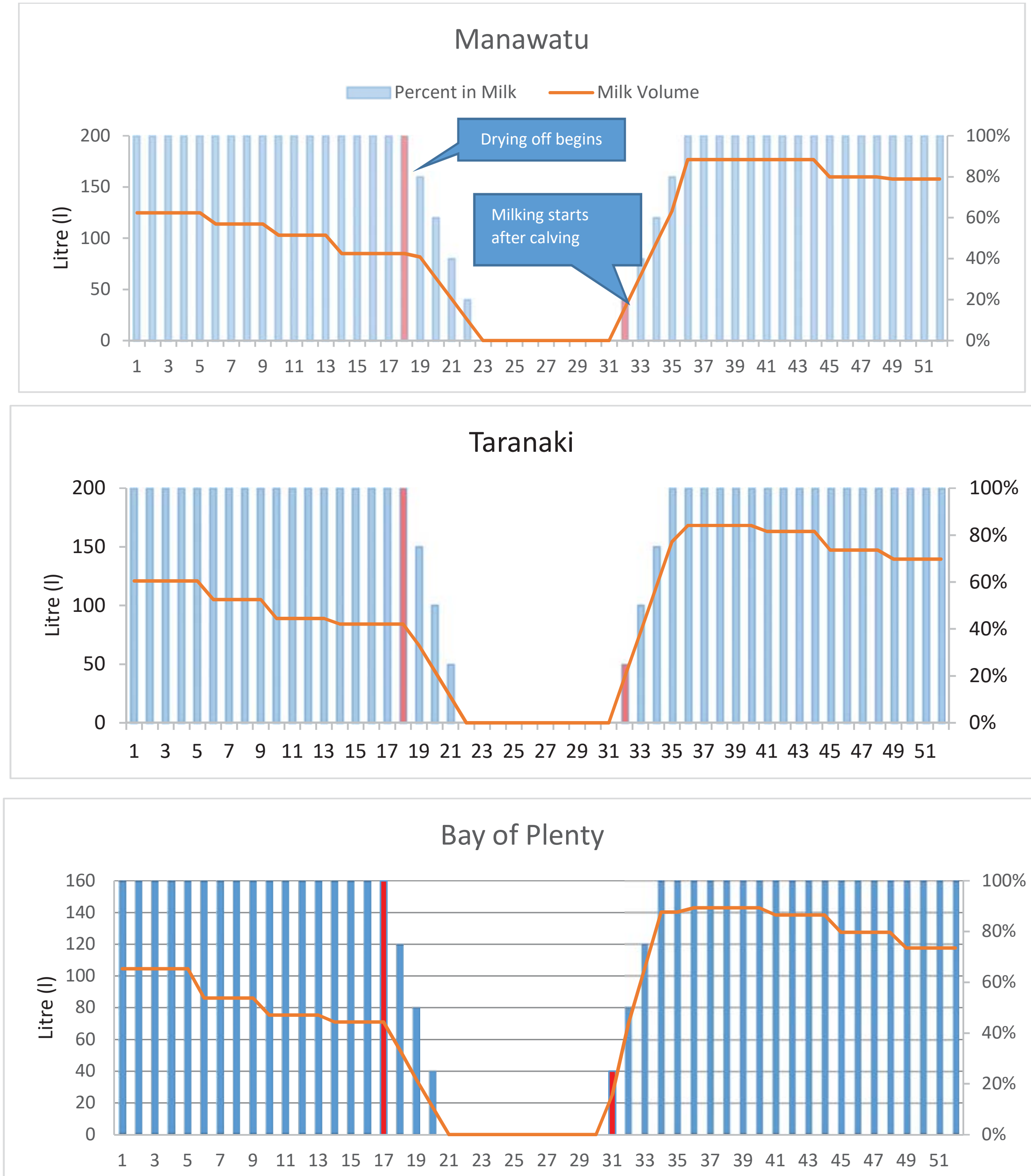

Figure 13: Modelled annual weekly per cow milk production curve (line) and percent of cows in milk (bars) for the three study regions

The lack of regional milk production data made it difficult to establish the validity of the modelled milk production curve. However, the similarity between the seasonal trends for the regional and national production curves conformed well enough for the purposes of the study.

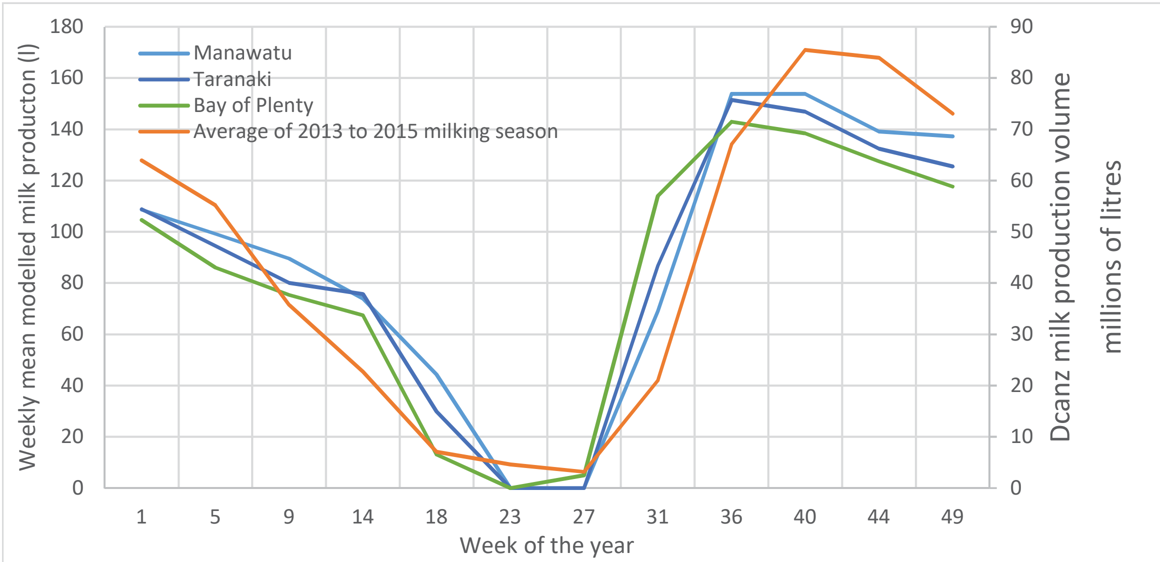

Figure 14: The monthly modelled milk production curve for the Manawatu, Taranaki and Bay of Plenty with the milk production curve for the 2013 to 2015 seasons. The season running from July to May (Dcanz, 2016)

4.1 Regional variations

The total annual electricity consumption per cow in the base farm model was 177 kWh, 174 kWh and 172 kWh respectively in the Manawatu, Taranaki and Bay of Plenty regions. Taranaki and Bay of Plenty had slightly shorter milking times than the Manawatu with the average milking time for the three regions varying by 0.2 hours per day. This resulted in reduced electricity consumption for all milking dependent subsystems, the largest of which was the vacuum pump. The change in the ground water temperature affected the hot water and refrigeration systems with the hot water system electricity consumption reducing as the groundwater temperature increased and the refrigeration electricity consumption increased. The effect was larger on the hot water system when compared with the refrigeration system because of the difference in the efficiency. The key differences in the regional electricity consumption were the length of milking time and the ground water temperature. The number of cows in milk, milk production per cow, ground water temperature and monthly effluent pumping were variable between the three study regions. On an annual basis, this resulted in a variation of only 5 kWh/cow/year (Table 9).

Table 9: Variation in the base farm model for three study regions (kWh/cow/year)

	Manawatu	Taranaki	Bay Of Plenty
Vat heat loss	8	8	7
Milk cooling	25	26	26
Hot water	45	43	43
Vacuum pump	30	30	29
Water pump	34	33	33
Effluent pump	16	16	16
Other	19	18	18
Total	177	174	172

4.1.1 Monthly load profile

The electricity consumption correlated most strongly with production in the Bay of Plenty with an R^2 squared value of 0.89. Manawatu and Taranaki showed the least correlation with values of 0.86 and 0.84 respectively.

The high ground water temperature in the Taranaki and Bay of Plenty regions resulted in increased electricity consumption between September and December; the Bay of Plenty having the highest electricity consumption during that period but the lowest milk production. The decline in electricity demand relating to milk production was offset by the increase in electricity demand for effluent pumping during January and February (Fig 15).

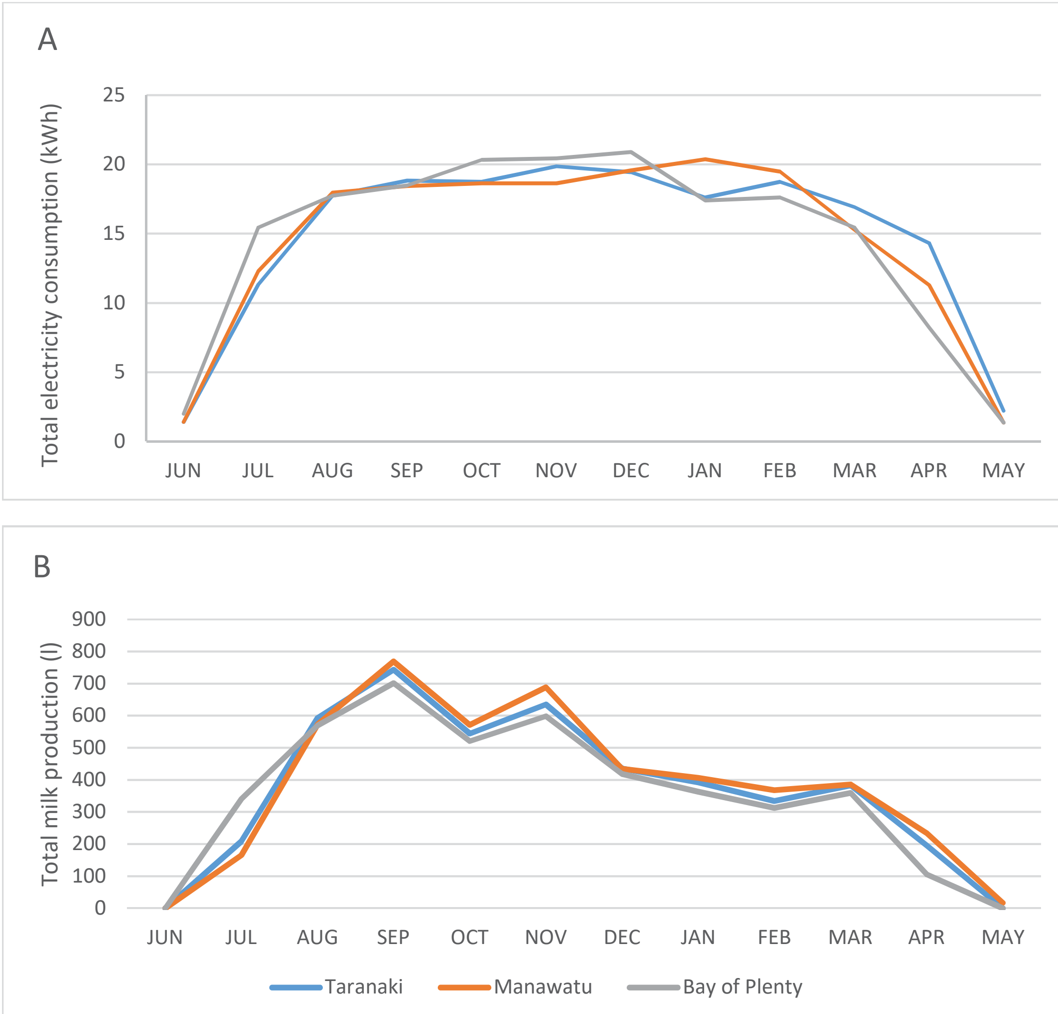

Figure 15: Farm monthly electricity consumption per cow (A) and milk production per cow(B) for the three study regions

4.1.2 Daily load profile

There was little variation in the daily load profile and peak average electricity consumption for the three study regions. The load profile for a small farm for each region is shown in Appendix 10. The annual average peak electricity consumption for all three regions was 0.08 kW/cow in the morning and 0.05 kW/cow in the afternoon.

4.2 Refrigeration

Cooling requirements are dependent on the ground water temperature recorded in each month and the milk production curve. Due to a lack of reliable data on monthly changes in groundwater temperatures average annual values have been used. Therefore, the energy demand is totally dependent on milk production. In the Manawatu during peak production 0.83 kWh of electricity was required to cool the milk produced by one cow each week (Fig 16). At its lowest point, just before all cows were removed from the herd for calving, total milk cooling time for the whole dairy shed was only one hour. This rose to 8.5 hours during the peak milking season. During the part of the year where cows were producing the most milk between week 36 and 51, the time required to cool the milk from the morning milking extended out to the middle of the day (Fig 17). This would allow better utilisation of solar resources during peak milking season. During the end of the milking season most milking occurred before dawn.

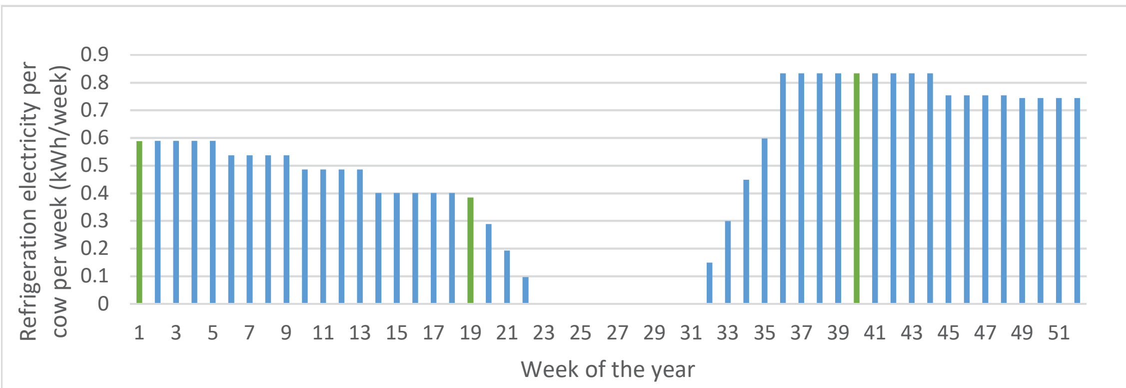

Figure 16: Weekly electricity demand for milk refrigeration per cow during a year between calving and drying off

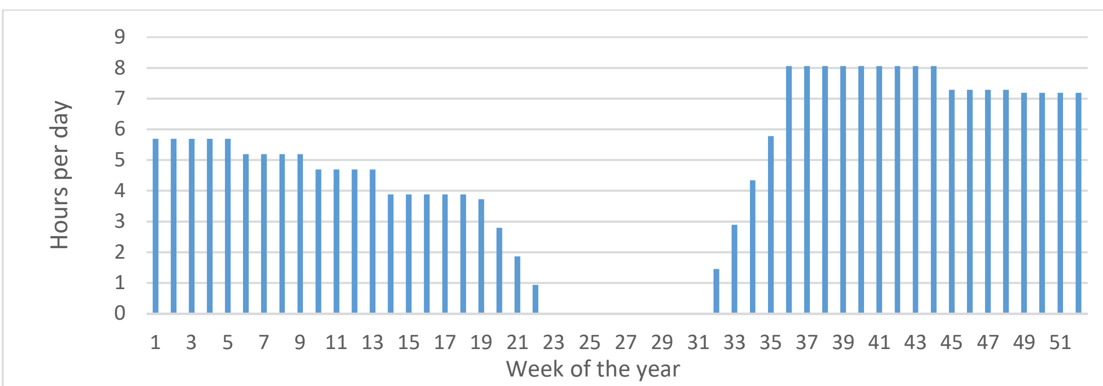

Figure 17: Daily milking time for the Manawatu region per week during a year between calving and drying off

The base farm model annual electricity consumption for refrigeration was 33 kWh/cow which was 3 to 4 kWh higher than average refrigeration energy consumption on New Zealand farms (Sims *et al.*, 2004; Miller and Glenn, 2011). When compared with data from records from actual farms with uninsulated vats that were housed inside which averaged 31.7 kWh/cow with a standard deviation of

3.12 kWh/cow the model's projected refrigeration electricity consumption was low when compared to data from all farms in Fig 18. However, the factors used to generate this electricity consumption were all conservative tending to increase electricity consumption when compared to the sources for those values.

The model annual electricity consumption of an insulated vat was 27 kWh/cow. This was higher than all values for insulated vats for which the average of indoor and outdoor vats was 22 kWh/cow (standard deviation of 0.9 kWh/cow). Insulation reduced the overall refrigeration electricity consumption by 13%. This was a mid-range reduction when compared to other studies. It should be noted that the number of data points for the insulated vats was extremely low. The indoor and outdoor data set was small consisting of six points (Fig 18). Other factors influence electricity consumption of the cooling system. The addition of insulation addresses heat loss.

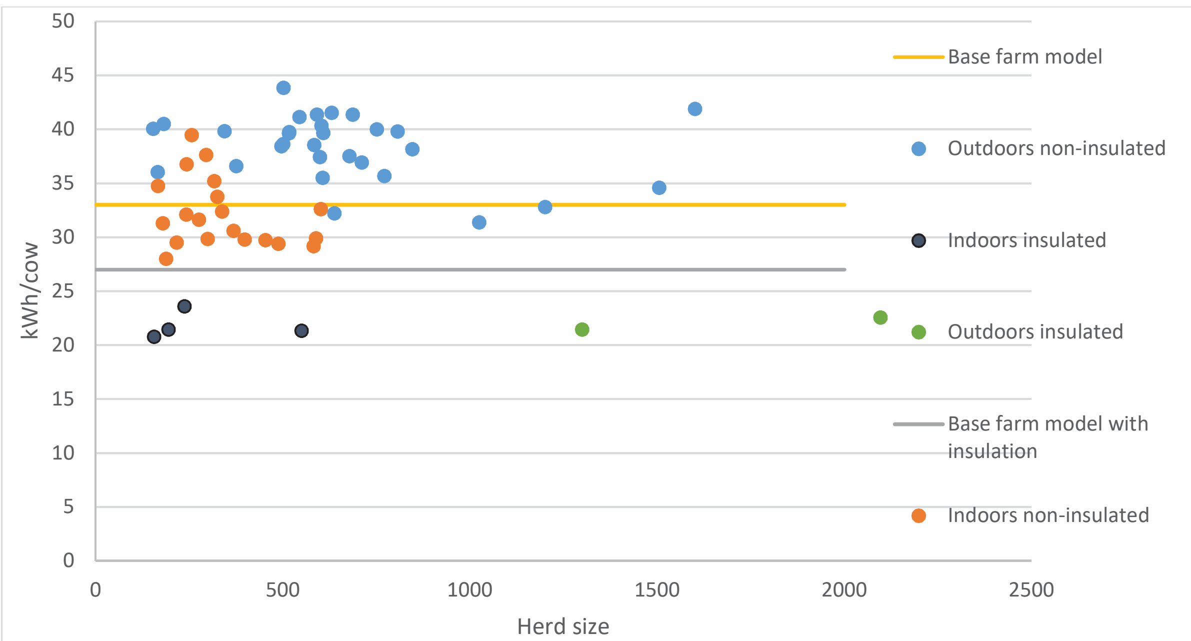

Figure 18: Model annual refrigeration electricity consumption compared with 62 farms surveyed (Sims *et al.*, 2004)

4.3 Milking machine

The data available was for the whole milking machine which includes the vacuum pump and the milk pump. The modelled milking machine energy consumption was 29.2 kWh/cow/year. The average of farms without VSD milking machines was higher at 31 kWh per cow/year. The spread of data points in Fig 19 was not even throughout the range of farm sizes. Small farms showed a much greater range of energy consumption. The energy consumption of farms was more consistent as size of farm increased. When a VSD was used, the annual electricity consumption was 19.8 kWh/cow/year. This was consistent with the data points shown in Fig 19 that were approximately equal to the highest farm with VSD surveyed. There was a lack of data on VSD electricity consumption in the figure with only four farms using it. The data presented in Fig 19 only accounted for the presence of a VSD based milking machine.

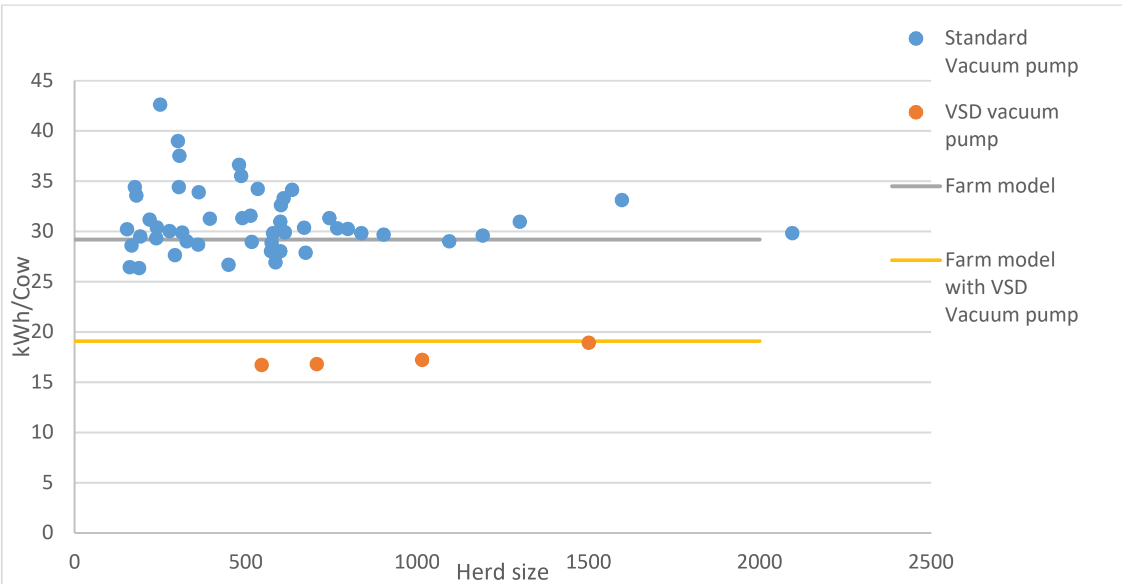

Figure 19: Model milking machine electricity consumption compared with 62 farms surveyed (Sims *et al.*, 2004)

4.4 Hot water

The **base farm model** gave a hot water electricity consumption of 45 kWh/cow/year which was low compared with hot water electricity consumption average of 50 kWh/cow/year found by Sims *et al*.(2004). This difference was explained by the trend of moving from two to one hot wash per day (Table 1). Refrigerant superheat heat pumps reduced hot water electricity consumption by 58% to 18 kWh/cow/year for the direct expansion refrigeration system and 65% to 15 kWh/cow/year for the ice bank system (Fig 20). The difference arose because at some times of year the refrigeration system didn't operate for long enough to generate the volume of hot water required and therefore the water was heated using the standard resistance heater.

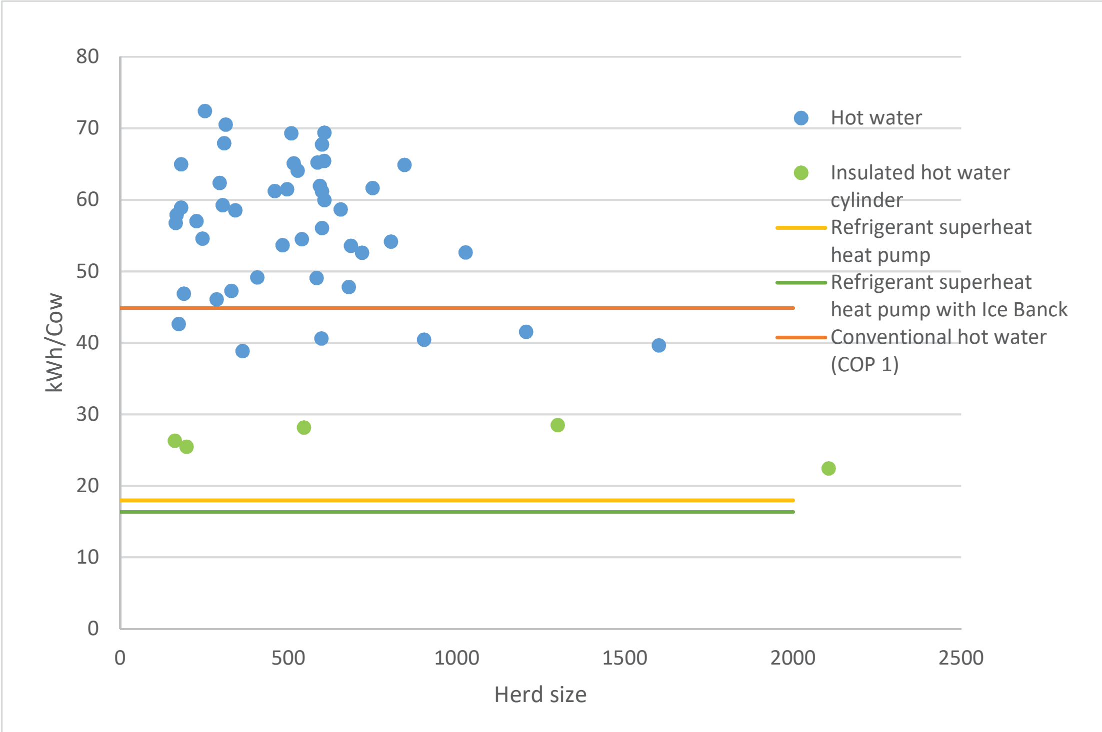

Figure 20: Comparison of modelled hot water electricity consumption and hot water electricity consumption with 62 farms surveyed (Sims *et al*. 2004)

4.5 Water pump

The model estimated the electricity consumption for the water pump to be 33.5 kWh/cow/year. This as higher than the average of the farms shown in Figure 21 of 29 kWh/cow/year but was within one standard deviation. Water pump electricity consumption was found to be 38 kWh/cow/year by other studies (Morison, Gregory and Hooper, 2007; Miller and Glenn, 2011). The value found in the water component model was an intermediate value between these three studies.

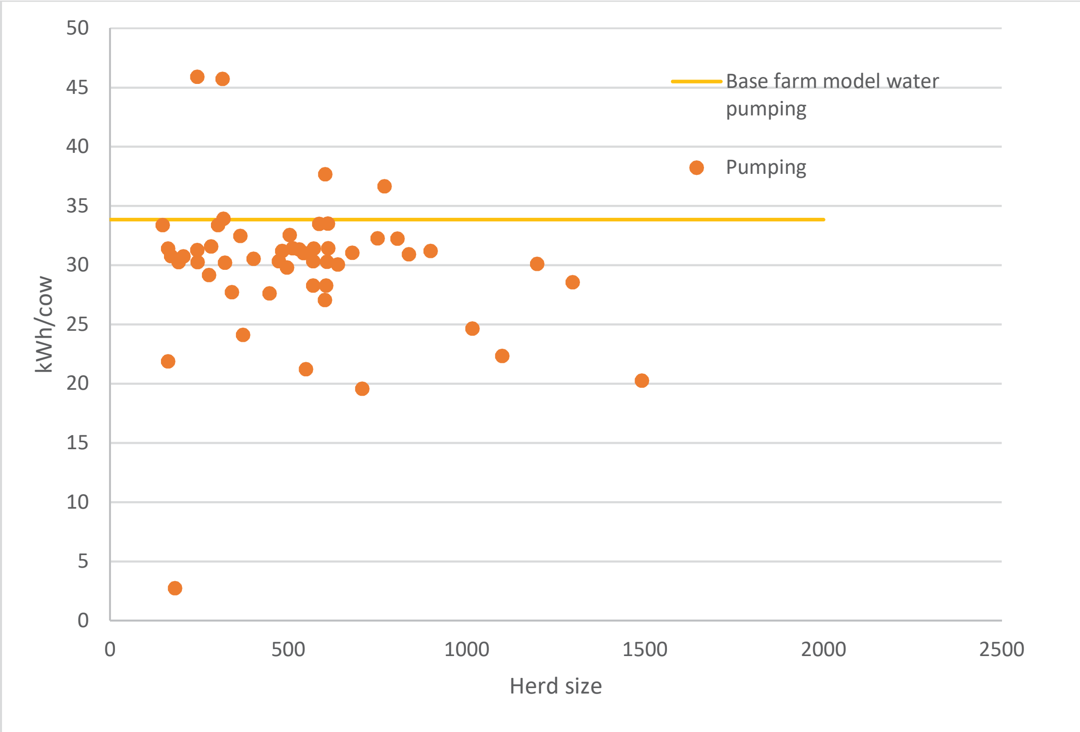

Figure 21: Modelled water pump electricity consumption per cow compared with 62 farms surveyed (Sims *et al.*, 2004)

4.6 Lighting

The model annual lighting electricity consumption was 2.62 kWh/cow/year. This was extremely low when compared with Sims *et al*. (2004) in which the survey average lighting electricity consumption was 19 kWh/cow/year with a range of between 15 kWh/cow/year and 31 kWh/cow/year. Increasingly efficient lighting sources have resulted in the portion of electricity consumption that related to lighting electricity consumption dropping steadily in other sectors (IEA, 2016). More recent studies found an average electricity consumption relating to lighting to be 3.4 kWh/cow/year which was more in line with the model's outputs Miller & Glenn (2011).

4.7 Effluent pumping validation

The modelled annual electricity consumption from effluent pumping was 16.4 kWh/cow/year only. Miller & Glenn (2011) included effluent pumping in their survey of dairy shed electricity consumption. The survey average electricity consumption was 15.6 kW/cow/year. The model matched this relatively closely with only a .8 kWh/cow/year difference between the model and study.

4.8 Technologies

Technological changes in dairy sheds can enable new practices such as load shifting to reduce peak demand and increased dairy shed efficiency. The effect on the base farm model scenario of each of the technologies is shown in Table 10. The focus of the discussion in this paragraph will be on the whole electricity demand and how that relates to dairy farm electricity consumption found in the literature. The technology scenario showed much greater variation in electricity consumption than the regional scenario variations. Technological variation would affect the electricity consumption of the three regions slightly differently. The differences in the load profile of the regions was relatively small, therefore the effect of load shifting and energy efficiency technology was modelled on the Manawatu region and the most cost-effective combination for each farm size for the Manawatu region was modelled with the other two regions and compared with the farm model base scenario.

Table 10: Effect of five technologies on the electricity consumption of the farm model

Technology	per cow	Saving from base	Small farm	Medium farm	Large farm
Unit	kWh/year	%	Total kWh/day	Total kWh/day	Total kWh/day
Base scenario	177		73	166	340
Vat installation	171	3%	70	161	328
Ice bank pre-cooling	204	-15%	84	192	392
Hot water heat pump	144	14%	62	143	291
Variable speed drive vacuum pump	167	6%	69	157	320
Hot water heat recovery	132	25%	54	124	253

The base farm model was higher for all regions than in the two largest studies of New Zealand dairy farm electricity consumption from the literature. The base farm model has an energy consumption greater than 65% of the farms surveyed (Fig 22). The energy savings achieved by vat insulation, VSD vacuum pumps and hot water superheat pump which are all energy efficient technologies were all in the low end of the energy savings found in the literature (DairyNZ, 2015a). The combined efficiency improvements by using three of the energy efficient technologies reduces electricity consumption to 134 kWh, which is a 24% reduction. This had an energy consumption of less than that of 75% of the farms in Fig 22. The ice bank had an electricity consumption greater than that of 87% of the farms in Fig 22.

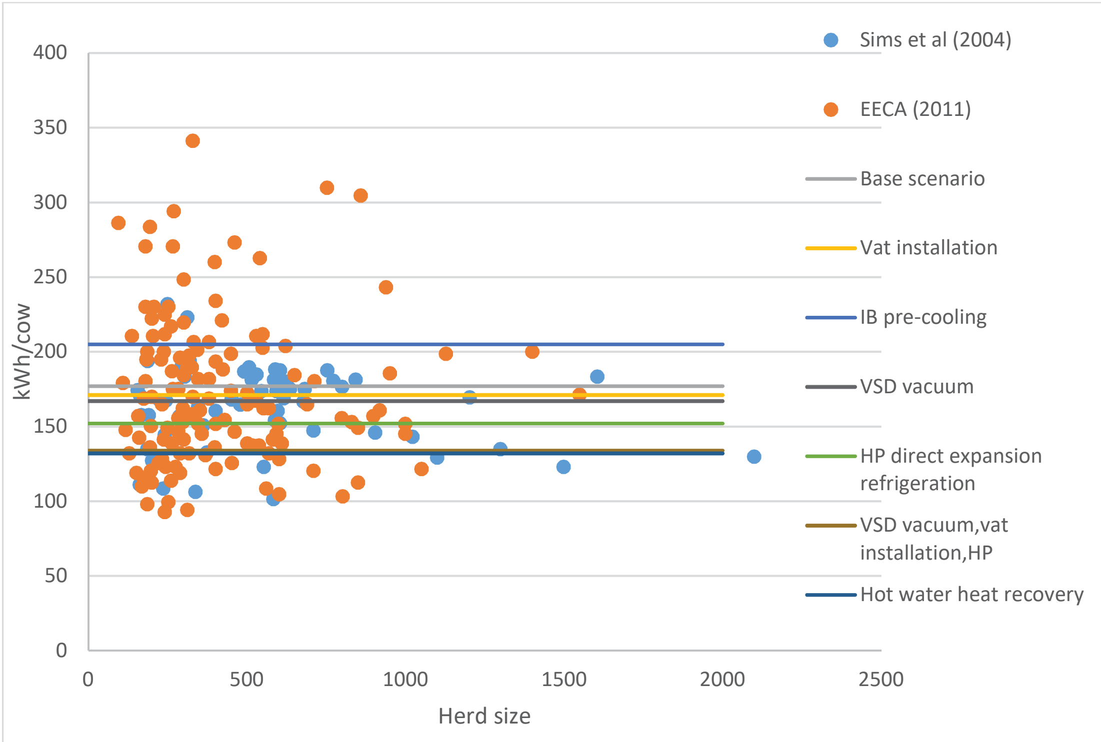

Figure **22:** Farm model technology scenario options compared with 62 farms surveyed (Sims *et al.*, 2004; Miller and Glenn, 2011)

4.8.1 Effect of technologies on the daily load profile

The superheat heat pump can only be operated in conjunction with the refrigeration system, therefore when combined with a conventional direct expansion refrigeration system, it shifted the time of the hot water electricity consumption into the milking period (Fig 23). This increased peak electricity consumption even though total electricity consumption was reduced; it shifted the average daily peak time of 0.05 kW/per cow to 7.00 am with electricity consumption decreasing steadily after 08:00. 61% percent of electricity was used between the hours of 06:00 to 08:30 and 16:00 to 18:30.

When used in conjunction with an ice bank, load profile peak electricity consumption of 0.04 kW/per cow occurred at 9:00. Electricity demand during milking was reduced. 41% of electricity was used between the hours of 06:00 to 08:30 and 16:00 to 18:30. When the ice bank was used on its own with a standard hot water system the peak electricity consumption was further increased compared with ice bank only systems that had peak consumption at 09:00 of 0.05kW per cow. 35% of electricity was used between the hours of 06:00 to 08:30 and 16:00 to 18:30.

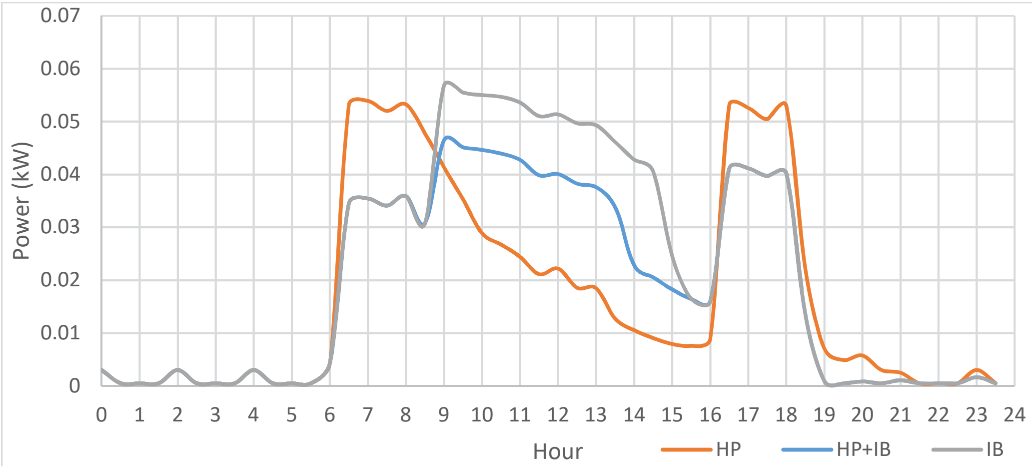

Figure 23: Farm model load profile for heat pump (HP) and ice bank (IB) technology scenario options

The farm model was designed to be a conservative model of dairy farm electricity consumption. As such it has tended to overestimate the farm electricity consumption and underestimate the efficiency improvement available.

- The farm model assumed that electricity was the only energy source used to supply the dairy shed.
- Not all dairy sheds included all of the components that were modelled on the farm model.
- Some dairy farms would have very low electricity consumption for some components. For example, if gravity fed water was available then pumping electricity demand would be low.

4.9 Comparison with sites from the literature

The farm model was applied to two real farms as a means of assessing its performance. The farm model inputs were adjusted so that they best replicated the data available from the farm. The two farms were taken from the case study farms in Sims *et al*. (2004). These represented a range of farms of different shed types (rotary and herringbone) and at different scales (400 to 800 cows). The model did not explicitly model rotary milking sheds, but the literature did not indicate that the energy used by the rotary platform was significant.

4.9.1 Applying the **base farm model** to the Massey University number 4 research farm

The Massey University number 4 research farm (Massey farm) had 450 cows milked through a 50-bail rotary milking platform located in the Manawatu region. The average milking during the study period took 3.5 hours in the morning and 2.7 hours in the evening. The farm model milking time per cow, milking time per litre and the cleaning time were adjusted so that the average milking time matched the milking time of the Massey farm.

The coefficient of performance of the refrigeration system was taken to be 2.5 (Table 11) which was the same as the coefficient of performance used in the farm model. The Massey farm milking machine power was higher than the farm model milking power (Table 11). The hot water system contained two 5 kW electric elements on independent thermostats.

Table 11: Comparison of Massey University number 4 farm model and base farm model input parameters

	Massey University	Model
Milking machine (kW)	15	33
Morning evening milking times (hours)	3.5, 2.7	NA
Number of cows	450	
Number of clusters	50	
Under-utilisation of milking clusters*	10%	
Refrigeration(kW)	9	20
Temperature difference between vat set point and outlet of heat exchanger**(℃)	18	
Vat heat loss	10%	
Refrigeration coefficient of performance	2.5	NA
Hot water heat loss	10% max.	20%
Temperature difference between the water supply and hot water set point**(℃)	70	

Assumed*, assumed by study author**

The data in Table 11 only shows the portion of the year that was covered by the Massey University farm study. The farm model produced a 10% larger average electricity consumption per day than the

Massey dairy farm. The fit of the individual components was more variable than the overall fit. The vacuum pump and chiller inputs fit the farm model with variances of 6% and -2% respectively.

The electricity consumption of the vacuum pump is controlled by the size of the pump, number of milking washes and number of cows per cluster time (Equation 2). As expected given the available inputs the fit between the farm model and the Massey dairy farm for the chiller was very close with a variance of -2%. The volume of milk produced by the herd was the major uncertainty. From the limited data available the farm model regional milk production curve and the farm's milk production curve fitted accurately.

Milk production between the periods 9th of November to 6th of December was 18 L per cow per day which in the same period in the farm model was 20 L per cow. Milk production information was not available for the whole season but based on the one month of data available for the Manawatu, farm model milk production differed by 10% which given that the farm model was generic for the Manawatu region and based on 2015 season data was a reasonable variation.

The heater and miscellaneous consumption showed a poor fit overall -18% and 45% respectively. The main uncertainty with the heater was the volume of hot water used. The farm model and the Massey farm were not inconsistent (Table 12). The miscellaneous electricity consumption made up the remainder of the electricity used on the dairy farm all of which were unspecified. Given these uncertainties the farm model couldn't be applied with any accuracy. This was reflected by the 45% variance between the farm model and the Massey farm data. For the 116 days for which data was available, the fit between the average electricity consumption of the farm model and the Massey university dairy farm was consistent

Table 12: Comparison of Massey University number 4 research dairy farm with its model (Sims *et al.*, 2004)

	Farm model			Actual results		
	kWh/day	Fraction of load	Maintenance	kWh/day	Fraction of load	Maintenance
Vacuum pump	92	26%		98	31%	
Chiller	70	20%	10%	71	22%	10%
Heater	69	19%	20%	82	26%	20%
Miscellaneous	125	35%		68	21%	
Total	356			319		

4.9.1.1 Daily load profile

In the Massey University dairy farm load profile, there was enough inter-day variation to account for the operation of the effluent pump but there was no visible trend in its operational time. The farm model assumed that there was a daily effluent pumping requirement that occurred at a fixed interval daily. Effluent was left out when from the daily load profile comparison but left used on the total annual electricity consumption.

The farm model fitted the Massey dairy farm's load curve with R2 = 0.92 (Fig 24). The transition into milking occurred more quickly in the farm model and the afternoon milking began later. The sharp peak at the beginning of the afternoon milking period occurring at interval 56 was accounted for by the hot water cylinder starting operation. The farm model assumed a fixed starting time for the hot water irrespective of the time of use of the hot water. This was because in the farm model it was assumed that the hot water system would operate on a time clock. The start time in this case was chosen to approximate the time of morning milking but this varied depending on milk production. In the Massey University dairy farm the hot water system began operation at the end of the morning milking rather than a fixed time each day. The time taken to heat the hot water cylinder was relatively constant so the variation and start time of the hot water heating caused a general increase in the afternoon peak electricity consumption. The time taken to heat the hot water cylinder was relatively constant so the variation and start time of the hot water heating caused a general increase in the afternoon peak electricity consumption.

Due to the relatively long milking times used as inputs to the farm model there were instances where the refrigeration system completed its daily milk cooling load before the completion of milking. The Massey farm data showed that there were instances where the chiller operated at a lower power state and was shut off during milking (Appendix 11). The chiller shut off when it reached its temperature set point. As more milk was added the temperature of the milk would rise and the chiller would begin operation. This meant that the chiller load was spread out over an extended period. This extended the time taken to cool the milk. The same kind of operation occurred in the miscellaneous device category of the Massey farm data. This hysteresis in the Massey farm miscellaneous device category would contribute to the over-prediction of the farm model which did not allow for hysteresis. This could be seen in the rate of decline of the afternoon milking with the farm model load dropping close to 0 very quickly whilst the load at the Massey farm declined slower as milk chilling completed and miscellaneous loads ceased operation.

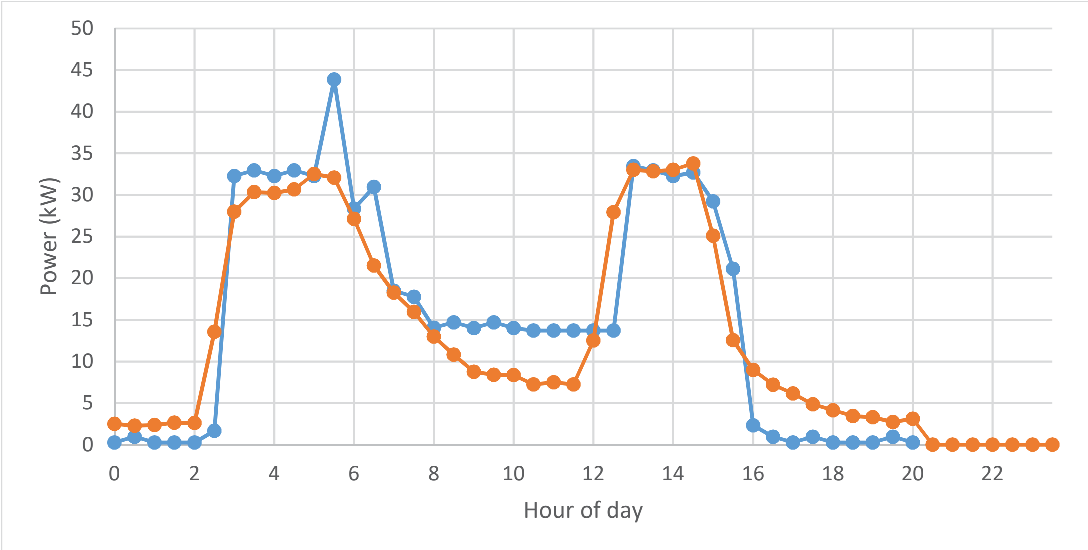

Figure 24: Comparison of daily load profiles between the Massey University farm model (blue) and actual (orange) readings. (Sims *et al.*, 2004)

4.9.1.2 Monthly load profile

Correlation between the model and the real data on a monthly basis is R^2=0.94. This is acceptable given that it is the application of a generic model to one specific farm, even though model electricity consumption was higher than the Massey dairy farm in all but the month of Jul y (Fig 25). The largest variance between the two occurred in November and December where the electricity consumption of the Massey dairy farm dropped by 125 kWh per day compared to the previous two months. This was in the months just after peak milk production.

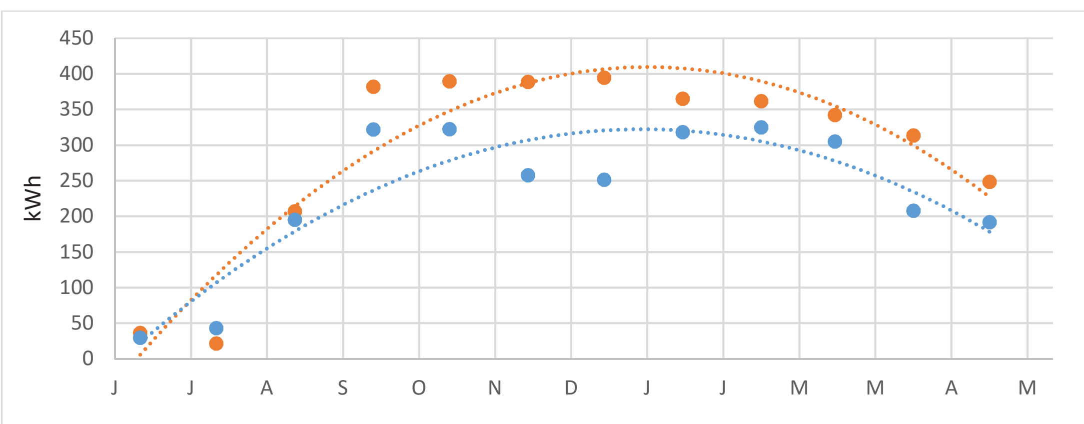

Figure 25: Comparison of monthly electricity consumption between Massey University farm model (orange) and actual (blue) (Sims *et al.*, 2004)

With a limited number of inputs the Massey farm model simulated the electricity consumption on the yearly, monthly and daily timescales with reasonable accuracy. The most prominent differences arose from the electricity consumption of the miscellaneous devices used within the dairy shed. Much of this was pumping load which was less dependent on milk production. When comparing, the daily load profiles the differences were caused primarily by the start time hot water cylinder and in the variance in the time taken to complete chilling of the milk due to hysteresis during operation of the Massey dairy farm chiller. On the monthly timescale, the **base farm model** did not project the electricity consumption decline during November and December which likely related to variation specific to the 2005 milking season. Otherwise the **base farm model** projection showed a good correlation.

4.9.2 Applying the base farm model to a farm near Waipawa

Waipawa farm is a large-scale, 800 cow, herringbone dairy shed located in the Central Hawke's Bay. The milking times were relatively even with the average milking time 4.7 hours and 4.2 hours for the morning and afternoon milkings respectively.

For the number of cows this dairy shed was small which resulted in long milking times. 20 cows per cluster was assumed based on the size of the milking machine and the number of cows. The hot water system was undersized when compared to the number of clusters in the base farm model. Using the standard volume of water required for cleaning per cluster the hot water cylinder was required to operate 16 ½ hours per day to produce sufficient quantities (Table 13).

No regional model has been developed for milk production in the Central Hawke's Bay. The Manawatu milk production curve was used as it was the closest to the region. The difference between the two regions in terms of milk production per cow was low. In 2015 milk production per cow per year for the Manawatu was 4596l compared with the Hawke's Bay 4125l. The two regions were included within the same measurement of median calving dates and planned start of calving. The Hawke's Bay had a slightly shorter season by three days. These differences should have resulted in the model over-predicting electricity consumption but not substantially.

Table 13: Comparison of Waipawa farm model and base farm model input parameters

	Waipawa	Model
Milking machine(W/cow)	10	12.5
Morning evening milking times	4.7, 4.2	NA
Number of cows	800	
Refrigeration(W/cow)	9	11.25
Vat heat loss	1%	
Hot water heat loss	10%	5%
Cows per cluster*	20	

Assumed*

The Waipawa model under-predicted the electricity consumption by 13%. The biggest difference was from the chiller. The farm model had an electricity consumption of 72 kWh/day. That of the Waipawa farm was much higher with 149 kWh/day (Table 14). The only available refrigeration energy input consumption data from Waipawa was the vat heat loss. The remainder of the inputs were the default inputs used in the Waipawa model. The electricity consumption of the Waipawa farm for refrigeration was high when compared to other dairy farms. This indicated that the milk cooling system was inefficient due to any or all the following factors: a lack of low-temperature groundwater, poor heat exchanger performance or a low refrigeration COP. The relatively low electricity consumption from the hot water system and high consumption of the chiller indicates that the temperature of the farm's groundwater could be high. The remainder of the inputs vary between 21% and -20%. The vacuum pump's base farm model electricity consumption was smaller by 20%, and the base farm model over predicted electricity consumption by 21% and 10% respectively for the heater and miscellaneous.

Table 14: Comparison of Waipawa dairy farm with its model (Sims *et al.*, 2004).

	Model			Actual dairy farm		
	kWh/Day	Fraction of load	Maintenance	kWh/Day	Fraction of load	Maintenance
Vacuum pump	72	17%		86	18%	
Chiller	72	17%	3%	149	31%	1%
Heater	71	17%	10%	56	12%	10%
Miscellaneous	214	50%		191	40%	
Total	428			482		

The Waipawa model was less accurate for the Waipawa farm compared with the Massey model except for the chiller where the Waipawa model fitted the small number of inputs available. Peak electricity consumption matched well with the Waipawa model peak higher than the Waipawa dairy farm's peak overnight load (Fig 26). Areas where the Waipawa model and Waipawa farm data diverge was at the end of each milking. The cause of this was primarily differences in refrigeration electricity consumption. The Waipawa model showed milk chilling being completed shortly after the end of milking whereas milk chilling continued for several hours after milking in the Waipawa farm slowing the decline in electricity consumption from its peak during milking.

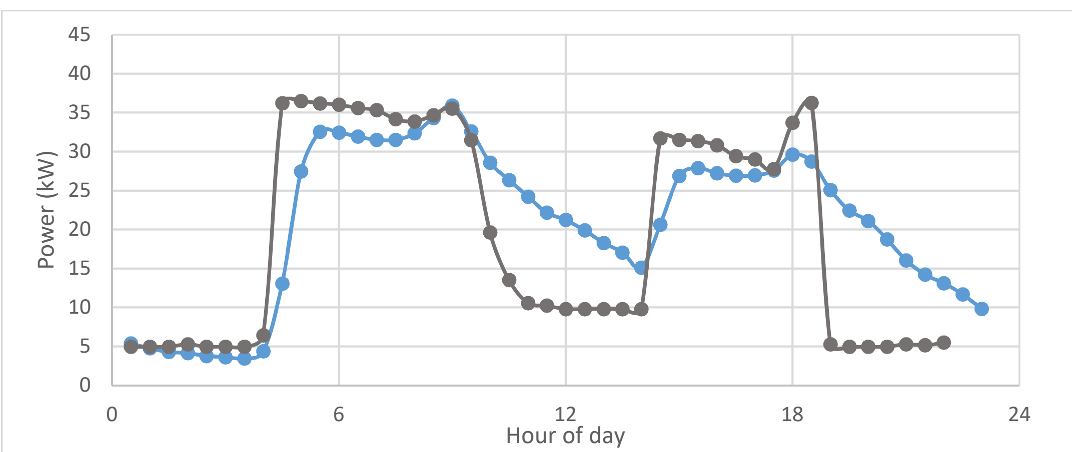

Figure 26: Comparison of the Waipawa farm model (gray) with data from the site (blue). The load profile excludes the effluent pumping load. (Sims *et al.*, 2004)

4.9.2.1 Monthly Load profile

The monthly electricity consumption data was not available and so the overall annual comparison was not able to be performed.

The model for Waipawa was based on limited inputs. The only influential variables available were vacuum pump size, milking times, hot water and chiller heat loss. With only the small number of inputs available the model matched the electricity consumption of Waipawa within 10%. The electricity consumption of the chiller was under-predicted. Hot water and miscellaneous load were slightly over-predicted. The peak daily load at the Waipawa site matched well with base farm model. Gradual reduction of electricity consumption was not modelled. This was primarily linked to the refrigeration electricity demand.

The model of the Waipawa and Massey farms showed that the simple model of dairy electricity loads developed could simulate an individual farm's load profile based on limited inputs. However, without sufficient detail relating to individual components, the simulation would give results of limited use.

5 Stand-alone power system for meeting electricity demand of a milking shed

The stand-alone power system model has focused only on the solar battery/diesel hybrid system and solar battery/diesel biogas/systems. Wind and micro-hydro were specifically excluded from this analysis since both these renewable resources are site specific requiring detailed assessments of individual sites to identify if these resources are available. In contrast, with assumptions about shading from vegetation and topography, the solar resource available can be estimated for any given location with reasonable accuracy. Biogas production is largely controlled by availability of feedstock and investment in infrastructure. Both factors could be controlled by the farmer.

In this Section, HOMER Pro[6] was applied to the dairy shed loads developed from Section 3. The software can be used for high-level assessments of the technical and financial viability of a power system. Each of the regional and technology scenarios was simulated under the sensitivity variables of farm size, fuel price and capital price. HOMER Pro was also used to assess special cases such as the effect of including deferrable storage.

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[6] HOMER Pro is an acronym for 'hybrid optimisation model for electric renewable power systems.' The software is commonly used as a tool for simulation, optimisation and sensitivity analysis of microgrid and grid connected electricity systems (Bahramara, Moghaddam and Haghifam, 2016).

HOMER Pro was chosen because it is a cost-effective and simple tool that can rapidly simulate and optimise power systems for a given load. HOMER Pro is available at a cost within the project budget. The simplicity was an advantage because the time constraints did not allow for development of a dedicated model that fitted the requirements exactly. Other programs which are suitable for this kind of simulation such as Trnsys or developing a custom model would have significantly limited the scope of the project (Zhou *et al.*, 2010).

HOMER Pro requires the input of discount rate, inflation rate, load data, climate data, financial cost and technical characteristics of each power system component. The size range of each of the system components was also included and every possible combination of sizes was simulated to find the lowest cost power system which met the technical requirements to supply electricity. Sections 5.2 to 5.6 summarise the HOMER Pro model inputs and assumptions. The data used for the physical components of the power system were sourced from the manufacturer's data sheets, the literature and from data gathered from PowerCo's test site situated near Marton New Zealand. The test site was used to test the power systems that supply farmhouses and wool sheds. It was used to validate manufacturer's claims about power system performance. The power system that the data was gathered from was used as the basis for the larger scale dairy shed power system modelled in this study.

Only one New Zealand study of SAPS specifically for dairy sheds was found in the literature. It presented an assessment of the technical feasibility of a solar-battery-LPG hybrid power system and found that the electricity demands of the modelled dairy shed milking 600 cows in Gore, New Zealand could achieve a 94.3% renewable fraction using a 30-kW PV array and biogas generated from covered effluent ponds (Parshotam *et al.*, 2011). The study was conducted on a weekly basis with a similar total energy demand per cow as was used in this study. The biogas, battery, hot water and ice storage mechanism were assumed to have unlimited storage. Storage forms a crucial part of a stand-alone power system. Large time steps and unconstrained storage would tend to lead to under-estimates of the PV array size required and the amount of detachable fuel resources required, in this case biogas or LPG. The study assumed that using an ice storage system did not change the electricity consumption used for milk chilling. Given the lower evaporation temperature required for ice storage systems this assumption would lead to an under-estimation of the refrigeration percentage and total load. This study improved upon the work of Parshotam *et al*. (2011) by using half hourly time steps. Modelling of storage remains problematic within the study, however it was investigated using sensitivity scenarios.

5.1 Discount and inflation rates

A discount rate of 8% was chosen. PowerCo's profitability between April 1, 2012 and March 31, 2015 was 7.13% (Commerce Commission New Zealand, 2016). The slightly higher discount rate than PowerCo's internal rate of return accounts for the additional risk in switching from a business as usual practice. Inflation rate of 2% was used based on the reserve bank's current monetary policy (Reserve Bank of New Zealand, 2016).

The model was run over a 25 year lifetime. The systems are designed to be long-term investments and this represents the lifetime of the longest lasting component the PV array (Renvu Solar Equipment Distribution, 2016). At the end of the PV array's lifetime significant redevelopment will be required. This redevelopment was assumed to be an entirely new project.

5.2 Solar radiation

The NIWA Solar View database gives an aggregate of available solar resource data for the weather station closest to the study locations. The Manawatu site weather station is located in Palmerston North city, latitude 40.3820° south longitude 175.6091° east. This location is adjacent to the Manawatu River and is close to the two Massey University research farms. It has extremely good Skyview[7] with the only topographic features some low hills to the north which have little impact on the solar radiation. Climate data is based on 16 years of recordings at the site. Solar radiation peaks in December with a daily average of 6.25 kWh and an average daily peak of 750 W/m^2 occurring between 12 and 1 PM (Fig 27). Sunrise times vary between 8 AM at the winter solstice to close to 5 AM at summer solstice (Fig 27).

[7] Skyview factor is a ratio of the amount of radiation received by a plane and that from the entire hemispheric radiating surface. Skyview factor ranges from 0 to 1. It is affected by both topographic, built environment and vegetative shading (Duffie and Beckman, 1991).

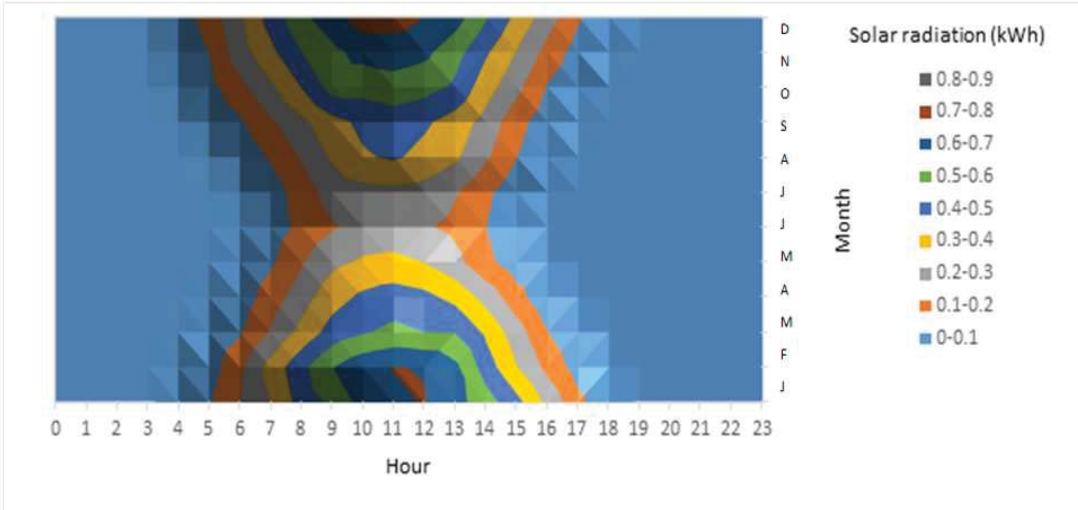


Figure 27: Manawatu site solar resource (NIWA, 2016a)

In the Bay of Plenty the solar resource and temperature data was taken from an automatic weather station located at latitude 37.82 ° south, longitude 176.32° east, located 4 km south-south-east of Te Puke. The area surrounding the weather station is primarily horticultural with dairying being near the coast to the north and to the east. Bay of Plenty is the northernmost region in the study. The area has a good Skyview factor with a small number of low hills to the south that have only a minor impact on the available solar energy. There are 14 years of solar resource records from this station. The solar resource peaks in January with the average hourly solar radiation between 12.00PM and 1PM reaching 0.8-0.9 kWh/m^2 (Fig 28). The average daily solar radiation is 6.29 kWh/m2. A minimum solar radiation occurs in June (Fig 28).

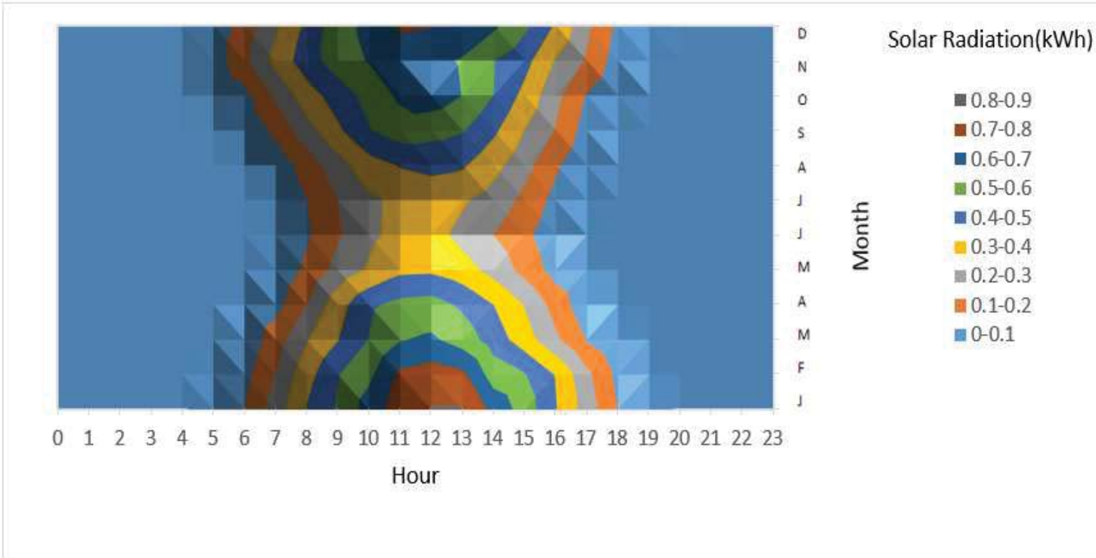


Figure 28: Bay of Plenty site solar resource (NIWA, 2016a)

The climate data for Taranaki was taken from an automatic weather station located in the town of Stratford at 39°20’24.0” south, 174°18’00.0”east. In the surrounding area, the predominant land-use is dairying. The site has an excellent Skyview factor; the only topographic feature of note is Mount Taranaki. This has very little impact on the solar resource with a minor impact between March and June but no impact for the remainder of the year. The peak month is January with an average daily solar radiation of 6.73 kWh/day and peak solar resource of 820 W/m^2 occurring between 12PM and 1PM in the afternoon (Fig 29). The winter low occurring in June is 1.73 kWh/day(Fig 29).

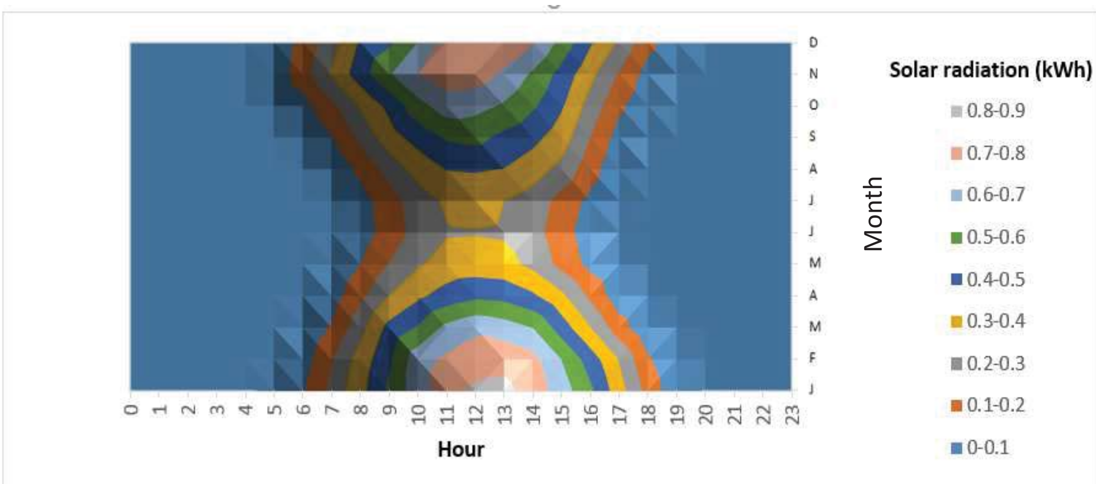


Figure 29: Taranaki site solar resource (NIWA, 2016a)

Of the three locations Manawatu has the poorest overall solar resource and Bay of Plenty has the best. This was to be expected as it is the most northern of the study regions with similar summer peaks to Taranaki but higher than both Manawatu and Taranaki throughout the winter months. Taranaki shows greater variation throughout the year than the Bay of Plenty but has a similar peak.

5.3 Biomass resource

The biomass resource in HOMER Pro was used to input the monthly data from the biogas model (Section 3.11). The inputs required were available biomass in t/day, average price per tonne, carbon content percent, gas ratio and the lower heating value (megajoules per kg). The biomass available was calculated from the volume of methane produced from Section 4.5 using a density value of 0.00067 $tCH4/m^3$ animal manure feedstock based on a temperature of 20℃ and pressure of 1 atmosphere (Stewart & Trangmar 2008). The carbon content was set to 0. This was used to calculate the CO_2 relating to the combustion of the biogas and it was calculated outside the HOMER Pro model. The lower heating value was taken to be 90.0% of the higher heating value (Petchers 2003) of 54.3MJ/kg (Dale *et al*. 2002). The capital cost and maintenance cost are shown in Appendix 12 and Appendix 13. A 5% reduction in generator efficiency was assumed when biogas was used (Section 2.15).

5.4 Generator

The revolving field brushless AC generator model, driven by a Kubota SQ-33SW 24 kW diesel engine, produced 50 Hz three phase power. The generator fuel curve was taken from the manufacturer's data sheet (Appendix 14).

If the generator was required as back-up when the renewable power generator was not high enough to meet the load threshold, the remainder was used to charge the battery. A minimum load ratio of 30% was chosen as a site-specific value that did not specifically relate to the generator. 30% was a common value used in other studies (Bernal-Agustín & Dufo-López, 2009) with a minimum runtime of 2 minutes as specified in the model. This was designed to eliminate repeated short-term hysteresis of generator operation. The default diesel properties were used (Table 16).

Table 16: Properties of diesel fuel (HOMER, 2016)

Lower Heating Value (MJ/kg):	43.2
Density (kg/m3):	820
Carbon Content (%):	88
Sulfur Content (%):	0.001

5.4.1 Generator lifetime and maintenance schedule

The lifetime of a diesel generator depends largely on its frequency of use and maintenance. Manufacturers don't typically specify expected lifetimes for the generators. The annual maintenance approach used by the study was regardless of generator runtime. Therefore, there was no runtime based maintenance. A lifetime of 15,000 operating hours for a generator was assumed (Bernal-Agustín and Dufo-López, 2009; Sen and Bhattacharyya, 2014).

5.4.2 Fuel price

To test the sensitivity of the model to fuel prices, three diesel prices were modelled based on the IEA projections for the oil market and carbon markets. The oil price model took the 15-year average between 2000 and 2015, the importer's gross margin, the difference between the New Zealand oil price and the IEA oil price and the New Zealand/US exchange rate and the 2015 value of the duty taxes and levies (Table 17).

Table 17: 25-year oil price projection model inputs

Import cost plus freight and insurance	30% above the projected IEA market price
Duties, taxes and levies	0.0038 $/l
Importer's gross margin	.22 $/l
Carbon price under the ETS	Based on the projected IEA carbon price
GST	15%
exchange rate (NZD/USD)	NZ 1.56/ US 1

The inputs in Table 17 were combined with the IEA 2015 price scenarios from Table 6 to derive a future New Zealand diesel price for 2020, 2030 and 2040.

This assumed no future significant change in the taxation or pricing structure of oil products. The price ignored any short-term effects due to variations in the 'Importer's gross margin' and ignored price variations due to bulk discounts or regional variations both of which have significant effects on the price of diesel paid at the pump. The model fitted the historic values with R^2=0.93. The importer's gross margin affected the accuracy of the model particularly in 2014 and 2015 (Fig 30).

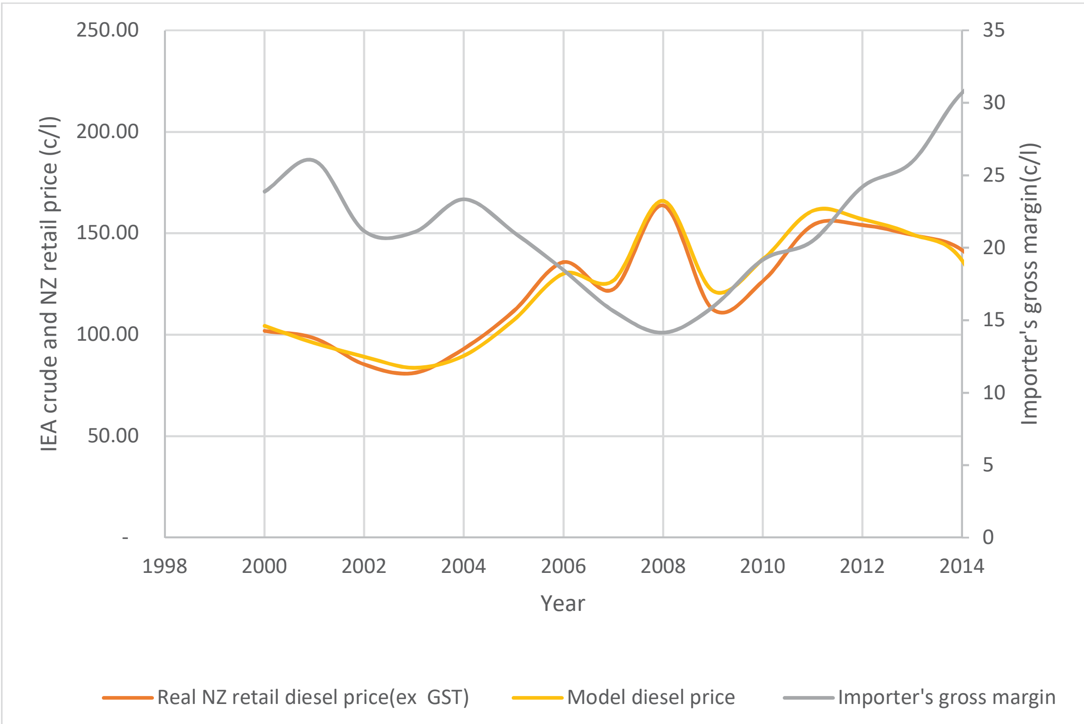


Figure 30: The fit of the model to prices between 2000 and 2015 with the importer's gross margin

Only the 'New policy' scenario, the 'Current policy' scenario and the 'Low oil price' scenarios were used in the HOMER Pro model as oil price sensitivity cases because of the close similarities between the New policy and the 450 scenarios (Table 18) The 450 scenarios for carbon price have been used along with the carbon price for the 'Low oil price' and 'New policy' scenario which is similar to the 'Current policy' scenario. The HOMER Pro software simulation only allowed the input of a single fuel price which was used in the model and expected to remain constant through the whole analysis period. The discounted cash flow analysis that HOMER Pro used to derive total system costs meant that the near-term oil price was more important than the future oil price. A single fuel price and carbon price was created using the present value factor (Appendix 15). This gave the three oil prices required for the sensitivity analysis. The upper value of $1.74 per litre of diesel, a mid-range value of $1.61 per litre of diesel and a low range value of $1.23 per litre of diesel were based on the 'Current policies' scenario, the 'New policy' scenario and the 'Low oil price' scenario respectively. The 'Low oil price' scenario was close to the 2016 oil price and as such could represent a steady-state modelling approach which took current prices and assumed no change in the future.

Table 18: Diesel in NZD/l and carbon price in NZD/t $CO_{2\ equivalent}$ used in the model (2015-2040)

Scenario		*2015*	*2020*	*2030*	*2040*
New	diesel	94.9	141	201	228
	carbon	0.72	8.8	15	20.0
Current	diesel	94.9	151	222	254
	carbon	0.72	8.8	12	16
450	diesel	94.9	138	208	224
	carbon	0.72	8.8	40.0	56
Low Oil	diesel	94.9	111	141	168
	carbon	0.72	8.8	15	20

5.4.3 Costs of methane emissions

The future cost of methane emissions assumed that agriculture entered the emissions trading scheme fully by 2020. The total present value ranged between $64,200 and $178,000 for a large 700 cow farm (Table 19). The present cost of methane emissions was calculated by applying the discounting factor from Appendix 15 and applying it to the carbon price (Table 18) for each year of the analysis. All the methane was assumed to be captured and combusted completely and the global warming potential for methane of 25 was used (Section 2.15).

Table 19: The net present cost of emissions from the anaerobic pond for an individual cow and the three farm sizes ($NZ).

Number of cows in herd	Current policy	New policy	450 policy
1	$ 91.6	$ 110.00	$ 254.00
150	$ 13,700	$ 16,500	$ 38,200
343	$ 31,400	$ 37,800	$ 87,000
700	$ 64,200	$ 77,100	$ 178,000

5.5 PV array

The solar model was based on the Renesolar Virtus 2 module (Appendix 16).

Performance degradation over time was considered. The solar cell degradation curve began with a short period of exponential degradation in solar cell performance then a slower linear degradation which continued until the end of life of the technology (Fig 31). The warranty period for this solar cell was 10 years at 90% of original performance and 25 years at 80% of original performance.

Figure 31: Manufacturer's warranty performance figures (Renvu Solar Equipment Distribution, 2016)

Temperatures above the standard test condition temperature of 20°C cause a reduction in efficiency in PV cells. This was modelled within HOMER Pro by specifying the temperature coefficient, nominal operating temperature and rated efficiency under standard test conditions to calculate the effect of temperature on the PV cell's efficiency at each time step. The program followed the method presented by Duffie & Beckman (1991) which stated the amount of heat absorbed by the solar array, the sum of the electricity produced and the heat transferred to the surroundings were balanced (Equation 9). Equation 10 panel efficiency was given for ambient temperature and solar radiation. The product of τ and α are assumed to be 0.9 (Duffie and Beckman, 1991).

$$T_C = T_a + G_T\left(\frac{T_{C,N} - T_{a,n}}{G_{T,n}}\right)\left(1 - \left(\frac{n_c}{\tau\alpha}\right)\right) \qquad \text{Equation 9}$$

where:

T_c is PV array temperature (℃),

T_a is ambient temperature (℃),

G_T is solar radiation striking the array (W/m^2),

$T_{c,n}$ is nominal operating temperature (℃),

$T_{a,n}$ is the nominal ambient temperature (℃),

$G_{T,n}$ is nominal incident radiation (W/m^2),

n_c is electrical efficiency,

τ is solar transmittance, and

α is solar absorbance.

$$\eta_c = \eta_{c,s}\,[1 + \alpha_p(T_c - T_{c,s}) \qquad \text{Equation 10}$$

where:

$\eta_{c,s}$ is efficiency under standard test conditions,

α_p is temperature coefficient, and

$T_{c,s}$ is solar cell temperature at standard test conditions (℃).

The area surrounding the solar panel installation on a dairy farm was assumed to be grass therefore the surface albedo was taken to be 20%. The model of ground albedo was assumed to be constant throughout the simulation. Surface albedo varies throughout the day with solar angle (Minnis, 1997) and changes based on the colour of the grass or the presence of snow (Wang and Davidson, 2007).

A derating factor was used to account for other non-specified real-world losses such as accumulation of dirt, shading, snow cover and wiring losses. Temperature related losses and ageing related losses were specifically excluded because they were accounted for elsewhere. A factor of 0.9 was chosen. This was higher than the value typically used in most simulations of 0.85 but because temperature and ageing were already accounted for, a higher factor was chosen (Duffie and Beckman, 1991). Budget was allocated within the maintenance schedule for a once-yearly cleaning of the panels. It also assumed that the panels were in an area free of shade. The temperature data used in the HOMER Pro model was sourced from the solar view database at the same locations as this solar data (NIWA 2016a)

5.5.1 Solar array costs

The installed cost of a solar array was developed using information from the literature, equipment wholesalers and through communication with project managers at PowerCo. The cost of a PV is made up of the install costs, modules, array framing, inverter and wiring. from the same locations BRANZ Ltd (2016) estimated the installed cost of a 3 kW array to be $8500 excluding GST in 2013. This was for a property in Auckland with a standard roof mounted PV system. PowerCo's installed cost of a 3kW solar array mounted on steel framing into the ground was $15,000 excluding GST in 2016. The difference in these prices could primarily be attributed to the difference in framing cost and install costs, although PowerCo was using top tier inverters which do come at a price premium compared to other lower quality equipment. The installation was assumed to be a typical roof mounted installation due to better cost performance.

Inverter and solar array could be modelled independently allowing the inverter to be chosen based on peak electricity demand and the array to be chosen based on the optimal size to meet the load. This would require separation of the PV and inverter costs. This would also allow different lifetimes, sizes and costs for the inverter and PV array to be specified. So far costs have been presented for the whole solar power system installed. Modelling the inverter and solar array separately made it necessary to divide the whole system costs between the inverter and the solar array. This was simplified by the fact that the systems could not exist independently therefore the fixed costs could be allocated to either component but the marginal cost of each additional watt installed must be correctly apportioned between the two systems.

The costs of parts, labour and margin were divided evenly between the solar inverter and solar panels. All mounting costs were assumed to relate to the solar panels as mounting costs for the solar inverters were minimal.

Large installations have a lower cost per watt installed (Fig 32). To account for this cost reductions for installation size are accounted for in the model. These reductions were based on the differences in the cost per watt installed of PV systems from Miller *et al.* 2015. The two datasets showed a similar trend with the prices reducing logarithmically (Fig 32). Both trend lines fitted the data well with r^2 values of 0.94 and 0.91 respectively. The equation from the trend line for series 1 in Fig 32 was used to determine the changes in installed cost for PV arrays of different sizes. Five times increase in array size resulted in an 11% reduction in total cost; a 10 times increase resulted in a 16% reduction in costs overall (Fig 32).

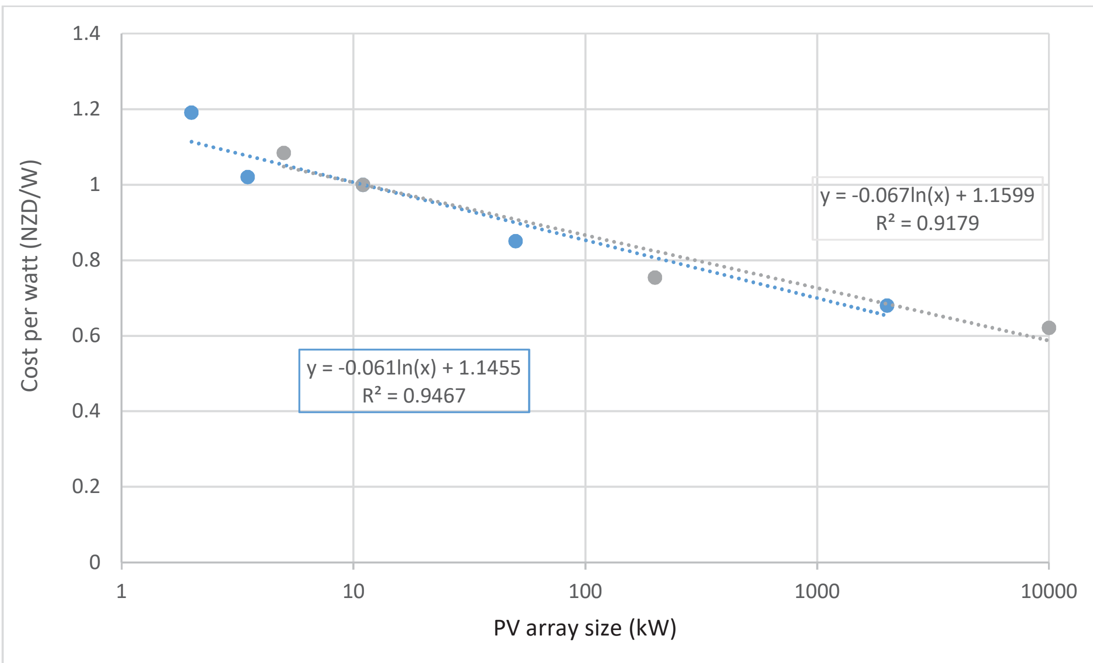


Figure 32: Installation cost per watt of roof mounted grid connected PV systems in New Zealand (blue) and the United States (grey) (Sangster, 2014; Miller *et al.*, 2015)

The solar inverter and the solar panels make up 33% of the overall cost (Appendix 17). The total price used in this model works out to be between the costs provided by PowerCo and those estimated by BRANZ Ltd (2016). This allowed for an increase in costs above the BRANZ cost estimates due to the remote location but a reduction from the PowerCo cost estimates because of the dairy shed roof mounting method instead of ground-based mounting. The breakdown between the solar inverter and PV panel to the total PV costs was 65% ($29,707) compared with the inverter costs making up 35% ($16,225) and the total overall cost for an 11 kW PV system at $45,932 excluding GST.

It was assumed that the PV array would be maintained on an annual basis. Maintenance requirements of PV systems are low. In most years maintenance would consist of cleaning panels to maintain optimal performance, inspecting for damage or excessive wear and removing branches from trees that may have begun shading the PV array.

The inverter had a lifetime of 15 years (Jäger-Waldau, 2012). The inverter was replaced during a scheduled annual maintenance period. It was assumed that the inverter used as a replacement was functionally identical to the unit originally installed and that its real price remained the same throughout the period. A part and labour cost of $1000 was added to this to account for any discrepancies in wiring and installation between the original and replacement.

As the system would be installed in a relatively remote location and there were no on-site technicians, a major cost component of maintaining the system was simply the costs of sending an employee to the site. However, the maintenance model was such that a technician would ideally only attend the site once to perform annual maintenance on the whole power system. This meant that the costs of maintenance were spread across all system components and therefore the costs of the technician's travel time were spread.

There was wide variation between costs in the table. Given the remote location of the system the mid-range figure of $30 per kW was chosen (Table 20).

Table 20: Summary of PV maintenance costs from the literature including prices for autonomous and grid connected systems.

<10 kW	$20	NZ	(Miller *et al.*, 2015)
<10 kW	$33	NZ	(White, Lloyd and Wakes, 2013)
<10 kW	$21 (s.d. $20)	US	(Sangster, 2014)
10–100 kW	$19 (s.d. $18)	US	(Sangster, 2014)
100–1,000 kW	$19 (s.d. $15)	US	(Sangster, 2014)
1–10 MW	$16 (s.d $9)	US	(Sangster, 2014)

5.6 Battery and battery inverter

The model of the battery inverter within HOMER Pro was extremely simple, the requirements being only the specification costs, life time, output efficiency, input relative capacity and input efficiency. The HOMER Pro model used the SMA Sunny Island 8.0 H 6 kW continuous battery inverter with a 30-

minute peak of 8 kW and a 48 V lithium ion phosphate battery pack. Costings were based around PowerCo's (energy storage unit) ESU which is a modularised system that contains a battery pack and up to 3 inverters housed within the same module. All dairy shed systems were assumed to be three phase and therefore would require a minimum of three inverters.
System sizes within the HOMERPro model were chosen based on multiples of three of the SMA sunny island series battery inverters which are available in sizes of 4 kW and 6 kW countinuous. The minimum size used in the HOMER Pro model was 12 kW

Data from the PowerCo test site was used to determine the real-world efficiency of the SMA Sunny Island 8.0 H. Source data for the efficiency of the battery, the inverter output efficiency, the inverter input efficiency and the overall efficiency over a nine-month period (Fig 33) was from an active trial site and covered the period from where a new battery management system was installed before undergoing tests to determine its efficacy. Some of these tests would have effects on the battery efficiency. Things such as testing the balancing abilities of the battery management system could result in a decrease in battery efficiency. There should be little effect on the efficiency of the inverter. The efficiency was determined using measurements taken by the SMA Sunny Island Inverter which used internal sensors to measure the AC power flows and the combination of an external current shunt and internal voltage measurements to determine DC power flows. These measurements were integrated and reported in kilowatt-hours at five minute intervals. The snapshots of data were all taken when the battery static charge was equal to 100%. This was important as at 100% state of charge, the battery state of charge was determined through voltage measurement whereas at other points, state of charge was determined by Coulomb counting[8] which over long periods could introduce inaccuracy.

The battery efficiency had the largest range from 90% to 99% with an average over the whole period of 95%. Over the period the battery received 3548 kWh of charge and discharged 3380 kWh. This corresponded to 173 charge cycles. The batteries and Amp hour efficiency was 98%. This was higher than has been reported in the literature (Burke and Miller, 2009; Marongiu, Damiano and Heuer, 2010). The average battery efficiency was also higher than reported in the literature with most studies finding efficiencies of between 90 and 93% during testing for energy efficiency and 91 to 93% for Coulombic efficiency (Marongiu, Damiano and Heuer, 2010; Kushnir and Sandén, 2011). It was unlikely that this battery would perform better than batteries surveyed in the literature. Therefore, it

[8] Coulomb counting is a method of state of charge determination which integrates the flow of current through the battery to determine the remaining charge (Lu *et al.*, 2013)

was more likely that the high efficiency reported was because of measurement error especially given the data was taken from a source of unknown calibration. The middle range value of 92% was used in this model.

The SMA Sunny Island inverter's output efficiency ranged from 93% to 96% with an average value of 95%. When compared to the efficiency curve from the manufacturer (Fig 33) the upper value in the range would be outside the manufacturer's reported efficiency range. The average value would indicate relatively low loading and battery voltage. The inverter efficiency was dependent on battery voltage range (Fig 33). Battery voltage in this system was between 37.5 V and 54.75 V. The average value would depend on the battery's state of charge, but lithium ion phosphate cells have an extremely flat voltage curve much of which is between 49 V and 48 V. Like the battery efficiency, when comparing the data gathered through on-site monitoring with the manufacturer's efficiency curve, the efficiency calculated from field data appeared to be slightly too high. A value of 94% was used in the model. This indicated an average inverter loading of less than 50%.

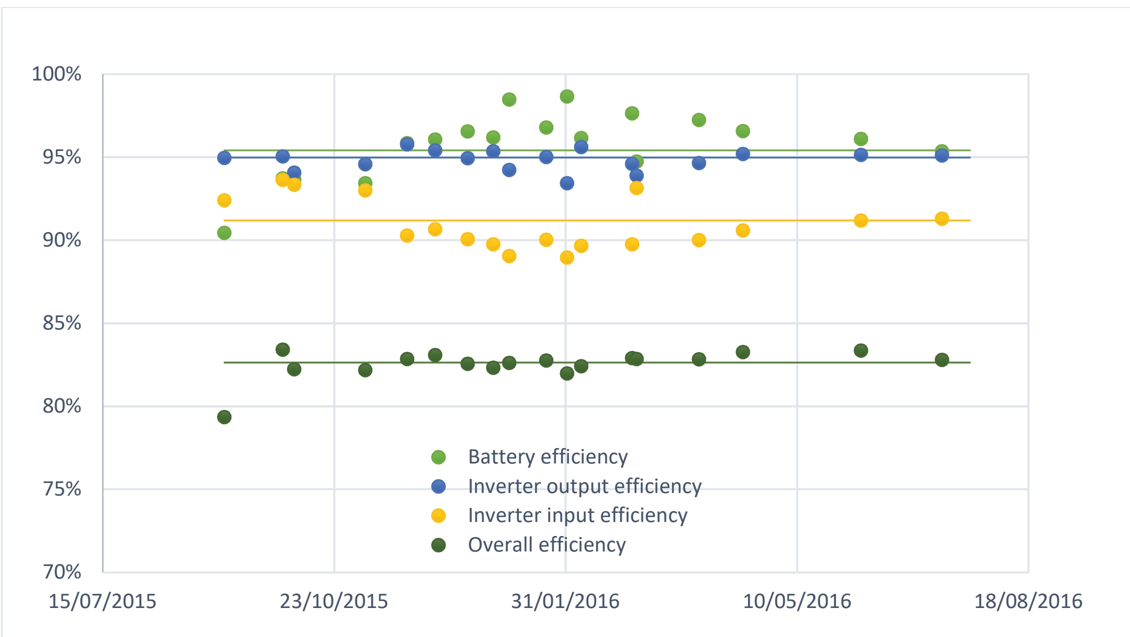


Figure 33: Battery and inverter efficiency from PowerCo's test site in the lower North Island

The inverter's input efficiency ranged from 89%-94% and had an average value of 91%. This was lower than the output efficiency of the inverter by 4%. This efficiency was low compared to what would be expected based on the manufacturer's efficiency curve (Fig 34). Given that all other values were relatively high compared to what was expected from the literature and manufacturer's data and that the means of calculation would result in the opposite trend for the input efficiency, an efficiency of 92% was used in this model.

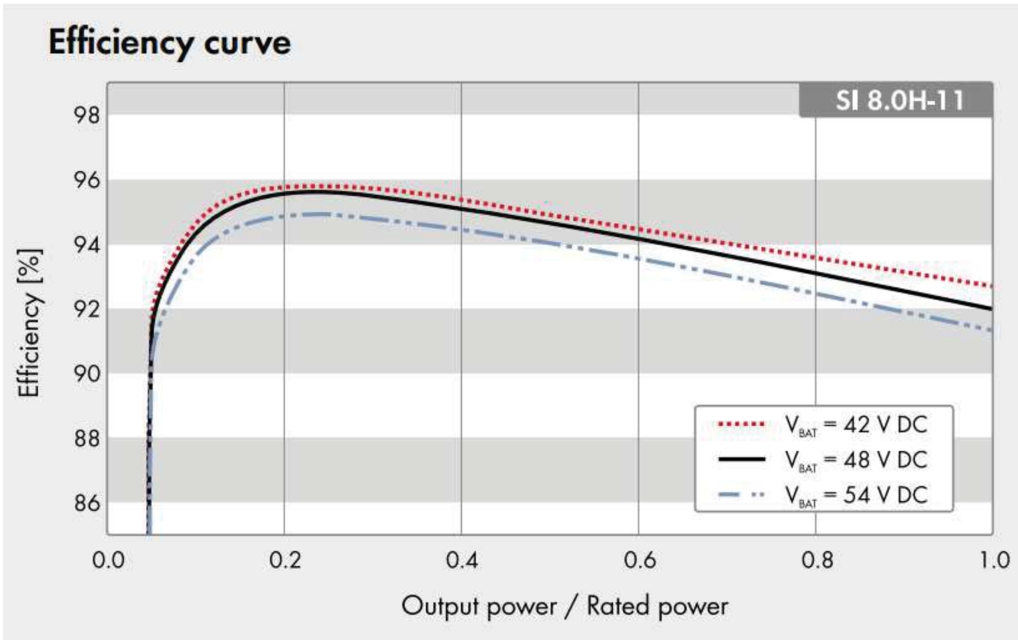


Figure 34: Manufacturer's efficiency curve for the SMA Sunny Island 8.0H (SMA Solar Technology AG, 2015)

5.6.1 Lithium battery model

The HOMER Pro model allows users to specify the reversible and irreversible losses that were dependent on discharge rate, temperature and depth of discharge. This modelled the reversible capacity loss in LiFePO4 cells accurately. However, there was no allowance for the effect of irreversible capacity loss on reversible capacity loss. It has been shown that a battery's reversible capacity loss changed as internal impedance increased (Li *et al.*, 2011).

The battery model in HOMER Pro simulated irreversible capacity loss, dependent on either depth of discharge and total energy flow through the battery or storage temperature and elapsed time for LiFePO4 cells. This model was better suited to lead acid batteries than it is to LIFePO4 batteries. Aging in lithium ion batteries is caused by the loss of active lithium and carbon within the cell primarily due to damage to the solid-electrolyte interphase layer on the negative carbon electrode (Dubarry *et al.*, 2011; Li *et al.*, 2016). This is a function of temperature, current, state of charge, calendar cell age and energy flow (Marongiu, Damiano and Heuer, 2010; Dubarry *et al.*, 2011).

The advanced battery module in HOMER Pro splits the irreversible capacity loss into two groups cycles vs depth of discharge and temperature vs shelf life.

Depth of discharge within the cell's open circuit voltage threshold had a negligible effect on the cell's life (Wang *et al.*, 2011). Temperature increased the rate of capacity loss under cycling and cell aging (Li *et al.*, 2016). Charge and discharge rate also influenced capacity loss (Wang *et al.*, 2011; Li *et al.*, 2016). Capacity loss from calendar aging increased exponentially (Wang *et al.*, 2011) but in a system where a large portion of the battery capacity was being utilised on a daily basis, the primary causes of loss of capacity would be cycling related to the rate of loss controlled by charge and discharge rate and temperature (Li *et al.*, 2011).

HOMER Pro could not model this capacity loss mechanism therefore the sole determinant of capacity loss was taken as total kWh discharge through the battery system. The batteries were assumed to be thermally isolated and have air exchange cooling. For the simplicity of the simulation it was assumed that battery temperature remained at a constant 20°C.Based on the specifications of the Sinopoly SP-LFP-200AHA this was rated to retain 80% of rated capacity after discharging 1080000Ah using a simplified linear capacity degradation curve. HOMER Pro used battery energy throughput. This figure was calculated using the battery's normal voltage, cell capacity. A value of 51.84 MWh for a 48V pack at the battery's rated cycles was found.

5.6.2 Battery and inverter costs

Base power ESU indicative costs were $55,000 excluding GST (Chiristionson, 2016). The ESU was fitted with a single Sunny Island 8.0 H inverter and 600 amp hours of battery capacity. Total cost of a three-phase 1200 amp-hour system was $93,000 of which 25% was the cost of the inverters and 40% was the cost of batteries with the remainder for installation and housing costs that are split evenly between the inverter and battery.

Most of the systems within the ESU were shared between the battery and inverter and therefore there was no simple manner to divide the costs between them. The battery was responsible for two-thirds of the costs and the inverters were responsible for the remaining one-third. If more than two three-phase modules were required, it was assumed that the costs increased based on per watt or per battery costs of the two modules.

The maintenance regime for the ESU was minimal and would be limited to inspecting the unit for damage and cleaning fans and air vents. It was estimated to be $10 per kW installed.

5.7 Results

5.7.1 Technology scenarios

Compared to the base scenario the use of efficient technology resulted in savings in the total net present cost (NPC). Farm size was an important factor with the larger farms showing the most benefit. The lowest cost technology scenario option reduced the net present cost of the large farm (LF) medium farm (MF) and small farm (SF) by 12%, 10%, and 3% respectively when compared to the base system(Table 21).

If only considering power system costs, using an ice bank has reduced NPC for all farm sizes compared to the base scenario. However, when the cost of purchase and installation of the ice bank is included, the NPC was higher for the SF, MF and LF an increase of 5%, 7% and 7% in NPC when compared with the base scenario (Table 21).

The lowest cost technology scenarios were the IN+VSD+HP and IN+VSD the for the SF. All other options showed higher NPC by more than $4000 for the SF. For the MF the lowest cost technology options were the IN+VSD+HP+IB and IN+VSD (Table 21).

IN+IB+HP+VSD has the lowest NPC in the case of the LF, and this is followed by VSD+HP+IB (Table 21).

Table 21: Net present cost of technology scenario options for the three farm sizes under the 'new' policies oil price sensitivity scenario

Option	Small	Medium	Large
Base	$ 279,000	$ 533,000	$ 1,038,000
IN	$ 278,000	$ 526,000	$ 1,024,000
IB	$ 298,000	$ 562,000	$ 1,079,000
HP	$ 279,000	$ 589,000	$ 1,055,000
VSD	$ 274,000	$ 513,000	$ 994,000
IN+IB	$ 298,000	$ 568,000	$ 1,079,000
IN+HP	$ 274,000	$ 564,000	$ 1,019,000
IN+VSD	$ 270,000	$ 503,000	$ 969,000
IB+HP	$ 288,000	$ 525,000	$ 998,000
IB+VSD	$ 294,000	$ 555,000	$ 1,048,000
HP+VSD	$ 274,000	$ 560,00	$ 1,010,000
IN+IB+HP	$ 289,000	$ 524,000	$ 996,000
IB+HP+VSD	$ 283,000	$ 509,000	$ 962,000
IN+VSD+HP	$ 270,000	$ 555,000	$ 994,000
IN+IB+HP+VSD	$ 281,000	$ 503,000	$ 892,000

Each of the abbreviations stands for a change to the base scenario with all other parameters remaining the same. IN =insulation of the vat. IB =ice bank milk cooling. HP = hot water superheat heat pump. VSD = variable speed drive milk pump

5.7.2 Component size

The system that included an ice bank tended to have larger solar arrays than the other technology scenarios and larger solar inverters. There was no change in the other system components. The ice bank systems had the largest renewable fraction for all farm sizes. The use of a superheat heatpump reduced the renewable fraction in all cases where it was used without an ice bank (Appendix 18).

The inclusion of a heat pump reduced the size of the PV Array and inverter by up to 50%. It increased generator utilisation and for the MF and LF increased generator size by 15 kW (Appendix 18). In the MF, it also increased the size of the battery storage. These systems had a low renewable energy fraction. Including IN and VSD had no effect on the SAPS configuration when compared to the base scenario. They did, however, lead to reduced fuel consumption and an increased renewable fraction (Appendix 18).

5.7.3 Sensitivity scenarios

5.7.3.1 Oil price

The relative benefit of the ice bank increased as fuel price increased. However, the NPC remained higher than the IN+VSD+HP system in all three fuel price cases for the MF and SF (Table 22). The breakeven point for the ice bank in the SF case was a levelised cost of fuel of $1.60.

Increasing fuel price lead to larger PV arrays and reduced fuel consumption. The fixed loads that occur in the morning and the late afternoon meant only a small amount of the load could be supplied by the PV array by increasing the array size. Increasing fuel price led to greater reliance on the battery.

Table 22: The sensitivity to oil price base scenario and lowest cost technology scenario for the three farm sizes.

	Low oil policies	New policies	Current policies
		Small farm	
BASE	$262,000	$279,000	$283,000
IN+VSD	$253,000	$270,000	$271,000
IN+VSD+HP	$254,000	$270,000	$274,000
IN+IB+HP+VSD	$270,000	$281,000	$284,000
		Medium farm	
BASE	$497,000	$533,000	$543,000
IN+VSD+HP	$466,000	$503,000	$507,000
IN+VSD+HP	$507,000	$555,000	$567,000
IN+IB+HP+VSD	$475,000	$503,000	$511,000
		Large farm	
BASE	$951,000	$1,038,000	$1,061,000
IN+VSD	$897,000	$969,000	$980,000
IN+VSD+HP	$896,000	$992,000	$1,018,000
IN+IB+HP+VSD	$832,000	$892,000	$906,000

Each of the abbreviations stands for a change to the base scenario with all other parameters remaining the same. IN = insulation of the vat. IB = ice bank milk cooling. HP= hot water superheat heat pump. VSD = variable speed drive milk pump

5.7.4 Capital costs

The base and IN+IB+HP+VSD showed very similar sensitivity to capital costs. Both systems were most sensitive to changes in PV capital costs and least sensitive to changes in the inverter costs (Appendix 19; Appendix 20). Increasing PV array, battery or inverter costs to a lower renewable fraction and increasing the cost of the generator led to a lower renewable fraction (Appendix 21).

5.7.5 Regional

The regional price scenario compared the Manawatu, Taranaki and Bay of Plenty. The Bay of Plenty was the lowest cost region over all farm sizes. HP+VSD +IN had the lowest costs in the MF and LF for the ‘Low oil price’ and ‘New policies’ fuel prices in the Bay of Plenty (Table 23). HP+VSD +IN+IB was more cost effective for the ‘Current policy’ fuel price in the Bay of Plenty.

There is no change in the SAPS in the regional sensitivity scenarios. Bay of Plenty had the highest renewable fraction of all the regions followed by the Taranaki (Appendix 22 and Appendix 23). Fuel price change affected the three regions similarly.

Table 23: Net present cost for each of the three regions under the three oil price sensitivity cases

		Small	Medium	Large
		Low oil policies		
Base	Manawatu	$262,000	$497,000	$951,000
Base	Taranaki	$249,000	$530,000	$977,000
Base	Bay of Plenty	$247,000	$463,000	$891,000
IN+VSD	Manawatu	$253,000	$466,000	$898,000
IN+VSD	Taranaki	$239,000	$438,000	$841,000
IN+VSD	Bay of Plenty	$242,000	$440,000	$834,000.
IN+VSD+HP	Manawatu	$254,000	$507,000	$896,000
IN+VSD+HP	Taranaki	$246,000	$489,000	$863,000
VSD+IN+HP	Bay of Plenty	$246,000	$421,000	$791,000
IN+VSD+HP+IB	Manawatu	$270,000	$475,000	$832,000
IN+VSD+HP+IB	Taranaki	$259,000	$450,000	$837,000
IN+VSD+HP+IB	Bay of Plenty	$257,000	$445,000	$831,000
		New policies		
Base	Manawatu	$279,000	$533,000	$1,038,000
Base	Taranaki	$263,000	$564,000	$1,045,000
Base	Bay of Plenty	$261,000	$495,000	$964,000
IN+VSD	Manawatu	$270,000	$503,000	$969,000
IN+VSD	Taranaki	$250,000	$466,000	$900,000
IN+VSD	Bay of Plenty	$253,000	$468,000	$888,000
IN+VSD+HP	Manawatu	$270,000	$555,000	$992,000
IN+VSD+HP	Taranaki	$262,000	$534,000	$951,000
VSD+IN+HP	Bay of Plenty	$260,000	$460,000	$869,000
IN+VSD+HP+IB	Manawatu	$281,000	$503,000	$892,000
IN+VSD+HP+IB	Taranaki	$268,000	$474,000	$889,000
IN+VSD+HP+IB	Bay of Plenty	$266,000	$467,000	$877,000
		Current policies		
Base	Manawatu	$283,000	$543,000	$1,061,000
Base	Taranaki	$267,000	$572,000	$1,063,000
Base	Bay of Plenty	$265,000	$503,000	$982,000
IN+VSD	Manawatu	$271,000	$507,000	$980,000
IN+VSD	Taranaki	$253,000	$472,000	$915,000
IN+VSD	Bay of Plenty	$256,000	$476,000	$902,000
IN+VSD+HP	Manawatu	$274,000	$567,000	$1,018,000
IN+VSD+HP	Taranaki	$265,000	$542,000	$974,000
VSD+IN+HP	Bay of Plenty	$263,000	$470,000	$890,000
IN+VSD+HP+IB	Manawatu	$284,000	$511,000	$906,000
IN+VSD+HP+IB	Taranaki	$271,000	$480,000	$902,000
IN+VSD+HP+IB	Bay of Plenty	$268,000	$473,000	$889,000

Each of the abbreviations stand for a change to the base scenario with all other parameters remaining the same. IN = insulation of the vat. IB = ice bank milk cooling. HP = Hot water superheat heat pump. VSD = variable speed drive milk pump

5.7.6 Hot water and ice storage

Modelling the ice bank and hot water as deferrable components in HOMER Pro did not show significant differences from when these elements were modelled as part of the fixed load profile. Doubling the deferrable storage volume did reduce the system NPC in all cases.

For the SF the lowest cost option was IN+VSD. For the MF the lowest NPC option was IN+VSD+HP+IB. However, the difference between IN+VSD+HP+IB and IN+VSD with two days of hot water storage was only $300. This price difference does not include the cost of the additional hot water storage (Table 24). For SF; the IN+VSD was the only technology scenario option which had lower cost systems than the IN+VSD+HP from Table 22. In the case of the LF the IN+VSD+HP+IB with deferable hot water and IB scenario had the lowest NPC (Table 24).

Table 24 Hot water and ice bank electrical loads models using the deferrable load model in HOMER Pro

Days of storage			1	2	1	2	1	2
Farm size			Small		Medium		Large	
Base	Hot water*		$276,000	$273,000	$525,000	$518,000	$1,000,00	$994,000
IN+VSD			$265,000	$264,000	$491,000	$484,000	$945,000	$931,000
IN+VSD+HP+IB	Ice bank**		$280,000	$279,000	$497,000	$493,000	$870,000	$861,000
IN+VSD+HP+IB	Hot water and ice bank***	#	$275,000	$273,000	$483,000	$481,000	$819,000	$810,000
IN+VSD+HP+IB		##	$276,000	$274,000	$484,000	$480,000	$834,000	$826,000

Each of the abbreviations stand for a change to the base scenario with all other parameters remaining the same. IN = insulation of the vat. IB = ice bank milk cooling. HP = hot water superheat heat pump. VSD = variable speed drive milk pump. HOMER Pro only allowed a single deferrable load but that dairy farm model included multiple deferrable loads. *Hot water component modelled as a deferrable load,**Ice bank component modelled as a deferrable load and ***Hot water and ice bank modelled together as a combined load. # Hot water is dispatched first in the deferrable load. ##The ice bank is dispatched first in the deferrable load

Modelling hot water (HP) and ice bank (IB) individually as a deferrable load reduced the NPC when compared to the fixed daily load profile from Table 23 by between 0.4% and 2.8% when compared to their respective non deferrable load option (Table 25). The effect of deferrable storage was larger when deferrable hot water and ice banks were modelled together. The difference between the fixed load and deferrable load ranged between 2.3% for a SF and 8.2% for a LF (Table 25). These differences arose because of the reduced need for battery storage and generator operation and increased solar utilisation (Appendix 24).

Table 25: Comparison of hot water and ice bank options in the storage sensitivity scenario with one day's worth of storage with their fixed storage equivalent.

			Small	Medium	Large
Base	Hot water*		1.0%	1.6%	2.9%
IN+VSD	Hot water*		1.8%	2.3%	2.7%
IN+VSD+HP+IB	Ice bank Hot water ***	#	2.3%	4.0%	8.2%
IN+VSD+HP+IB		##	2.3%	4.0%	8.2%

Each of the abbreviations stand for a change to the base scenario with all other parameters remaining the same. IN = insulation of the vat. IB = ice bank milk cooling. HP = Hot water superheat heat pump. VSD = variable speed drive milk pump. HOMER Pro only allowed a single deferrable load but the dairy farm model included multiple deferrable loads *Hot Water Component modelled as a deferrable load and ***Hot water and ice bank modelled together as a combined load. #Hot water is dispatched first in the deferrable load. ##The ice bank is dispatched first in the deferrable load.

For the SF and MF options the models using deferrable loads in HOMER Pro had the same system configuration as the standard fixed load models. Large farms differed in the IN+VSD+HP+IB with deferrable hot water and ice bank options, one and two-day storage and the IN+VSD+HP+IB. With ice bank with two-day storage where the battery storage was reduced from two units to one unit, the minimum peak load in the IN+VSD+HP+IB with deferrable hot water and ice bank options had only a small effect on the SF and MF. The effect was greater on the LF (Table 24).

LF differed in the IN+VSD+HP+IB scenario with deferrable hot water and ice bank option where peak load was set to 66.7% and two days of storage. The solar array size increased from 100 to 120 kW (Appendix 24).

The number of generator starts increased when a deferrable load was used from 826 to 1200 per year and the lifetime of the generator decreased slightly from 10 to 9.5 years. Intermittent operation at night-time increased under the deferrable load sensitivity scenario (Fig 35). The generator produced 5185 kWh/year to meet the deferrable load during night-time. During these operations, the generator would be under minimal load between 20 and 30 kW which would bring the overall efficiency of the generator down.

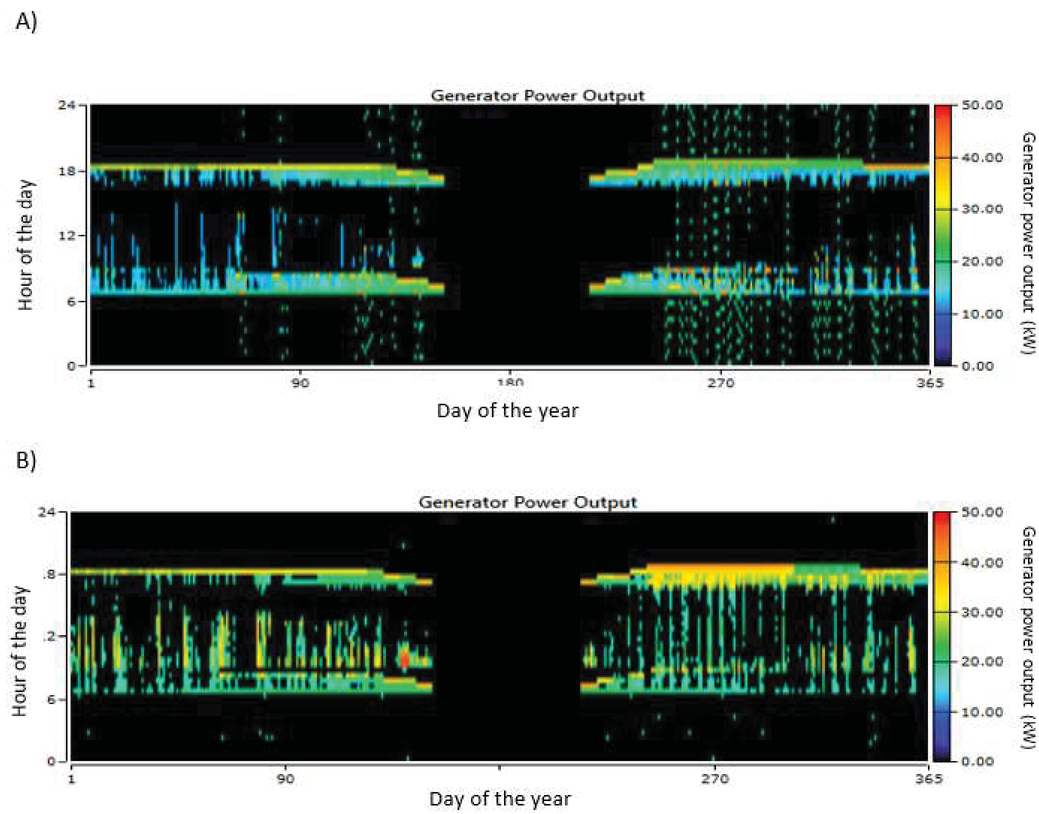


Figure 35: Generator power output on a large farm with insulation, variable speed drive, superheat heat pump and ice bank. A) modelled with deferrable hot water and ice bank; B) modelled with fixed load hot water and ice bank

5.7.6.1 Deferrable effluent

Modelling the effluent pump as a deferrable load in HOMER Pro did not substantially change the net present cost when compared with static load modelling. The variation was less than 2.2% for the SF 3.6% for the MF and 5.8% for the LF (Table 26).

Increasing the volume of storage in the deferrable load model had little effect on the net present cost. The largest reduction from increasing storage volume from 7 to 14 days occurred in the VSD+HP+IN option. This option was the most dependent on fossil fuel resources with lowest renewable fraction. Storage volume did affect solar PV sizing in two instances but did not substantially affect fuel consumption.

Table 26: NPC of Base, IN+VSD+HP, IN+VSD+HP+IB technology scenarios with deferrable effluent pumping

	Small		Medium		Large	
Days of storage	7	14	7	14	7	14
Base	$274,000	$274,000	$520,000	$520,000	$1,000,000	$1,000,000
VSD+HP+IN	$265,000	$264,000	$461,000	$459,000	$860,000	$854,000
VSD+HP+IN+IB	$275,000	$275,000	$487,000	$487,000	$844,000	$843,000

Each of the abbreviations stand for a change to the base scenario with all other parameters remaining the same. IN = insulation of the vat. IB = ice bank milk cooling. HP = Hot water superheat heat pump. VSD = variable speed drive milk pump

5.8 Biogas

In conditions where agriculture remains outside the ETS, the biogas scenario had a higher NPC than the standard scenario. The difference is greatest for SF and decreases as farm size increases (Table 27). These decreases occur at the same rate as the decreases for farms without a biogas system. As farm size increases biogas will remain more expensive than the conventional system (Appendix 25). In comparison with a conventional scenario the biogas scenario was less sensitive to changes in the oil price. To reach cost parity with the conventional scenario, the levelised cost of diesel would have to be more than $2.25. This is well outside the range considered in the study.

Table 27: NPC of biogas scenarios under the three oil price sensitivity cases

	Small	Medium	Large
	Low oil policies		
Base	$ 339,000	$ 620,000	$ 1,087,000
IN+VSD+HP	$ 321,000	$ 560,000	$ 959,000
IN+VSD+HP+IB	$ 338,000	$ 599,000	$ 927,000
	New policies		
BASE	$ 348,000	$ 638,000	$ 1,134,000
IN+VSD+HP	$ 328,000	$ 583,000	$ 1,010,000
IN+IB+HP+VSD	$ 341,000	$ 608,000	$ 968,000
	Current policies		
BASE	$ 350,000	$ 642,000	$ 1,147,000
IN+VSD+HP	$ 330,000	$ 589,000	$ 1,023,000
IN+IB+HP+VSD	$ 342,000	$ 611,000	$ 994,000

Each of the abbreviations stand for a change to the base scenario with all other parameters remaining the same. IN = insulation of the vat. IB = ice bank milk cooling. HP = hot water superheat heat pump. VSD = variable speed drive milk pump.

There is no change in the system configurations from base scenario without biogas (Appendix 25).If agriculture participates fully in the ETS in the future, then it is only under the 450 option (the highest carbon price option) that biogas has a cost advantage and this is only for large farms (Table 28).

Table 28: Net present cost of biogas scenarios under different carbon price sensitivity cases

*the 450 scenario is simulated using the new policies fuel price

	Small	Medium	Large
	Low oil price policies		
BASE	$323,000	$582,000	$1,010,000
IN+VSD+HP	$304,000	$522,000	$882,000
IN+VSD+HP+IB	$322,000	$561,000	$968,000
	New policies		
BASE	$332,000	$600,000	$1,057,000
IN+VSD+HP	$312,000	$545,000	$933,000
IN+VSD+HP+IB	$324,000	$571,000	$913,000
	450 policies *		
BASE	$310,000	$551,000	$956,000
IN+VSD+HP	$290,000	$496,000	$832,000
IN+VSD+HP+IB	$303,000	$521,000	$812,000
	Current policies		
BASE	$336,000	$611,000	$1,083,000
IN+VSD+HP	$316,000	$557,000	$959,000
IN+VSD+HP+IB	$328,000	$579,000	$930,000

Each of the abbreviations stand for a change to the base scenario with all other parameters remaining the same. IN = insulation of the vat. IB = ice bank milk cooling. HP = hot water superheat heat pump. VSD = variable speed drive milk pump.

The largest additional cost component of the biogas scenario is the maintenance cost of the biogas system. A 50% reduction in the maintenance cost is required for the biogas scenario to reach parity with the standard scenario.

5.8.1 Heat recovery from the generator

IN+VSD was the lowest cost option for the small and medium farm. IN+VSD+IB was lowest for the large farm. The solar diesel biogas fuel options followed the same trend, however they had a higher NPC than the solar diesel options (Table 29). Large farms for the solar diesel biogas options and solar diesel options had excess hot water production all year. Medium and small farms had shortfalls in hot water heat recovery from the generator but, excess solar electricity production could balance the shortfalls. Biogas served to displace diesel use (Fig 36 and Fig 37).

Table 29: Net present cost when heat recovery from the generator is used to supply hot water

	Small	Medium	Large
Solar-Diesel			
IN[1]+VSD[2]	$244,000	$434,000	$831,000
IN+VSD+IB[3]	$260,000	$468,000	$810,000
Solar-Diesel-Biogas	Small	Medium	Large
IN+VSD	$304,000	$481,000	$854,000
IN+VSD+IB	$336,000	$533,000	$851,000

Each of the abbreviations stand for a change to the base scenario with all other parameters remaining the same. IN = insulation of the vat. IB = ice bank milk cooling. HP = hot water superheat heat pump. VSD = variable speed drive milk pump.

The hot water heat recovery scenario had a decrease in the size of the PV and relative to the storage sensitivity scenarios which included hot water (Appendix 26 and Appendix 27).

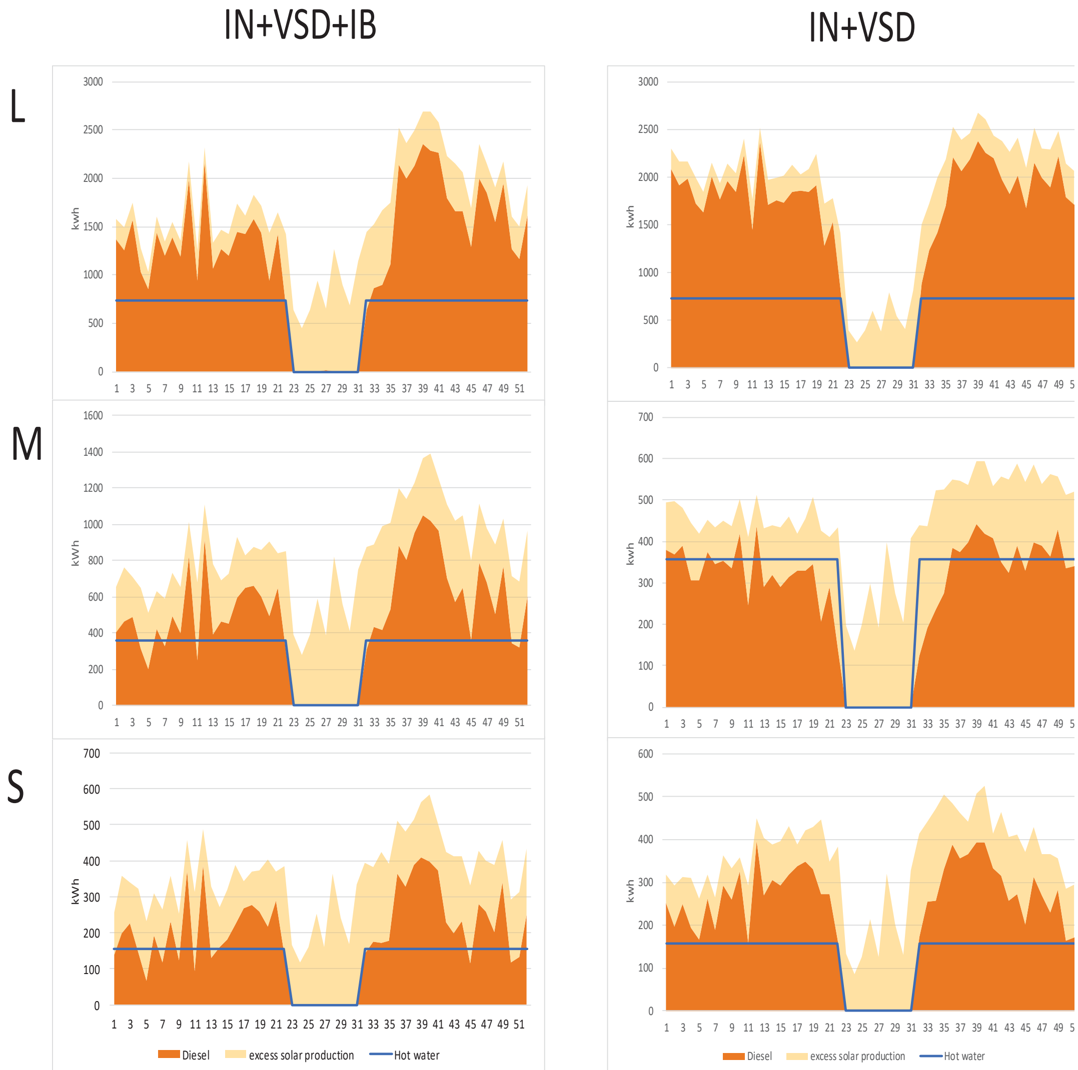


Figure 36: Weekly hot water demand from an insulation and variable speed drive milk pump (IN+VSD) and insulation, variable speed drive milk pump and ice bank milk cooling (IN+VSD+IB) with heat recovered from generator and excess for the solar-diesel hybrid system

L = large farm, M=medium farm and S=small farm

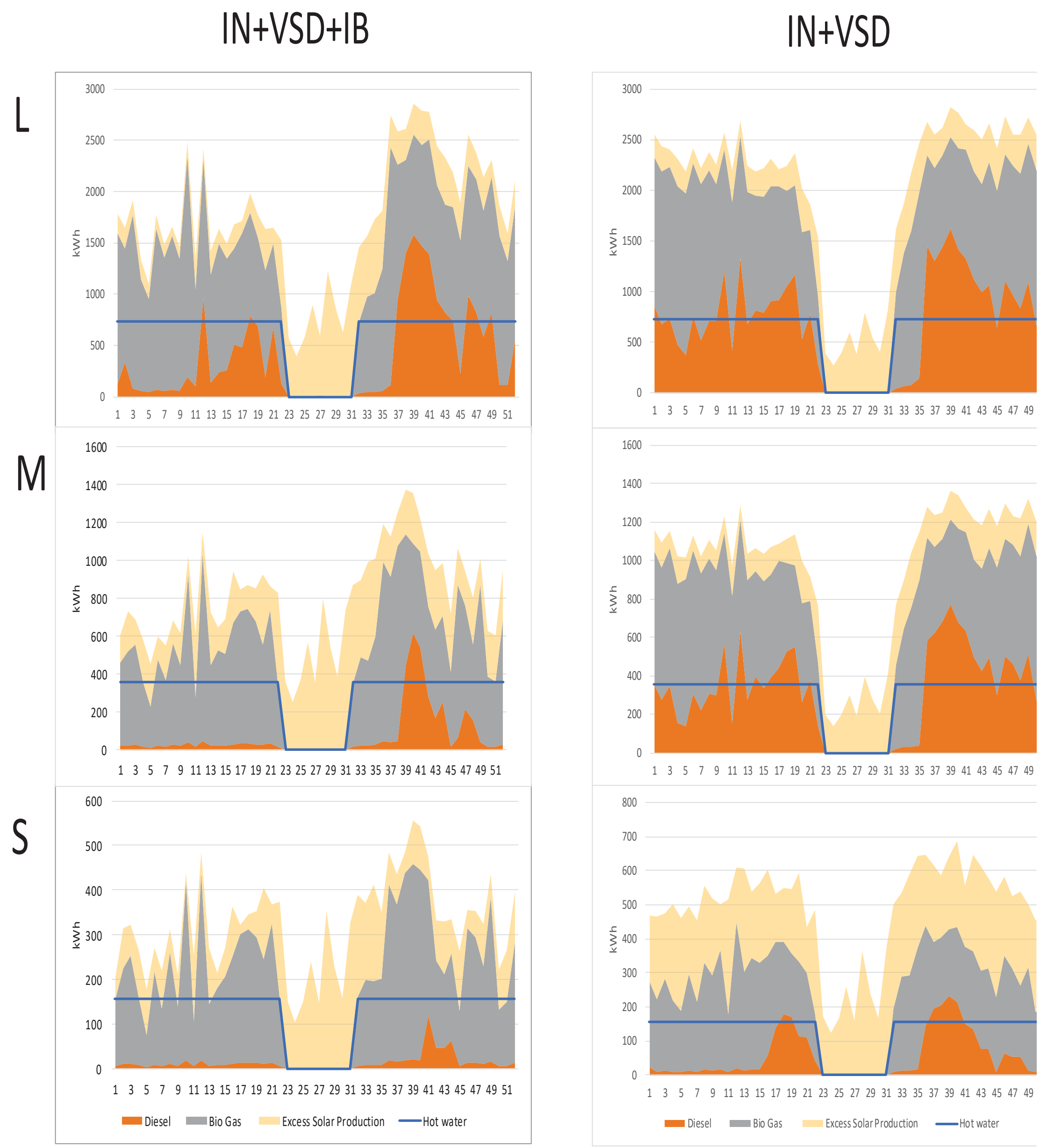


Figure 37: Hot water electricity demand and insulation and variable speed drive milk pump (IN+VSD) and insulation, variable speed drive milk pump and ice bank milk cooling (IN+VSD+IB) with heat recovered from the generator and excess solar energy for a solar-diesel-biogas hybrid system

L = large farm, M=medium farm and S=small farm

6 Discussion

The purpose of the study was to conduct an analysis of a stand-alone power system for dairy sheds and to investigate efficiency and load shifting technologies in the context of off-grid power supply. Sensitivity analysis was undertaken to investigate how this changed between the Manawatu, Taranaki and Bay of Plenty regions as well as considering fuel price and modelling uncertainties.

Not all efficiency investments are compatible with a stand-alone power system

The characteristics of stand-alone power systems make assessing energy efficiency and load shifting much more challenging than grid connected systems. The unit cost of electricity in a stand-alone power system changes dramatically depending on the source of the electricity generated when compared with the relatively stable electricity prices for a grid connected farm. The balance of efficiency and load flexibility was a key theme of this study.

Variable speed drives and milk vat insulation were found to be worthwhile investments in off-grid dairy farms. These efficiency improvements reduced total electricity consumption without changing the timing of the electricity demand. They were beneficial in all scenarios. Variable speed drives and milk vat insulation were most beneficial in systems with low renewable penetration.

Investment decisions around superheat heat pumps when used with direct expansion refrigeration and ice banks should be treated with caution. Superheat heat pumps with direct expansion refrigeration had a small benefit on small and medium farms in the Bay of Plenty but increased dependence on diesel generation when compared with the base scenario. In the Manawatu and Taranaki superheat heat pumps increased the overall system costs more than the capital costs of installation therefore if present in prospective farms for SAPS conversion they should be removed. Furthermore, storage sensitivity analysis showed modelling bias against deferrable loads such as hot water.

The benefits of superheat heat pumps did not match those shown by generator heat recovery. While the capital cost of installing generator heat recovery was not able to be included in the analysis due to lack of costings information, the difference in the NPC of the two technologies was sufficiently large to recommend generator heat recovery over superheat heat pumps. Where a superheat heat pump was coupled with an icebank there was benefit compared with standard hot water systems but when considered against generator heat recovery the net present cost difference was within the margin of error of the study.

Further investigation into generator heat recovery is necessary. The modelling approach used for generator heat recovery was simplistic. The analysis of generator heat recovery was performed outside Homer Pro and based on a calculation of recoverable heat from generator operation to meet the electricity demand. This showed that generator heat recovery produced enough hot water on a weekly basis to meet hot water demand for most weeks in the year and where there was a shortfall there was sufficient excess electricity to produce the required hot water. However, the storage requirement for the hot water system was uncertain and increasing the hot water storage volume would have implications for the investment case of generator heat recovery. Furthermore, the additional storage would require more electricity to maintain the hot water cylinders at the temperature set point.

The analysis of generator heat recovery in conjunction with the biogas scenario supported the finding by Parshotam *et al*. (2011) that biogas captured from the effluent pond could meet hot water heating demands through heat recovery from generator operation. The study found greater variation in hot water yield and in some weeks small shortfalls in availability of hot water were present.

Effluent ponds are marginal as a source of additional renewable power

Biogas capture was found to be able to supply a large portion of the generator fuel requirements thereby increasing the renewable fraction to levels similar to those found by Parshotam *et al*. (2011). Biogas capture was not worth investing in for the range of farm sizes considered in this study. Furthermore, in off-grid systems other incentives for covering effluent ponds such as to reduce the smell are less likely to be important in remote rural areas than in more closely populated areas where reducing smell may be important to neighbours (Parshotam *et al.*, 2011). Biogas capture in grid connected systems became viable in farms of more than 1000 cows or where effluent capture rates were increased through the use of winter housing or feeding pads (Stewart and Trangmar, 2008; Milet *et al.*, 2015). This was supported by the trends seen in this study of biogas capture becoming a better investment with increasing farm size. Further investigation into biogas capture is warranted on farms where there are more than 1000 cows or opportunity for higher effluent capture rates with farms using feeding pads or winter housing.

Under the ‘450 fuel-price’ option, biogas capture was worth investing in when compared to systems without biogas capture. However, carbon prices at the level of the ‘450 fuel price’ would fundamentally change the economics of dairy farming in New Zealand. Covering ponds is a simple and effective means of addressing greenhouse gas emissions (Laubach *et al*., 2015). In large dairy farms with high capture rates minor policy interventions may change the economics of biogas for off-grid dairy farms.

Location affects the optimal solution

The three study regions differed in their milk production profiles, solar resource and groundwater temperatures. The optimal system configuration results for the Bay of Plenty were different from those for the Manawatu and Taranaki Table 22). The Bay of Plenty showed better results for systems that included superheat heat pumps than were found in the Manawatu and Taranaki. Investigating in generator heat recovery in the Manawatu shows that this technology has considerable advantages in cost over superheat heat pumps. Therefore, even given that this system was optimal the better performance of generator hot water heat recovery makes this a preferable option to superheat heat pumps. Therefore, superheat heat pumps are not recommended even in the Bay of Plenty. Ice banks performed poorly in the Bay of Plenty compared with the other regions. The lower overall efficiency of the ice bank when compared to the direct expansion refrigeration system made the higher ground water temperature have a greater effect on the overall electricity consumption (Appendix 18), making ice banks more costly in the Bay of Plenty.

The results of the sensitivity analysis in the Manawatu show that the fixed daytime load modelling approach used for the regional analysis was biased against deferrable load (Table 23). Due to this bias ice banks remain recommended technology in larger farms in the Bay of Plenty. However, caution should be exercised when considering investment in ice banks where groundwater temperatures are high.

This analysis selected the power system with the lowest total NPC for any given simulation. While this approach minimised overall costs, these costs may not be aligned with the best system for sharing costs between the distribution company and the dairy farmer. A major problem for farmers is the high operational cost compared to grid connection. In the scenarios that don't use biogas most of the operational costs are fuel costs. This would further tie the farmer's overall operational costs to the price of oil. This increase in exposure to oil prices may be of concern to some farmers who see future oil costs increasing.

Effect of fuel price and capital costs

The model required inclusion of at least one battery and inverter and a minimum of 10 kW of solar and generator power to be able to supply peak load. Two batteries were the maximum used in all the scenarios. Storage was utilised more when fuel prices were higher. Capital price decreases of <10% increased the number of batteries from one to two. A single battery module capacity was sized to be appropriate for a typical farmhouse load. The smallest farms considered in the study had a daily load 3 to 4 times that of a typical domestic load (BRANZ, 2006). This may be due to the differences in load profile between a dairy farm and farmhouse. However it is necessary to investigate whether the differences between the modelled and actual power system influence the economics of battery storage. For instance in actual power systems the battery inverter was specified to meet peak load and is the primary regulator. This was not a control option in HOMER pro and in most cases the lowest cost optimal farms had an inverter that was not able to meet peak load. The battery was therefore not able to be used to meet peak demand and therefore not able to supply a full day's worth of storage without the use of either the generator or the PV array. The capital cost of the inverter had no influence on size selection in the HOMER Pro model. Utilisation was increased with higher fuel prices and decreased with lower fuel prices but size remained the same. PV sizing was the most responsive component to changes in capital and fuel prices. Generator size was set based on the peak load. Generators larger than this were included in the financial optimisation but the size remained static therefore fluctuating capital cost had no influence on the size of components selected. Fluctuating fuel price reacted as expected increasing generator utilisation under the 'low oil' option in fuel price sensitivity scenarios and decreasing it under the higher priced fuel price sensitivity scenario options.

Deferrable loads

The HOMER Pro model only allows for a single deferrable load which limited the model's accuracy. The farm model had up to three possible deferrable loads that operated on different timescales: the effluent pump, ice bank and the hot water system. Using HOMER Pro these could not be accurately modelled together without introducing significant inaccuracies. Treating hot water, ice bank and effluent pumping as independent deferrable loads would improve modelling substantially. The lack of deferrable loads tended to preference the dispatchable generation sources over the non-dispatchable. This led to under-sizing of the solar arrays, higher operating costs and a lower renewable fraction.

The ice bank model was used to cool the milk to its set temperature set point before reaching the milk vat. The direct expansion refrigeration system is only used to maintain the milk at its set point temperature. Further investigation is warranted into different control strategies for the ice bank. These control strategies could consider only using the ice bank for the period of milking where there is insufficient solar energy to operate the direct expansion refrigeration system. The ice bank was less efficient at cooling milk than the direct expansion refrigeration system. Another control strategy could only charge the ice bank using the PV array and using the direct expansion refrigeration system for the remainder of the milk cooling requirements. Both control strategies would lead to more efficient milk cooling increasing the overall benefit of the ice bank even if it had a reduced utilisation. The deferrable load modelling in HOMER Pro was extremely limited and control strategies were not able to be implemented. In fact the deferrable load model resulted in more generator operation throughout the night (Fig 40) and a shorter life time of the generator.

Options to further develop models

The dairy farm model developed in this study was intended to investigate off-grid power systems however the detail of 30-minute time slices used can also be applied to grid connected systems. This would allow the cost benefit of real-time electricity pricing coupled with distributed generation technologies such as PV or biogas, load deferral technologies such as ice banks for example and practice change such as shifting to once a day milking to be assessed in much greater detail than has been done previously (Process Developments Limited, 2004; Sims *et al.*, 2004; Miller and Glenn, 2011).

Further developments of the HOMER Pro model in conjunction with the farm model could be used to investigate strategies for using batteries to improve reliability of dairy farm supply during short outages and to assess the use of technologies for example ice banks and/or batteries to improve network utilisation and reduce demand peaks.

The mechanistic modelling approach was not able to be applied effectively to water pumping and effluent pumping because of their extremely site-specific nature. Identifying a case study farm for which the model can be used to investigate specific innovations relating to the farm and to gather real data to further validate the farm model is recommended for future work.

The study only looked at a few efficiency and load deferral options that were considered likely to be beneficial due to constraints in available data and limitations of time. There are many other options to improve efficiency or shift loads. Load deferral using water tower, multi-day hot water storage and vat based ice banks could all potentially benefit an off-grid dairy farm.

The study did not specifically consider rotary dairy farms. Understanding the differences in electricity consumption of rotary milking platforms and assessing the electricity demand of the rotary platform is an area that requires further investigation and was not performed because there were no data sources with information about rotary platform electricity consumption.

The study looked at only three locations in the North Island of New Zealand. These areas were chosen because they are of interest to PowerCo. Further work could apply this model to areas of high dairy growth where off-grid power systems could be used to avoid investing large amounts of money in network connection costs. Additionally, the study looked at a regional average dairy farm but stand-alone power systems would only be considered for extremely remote dairy farms in these regions since these may have special characteristics which should be accounted for within the model.

Most farms include at least one residence in which the farmer and the farmer's family live. Where a dairy shed is taken off-grid it's likely that the farmhouse would also require power supply. Future modelling should include farmhouse electricity load as part of the total dairy shed electricity load.

7 Conclusions and recommendations

The electricity load profile of a dairy farm depends on the number of cows on a farm and the amount of milk each cow produces as well as the type and configuration of dairy shed farmer practices and age of equipment. This does not change significantly with farm size but regions do show different electricity load profiles. The model showed

- There was clear benefit in using insulation and variable speed drives on all farms and in all regions. These technologies reduced electricity consumption of their respective dairy shed components without shifting electricity demand.
- Superheat heat pumps were a poor investment in the Manawatu and Taranaki regions when compared with other technology scenario options. In the Bay of Plenty superheat heat pumps were beneficial however when considering the results of fuel price sensitivity analysis superheat heat pumps remained a poor investment especially as fuel prices increase. Superheat heat pumps increased electricity demand during the time that the refrigeration system was operating when used with a direct expansion refrigeration system. This meant shifting electricity demand from a deferrable load to a fixed morning and afternoon load. Heat pumps reduced the renewable fraction.
- The high capital cost of ice banks made them less attractive as an investment for small and medium farms but were a worthwhile investment for large farms. When ice banks were used, the renewable fraction was high reducing reliance on fossil fuels.
- Generator heat recovery was a good investment but requires further investigation because it was modelled with a large time step outside the HOMER Pro model.
- Biogas collection was a poor investment and was only viable with extremely high carbon prices.

The lack of reliable data posed challenges to providing firm recommendations and further work is required to validate and improve the load model particularly focused on

- Uncertainties with thermal storage modelling due to limitations of HOMER Pro. This could include using a different modelling program better able to handle multiple deferrable loads.
- Investigating control strategies for deferrable loads to maximise their benefit.
- Investigating a wider range of efficiency and load shifting technologies.
- Applying this work to grid connected systems.
    - To assess potential benefits that the technologies assessed in this study could have to the distribution network.
    - Investigate the benefits of real time electricity pricing.
- Applying the farm model to a case study farm to further refine the model.

8 Appendices

Appendix 1 Planned start of calving and median calving date in regions of New Zealand(DairyNZ, 2015d)

	Planned start of calving 2014/15		Median calving 2014/15	
	day	week	day	week
Northland	15/07/2015	29	4/08/2015	32
Waikato	18/07/2015	30	6/08/2015	32
Bay of Plenty/East coast	17/07/2015	30	5/08/2015	32
Taranaki	24/07/2015	31	12/08/2015	33
Manawatu/Wairarapa	27/07/2015	31	15/08/2015	34
Tasman/Westland	1/08/2015	32	21/08/2015	35
Marlborough/Canterbury	31/07/2015	32	18/08/2015	34
Otago/Southland	6/08/2015	32	24/08/2015	35

Appendix 2 The base farm scenario and technology scenario simulations for three different farm sizes

Each row in the table represents a set of simulations in HOMER Pro. The columns show the region, the technology options being simulated, the oil price used, the farm sizes simulated and the number of simulations per set

Region	Technology included	Oil Price	Farm size	Number of simulations
Manawatu	Base only	New ($1.61)	Small (150), Medium (343), Large(700)	3
Manawatu	Milk vat insulation	New ($1.61)	Small (150), Medium (343), Large(700)	3
Manawatu	Ice bank	New ($1.61)	Small (150), Medium (343) and Large(700)	3
Manawatu	Superheat heat pump	New ($1.61)	Small (150), Medium (343), Large(700)	3
Manawatu	Variable speed drive vacuum pump	New ($1.61)	Small (150), Medium (343), Large(700)	3
Manawatu	Milk vat insulation and superheat heat pump	New ($1.61)	Small (150), Medium (343), Large(700)	3
Manawatu	Milk vat insulation and variable speed drive vacuum pump	New ($1.61)	Small (150), Medium (343), Large(700)	3
Manawatu	Milk vat insulation and ice bank	New ($1.61)	Small (150), Medium (343), Large(700)	3
Manawatu	Ice bank with superheat heat pump	New ($1.61)	Small (150), Medium (343), Large(700)	3
Manawatu	Ice bank and Variable speed drive vacuum pump	New ($1.61)	Small (150), Medium (343), Large(700)	3
Manawatu	Superheat heat and variable speed drive vacuum pump pump	New ($1.61)	Small (150), Medium (343), Large(700)	3
Manawatu	Milk vat insulation and Ice bank with superheat heat pump	New ($1.61)	Small (150), Medium (343), Large(700)	3
Manawatu	Milk vat insulation, Ice bank and Variable speed drive vacuum pump pump	New ($1.61)	Small (150), Medium (343), Large(700)	3
Manawatu	Milk vat insulation, Variable speed drive vacuum pump and superheat heat pump	New ($1.61)	Small (150), Medium (343), Large(700)	3
Manawatu	Milk vat insulation, Ice bank with superheat heat pump, and Variable speed drive vacuum pump	New ($1.61)	Small (150), Medium (343), Large(700)	3

Appendix 3 Biogas simulations including oil price sensitivity scenario and carbon price for three farm sizes.

Each row in the table represents a set of simulations in HOMER Pro. The columns show the region, the technology options being simulated, whether agricultural emissions are included, the oil price and carbon price used, the farm sizes simulated and the number of simulations per set

Region	**Technology included**	**Emissions form effluent included**	**Oil Price and carbon price**	**Farm size**	**Number of simulations**
Manawatu	Biogas	No, Yes	Current ($1.74), New ($1.61), Low ($1.23) and 450* ($1.61)	Small (150), Medium (343), Large(700)	18
Manawatu	Milk vat insulation superheat heat pump, Variable speed drive vacuum pump and biogas	No, Yes	Current ($1.74), New ($1.61), Low ($1.23) and 450* ($1.61)	Small (150), Medium (343), Large(700)	18
Manawatu	Milk vat insulation, Ice bank with superheat heat pump, Variable speed drive vacuum pump and biogas	No, Yes	Current ($1.74), New ($1.61), Low ($1.23) and 450* ($1.61)	Small (150), Medium (343), Large(700)	18

*The 450 scenario uses the same oil price as the new policy scenario but uses a different carbon price. It is only applied to simulations that include agricultural emissions.

Appendix 4 Generator hot water heat recovery simulations for both diesel and biogas supplied systems for three farm sizes

Each row in the table represents a set of simulations in HOMER Pro. The columns show the region, the technology options being simulated, the oil price used and the farm sizes simulated. The superheat heat pump was excluded due to constraints in the simulation postprocessing process which determined whether there was sufficient excess energy for generator hot water heat recovery to be a viable option. Due to the large amount of processing required the base farm scenario was also excluded

Region	Technology included	Oil Price	Farm size(cows)
Manawatu	Milk vat insulation, Variable speed drive vacuum pump and hot water heat recovery from the generator and biogas	New ($1.61)	Small (150), Medium (343), Large(700)
Manawatu	Milk vat insulation, Ice bank and Variable speed drive vacuum pump and hot water heat recovery from the generator and biogas	New ($1.61)	Small (150), Medium (343), Large(700)
Manawatu	Milk vat insulation, variable speed drive vacuum pump , hot water heat recovery from the generator and biogas	New ($1.61)	Small (150), Medium (343), Large(700)
Manawatu	Milk vat insulation, Ice bank and Variable speed drive vacuum pump hot water heat recovery from the generator and biogas	New ($1.61)	Small (150), Medium (343), Large(700)

Appendix 5 Regional scenarios and oil price sensitivity scenarios.

Each row in the table represents a set of simulations in HOMER Pro. The columns show the region, the technology options being simulated, the oil price used, the farm sizes simulated and the number of simulations per set

Region	Technology included	Oil Price	Farm size	Number of simulations
Manawatu	Base Only	Current ($1.74), New ($1.61) and Low ($1.23)	Small (150), Medium (343), Large(700)	9
Taranaki	Base Only	Current ($1.74), New ($1.61) and Low ($1.23)	Small (150), Medium (343), Large(700)	9
Bay of Plenty	Base Only	Current ($1.74), New ($1.61) and Low ($1.23)	Small (150), Medium (343), Large(700)	9
Manawatu	Milk vat insulation and Variable speed drive vacuum pump	Current ($1.74), New ($1.61) and Low ($1.23)	Small (150), Medium (343), Large(700)	9
Taranaki	Milk vat insulation and Variable speed drive vacuum pump	Current ($1.74), New ($1.61) and Low ($1.23)	Small (150), Medium (343), Large(700)	9
Bay of Plenty	Milk vat insulation and Variable speed drive vacuum pump	Current ($1.74), New ($1.61) and Low ($1.23)	Small (150), Medium (343), Large(700)	9
Manawatu	Milk vat insulation, Variable speed drive vacuum pump and superheat heat pump	Current ($1.74), New ($1.61) and Low ($1.23)	Small (150), Medium (343), Large(700)	9
Taranaki	Milk vat insulation, Variable speed drive vacuum pump and superheat heat pump	Current ($1.74), New ($1.61) and Low ($1.23)	Small (150), Medium (343), Large(700)	9
Bay of Plenty	Milk vat insulation, Variable speed drive vacuum pump and superheat heat pump	Current ($1.74), New ($1.61) and Low ($1.23)	Small (150), Medium (343), Large(700)	9
Manawatu	Milk vat insulation, Ice bank with superheat heat pump, and Variable speed drive vacuum pump	Current ($1.74), New ($1.61) and Low ($1.23)	Small (150), Medium (343), Large(700)	9
Taranaki	Milk vat insulation, Ice bank with superheat heat pump, and Variable speed drive vacuum pump	Current ($1.74), New ($1.61) and Low ($1.23)	Small (150), Medium (343), Large(700)	9
Bay of Plenty	Milk vat insulation, Ice bank with superheat heat pump, and Variable speed drive vacuum pump	Current ($1.74), New ($1.61) and Low ($1.23)	Small (150), Medium (343), Large(700)	9

Appendix 6 Storage sensitivity scenario for the ice bank, hot water and effluent pump.

Each row in the table represents a set of simulations in HOMER Pro. The columns show the region, the technology options being simulated, the storage sensitivity, the amount of storage, the minimum load and the oil price. The amount of storage was based on the storage type being simulated. The minimum load is a setting in HOMER Pro which sets a percentage of the load that the deferrable load is allowed to operate at. This allows greater flexibility in dispatch.

Region	**Technology included**	**Sensitivity**	**Amount of storage**	**Minimum load**	**Oil Price**
Manawatu	Base Only	Hot water modelled as a deferable load in HOMER Pro	One day, two day	80%	New ($1.61)
Manawatu	Milk vat insulation and Variable speed drive vacuum pump	Hot water modelled as a deferable load in HOMER Pro	One day, two day	80%	New ($1.61)
Manawatu	Milk vat insulation, Ice bank with superheat heat pump, and Variable speed drive vacuum pump	Ice bank modelled as a deferable load in HOMER Pro	One day, two day	80%	New ($1.61)
Manawatu	Milk vat insulation, Ice bank with superheat heat pump, and Variable speed drive vacuum pump	Ice bank and hot water modelled as a deferable load in HOMER Pro	One day, two day	33% of combined total and 66% of combined total	New ($1.61)
Manawatu	Base Only	Effluent pump modelled as a deferable load in HOMER Pro	Seven day, fourteen day	80%	New ($1.61)
Manawatu	Milk vat insulation, Variable speed drive vacuum pump and superheat heat pump	Effluent pump modelled as a deferable load in HOMER Pro	Seven day, fourteen day	80%	New ($1.61)
Manawatu	Milk vat insulation, Ice bank with superheat heat pump, and Variable speed drive vacuum pump	Effluent pump modelled as a deferable load in HOMER Pro	Seven, day fourteen day	80%	New ($1.61)

Appendix 7 Capital price sensitivity scenario. This scenario tested the sensitivity of the stand-alone power system to changes in the price of the battery, PV, inverter and generator

Each row in the table represents a set of simulations in HOMER Pro. The columns show the region, the technology options being simulated, the power system component, the range of price variation, the oil price used, the farm sizes simulated and the number of simulations per set

Region	Technology included	Power system component	Price variation	Oil price	Farm size	Number of simulations
Manawatu	Base Only	Battery,PV,Generator and inverter	0.8-1.2 in 0.1 increments	New ($1.61)	Small (150), Medium (343), Large(700)	96
Manawatu	Milk vat insulation, Ice bank with superheat heat pump, and variable speed drive vacuum pump	Battery,PV,Generator and inverter	0.8-1.2 in 0.1 increments	New ($1.61)	Small (150), Medium (343), Large(700)	96

Appendix 8 Biogas production as a percentage of the monthly average production over a year (Parshotam *et al.*, 2011)

Month	Biogas profile
1	133%
2	133%
3	110%
4	100%
5	80%
6	25%
7	25%
8	66%
9	80%
10	90%
11	110%
12	120%

Appendix 9 Farm model input data

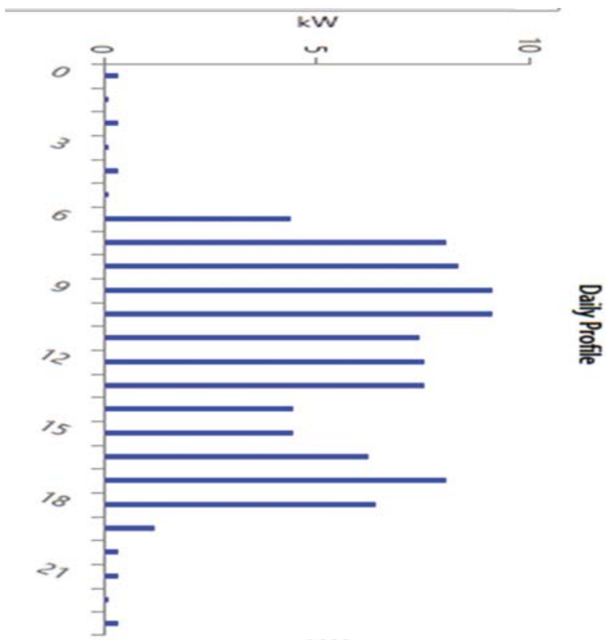
Item	Value	Source	Notes
Refrigeration			
Heat capacity of milk	3.9 kj/kg K	(Madoumier *et al.*, 2015)	
Density of milk	1.050 kg/l	(Madoumier *et al.*, 2015)	
Water milk delta	4°C	(Murphy et al. 2013).	
Target temperature	5°C	(Barker, 2015)	The requirement is below 6°C this is taken to be 5°C
Vat refrigeration systems cop	2.5	Section 2.9	
Ice bank refrigeration systems cop	1.5	Table 9	
Vat Temperature rise	4°C	Estimated	
Vat Temperature rise with Insulation	1°C	Estimated	
Direct expiation refrigeration power	8.7 W/cow	Estimated based on cooling time requirements	
Vacuum pump			
Vacuum pump	22 W/cow	(Process Developments Limited, 2004)	
Milking time per cow	3.66min	(DairyNZ 2015c)	
Time to extract 1 L of milk	0.41 min per liter	(DairyNZ, 2015c)	
Independent of the number of cows or milk volume	30min	Estimated	
Ratio of milk production between morning and afternoon	3:2	(Woods 2007)	
Number of cows to each bail	11.5	(Process Developments Limited, 2004)	
Hot water			
Hot water consumption	1.8 l/cow	(DairyNZ, 2017e)	
Target temperature	85°C	(DairyNZ, 2017e)	
Specific heat capacity of water	4.2 kJ/kg K	(Sapali *et al.*, 2014)	
Density of water	1 kg/l	(Sapali *et al.*, 2014)	
Hot water maintenance	12 W/cow	(Process Developments Limited, 2004)	
Hot water COP	3	Section 2.12	

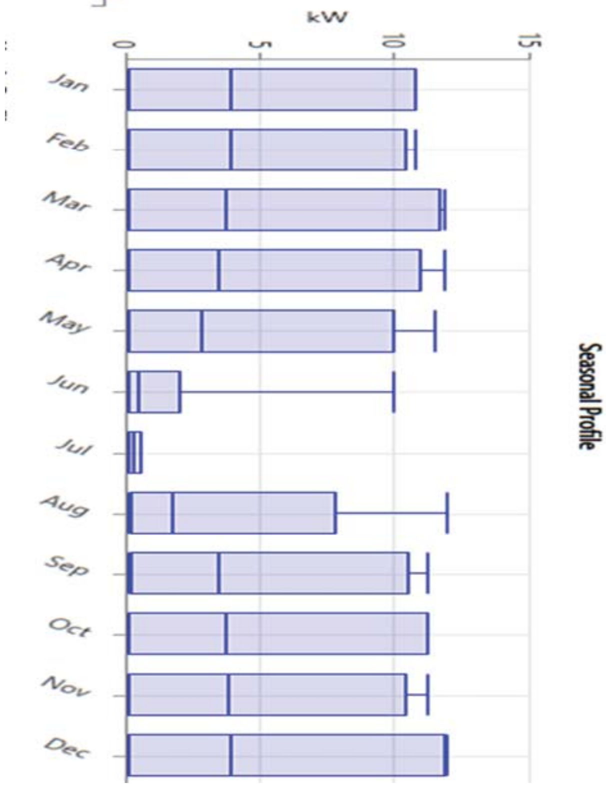
Effluent pump			
Effluent pump	18 W/cow	(Process Developments Limited, 2004)	
Water pumps			
Water pump	7.3 W/cow	(Process Developments Limited, 2004)	
Drinking water	70l	(DairyNZ, 2012).	
Wash-down pump volume	45l	(DairyNZ, 2012).	
Water pump capacity	9.8l /cow hour	(Process Developments Limited, 2004)	
Wash-down pump	18.2 W/cow	(Process Developments Limited 2004)	
Lighting			
Luminous efficiency	82Lm/W	(Lighting Research Center, 2015)	
Coefficient of utilisation	0.88	(GE Lighting, no date)	
Loss factor	0.86	(GE Lighting, no date)	
Lux required	538	(DairyNZ, 2012)	
Area of dairy shed per bail	$4.4m^2$	(DairyNZ, 2012).	
Miscellaneous			
Gate drive	0.6 W/cow	(Process Developments Limited, 2004)'	
Vat stirrer	1.5 W/cow	(Process Developments Limited, 2004)'	
Milk pump	3.6 W/cow	(Process Developments Limited, 2004)	

Appendix 10 Daily average electricity load profile for the three study regions and monthly("seasonal") demand profile

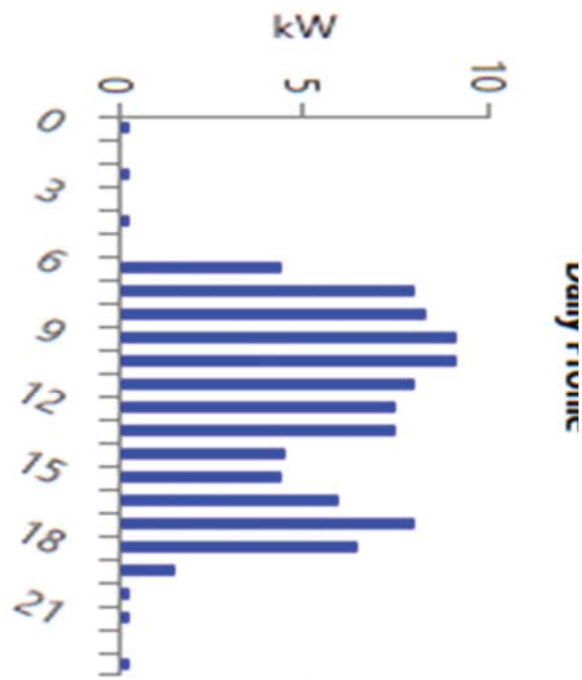
The average daily electricity load profile for the Manawatu, Taranaki and Bay of Plenty. The load profiles are scaled directly for the other farms sizes based on the number of cows.

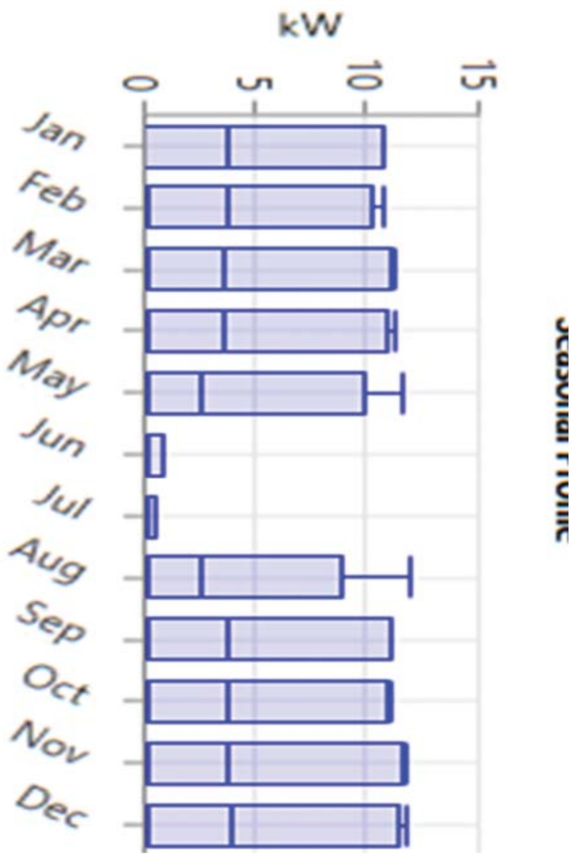
Manawatu



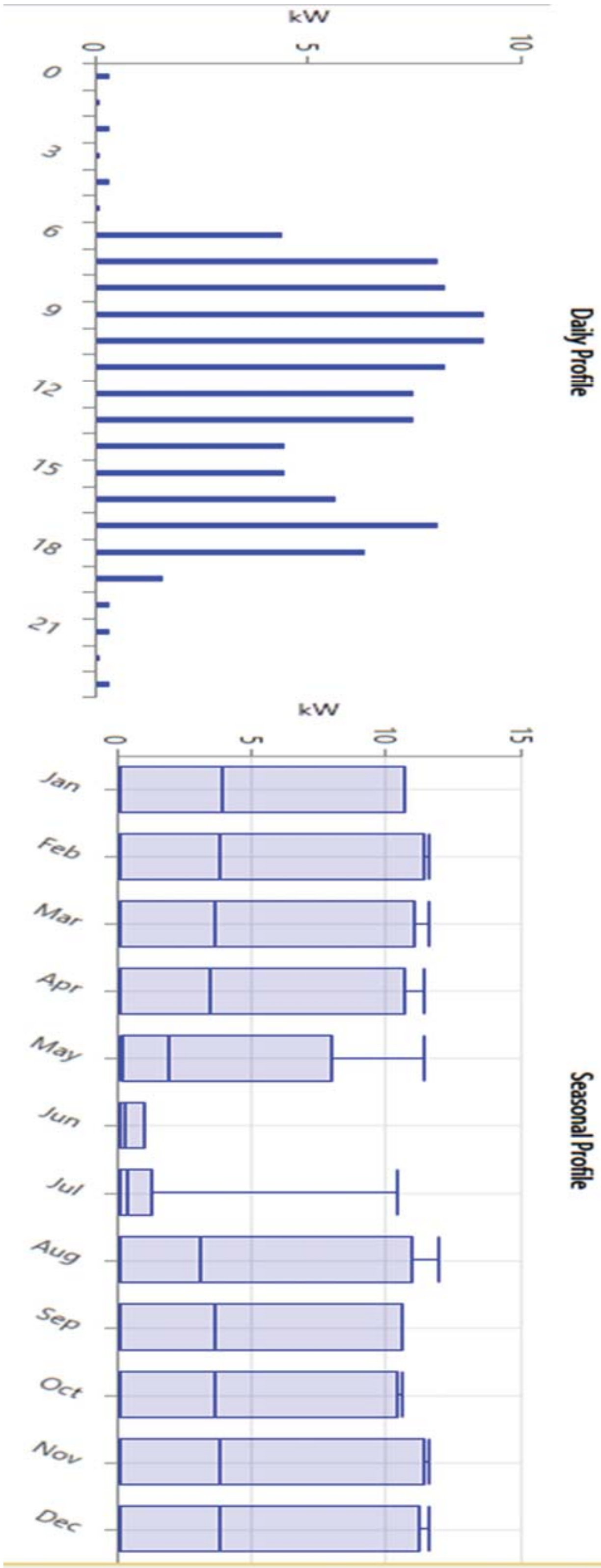


Taranaki


kW
0
5
10
0
3
6
9
12
15
18
21

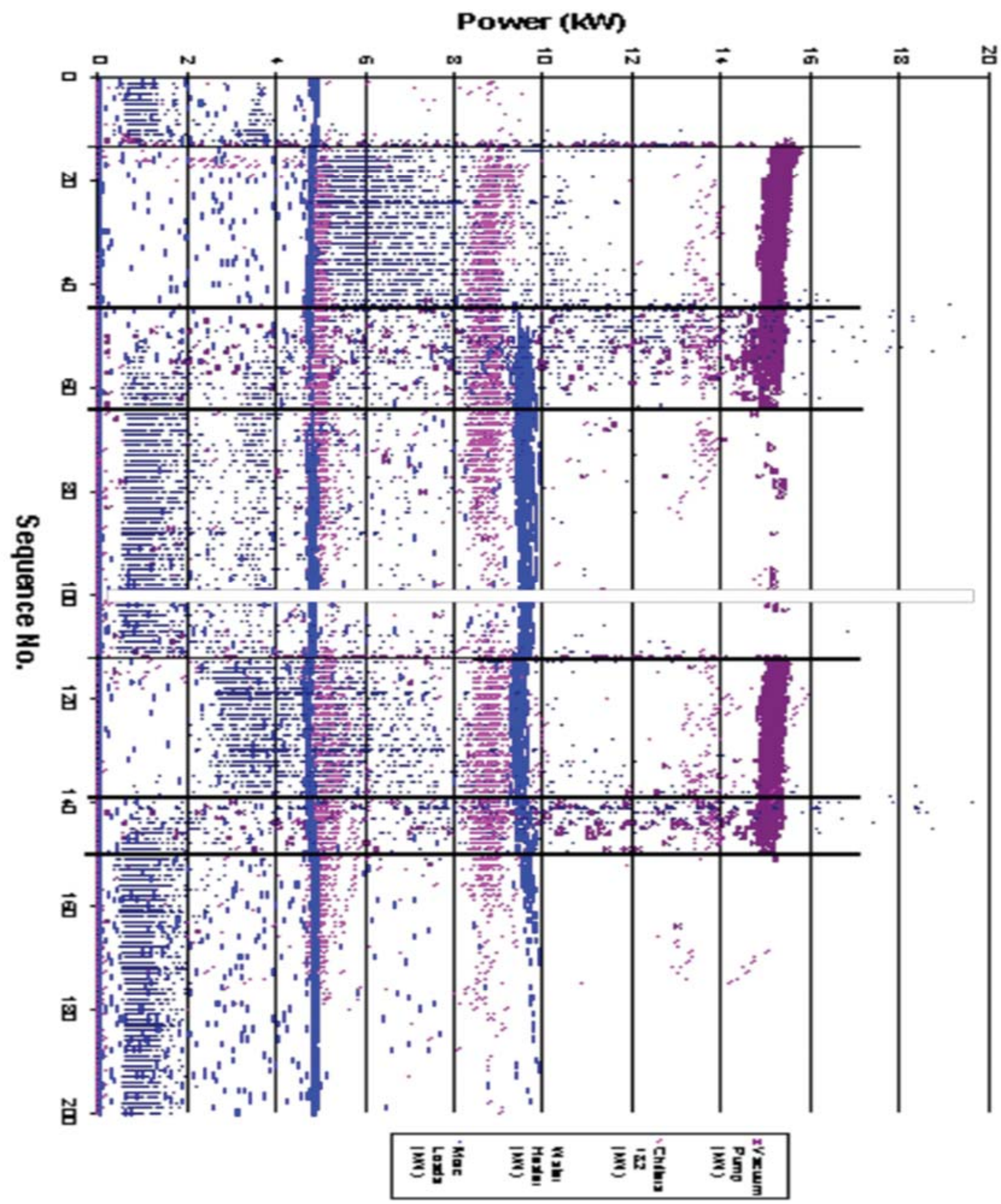

kW
0
5
10
15
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

Bay of Plenty

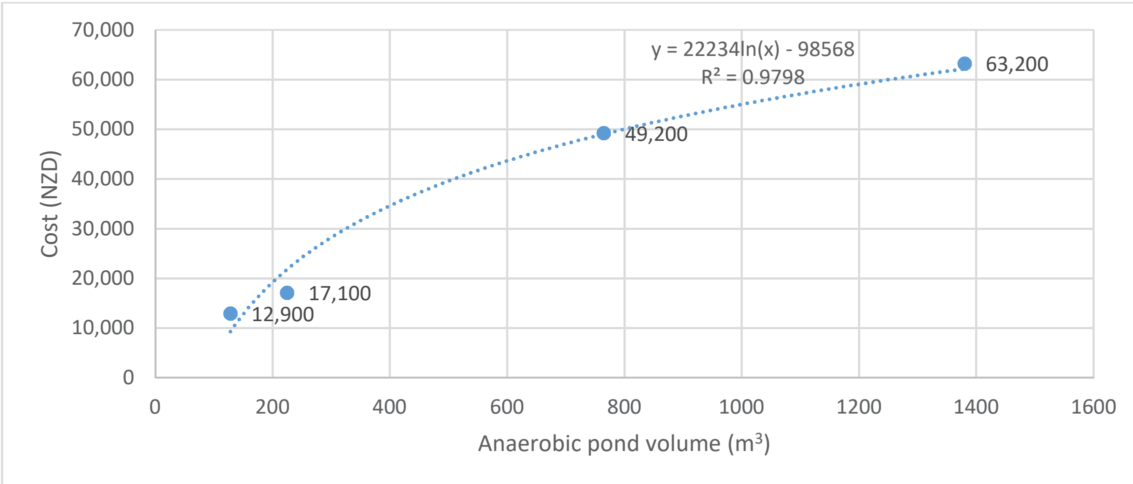


Appendix 11 Electricity consumption of different components of the dairy shed on Massey number six farm at five minute intervals(Sims *et al.*, 2004)

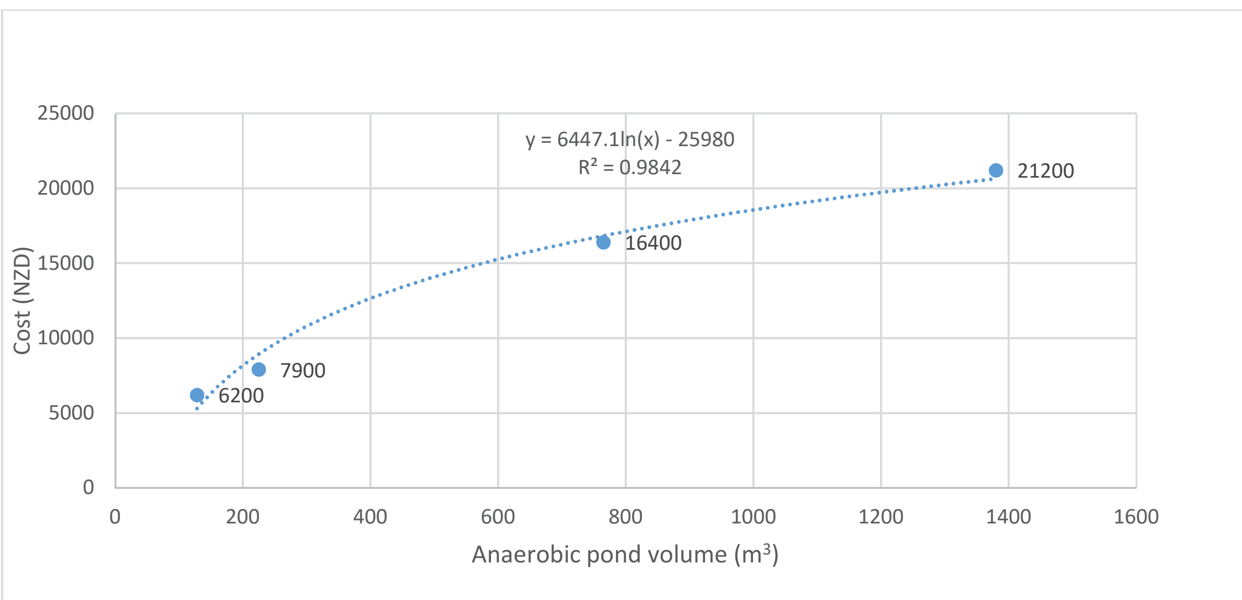
There are six black horizontal lines on the chart (that intersect the sequence number axis). The first and fourth of these lines represent the beginning of the milking period. The second and fifth line represent the completion of milking and beginning of wash down. The third and sixth lines represent the end of wash down. This is most evident by the operation of the vacuum pump (dark purple) . Pink represents the operation of the chiller, light blue represents the hot water heating element and dark blue represents other loads.



Appendix 12 Costs of installing a biogas collection system on an existing anaerobic pond for different pond volumes (Stewart and Trangmar, 2008)



Appendix 13 Maintenance costs of a covered anaerobic pond digester(Stewart and Trangmar, 2008)



Appendix 14 Specification sheet for the Kubota SQ series diesel generator(Kubota New Zealand, 2017).

Data for the Kubota SQ-33SW 24 kW was used to as an input for the generator efficiency in the HOMER Pro simulation

MODEL		Unit	SQ-14	SQ-21	SQ-26SW			SQ-33SW		
Type		–	Revolving field, brushless AC generator							
Frequency		Hz	60							
Standby Output		kVA (kW)	14.2 (14.2)	21.6 (21.6)	27.6 (22.1)		20.5(20.5)	34.8 (27.8)		25.2(25.2)
Prime Output		kVA (kW)	13.5 (13.5)	20.6 (20.6)	26.3 (21.0)		19.5(19.5)	33.1 (26.5)		24.0(24.0)
Voltage - Single Phase		V	120/240	120/240	–	–	120/240	–	–	120/240
Voltage - Three Phase		V	–	–	480	240	–	480	240	–
Armature Connection		–	Series	Series	Star with neutral		Zig-Zag	Star with neutral		Zig-Zag
Phase / Wire		–	1-3	1-3	3-12			3-12		
Power Factor		–	1.0	1.0	0.8		1.0	0.8		1.0
No. of Poles		–	4							
Insulation		Class	H							
Voltage Regulation		%	2.5 (No load to full load)							
Type of Coupling		–	Direct coupled							
AMPS										
Single Phase 120V		A	56.3 x 2	85.8 x 2	–	–	81.3 x 2	–	–	100.0 x 2
Single Phase 240V		A	56.3	85.8	–	–	81.3	–	–	100.0
Three Phase 208V		A	–	–	–	63.3	–	–	79.6	–
Three Phase 480V		A	–	–	31.6	–	–	39.8	–	–
NO. OF RECEPTACLES										
5-15R (GFCI)		–	–	–	–			–		
5-20RA (GFCI)		–	1	1	1			1		
6-15R		–	–	–	–			–		
L5-20R		–	–	–	–			–		
L5-30R		–	1	1	1			1		
L6-30R		–	–	–	–			–		
L14-30R		–	1	–	–			1		
CS-6369		–	1	2	2			2		
TERMINAL										
Terminal		–	Available	Available	Available			Available		
DIESEL ENGINE										
Type		–	Vertical, liquid-cooled, 4-cycle diesel engine							
Model		–	D1703-M	V2403-M	V2403-M			V3300		
No. of Cylinders		–	3	4	4			4		
Bore x Stroke		mm (in.)	87 x 92.4 (3.43 x 3.64)	87 x 102.4 (3.43 x 4.03)	87 x 102.4 (3.43 x 4.03)			98 x 110 (3.86 x 4.33)		
Displacement		LL (cu. in.)	1.647 (100.5)	2.434 (148.5)	2.434 (148.5)			3.318 (202.5)		
Engine Speed		rpm	1800							
Continuous Rated Output		kW (HP)	17.3 (23.2)	23.7 (31.8)	23.7 (31.8)			29.9 (40.1)		
Lubricant (API classification)		–	Above CF grade							
Oil Capacity		L(qts.)	7.0 (7.4)	9.5 (10.0)	9.5 (10.0)			13.2 (13.9)		
Coolant Capacity		L(qts.)	6.9 (7.3)	7.8 (8.2)	7.8 (8.2)			9.5 (10.0)		
Starting System		–	Electric - 12 volt DC							
SET										
Fuel		–	Diesel fuel No.2 (ASTM D975)							
Fuel Consumption	at Full Load	L/h(gal./h)	4.24 (1.12)	6.82 (1.80)	6.82 (1.80)			9.0 (2.38)		
	at 3/4 Load	L/h(gal./h)	3.49 (0.92)	4.94 (1.31)	4.94 (1.31)			6.96 (1.84)		
	at 1/2 Load	L/h(gal./h)	2.76 (0.73)	3.60 (0.95)	3.60 (0.95)			5.31 (1.40)		
	at 1/4 Load	L/h(gal./h)	1.79 (0.47)	2.54 (0.67)	2.54 (0.67)			3.81 (1.01)		
Fuel Tank Capacity		L(gal.)	81.4 (21.5)	81.4 (21.5)	81.4 (21.5)			81.4 (21.5)		
Continuous Operation Hours	at Full Load	h	19.2	11.9	11.9			9.0		
	at 3/4 Load	h	23.3	16.5	16.5			11.7		
	at 1/2 Load	h	29.5	22.6	22.6			15.3		
	at 1/4 Load	h	45.5	32.0	32.0			21.4		
Battery (Ah/5h)		–	12V (64Ah)	12V (64Ah)	12V (64Ah)			12V (92Ah)		
Dimensions L x W x H		mm	1750 x 914 x 1044	1845 x 914 x 1044	1845 x 914 x 1044			2047 x 914 x 1044		
		(in.)	70.0 x 36.6 x 41.8	73.8 x 36.6 x 41.8	73.8 x 36.6 x 41.8			81.9 x 36.6 x 41.8		
Approx. Net Weight		kg(lbs.)	668 (1470)	728 (1605)	742 (1632)			917 (2017)		
Sound Level (Full Load at 23 ft. [7m])		dB (A)	63.0	64.0	64.0			65.0		
Emergency Stop System		–	In case of abnormal: Oil pressure, water temperature, fan belt broken, when the side cover and door open while running							

Appendix 15 *Present value factor calculation* (Short, Packey and Holt, 1995)

Present value factor calculation. Present value accounts for the time value of money. Money received today can be used and return interest immediately. The same amount of money received in the future is worth less because the opportunity to earn interest from it is lost. The effects of inflation on the value of money must also be accounted for.

$$d_r = \left[\frac{1 + d_n}{1 + e}\right] - 1$$

where

d_r is the discount rate in the absence of inflation (real),

d_n is the nominal discount rate and

e is the inflation rate

$$PVF = \frac{1}{(1 + d_r)^n}$$

where

PVF is present value factor,

d_r is the nominal discount rate and

n is the number of years in the future

These equations assume that inflation rates and discount rates are constant over the analysis period.

Appendix 16 Renesolar Virtus 2 data sheet specifications

Renesolar Virtus 2	
Power	250 W
Rated efficiency at standard test conditions	15.4 %
Life time	25 years
Temperature coefficient	-0.4% per degree Celsius
Nominal operating temperature	45°C
PV cell type	Poly-crystalline
Nominal ambient temperature	20 °C
Nominal radiation	800 W per square metre

Appendix 17 PV array and inverter costs

Total installed cost of the photovoltaic system including inverter. This cost model was developed using install cost estimates from PowerCo and sources from the literature (Miller et al., 2015; BRANZ Ltd, 2016). The total inverter costs and the total array costs were used as the cost input in the HOMER Pro simulation

	per kW	11kW	55kW	110kW
PV inverter		$4,475	$22,375	$44,750
PV panel		$10,957	$54,788	$109,576
Mounting		$7,000	$35,000	$70,000
Parts		$1,500	$7,500	$15,000
Labour		$7,000	$35,000	$70,000
Installer's margin		$15,000	$75,000	$150,000
Total costs before reductions due to scale	$4,175	$45,932	$229,663	$459,326
Total cost reduction		100%	89%	84%
Total inverter costs		$16,212	$72,315	$137,096
Total array costs		$29,685	$132,408	$251,020
Total		$45,897	$204,724	$388,116

Appendix 18 System configuration under the three fuel price sensitivity scenarios and for each of the lowest cost technology scenario .

A: Large farm

Type	Fuel Price	Daily Load(kWh)	Solar PV(kW)	Inverter (kW)	Gen (kW)	Battery	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	Renewable Fraction	Fuel(l)	Solar Production (kWh)
Base	LOW	339	100	44	60	2	18	$ 951,000	$ 37,000	$ 472,000	59%	19,796	287,744
Base	NEW	339	100	44	60	2	18	$ 1,038,000	$ 44,000	$ 472,000	59%	19,796	287,744
Base	CURR	339	100	44	60	2	18	$ 1,061,000	$ 46,000	$ 472,000	59%	19,796	287,744
IN+VSD	LOW	309	100	44	60	2	18	$ 898,000	$ 32,000	$ 481,000	62%	17,004	96,905
IN+VSD	NEW	309	120	44	60	2	24	$ 963,000	$ 33,000	$ 541,000	69%	13,894	105,619
IN+VSD	CURR	309	120	44	60	2	24	$ 980,000	$ 34,000	$ 541,000	69%	13,890	105,619
IN+VSD+HP	LOW	257	50	22	75	2	18	$ 896,000	$ 40,000	$ 375,000	40%	22,164	48,453
IN+VSD+HP	NEW	257	60	22	75	2	18	$ 992,000	$ 46,000	$ 398,000	43%	21,253	52,810
IN+VSD+HP	CURR	257	60	22	75	2	18	$ 1,018,000	$ 48,000	$ 398,000	43%	21,253	52,810
IN+IB+HP+VSD	LOW	281	80	55	45	1	18	$ 832,000	$ 28,000	$ 466,000	61%	14,994	90,452
IN+IB+HP+VSD	NEW	281	100	55	45	2	18	$ 892,000	$ 28,000	$ 531,000	68%	12,391	106,732
IN+IB+HP+VSD	CURR	281	100	55	45	2	18	$ 906,000	$ 29,000	$ 531,000	68%	12,375	106,732

B: Medium farm

Type	Fuel Price	Daily Load(kWh)	Solar PV(kW)	Inverter (kW)	Gen (kW)	Battery	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	Renewable Fraction	Fuel(l)	Solar Production (kWh)
Base	LOW	166	40	22	30	1	12	$ 497,000	$ 21,000	$ 229,000	55%	10,513	127,628
Base	NEW	166	60	22	30	2	12	$ 533,000	$ 18,000	$ 297,000	67%	7,731	173,430
Base	CURR	166	60	22	30	2	12	$ 543,000	$ 19,000	$ 297,000	67%	7,734	173,430
IN+VSD	LOW	151	50	22	30	1	12	$ 466,000	$ 16,000	$ 260,000	65%	7,617	48,453
IN+VSD	NEW	151	50	22	30	1	12	$ 499,000	$ 18,000	$ 260,000	65%	7,609	48,453
IN+VSD	CURR	151	60	22	30	1	12	$ 507,000	$ 17,000	$ 282,000	69%	6,736	52,810
IN+VSD+HP	LOW	126	30	11	45	1	12	$ 507,000	$ 21,000	$ 230,000	44%	10,826	26,405
IN+VSD+HP	NEW	126	30	11	45	1	12	$ 555,000	$ 25,000	$ 230,000	44%	10,826	26,405
IN+VSD+HP	CURR	126	30	11	45	1	12	$ 567,000	$ 26,000	$ 230,000	44%	10,826	26,405
IN+IB+HP+VSD	LOW	139	40	22	30	1	12	$ 475,000	$ 15,000	$ 277,000	65%	7,275	42,693
IN+IB+HP+VSD	NEW	139	50	22	30	1	12	$ 503,000	$ 16,000	$ 300,000	70%	6,228	48,453
IN+IB+HP+VSD	CURR	139	50	22	30	1	12	$ 511,000	$ 16,000	$ 300,000	70%	6,226	48,453

C: Small Farm

Type	Fuel Price	Daily Load(kWh)	Solar PV(kW)	Inverter (kW)	Gen (kW)	Battery	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	Renewable Fraction	Fuel(l)	Solar Production (kWh)
Base	LOW	73	20	11	15	1	12	$ 262,000	$ 9,000	$ 146,000	62%	4,264	21,346
Base	NEW	73	20	11	15	1	12	$ 279,000	$ 10,000	$ 146,000	62%	5,574	21,346
Base	CURR	73	30	11	15	1	12	$ 283,000	$ 9,000	$ 169,000	71%	4,570	26,405
IN+VSD	LOW	66	20	11	15	1	12	$ 253,000	$ 8,000	$ 152,000	67%	3,227	21,346
IN+VSD	NEW	66	20	11	15	1	12	$ 267,000	$ 9,000	$ 152,000	67%	3,208	21,346
IN+VSD	CURR	66	20	11	15	1	12	$ 271,000	$ 9,000	$ 152,000	67%	3,198	21,346
IN+VSD+HP	LOW	55	10	11	15	1	12	$ 254,000	$ 9,000	$ 137,000	44%	4,278	11,434
IN+VSD+HP	NEW	55	20	11	15	1	12	$ 270,000	$ 8,000	$ 160,000	58%	3,227	21,346
IN+VSD+HP	CURR	55	20	11	15	1	12	$ 274,000	$ 9,000	$ 160,000	58%	3,226	21,346
IN+IB+HP+VSD	LOW	61	20	11	15	1	12	$ 270,000	$ 7,000	$ 183,000	72%	2,591	21,346
IN+IB+HP+VSD	NEW	61	20	11	15	1	12	$ 281,000	$ 8,000	$ 183,000	72%	2,562	21,346
IN+IB+HP+VSD	CURR	61	20	11	15	1	12	$ 284,000	$ 8,000	$ 183,000	72%	2,558	21,346

Insulation=IN, Variable speed drive vacuum pump = VSD , Superheat heat pump = HP and Ice bank milk cooling = IB

Low oil price = LOW , New policy's = NEW and Current policy's = CURR

Appendix 19 Capital cost sensitivity for each of the system components in the base scenario

Base					
Small					
	0.8	0.9	1	1.1	1.2
Generator	$272,000	$275,000	$279,000	$281,000	$284,000
Photovoltaic	$264,000	$272,000	$279,000	$284,000	$289,000
Battery	$268,000	$273,000	$279,000	$284,000	$289,000
Inverter	$274,000	$276,000	$279,000	$281,000	$283,000
Medium					
	0.8	0.9	1	1.1	1.2
Generator	$515,000	$523,000	$533,000	$540,000	$548,000
Photovoltaic	$502,000	$517,000	$533,000	$544,000	$556,000
Battery	$519,000	$525,000	$533,000	$537,000	$542,000
Inverter	$527,000	$529,000	$533,000	$534,000	$536,000
Large					
	0.8	0.9	1	1.1	1.2
Generator	$999,000	$1,016,000	$1,038,000	$1,051,000	$1,068,000
Photovoltaic	$977,000	$1,006,000	$1,038,000	$1,060,000	$1,083,000
Battery	$1,018,000	$1,026,000	$1,038,000	$1,041,000	$1,049,000
Inverter	$1,025,000	$1,029,000	$1,038,000	$1,037,000	$1,041,000

Appendix 20 Sensitivity to fluctuations in capital cost for each of the system components in the base scenario

Base					
Small					
	0.8	0.9	1	1.1	1.2
Generator	$272,000	$275,000	$279,000	$281,000	$284,000
Photovoltaic	$264,000	$272,000	$279,000	$284,000	$289,000
Battery	$268,000	$273,000	$279,000	$284,000	$289,000
Inverter	$274,000	$276,000	$279,000	$281,000	$283,000
Medium					
	0.8	0.9	1	1.1	1.2
Generator	$515,000	$523,000	$533,000	$540,000	$548,000
Photovoltaic	$502,000	$517,000	$533,000	$544,000	$556,000
Battery	$519,000	$525,000	$533,000	$537,000	$542,000
Inverter	$527,000	$529,000	$533,000	$534,000	$536,000
Large					
	0.8	0.9	1	1.1	1.2
Generator	$999,000	$1,016,000	$1,038,000	$1,051,000	$1,068,000
Photovoltaic	$977,000	$1,006,000	$1,038,000	$1,060,000	$1,083,000
Battery	$1,018,000	$1,026,000	$1,038,000	$1,041,000	$1,049,000
Inverter	$1,025,000	$1,029,000	$1,038,000	$1,037,000	$1,041,000

Appendix 21 Capital price sensitivity for the Manawatu region for the base farm scenario

		Type	Gen	Base							
Farm size	Multiplier	Daily Load(kWh)	Solar PV(kW)	Solar Inverter (kW)	Gen (kW)	Battery	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	Renewable Fraction
Small	0.8	73	20	11	15	1	12	272,000	10,000	141,000	61
Small	0.9	73	20	11	15	1	12	275,000	10,000	143,000	62
Small	1.1	73	30	11	15	1	12	281,000	8,000	171,000	71
Small	1.2	73	30	11	15	1	12	284,000	8,000	174,000	72
Medium	0.8	166	50	22	30	1	12	515,000	21,000	243,000	60
Medium	0.9	166	60	22	30	1	12	523,000	20,000	270,000	64
Medium	1.1	166	60	22	30	1	12	540,000	20,000	279,000	64
Medium	1.2	166	60	22	30	1	12	548,000	20,000	284,000	64
Large	0.8	339	120	44	60	2	18	999,000	39,000	497,000	62
Large	0.9	339	120	44	60	2	18	1,016,000	39,000	506,000	62
Large	1.1	339	120	44	60	2	18	1,051,000	41,000	524,000	62
Large	1.2	339	120	44	60	2	18	1,068,000	41,000	533,000	62

		Type	PV	Base							
Farm size	Multiplier	Daily Load(kWh)	Solar PV(kW)	Solar Inverter (kW)	Gen (kW)	Battery	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	Renewable Fraction
Small	0.8	72.72	30.00	11.00	15.00	1.00	12.00	264,000.00	9,000.00	154,000.00	70.76
Small	0.9	72.72	30.00	11.00	15.00	1.00	12.00	272,000.00	9,000.00	162,000.00	70.76
Small	1.1	72.72	20.00	11.00	15.00	1.00	12.00	284,000.00	10,000.00	131,000.00	62.23
Small	1.2	72.72	20.00	11.00	15.00	1.00	12.00	289,000.00	10,000.00	136,000.00	62.23
Medium	0.8	166.29	70.00	22.00	30.00	1.00	12.00	302,000.00	18,000.00	263,000.00	67.34
Medium	0.9	166.29	60.00	22.00	30.00	1.00	12.00	317,000.00	20,000.00	260,000.00	64.29
Medium	1.1	166.29	50.00	22.00	30.00	2.00	12.00	544,000.00	20,000.00	287,000.00	62.45
Medium	1.2	166.29	50.00	22.00	30.00	2.00	12.00	556,000.00	20,000.00	299,000.00	62.45
Large	0.8	339.37	130.00	44.00	60.00	2.00	18.00	977,000.00	39,000.00	478,000.00	63.73
Large	0.9	339.37	120.00	44.00	60.00	2.00	18.00	1,006,000.00	40,000.00	488,000.00	62.12
Large	1.1	339.37	100.00	44.00	60.00	2.00	18.00	1,060,000.00	44,000.00	495,000.00	58.12
Large	1.2	339.37	100.00	44.00	60.00	2.00	18.00	1,083,000.00	44,000.00	518,000.00	58.12

		Type	BATTERY	Base							
Farm size	Multiplier	Daily Load(kWh)	Solar PV(kW)	Solar Inverter (kW)	Gen (kW)	Battery	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	Renewable Fraction
Small	0.8	72.72	30.00	11.00	15.00	1.00	12.00	268,000.00	8,000.00	162,000.00	72.49
Small	0.9	72.72	30.00	11.00	15.00	1.00	12.00	273,000.00	8,000.00	165,000.00	71.65
Small	1.1	72.72	20.00	11.00	15.00	1.00	12.00	284,000.00	10,000.00	130,000.00	61.70
Small	1.2	72.72	20.00	11.00	15.00	1.00	12.00	289,000.00	10,000.00	133,000.00	61.15
Medium	0.8	166.29	50.00	22.00	30.00	2.00	12.00	519,000.00	20,000.00	262,000.00	62.49
Medium	0.9	166.29	50.00	22.00	30.00	2.00	12.00	525,000.00	20,000.00	268,000.00	62.50
Medium	1.1	166.29	60.00	22.00	30.00	1.00	12.00	537,000.00	20,000.00	279,000.00	64.28
Medium	1.2	166.29	60.00	22.00	30.00	1.00	12.00	542,000.00	20,000.00	282,000.00	64.20
Large	0.8	339.37	120.00	44.00	60.00	2.00	18.00	1,018,000.00	40,000.00	503,000.00	62.12
Large	0.9	339.37	120.00	44.00	60.00	2.00	18.00	1,026,000.00	40,000.00	509,000.00	62.12
Large	1.1	339.37	120.00	44.00	60.00	2.00	18.00	1,041,000.00	40,000.00	521,000.00	62.12
Large	1.2	339.37	120.00	44.00	60.00	2.00	18.00	1,049,000.00	40,000.00	527,000.00	62.12

		Type	INVERTER	Base							
	Multiplier	Daily Load(kWh)	Solar PV(kW)	Solar Inverter (kW)	Gen (kW)	Battery	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	Renewable Fraction
Small	0.8	72.72	20.00	11.00	15.00	1.00	12.00	274,000.00	10,000.00	142,000.00	62.23
Small	0.9	72.72	20.00	11.00	15.00	1.00	12.00	276,000.00	10,000.00	144,000.00	62.23
Small	1.1	72.72	20.00	11.00	15.00	1.00	12.00	281,000.00	10,000.00	148,000.00	62.23
Small	1.2	72.72	20.00	11.00	15.00	1.00	12.00	283,000.00	10,000.00	149,000.00	62.23
Medium	0.8	166.29	60.00	22.00	30.00	1.00	12.00	327,000.00	20,000.00	271,000.00	64.29
Medium	0.9	166.29	60.00	22.00	30.00	1.00	12.00	329,000.00	20,000.00	273,000.00	64.29
Medium	1.1	166.29	60.00	22.00	30.00	1.00	12.00	334,000.00	20,000.00	277,000.00	64.29
Medium	1.2	166.29	60.00	22.00	30.00	1.00	12.00	336,000.00	20,000.00	278,000.00	64.29
Large	0.8	339.37	120.00	44.00	60.00	2.00	24.00	1,023,000.00	39,000.00	522,000.00	63.60
Large	0.9	339.37	120.00	44.00	60.00	2.00	18.00	1,029,000.00	40,000.00	512,000.00	62.12
Large	1.1	339.37	120.00	44.00	60.00	2.00	18.00	1,037,000.00	40,000.00	518,000.00	62.12
Large	1.2	339.37	120.00	44.00	60.00	2.00	18.00	1,041,000.00	40,000.00	522,000.00	62.12

Appendix 22 Capital price sensitivity for the Manawatu region for the IN+VSD+HP+IB farm scenario

		Type	Gen	IN+VSD+HP+IB							
Farm size	Multiplier	Daily Load(kWh)	Solar PV(kW)	Solar Inverter (kW)	Gen (kW)	Battery	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	Renewable Fraction
Small	0.8	60	20	11	15	1	12	278,000	8,000	178,000	70
Small	0.9	60	20	11	15	1	12	280,000	8,000	181,000	71
Small	1.1	60	20	11	15	1	12	286,000	8,000	185,000	72
Small	1.2	60	30	11	15	1	12	288,000	6,000	211,000	82
Medium	0.8	138	50	22	30	1	12	493,000	16,000	291,000	69
Medium	0.9	138	50	22	30	1	12	499,000	16,000	296,000	69
Medium	1.1	138	50	22	30	1	12	512,000	16,000	305,000	70
Medium	1.2	138	50	22	30	2	12	518,000	14,000	332,000	73
Large	0.8	281	100	44	45	1	18	861,000	29,000	482,000	66
Large	0.9	281	100	44	45	1	18	873,000	30,000	488,000	66
Large	1.1	281	100	44	45	2	18	895,000	29,000	524,000	67
Large	1.2	281	100	44	45	2	18	907,000	29,000	531,000	67

		Type	PV	IN+VSD+HP+IB							
Farm size	Multiplier	Daily Load(kWh)	Solar PV(kW)	Solar Inverter (kW)	Gen (kW)	Battery	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	Renewable Fraction
Small	0.8	60.27	20.00	11.00	15.00	1.00	12.00	241,000.00	8,000.00	179,000.00	71.71
Small	0.9	60.27	20.00	11.00	15.00	1.00	12.00	243,000.00	8,000.00	181,000.00	71.71
Small	1.1	60.27	20.00	11.00	15.00	1.00	12.00	248,000.00	8,000.00	185,000.00	71.71
Small	1.2	60.27	20.00	11.00	15.00	1.00	12.00	250,000.00	8,000.00	186,000.00	71.71
Medium	0.8	137.81	60.00	22.00	30.00	1.00	12.00	429,000.00	14,000.00	294,000.00	73.49
Medium	0.9	137.81	60.00	22.00	30.00	1.00	12.00	444,000.00	14,000.00	308,000.00	73.49
Medium	1.1	137.81	50.00	22.00	30.00	1.00	12.00	469,000.00	16,000.00	312,000.00	69.45
Medium	1.2	137.81	50.00	22.00	30.00	1.00	12.00	481,000.00	16,000.00	324,000.00	69.45
Large	0.8	281.25	120.00	44.00	45.00	2.00	18.00	766,000.00	25,000.00	486,000.00	71.19
Large	0.9	281.25	100.00	44.00	45.00	2.00	18.00	793,000.00	28,000.00	474,000.00	67.25
Large	1.1	281.25	90.00	44.00	45.00	2.00	18.00	839,000.00	30,000.00	497,000.00	64.81
Large	1.2	281.25	90.00	44.00	45.00	2.00	18.00	859,000.00	30,000.00	517,000.00	64.81

		Type	BATTERY	IN+VSD+HP+IB							
Farm size	Multiplier	Daily Load(kWh)	Solar PV(kW)	Solar Inverter (kW)	Gen (kW)	Battery	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	Renewable Fraction
Small	0.8	60.27	20.00	11.00	15.00	1.00	12.00	273,000.00	8,000.00	175,000.00	72.99
Small	0.9	60.27	20.00	11.00	15.00	1.00	12.00	278,000.00	8,000.00	179,000.00	72.33
Small	1.1	60.27	20.00	11.00	15.00	1.00	12.00	288,000.00	8,000.00	187,000.00	70.65
Small	1.2	60.27	20.00	11.00	15.00	1.00	12.00	293,000.00	8,000.00	191,000.00	69.69
Medium	0.8	137.81	50.00	22.00	30.00	2.00	12.00	491,000.00	14,000.00	310,000.00	73.24
Medium	0.9	137.81	50.00	22.00	30.00	2.00	12.00	499,000.00	14,000.00	316,000.00	72.53
Medium	1.1	137.81	50.00	22.00	30.00	1.00	12.00	510,000.00	16,000.00	304,000.00	69.23
Medium	1.2	137.81	50.00	22.00	30.00	1.00	12.00	517,000.00	16,000.00	308,000.00	68.79
Large	0.8	281.25	100.00	44.00	45.00	2.00	18.00	869,000.00	28,000.00	505,000.00	67.40
Large	0.9	281.25	100.00	44.00	45.00	2.00	18.00	876,000.00	28,000.00	511,000.00	67.40
Large	1.1	281.25	100.00	44.00	45.00	1.00	18.00	891,000.00	30,000.00	499,000.00	65.73
Large	1.2	281.25	100.00	44.00	45.00	1.00	18.00	896,000.00	30,000.00	503,000.00	65.64

		Type	INVERTER	IN+VSD+HP+IB							
Farm size	Multiplier	Daily Load(kWh)	Solar PV(kW)	Solar Inverter (kW)	Gen (kW)	Battery	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	Renewable Fraction
Small	0.8	60.27	30.00	11.00	15.00	1.00	12.00	271,000.00	6,000.00	191,000.00	79.77
Small	0.9	60.27	20.00	11.00	15.00	1.00	12.00	277,000.00	8,000.00	178,000.00	71.71
Small	1.1	60.27	20.00	11.00	15.00	1.00	12.00	288,000.00	8,000.00	188,000.00	71.71
Small	1.2	60.27	20.00	11.00	15.00	1.00	12.00	293,000.00	8,000.00	193,000.00	71.71
Medium	0.8	137.81	50.00	22.00	30.00	1.00	12.00	301,000.00	16,000.00	297,000.00	69.45
Medium	0.9	137.81	50.00	22.00	30.00	1.00	12.00	303,000.00	16,000.00	299,000.00	69.45
Medium	1.1	137.81	50.00	22.00	30.00	1.00	12.00	307,000.00	16,000.00	302,000.00	69.45
Medium	1.2	137.81	50.00	22.00	30.00	1.00	12.00	310,000.00	16,000.00	304,000.00	69.45
Large	0.8	281.25	100.00	44.00	45.00	2.00	18.00	876,000.00	28,000.00	511,000.00	67.25
Large	0.9	281.25	100.00	44.00	45.00	2.00	18.00	880,000.00	28,000.00	514,000.00	67.25
Large	1.1	281.25	100.00	44.00	45.00	2.00	18.00	888,000.00	28,000.00	521,000.00	67.25
Large	1.2	281.25	100.00	44.00	45.00	2.00	18.00	892,000.00	28,000.00	524,000.00	67.25

Appendix 23 System configuration for the three regional scenarios with oil price and technology scenarios

A: Small farm

Type	Base												
location	Fuel Price	Daily Load	SOLAR PV	SOLAR INVERTER	Gen (kW)	BATTERY	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	RENEWABLE FRACTION	Solar prediction(kWh)	Fuel(l)
Taranaki	LOW	72	20	11	18	1	12	249,000	8,000	146,000	74	34,180	3,322
Taranaki	NEW	72	20	11	18	1	12	265,000	9,000	146,000	78	34,180	3,314
Taranaki	CURR	72	20	11	18	1	12	267,000	9,000	146,000	79	34,180	3,309
Bay of Plenty	LOW	71	20	11	18	1	12	247,000	8,000	146,000	73	34,180	3,266
Bay of Plenty	NEW	71	20	11	18	1	12	261,000	9,000	146,000	78	34,180	3,253
Bay of Plenty	CURR	71	20	11	18	1	12	265,000	9,000	146,000	79	34,180	3,248
Type	VSD+IN											-	-
location	Fuel Price	Daily Load	SOLAR PV	SOLAR INVERTER	Gen (kW)	BATTERY	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	RENEWABLE FRACTION	Solar prediction(kWh)	Fuel(l)
Taranaki	LOW	65	20	11	18	1	12	248,000	7,000	160,000	73	34,585	2,558
Taranaki	NEW	65	20	11	18	1	12	258,000	8,000	160,000	74	34,585	2,529
Taranaki	CURR	65	20	11	18	1	12	261,000	8,000	160,000	74	34,585	2,523
Bay of Plenty	LOW	65	20	11	18	1	12	250,000	7,000	160,000	72	33,546	2,703
Bay of Plenty	NEW	65	20	11	18	1	12	261,000	8,000	160,000	72	33,546	2,683
Bay of Plenty	CURR	65	20	11	18	1	12	265,000	8,000	160,000	72	33,546	2,683
Type	VSD+IN+HP												
location	Fuel Price	Daily Load	SOLAR PV	SOLAR INVERTER	Gen (kW)	BATTERY	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	RENEWABLE FRACTION	Solar prediction(kWh)	Fuel(l)
Taranaki	LOW	54	10	11	18	1	12	248,000	8,000	137,000	48	18,272	3,556
Taranaki	NEW	54	20	11	18	1	12	262,000	8,000	160,000	62	34,585	2,877
Taranaki	CURR	54	20	11	18	1	12	265,000	8,000	160,000	62	34,585	2,872
Bay of Plenty	LOW	54	10	11	18	1	12	246,000	8,000	137,000	49	12,898	3,596
Bay of Plenty	NEW	54	20	11	18	1	12	260,000	8,000	160,000	63	33,917	2,782
Bay of Plenty	CURR	54	20	11	18	1	12	265,000	8,000	160,000	63	33,917	2,776
Type	IN+VSD+HP+IB												
location	Fuel Price	Daily Load	Solar PV	Solar inverter	Gen (kW)	BATTERY	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	RENEWABLE FRACTION	Solar prediction(kWh)	Fuel(l)
Taranaki	LOW	61	20	11	18	1	12	259,000	6,000	183,000	77	34,180	2,095
Taranaki	NEW	61	20	11	18	1	12	268,000	7,000	183,000	77	34,180	2,079
Taranaki	CURR	61	20	11	18	1	12	271,000	7,000	183,000	77	34,180	2,076
Bay of Plenty	LOW	61	20	11	18	1	12	257,000	6,000	183,000	78	34,180	2,020
Bay of Plenty	NEW	61	20	11	18	1	12	266,000	6,000	183,000	78	34,180	1,999
Bay of Plenty	CURR	61	20	11	18	1	12	268,000	7,000	183,000	78	34,180	1,997

C: Medium Farm

Type	Base												
location	Fuel Price	Daily Load	SOLAR PV	SOLAR INVERTER	Gen (kW)	BATTERY	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	RENEWABLE FRACTION	Solar prediction(kWh)	Fuel(l)
Taranaki	LOW	164	60	22	48	1	18	550,000	18,000	297,000	68	59,175	8,335
Taranaki	NEW	164	60	22	48	2	18	564,000	18,000	335,000	73	59,175	6,600
Taranaki	CURR	164	60	22	48	2	18	572,000	18,000	335,000	74	59,175	6,600
Bay of Plenty	LOW	163	50	22	30	1	12	465,000	16,000	252,000	60	54,870	7,851
Bay of Plenty	NEW	163	60	22	30	1	12	495,000	17,000	275,000	64	59,175	6,889
Bay of Plenty	CURR	163	60	22	30	1	12	505,000	18,000	275,000	68	59,175	6,889
Type	VSD+IN											-	-
location	Fuel Price	Daily Load	SOLAR PV	SOLAR INVERTER	Gen (kW)	BATTERY	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	RENEWABLE FRACTION	Solar prediction(kWh)	Fuel(l)
Taranaki	LOW	150	50	22	30	1	12	446,000	14,000	268,000	71	55,169	6,296
Taranaki	NEW	150	50	22	30	1	12	474,000	16,000	268,000	71	55,169	6,294
Taranaki	CURR	150	50	22	30	2	12	480,000	18,000	290,000	74	55,169	5,657
Bay of Plenty	LOW	149	50	22	30	1	12	448,000	14,000	268,000	70	53,146	6,429
Bay of Plenty	NEW	149	50	22	30	1	12	476,000	16,000	268,000	70	53,146	6,422
Bay of Plenty	CURR	149	50	22	30	1	12	484,000	17,000	268,000	70	53,146	6,420
Type	VSD+IN+HP												
location	Fuel Price	Daily Load	SOLAR PV	SOLAR INVERTER	Gen (kW)	BATTERY	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	RENEWABLE FRACTION	Solar prediction(kWh)	Fuel(l)
Taranaki	LOW	124	20	11	48	1	12	489,000	21,000	206,000	42	34,585	11,067
Taranaki	NEW	124	40	22	48	2	18	534,000	18,000	305,000	63	49,187	6,854
Taranaki	CURR	124	40	22	48	2	18	542,000	18,000	305,000	63	49,187	6,544
Bay of Plenty	LOW	124	20	11	30	1	12	421,000	18,000	184,000	42	33,917	9,768
Bay of Plenty	NEW	124	30	11	30	1	12	460,000	20,000	207,000	50	29,418	8,596
Bay of Plenty	CURR	124	30	11	30	1	12	470,000	20,000	207,000	50	29,418	8,596
Type	IN+VSD+HP+IB												
location	Fuel Price	Daily Load	Solar PV	Solar inverter	Gen (kW)	BATTERY	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	RENEWABLE FRACTION	Solar prediction(kWh)	Fuel(l)
Taranaki	LOW	139	40	22	30	1	12	450,000	13,000	277,000	70	48,261	6,098
Taranaki	NEW	139	50	22	30	1	12	474,000	13,000	300,000	75	54,870	5,063
Taranaki	CURR	139	50	22	30	1	12	480,000	14,000	300,000	75	54,870	5,079
Bay of Plenty	LOW	139	40	22	30	1	12	445,000	13,000	277,000	71	48,261	5,892
Bay of Plenty	NEW	139	50	22	30	1	12	467,000	13,000	300,000	78	54,870	4,855
Bay of Plenty	CURR	139	50	22	30	1	12	473,000	13,000	300,000	78	54,870	4,833

B: Large Farm

Type	Base												
location	Fuel Price	Daily Load	SOLAR PV	SOLAR INVERTER	Gen (kW)	BATTERY	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	RENEWABLE FRACTION	Solar prediction(kWh)	Fuel(l)
Taranaki	LOW	335	120	44	75	2	24	977,000	33,000	555,000	62	118,351	16,112
Taranaki	NEW	335	120	44	75	2	24	1,048,000	36,000	576,000	66	122,041	18,226
Taranaki	CURR	335	120	44	75	2	24	1,068,000	38,000	576,000	67	122,041	18,226
Bay of Plenty	LOW	333	100	44	60	2	18	891,000	31,000	472,000	57	109,341	17,071
Bay of Plenty	NEW	333	120	44	60	2	18	984,000	35,000	515,000	61	118,251	18,312
Bay of Plenty	CURR	333	120	44	60	2	18	982,000	35,000	532,000	62	118,351	14,376
Type	VSD+IN											-	-
location	Fuel Price	Daily Load	SOLAR PV	SOLAR INVERTER	Gen (kW)	BATTERY	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	RENEWABLE FRACTION	Solar prediction(kWh)	Fuel(l)
Taranaki	LOW	308	100	44	60	2	18	849,000	28,000	489,000	66	110,238	14,217
Taranaki	NEW	308	100	44	60	2	24	909,000	31,000	506,000	70	110,238	12,062
Taranaki	CURR	308	120	44	60	2	24	925,000	29,000	549,000	74	118,877	11,591
Bay of Plenty	LOW	304	100	44	60	2	24	842,000	26,000	506,000	71	112,565	12,654
Bay of Plenty	NEW	304	100	44	60	2	24	887,000	30,000	506,000	71	112,565	12,629
Bay of Plenty	CURR	304	120	44	60	2	24	910,000	28,000	549,000	75	120,894	10,950
Type	VSD+IN+HP												
location	Fuel Price	Daily Load	SOLAR PV	SOLAR INVERTER	Gen (kW)	BATTERY	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	RENEWABLE FRACTION	Solar prediction(kWh)	Fuel(l)
Taranaki	LOW	254	40	22	75	2	18	865,000	40,000	352,000	41	49,187	21,685
Taranaki	NEW	254	60	22	75	2	18	951,000	42,000	412,000	48	73,780	19,049
Taranaki	CURR	254	60	33	75	2	18	974,000	44,000	412,000	48	73,780	19,049
Bay of Plenty	LOW	253	50	22	60	2	18	781,000	34,000	355,000	45	54,249	18,921
Bay of Plenty	NEW	253	60	33	60	2	18	869,000	37,000	389,000	50	71,750	17,283
Bay of Plenty	CURR	253	60	33	60	2	18	890,000	38,000	389,000	50	71,750	17,283
Type	IN+VSD+HP+IB												
location	Fuel Price	Daily Load	Solar PV	Solar inverter	Gen (kW)	BATTERY	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	RENEWABLE FRACTION	Solar prediction(kWh)	Fuel(l)
Taranaki	LOW	283	90	44	60	2	18	837,000	25,000	518,000	71	105,847	12,318
Taranaki	NEW	283	100	44	60	2	18	889,000	27,000	540,000	73	109,341	11,455
Taranaki	CURR	283	100	44	60	2	18	902,000	28,000	540,000	73	109,341	11,455
Bay of Plenty	LOW	283	90	44	60	2	18	831,000	24,000	518,000	71	105,847	12,180
Bay of Plenty	NEW	283	100	44	60	2	24	877,000	25,000	557,000	76	109,341	10,000
Bay of Plenty	CURR	283	100	44	60	2	24	889,000	26,000	557,000	76	109,341	9,979

Insulation=IN, Variable speed drive vacuum pump = VSD , Superheat heat pump = HP and Ice bank milk cooling = IB

Appendix 24 System configuration of a system simulated using the deferrable load module in HOMER Pro

Type	Deferrable Ice Bank			IN+VSD+HP+IB							
Daily Load	Daily Load	STORAGE	SOLAR PV	SOLAR INVERTER	Gen (kW)	BATTERY	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	Renewable Fraction
43	17	30	30.00	11.00	15.00	1.00	12.00	280,000.00	6,000.00	206000.00	83
43	17	60	30.00	11.00	15.00	1.00	12.00	279,000.00	6,000.00	206000.00	84
98	40	69	60.00	22.00	30.00	1.00	12.00	497,000.00	11,000.00	321000.00	77
98	40	138	60.00	22.00	30.00	1.00	12.00	493,000.00	11,000.00	321000.00	77
200	81	141	120.00	44.00	45.00	2.00	18.00	870,000.00	24,000.00	560000.00	74
200	81	281	120.00	44.00	45.00	1.00	12.00	861,000.00	26,000.00	521000.00	72
Type	Deferrable Hot Water			Base							
Daily Load	Daily Load	STORAGE	SOLAR PV	SOLAR INVERTER	Gen (kW)	BATTERY	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	Renewable Fraction
54	19	22	30.00	11.00	15.00	1.00	12.00	276,000.00	8,000.00	169000.00	71
54	19	45	30.00	11.00	15.00	1.00	12.00	273,000.00	8,000.00	169000.00	73
124	43	51	60.00	22.00	30.00	1.00	12.00	525,000.00	19,000.00	275000.00	65
124	43	102	60.00	22.00	30.00	1.00	12.00	518,000.00	19,000.00	275000.00	66
253	87	104	120.00	44.00	60.00	2.00	18.00	1,008,000.00	38,000.00	515000.00	64
253	87	209	120.00	44.00	60.00	2.00	12.00	984,000.00	38,000.00	499000.00	64
Type	Hot Water			Base							
Daily Load	Daily Load	STORAGE	SOLAR PV	SOLAR INVERTER	Gen (kW)	BATTERY	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	Renewable Fraction
55	6	15	20.00	11.00	15.00	1.00	12.00	280,000.00	7,000.00	181000.00	73
55	6	7	20.00	11.00	15.00	1.00	12.00	282,000.00	8,000.00	181000.00	72
125	14	17	50.00	22.00	30.00	1.00	12.00	501,000.00	15,000.00	300000.00	71
125	14	34	50.00	22.00	30.00	1.00	12.00	497,000.00	15,000.00	300000.00	71
255	29	35	120.00	44.00	60.00	2.00	18.00	936,000.00	27,000.00	581000.00	73
255	29	70	120.00	44.00	60.00	2.00	18.00	929,000.00	27,000.00	581000.00	73
Type	Hot Water			IN+VSD							
Daily Load	Daily Load	STORAGE	SOLAR PV	SOLAR INVERTER	Gen (kW)	BATTERY	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	Renewable Fraction
48	18.60	22.35	20.00	11.00	15.00	1.00	12.00	273,000.00	9,000.00	160000.00	67
48	18.60	22.35	20.00	11.00	15.00	1.00	12.00	273,000.00	9,000.00	160000.00	67
109	42.60	51.10	60.00	22.00	30.00	1.00	12.00	499,000.00	16,000.00	290000.00	70
109	42.60	51.10	60.00	22.00	30.00	1.00	12.00	499,000.00	16,000.00	290000.00	70
223	86.90	104.28	120.00	44.00	60.00	2.00	18.00	953,000.00	31,000.00	532000.00	68
223	86.90	104.28	120.00	44.00	60.00	2.00	18.00	953,000.00	31,000.00	532000.00	68
Type	Deferrable Ice Bank and Hot Water			IN+VSD+HP+IB			Peek Load %	33			
Daily Load	Daily Load	STORAGE	SOLAR PV	SOLAR INVERTER	Gen (kW)	BATTERY	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	Renewable Fraction
37	4.50	37.58	20.00	11.00	15.00	1.00	12.00	275,000.00	7,000.00	181000.00	75
84	10.29	83.98	50.00	22.00	30.00	1.00	12.00	451,000.00	14,000.00	268000.00	74
171	21.00	175.36	100.00	44.00	45.00	1.00	12.00	752,000.00	26,000.00	411000.00	71
37	4.50	37.58	20.00	11.00	15.00	1.00	12.00	360,000.00	7,000.00	168000.00	75
84	10.29	83.98	50.00	22.00	30.00	1.00	12.00	444,000.00	14,000.00	261000.00	74
171	21.00	175.36	100.00	44.00	45.00	1.00	12.00	852,000.00	30,000.00	461000.00	93
Type	Deferrable Ice Bank and Hot Water			IN+VSD+HP+IB			Peek Load %	66			
Daily Load	Daily Load	STORAGE	SOLAR PV	SOLAR INVERTER	Gen (kW)	BATTERY	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	Renewable Fraction
36.71	4.50	37.58	20.00	11.00	15.00	1.00	12.00	276,000.00	7,000.00	181000.00	74
36.71	4.50	73.16	30.00	11.00	15.00	1.00	12.00	274,000.00	5,000.00	206000.00	84
83.94	10.29	83.98	50.00	22.00	30.00	1.00	12.00	484,000.00	14,000.00	300000.00	73
83.94	10.29	171.86	50.00	22.00	30.00	1.00	12.00	480,000.00	14,000.00	300000.00	74
171.31	21.00	175.36	100.00	44.00	45.00	1.00	12.00	834,000.00	27,000.00	480000.00	69
171.31	21.00	350.72	120.00	44.00	45.00	1.00	12.00	826,000.00	21,000.00	521000.00	74

Insulation=IN, Variable speed drive vacume pump = VSD , Superheat heat pump = HP and Ice bank milk cooling = IB

Appendix 25 System configuration under the three fuel price sensitivity scenarios and for each of the lowest cost technology scenarios for a system that includes biogas

Small farm

Type	Fuel Price	Daily Load	SOLAR PV	SOLAR INVERTER	Gen (kW)	BATTERY	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	RENEWABLE FRACTION
Base	LOW	73	20	11	15	1	12	$ 339,246	$ 14,096	$ 157,024	80%
Base	NEW	73	20	11	15	1	12	$ 348,049	$ 14,777	$ 157,024	80%
Base	CURR	73	30	11	15	1	12	$ 350,032	$ 13,124	$ 180,370	89%
IN+VSD+HP	LOW	55	10	11	15	1	12	$ 320,844	$ 14,131	$ 151,124	69%
IN+VSD+HP	NEW	55	20	11	15	1	12	$ 328,412	$ 12,064	$ 176,069	83%
IN+VSD+HP	CURR	55	20	11	15	1	12	$ 329,945	$ 13,029	$ 174,470	83%
IN+IB+HP+VSD	LOW	61	20	11	15	1	12	$ 270,453	$ 6,768	$ 213,720	72%
IN+IB+HP+VSD	NEW	61	20	11	15	1	12	$ 281,398	$ 7,615	$ 213,720	72%
IN+IB+HP+VSD	CURR	61	20	11	15	1	12	$ 284,436	$ 7,850	$ 213,720	72%

Medium Farm

Type	Fuel Price	Daily Load	SOLAR PV	SOLAR INVERTER	Gen (kW)	BATTERY	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	RENEWABLE FRACTION
Base	LOW	166	40	22	30	1	12	$ 619,930	$ 27,680	$ 260,231	74%
Base	NEW	166	60	22	30	1	12	$ 638,000	$ 25,534	$ 306,033	83%
Base	CURR	166	60	22	30	2	12	$ 642,425	$ 24,167	$ 328,133	85%
IN+VSD+HP	LOW	126	20	11	30	1	12	$ 558,744	$ 24,371	$ 199,023	64%
IN+VSD+HP	NEW	126	30	11	30	1	12	$ 581,939	$ 26,505	$ 240,305	71%
IN+VSD+HP	CURR	126	30	11	30	1	12	$ 587,855	$ 24,817	$ 222,370	71%
IN+IB+HP+VSD	LOW	139	40	22	30	1	12	$ 588,177	$ 22,348	$ 328,167	86%
IN+IB+HP+VSD	NEW	139	50	22	30	1	12	$ 597,640	$ 21,274	$ 351,513	91%
IN+IB+HP+VSD	CURR	139	50	22	30	1	12	$ 599,911	$ 21,450	$ 351,513	91%

Large Farm

Type	Fuel Price	Daily Load	SOLAR PV	SOLAR INVERTER	Gen (kW)	BATTERY	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	RENEWABLE FRACTION
Base	LOW	339	100	44	60	2	18	$ 1,086,831	$ 43,763	$ 518,983	77%
Base	NEW	339	100	44	60	2	18	$ 1,134,363	$ 47,439	$ 518,983	77%
Base	CURR	339	100	44	60	2	18	$ 1,147,387	$ 48,447	$ 518,983	77%
IN+VSD+HP	LOW	257	50	22	60	2	18	$ 956,193	$ 40,695	$ 369,661	67%
IN+VSD+HP	NEW	257	50	22	60	2	18	$ 1,006,951	$ 47,037	$ 399,658	67%
IN+VSD+HP	CURR	257	60	22	60	2	18	$ 1,020,169	$ 43,907	$ 392,117	69%
IN+IB+HP+VSD	LOW	281	80	55	45	1	18	$ 937,326	$ 35,024	$ 513,213	84%
IN+IB+HP+VSD	NEW	281	100	55	45	2	18	$ 959,569	$ 31,699	$ 578,445	91%
IN+IB+HP+VSD	CURR	281	100	55	45	2	18	$ 963,561	$ 32,007	$ 578,445	91%

Appendix 26 Generator hot water heat recovery system configuration for a solar diesel system

Type	Generator hot water			IN+VSD						
	Daily load	Solar PV	Solar inverter	Gen (kW)	Battery	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	Renewable fraction
Small	48	20	11	15	1	12	252,000.00	7,000.00	160,000.00	66
Medium	108	30	11	30	1	12	443,000.00	18,000.00	207,000.00	51
Large	222	60	22	60	2	18	839,000.00	36,000.00	375,000.00	50

Type	Generator hot water			IN+VSD+IB						
	Daily load	Solar PV	Solar inverter	Gen (kW)	Battery	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	Renewable fraction
Small	60	20	11	15	1	12	268,000.00	7,000.00	183,000.00	76
Medium	138	50	22	30	1	12	443,000.00	14,000.00	268,000.00	74
Large	280	90	33	45	1	12	752,000.00	29,000.00	378,000.00	65

Insulation=IN, Variable speed drive vacuum pump = VSD and Ice bank milk cooling = IB

Appendix 27 Generator hot water heat recovery system configuration for a solar diesel biogas system

Type	Generator hot water			IN+VSD						
	Daily load	Solar PV	Solar inverter	Gen (kW)	Battery	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	Renewable fraction
Small	48	20	11	15	1	12	322,000.00	12,000.00	172,000.00	92
Medium	108	30	11	30	1	12	499,000.00	22,000.00	220,000.00	79
Large	222	60	22	60	2	18	873,000.00	37,000.00	392,000.00	77

Type	Generator hot water			IN+VSD+IB						
	Daily load	Solar PV	Solar inverter	Gen (kW)	Battery	SMA (kW)	NPC ($)	Operating cost ($)	Initial capital ($)	Renewable fraction
Small	60	20	11	15	1	12	338,000.00	11,000.00	194,000.00	98
Medium	138	50	22	30	1	12	502,000.00	17,000.00	281,000.00	96
Large	280	90	33	45	1	12	787,000.00	30,000.00	395,000.00	89

Insulation=IN, Variable speed drive vacuum pump = VSD and Ice bank milk cooling = IB

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