Agrivoltaics: Integrating Solar Energy Generation with Livestock Farming in Canterbury

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Executive Summary

Agrivoltaics is the integration of agriculture and solar energy production and seeks to find synergies between the two to create a complementary system. Agrivoltaics relates to all agricultural activities. However, for the purpose of this report, solar integration with livestock farming is the focus.

With increased interest in renewable energy generation and utility-scale solar photovoltaic (PV) systems in Aotearoa New Zealand, agrivoltaics provides the opportunity to increase the productivity of land, contribute to the generation of renewable energy without displacing food production, and potentially optimise farming and environmental outcomes.

A significant area of Canterbury is classified as suitable for agrivoltaics and innovations in solar array designs and configurations are developing rapidly. In saying that, certain factors remain challenging, such as the increase in wind shear effects and financial expense when panels are elevated to reduce shading and prevent damage from larger grazing livestock, such as cattle. The trade-offs to consider when selecting the most appropriate design for agrivoltaic systems add additional complications. Some of the factors to balance include electricity generation, cost-effectiveness, degree of shading produced, ability to withstand the site environment, and ability to withstand livestock grazing underneath.

Shade provision to mitigate heat stress risk, and sheltering from harsh weather, are perhaps the greatest potential benefits of agrivoltaics for livestock. However, given the condensed siting (eg, one paddock) of the panels, and limitations with cattle, the benefits are limited for the overall farming system. This may change as capital cost of PV investments decrease. Also, the impacts of agrivoltaics on crops and pasture in an Aotearoa New Zealand context are largely unknown.

While much is known theoretically of the environmental impacts associated with the manufacture and end-of-life disposal and recycling of solar PV panels, there are relatively few mitigators and solutions at present in Aotearoa New Zealand. The end-of-life disposal and recycling is of particular consequence to this country, and will require rapid investment, development and likely legislation to create solutions and reduce future harm to the environment. In terms of environmental impacts on the farmland where agrivoltaic systems are located, there is, again, a lack of research to refer to, particularly in Aotearoa New Zealand.

Case study analyses were carried out on a dairy farm and a sheep and beef farm, both located in Canterbury. These considered both technical design and financial analysis. The sheep and beef case study analysis indicated a significant opportunity for sheep and beef farmers to increase their profitability by incorporating agrivoltaics into their farming enterprise. This comes at a time of increased interest in complementary revenue streams due to reduced farmgate product prices, increased working expenses and increased compliance costs and associated administrative workload.

The financial analysis of agrivoltaics in the dairy farm case study suggested it was significantly less lucrative and indicates that incorporation of solar generation on dairy farms might be best suited to non-productive areas and/or the installation of panels on shed roofs, rather than agrivoltaics.

A workshop was run that included both dairy and sheep and beef farmers. Attendees were initially presented with pertinent information regarding agrivoltaics, before being invited to participate in a design thinking inspired workshop to identify potential barriers and benefits of agrivoltaics and possible solutions to overcome the barriers to adoption. The participants' feedback demonstrated that farmers were open to the idea of agrivoltaics, assuming it was financially viable and key concerns were addressed. The need for accessible and easily understood resources to inform decision making and provide confidence to engage in conversations and form partnerships with solar energy companies was identified as a key requirement going forward.

The study provides evidence that agrivoltaics is worthy of further consideration, particularly due to the way in which it offers solutions to some of the major challenges of standard utility-scale solar electricity generation. It is evident that the significant gaps in literature need to be addressed to further understand what the potential financial, environmental and social impacts are for the people of Aotearoa New Zealand.

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Acronyms and Abbreviations

Acronym	Definition
2T	Two-tooth ewe – age classification of a young sheep with two adult teeth
EBITDAR	Earnings before Interest, Tax, Depreciation, Amortisation and Restructuring or Rent costs
EV	Electric Vehicle
FWE	Farm Working Expenses
GWh	Gigawatt hours
Ha	Hectares
IPCC	Intergovernmental Panel on Climate Change
kW	Kilo-watt
kWh	Kilo-watt hour – unit of measurement for the system yield
kWp	Kilo-watt peak – unit of measurement for the output of a photovoltaic system
LCOE	Levelised Cost of Energy
LER	Land Equivalent Ratio
MA	Mixed-age – age classification for adult sheep
MS	Milk Solids
MV Transformer	Medium Voltage transformer
MW	Mega-watt
PV	Photovoltaic(s)
RWR	Run-with-ram
SR	Stocking rate
SU	Stock unit – standardised measure of livestock equivalents, a stock unit is based on the annual feed needed for a 55kg ewe rearing a single lamb
TFI	Total Farm Income
V	Volts
W	Watts

1 DESKTOP REVIEW

1.1 Introduction

The latest Intergovernmental Panel on Climate Change (IPCC, 2022) report emphasises the importance of solar technologies for the energy transition to renewables at a global level. In Aotearoa New Zealand, renewable energy currently makes up around 83% of the net electricity generation mix and the Government has set a target of 100% by 2030 (He Pou a Rangi Climate Change Commission, 2021). Disruptive scenarios for Aotearoa New Zealand also project that the current electricity generation capacity can be doubled by 2050 with, among others, utility-scale solar farms (Pincelli et al., 2022). The fast-paced development of the sector has already commenced with the Electricity Authority indicating that nearly 80% of new generation projects – or just under 2 GW to be commissioned by 2025 – are solar farms (Concept Consulting, 2022). Nevertheless, the IPCC (2022) report notes that for the transition to be feasible at the necessary scale and speed both agriculture and centralised solar production must be integrated on the same land where possible. This is an opportunity to obtain multifunctional outcomes from our land and thereby maximise the current and future value of land resources in terms of net agricultural return, as well as reducing greenhouse gas emissions and delivering benefits for farming communities (MacKenzie et al., 2022). In addition, some countries, such as Italy and Germany, are restricting solar farm development to areas so as to not encroach on quality farmland (Andrew et al., 2021).

To facilitate the integration of dual land usage Goetzberger and Zastrow (1982) proposed agrivoltaic systems as a solution in the early 1980s. Agrivoltaic systems establish synergistic combinations of agricultural production and electricity generation on the same land and are receiving much attention globally as a viable alternative to conventional large-scale solar photovoltaic (PV) installations – to create mutual benefits for each sector (Macknick et al., 2022). With agrivoltaics systems agricultural activities have an influence on solar generation and vice versa – positive and negative. This means systems that reside on the roofs of buildings or adjacent to productive land would not be considered agrivoltaics (Macknick et al., 2022).

Agrivoltaic systems differ from conventional ground-mounted solar arrays in that the panels are typically given more ground clearance and are spaced further apart (Trommsdorff et al, 2020). This provides enough space for farming equipment to operate and allows light to reach the crops below. A yield decrease can be expected due to the shadows under module arrays, but this amount depends on the climate as well as the specific crop (Cuppari et al., 2021). On the other hand, if agrivoltaic systems are designed well, land productivity could rise by 60 to 70% compared to operating solar collection alone (Kumpanalaisatit et al., 2022). Additionally, agrivoltaic systems have been used in pastoral lands, with added shelter to protect livestock against heat stress and adverse winter weather.

The objective of this study is to provide further insights into open-field agrivoltaic system configurations and their potential implications for livestock farming in the context of Aotearoa New Zealand, particularly the Canterbury region. Over half of Aotearoa New Zealand's land is agricultural, including livestock farming and horticulture. MacKenzie et al. (2022) studied the suitability of agricultural land for agrivoltaic systems, taking inputs of a location's solar resource, slope, distance from transmission lines and aspect (north alignment). The subsequent pairwise comparison produced a 4-category map ranked by the potential for agrivoltaic systems (see Figure 1).

Over 80% of agricultural land in Aotearoa New Zealand was found as good or fairly suitable (around 10 million hectares). The total amount of grazing grassland with a good suitability rating is significantly larger than cropland. This suggests that small-scale agrivoltaics would be suitable for cropland and that grassland is more suitable for large-scale agrivoltaic systems.

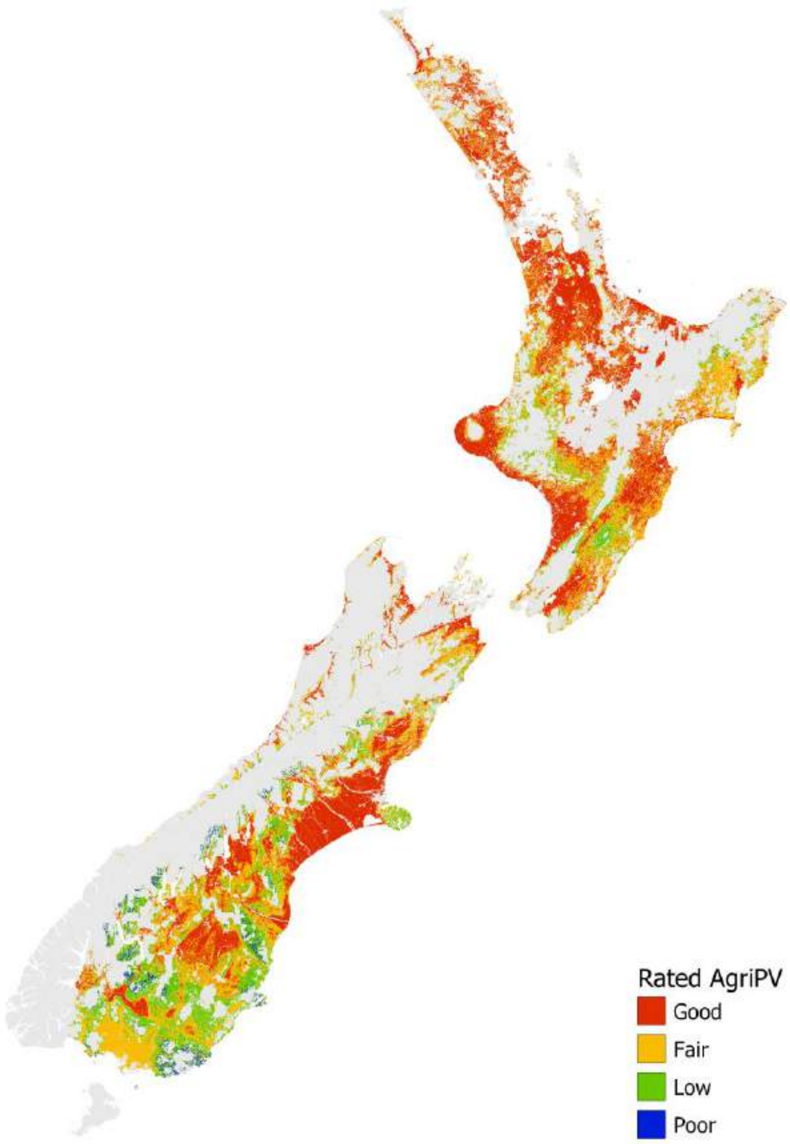

Figure 1. Land suitability for agrivoltaic systems in Aotearoa New Zealand (MacKenzie et al., 2022).

1.2 Solar PV Systems

Many different solar array configurations are being applied for agrivoltaic systems (see some examples in Figure 2). Of key importance for optimal electricity generation are the mounting structures, the type of PV modules, and the solar array layout in terms of spacing – all affecting the techno-economics.

Figure 2. Agrivoltaic technologies in use today (Trommsdorff et al., 2020).

Mounting Structures

The feasibility of an agrivoltaic system depends on the mounting structures used, as different panel arrangements can affect the machinery access and how much light reaches the crops. There are two prevailing arrangements of the panels – a straight-line or checkerboard pattern (see Figure 3). The checkerboard pattern distributes solar radiation more heterogeneously, but generates less electricity per area of land, and so straight-line structure are the most common in practice.

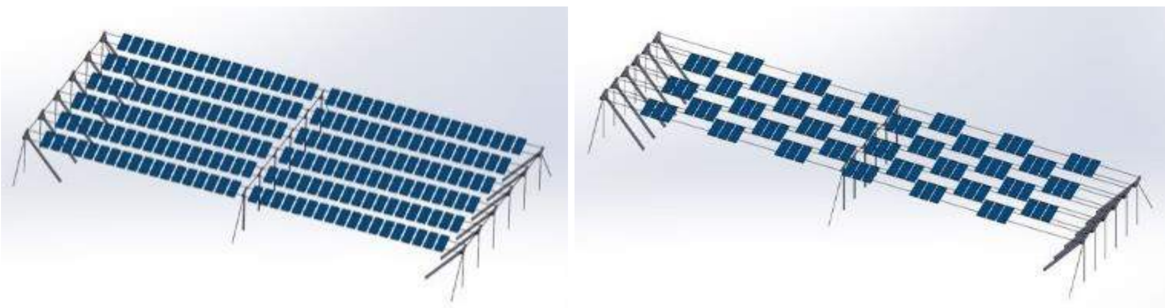

Figure 3. Conventional panel arrangements – straight line (left) and checkerboard (right) (Trommsdorff, et al., 2020).

The mounting structures accommodate fixed tilt (facing north), or north-south aligned tracking systems – to follow the sun (see Figure 4). With fixed tilt systems the panels are usually about 2 metres above ground level, with distances between rows at least three times the height of the modules (to achieve a reasonably uniform radiation on the ground). Higher stilted agrivoltaics are possible, with more than 4 metres in some commercial systems (Toledo & Scognamiglio, 2021), but low height mounting structures are preferred to minimise wind shear and the associated costs for strengthening the structures. The benefit is also the microclimate that is created underneath the panel with, for example, better moisture retention.

Figure 4. Fixed tilt and tracking systems (Toledo & Scognamiglio, 2021).

The optimal tilt for a fixed system varies with location and is ideally similar to the latitude of the location (Patel et al., 2019). However, horizontal and vertical mounting systems are also used (see Figure 5). For the latter the rows are north-south aligned.

Figure 5. Next2Sun vertical system in Guntramsdorf, Austria (Toledo & Scognamiglio, 2021).

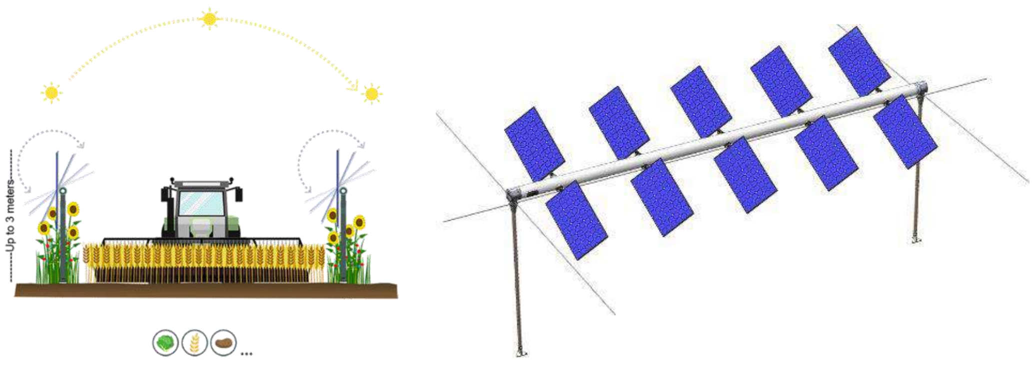

Figure 6. Single-axis (left) and dual-axis (right) tracking systems.

Tracking systems, while more expensive, can allow solar radiation to pass accordingly at varying stages of crop growth (Valle et al., 2017). They may also redistribute rain to prevent heterogenous runoff and thus soil erosion (Elamri et al., 2018). The land productivity has been shown to increase by up to 14% with tracking systems compared to fixed tilt systems (Amaducci et al., 2018). They are classed into single- and dual-axis tracking systems (see Figure 6). However, single axis tracking is most economical and therefore commonly used.

PV Modules

Different types of solar PV modules are now widely available in the market. The traditional polycrystalline (13 to 16% efficiency) and monocrystalline (15 to 20% efficiency) modules have been used in agrivoltaic systems. However, from an economics perspective monocrystalline modules are more effective.

Bifacial panels are becoming the industry standard as they can capture the reflected light from the ground (Sojib Ahmed et al., 2022). Although roughly 10% more expensive, they have the same order of gains over monocrystalline modules (Deline et al., 2019). Especially in areas of little sunlight, they can offer a better return of investment (Sojib Ahmed et al., 2022).

Tinted semi-transparent modules can selectively allow frequencies of light that are important for photosynthesis, typically green to red parts of the spectrum, through while capturing the rest (Meitzner et al., 2021). Although holding much promise they are currently mostly used with greenhouses, and not for larger, open field agrivoltaic systems.

Solar Array Layout

A crucial aspect is the layout of the solar arrays, which need to cater for the targeted agricultural production and consider the effects on, among others, water and the microclimate. Toledo and Scognamiglio (2021) provide the current state of the art in the designs in terms of geometry and density, as well as indicative heights (see Figure 7). In the majority of reported literature, however, the use of a half-density or patterned array layout allowed for higher production in plant growth (Reasoner & Ghosh, 2022). The industry standard – for livestock grazing – is a ground coverage ratio (GCR) of 44% for fixed-tilt systems, and 33% for tracking systems (Horowitz et al., 2020).

Movable agrivoltaic systems, although having a higher cost, can also reduce losses in pastoral crop yields because the available light can be increased in critical growth phases (Trommsdorff et al., 2020). To minimise the amount of land used, bifacial vertical designs are the best (GCR <1%) with power generation highest in the mornings and late afternoons (Trommsdorff et al., 2020).

Aotearoa New Zealand has no standard regarding the land-use of agrivoltaic systems. The German standard for agrivoltaic systems may then be a reasonable benchmark (Lettenmeier et al., 2021). This states that the agriculturally unusable land must not exceed 10% for category I farming (overhead systems, >2.1 m high) or 15% for category II farming (interspace systems, <2.1 m high). Furthermore, the area directly under the panels for category II is deemed unusable unless crops retain at least 66% of the reference yield, which is defined as the overall yield limit on feasible agrivoltaic installations.

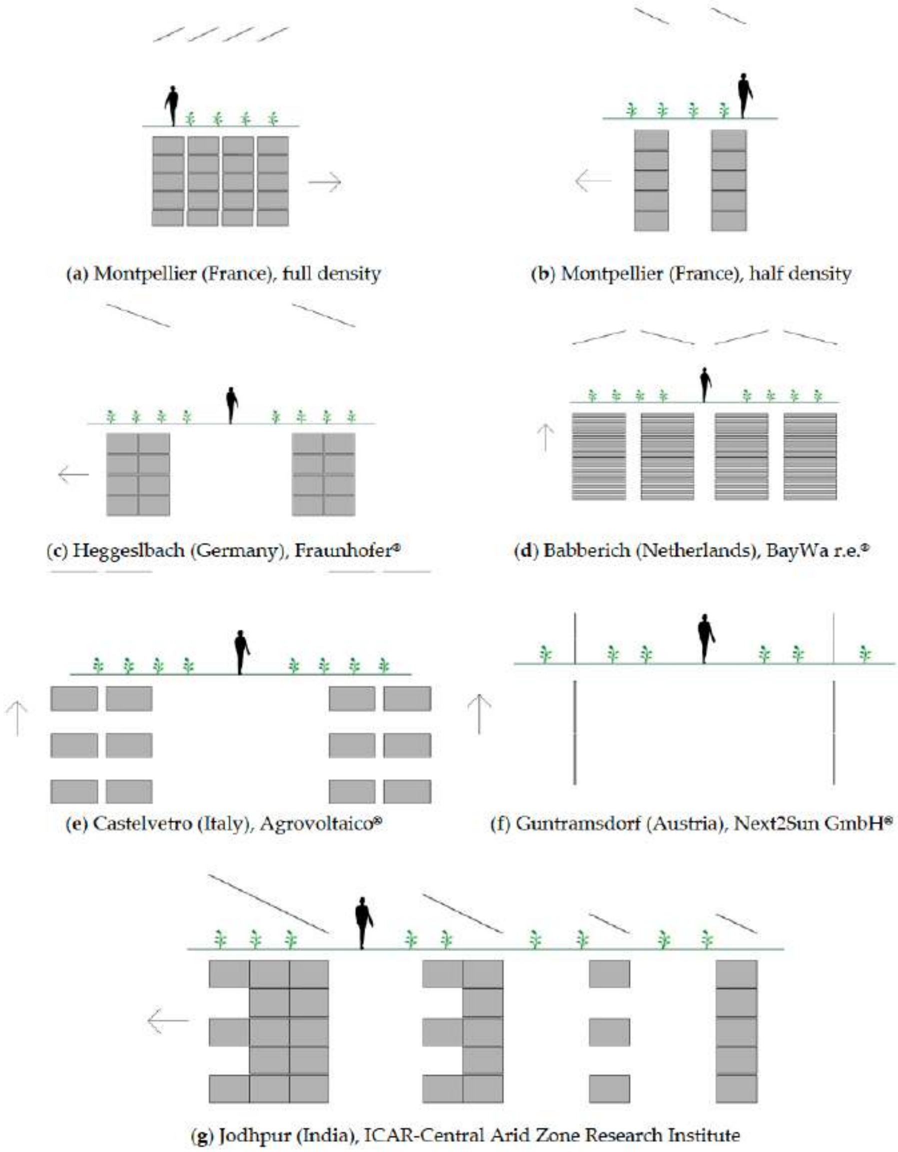

Figure 7. Different layouts for open-field agrivoltaic systems; arrows point south (Toledo & Scognamiglio, 2021).

1.3 Impacts of Agrivoltaics on Agriculture

Aotearoa New Zealand farming systems are highly dependent on grazing animals in pastural based systems. Of key importance to the feasibility of agrivoltaic systems is the impact on livestock and forage production which effects overall productivity.

Livestock Benefits

Solar panels shade the area directly beneath them and it is considered that they may provide welfare and productivity benefits to livestock grazing under them by providing a shade option to mitigate the risk of heat stress, as well as shelter against harsh weather (Maia et al., 2020).

Dairy NZ has produced a table that summarises the average periods of heat stress in different areas of Canterbury, and the estimated impact on milk solid production per cow each summer. This shows that the provision of shade is a significant factor for dairy farmers to be aware of from an animal welfare, productivity and social license perspective.

Table 1. Dairy NZ Heat Stress Table (Dairy NZ, 2023)

Weather station	Average hours per day too warm for comfort	Average hours per day warm enough to reduce milk production	Days warm enough to reduce milk production	Estimated milk solids impact per cow each summer
Balmoral East	9	5	48	3.5
West Eyreton	7	3	39	2.5
Lincoln	8	4	43	3.1
Winchmore	7	3	44	3.4
Orari	7	3	42	2.6
Timaru	5	2	25	1.2

AgResearch NZ are working to produce a similar summary of heat stress risk for sheep and it is expected that this will be available within the next 12 months. Additionaly, if climate change effects occur as predicted we may expect to see more extreme variations, including more frequent hot extremes (Royal Society Te Aparangi, 2023).

Trials in the Waikato suggest that cows experience mild heat stress in summer, which impacts cow comfort and productivity (Bluett et al., 2005). Fisher et al. (2008) showed that dairy cows that were provided shade had improved feed intake, milk yield, respiration rate, body temperature and cow comfort. In this study, milk production was 3% greater for cows with shade compared to those with no shade. Similarly, Gregory (1995) found that access to shade also improved milk fat percentage, decreased mastitis incidences, improved conception rates in dairy cattle, and growth rates in beef cattle. Animals in shade were observed with lower respiration rates and body temperatures in the afternoon (Sharpe et al., 2020), a key indicator for animal comfort (Van Laer et al., 2015).

Marcone et al. (2021) concluded that sheep can experience heat stress in moderately warm conditions. Their research found 54% of woolly ewes will seek shade when the average air temperature exceeds 19^{o}C. Under shade, sheep were observed panting less, eating and ruminating more. Sheep have been shown to spend 38% of their time under photovoltaic panels (Maia et al., 2020). Additionally, lactating sheep that experience temperatures above their thermoneutral zone (25^{o}C) decrease their feed intake, milk yield, and quality (Sevi, 2012). Summer lambs grazed under solar panels consumed less water than those in open fields (Andrew et al., 2021).

Shade provides the animals an opportunity to stay out of solar radiation during the hottest hours of the day. In a trial looking at beef cows in Aotearoa New Zealand, the provision of shade resulted in more time spent grazing (Betteridge et al., 2012). While this study could not conclude more grazing resulted in higher production, it could offer an indication as to the benefits of giving animals access to shade.

Furthermore, the panels can provide shelter from the rain, protecting the animals from the elements and supporting higher animal welfare (Andrew et al., 2021; Clean Energy Council, 2021).

Forage Considerations

Integrating agrivoltaic systems on farms offers income from both energy production and crop production (Kumpanalaisatit et al., 2022). In some overseas trials, integration improves water use efficiency while potentially not impacting yield. Payne and Norton (2011) discuss that plants that experience periods of shade have greater available water in soils and foliage. The shade leads to lower evapotranspiration which reduces water demands of vegetation (Macknick et al., 2022; Sekiyama & Nagashima, 2019). However, moisture availability directly under the panels can become a limiting factor (Macknick et al., 2022). Beatty et al. (2017) indicates that any area under panels greater than 0.5m from the edge may receive limited water from rain. In arid and semi-arid environments, plants under solar arrays have been shown to benefit from the shading by reducing the level of solar radiation and reducing water losses (Weselek, 2019).

The Aotearoa New Zealand pastural system is highly dependent on ryegrass and white clover. Perennial ryegrass has significant reductions in production and quality at temperatures above 20^{o}C (Kauffman et al., 2007). Studies show that soil under solar panels have lower soil temperatures than those in full sun (Barron-Gafford et al., 2019; Marrou et al., 2013b). However, an experiment assessing the effect of permanent shade on a white clover and perennial ryegrass mix showed a reduction in production in line with increasing shade (Ehret et al., 2015).

Partial shading could allow adequate exposure to sunlight required for photosynthesis and minimise the harm caused by over exposure (Sekiyama & Nagashima, 2019). Improved yields have been observed in shade intolerant species under a low module density solar array compared to a control (no modules) and high module density. This indicates the crop does not need to be shade-loving to maintain production under a partially shaded system (Beatty et al., 2017; Kumpanalaisatit et al., 2022). Adeh et al. (2018) found that pasture grasses in partial shade grew significantly more biomass with greater water efficiency than those in full sun. The study attributed this to plants being exposed to less solar radiation and thus slower drying of stored water. The findings are similar to Andrew et al. (2021) who carried out an agrivoltaic experiment and found a significant reduction in herbage yield in fully shaded areas. For partially shaded pastures however, production was very similar to those with no shading.

The literature shows under a full shade system, forage production is reduced through moisture constraints and plants intercepting less solar radiation. Partial shade offers the benefits of shade such as slower evapotranspiration and lower soil temperatures while not comprising growth. The design of the solar farm impacts the success of agrivoltaics the most. For example, the area shaded is influenced by the area and height of the panels. As the height of panels increases, the shaded area decreases (Toledo & Scognamiglio, 2021). Marrou et al. (2013a) shows with panels 1.6m apart lettuce yield was 48% less than those under full sun, whereas at 3.2m the yield was hardly affected. Design also impacts the ease of cultivation and ability to use machinery between the rows.

The impact of integrating agrivoltaic systems is dependent on site-specific conditions, characteristic of the specific plant, and the design and configuration of the panels. Improving water use efficiency and improving production are potential benefits to be offered by a successful integration of solar and pastural farming.

Environmental Considerations of Agrivoltaics

An assessment of the lifecycle of solar panels highlights several environmental considerations to be aware of. The addition of grazing livestock in an agrivoltaic system further complicates this. However, there is limited research regarding the environmental impacts of agrivoltaics.

The energy demands required for the production of solar panels are significant, when considered from a life cycle perspective. This includes mining, manufacturing and transportation. There are also hazardous chemicals involved in the production of solar-grade silicon (Kuby Energy, 2023). In addition, the installation of panels can cause compaction that effects soil structure (Macknick et al., 2022). Decompaction after installation needs to be carried out to minimise any long-term effects.

The presence of panels causes localised changes to agrivoltaic sites. The changes are caused by the infrastructure and animals interacting with it. Water use efficiency, climate regulation, air pollution regulation, and erosion prevention are some of the potential benefits of integrating the systems (Hernandez et al., 2019). Elevated solar panels reduce the speed of wind under the panels and cause a change in wind direction perpendicular to the orientation of the panels (Adeh et al., 2018).

The improvement in water use efficiency as a result of shading from the panels may reduce the detrimental effects of extracting ground water for irrigation (Hernandez et al., 2019; Macknick et al., 2022). Systems can further their efficiency by the addition of a water collection and storage system on the panels so rainwater could be redistributed (Macknick et al., 2022). This could increase productivity when panels are used on dryland areas.

Betteridge et al. (2012, p.5) found that 50% of urination events happened in 10% of the paddock where animals camped near water and shade. This paper discussed that these zones cause soils to become overloaded, increasing leachate. However, no studies have investigated this impact in the context of agrivoltaics where the area of shade is greater and therefore camping may be more evenly distributed.

There are limited peer reviewed, experimental studies on the ecological impacts of solar photovoltaic developments (Harrison, 2017). Solar panels reflect light and have been shown to confuse birds and polarotactic insects who mistake the panels for a body of water and are attracted to them. This can have disruptive effect on insect reproductive behaviour and cycles as they are attracted to the panels but may then perish before reproducing or lay eggs near the panels which then have no chance of survival (Fritz, 2020). Panel coatings are being developed to reduce this effect and will continue to evolve.

Typically, the ‘lifespan’ of a solar panel is 25 to 30 years (Singh, 2021). 78 million tonnes of solar photovoltaic waste are estimated to exist worldwide by 2050, assuming that they are not replaced before their full lifespan, in which case this figure could be higher (Chowdhury, 2020). Recycling of valuable materials and safe disposal of panels is an important consideration to reduce the environmental impacts as this waste does not biodegrade and contains dangerous chemicals which can leach into the ground, causing contamination (Chowdhury, 2020). Recycling processes are complex, energy intensive and expensive (Tawalbeh, 2021). In addition, due to the complexity and current low demand, there are no photovoltaic options available in Aotearoa New Zealand.

This is something that needs to be addressed given the forecast increase in photovoltaic installations in the country. Tawalbeh et al. (2021) recognise this as an issue at a global level and recommend regulation be imposed on photovoltaic manufacturers.

Social Considerations of Agrivoltaics

Solar has relatively high land area requirements compared to some other energy technologies. This puts solar at risk of competing with and displacing food and fibre production (Tawalbeh, 2021). Agrivoltaics is one way of addressing this issue. A report into utility scale solar generation in Aotearoa New Zealand predicts that the MacKenzie Country and Waitaki basin (South Canterbury) with poorer grasslands may be earlier sites for development (Miller, 2020).

Visual impacts of agrivoltaics are important to consider as large-scale solar sites significantly change the visual landscape of rural areas. Careful site selection, and screening by landscape features or planting trees or hedges can all reduce the visual impacts of agrivoltaic systems (Tawalbeh, 2021).

A qualitative study by Pascaris et al. (2020) interviewed sector stakeholders on their concerns. Many farmers expressed the need for a land use contract to provide certainty and stability. In most locations, agrivoltaics is not well-defined in terms of policies and regulations, hindering initial investment due to zoning laws (Pascaris et al., 2021). Farmers expressed that the land should remain agricultural in an agrivoltaic setup, as the permanency of the panels may prove challenging for regular activities to be conducted productively (Pascaris et al., 2020). There were also concerns about the flexibility of the system to respond to agricultural market changes (Pascaris et al., 2020). Nevertheless, most participants reacted positively to the concept, especially running livestock under the panels as this reduces mowing costs and provides shade. Another survey suggested that land use efficiency was the lowest reported priority for farmers (Guerin, 2017). The respondents were more likely to support agricultural interests and the economic benefits that come out of it (Guerin, 2017). Market unknowns pose the biggest barrier to farmer uptake of agrivoltaics (MacKenzie, 2022). The establishment of a code of ethics and long-term contracts between farmer and photovoltaic developers is recommended (MacKenzie, 2022).

1.4 Techno-Economics of Electricity Generation

The economic feasibility of the solar PV system (on its own) heavily depends on the location and other external factors. However, numerous studies have captured the costs of construction and maintenance in a techno-economic framework that utilises the concept of Levelized Cost of Energy (NREL, 2015). LCOE is the total cost of the project per total energy generated, as per the following formula:

$$LCOE = \frac{\sum \text{costs over lifetime}}{\sum \text{electrical energy produced over lifetime}} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

$$I_t = \text{investment expenditure in year } t, M_t = \text{operations \& maintenance costs in year } t,$$
$$E_t = \text{electrical energy generated in year } t, r = \text{discount rate}, n = \text{lifetime}$$

If the LCOE is lower than the cost of purchasing electricity, then the solar PV system should be profitable.

Horowitz et al. (2020) provide the total installed costs for various agrivoltaic systems in the USA, including fixed-tilt and tracking systems with grazing (see Figure 8). With similar installation costs Trommsdorff et al. (2022) indicate a LCOE of between NZ$0.12 and NZ$0.21 for Germany. Given that the solar resource of Aotearoa New Zealand is between 10% and 40% better than different locations in Germany, the LCOE is expected to be between NZ$0.09 and NZ$0.19, which is on par with wholesale prices and lower than the NZ$0.21 per kWh forecasted for 2022-23 (IBISWorld, 2022). This means that the solar PV systems alone would be economically feasible.

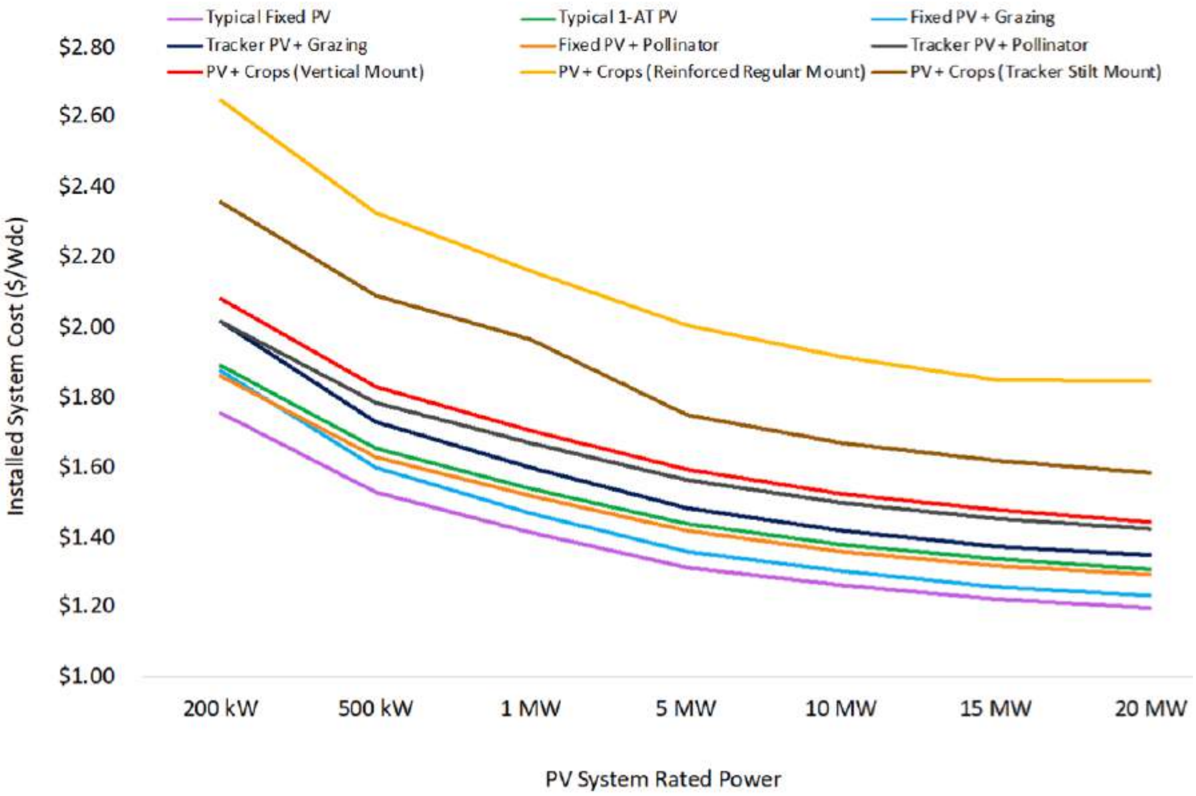

Figure 8. Installed system costs versus PV system rated power (DC) (Horowitz et al., 2020).

Impact on Overall Farm System Productivity

The Land Equivalent Ratio (LER) is often used as a metric for land productivity, and is defined as:

$$\text{LER} = \text{farming ratio} + \text{energy ratio} = \frac{\text{farming yield}_{\text{APV}}}{\text{farming yield}_{\text{normal}}} + \frac{\text{energy yield}_{\text{AV}}}{\text{energy yield}_{\text{normal}}}$$

An LER over 1 would suggest that the land is being used more efficiently than a farming-only or PV-only system.

Sojib Ahmed et al. (2022) investigated the optimal panel at six different locations around the world. They found the energy ratio is maximised with a fixed-tilted arrangement, with a horizontal array following closely. The energy ratio decreases as a function of the pitch (row spacing). The crop ratio is maximised with the vertical arrangement, as this has a lower coverage ratio compared to the remaining options. At higher pitch, the horizontal arrangement is close to the vertical system. These are general findings, and highly dependent on the chosen PV panels, and the specific farming activities.

1.5 Relevant Policy and Legislation

Solar power systems that are connected to the grid in Aotearoa New Zealand must comply with both local council and local lines company regulations. Typically, a land use resource consent is required to establish a solar farm. The exception to this is where the activity has been categorised as a permitted activity by the relevant local authority (Johnson et al., 2022).

Currently several large-scale solar energy projects are facing delays due to network capacity limitations and it has been estimated that consenting delays will result in Aotearoa New Zealand missing out on 11-15% of the emission reductions required from the energy and transport sectors by 2050, which is forecast to create an emissions liability between $5 billion and $7 billion by 2050 (Moore, 2023). The Government has introduced a Fast-track Consenting Act as part of the Covid-19 recovery. The Act is an alternative consenting pathway to the Resource Management Act. This act will take effect from 8 July 2023 for projects that can boost employment and economic recovery. The act has a sunset clause three years from the commencement date (Ministry for the Environment, 2022). Several large-scale solar projects have been referred to an independent fast-track consenting panel made available via the new Act legislation (Carroll, 2023).

Highly productive land is Aotearoa New Zealand's most fertile and versatile land and makes up about 15% of the country's total land resource. The National Policy Statement for Highly Productive Land 2022 requires that regional councils identify, map and manage highly productive land to ensure it remains available for food and other primary production that is reliant on the soil resource of the land. (MPI Manatu Ahu Matua, 2023). It is therefore possible that agrivoltaics and the preservation of livestock grazing may be viewed more favourably than a conventional utility-scale solar development.

The Electricity Authority requires grid connected inverter systems to comply with regulations and those exporting more than 10MW back into the grid need to register with the Electricity Authority as generator providers. Communication is also required with the local lines company and/or Transpower. Each company will have established criteria and require approval, and also have a limited capacity. This limited capacity will directly impact the viability of an agrivoltaic development (Johnson et al., 2022).

1.6 Aotearoa NZ Agrivoltaic Commercial Developments

There was a significant increase in resource consent applications for large scale solar sites during 2022, which equates to close to 2100MW generation potential (based on publicly available information on planned developments) across 14 projects (Wolfe, 2022).

Whilst it is difficult to identify how many of these developments are designed to allow agrivoltaics, Lodestone Energy (2023) claims that their solar farms have been designed with agrivoltaics in mind. When the solar farms are operational, they are expecting over 85% of baseline farming yield to be achievable (Lodestone Energy, 2023). It is not detailed how this figure was reached.

Sheep will also graze a 90-hectare solar farm site at Lauriston, which will have 80,000 solar panels, generating 80 GWh annually. This project is owned by FRV Australia and Genesis Energy (Raghuvanshi, 2023). At the time of writing, no details were publicly available regarding the design to minimise agricultural yield loss.

1.7 Identification of Research Gaps

Limited research has been undertaken on photovoltaic systems in Aotearoa New Zealand and even less on agrivoltaic systems on pastoral lands, to:

- Quantify the impacts on pasture and livestock product yields and therefore financial implications;
- Understand agrivoltaics from a farm systems perspective by modelling typical farm system activities, such as cropping and pasture renewal rotations with the inclusion of areas of agrivoltaics; and
- Identify opportunities panels present to improve lamb survival and dairy calf well-being outcomes.

The potential benefits to livestock and forage are mostly derived from research that focuses on the impacts of shade on these various systems in isolation. There is limited research that investigates the impacts directly caused by agrivoltaics. Further research is also needed to understand the environmental impacts of agrivoltaics, specifically quantifying the financial, technical and labour requirements for end of solar panel life and associated land remediation.

2 CASE STUDIES

Two Canterbury farms were used as case studies to model, assess and analyse potential agrivoltaic design and the likely impacts on farm system financial outcomes. Physical details were unchanged but financial data was standardised to maintain confidentiality.

2.1 General Solar Technical Details

The panels used in this assessment are CS7N-660MB-AG 1500V. They are 660W each and measure 2384 x 1303 x 35 mm. These panels are bifacial so can capture light from both sides during operation. Rows span east-west for the fixed-tilt system, tilted 25° from horizontal to face north, and north-south for the tracker system. Height for cattle systems were designed to exceed the height of cattle at 2.5 m ground clearance. Ground clearance is defined as the distance from ground to the lowest point of the solar panels.

Figure 9 is a schematic of the Schletter FS Duo frame (fixed-tilt). Its dual pile design allows greater stability at high wind loads and can be placed in more soil types. The cattle system at the WCROC in Minnesota, USA uses a single pile system (see Figure 10). However, framing suppliers have indicated that it may be difficult to engineer a cost-effective single pile system for Aotearoa New Zealand's wind speeds. The Schletter Solar Tracking System is shown in Figure 11. It tilts the module array from east to west throughout the day to track the sun.

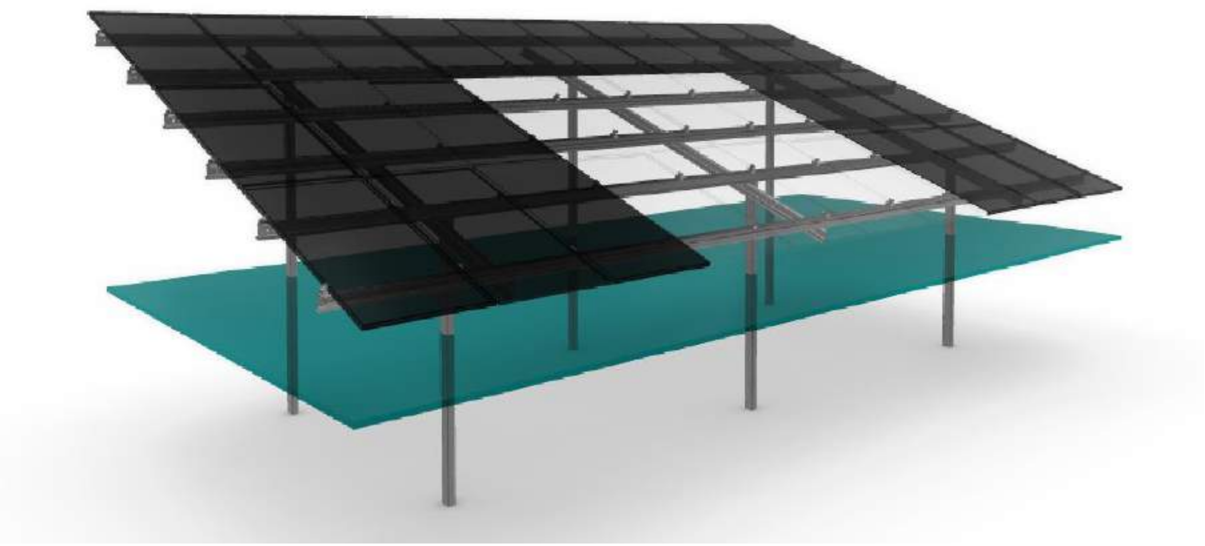

Figure 9. Schematic of the Schletter FS Duo Frame (fixed-tilt).

Figure 10. Single pile system at the University of Minnesota West Central Research Outreach Centre (WCROC).

Figure 11. Schletter Solar Tracking System.

Key Assumptions

- System prices include all materials and installation needed for a typical system as delivered by Infratec New Zealand, subject to further site investigations. Material prices, physical site conditions, local grid capacity as well as division of scope with the landowner will significantly impact costs.
- Development and grid connection costs are indicative of a typical system that size but can vary significantly based on the studies required and potential line/grid upgrades.
- Revenue is estimated based on historical average wholesale electricity prices subject to confirmation during project development.
- Yield is estimated based on the specified system configuration and can vary significantly based on site location, shading elements, and further development of the design.
- Space between array for tracker systems is defined when the modules are tilted towards a horizontal position (minimum row space).
- The specified panels are guaranteed to decay at a linear rate for 30 years. However, other components, such as inverters, will need maintenance and may require replacement during that project lifespan.
- End of panel life replacement and safe disposal and recycling has not been accounted for in this analysis. At present, there are no recycling facilities for solar waste in Aotearoa New Zealand, so it was not possible to budget a figure for this. The responsible management of panel waste will need to be addressed over the next 20 to 30 years in preparation for the large volume of panels that will be due for replacement at this time.
- Cost of borrowing has been valued at 5.5%. This has been used to reflect a 30-year average.

2.2 Sheep and Beef Farm Case Study

The sheep and beef farm modelled was a 1,300 ha (1,100 ha effective) property in the Hurunui area, wintering 7,500 stock units. The farm has approximately 800 ha of effective hill country and 300 ha of effective flats. The proposed site for the agrivoltaic system was an 8 ha paddock that had good vehicle access and proximity to the nearest electricity transformer.

Livestock Numbers (1 July 2022)

1,230	Early ewes
2,300	Mainline 2T and MA ewes
1,085	Ewe hoggets
175	Beef cows
330	Cull dairy cows (numbers vary depending on season and trade margin)

Farm Policy

- 1,230 ewes are mated to a terminal ram and lamb mid-August. Of these, 760 are purchased as run with the ram ewes (RWR) in late Autumn/early winter. The majority of the early ewes are sold to the works at weaning in late November. A small number will remain in the early lambing mob for a subsequent year.
- 2,300 mainline two-tooth and mixed ages ewes are mated to a maternal ram and lamb early September.
- 1,085 ewe lambs are taken through to mating. Anything not up to mating weight or that is scanned dry is sold in August.
- The majority of lambs are sold at weaning. 600 smaller lambs are taken through summer and sold in the Autumn, along with any cull ewe lambs.

- There is a self-replacing beef herd consisting of 175 Angus cows. 330 cull dairy cows are purchased in May and sold in August.
- The cropping and pasture renewal policy consists of 30ha of kale, followed by 30ha of summer rape before going into permanent pasture.

2.2.1 Sheep and Beef Solar Technical Details

Two layouts for the site are shown in Figure 12 and Figure 13. These utilise the majority of the paddock but have wider inter-row clearances than typical solar farms to allow farm equipment to move between the rows to enable dual use of the paddock. There is also a large setback between the array and the paddock boundary. This ensures ease of access and manoeuvrability.

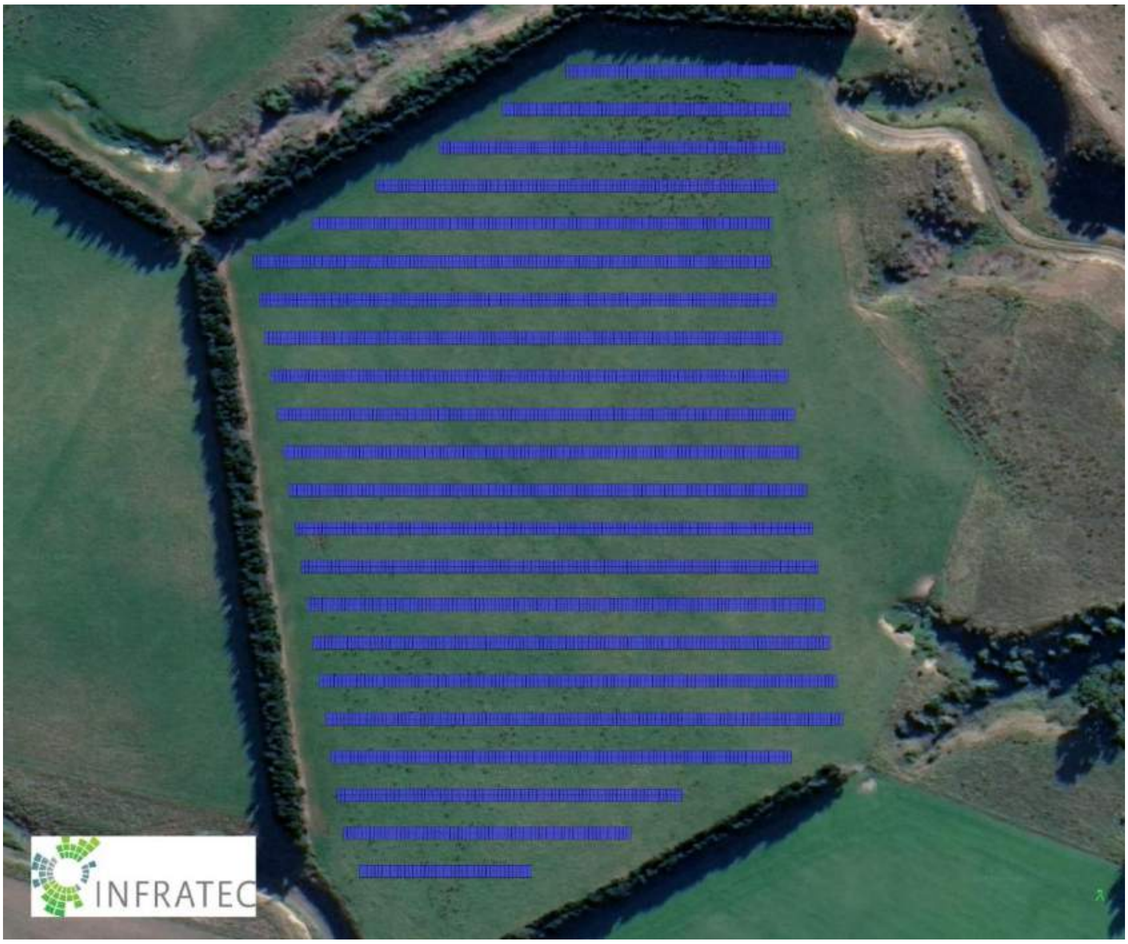

Figure 12. View of the fixed-tilt arrangement[1].

Figure 13. View of the Tracker arrangement.

Table 2. Sheep and Beef Case Study Technical Details

Site Coordinates	42.651 °S, 173.256 °E	
Global Horizontal Irradiance (W/m²)	1,418	
PV Array Area (ha)[1]	5.8	
Racking	Fixed	Tracking
Inverter	2.5 MW Central Inverter	2.2 MW Central Inverter
Row Spacing (centre to centre) (m)	13.3	8.4
Space Between Rows (m)	9.0	6.0
Cover Ratio	35%	28.9%
DC size (kW)	3346.2	2692.8
AC size (kWac)	2,500	2,195

[1] A central inverter design (single large inverter) was chosen due to the scale of the project

Table 3. Sheep and Beef Case Study Energy Generation

Racking	Fixed	Tracking
Specific Yield (kWh/kWp)	1,533	1,802
Annual Energy (MWh)[2]	5,129	4,852

Table 4. Sheep and Beef Case Study Agrivoltaic System Costs and Revenue

System	Fixed-tilt	Single-axis tracking
Project Development, Consent, & Grid Connection ($ NZD)	625k	625k
Project Design & Build ($ NZD)	4.7 - 6.3 million	4.3 - 5.7 million
Estimated Revenue per Megawatt-hour ($/MWh)	96-144	96-144
Estimated Revenue per Hectare ($/ha)	$84k-127k	$81k-123k

Tracking systems are more expensive per installed power unit (kWp) but generate more electricity per panel and therefore the overall capital cost is lower. They are, however, more expensive to maintain and they can be more susceptible to weather conditions, especially if raised higher above the ground. Overall, the expected revenue is similar, and the choice of design depends on how the land will be used.

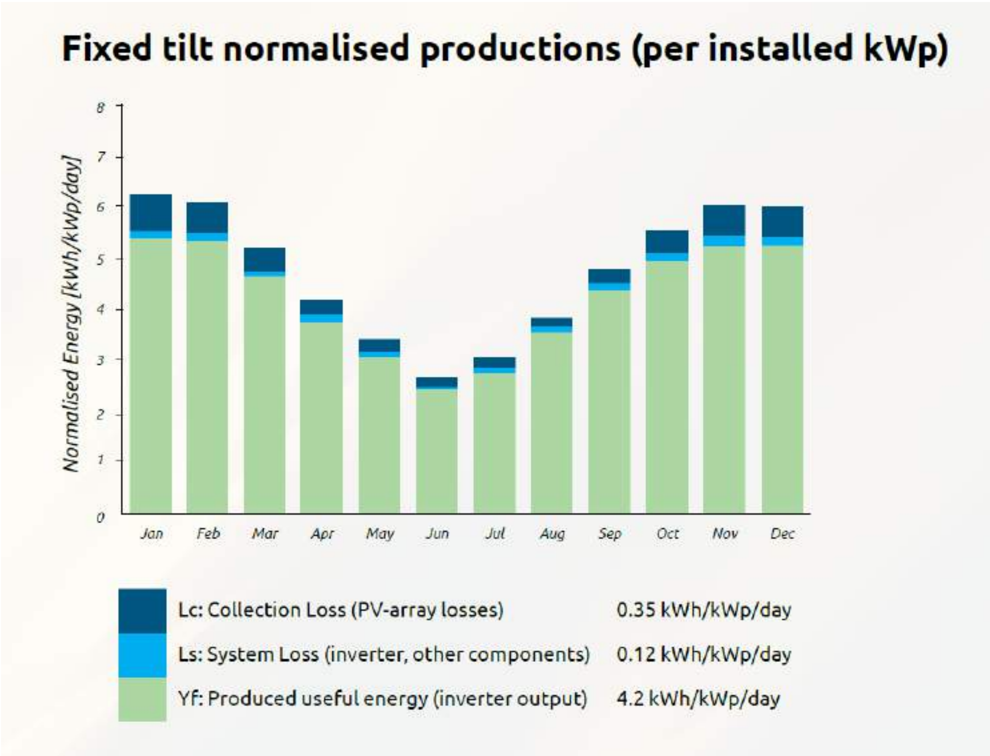

Figure 14. Fixed-tilt monthly production per kilowatt-peak.

[2] Generation data applies for the project's first year and will degrade over the project lifespan.

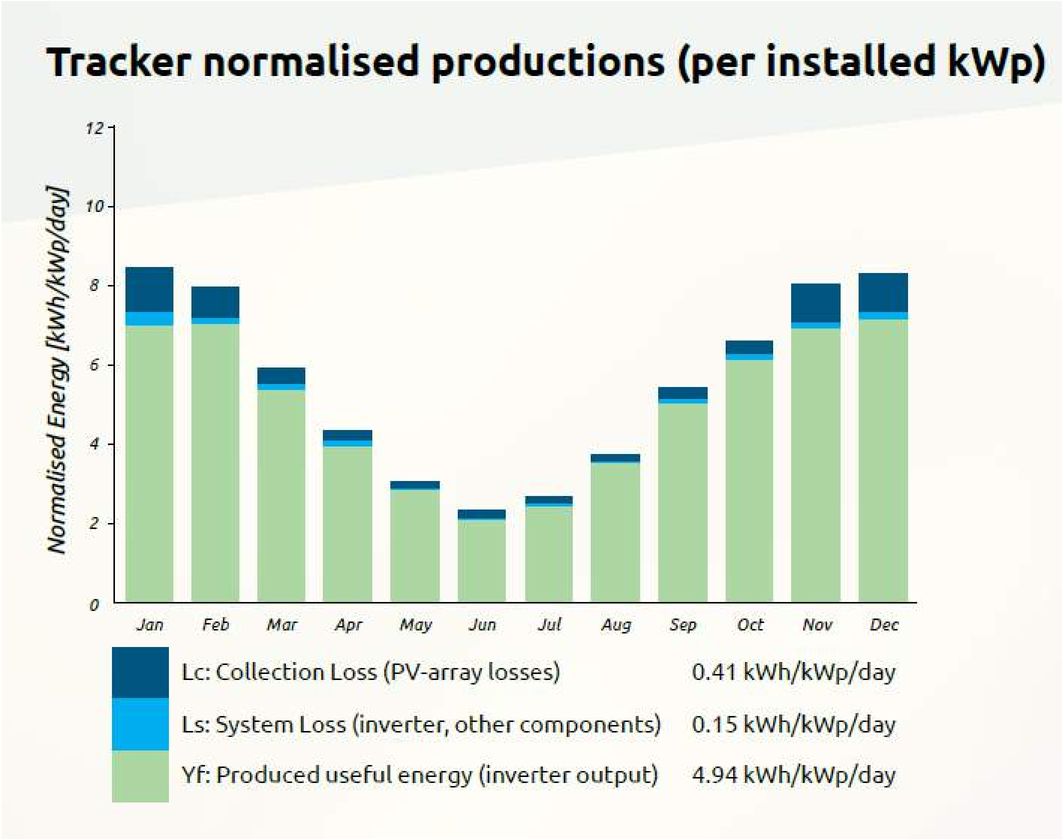

Figure 15. Tracker monthly production per kilowatt-peak.

2.2.2 Sheep and Beef Financial Analysis

Table 5. Agrivoltaics Detailed Financial Analysis Year End 30 June 2024 for a Sheep and Beef Farm in North Canterbury

	Status Quo - No Solar			5.8 ha Agrivoltaics @ 30% SR reduction			5.8 ha Agrivoltaics @ 100% SR reduction		
Financial Analysis	**Open**	**Close**		**Open**	**Close**		**Open**	**Close**	
Effective Hectares	1,180	1,180		1,180	1,180		1,180	1,180	
Sheep SU	5,710	5,710		5,670	5,670		5,652	5,652	
Cattle SU	1,764	1,764		1,764	1,764		1,764	1,764	
Total SU	7,474	7,474		7,434	7,434		7,416	7,416	
Farm Income	**Total**	**Per SU (Open)**	**Per Ha**	**Total**	**Per SU (Open)**	**Per Ha**	**Total**	**Per SU (Open)**	**Per Ha**
Sheep	$738,127	$129.27	$625.53	$727,865	$128.38	$616.83	$723,210	$127.97	$612.89
Wool	$44,895	$7.86	$38.05	$44,591	$7.86	$37.79	$44,514	$7.88	$37.72
Cull cow/Trade	$281,700	$159.69	$238.73	$281,700	$159.69	$238.73	$281,700	$159.69	$238.73
Beef cattle	$107,951	$61.20	$91.48	$107,951	$61.20	$91.48	$107,951	$61.20	$91.48
Other (Solar) Income	$0	$0.00	$0.00	$960,000	$129.14	$813.56	$960,000	$129.45	$813.56
Less Stock Purchases	-$343,520	-$45.96	-$291.12	-$336,680	-$45.29	-$285.32	-$333,080	-$44.91	-$282.27
Total Farm Income	**$829,153**	**$110.94**	**$702.67**	**$1,785,426**	**$240.17**	**$1,513.07**	**$1,784,295**	**$240.60**	**$1,512.11**
Farm Expenses									
Stock Costs:									
Employment Costs	$58,696	$7.85	$49.74	$58,696	$7.90	$49.74	$58,696	$7.91	$49.74
Protective Clothing	$1,000	$0.13	$0.85	$1,000	$0.13	$0.85	$1,000	$0.13	$0.85
Animal Health	$32,770	$4.38	$27.77	$32,550	$4.38	$27.58	$32,450	$4.38	$27.50
Breeding (Scanning + Ram Lease)	$7,300	$0.98	$6.19	$7,300	$0.98	$6.19	$7,300	$0.98	$6.19
Shearing	$42,177	$5.64	$35.74	$41,951	$5.64	$35.55	$41,892	$5.65	$35.50
Electricity	$12,000	$1.61	$10.17	$12,000	$1.61	$10.17	$12,000	$1.62	$10.17
	$153,943	**$20.60**	**$130.46**	**$153,497**	**$20.65**	**$130.08**	**$153,338**	**$20.68**	**$129.95**

	Status Quo - No Solar			5.8 ha Agrivoltaics @ 30% SR reduction			5.8 ha Agrivoltaics @ 100% SR reduction		
Feed Costs:									
Supplements (Made on Farm)	$11,900	$1.59	$10.08	$11,900	$1.60	$10.08	$11,900	$1.60	$10.08
Dogs and Horses	$6,000	$0.80	$5.08	$6,000	$0.81	$5.08	$6,000	$0.81	$5.08
	$17,900	**$2.39**	**$15.17**	**$17,900**	**$2.41**	**$15.17**	**$17,900**	**$2.41**	**$15.17**
Land Costs:									
Fertiliser (maintenance)	$72,000	$9.63	$61.02	$72,000	$9.69	$61.02	$72,000	$9.71	$61.02
Lime	$6,000	$0.80	$5.08	$6,000	$0.81	$5.08	$6,000	$0.81	$5.08
Freight	$18,400	$2.46	$15.59	$18,400	$2.48	$15.59	$18,400	$2.48	$15.59
Regrassing (all costs associated)	$30,000	$4.01	$25.42	$30,000	$4.04	$25.42	$30,000	$4.05	$25.42
Forage Crops (all costs associated)	$63,000	$8.43	$53.39	$63,000	$8.47	$53.39	$63,000	$8.50	$53.39
Weeds & Pests	$15,000	$2.01	$12.71	$15,000	$2.02	$12.71	$15,000	$2.02	$12.71
Repairs & Maintenance	$21,560	$2.88	$18.27	$21,560	$2.90	$18.27	$21,560	$2.91	$18.27
Vehicle Running	$37,350	$5.00	$31.65	$37,350	$5.02	$31.65	$37,350	$5.04	$31.65
Contractors	$6,382	$0.85	$5.41	$6,382	$0.86	$5.41	$6,382	$0.86	$5.41
	$269,692	**$36.08**	**$228.55**	**$269,692**	**$36.28**	**$228.55**	**$269,692**	**$36.37**	**$228.55**
Solar Costs									
Running expenses (incl insurance)	**$0**	**$0.00**	**$0.00**	**$41,250**	**$5.55**	**$34.96**	**$41,250**	**$5.55**	**$34.96**
Fixed Costs									
Administration	$17,616	$2.36	$14.93	$17,616	$2.37	$14.93	$17,616	$2.38	$14.93
Standing Charges	$33,140	$4.43	$28.08	$33,140	$4.46	$28.08	$33,140	$4.47	$28.08
	$50,756	**$6.79**	**$43.01**	**$50,756**	**$6.83**	$43.01	**$50,756**	$6.84	$43.01
Total Farm Expenses	**$492,291**	**$65.87**	**$417.20**	**$533,095**	**$71.71**	**$451.78**	**$532,936**	**$71.86**	**$451.64**
Expenses as a percentage of Income	**59%**			**30%**			**30%**		
EBITDAR	**$336,862**	**$45.07**	**$285.48**	**$1,252,331**	**$168.46**	**$1,061.30**	**$1,251,359**	**$168.74**	**$1,060.47**
Interest	$88,000	$11.77	$74.58	$395,544	$53.21	$335.21	$395,547	$53.34	$335.21
Capital Purchases/Development	$25,000	$3.34	$21.19	$25,000	$3.36	$21.19	$25,000	$3.37	$21.19

	Status Quo - No Solar			5.8 ha Agrivoltaics @ 30% SR reduction			5.8 ha Agrivoltaics @ 100% SR reduction		
Drawings	$80,000	$10.70	$67.80	$80,000	$10.76	$67.80			
Principal	$0	$0.00	$0.00	$0	$0.00	$0.00	$0	$0.00	$0.00
Cash Surplus	**$87,897**	**$11.76**	**$74.49**	**$592,414**	**$79.69**	**$502.05**	**$591,306**	**$79.73**	**$501.11**
Non-Cash Adjustments									
Depreciation	$25,000	$3.34	$21.19	$212,500	$28.58	$180.08	$212,500	$28.65	$180.08
Capital Analysis									
Total Operating Assets (Closing)	$9,545,084	$1,277.11	$8,089.05	$14,527,554	$1,954.20	$12,311.49	$14,524,578	$1,958.55	$12,308.96
Total Liabilities (Closing)	$1,600,000	$214.08	$1,355.93	$7,225,000	$971.89	$6,122.88	$7,225,000	$974.24	$6,122.88
Owners Equity (Closing)	$7,945,084	$1,063.03	$6,733.12	$7,302,723	$982.34	$6,188.75	$7,299,578	$984.30	$6,186.08
Total Farm Income (Including Off Farm Income)	$829,153	$110.94	$702.67	$1,785,426	$240.17	$1,513.07	$1,784,295	$240.60	$1,512.11
Total Farm Expenses (Including Off Farm Expenses)	$492,291	$65.87	$417.20	$533,095	$71.71	$451.78	$532,936	$71.86	$451.64
Capital Purchases, Drawings and Tax	$160,966	$21.54	$136.41	$264,373	$35.56	$224.04	$264,506	$35.67	$224.16
Interest Charges (Incl Current Account)	$88,000	$11.77	$74.58	$395,585	$53.21	$335.24	$395,547	$53.34	$335.21
Operating Income	$87,897	$11.76	$74.49	$592,373	$79.68	$502.01	$591,306	$79.73	$501.11
EBITDAR on Equity	**4.24%**			**17.15%**			**17.14%**		
EBITDAR/Total Assets:	**3.53%**			**8.62%**			**8.62%**		
Taxable Profit	**$223,862**			**$644,287**			**$643,312**		

Table 6. Sheep and Beef Financial Analysis Summary

	Status Quo - No Solar		5.8 ha Agrivoltaics @ 30% SR reduction		5.8 ha Agrivoltaics @ 100% SR reduction	
Physical Properties	**Open**	**Close**	**Open**	**Close**	**Open**	**Close**
Effective Hectares	1,180	1,180	1,180	1,180	1,180	1,180
Sheep SU	5,710	5,710	5,670	5,670	5,652	5,652
Cattle SU	1,764	1,764	1,764	1,764	1,764	1,764
Total SU	**7,474**	**7,474**	**7,434**	**7,434**	**7,416**	**7,416**
Financial Summary						
Total Farm Income (TFI)	$829,153	$111	$1,785,426	$240	$1,784,295	$241
Farm Working Expenses (FWE)	$492,291	$66	$533,095	$72	$532,936	$72
FWE/TFI	**59%**		**30%**		**30%**	
EBITDA	**$336,862**	**$45.07**	**$1,252,331**	$168	**$1,251,359**	**$169**
Depreciation	$25,000	$3	$212,500		$212,500	
Debt Servicing	$88,000	$12	$395,485	$53	$395,485	$53
Net Profit (after Debt Servicing and Depreciation)	**$223,862**	**$30**	**$644,346**	**$87**	**$643,374**	**$87**
Debt Servicing/TFI	11%		22%		22%	
Total Assets	$9,545,084	$1,277	$14,527,554	$1,954	$14,524,578	$1,959
Equity	$7,945,084	$1,063	$7,302,554	$982	$7,299,578	$984
Total Debt / Land Reserves	$1,600,000	$214	$7,225,000	$972	$7,225,000	$974
% Equity	83%		50%		50%	
Charges/Debt Detail	**% TFI**	**Per SU**	**% TFI**	**Per SU**	**% TFI**	**Per SU**
Finance Charges (Incl. Curr Acc)	10.61%	$12	22.2%	$53	22.2%	$53
Total Charges	**10.61%**	**$12**	**22.2%**	**$53**	**22.2%**	**$53**
EBITDAR/Total Asset Value	**3.53%**		**8.62%**		**8.62%**	
Return on Equity	**2.35%**		**4.44%**		**4.43%**	

Assumptions

- Carrying capacity of this area of farm modelled for agrivoltaics is 10su/ha.
- Scenario 1 is status quo with no agrivoltaics.
- Scenario 2 includes 5.8 ha of panels and models a 30% reduction in stocking rate to reflect the 30% cover ratio of panels to paddock area.
- Scenario 3 includes 5.8 ha of panels and models a 100% reduction in stocking rate to reflect farm income implications of removing all grazing from that area other than for pasture/weed control.
  - The reduction in stocking rate in both agrivoltaic scenarios has come from the 1-year trade ewes which typically lamb in and around the paddock selected for the solar panel modelling.
- Maintained fertiliser, although there are uncertainties regarding solar panel warranties and the use of fertiliser that would need to be investigated further.
- Maintained cropping and pasture renewal, although practicalities and logistics would need to be considered before cropping or renewing pastures under the panels.
- Annual operating, maintenance and insurance costs for solar panels is based on 0.5% of the capital costs.
- Also included is the cost to replace the inverter in year 12-15. This cost of approximately $350,000 has been split over the 30-year lifespan for the purposes of this financial modelling.
- Depreciation of solar panels has been calculated over expected lifespan of 30 years.
- End of panel life removal, waste management and remediation of the land back to farming or installing new panels has not been included in this modelling.
- Tax has not been calculated or included in these analyses.
- Does not include principal repayments as the solar panel costs are covered through depreciation.

Key Findings

Due to minimal impacts of reducing stock numbers on the overall financial outcome, comparisons are made below between the Status Quo - No Solar, and Agrivoltaics 100% SR Reduction.

- Income increased due to additional solar income by $955,142.
- Expenses increased by $40,645, due to solar running costs.
- Depreciation lifted by $187,500 ($5,625,000/30 years), due to 30-year life span of solar panels.
- 100% of solar panel development funded through borrowings, therefore the term loan increases by $5,625,000.
- Net Profit (after debt servicing and depreciation) increased by $419,450.
- Return on Asset (EBITDAR/Total Asset Value) increased from 3.53% to 8.62%.
- Return on Equity (Net Profit/Equity) increased from 2.35% to 4.43%.

The sheep and beef case study analysis indicates that the proposed site would be suitable and the technical requirements feasible to install an agrivoltaics system. Both the Return on Asset and Return on Equity is significantly greater with both the agrivoltaics and solar-only scenarios, compared to status quo, indicating that incorporating solar onto this sheep and beef farm would have financial benefits for the landowner. The difference between the agrivoltaics and 100% solar (100% SR Reduction) is minimal and this presents a challenge for agrivoltaics. If considering the proposition from a purely financial perspective, this result indicates that it would be a better financial return to use a standard PV design, in which design is focused on maximizing solar generation. This results in panels being installed in close proximity to each other, increasing the shading over the area, resulting in a significant reduction in pasture yield and livestock carrying capacity. Narrow row gaps would also make it more difficult to move livestock and vehicles between panel rows, again acting as a deterrent to utilize this area for farming purposes. It could be argued that the increased revenue could allow for investment in on-farm actions and projects that produce a greater overall benefit to the environment and rural community than would be achieved by modifying the design to better achieve an agrivoltaic outcome. However, there is no certainty that this would eventuate. In addition, the National Policy Statement on Highly Productive Land 2022, places limitations on development of Aotearoa New Zealand's most fertile and versatile land and this will likely affect solar development applications. Given that the income from the agrivoltaics (30% SR reduction) scenario is still significantly greater than status quo, there is a good argument to pursue agrivoltaics, which creates less impact on the farming potential of the land.

2.3 Dairy Farm Case Study

The dairy farm case study is a 235 ha property, milking 860 cows. The proposed site is a 2 ha dryland area, that cows have access to, but is not included in the effective milking area. Supplementary feed is made from the 2 ha area.

Table 7. Dairy Farm Key Physical Performance Indicators

Key Physical Performance Indicators:	
Total Cows	860
Total Hectares	235.05
Cows/ha	3.66
Total Milksolids (kg MS)	413,000
Milksolids/ha (MS/ha)	1,755
Milksolids/cow (MS/cow)	480
Feed Allowance/cow (Excluding Winter Grazing) (kg DM/cow)	5,650
Cow Liveweight (kg LWT/cow)	470
Kg MS/Kg LWT	1.02
Kg MS/Kg DM (Feed Conversion Efficiency)	11.77
Liveweight/ha	1,720
Days In Milk	1,720
Comparative Stocking Rate (Excluding Winter Grazing)(kg LWT/t DM)	83

2.3.1 Dairy Farm Solar Technical Details

Two possible layouts for the site are shown in Figures 16 and 17. These have targeted the use of a 2 ha dryland area on the edge of an irrigated paddock.

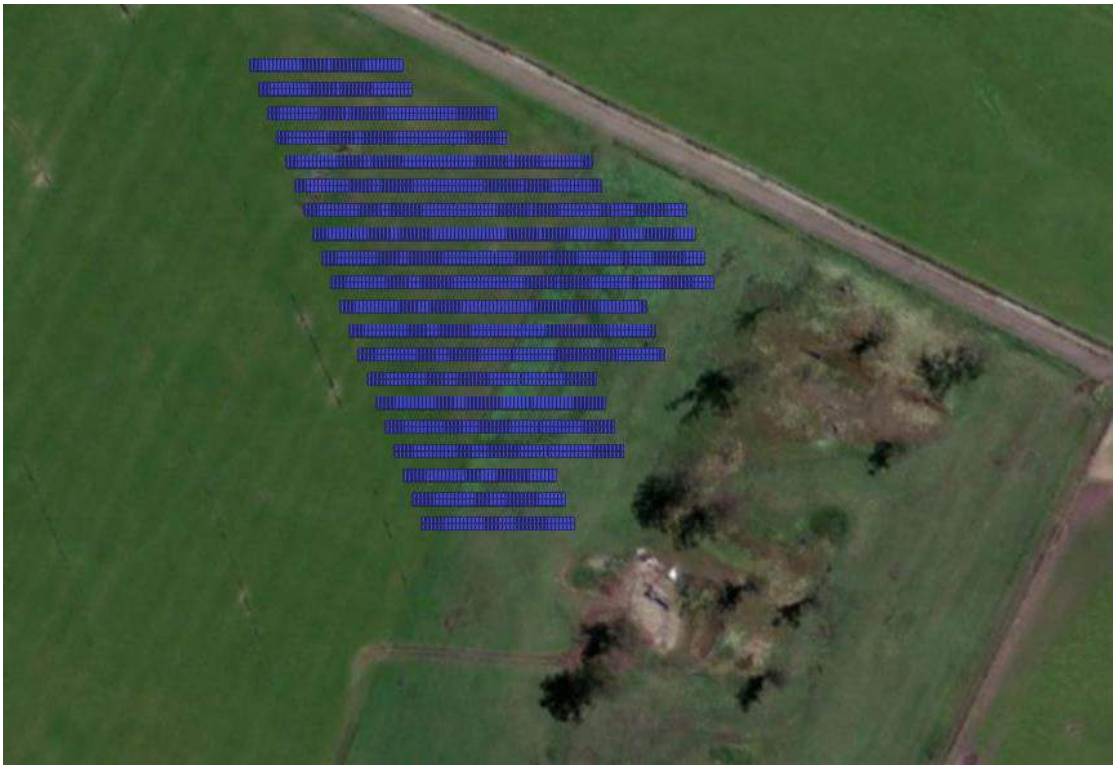

Figure 16. View of the fixed-tilt layout.

Figure 17. View of the tracker layout.

For reference, a possible design for panels under an irrigation pivot is also provided. This may be an option with further technical investigation, but at this stage is not recommended as this configuration increases cost and there may be warranty concerns for the PV modules and framing.

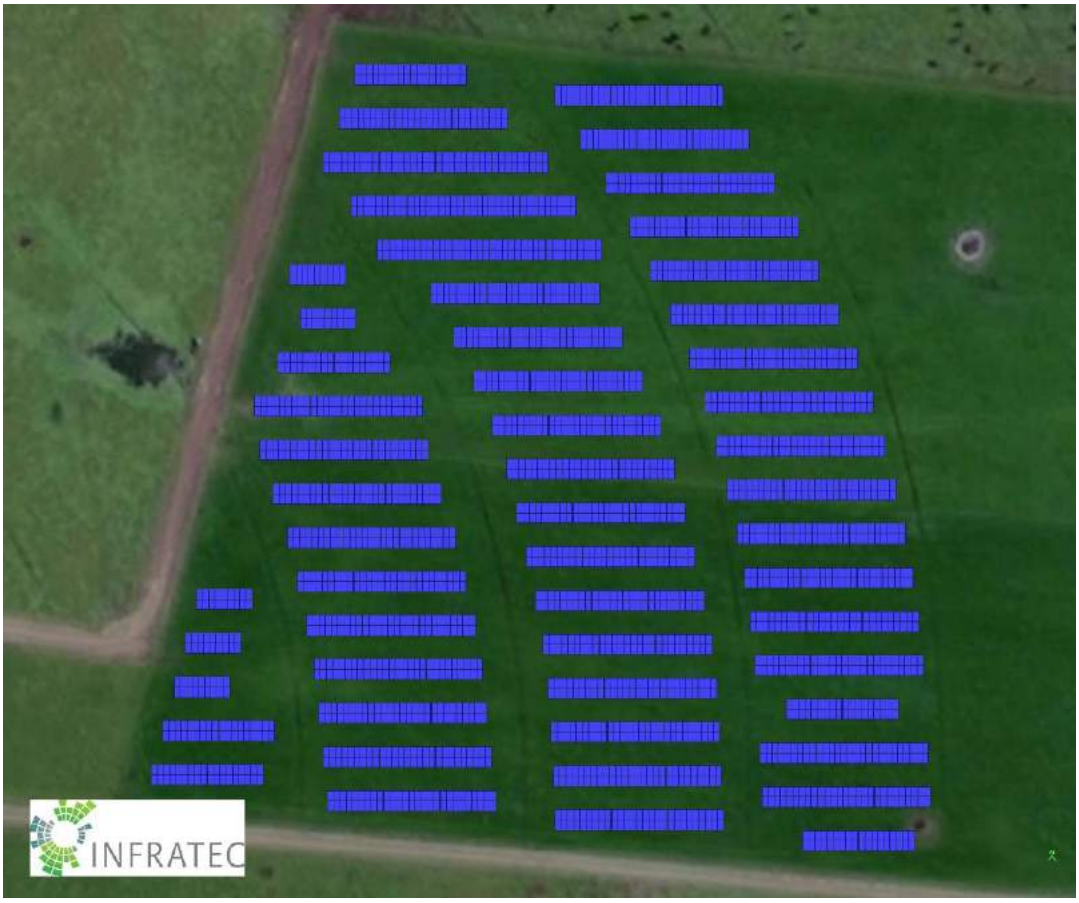

Figure 18. Potential layout under pivot irrigation.

Table 8. Dairy Case Study Technical Details

Site Coordinates	43.761 °S, 172.206 °E	
Global Horizontal Irradiance (W/m²)	1380	
PV Array Area (ha)	2.0	
Racking	**Fixed**	**Tracking**
Panel Arrangement	2-in-portrait (2P)	1-in-portrait (1P)
Inverter	10 x 110 kW String Inverter	9 x 110 kW String Inverter
Row Spacing (centre to centre) (m)	10.3	6.4
Space Between Rows (m)	6.0	4.0
Cover Ratio	45%	36%
DC Size (kW)	1,452	1,214.4
AC Size (kWac)	1,100	990

Table 9. Dairy Case Study Energy Generation

Racking	Fixed	Tracking
Specific Yield (kWh/kWp)	1,408	1,649
Annual Energy (MWh)	2,045	2,003

Generation data applies for the project's first year and will degrade over the project lifespan.

Table 10 Dairy Case Study Agrivoltaic System Costs and Revenue

System	Fixed-tilt	Single-axis tracking
Project Development, Consent, & Grid Connection ($ NZD)	350k - 390k	350k - 390k
Project Design & Build ($ NZD)	2.6 - 2.9 million	2.1 - 2.7 million
Estimated Revenue per Megawatt-hour ($/MWh)	96-144	96-144
Estimated Annual Revenue per Hectare ($/ha)	98k-147k	96k-144k

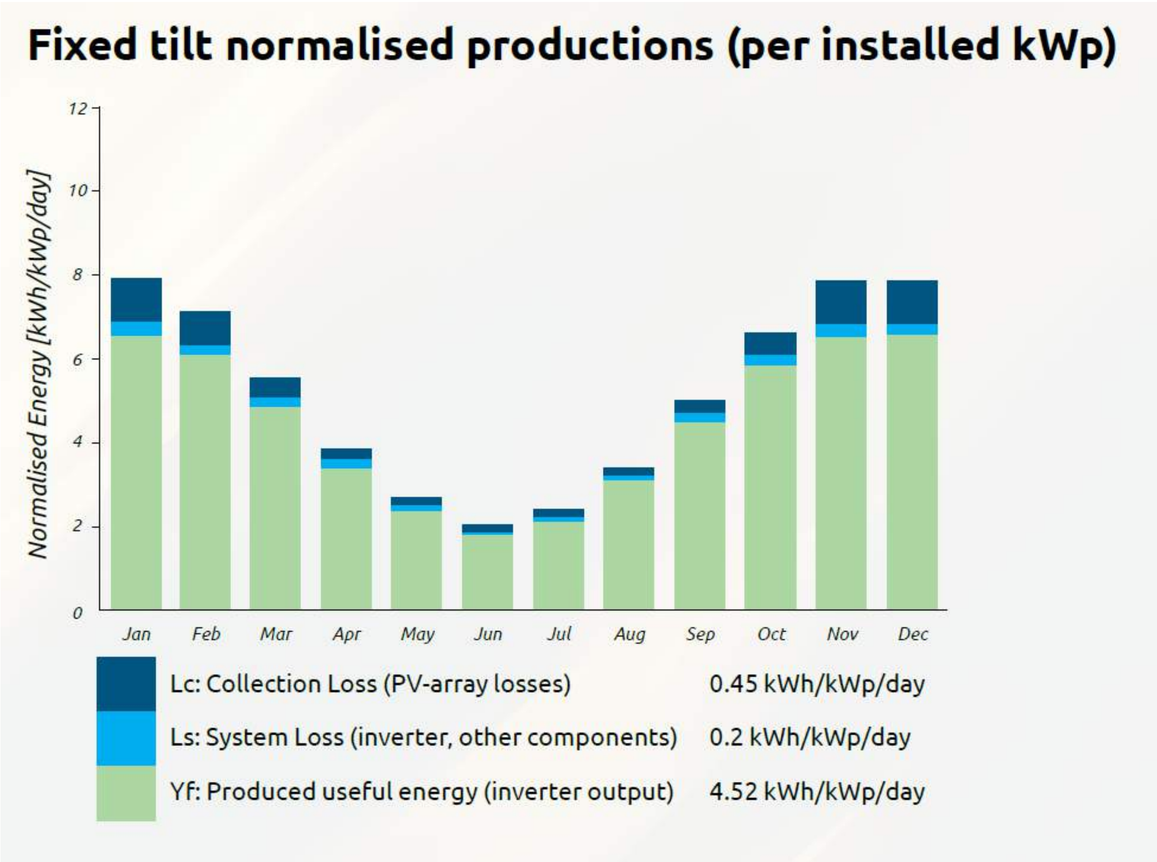

Figure 19. Fixed Tilt Layout – Monthly Production per kilowatt-peak.

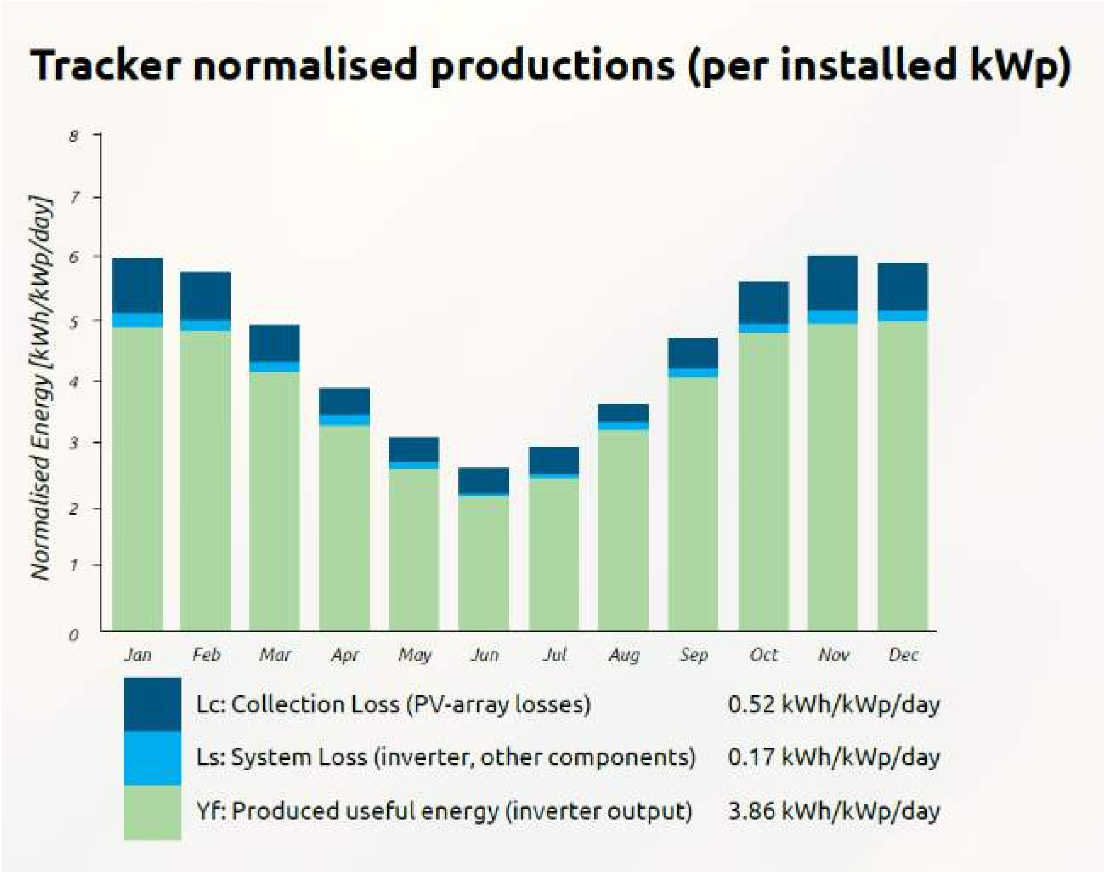

Figure 20. Tracking Layout – Monthly Production per kilowatt-peak.

2.3.2 Dairy Farm Financial Analysis

Table 11. Dairy Case Study Financial Analysis Summary

	Status Quo – No Solar			2 ha Agrivoltaics – No Grazing			Variance		
Key Financial Performance Indicators:	**Total**	**Per Ha**	**Per kg MS**	**Total**	**Per Ha**	**Per kg MS**	**Total**	**Per Ha**	**Per kg MS**
Total Farm Income (TFI)	$3,395,045	$14,441	$8.22	$3,635,045	$15,462	$8.80	$240,000	$1,020.84	$0.58
Farm Working Expenses (FWE)	$2,259,307	$9,610	$5.47	$2,288,113	$9,733	$5.54	$28,806	$122.53	$0.07
FWE/TFI	**67%**			**63%**					
EBITDA	**$1,135,738**	**$4,831**	**$2.75**	**$1,346,932**	**$5,729**	**$3.26**	**$211,194**	**$898.32**	**$0.51**
Depreciation	$72,000			$176,000			$104,000	$0.00	$0.00
Loan Interest Payments	$357,225	$1,519	$0.86	$528,825	**$2,249**	$1.28	$171,600	$729.90	$0.42
Current ACC Interest	$18,438	$78	$0.04	$18,438	**$78**	$0.04	$0	$0.0	$0.0
Total Debt Servicing & Depreciation	**$447,663**	**$1,904**	**$1.08**	**$723,263**	**$3,076**	**$1.75**	$275,600	**$1,172.27**	**$0.67**
Net Profit (after Debt Servicing and Depreciation)	**$688,075**			**$623,669**			-$64,406		
Total Assets	$14,231,590	$60,534	$34.46	$17,351,590	$73,805	$42.01	$3,120,000	$13,270.95	$7.55
Equity	$7,736,590	$32,908	$18.73	$7,736,590	$32,908	$18.73	**$0**	$0.00	$0.00
Total Debt	**$6,495,000**	**$27,627**	**$15.73**	**$9,615,000**	**$40,897**	**$23.28**	**$3,120,000**	**$13,270.95**	**$7.55**
% Equity	**54%**			**45%**					
EBITDA/Total Asset Value	7.98%			7.76%			-0.2%		
Return on Equity	8.89%			8.06%			-0.8%		

Assumptions

- 10.5t DM/ha pasture annual pasture production from the 2ha dryland area in question.
- Fertiliser and re-grassing costs would reduce by $775.80/ha.
- Supplement harvesting costs (9.5t DM total @ $0.19 kg DM) would be reduced by $893/ha, as the majority of the dryland feed is grown when there is a surplus.
- The reduction in pasture would be replaced by PKE (16t DM @ $480/t) which would equate to $3840/ha.
- There would be additional running costs from the increase in bought-in supplements of $792/ha.
- Tax has not been calculated or included in these analyses.
- Does not include principal repayments as the solar panel costs are covered through depreciation.

Key Findings

As the inclusion of PV panels had little effect on current income, only the 100% SR Reduction scenario was modelled against the status quo.

- In the dairy scenario, the capital cost is greater due to the increased panel height above the ground that is required to allow cows to graze underneath. However, there is a greater opportunity to use electricity generated in the dairy business to run the dairy shed, irrigation and potentially in the future any electric vehicles than there is in the sheep and beef scenario, due to the greater electricity demands of the dairy system.
- Income lifted due to additional solar income by $240,000.
- Expenses increased by $28,606, mainly due to solar running costs, but also additional supplement to offset the loss of dryland.
- Depreciation lifted by $104,000 ($3,120,000/30 years) due to 30-year life span of solar panels.
- 100% of solar panel development funded through borrowings, and therefore the term loan increased by $3,120,000.
- Net Profit (after debt servicing and depreciation) dropped by $64,400 due to increased borrowing, as 5.5% interest rate was not being covered by increased income.
- Return on Asset (EBITDAR/Total Asset Value) dropped from 7.98% to 7.76%.
- Return on Equity (Net Profit/Equity) dropped from 8.89% to $8.06%.

Both the Return on Asset and Return on Equity are less with the PV system installed than the status quo scenario for the dairy case-study. This reflects the greater return from land asset generated by dairy compared to sheep and beef enterprises and the significant capital investment that is required for solar developments.

3 FARMER WORKSHOPS

On 23 March 2023, a small number of farmers who had expressed interest in wanting to know more about agrivoltaics gathered in Christchurch. The purpose of the workshop was to explore the farmers' understanding of the constraints and opportunities and engage with them as to how the challenges can be overcome and how to capitalise on the opportunities.

Sheep and beef, and dairy farmers participated in the workshop. The workshop started with presentations from experts to provide an overview of agrivoltaics that may be appropriate for Aotearoa New Zealand pastural systems. Alan Brent from Victoria University of Wellington provided a brief status quo of the technology from a global perspective, followed by Ian Hyde from Ashburton District Council to discuss consenting implications. Infratec presented the findings of techno-economic analyses that were undertaken for two case studies in the Canterbury region and finally Megan Fitzgerald from Tambo spoke about the findings from the literature review and project. After these presentations, the participants undertook a design-thinking inspired session addressing the following questions:

- What do you think are the opportunities of integrating solar and livestock?
- What risks could integration present? How might we manage these?
- What might be barriers to successful integration? How might we address these?
- What are some environmental, land and water opportunities and risks we have not thought of?

Workshop participants were asked to write their answers individually and then discuss with their neighbour before adding all ideas to a white board. Once all answers were placed, the key themes were identified and there was a group discussion to delve into these themes in greater depth. The following sections highlight and discuss the themes.

Opportunities

The most common opportunity identified by both sheep and beef, and dairy farmers was the potential to diversify income. This included selling the energy and the potential for income from leasing the area to solar providers. One farmer highlighted that agrivoltaics could present a constant revenue stream. Another said:

> "It is renewable energy that doesn't break the bank"

Farmers, especially dairy, stated they saw a real opportunity in improving animal welfare. The benefits were potentially two-fold: positive public perception and improved animal production. Another farmer highlighted the opportunities for a more positive environmental outcome, it was not surprising that the next largest opportunity identified was that agrivoltaics could protect farmers' social license to farm. Reduced emissions, better animal welfare, and potentially lower environmental impact aligns with many of the farmers' values.

The increasing availability of Electric Vehicles (EVs) could present an opportunity for farmers to decrease their reliance on fossil fuels. One farmer suggested that milk tankers could be charged at farm during milk pickups, and this could extend to farm bikes and vehicles.

When asked in the final survey "what excites you the most about integrating […]" one farmer replied: "money". While diversification was important, farmers recognised that given the right ROI and capital requirements, agrivoltaics could be a good source of revenue whilst having the potential to reduce costs. Some banks are also starting to offer green loans, in which documented sustainable practices are rewarded with a lower interest rate. There are market trends of demanding sustainably produced food with agrivoltaics ticking many of these boxes.

Risks

The risks identified by the farmers are the lack of confidence they feel towards investing in solar over the long term. They identified unknown restrictions on current farm production, future ability to sell land with implemented agrivoltaics, and lengthy time horizons for pricing as some of the key risks for investment into agrivoltaics.

A common risk identified was the potential restriction on current or future land by the addition of agrivoltaics. This included disrupting or restricting current operations and that change being locked in for 30 years. Land use could be changed, but this would compromise the economic viability of the initial investment. Additionally, the time horizon could mean farmers forgo future better paying opportunities, and that the panels could become old technology quickly.

The future value and ability to sell the land was also a concern of farmers. Farmers identified that they face significant risk in not knowing how the assets and any agreements with providers could be negotiated or what the implications could be.

Damage can occur to the panels through extreme weather or by stock. Farmers were concerned how this might affect insurance premiums.

Barriers

Barriers are the factors that would or are stopping farmers from investing in agrivoltaics. They are the key factors that need to be overcome for farmers to have confidence in successful integration. All sheep and beef, and dairy farmers identified that cost was the largest barrier. This included the ROI not being great enough. One dairy farmer said:

> "[…] land is more profitable to milk cows than subdivide for solar"

Others were concerned about the capital cost saying that the

> "Initial investment is prohibitive"

Workshop participants noted a potential effect on farm management and a lack of skills in managing and negotiating deals with renewable energy. This translated to farmers being worried if they know they are reaching a fair deal, or that rather than doing one system well (farming or solar) it could end up being two poorly run systems, with one acting as a distraction to the successful management of the other. As an emerging industry there are few pre-existing deals or well-established markets that interested parties could inform themselves with.

As with any markets or technologies in the early adopter phase, there is regulatory uncertainty and apprehension. For agrivoltaics, farmers highlighted this could be exacerbated by the need to get council and neighbours' buy in for visual disturbance. Coupled with uncertainty of distribution capacity, farmers were aware of the new and varied negotiations they would need to have.

Environmental risks and opportunities

Farmers have a strong interest in what agrivoltaics could do for their farm beyond the potential financial income. Many of the key points were highlighted in the discussion throughout the workshop, such as the reduction in reliance on fossil fuels, potential to decrease nitrogen leaching, and animal welfare benefits to improve farming productivity.

Concerns were raised over the life cycle of the panels potentially causing net negative environmental impact. Extreme weather conditions, such as snow, wind, and hail, as well as potential damage by animals, could accelerate the wear on the solar PV panels, potentially compromising the net benefit of the panels.

There was little information available to farmers to inform them if there could be any long-term risks, such as leaching from the panels that could compromise production and therefore the value of the land under the panels. The participants also queried if the reduction in grass growth could result in an increase in nutrient leaching.

This discussion highlighted environmental impacts are an important consideration when farmers are assessing agrivoltaics options. Farmers drew strong connections between environmental performance and their ability to farm as normal.

This theme raised more questions than answers and shows a significant gap in research relating to environmental factors landowners need to address when assessing the feasibility of solar on their property.

Farmer developed solutions to risks and barriers

After discussing the risks and barriers, potential solutions were developed by the workshop participants. The aim was to hear farmers and industry professionals' solutions to addressing the risks and barriers. There were two main findings. Firstly, the need for quality information dissemination, and secondly, more knowledge and information regarding the ownership and relationship model between farmers and solar companies.

Farmers noted that the largest barriers are the capital investment required and their lack of skills in running an effective agrivoltaic system. They noted that the financial opportunities could incentivize them to form relationships and agreements with other organizations that have the skills. However, currently farmers feel like they do not have knowledge to maximize their return from investments into solar.

To help farmers address knowledge and management gaps regarding photo-voltaic systems, workshop attendees suggested this could be assisted by thorough farmer education and facilitating peer-to-peer discussion. Farmers identified that support is needed to assist farmers in contract negotiations. There was a strong need for transparency considering the early stages of the industry in Aotearoa New Zealand. Farmers identified the need for an industry guide as a means to disseminate much of this information.

The cost of establishing agrivoltaics was the most discussed constraint in the workshop. To manage this capital cost, whilst still maintaining ownership of the land, farmers identified three potential ownership models: owner/operator, leasehold, and partnerships. Table 12 summarises the strengths and weaknesses of the arrangements as identified by the workshop participants.

Table 12. Workshop summary of potential agrivoltaics arrangements.

	Owner/operator	Leasehold	Partnerships
Strengths	Farmer realises benefits of solar and value of energy generated.	Farmers do not need to make capital investment. Farmers do not need expertise in managing solar.	Farmers and investment parties can negotiate terms. Farmers do not need expertise in managing solar.
Weaknesses	Farmers must cover cost and risk of investment in panels. Farmers need to negotiate and manage solar panels.	May disincentivise agrivoltaics. Farmers may not be rewarded for solar generation.	May disincentivise agrivoltaics. Complex relationship. Farmers may not be rewarded for solar generation.
Key considerations for success	Farmers need to have the knowledge to participate in the industry.	Detailed and explicit lease terms that have flexibility to change over the length of the asset's life.	Information had to be an open book regarding percentage share of electricity produced.

Details of the arrangements that were discussed included:

> "land subdivided with a right to graze. You still own the land and lease to a solar company"

> "give up an area of land for solar for 30 years and no income, but after x years, the farmer has the opportunity to purchase back land and technology for $1 transfer"

For farmers to be able to leverage their asset – the land, they need clear information on how relationships should operate. Co-operation between solar companies and farmers means site selection and financial agreements could optimise both solar production and livestock production system outcomes.

Key findings from the workshop

One dairy farmer summarises agrivoltaics as:

> "Financially not feasible for us but can tick other boxes such as social license. It helps being seen to do our bit for the environment"

Farmers in the workshop could see the benefits to their farm business. However, currently the barriers to entry are too great. Drawing on the number 8 wire mentality farmers could make agrivoltaics successful.

> "if you figure out the finances, farmers will solve [the challenges of integration]"

However, much of the technical knowledge and skills sits within solar company expertise. Farmers need to be brought into discussions and agreements so all parties can be informed.

At the end of the workshop farmers were asked how interested they were in agrivoltaics before and after the workshop. Most increased their interest from “somewhat interested” to “very interested”. However, one participant went from “somewhat” to “not interested”, citing with the understanding of what is required – agrivoltaics is not for their farming system. Farmers will make the best decision for their farm given the right information and opportunity.

4 FARM ASSESSMENT TOOL AND BOOKLET

An assessment tool was developed to provide farmers with a preliminary assessment of a potential site's suitability for agrivoltaics. In addition, a booklet summarising the key findings from the project was created for farmers to gain further knowledge on agrivoltaics. These will be available on the tambo.co.nz website and the pdf copies of the booklet will be available to all interested parties on request.

5 CONCLUSION

The project outputs indicate that agrivoltaics is technically and economically feasible in the Canterbury region, and likely to be of particular interest to sheep and beef farmers.

There is a lack of evidence in the literature in relation to the impact of agrivoltaics in an Aotearoa New Zealand context due to minimal examples of agrivoltaic systems currently in existence in the country. Based on overseas research, there are potential benefits for integrating solar production with agriculture in Canterbury and other regions of Aotearoa New Zealand. These include livestock wellbeing and productivity; pasture and crop production, particularly in dryland areas; and an increase in overall land productivity. However, potential downsides are also highlighted, particularly relating to pasture production losses due to shading, environmental impacts and economic outcomes compared to standard solar energy systems.

The risk of displacement of food production by traditional solar energy developments is a major contributor to the interest and investment in agrivoltaics system. However, without definitions of what constitutes agrivoltaics in Aotearoa New Zealand, there is a risk of green-washing, where standard utility-scale solar farms claim agrivoltaics status, simply by grazing sheep underneath panels, but without making any adaptations to design to reduce food production losses and environmental impacts of the farmland it is situated on.

Agrivoltaic trials and modelling based in Canterbury and other areas of Aotearoa New Zealand will be critical to obtaining a more comprehensive understanding of how agrivoltaic systems might align with the country's long-term goals of increasing renewable energy production, without displacing food production or negatively affecting environmental outcomes. End of panel life recycling options also need to be developed and the environmental impacts explored in further detail. Finally, there is a need for further dissemination of information for farmers, and support to build long-term trust-based relationships with potential investors and solar business partners. It is intended that the agrivoltaics assessment tool and agrivoltaics information booklet produced as part of this project will begin to address this need.

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