Can innovative energy and storage solutions reduce the cost of energy and reduce the carbon footprint of irrigators in the Australian Sugar industry?

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The work described in this thesis was funded by;

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Signature: 

Date: 15th February 2021

SUMMARY

National environmental objectives have led to the development of government policies that create incentives for businesses to invest in renewable energy. Increasingly affordable renewable energy and storage technology have aligned with these policies to potentially deliver both economic benefits to farmers and co-benefits to the environment in on- and off-grid scenarios. In Australian sugarcane production, 90% of irrigation pumps are connected to the national electricity grid where the energy is mostly generated from fossil fuels.

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Results indicated that investment in renewables can reduce the 25-year net present cost of pumping by up to 25% and can contribute to an improved environmental footprint for Australian sugarcane irrigators, by reducing emissions by up to 1324t CO_2e over the 25 years.

The study (outlined in Chapter 2) considered economic feasibility from the viewpoint of an individual farmer investor. Using a case study approach, a cost benefit analysis was applied to three case study sites, in three of Australia's largest sugarcane growing regions: Ayr, Marian and Bundaberg. For each location, the most typical irrigation method was chosen: furrow, centre pivot and Big Gun respectively. The case-study farm's electricity demand and pricing agreements were assessed using the Hybrid Optimisation of Multiple Energy Resources (HOMER) design software to analyse a range of hypothetical micro grid installations.

The optimal micro grid solution was ranked based on the lowest Net Present Value of the site's energy costs over 25 years. The flexibility to shift energy demands of irrigation to periods of renewable generation was found to improve economic outcomes.

This finding can be applied to any small scale industrial intermittent load in regional QLD where solar PV is being assessed. Where the site had an existing connection to the electricity grid, embedding solar photovoltaics (PV) to complement the grid had the highest economic feasibility. The study results were relatively inelastic to battery storage prices for irrigation pumps with a seasonal load. Connection rules such as feed-in tariffs and export limits applying to embedded generation were found to influence the abatement costs and investment returns, indicating a disincentive for renewable installations rated over 30 kW. Additionally, the study found the marginal cost of abatement under the Renewable Energy Target (RET) was reduced substantially when excess renewable energy was able to be exported.

If embedded generation can reduce irrigation costs and a sugar farm's environmental footprint – why is the adoption rate of solar PV so low for Australian sugarcane irrigation? Can the adoption level and rate be improved?

Adoption levels and rates are influenced not only by the technology but also by many factors in the investor's operating environment. Chapter 3 aimed to identify the factors influencing Australian sugarcane irrigators' potential adoption of solar PV.

The level and rate of adoption were assessed using the ADOPT model. ADOPT evaluates a technology and specific market to predict the likely peak level and rate of adoption. Results indicated that after 10 years, 50% of the sugarcane farms were likely to adopt solar PV for irrigation plant.

The factors estimated to influence farmers' adoption decisions for solar PV were economic and environmental benefits, ease of use, existing knowledge, business risk and the farmer's current financial position. Sensitivity testing suggested that grid connection policies or government renewable energy subsidies that increased income or reduced capital costs, and thereby increased economic returns for sugarcane irrigators, could improve peak adoption levels by up to 40%.

Government policies were found to have a greater impact on adoption than the environmental benefits generated by the PV systems. From the results we infer that the historically changing relative advantage of the technology has resulted in some farmers exercising the option to hold off investing until they feel the relative advantage has peaked.

This is the first study using the ADOPT framework to consider solar technology in Australia. The findings can be applied to the entire Australian sugarcane industry and may be used by industry to refine future extension strategies or advocacy groups hoping to influence policy design to ensure both industry economic and sustainability goals are achieved.

Which Australian renewable energy policies apply to sugarcane irrigators? How can these policies be altered to improve the adoption of renewable energy?

The first two parts of the study (Chapter 2 and 3) found that connection rules and government policy influence both the economic benefits and the potential adoption of embedded renewable energy for Australian sugarcane irrigators.

Chapter 4 aimed to outline the policy and regulatory levers available to influence the adoption of renewable energy, the policies that applied to Queensland sugarcane irrigators and how some policies may be refined to increase the adoption of renewable energy.

In Australia, the Renewable Energy Target (RET) and Emissions Reduction Fund (ERF) have successfully incentivised the adoption of renewable technologies across a range of industries. In the Australian sugarcane industry, renewable uptake has been limited for irrigation largely due to an export limit of 30 kW and diminishing FiTs.

Refining grid policy settings to increase export limits and/or allow Time-of-Use (TOU) feed-in-tariff pricing, increases the amount of income that can be generated for a renewable investment such as solar PV. The ability to generate income from renewable energy that is excess to the requirements of an intermittent load can improve the feasibility of including solar PV in addition to the grid. Collaboration between water and energy government departments also offer an alternative design of incentives for sugarcane irrigators, by offering rebates for water pumping from micro grids with a renewable component. The policy changes outlined in Chapter 4, if applied, would improve the economic feasibility of solar PV for any small-scale industrial load – particularly those with intermittent loads. The findings could be used by advocacy groups and policy makers when considering the implications of policy design.

Collectively the results of this thesis can inform Australian sugarcane farmers about the potential economic and environmental benefits of using renewable energy in irrigation. Broadly, the results can be applied to intermittent, small scale industrial loads considering renewable energy. The sugarcane industry can use this knowledge to improve their decision-making about investment in renewable energy and design extension materials to build farmers knowledge about which water pumping scenarios are most suitable to solar PV. Advocacy groups focusing on sustainability metrics can use the findings of this thesis to build understanding on policy implications and where to target policy change. Finally, government policy makers may consider changes to policy that can improve productivity and increase the rate and level of adoption of renewable energy in the Australian sugarcane industry.

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AUTHORSHIP DECLARATION: CO-AUTHORED PUBLICATIONS

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Student signature: Date: 15th February 2021
I, David Pannell, certify that the student's statements regarding their contribution to each of the works listed above are correct. Coordinating supervisor signature: Date: 9 Feb 2021

1. Introduction

Sugarcane in Australia is produced under irrigation, with 90% of irrigation pumps being connected to the national electricity grid with its electricity being generated mostly from fossil fuels. Electricity costs can represent up to 30% of variable cost in the sugarcane gross margin (Welsh and Powell 2017), with sugarcane growers paying some of the highest power prices in the world, thereby weakening their operating margins and export competitiveness (Australian Energy Council 2017). Moreover, in the state of Queensland, the combined electricity costs (line rental plus wholesale prices) have increased by approximately 400% since the year 2000. Inflation over the same period has been around 45–50% (National Irrigators Council 2014).

While efforts to increase irrigation application and water pumping efficiencies are ongoing, opportunities exist to integrate new energy technologies into irrigation water supply. For example, improved use of energy storage equipment to overcome intermittency issues with renewable energy pumping applications has been identified as having high potential and high value to the Australian water sector (Beca 2015).

1.1. Renewables in irrigation

The application of renewable energy in Australian irrigated agriculture at an industrial scale is relatively under-examined. A feasibility study into alternative energy sources for irrigated cotton production by Chen et al. (2013a) found solar resources to be unsuitable for irrigation, but useful in offsetting domestic electricity consumption. The study found wind resources were regarded as unreliable and expensive. Eyre et al. (2014a) concluded that renewable energy infrastructure is not cost-effective and was unable to meet peak irrigation demands. Similar studies undertaken abroad concur with these findings, including for irrigated rice in Quinghai Province in China by Campana et al

(2013); irrigated cotton, corn and wheat in the United States by Vick and Clark (2009), Vick and Almas (2011), Vick and Neal (2012); and vineyard drip-irrigation in the Mediterranean area Carroquino et al (2015).

More recent studies of irrigated cotton (Powell and Welsh 2016a, c) found that unless renewable energy generation closely matched the timing of irrigation energy demand, or the water could be pumped and stored in reservoirs, the economics become marginal at best. Utilisation of surplus renewable energy generation was identified as a potential area for improving project economics when incorporating renewable sources into existing loads. Advances in solar PV and pumping technology have reduced the capital cost of installation. These advances, in conjunction with substantial increases in power prices and storage capabilities becoming more affordable, have changed the economic equation considerably.

Welsh and Powell (2017) identified that the sugar farms applying the highest rates of irrigation water or using relatively high energy to lift or pressurise water presented the best business case for innovative energy solutions. The same study also concluded that the energy solutions would most likely be in the form of pump site microgrids. No research has been conducted on the economic feasibility of microgrids applied to irrigation in the Australian sugarcane industry.

1.2. Micro grids

Diesel direct drive and diesel generators (DG) are widely used in irrigated agriculture throughout the world. It is not always viable to build electricity grid extensions over long distances to pump sites, even prior to considering ongoing running costs. Advances in inverter, drive and control systems have supported mixing sources of Alternating Current (AC) and Direct Current (DC) to maintain a constant power source to a load such as a water pump. The term 'micro grid' is often used to describe electricity generation encompassing a mix of traditional (such as grid and diesel) and renewable power source technologies. Micro grids can be defined as clusters of generators which are operated as single controllable entities (Gamarra and Guerrero 2015). An example of a possible micro grid is shown in Figure 1.

Energy storage is destined to play a crucial role in renewable power penetration in the future, enabling electricity systems greater supply-side flexibility. Behind-the-meter applications allow grid connected consumers to manage their energy bills, reduce peak demand charges and increase 'self consumption' from adopting micro grids. In 2015, an off-grid New South Wales irrigator installed a micro grid that was anticipated to displace over one million litres of diesel and halve extraction costs over the modelled project life through renewable energy technology (Welsh 2016). Analysis is needed to understand if micro grids could help lower the cost of energy for Australian sugarcane irrigators.

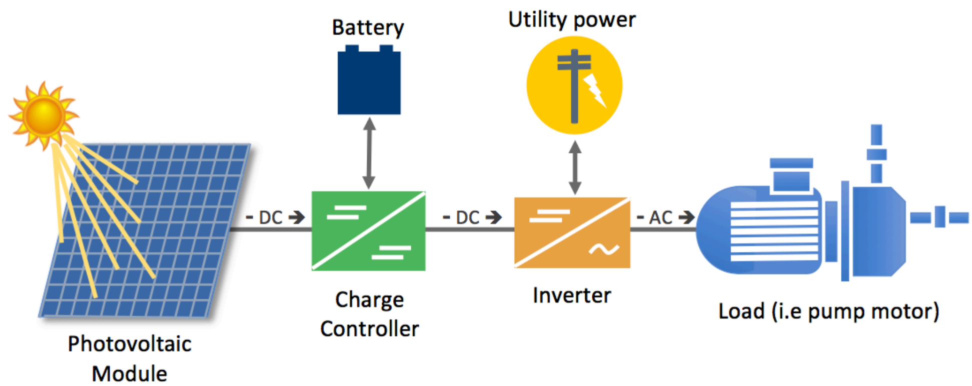

Figure 1: An example of a micro grid schematic, with many power sources feeding into one load source such as an irrigation pump. Image source: Ag Econ

Diesel generators

Research indicates that, in conjunction with a renewable source, the Diesel direct drive and diesel generators (DG) can be controlled using a 'load-following strategy' to power irrigation plant: when load falls below a given threshold and the renewable source cannot provide sufficient power, the DG is called upon to make up the difference (Carroquino, Dufo-López, and Bernal-Agustín 2013, 2015). Using this strategy during peak demand for irrigation, the DG starts to generate the power demanded by the pump until renewable sources can achieve the required load threshold. Then the DG idles down or shuts off. Life cycle assessment by Carroquino et al. (2015) also concludes that aside from lowering installation cost, the addition of a diesel DG can also reduce overall life cycle CO_2 emissions per unit of output. Those systems without diesel generators must be over-sized (more kilowatts installed than the system requires) to ensure energy supply to the whole load during periods of low meteorological sources, such as partially cloudy weather, releasing more life cycle emissions than adding a DG to the system (Sen and Bhattacharyya 2014). Chapter 2 within this thesis investigates the optimal micro grid componentry for lowest cost energy and considers diesel generators.

Battery storage

The economic feasibility for battery storage is likely to be influenced by the economic opportunities to provide electricity time-shift services to increase self-consumption or avoid peak demand charges in the irrigation sector. There may also be emerging demand driven by incentives from commercial distribution or generators to manage grid feed-in. In 2017 Australia was identified in a report by the International Renewable Energy Agency (2017) as having significant growth potential due to current high electricity prices, excellent solar resources and relatively low grid feed-in remuneration.

Battery energy storage has many combinations of chemistry. Suitability differs between application scenario, including space restrictions, temperature, and the frequency, duration and load of power requirements. Round-trip efficiency – energy on discharge and energy used to charge – is expected to improve substantially towards 2030. In broad terms, battery storage can be separated into traditional Lead-Acid, High Temperature, Flow and Lithium-ion. The forecast 2030 installed price and 2016 to 2030 price reduction for battery energy is shown in Figure 2. The largest expected declines in price are predicted to occur with flow and lithium-ion batteries. Pricing of lithium-ion batteries are sensitivity tested in Chapter 2 which investigates which optimal microgrid componentry for lowest cost energy supply.

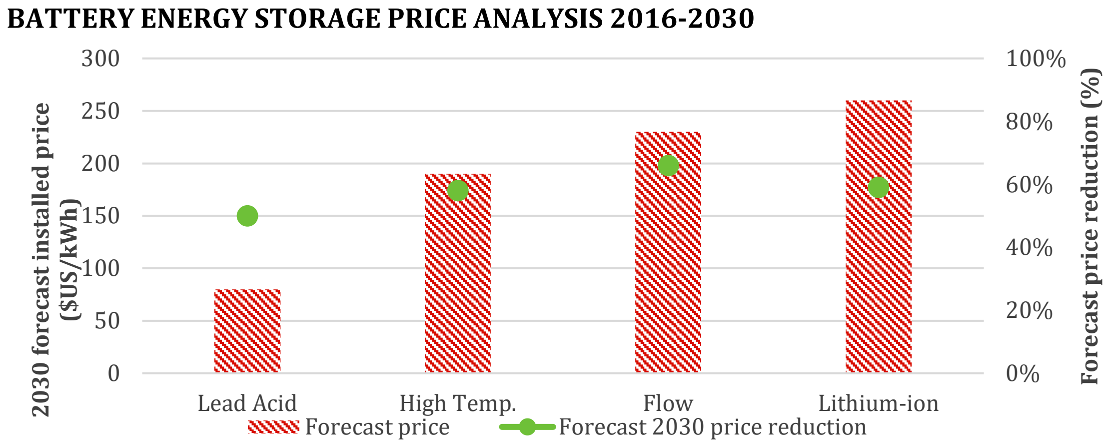

Figure 2: Battery future energy storage installed price denoted by the red bars ($US/kWh) and price reductions to 2030 (green dots) for a range of battery chemistries. Data source: International Renewable Energy Agency (2017)

1.3. Policy, network and retail considerations

Most Australian electricity demand is supplied by energy generated from fossil fuels such as natural gas, fuel oil and coal. However, the use of fossil fuels in electricity generation causes carbon dioxide (CO_2) emissions which negatively affect the environment. In recent years, many efforts have been made to increase the implementation of renewable sources of energy through research and application. From a policy viewpoint, a future energy mix has been proposed to replace energy supply from fossil fuels and encourage sustainable energy development from renewable sources.

Grid-connected irrigators, particularly in Queensland have been subject to a sustained period of electricity price increases. Queensland's electricity prices doubled between 2007–2008 and 2013–2014, predominantly driven by increases in network charges which increased sixfold from 2004–2005 to 2014–2015, accounting for over 95% of the total electricity price increases during the period (Davis 2018b). Of relevance to national policy initiatives that strive for more efficient use of water, Eyre et al. (2014) found more water-efficient systems were generally more energy-intensive systems. For example, water transfer occurring in closed pipes rather than channels, or installing drip or pivots to replace flood irrigation requires more energy than the systems they replace. The policy nexus between efficient use of energy and irrigation water is discussed in Chapter 4 of this thesis.

1.3.1. Policy installation incentives

Renewable energy installation falls under the Australian Government's Renewable Energy Target (RET). The RET has two parts: Large-scale Renewable Energy Target (LRET), and the Small-scale Renewable Energy Scheme (SRES). These schemes are discussed in detail in terms of the Australian cotton industry in Powell and Welsh (2016b). In the context of this study, the two key differences were considered when participating in either scheme: (a) solar installations limited to 100 kW in the SRES and where the government rebate is received upfront for the SRES as Renewable Energy Certificates (RECs); and (b) while in the LRET, Large-scale Certificates (LGCs) are sold at auction annually for 15 years of generation, with estimations made for future pricing. The SRES market has a price ceiling of $40 per certificate set by the Australian Energy Regulator, as opposed to the LRET's free market price discovery and delivery on forward contracts. Participating in these schemes lowers the cost of renewable installations. The LRET includes legislated annual targets which will require significant investment in new renewable energy generation capacity in coming years. The large-scale targets ramp up until 2020 when the target will be 33,000 gigawatt-hours of renewable electricity generation (Department of the Environment and Energy 2018b).

1.3.2. Network considerations

Reliability of electricity supply over a vast land mass with a sparse population has been an ongoing challenge for governments since the rollout of the national electricity grid in the 1960s. The network operator or Distribution Service Network Provider (DSNP) in regional Queensland is government-owned and hence is a highly regulated asset. DSNPs are required to maintain supply to a connection point to a set of standards consistent with rules set by the Australian Energy Regulator.

In some states and territories of Australia, the government regulates retail energy prices. That means the price is determined by the government and retailers must charge this price on their contracts. The state of Queensland has a highly regulated distribution and retail electricity market. Unlike other states, in Queensland, Ergon Energy, a government owned organisation, is both the DNSP and the energy retailer. In deregulated markets, such as south-east Queensland and New South Wales, consumers are free to move between energy retailers offering the least-cost alternative. In regional Queensland (and for all case study sites) Ergon Energy is the only provider. The customer has pricing options divided into tariffs designed to offer choice to the consumer and to best fit their individual demand profiles.

Irrigation electricity tariffs in Queensland have risen over 136% in the past decade. There remains uncertainty over future energy pricing, with Ergon Energy’s tariff reform resulting in many irrigation tariffs becoming obsolete in 2021. Analysis by Davis (2018b) found that, out of an estimated 42,000 electricity connections for businesses in regional Queensland, almost a third are on eight different tariffs classified as transitional or obsolete. Almost half of connections are for agricultural purposes.

Feed-in-Tariffs and eligibility

A feed-in-tariff (FIT) is a premium rate paid for electricity fed back into the electricity grid from a designated renewable generation source. FITs can be used as a policy lever or static subsidy or can gradually decrease over time to promote behind-the-meter innovation (Parliament of Australia 2018). Connection conditions such as FIT rate, available metering and inverter capacity can have a large impact on the economic feasibility of connecting energy generation and storage solutions. According to the Queensland Government (2018), to be eligible for a FIT in regional Queensland, you must satisfy the following criteria:

- Operate a solar system with a maximum inverter capacity not exceeding 30 kW (approximately 38kW of PV)
- Be a small business customer (consume less than 100MW per annum)
- Be a retail customer of Ergon Energy and be connected to the grid
- Have a network connection agreement with an electricity distributor approving the system for installation
- Have only one power system receiving the FIT per National Meter Identifier (NMI)

Connecting embedded generation greater than 30kW

Connecting to the Ergon Energy networks requires different levels of assessment and technical applications. DNSPs such as Ergon Energy have an obligation to ensure the network can provide a reliable network and safe connection for customers. Distributors’ connection guidelines place limitations on the network connection of embedded generation to manage high voltage. This means many renewable energy connection applications go through the technical assessment process with the effect of adding time (and in some cases cost) to the process of installations. Technical assessments may require customers to modify the size (or export capacity) of their chosen system, restrict the system's ability to export excess solar generation to the grid or, for larger systems, pay a capital contribution (of between $10,000 and $60,000) toward the cost of a network upgrade before the system is installed. This can impact the attractiveness and financial viability of installing solar PV for some customers, and the renewable energy industry's ability to grow (Dept of Energy and Water Supply 2017). Analysis has not been conducted on how these policy and network considerations may influence the adoption of energy and storage options for irrigation in Australian sugarcane farming systems.

1.4 Research questions

Government incentives combined with technological advancement suggest there is potential for solar PV to meet the ongoing energy demands of Australian sugarcane irrigation. There has been limited research on the application of renewable energy and storge options for irrigation and no research has focused on a sugarcane farming system. Additionally, no research has focused on the drivers of adoption for renewable energy applied to agricultural irrigation. Knowledge gaps exist around the complex set of network considerations that require analysis to understand if innovative energy and storage solutions can reduce the cost of energy and reduce the carbon footprint of Australian sugarcane irrigators.

The existing knowledge gaps lead to the key research question: 'Can innovative energy and storage solutions reduce the cost of energy and reduce the carbon footprint of irrigators in the Australian Sugar industry?' Aspects of this question were addressed in four sub-questions.

1. Are commercially available renewable energy and storage solutions economically feasible for irrigation pumps on Australian sugarcane farms? This question is addressed in Chapter 2.
2. What are the potential avoided emissions for Australian sugarcane farms investing in innovative energy and storage solutions? This question is addressed in Chapter 2.
3. Considering the technology characteristics and the preferences of agricultural farm irrigators, what is the likely level of adoption for innovative energy and storage solutions? This question is addressed in Chapter 3.
4. What are the major energy policies influencing Australian sugarcane irrigators? This question is addressed in Chapter 4.

The conclusions of the four research questions are discussed at the end of the thesis.

2. Can applying renewable energy for Australian sugarcane irrigation reduce energy cost and environmental impacts? A case study approach

Powell J.W, J.M Welsh, D. Pannell and R. Kingwell. 2019 Can applying renewable energy for Australian irrigated sugarcane reduce energy costs and environmental impacts? A case study approach. *Journal of Cleaner Production. 240: 118-177*

2.1. Abstract

In Australian sugarcane production, 90% of irrigation pumps are connected to the national electricity grid. In regional Queensland, where irrigated sugarcane is grown, both the retailer and distribution network service providers are government owned and highly regulated. This study investigates options for on-farm embedded generation from a range of commercially available components, to reduce energy costs of furrow, centre pivot, and Big Gun® irrigation. This study confirms that demand-side management crucially affects the economic feasibility of embedded generation. Connection rules, such as feed-in tariffs and export limits affecting renewable embedded generation can also influence emissions abatement costs and investment returns. When export limits are allowed on larger sites (solar PV systems >40kW), abatement costs fall from \$109 /t CO_2e to \$18/t CO_2e and the present value of the investment improves substantially. The analysis reveals economically feasible opportunities exist for small-scale solar PV system installations (under 40 kilowatts), reducing NPC of pumping from 12 to 25% and emission reductions ranging from 1,245 t CO_2e to 1,314 t CO_2e per installation over 25 years. Where a site is not eligible for a feed-in tariff, high renewable energy utilisation rates are required to make the site feasible. Batteries did not feature as an optimal component, even when battery storage and replacement values were discounted by 60%, indicating that seasonal load profiles under-use a battery investment. Therefore, batteries are inefficient and can be avoided in an irrigation microgrid.

2.2. Highlights

- Connection policies create an economic disincentive for renewable installations rated over 30 kW;
- Load-shifting energy demand to periods of renewable generation improves economic outcomes;

- Results are relatively inelastic to battery storage prices for irrigation pumps with a seasonal load; and
- The marginal cost of abatement under the Renewable Energy Target (RET) is reduced substantially when excess renewable energy can be exported.

2.3. Abbreviations

Carbon Dioxide equivalent – CO_2e

Emissions Reduction Fund – ERF

Feed-in tariff – FiT

Diesel Generator – genset

Distribution Network Service Provider – DNSP

Kilowatts of power – kW

Levelised Cost of Energy – LCOE

National Meter Identifier – NMI

Photovoltaic – PV

Renewable Energy Target – RET

Small Technology Certificates – STCs

Time-of-Use – TOU

2.4. Introduction

Most Australian electricity is generated from fossil fuels that produce carbon dioxide (CO_2) emissions (Department of the Environment and Energy 2018a). In recent years, increased use of renewable sources of energy has been encouraged by high prices of electricity and by research and innovation in renewable technologies (Beca 2015, Australian Renewable Energy Agency 2018).

Irrigators often depend on electricity for pumping, and they have several options to improve their on-farm water application efficiency, thereby reducing their demand for energy. Energy productivity gains can accompany pump efficiency (Chen, Baillie, and Kupke 2009, Foley et al. 2015), automation and application of new technology (Roth et al. 2013, Koech, Smith, and Gillies 2014, Farquharson and Welsh 2017, Roocke 2014). However, this study mostly focuses on use of renewable energy as a means of reducing energy costs and emissions through the installation of microgrids. Microgrids are clusters of generation operated as a single controlled entity and can include renewables. They can operate with or without a grid connection.

The application of alternative energy solutions in Australian irrigated agriculture is relatively under-examined. A feasibility study of alternative energy sources for irrigated cotton (Chen et al. (2013b) found solar resources to be unsuitable for irrigation, but useful in offsetting domestic electricity consumption. The study regarded wind resources as unreliable and expensive. Eyre et al. (2014b) concluded that renewable energies, such as wind and solar, were not cost effective and failed to meet peak irrigation energy demands, unsupported from fossil fuel-based generation. International studies have generated similar findings: irrigated rice in Qinghai Province in China by Campana, Li, and Yan (2013); irrigated cotton, corn and wheat in the United States by Vick and Clark (2009), Vick and Almas (2011), Vick and Neal (2012); and vineyard drip-irrigation in the Mediterranean area (Carroquino, Dufo-López, and Bernal-Agustín 2015). In a review of solar PV systems for irrigation and community drinking water Chandel, Nagaraju Naik, and Chandel (2015) found a mismatch between water demand and energy supply patterns had a major effect on economic viability of PV pumping and required careful design. They found the up-front capital cost and lack of awareness about the technology the main factors inhibiting implementation and incentives are required by governments to encourage users to switch. However, research in Australian irrigated cotton (Powell and Welsh 2016a, c) using photovoltaic (PV) energy found favourable economic outcomes could be achieved in both on-grid and islanding-mode, conditional on access to reservoirs to lengthen the duration of daytime pumping operations to times outside the growing season.

As the cost of PV components has decreased, islanded microgrids incorporating PV and diesel gensets have become a feasible alternative for irrigators in Bangladesh. Md Asaduzzaman and Shafiullah (2018) found load-shifting irrigation to daylight hours was an economic and environmental imperative. Battery storage was a high-cost option, so diesel gensets were called upon on cloudy days to meet peak demand. Utilisation rates and solar PV is overcome in China by irrigation in greenhouses whereby panels are mounted cheaply on the shed structures and excess energy is fed back into the grid. In a study by Schultz et al. (2018) on the progress on solar PV pumping in China concluded favourable policies, new innovative and collaborative business models were necessary to enhance the extension of solar PV irrigation technology and scale up adoption. The importance of a feed-in-tariff was identified by Rubio-Aliaga et al. (2019) in a multi-dimensional analysis on solar PV systems on irrigated crops where those grown on an annual scale can inject excess energy into the grid, thereby generating an economic profit. The study also concurred that government need to facilitate the adoption of renewables into irrigation pumps to reduce emissions and displace cheaper diesel-driven pumps. A review of incorporating renewable energy into irrigation pump sites by Rizi, Ashrafzadeh, and Ramezani (2019) emphasized the role of macro policies on feasibility and the importance of such studies to facilitate policy making and encourage investment and low-emissions technology adoption. The authors also note the importance on local resource characteristics, implementation of feed-in-tariffs and fossil fuel subsidies that impact feasibility changes with each location. In Iran, fossil fuel inflation of 17% still remained a cheaper energy pumping source through the 25-year investment life, than the alternative solar PV electrical system. In a nationwide approach using a multilevel modelling approach to adoption of solar and wind on US farms, a separate study by Borchers, Xiarchos, and Beckman (2014) suggests net metering and interconnection polices are shown to increase investment and uptake. Importantly, the research also found the effectiveness of other policy variables providing incentives for uptake was reduced when not achieved simultaneously with connection policies.

Previous analysis of sugar cane energy use by Welsh and Powell (2017) estimate industry grid consumption from irrigation could be upwards of 160,000 MW per annum, emitting around 155,000 tonnes of CO_2e per annum. Therefore, a large potential exists for economic rewards from lower pumping costs, while simultaneously lowering carbon emissions and formally contributing to the national effort of meeting agreed emissions reduction targets by 2030.

In this paper, we use case studies to assess the economic and environmental impacts of installing alternative energy sources to offset the cost of grid-connected irrigation pumps used in sugarcane production in Queensland. While other studies have reviewed the cost of energy to the Australian agricultural sectors (Heath, Darragh, and Laurie 2018, Davis 2018a), this analysis focuses on sugarcane irrigators in a unique setting of the highly regulated regional Queensland electricity network and monopoly retail market.

2.5. Method

This study's multiple-case study design deliberately tests the conditions under which the same findings might be replicated in other settings of the study regions. The case study sites are located in three of the largest sugarcane-growing regions in Australia. The most typical irrigation method in each region was selected, using data from a previous review of energy costs by Welsh and Powell (2017). The three regions, when aggregated, make up approximately 81% of energy use for irrigation in the Australian sugar industry.

The study method's framework using a step process (from a-e) is shown in Figure 3. HOMER decision support software is used to design optimised microgrid systems for each site (Hybrid Optimisation of Multiple Energy Resources 2018).

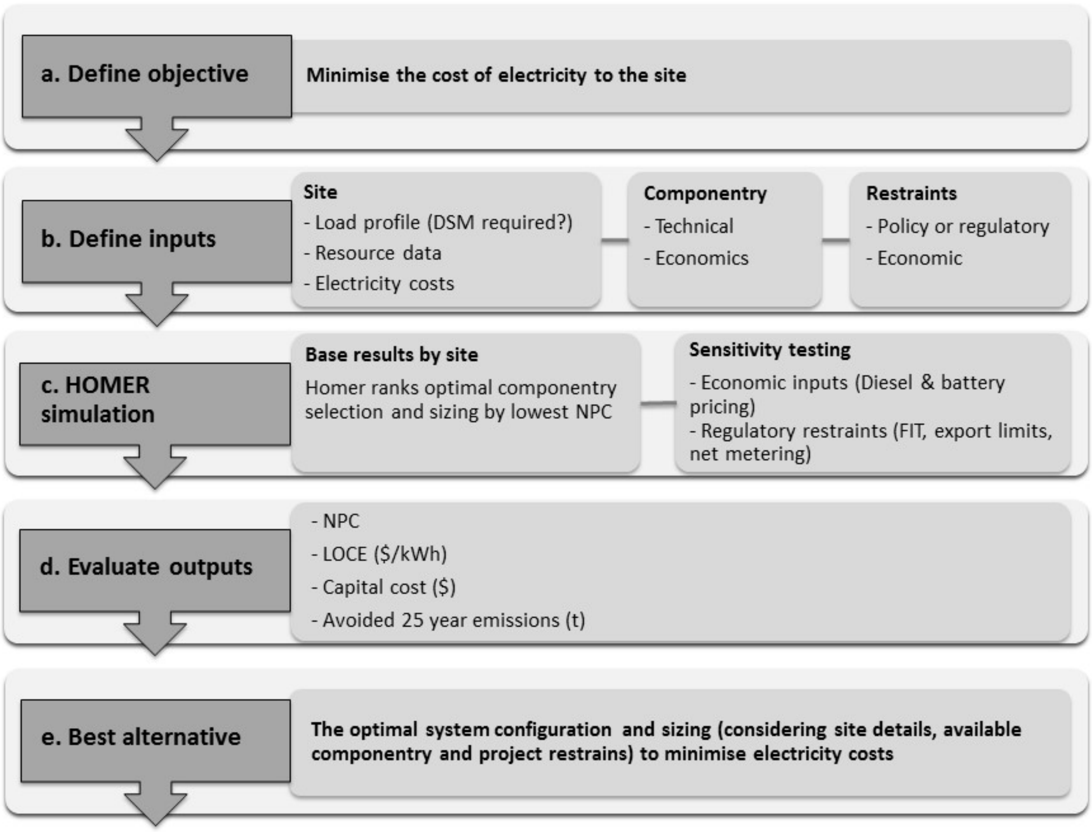

Figure 3: Methodology framework

The steps are summarised as follows:

a. ***Define objective:*** to find optimal combination of components to provide least cost energy and lower emissions,

b. *Define inputs:* At each site, a detailed assessment was conducted of its load, site layout, resources, electricity costs, componentry and constraints. A seasonal energy load pattern was developed prior to considering the need for load shifting into sunlight hours. A demand-side management (DSM) approach was applied where the consumer shifts their load to reduce energy costs, i.e. into times of solar production, or to avoid peak tariffs at two sites to utilise behind-the-meter generation. At two of the three sites (see Figure 4), the energy-use time-period was altered from existing off-peak periods, while still retaining necessary irrigation parameters that met the crops' water demand. For the remaining site, existing consumption patterns were retained due to agronomic and irrigation management preferences. Quantities of energy consumed were not changed under the modelled scenarios. The rules and regulations of the distribution network service provider (DNSP) underpin this study. Appendix 2 outlines in detail the DNSP policies for connecting embedded generation (including export limits), net metering, and FiTs (both FiT eligibility and time-of-use (TOU) FiTs).

c. *HOMER Simulation:* once data was collected, and technical details were verified by engineers and transmission service providers, the information was entered into the HOMER model. HOMER is a popular hybrid renewable energy systems optimisation and economic model, used by researchers around the world. A review of HOMER by Bahramara, Moghaddam, and Haghifam (2016) found over one hundred articles published in scientific literature in a range of locations. In addition, Amutha and Rajini (2016) compared options for renewable energy optimisation and sensitivity analysis with conventional methods and found HOMER to be simple and cost effective. Thus, based on the literature reviews, HOMER software is taken for the purpose of this study to carry out feasibility assessments.

d. ***Evaluate outputs:*** the HOMER model combines engineering design with economic assessment, by comparing a wide range of equipment, each with different initial and ongoing cost structures and constraints to determine the optimal system design, ranked on lowest Net Present Cost (NPC) of providing a defined level of electricity supply. The NPC is the present value of all the costs of installing and operating the components over the project lifetime, minus the present value of all the revenues that it earns over the same period.

Sensitivity analysis was used to investigate potential changes and their impacts on conclusions drawn from the modelling results. In this study, sensitivity analyses were conducted on FiT pricing, available export limits, net metering, and reduced battery storage costs.

Avoided emissions are calculated using the total electricity offset by renewable energy sources over a 25-year life of a project. Emissions from diesel fuel combustion are also considered. The emissions factor of 2.697 kg CO_2e per litre of diesel was used. This factor underpins the Intergovernmental Panel on Climate Change reports (United States Environmental Protection Agency 2016), and includes all nitrous oxide and methane emissions. Electricity generation and environmental impacts vary depending on jurisdiction and types of fuel sources used for electricity generation. For example, the emissions factor in Tasmania, with abundant hydro and wind power is 0.14 kg CO_2e/kWh as opposed to Victoria with traditional coal-fired generation showing 1.08 kg CO_2e/kWh. Emission factors are sourced from the Australian Government's Department of the Environment and Energy (2017). For Queensland electricity, its scope two emission factor is 0.79 kg CO_2e per kilowatt hour (kWh).

e. ***Best alternative:*** the NPCs were then ranked from lowest to highest with the highest ranked alternative showing the lowest NPC. Other factors influencing system design included investigation of all interacting variables within the system, including physical variables (plant and soil type, irrigation system specifications, renewable plant and battery sizing, site attributes), meteorological variables (solar radiation, air temperature, relative humidity, wind speed, precipitation) and managerial variables (irrigation scheduling) (Maurya et al. 2015). HOMER simulates the operation of a simplified microgrid in hourly intervals for 25 years, and derives results for the produced energy, the cost, the fuel consumption and the emitted pollutants.

Site characteristics

The case study sites are all broadacre irrigated sugarcane farms located on the east coast of Queensland, Australia. The nearest towns to sites A, B and C are Ayr, Marian and Bundaberg respectively, situated across a 930 km north-to-south transect (see Figure 4).

Figure 4: A map of the case study sites: Site A (Ayr), Site B (Marian) and Site C (Bundaberg)

Each farm has its own unique irrigation application: furrow irrigation (Site A), centre pivot (Site B), and Big Gun[1] (Site C). The water source varies at each site: shallow well pumps (Site A), river (Site B), and well (Site C). Some features of the case study sites are given in Table 1, including energy use for irrigation by each case study region as a percentage of energy use across the entire sugar industry. The Burdekin catchment and

[1] Big Gun® irrigators refer to large-volume, high-pressure sprinklers (also known as travelling irrigators or water winches).

location of Site A has a large proportion of the cane industry's irrigation, with industry sources estimating around 12,000 operation pumps, most of which are grid-connected (Jaramillo 2018).

Table 1: Case study site details

Particulars	Details		
Site reference	A	B	C
Nearest township	Ayr	Marian	Bundaberg
Catchment	Burdekin	Pioneer	Burnett
Latitude	19°35'50"	21°08'41"	24°47'40"
Longitude	147°22'47"	148°57'12"	152°20'36"
Elevation	11 m	38 m	3 m
Irrigation application	furrow	pivot	Big Gun
Annual mean rainfall[1]	1058 mm	1655 mm	1048 mm
Industry proportion of energy use for irrigation[2]	64%	8%	9%

1. Australian Bureau of Meteorology (2017)
2. Welsh and Powell (2017)

Sugarcane is the primary source of income for the farms in this study. However, energy demand varies depending on seasonal conditions and access to irrigation water. The annual irrigation water use and energy demand is assumed to be static.

2.5.1. Resource assessment

The analysis considers solar and wind resources for each case study farm. Solar exposure and wind resource data were both downloaded from the NASA (2018) Surface Meteorology and Solar Energy website for each case study location. Solar irradiance varies considerably throughout the calendar year at each location. However, trends remain consistent with day length and seasonality. All sites can provide consistent solar production throughout the year, although cloudiness affects the clearness index during the wet season (Dec–Mar) and improves considerably during the drier winter months.

Peak months for energy production are November, December and January when day lengths increase, which also aligns to crop water demand.

The annual average wind speed for the sites varies from 4.6 m/s to 5.3 m/s at a height of 10 m. Significant variance exists in wind resources between locations due to existing vegetation, topography and proximity to buildings.

2.5.2. Load assessment and electricity pricing

An electric load is the power consumption of one or more components, for a specific time frame, usually measured by a meter. The load profile considers the variation of usage over time. The case study farms have individual electricity connection points with different seasonal load profiles and random variability. Because current irrigation tariffs are split into peak, shoulder and off-peak periods, DSM is a key driver of energy demand and load profiles. The load-shifting DSM strategy is featured at sites A and B. Site C irrigation involves shifting the Big Gun irrigators every 23 hours. The hourly load pattern is developed from energy consumption data derived from irrigation practice and historical data. It evaluates the duration and use of the pumps at different hours of the day. The next section examines the characteristics of each connection in more detail.

Site A: Shallow well pumps

Two grid-connected pumps, located near each other, are used simultaneously to supply furrow-irrigated fields growing winter and summer crops. The pump motors are 18 kW and 15 kW, respectively. High crop evapotranspiration in summer results in more water being applied to the summer crops, particularly early in the season prior to the onset of the monsoon. The period from October to March has the highest electricity use. Month-by-month demand is heavily influenced by crop evapotranspiration. During April to September, pumping load is reduced as crop demand for water is less due to harvest and cooler season growing conditions.

Site B: Pivot pumphouse

Three grid-connected pumps make up the load for this connection. Two pump motors (75 kW and 55 kW) drive centre pivots, and a third (45 kW) is a transfer pump used for irrigating smaller areas of furrow irrigation. Site B has a higher annual rainfall that reduces reliance on irrigation water for crop production. Consequently, the pumps can be idle for long periods but then operate at a consistent level for 24 hours a day, often for several days. A six-month load profile of half-hourly interval data was sourced from the DNSP and analysed. A synthetic load was designed, using pumping information from the landholder and load variability from the interval data set. The usage showed a large day-to-day variance in the electricity load, with the components off (0 kW) or all pumps on (max. 172 kW). However, as the pumps are off for weeks at a time and on (in various combinations) for days at a time, the hour-to-hour variance is high. October, November and December have the highest monthly energy usage. The random day-to-day and timestep variability of the pivot pump house is summarised in Table 2.

Site C: Bore pump

A 55 kW capacity electric motor is the only load for this connection. The pump supplies water to irrigated fields via a Big Gun application. The pump is off for long periods and then operational at a consistent level until the gun is shifted. For this study, a synthetic load has been created using historical retailer data provided by the landholder. A synthetic load is not observed data, but a load created manually to reflect in greater detail the energy use of the pump. The assumed 50 kW operating load has been calculated at 90% of the 55 kW electric motor capacity. Consistent with sites A and B, spring season has the highest energy demand, with the pump operating for around 19 hours per day. Consumption and day-to-day variability details entered into HOMER decision support are summarised in Table 2.

Table 2: Case study site description and demand profile

Site	Description	Capacity (kW)	Peak (kW)	Average kWh/day	Day-to-day variability (%)
A	Shallow well pumps	33	33	168	115
B	Pivot pump house	175	173	258	157
C	Bore pump	55	55	231	142

The monthly energy use at each site is skewed towards late-spring and summer seasons when crop water use is highest, with minimal energy use during winter after crop harvest.

2.5.3. Component assessment

The components within a microgrid system either generate, store, control or use energy. Within this analysis, the generating resources considered were: solar PV, wind turbines, diesel generators, and the existing grid and tariff structure. These technologies were selected as they were commercially available and would allow adoption and replication across sugar growing regions. Lithium-ion batteries were considered for storage, and inverters for the control of the energy. Figure 5 is the schematic system configuration for Site B, pivot pump house. All sites considered identical component costings, each with their own unique load profiles.

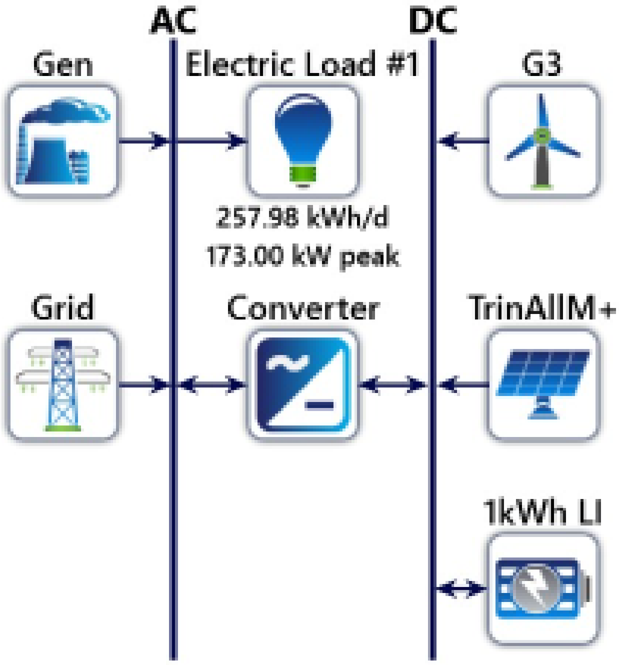

Figure 5: HOMER example schematic for Site B – Pivot pump house

Component pricing considered all applicable costs, using an 'installed and commissioned' price. All pricing and monetary terms were in AUD. A summary of components used in the analysis is shown in Table 3.

Table 3: details of components considered for microgrid

Component	Cost	Operation and maintenance ($/yr)	Replacement year
Solar PV install	$1400/kW	$10/kW	25 years
3 kW wind turbine	$4000/kW	$60/kW	20 years
Diesel genset	$240/kW	$0.03/h per kW	15000 hrs
Lithium-ion battery	$800/kWh	$10/kWh	15 years
System converter	$300/kW	$0	15 years

The solar PV system capital costs were $1400/kW ground mounted. These prices were net of the government's renewable energy small technology certificates (STCs). The Solar PV pricing corresponded to a brand – Trina Allmax M Plus. This 290-watt monocrystalline module has a 25-year lifetime, so required no replacement within the 25-year analysis (Trinasolar 2018). To account for the effects of temperature, dust and time, a derating factor of 88% was used. The panels were modelled on a fixed tilt facing north, with a slope of 26.3°. Tracking systems were not considered. Panel specifications from the chosen brand relating to temperature effects on power and nominal operating cell temperature were automatically uploaded into the model. Although life cycle emissions of all PV modules have decreased, the high energy efficiency of mono-crystalline silicon modules comes at a cost of higher life cycle emissions (Srinivasan and Kottam 2018). Their production and disposal costs are not considered in the HOMER model.

Although 3 kW wind turbines were included in the analysis, providers warned of the practicalities of increased maintenance costs in a cyclone-prone area - which applies to all case study locations. Due to the localised nature of wind flow and impacts of nearby buildings, land formation and vegetation in the area, turbine providers recommended at least 12 months of wind monitoring before installation.

A diesel generator with a capital cost of $240/kW with annual operating and maintenance costs were $0.03/h per kW genset capacity. The diesel price was modelled at $1 per litre (net of excise, goods and services taxes), derived from the current 12-week average regional Queensland diesel price (Australian Institute of Petroleum 2018).

The storage option in the modelling was an autosize generic lithium-ion battery, with a capital cost of $800 for 1 kWh, a lifetime of 15 years, and a replacement cost of $500/kWh. The annual operating and maintenance costs were $10/kW/yr.

The capital costs for a generic system converter were $300/kW, a lifetime of 15 years, and a replacement cost of $200, with no annual operating and maintenance costs. The inverter and efficiencies were modelled at 95%.

2.5.4. Indexation of energy inputs

Each site was connected to the grid, so the grid scenario was the base case in HOMER. The grid was modelled using the existing regulatory environment and policy frameworks for the DNSP and retailer. The tariffs outlined in Section 2.5.7 were used for each site. Queensland grid price indexation (2.8%) and Queensland regional diesel prices for genset fuel inputs (2.79%) were factored into the 25-year investment. Indexation calculations are explained in Appendix 4: Indexation of energy pricing.

2.5.5. Sensitivity of inputs

A novel aspect of this analysis is that, unlike the situation in other states of Australia, the government of Queensland is both retailer and DNSP in the regional Queensland electricity market – a monopoly provider. We used sensitivity testing to measure the effects of connection policies, such as scale of embedded generation proposed, FiTs, and export limits available for renewable generation sources. The grid-connection policy scenarios were chosen from those offered to other irrigators in New South Wales. These issues are out of consumers' control, and it is essential to offer details about the behaviour of the system and the variations in the parameters of the system. A list of scenarios in the sensitivity analysis is shown in Table 4.

Table 4: Sensitivity parameters

Site	Feed-in tariff (10.2c/kWh)	Net metering	Export limit (kW)	Battery pricing ($/kWh)	Restrict PV sizing
A	+/- 30%	Yes	No (eligible)	-20%, -40%, -60%	No optimal
B	+/- 30%	Yes	Yes (10-20-30-40-50)	As above	Yes, 39 kW
C	+/- 30%	Yes	Yes (10-20-30-40-50)	As above	Yes, 39 kW

Sizing of PV equipment was also tested at sites B and C, where a 39 kW PV array was matched to comply with FiT eligibility and DNSP connection rules. Emission scenarios and project returns were tabled and compared with HOMER optimisation results.

2.5.6. Economic modelling and optimisation of system components

The HOMER model optimises system componentry to minimise and rank the lowest Net Present Cost (NPC) and Levelised Cost of Energy (LCOE) using simulation. LCOE is the net present value of the unit cost of electricity over the lifetime of a generating asset ($/kWh). It is used as a reference to compare, through a life cycle period, different technologies and systems that produce energy. Equations used to calculate LCOE and annualised component costs are shown in Appendix 1: Levelised cost of energy. The LCOE is a key metric to isolate the change in BAU energy cost from unshifted loads to daytime-shifted loads with the addition of renewable and genset componentry. DNSP policy for connecting embedded generation (see Appendix 2: Network considerations) was a key consideration within the modelling. For all sites, higher economic returns were generated when the system size was restricted to a 30 kW inverter and 39 kW PV to remain eligible for a FiT. All other components were subject to optimisation by HOMER at each site.

2.5.7. Retailer prices and tariffs

As the case study farms are in regional Queensland, the landholder has only one available electricity retailer – Ergon Energy – but there are several tariff options for each connection to best fit energy consumption. With Ergon Energy reforming tariffs post-2020, making assumptions over the 25-year investment is challenging (Ergon Energy 2016). Because speculation on future tariff structures and charges is outside the scope of this study, modelling has considered currently available tariffs. Any future increase in electricity prices would further improve the economic feasibility of on-farm embedded generation reported in this analysis.

A summary of the tariffs used within the analysis is provided in Table 5. Ergon's TOU Tariff 62 is the business-as-usual (BAU) tariff for all case study sites. Due to the load shifting into the daylight, Site A swapped to Tariff 20, which has a flat rate with the microgrid solution. All sites meet the eligibility criteria set out in Appendix 2 on 'connecting embedded generation'.

Table 5: Tariff assumptions – all sites

Tariff Name	Supply charge	Peak tariff	Off-peak tariff	Export limit	FiT (flat)
Tariff 62	$286	$0.410	$0.165	30 kW	$0.1020
Tariff 20	$449	$0.271	$0.271	30 kW	$0.1020

2.6. Results and discussion

This section shows the results of the analysis. The optimisation results are presented, followed by the outcomes of the sensitivity analysis and environmental outcomes.

2.6.1. Optimisation results

The optimal componentry combinations for each site, based on lowest NPC, are summarised. The economic and environmental results of the optimisation across the three case study sites (Table 6) indicate varied economic feasibility of installing a renewable energy-based microgrid to lower energy costs.

Analysis of Site A found the optimal microgrid componentry for the 33 kW peak load was to stay connected to the grid, and install a 39 kW PV array and a 30 kW inverter. This is the maximum size array allowed in the DNSP connection rules to remain eligible for 30 kW export and a FiT. Ability to export excess energy resulted in no unused or wasted generation on this site. With 100% of the load being shifted from nights (off-peak tariffs) to daylight (peak tariffs), a lower daytime tariff was needed for cloudy days when the solar could not meet the energy demands. The tariff for the site was changed to T 20 (see Table 5). Due to the seasonality of the energy demand, and with the load shifting neatly into daylight hours, batteries were required only sporadically to back up the solar energy in periods of cloudiness. The minimal use of batteries resulted in a relatively high LCOE from the batteries, and they were not included in the lowest cost microgrid. A generator does not feature in the optimal componentry because the grid (on the flat tariff) was a more cost-effective substitute than a generator.

The NPC of the microgrid for Site A was $177,000 (see Table 6), or 26% lower than BAU. The annual energy consumption of the site is approximately 62 MWh. The LCOE of $0.128/kWh was 53% less than for the BAU scenario. The results were primarily due to the high proportion (49%) of the load offset by PV, and also by the ability to generate revenue from the rest of the solar energy system through the FiT. A higher utilisation of PV was achieved compared with other sites, as the PV was sized appropriately to the load. The change in abatement over the period amounted to 1303 t/CO_2e.

Site B, with three irrigation pumps, had the largest and most variable seasonal energy load of the three sites. To offset the peak load of 173 kW, up to 200 kW of renewable generation was required. However, when the DNSP FiT eligibility was considered (see Appendix 2), the optimal microgrid was much smaller. The energy use of a large microgrid (without export or a FiT) by a sporadic, seasonal load does not justify the capital expenditure. To remain eligible for a FiT, the microgrid solution was kept to a 39 kW PV, 30 kW inverter. To use the daytime energy generation of the PV, the transfer pump component of the load was shifted to daylight hours. The microgrid offset 9% of the 94 MWh annual energy consumption. A generator did not feature in the optimal componentry because most of the load occurs during off-peak tariff. The grid (during off-peak) was a more cost-effective energy substitute than a generator.

The NPC of $351,000 was 12% lower than BAU, and the LCOE at $0.16 c/kWh was 46% lower than BAU. The environmental benefits of substituting 9% of the irrigation load to renewable energy resulted in an emissions abatement of 1314 t/CO_2e over the 25-year analysis period (see Table 6).

Analysis of Site C also found that when DNSP FiT eligibility was considered, a 39 kW PV array in combination with the grid was optimal. The energy-use profile of the site consisted of intermittent periods of high demand when the bore pump was in operation up to 23 hours per day for several days, followed by periods of no use.

The NPC of installing the 39 kW solar array at Site C was $306,000, which is 20% lower than BAU (see Table 6). The addition of PV to the irrigation energy source absorbed only 15% of the current 84 MW annual demand from the grid, resulting in an abatement of 1245 t CO_2e over the 25 years. Each site had the same optimal solution consisting of 30 kW PV and a 30 kW inverter at a capital cost of $63,600. Gensets, battery storage and wind turbines featured in lower ranked alternatives, alongside PV for all sites.

Table 6: Economic and environmental results for optimal energy solutions (energy componentry, % of energy requirements met by PV, energy exports, Economic and environmental results for optimal energy solutions (Capital costs, LCOE, energy use, NPC, emissions abatement))

Site	Load profile	25-year usage (MWh)	PV share of load	Energy exported (MWh) (25 years)	LCOE $/kW	BAU LCOE $/kW	NPC	BAU (Grid only) NPC	Change in emissions from base (25 years) t/CO_2e
A	Shifted	1,539	49%	892	$0.128	$0.273	$177,000	$238,000	1,303
B	Partial shift	2,354	9%	1,503	$0.16	$0.299	$351,000	$400,000	1,314
C	Not shifted	2,108	15%	1,270	$0.159	$0.318	$306,000	$381,000	1,245

The reduced cost of energy under these investment scenarios will lower production costs, improve enterprise gross margins, and encourage more frequent irrigation practices which may potentially lead to higher yields. Within the analysis yields were assumed to remain the same due to uncertainty around potential change. Practical considerations such as array installations, loss of productive land, ease of farming operations (overhead irrigation infrastructure and machinery routes) will also vary between sites. Cane farms can often exist in flood zones, which may require additional engineering to ensure continued energy generation and installation integrity. Industry sustainability credentials will also be enhanced under this investment scenario. Previous studies by Renouf and Wegener (2007) found energy for irrigation contributes 22% of emissions of raw sugar cane across irrigated sites surveyed across known irrigation areas.

2.6.2. Sensitivity results

Sensitivity analysis helps assess the effects of variability of key inputs on the robustness of the results (Sinden and Thampapillai 1995). For this reason, further investigation was conducted, where there was uncertainty about baseline assumptions, to enable consideration of other feasible component combinations, or policy and connection variables.

For Site A, sensitivity analysis was conducted for export limits, the addition of net metering, FiT pricing and battery prices.

Microgrid installation was most profitable for sites eligible to export energy into the grid and to receive FiT income for the renewable energy in excess of the sites' requirements. Sensitivity testing (see Figure 6) found export limits had the largest impact on the LCOE. Where export limits were reduced from 30 kW to 0, LCOE increased by 167%. Also, an increase in export limits to 50 kW resulted in a 60% decrease in LCOE from the baseline. In contrast, the FiT elasticity for Site A was found to be relatively inelastic, with a +/-30% change in FiT resulting in only a +/-6% in the LCOE. These results indicate that the DNSP renewable energy connection rule (see Appendix 2: Network considerations) that restricts systems to a rated size of 30 kW to remain eligible for export is a key factor of the analysis. To be an economically feasible investment, microgrid systems designed to supply power for seasonal irrigation, such as the case study sites, need to be able to export excess energy and be paid for it.

Ergon’s connection policy allows sites to export 30 kW without special application. However, Ergon does not allow net metering, where the customer pays for the net amount of total energy purchased minus total energy exported (see Appendix 2: Network considerations). Analysis indicated that net metering was the second-most sensitive parameter tested for the Site A model. Allowing net metering resulted in a 30% lower LCOE.

Results were relatively insensitive to price reductions in batteries (see Figure 6). Reducing the battery prices up to 60% relative to current market cost did not cause the model to include batteries in the economically optimal strategy. These results indicate that batteries are not feasible for sporadic seasonal irrigation loads.

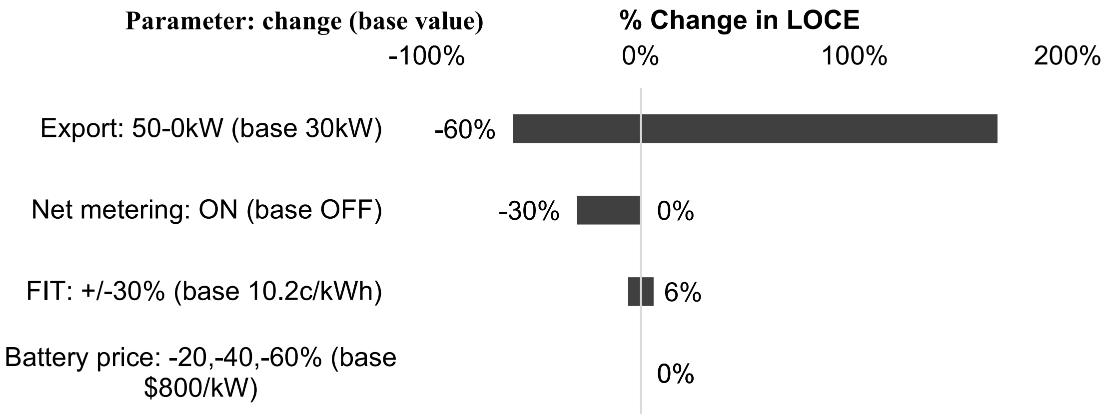

Figure 6: Sensitivity analysis of the key input parameters for Site A LCOE

Optimal microgrid componentry for sites B and C was restricted to remain eligible for export and a FiT. Sensitivity analysis for sites B and C focused on export limits and FiT modelling the microgrid appropriately sized for each site (rather than restricted to 39 kW PV as per the optimisation results) to better understand the effects that the DNSP policies have on the economic viability of renewables. In this analysis, the PV array sizes were 99 kW (Site B) and 70 kW (Site C), which remain eligible for upfront STCs while also servicing a large proportion of the irrigation pump loads. The change in avoided emissions was also calculated under each sensitivity scenario. Figure 7 and 6 show a graphical representation of Site B and C sensitivity analysis.

Because FiT incentives are highly regulated, a plus/minus 30% price differential from the baseline $0.102/kWh was examined. The plus 30% FiT is in line with those received in New South Wales and Victoria, two nearby states in eastern Australia. Sensitivity analysis found the model to be less sensitive to the FiT when less energy was exported. As the export limit increased, the model sensitivity to the FiT increased. With a zero export, the model is perfectly inelastic to FiT pricing. At a 10 kW export limit the +/- 30% change in FiT resulted in a corresponding +/- 3% and +/- 4% change in LCOE for sites B and C, respectively. With a 50 kW export limit, the +/- change in FiT resulted in +/- 19% and +/- 25% change in LCOE for sites B and C, respectively.

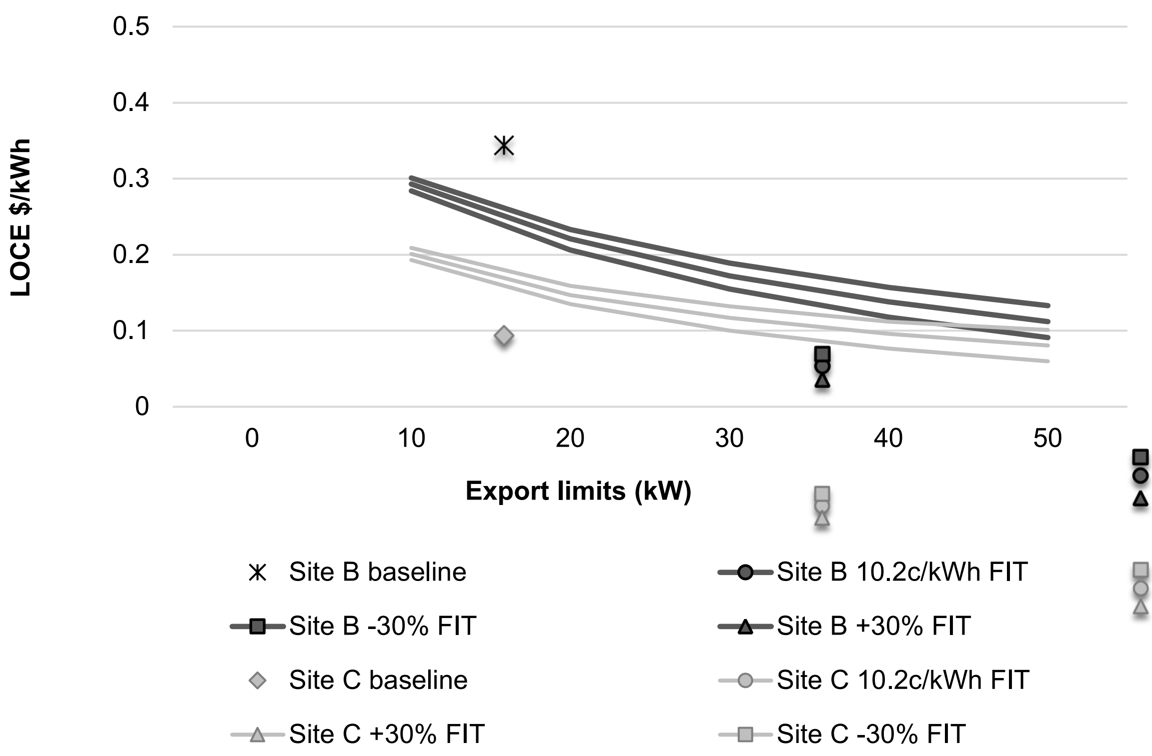

Figure 7: Site B and Site C sensitivity analysis, LCOE

A range of export limit scenarios (0-50 kW) for sites B and C were tested (Figure 7). The sensitivity analysis found LCOE improved substantially from zero export (current policy for microgrids rated over 30 kW) to a minimal export level of 10 kW with a FiT, resulting in a 33% and 36% gain for sites B and C, respectively. As the export limit increased, the marginal gain diminished, the difference in LCOE between 40 and 50 kW export limits was 19% and 16% for sites B and C, respectively. These results are in line with sensitivity testing of Site A and indicate the importance of being able to export and be paid for excess energy. Figure 8 also indicates the model increased the size of the optimal PV array as export limits increased. At Site B, for example, a 180 kW PV array was optimal under a 50 kW export limit scenario, an increase of 80% from zero export. These results indicate that the DNSP policy for FiT eligibility is restricting the economic returns and attractiveness of renewable energy for medium-sized loads (>30 kW, <100 kW).

Changes in avoided emissions (Figure 8) were proportionate to increases in export limits. Increases in abatement of 100% and 140% occurred from zero to 10 kW export for sites B and C. Moving from 0 kW to 50 kW exported, emissions abatement for Site B changed sixfold from 669 t CO_2e to 4021 t CO_2e.

Consistent with findings from Borchers, Xiarchos, and Beckman (2014), the sensitivity analysis across all sites highlights the importance of the DNSP policies for seasonal agricultural loads. For a site to remain eligible for export and a FiT, microgrids need to be restricted (as per the optimisation results). The analysis indicates that even marginal increases in these limits could promote larger renewable energy installations, lowering the cost of energy and increasing emission abatement.

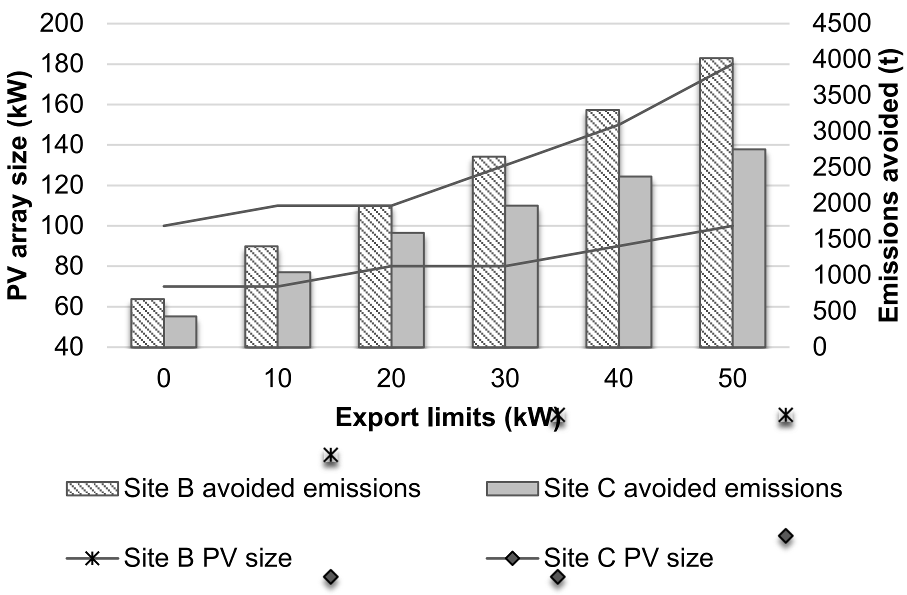

Figure 8: Site B and Site C sensitivity analysis; export limits and avoided emissions

2.7. Emissions and cost of abatement

The STC rebates available under the current Renewable Energy Target (for systems under 100 kW) are determined by an online calculator that considers the generation type, deeming period, and location of the proposed installation (Clean Energy Regulator 2018c). These rebates are paid upfront, and derived from the aforementioned equation where one certificate is equivalent to 1 MWh of generation (Clean Energy Regulator 2018b). The value of each certificate is determined by the market price; $37 per certificate has been used in this analysis (Green Energy Markets 2018). The cost of abatement per CO_2e paid by the Australian Government from each of the three sites is shown in Table 7. This cost is calculated by the STC paid divided by the 25-year emissions offset in baseline and sensitivity tests (net metering, 10 and 30 kW export) for the project period.

Table 7: Emissions abatement cost for all baseline scenarios, net metering (Site A) and two sensitivity tests: FiT and 10, 30 kW export limits (both Sites B and C).

Site	**PV Size**	**STC value**	**Abatement cost $/CO₂e**				
			Baseline	Net metering	0 kW	10 kW	30 kW
A	39 kW	$26,600	$20	$17	N/A	N/A	$20
B	99 kW	$66,452	$99	N/A	$99	$47	$25
C	70 kW	$46,509	$109	N/A	$109	$45	$18

Sensitivity analysis revealed that connection policy is the primary driver of the cost of emissions on PV installations for the case study sites. Site A had an abatement cost of $20/t CO_2e under the baseline scenario, and $17/t CO_2e when net metering was exercised. The larger pump sites with higher solar PV array sizes showed, having access to small quantities of export (10 and 30 kW), the cost of abatement was reduced up to six-fold from baseline calculations – a change of $74/t CO_2e (Site B) and $91/t CO_2e (Site C). The main difference is due to higher quantities of exported energy offsetting traditional grid-supplied energy. The average cost of abatement in the Australian Government's ERF auction was just below $14/t CO_2e (Clean Energy Regulator 2018a). An off-grid irrigation pumping analysis by Powell et al. (2019) found the annualised cost of abatement for an off-grid 100 kW irrigation system used year-round was $31/t CO_2e.

Therefore, sites approved for export, even at low levels on small, grid-connected industrial systems, can obtain low-cost emissions abatement comparable to values in the government's reverse auction ERF. As noted, the significant environmental consequences from solar PV system production and disposal was not accounted for in these calculations. Given the prospects to scale up these technologies across the sugar industry these public and private costs and benefits of solar PV, power electronics, gensets and other system components could be analysed separately. In addition, abatement calculations offsetting grid-powered electricity are not readily transferable to other states due to change in emissions factors of each jurisdiction.

2.8. Conclusion

This farm energy study has shown the cost of energy can be reduced, using microgrids in small-scale, seasonal irrigation (< 100 MW per annum) in the highly regulated electricity market in regional Queensland, Australia. Energy cost reductions of up to 26% and avoided emissions of 1303 t/CO_2e over a 25-year investment period indicate the potential industry wide gains if the technology were to be widely adopted. The optimal component selected by the HOMER software for integration into the grid-connected sugarcane irrigation scenarios was solar PV. With solar PV, the cost of energy for all sites was reduced. To achieve maximum cost reductions, two sites needed to undersize the microgrid to remain within DNSP eligibility criteria for export and FiT. When larger systems (sites B and C) exceeded embedded generation limits of a 30 kW inverter, and were ineligible for export, the microgrid was not economically feasible, as only minor reductions in the cost per kWh occurred compared to BAU scenarios. Sites with a sporadic seasonal load could not use enough renewable energy to warrant the microgrid installation, unless some unused energy could be exported, and a FiT received.

Sensitivity testing of microgrids exceeding the 30 kW export and FiT eligibility found embedded generation connection rules were the largest driver of economic and environmental rewards. A small export limit at current FiT rates showed a marked improvement in economic feasibility, with improvements in IRR and payback period, with similar gains in avoided emissions and cost of abatement. The model was more sensitive to changes in export limits compared to changes in the FiT.

Batteries did not feature as an optimal component, even when battery storage and replacement values were discounted by 60%, indicating that seasonal load profiles under-use a battery investment. Therefore, batteries are inefficient and can be avoided in an irrigation microgrid. Sensitivity analysis also showed an additional abatement and cost saving if net metering policies were implemented.

The RET's ability to encourage small-scale renewable investment for irrigators with seasonal energy demand is contingent on state-based distribution network service provider policies. At present, the policy discourages medium-scale renewables (30–99 kW) with the absence of a FiT for those systems. This study found lowest cost abatement from STCs is achieved when medium-sized grid-connected pumping systems can maximise exports with a FiT. Avenues for future research include flow-on effects of increased irrigation from the reduced cost of energy, sustainability calculations per tonne of cane produced under the investment scenarios and the inclusion of Life Cycle Assessment costs relating to the manufacture and disposal of solar PV systems at the end of life.

2.9. Appendices

Appendix 1: Levelised cost of energy

The levelised cost of energy (LCOE) equation is calculated by HOMER optimisation software as follows:

$$\frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

I_t = Investment expenditures in year t (including financing)
M_t = Operations and maintenance expenditures in year t
F_t = Fuel expenditures in year t
E_t = Electricity generation in year t
r = Discount rate
n = Life of system

Appendix 2: Network considerations

The enduring challenge of reliably and cheaply supplying electricity across Australia's vast land mass has been faced by governments since the rollout of the national electricity grid in the 1960s. There are four key roles in Australian electricity supply: generation, transmission, network distribution, and retail. Australian network operators, or Distribution Network Service Providers (DNSPs) in regional areas are, for the most part, government-owned and hence are highly regulated assets. These organisations are regulated to achieve minimum rates of return. For most small businesses in broad terms, about half of the current electricity bill is made up of network maintenance and 'green' costs – those costs for government programs to save energy and to support the development of renewable energy (Australian Energy Regulator 2018). DNSPs are required to maintain energy supply to a connection point to a minimum set of standards consistent with rules set by the Australian Energy Regulator.

In some states and territories in Australia, the government regulates retail energy prices so that retailers must charge the price set by government on their contracts. Queensland (except the south-east corner) has a highly regulated distribution and retail electricity market. Unlike other Australian states, the regional energy retailer is a state-government-owned monopoly organisation encompassing both the DNSP and the energy retailer – Ergon Energy. In deregulated retail markets, such as south-east Queensland and New South Wales, consumers are free to move between energy companies offering the least-cost alternative. Within Ergon, the customer has pricing options separated into several tariffs designed to offer choice (as a substitute for choice between energy retailers). These tariffs are part of demand-side management (DSM) aimed to encourage consumer behaviour. Typically, the goal of DSM is to increase energy use during off-peak times, and reduce energy use during peak times, thereby reducing peak demand and reducing the need for transmission infrastructure upgrades that would impose added financial strain on the consumer.

Feed-in Tariffs and eligibility

Over the past few decades, an increasing number of governments have started to stimulate the development of renewable energy sources. A feed-in tariff (FiT) is a rate paid for electricity fed back into the electricity grid from a designated renewable generation source. A high FiT is a widely accepted policy lever or static subsidy that can gradually decrease over time to promote behind-the-meter innovation (Parliament of Australia 2018, García-Álvarez, Cabeza-García, and Soares 2018, Carley et al. 2017). Connection conditions, such as FiT rate, available metering, and inverter capacity, can have a large impact on the economic feasibility of renewable energy and storage solutions (Martin and Rice 2018). FiT eligibility and export limits vary in each state of Australia.

According to the Queensland Government (2018), to be eligible for a FiT in regional Queensland, you must satisfy the following criteria:

- Operate a renewable system (i.e. solar) with a maximum inverter capacity not exceeding 30 kilowatts (kW) (approximately 39 kW of photovoltaic)
- Be a small business customer (consume less than 100 megawatts (MW) per annum)
- Be a retail customer of Ergon Energy and be connected to the grid
- Have a network connection agreement with an electricity distributor approving the system
- Have only one power system receiving the FiT per National Meter Identifier (NMI).

Time-of-use FiTs

Time-of-use FiTs are a new demand-management tool for network providers whereby rates can differ depending on time of day or night. In the 2017-18 financial year, domestic customers had a choice between a flat-rate tariff or a time-varying FiT. The rates for each option are shown below.

- Flat rate – 10.2c per kWh
- TOU rates – 13.606c (3pm-7pm) and 7.358c per kWh all other times.

In other states of Australia, more stringent and rewarding TOU FiTs are being implemented to encourage a shift in demand, to orientate their PV panels to the west, rather than to the north to change renewable supply, or to encourage battery storage. The Victorian state government has recently incorporated a 2.5c per kWh cost of carbon into that state's solar FiT. Considering these developments, and noting an ACIL Allen consulting (2017) study of the changing nature of the grid and demand management, it is likely that TOU FiT incentives will become more common in the future.

Net metering

Net metering is where a single meter records the net electrical flow between the customer and the grid. With net metering, both consumption from the distribution network and generation is measured, with only excess energy recorded in the customer's premises export register and sent to the grid (Essential Energy 2018). In regional Queensland, the DNSP offers gross 'smart' metering for new connections. Alterations to aging metering configurations are often required when embedded generation or energy storage connection applications for works are undertaken. Smart metering does not necessarily mean net metering. The features of smart meters for all customers are described below.

- Smart meters monitor average half-hourly power consumption and allow determination of the load profile (Power vs Time) of individual homes and businesses. This facilitates full cost-reflective pricing and peak-demand management.
- Gross smart metering (separate bi-directional meter for PV output and consumer load) allows full performance assessment of PV system output, normally via the inverter energy meter because most inverters log power/energy output. Measurement of energy use (kWh) and peak power demand (MVA) within residences or businesses allows full assessment of energy efficiency measures.

However, gross smart metering with import and export registers does not allow full measurement of demand with residences or businesses, and so cannot easily measure energy efficiency savings from solar. Gross smart meters measure only the exported part of PV energy generation, and do not show the part supplied directly to home or business appliances (Berril 2016). Ratnam, Weller, and Kellett (2015) assessed the benefits of net metering to residential customers and found most customers made savings under net metering. Further, Oliva H, MacGill, and Passey (2016) found net metering policies with low FiT rates provided moderate revenue to residential customers and adverse revenue impacts on DNSPs.

Connecting embedded generation

Connecting to the Queensland electricity network requires varying levels of assessment and technical applications depending on the size of the proposed generation. DNSPs such as Ergon have an obligation to ensure the network is reliable and safe for customers. Distributors' connection guidelines place limitations on the network connection of embedded generation to manage high voltage (oversupply) in the local network. All renewable energy connection applications go through a technical assessment process that is dependent on the size of the system. Grid connection applications for systems with 30 kW AC or less rating attract no charges and are relatively simple and quick. Larger projects (over 30 kW AC rating) require more detailed grid studies, and greater engineering and administrative requirements, thereby attracting an application charge of between $10,000 and $15,000 to the customer. Large connection approvals may include a condition to limit the size or export capacity of their chosen system, restricting the system's ability to export excess solar generation to the grid. On a rare occasion, a grid connection application for a system with an AC rating larger than 30 kW will be approved with the requirement to pay a capital contribution (of between $10,000 and $60,000) toward the cost of a network upgrade before the system is installed. In the event a significant network upgrade is needed, it would be identified early in the process, and will be a minimal expense to the customer. These potential hurdles can affect the attractiveness and financial viability of installing renewable generation or storage for some customers, and limit the renewable energy industry's ability to grow (Department of Energy and Water Supply 2017).

Appendix 3: Climate and implications for energy use

Australia has one of the most variable climates in the world, making farm management decisions challenging (Love 2005). On an irrigation farm, energy and climate are intrinsically linked in that plant demand for water is driven by evapotranspiration and seasonal climate variability. The Köppen rainfall classification for sites A and B is Summer Dominant zone, with a marked wet summer and drier winter (Bureau of Meteorology 2018). Site C, at Bundaberg, is classified as Summer Rainfall zone, depicting a wet summer and low winter rainfall. When considering rainfall and irrigation demand on each farm, most energy to pump water is required in the spring period until the summer monsoonal rain arrives. The timeliness of rainfall in the summer season can vary considerably. Demand for irrigation water can continue well into autumn to avoid soil moisture deficits and yield reductions. However, due to high energy prices in recent times, irrigators have conceded that optimal irrigation strategies for maximum yield and Commercial Cane Sugar (CCS) have been compromised. This study has not accounted for or modelled positive changes on the cane production function potentially occurring due to energy technology uptake and increased water use. Because management practices and water application efficiencies vary between farms, this is a minor weakness of the study.

Total crop water requirements are calculated from reference evapotranspiration (ETo) as identified by Allen et al. (2006). During the peak growth phase in summer, the plant water requirement is 1.25 times the reference ETo. For example, if the daily ETo value is 7 mm, the crop water demand equals 10.5 mm per day (Holden and McGuire 2014). Unlike in other horticulture or broadacre cropping systems, irrigation for sugarcane is not pumped out of the growing season into water storage for later use. Therefore, ETo drives demand for energy in an irrigated sugarcane system. Figure 9 shows the water-balance characteristics of each site.

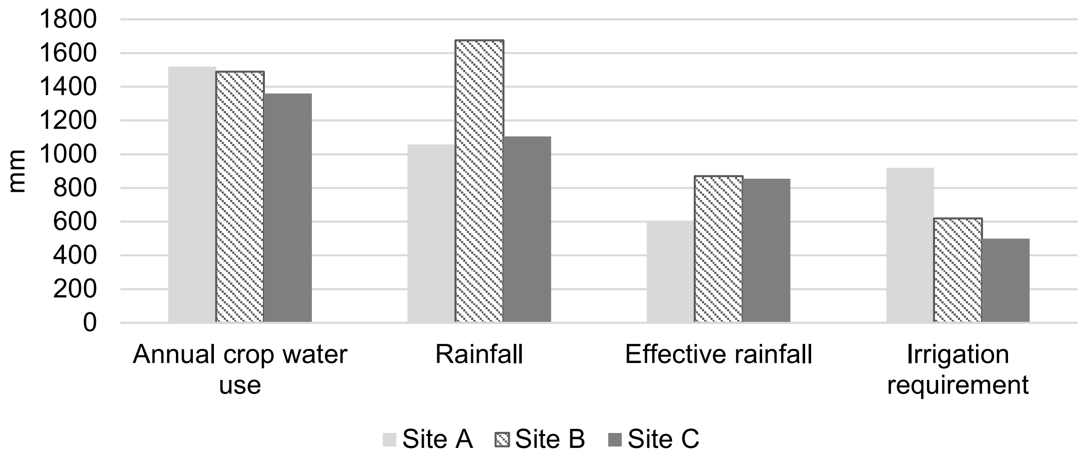

Figure 9: Water balance by case study site, including crop water use, annual rainfall, effective rainfall and irrigation requirement

Appendix 4: Indexation of energy pricing

Queensland's electricity prices doubled between 2007–2008 and 2013–2014, predominantly driven by increases in network charges, which increased six-fold from 2004–2005 to 2014–2015, accounting for more than 95% of the total electricity price increases during the period. The proportion of network charges relative to the wholesale price of power has also changed over time. Network charges now account for over half of Queensland's retail electricity prices, whereas in 2004–2005 they accounted for only about 20% (Davis 2018a). Research into future pricing scenarios by (Garnaut 2011), Graham, Brinsmead, and Hatfield-Dodds (2015), (Brinsmead, Hayward, and Graham 2014) concluded that carbon and energy policy will be a key driver of the level of increase of prices to 2040. We used a mid-point of future policy scenarios of 2.8% in our analyses to account for annual real price indexation of Queensland's grid energy.

To account for changes in diesel prices, global oil price outlooks towards 2040 served as a proxy. Although forecasts do not account for exchange-rate variation, Australia remains highly dependent on imported petroleum products and offshore oil market dynamics. All reporting agencies surveyed suggest four factors underpin the future price of oil: global economic growth and consumer demand; the rate of urbanisation in non-OECD countries (particularly China and India); energy innovation (nuclear and renewables); and government carbon policies/adoption of innovative technologies. Analysis by Powell, Welsh, and Farquharson (2018) found the average real indexation across various agencies to be 2.79%, which is used in this study (see Table 5).

3. Factors influencing Australian sugarcane irrigators adoption of solar photovoltaic systems for water pumping

3.1. Abstract

Sugarcane farmers have several options to manage their energy costs of irrigation. One option these farmers are yet to widely adopt is solar photovoltaic (PV) systems for energy generation. The objective of the study was to understand the potential rate and peak level of adoption by Australian sugarcane irrigators of solar PV energy systems for water pumping and the key factors influencing adoption. This study uses the ADOPT framework to examine farmers' adoption behaviour regarding solar PV systems. A small industry survey and focus group findings are used to apply the ADOPT framework, and sensitivity testing is performed. The study found that after 10 years, 50% of sugarcane farmers were estimated to adopt solar PV systems into irrigation plant. Farmers' adoption decisions were predicted to be influenced by several factors including economic and environmental benefits, ease of use, existing knowledge, business risk and the farmer's current financial position. Sensitivity testing revealed that improving the profitability from installing solar PV systems could markedly increase the level adoption. Grid connection policies and government renewable energy subsidies that increased income or reduced capital costs and thereby increased economic returns for sugarcane irrigators could improve peak adoption levels by up to 40%. Government policies had a greater impact on adoption than environmental benefits generated by the PV systems. From the results we infer that the historically changing relative advantage of the technology has resulted in some farmers exercising the option to hold off investing until they feel the relative advantage has peaked. This is the first study using the ADOPT framework to consider solar technology in Australia.

3.2. Introduction

Energy is one of the fastest growing costs for irrigated sugarcane growers, with electricity and, to a lesser extent, diesel accounting for a significant portion of total farm input costs.

Innovative energy technology applications could reduce pumping costs and improve irrigated sugarcane farm productivity in Australia. The proportion of pumping cost in the irrigated sugar cane gross margin has been identified (Welsh and Powell 2017) to range from eight to 30% of variable costs. Chapter 2 found solar photovoltaic (PV) to be the most cost-effective technology for this purpose when tested among a range of components including wind turbines, diesel gensets and battery storage. Renewable energy also offset emissions from fossil fuel-based energy resulting in reduced greenhouse gases under each scenario analysed Chapter 2. Although solar PV is a mature technology, the number of PV installations for irrigation pumping in Australian sugarcane production remains low.

This study investigates the barriers to adoption of PV systems to target subsequent research, development and extension that can enhance future adoption of these systems on irrigated sugarcane farms in Australia. In this study we specifically aim to understand adoption rate and the peak adoption potential for solar PV using the CSIRO Adoption and Diffusion Outcome Prediction Tool (ADOPT) (CSIRO 2019a). By applying ADOPT we also discover the importance of policy incentives in increasing sugarcane farmers' investment in PV systems. Findings will also contribute to knowledge of solar PV technology adoption in other broad acre irrigated industries such as grain, cotton and horticulture crops.

The potential of renewable energy in agriculture as a cheap and prevalent source of alternative fuel and preferred technology was recognised over 40 years ago. The first such work by Katzman and Matlin (1978) investigated the potential of solar PV systems and battery storage in broadacre crop irrigation. Under the assumption of high renewables utilisation rates and a seven-year payback period, the authors estimated that solar PV systems should see "widespread adoption" on irrigation farms by the year 2000, some 22 years later. In 2020, solar PV has not been widely adopted, we look to the literature to understand why.

Price risk can affect the attractiveness of a PV investment. Price risk usually refers to downside risk such as the risk of receiving lower output prices or facing higher input prices and consequently experiencing lower income, when deciding an investment. Surprisingly, in the study by Beckman and Xiarchos (2013), the price of grid-sourced electricity bore no impact on installation of solar PV system size on farms. Similarly, a study of cotton growers in Pakistan found well-educated farmers were more likely to adopt technologies on their farms due to being more capable of understanding and effectively applying new information (Zulfiqar et al. 2016). In developed agricultural economies, Borchers, Xiarchos, and Beckman (2014) examined nationwide adoption of renewables on US farms and found incentives that reduced capital costs were only effective when implemented in combination with net metering. This finding is consistent with that of Chapter 2 that examined grid connection policies (net metering and feed-in-tariffs (FiT)) in Australia. Additionally, findings in Chapter 2 suggest these policies principally affected the attractiveness of PV systems for Australian sugarcane irrigators who heavily relied on grid power for water pumping. Governments around the globe influence the uptake of new technologies using various policy levers. For example, renewable energy that contributes to national goals of emission reduction has been targeted specifically through the Australian governments Renewable Energy Target (RET).

Governments can consider behavioural science to increase the effectiveness of policy. In the USA, where agricultural productivity is being pressured by high electricity prices (Davis 2018b) and water available for irrigation, the government-supported Social and Behavioural Sciences Team (SBST) was formed to improve implementation of Federal policies and programs. Regarding renewable energy, the team aimed to facilitate informed decision-making to improve adoption.

The adaptation of any new technology to local needs and restrictions can greatly affect the adoption of the technology. This is particularly the case with solar PV systems integrated into water pumping infrastructure, because the failure of such technology under a standardised solution can adversely affect crop growth, income and livelihoods. In a study of adoption of solar PV systems and water pumping in traditional communities, Fedrizzi, Ribeiro, and Zilles (2009) found that knowledge of the receiving communities' social and cultural dynamics facilitated the achievement of high adoption rates. Of similar importance is the availability of trusted communication channels that ensure decisions and knowledge can be shared and technology limitations are revealed up-front, to avoid frustration once a decision to invest has been made.

Quality of information and delivery is also an important element of successful adoption of farm technologies (Abdullah and Samah 2013). A meta-analysis of agricultural best management practices by Baumgart-Getz, Prokopy Stalker, and Floress (2012) in the United States found access and quality of information had the largest impact on agricultural adoption. If communication channels inside a family farming business are poor, then this can lead to investment indecision and lower adoption rates. For example, Suess-Reyes and Fuetsch (2016) found a lack of connectivity between farming family members made scientific discourse on available technologies difficult. Applying systems theory, Arist von and Hermann (2013) found that effective communication between the family regarding the farm system affected farm innovation and consequently, adoption of innovations. Further to this, irrigator surveys in the Murray Darling Basin by Wheeler, Zuo, and Bjornlund (2013) found those farms who had identified a successor were positively associated with more innovative and environmentally conscious management decisions.

At an enterprise level, recent analyses on adoption of renewable energy in Australian broad acre irrigation have narrowed attention to a few key areas. A study by Cotton Australia (2018), covering four regions in New South Wales and Queensland, found barriers and challenges of adopting solar PV can be broken into technical (engineering-based understanding), economic (investment uncertainty) and quality of information (expert advice, connection information and lack of trust in farm-specific advice). These authors deduced the main barrier to adoption to be the significant lack of grower engineering expertise that prevented effective engagement with networks and PV suppliers/installers during early stages of a solar PV installation. In a survey across various commodities and involving 1000 farmers, sugarcane growers named energy pricing as having the largest impact (54%) on their businesses (Agri Insights 2018), yet adoption of energy technologies in cane growing remained low. A survey of 116 irrigated sugarcane growers (Welsh and Powell 2017) found low uptake of solar PV, despite it being a mature technology. The study identified irrigators' lack of knowledge around energy and investment feasibility to be the main limiting factors preventing investment in new energy technologies. Within the survey farmers recorded their own 'energy' knowledge score at an average of 4.8 out of 10 (1=low, 10=high). A lack of cash flow was also identified as a limitation to investment, consistent with other global studies, referencing the importance of national policy incentives to reduce the investment's capital requirements to encourage adoption. Other limiting factors noted include a lack of area suitable or large enough for solar PV installations, policy uncertainty and the fast-moving pace of energy technology – should farmers wait for the silver bullet? To a lesser degree, irrigators were concerned that a long-term solar PV installation would be superseded by something new soon after, devaluing their investment.

This review confirms the adoption of solar PV energy technology for sugarcane irrigation is a complex issue. It involves many factors including relative advantages, risks and trade-offs for sugarcane farmers, the learnability of the advantage and short-term constraints such as financial position.

The next sections outline this study's method and results. These results aim to provide further insight into why the adoption rate of the mature solar PV technology has been slow for the application of irrigation, compared to Katzman and Matlin (1978) prediction.

3.3. Method

There is a long and rich tradition of empirical research that seeks to explain farmers' adoption of agricultural innovations. In a review of methods used to estimate adoption of conservation farming by Knowler and Bradshaw (2007), the authors found differences in sample sizes, methods and statistical outcomes reflect differences in quality among the analyses.

In this study we use the ADOPT framework, chosen for its simplicity, relevance to real-world decision making and practical management. In a similar way to other adoption methods assessing technology, a mix of qualitative and quantitative questions structured around four categories of influence: characteristics of the innovation, characteristics or the target population, relative advantage of using the innovation and learning of the relative advantage of the innovation (CSIRO 2019a). The framework uses a step by step process to evaluate a technology and population to predict the likely level of adoption (Kuehne et al. 2017).

ADOPT has been applied in R&D and innovation analysis and has over 1000 registered users across 43 countries (CSIRO 2019b). Kuehne et al. (2012) used the ADOPT tool to measure expected benefits, adoption and diffusion issues relating to mixed farming R&D programs. The tool was also used to analyse uptake and predicted peak level of adoption of seasonal forecasting among Australian farmers across various industries such as grains, livestock and rice (Pearl 2018). It has also been the chosen method of analysis for other recent agricultural adoption studies both in Australia and overseas (Dhehibi et al. 2018, Andrew et al. 2019). Unlike other tools and methods used to analyse adoption, the ADOPT tool allows evaluation and prediction of the likely level of adoption of the technology, by making adoptability knowledge and considerations more transparent and understandable.

The ADOPT framework is based on a set of 22 questions about the population of potential adopters and the new technology or "innovation" (see Table 1). ADOPT has more commonly been used to assess emerging technologies. In this case, solar PV is a mature technology, so the questions were answered considering the technology, population and advantage of the innovation for the present day. Answers to these 22 questions were collected via a two-part process that included, firstly, a broad industry survey, followed by discussion and engagement with a carefully selected focus group. Initially, the questions were sent as a survey to sugarcane growers, industry extension staff and industry researchers. The survey had 24 respondents. There was no attempt to raise a representative sample, responses were gained across the key regions in which sugarcane is irrigated. A six person focus group selected due to their wide knowledge of the population consisted of industry extension staff, researchers, engineers and solar PV retailers. The group was formed to discuss the survey responses, particularly those where consensus seemed to be lacking. Questions that did not have a consensus answer from the focus group were identified and sensitivity testing was applied to gauge how the different possible responses might affect adoption outcomes. Inferences were made from the small survey sample and focus group discussions for use in the ADOPT framework. The small sample results in the framework outputs being indicative rather than definitive. Table 1 outlines the 22 questions, the consensus answer and reasoning. The schematic in Figure 2 illustrates the ADOPT framework, highlighting the inter-relating factors affecting farmer adoption.

3.4. Results

Application of the inputs outlined in Table 1 in the ADOPT framework generated the following results.

Peak adoption

Peak adoption has two elements. First is the maximum proportion of the target population who will adopt the innovation. Second is the number of years from now before that maximum proportion is reached. The ADOPT framework predicted the peak level of adoption for solar PV is estimated to be 52% of the target population, Australian sugarcane irrigators. Welsh and Powell (2017) estimated that 175,000 megawatts of grid power is used annually to irrigate sugarcane, costing the industry an estimated $47 million, and emitting approximately 165,000 t/CO_2e per annum. An adoption level of 52% would result in significant economic and environmental benefits across the sugarcane industry. The estimated time to near-peak adoption using ADOPT is 12 years from 2019 (when the survey was conducted).

Adoption rate and time to adoption

The ADOPT framework assumes that adoption of a new technology will proceed over time according to a sigmoidal response. Adoption would be slow at the start, gaining momentum and then slow at the end (Figure 10). Solar PV is a mature technology, with minimal adoption by sugarcane farmers, so the ADOPT questions were answered relative to the current situation – which would be considered year 0.

By year 5, the adoption level predicted by ADOPT for solar PV is around 25% of irrigated sugarcane farmers, and by year 10 adoption on 50% of farms is predicted. Considering the current minimal adoption of the technology to date, the next section discusses the sensitivity of the predictions for level and rate of adoption.

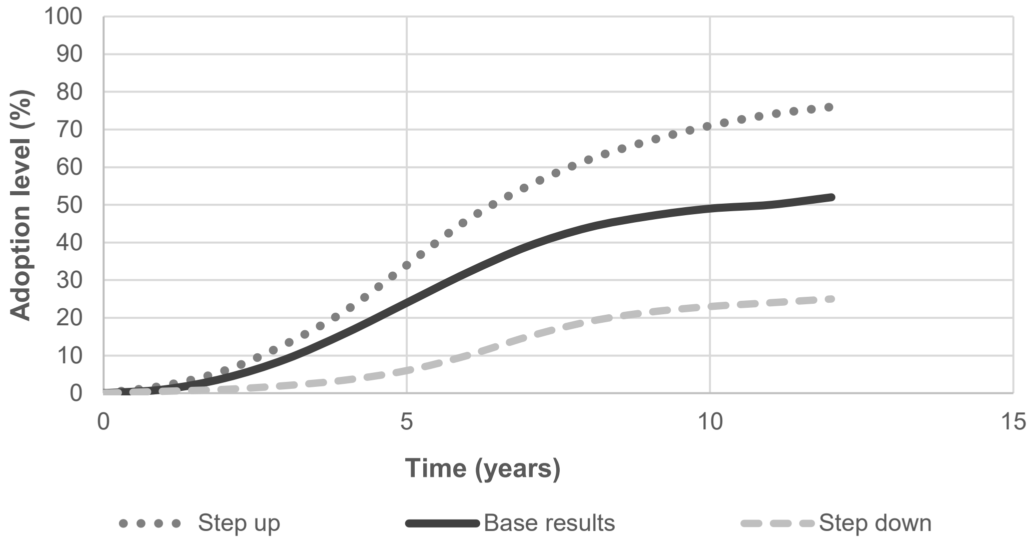

Figure 10 S-curve sensitivity analysis (ADOPT) under the original level (solid line), a step up in resourcing (dotted line) or a step down in resourcing (dashed line).

3.5. Discussion and sensitivity of adoption

Sensitivity tests help assess the effect of changes in key variables in the analysis on the robustness of the results (Sinden and Thampapillai 1995). Adoption is influenced by many factors. Figure 10 illustrates different adoption responses. The predicted level of peak adoption has a wide range: from 25% to 75% under different scenarios to aid (step up) or reduce adoption (step down).

Information from relevant sensitivity analyses can usefully inform governments and industry of the key opportunities to drive the rate and level of adoption.

Sensitivity of PEAK level adoption

The ADOPT framework (Figure 11) includes input questions likely to affect the peak adoption level. The level is most sensitive to the relative advantage of the technology in terms of the population and the innovation. The relative advantage to the population considers their orientation regarding profits, the environment, risk, the enterprise scale and management horizon. Individually, a step change in an answer to these questions can change the peak level of adoption by up to 27%.

The results show the most sensitive question to the level of peak adoption is input question 16, "to what extent is the use of the innovation likely to affect the profitability of the farm business in the years that is used?". The answer used was a moderate profit advantage. Depending on irrigation method (i.e. furrow, centre pivot, high pressure overhead), the cost of energy for sugar irrigation represents between approximately 8 to 33% of variable crop expenditure (Welsh and Powell 2017). Solar PV was found to effectively reduce the cost of energy for irrigation of Australian sugarcane by up to 25% (Chapter 2). Also identified were key influences on the profitability of solar PV for irrigation as; cost of installation and eligibility for a FiT. The falling market price of solar PV, together with government subsidies through the RET and Clean Energy Finance, has reduced the cost of solar PV, effectively increasing the relative advantage of the investment for all potential consumers. Conversely, sites with a total rated inverter capacity over 30 kW are not eligible for the Queensland Government mandated regional feed in tariff. The seasonal nature of irrigation results in long periods of energy being generated in excess of the sites' requirements, where this energy can be sold back to the grid, the investment is favourable. If the site is not eligible for a feed-in-tariff, the investment in solar PV is usually not economically feasible. An increase in the system size eligible for a FiT would increase the economic benefit of a solar PV installation and could result in a step increase in adoption of 27%.

Profit motivation (input question 1) is linked to input question 16 and is also a key influence on adoption. For this study, the strongest motivation – "almost all have maximising profit as a strong motivation" – was selected. However, while sugarcane farmers are motivated by profits, some of the population may have a perception that solar PV technology is not profitable due to earlier assessments on the technology; or growers are unaware of instances when it is (Welsh and Powell 2017).

The peak level of adoption results are also particularly sensitive to questions relating to, change in risk, the proportion of farms that could benefit and environmental benefits. The framework indicates sensitivity to a change in exposure to risk (input question 21). An investment in solar PV could increase financial risk for a business with marginal cash flow that requires an increase in debt to purchase the technology. However, a solar PV installation reduces the demand for grid energy and thus the exposure to input price risk. These factors result in a net zero change in risk. The target audience risk orientation (input question 3) is also linked. A change in risk profile could reduce the peak level of adoption by 18%.

The proportion of farms with a major enterprise that could benefit from the irrigation was input question 4 'majority of the target farms (irrigated sugarcane farms) have a major enterprise that could benefit'. The government could influence this factor by increasing the rated size of the solar PV system eligible for the mandated regional FiT. Not only would this increase the economic benefit of the investment, it would also increase the number of farms that would benefit. A stepped increase to input question 4 improves the peak level of adoption by 16%. Alternatively, an increase in grid energy prices and/or a decrease in the cost of solar PV, through either market forces or government incentives, would increase the number of farms that benefit and also trigger a step increase in the peak level of adoption by 16%.

The environmental benefit of solar PV for irrigated sugarcane is also a sensitive factor for adoption (input question 19). Chapter 2 identified the potential emission abatement from a solar PV system installed on a standard grid-connected irrigation pump as approximately 50t CO_2e per annum. The ADOPT framework also considers environmental protection (input question 2). The answer selected for this study was ‘About half have protection of the environment as a strong motivation’. The focus group identified there could be a big difference between motivation and practice. In many cases, the environment is less important than the profitability of the crop. A step change in environmental motivation changes the peak level of adoption by up to 5%.

Results indicate that the peak level of adoption is most sensitive to the profit advantage of the solar PC technology. The RET is an example of a successfully implemented policy strategy to improve the profit advantage and thus peak level of adoption for renewable technology broadly within Australia. This studies results also suggest that widening the eligibility of the Queensland Government’s mandated regional FiT could make a significant improvement to the peak level of adoption by up to 40%, by increasing both the economic benefit of the technology and the number of farms that would benefit. These results were consistent with those of Borchers, Xiarchos, and Beckman (2014) who identified a major benefit in creating policy incentives that increase the profitability of solar PV.

Sensitivity of Time to adoption

The two key factors influencing the time (or rate) of adoption are the ability for a population to learn about the relative advantage of the technology and the current financial conditions of the population. Learnability can be broken down into the characteristics of the population’s ability to learn and the technology.

Population-specific influences include advisory support, farmer group participation, existing skills and knowledge and innovation awareness. The most sensitive question in this study that impacted time to peak adoption level was input question 12 "What proportion of the target population will need to develop skills and knowledge to use the innovation?" Once the technology is installed by a certified installer, there is very little operational skill required; hence the answer *A minority will need new skills and knowledge*. However, farmers are practical people who like to understand the equipment on their farm. This is supported by Welsh and Powell (2017) who identified lack of skills and knowledge as a barrier to adoption. The focus group concluded that farmers have a distrust for solar providers due to the fact the farmers do not understand solar PV equipment and do not have the skills to identify good quality equipment. These findings suggest that building skills in renewable technologies would aid the rate of adoption. Each step change in the answer to this question for a higher proportion of sugarcane farmers requiring new skills or knowledge could increase the time to adoption by over 1.5 years.

Learnability characteristics of the innovation include; observability, trailing ease, and complexity. The trialability (input question 7) and complexity (input question 8) influence the time to peak adoption of solar PV for sugarcane irrigation. A step change in either of these factors would change the rate of adoption by over one year. As a technology, solar PV needs to be purchased and installed to gain the benefits. While the technology is not trailable, it can be scaled (e.g install a solar PV array on one site, identify the benefits then roll out to other sites). Once installed, the benefits of solar PV are immediately realised (input question 18), observable (input question 9) and easily evaluated (input question 8). The benefit is the reduction in energy bills, although there may be some variation of energy requirements depending on the season, it is relatively simple for a farmer to see if their total expenditure on energy has been reduced.

The time to peak adoption of solar PV in irrigated sugarcane is also influenced by the current financial situation of the population and capital outlay.

Sugarcane growers have on average an 85% equity position (ABARES 2015). This position has been improved by the rapid increase in coastal land values and the growing competition for agricultural land in some sugarcane growing regions from tree crops such as macadamias. Conversely, low sugar prices and poor yields have resulted in lower gross margins for sugarcane, and these reduced cash flows influence the input answer to 'About half currently have a severe short-term financial constraint'. A step increase or decrease in financial conditions will affect the time to adoption by approximately one year.

Sensitivity testing indicates that a step change in the relative upfront cost of the innovation (input question 14) can change the time to peak adoption by one year. The upfront cost of a solar PV system (under 100kW) is currently subsidised by the Australian Government's RET. The capital outlay depends on the size of the system; however, considering common pump sizes, the outlay is likely to be between $40,000 and $70,000. Relative to the variable cost of crop expenditure, a solar PV investment is a large initial investment. An increase to the cost (e.g. solar PV becomes more expensive due to the removal of RET) would increase the time to peak adoption by a year. The resulting change in rate of adoption is minimal. However, a removal of the RET would also reduce the relative economic benefit of an investment in solar PV and result in a large reduction in the peak level of adoption. A potential reduction in the size of the relative investment (e.g. sugarcane margins increase due to a sustained increase in the sugar price) would result in a decrease in the time to peak adoption by one year.

In this study, the strongest driver for the rate of adoption was the requirement for skills and knowledge. While the ADOPT survey suggests these skills are to operate the technology, the focus group also identified the need for skills to understand the technology and assess the relative advantage of solar PV for sugarcane irrigation. These results are consistent with other PV studies abroad such as Zulfiqar et al. (2016) and Zhou, Abdullah, and Yildiz (2017) and more recent Australian studies by Cotton Australia (2018). In the case of the rapidly advancing solar PV technology, farmers may not be motivated to develop these skills if they have previously assessed and found solar PV to be an unviable investment. Educating the population that the relative advantage of the technology is improving is important. Within Agriculture, industry technical extension and support services for irrigators seeking clarity on renewable energy information can assist in bridging gaps in capacity.

Alternatively, some farmers, having observed the improving advantage, may be exercising the option to wait until such a time they feel the advantage has peaked. The changing relative advantage can be accounted for in ADOPT through sensitivity testing of the potential peak level of adoption. The segment of the population waiting for the relative advantage of the technology to peak, affects the rate of adoption. Those farmers unwilling to reassess the technology or waiting for the relative advantage to peak could partly explain the slow rate of solar PV adoption to date in sugarcane irrigation.

This study highlights that Government policy can influence both the peak level and rate of adoption of solar PV technology. Policy can increase the peak level of adoption by up to 40% and increase the time to peak adoption by a year. Policy incentives that increase the peak level of adoption of solar PV also thereby reduce emissions. In addition, by reducing the energy cost of irrigation, investment in technologies that improve water use efficiency is also aided.

Co-benefits of improved sustainability metrics (CO2e per unit output) also have flow-on effects for irrigators seeking to meet expectations of more environmentally aware consumers and gain access to premium agricultural export markets.

3.6. Conclusion

Decisions about adopting energy technology, such as incorporating solar PV systems into irrigation pump sites, are influenced by a complex set of factors.

Factors influencing the level of adoption are focused around the relative advantage of the technology. In this study the greatest influence was how the technology affects farm profit, particularly grid and connection policies that affect profitability. Also influencing the level of adoption was the number of farms that could benefit, how the technology impacted farm business risk, its ease of use and environmental benefit.

Applying the ADOPT framework to assess farmers' adoption of solar PV systems for irrigation pumping revealed that the estimated peak level of adoption is around 50%, occurring after ten years. While the survey sample was small, inferences can still be made from the results.

The immediate economic benefits generated by the PV systems was the main rationale for their adoption. All factors that contribute to increasing revenue and reducing costs have an impact on profitability and therefore the level of adoption. The up-front capital cost of the systems and the ongoing revenue they generate from energy export via a FiT were major drivers of the financial model, as most sugarcane irrigation pumps were connected to grid power. Government incentives provided by the RET and CEFC to lower the cost of the technology and connection policies influencing FiT eligibility, both increased the profitability of the technology and can potentially increased the number of sites that could benefit. Together these incentives could potentially shift the level of adoption from 50% to 90%.

The factors influencing the rate of adoption were focused around the ability for a population to learn about the relative advantage of the technology and the current financial conditions of the population. The most sensitive factors around the learnability of the technology were the requirement for new skills by the population. While farmers did not require new skills to operate a solar PV installation, the lack of knowledge around the technology was likely to influence adoption. Increased industry communication around instances where and when the technology was most profitable, and demonstration of improved profitability could decrease the time to peak adoption by 1.5 years. The study's results indicate a larger change could be in made in the potential level rather than rate of adoption.

Existing adoption of solar PV technology for irrigation has been slow, this is likely to be influenced by the changing relative advantage of the technology. Some farmers who previously assessed the technology may be unaware the advantage has improved and those that understood the improving relative advantage may be waiting to invest when they feel the relative advantage has peaked. Both factors affect the rate and level of adoption.

Using the ADOPT framework in this study of solar PV technology uptake and investment provides richer interpretations, relevant inferences and reveals information that can be applied widely to further improve farm business profitability and sustainability.

The results obtained from ADOPT also can help policy makers assess likely impacts on farmers' adoption choices of changes in government policy and practice. The findings from this study can aid future extension strategies in irrigated industries, and potentially influence Australian or International government energy and industry policy design to ensure industry economic and sustainability goals are achieved. Increased adoption of solar energy directly improves farm productivity, lowers emissions and may indirectly improve on farm water use efficiency through increased investment in the more energy intensive technologies that improve water use efficiency.

Co-benefits of improved sustainability metrics (CO_2e per unit output) also have flow-on effects for irrigators seeking to meet expectations of more environmentally aware consumers and gain access to premium agricultural export markets.

Further research would be useful around the uncertainty in the factors influencing the relative advantage of solar PV and investment in an uncertain environment.

Table 8: ADOPT framework questions and consensus answer

ADOPT question	Consensus answer	Reasoning
1. What proportion of Australian (irrigated) sugarcane growers have maximising profit as a strong motivation?	Almost all have maximising profit as a strong motivation	Require profitability for longevity of a business
2. What proportion of Australian (irrigated) sugarcane growers has protecting the natural environment as a strong motivation?	About half have protection of the environment as a strong motivation	All consider the environment, usually profit is ranked above environment
3. What proportion of Australian (irrigated) sugarcane growers has risk minimisation as a strong motivation?	About half have risk minimisation as a strong motivation	Risk management is a higher level business skill
4. On what proportion of Australian (irrigated) sugarcane farms is there a major enterprise that could benefit from the irrigation?	A majority of the target farms have a major enterprise that could benefit	Most farms have an irrigation site with an electric motor under 80kW
5. What proportion of Australian (irrigated) sugarcane growers have a long-term (greater than 10 years) management horizon for their farm?	A minority have a long-term management horizon	Sugarcane farmers are an aging population. Most prioritise short term issues over long term planning
6. What proportion of Australian (irrigated) sugarcane growers are under conditions of severe short-term financial constraints?	About half currently have a severe short-term financial constraint	(ABARES 2015). Sugarcane farmers hold large assets, but often have limited cash flow
7. How easily can the innovation (or significant components of it) be trialed on a limited basis before a decision is made to adopt it on a larger scale?	Not trialable at all	Not trialable. Could install on one site only
8. Does the complexity of the innovation allow the effects of its use to be easily evaluated when it is used?	Not at all difficult to evaluate effects of use due to complexity	Easy to calculate using comparable electricity bills
9. To what extent would the innovation be observable to farmers who are yet to adopt it when it is used in their district?	Easily observable	Solar PV installations are visible, the effect (cost savings) are not visible
10. What proportion of the target population uses paid advisors capable of providing advice relevant to the project?	Almost none use a relevant advisor	Not many independent advisors with renewable skills. Distrust for sales people
11. What proportion of Australian (irrigated) sugarcane growers participate in farmer-based groups that discuss farming?	About half are involved with a group that discusses farming	Involved = attend. Milling groups, advisor groups, extension groups (SRA, prod services, cane growers)
12. What proportion of the target population will need to develop substantial new skills and knowledge to use the innovation?	A minority will need new skills and knowledge	Minimal skills required to operate, however farmers are unlikely to buy something they don't

		understand. Most have limited understanding of solar PV
13. What proportion of Australian (irrigated) sugarcane growers would be aware of the use or trialing of solar energy in their district?	A majority are aware that it has been used or trialed in their district	Innovators and early adopters have had solar PV installations for irrigation for up to 5 years
14. What is the size of the up-front cost of the investment relative to the potential annual benefit from using the innovation?	Large initial investment	Low in terms of additional capital, high in terms of proportionate cash flow
15. To what extent is the adoption of the innovation able to be reversed?	Moderately difficult to reverse	Physically reversible however would lose capital invested
16. To what extent is the use of the innovation likely to affect the profitability of the farm business in the years that it is used?	Moderate profit advantage in years that it is used	Highest benefit is from offsetting grid electricity demand. (Chapter 2)
17. To what extent is the use of the innovation likely to have additional effects on the future profitability of the farm business?	Small profit advantage in the future	Potential benefit from a FiT depending on connection policies.
18. How long after the innovation is first adopted would it take for effects on future profitability to be realised?	Immediately	Where a FiT is received, the benefits are realised when the sun is shining
19. To what extent would the use of the innovation have net environmental benefits or costs?	Moderate environmental advantage	Average 500 kg CO^2e p.a(Kuehne et al. 2017)
20. How long after the innovation is first adopted would it take for the expected environmental benefits or costs to be realised?	Immediately	Where a FiT is received, the benefits are realised whenever the sun is shining
21. To what extent would the use of the innovation affect the net exposure of the farm business to risk?	No increase in risk	Reduces price risk exposure for grid electricity, increases financial risk if increased debt is required
22. To what extent would the use of the innovation affect the ease and convenience of the management of the farm in the years that it is used?	Small decrease in ease and convenience	An extra element introduced to the farm, requires some cleaning, monitoring etc.

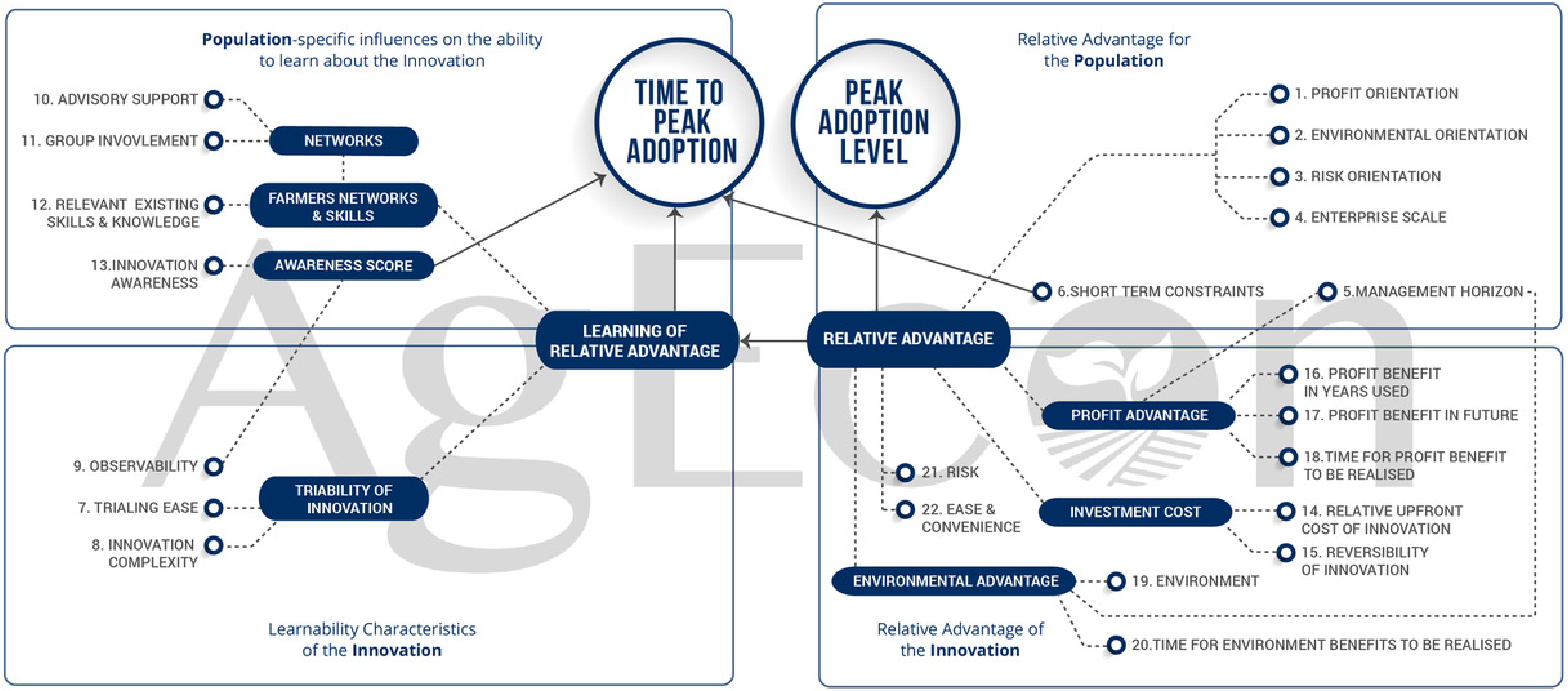

Figure 11: ADOPT framework

4. Australian renewable energy policy for sugarcane irrigators: policy and perspectives

4.1. Abstract

Australia's renewable energy policy has taken significant steps towards encouraging the deployment of lower-emission energy technologies. Solar energy is rapidly becoming one of the cheapest resources on a straight energy basis. Despite 90% of sugarcane irrigation pumps relying on grid power, Australian sugar cane irrigators have not widely adopted renewable energy. This paper presents a critical analysis of policy barriers faced by irrigators, transaction costs, public costs and benefits and discusses potential opportunities for change. These include introducing time-of-use feed-in tariffs and enhanced collaboration between water and energy government departments to ensure lower transactional costs and higher uptake of renewable energy.

4.2. Introduction

Two key concerns dominate the discussion of Australian agricultural energy: pricing volatility and government policy to support renewable energy. These concerns have stimulated interest in substitutes for fossil fuels. Additionally, environmental concerns related to climate change and market signals from consumers to improve sustainability have encouraged investigation of alternative energy sources to transform the relationship between the energy and agricultural sectors.

The irrigation sector is a vital component of the Australian economy, contributing $12.4 billion or 2.3% to Australia's GDP (Land and Water Australia 2020). The sector is heavily reliant on grid-energy for water pumping. Energy for irrigation contributes between 10-33% of variable costs in the irrigated sugarcane gross margin budget (Welsh and Powell 2017). Much of the electricity used by water pumps originates from coal-fired power stations. For example, it is estimated that Australian sugarcane irrigators consume around 175,400 MW of electricity for water pumping that in turn is associated with 165,000 tonnes of CO_2e emissions per annum (Welsh and Powell 2017). There is an opportunity to reduce these emissions if renewable energy can be integrated into pump stations.

Uptake of renewable energy sources among irrigators, along with improving pump energy efficiency, are suggested strategies to lower irrigators' production costs (QFF 2020). Energy and water are inextricably linked through efforts to improve water use efficiency and simultaneously reduce emissions from water pumping (Eyre et al. 2014b).

Research in some countries suggests that integration of water and energy policies facilitates end users' adoption of renewable energy (Perez et al. 2016). Policy and associated incentives are key drivers of adoption of sustainable practices in agriculture (Turner et al. 2013, Kuehne et al. 2012) including solar pumping (Zhou, Abdullah, and Yildiz 2017, Fedrizzi, Ribeiro, and Zilles 2009). There remain policy opportunities to improve the penetration of renewable energy technologies into the agricultural energy markets, and in doing so, contribute to a nation's effort to reduce emissions, simultaneously lower the cost of pumping, and enhance farmer profitability.

The purpose of this study was to review current energy policies affecting Australian sugarcane irrigators. Around 95% of sugarcane is grown along the coastline in the state of Queensland (Nelson, Xia, and Agbenyegah 2019) with access to the state-owned Transmission Service Provider network and monopoly retailer, Ergon Energy. The efficacy of these policies in encouraging farmers' adoption of renewable energy was assessed and potential opportunities to improve these policies were identified. Industry survey data and case study results obtained over a three-year Sugar Research Australia project (2017-2020) were analysed to assess the impact of energy policies on the penetration of renewables in sugarcane irrigation. The analyses and review aimed to objectively appraise the pros and cons of available policy levers, adoption levels and renewables penetration, transaction costs, public cost, and benefits. Findings contribute to knowledge on specific strategies to target the irrigation sector's adoption of renewable energy and may be used by policy makers and advocacy groups.

The remainder of the paper is structured as follows: Section 2 outlines the global energy policy landscape and the policy mechanisms commonly used to increase adoption of renewable energy. Section 3 reviews energy policy in Queensland, Australia. Section 4 qualitatively assess policy levers from the context of a sugarcane irrigation. Section 5 outlines opportunities for energy policy change. The last section presents the conclusion.

4.3. The global energy policy landscape

The Food and Agriculture Organisation 2030 Strategy for Sustainable Development promotes policies which encourage sustainable production and consumption patterns while ensuring high governance standards (Food and Agriculture Organisation 2019). Renewable energy targets are a clear policy signal to encourage the shift away from fossil fuels and support sustainable development. In 2019 the International Renewable Energy Agency estimated renewable energy made up 26% of global electricity generation, and by 2050 this share is predicted to increase to 86% (IRENA 2019). Targets vary and can be aimed at a regional, national, state or even industry level. Targets can be a loose objective or a formal regulation (IPCC 2014).

The fundamental goal of public policy is to address or solve societal problems or improve outcomes for the community (Peters et al. 2018). Studies about the formulation and implementation of policy design rest on the interplay of individual policy actors, regulatory organisations, and the general policy system (Wu, Howlett, and Ramesh 2017). Research on the effectiveness of incentives for solar PV found that a Feed-in-Tariff (FiT) is more efficient than mandated supply as a means of improving project economics for consumers considering the technology (Li, Chang, and Chang 2017). Their study used price and quantity-based panel regression to compare effectiveness of various policy initiatives through all 21 EU-member countries. A FiT was found to reduce costs to consumers and to result in larger deployment of renewable energy. Their analysis concluded that investor risks are lower in a FiT system, and that innovation incentives are larger. Their findings are consistent with other international studies.

Dijkgraaf (2018) empirically analysed the effectiveness of a FiT using sensitivity of linear models. This was part of a broader study examining a range of renewable incentives among 30 OECD member countries over the period 1990-2011. The maximum effect of a FiT was achieved when a long contract was in place, in combination with a consistent policy. De Arce and Sauma (2016) also identified FiTs and premium payments to be more cost effective in reducing carbon emissions and encouraging uptake of renewables than policies that applied penalties or taxes to energy consumers. Their analysis used a two-node power network grid model to account for incentive policy outcomes. Their findings were sensitive to electricity market structure (e.g. duopoly or full competition), suggesting a carbon tax may be more effective under a perfectly competitive electricity market.

Government incentives to encourage adoption of renewable energy initially included aggressive FiT policies above sustainable pricing levels, resulting in increased public spending. This occurred in many countries, including Australia. The Czech Republic saw a political backlash against what was considered wasteful public spending in support of renewable energy. Accordingly, FiTs were reduced and investment in PV almost stopped (Dvorak et al. 2017). Other countries have also been reducing their FiTs. A UK study found the reduction of a FiT reduced the incentive for solar PV but increased the incentive for battery storage, thereby encouraging load-shifting across the network and innovation. A more recent study (Castaneda et al. 2020) noted solar PV could be utilised behind the meter to charge batteries, where consumers on a standard domestic Time-of-Use tariff could invest in technologies that displaced peak-time grid-powered energy with stored renewable sources.

Examples of policy incentives for best practice within agriculture already exist. The European Union's Common Agricultural Policy supports adoption of renewable energy technology for a specific application (Li, Chang, and Chang 2017). At a state level, Californian producers adopting larger renewable energy due to favourable polices are realising the benefits of lower energy input costs (Beckman and Xiarchos 2013).

Implementing policy mechanisms to overcome market barriers has been found to be an effective way to drive investment in renewable energy and achieve targets. Conversely, suboptimal policies may be one reason for lagging renewable adoption and investment.

Policy and regulatory levers. Governments have a suite of policy mechanisms at their disposal, designed to overcome market impediments and increase adoption of renewable energy (IRENA 2018). Renewable energy targets are often incentivised through a combination of financial and regulatory reforms including renewable portfolio standards, grants, tax incentives, loans, Feed-in-Tariff (FiT) and net metering arrangements. These options are outlined below.

Renewable Portfolio Standards are a quantity-based instrument, regulating the increase in production of energy from renewable sources. Often a minimum supply of renewable energy in the wholesale system is mandated. The requirement of a fixed quota of renewable energy to be sold by distributors is a market-based solution that results in the market preferencing lowest cost generation. Generators of renewable energy benefit through energy sales or tradable certificates. In the USA these trades occur via auctions, long term contracting and economic competitiveness (Crago and Chernyakhovskiy 2017). Renewable Portfolio Standards go by many names including Renewable Energy Directives, Renewable Electricity Standards, Renewable Purchase Obligations or Renewable Mandates.

In the European Union, the Renewable Energy Directive sets a binding target of 32% renewable energy by 2030 (EC 2018). It also sets an industry-specific minimum target of 14% for renewable energy in road and rail transportation by 2030. The USA's Renewable Portfolio Standard provides regulatory policy for most USA states. California surpassed its ambitious goal of delivering 33% renewable energy of retail energy sales by 2020 and is on target for 60% by 2030. Some countries such as Uruguay rapidly achieved their goals. By 2017 their renewable generation accounted for 98% of their total electricity (IRENA 2019). Within Australia, South Australia's renewable target is 50% renewables by 2020 and 75% by 2030. In a separate jurisdiction, Queensland is targeting 50% of energy generation from renewable sources by 2030.

Grants or rebates are designed to lower the upfront capital requirements for renewable investment, thus increasing financial return. Studies on the effectiveness of renewable energy incentive programs in California found rebates or upfront subsidies had a positive effect on new solar PV sales, ahead of production-based incentives such as Feed-in-tariffs or (Crago and Chernyakhovskiy 2017, Burr 2014). However, the authors also learned marginal effects such as solar irradiance, income and environmental preference impacted investment across various states.

Tax incentives may be in the form of exemptions, deductions, or credits. In the USA, a key federal incentive for the adoption of solar PV is the *business energy investment tax credit* currently calculated at 26% of the purchase cost of the solar system. The investment tax credit includes solar PV systems used to provide power to farm equipment. The incentive of accelerated depreciation for renewable energy has been implemented in the USA, Australia, and India (Beaton et al. 2019, ATO 2020, Pick 2017).

Preferential Loans typically involve a low interest rate to promote investment by facilitating access to capital. The Clean Energy Finance Corporation is an Australian Government agency offering 0.7% interest subsidies for renewable energy purchases through banks as intermediaries (CEFC 2020b).

Feed-in-tariff (FiT) is an obligation placed on the energy retailer to purchase renewable energy fed back into the grid at a fixed rate. This instrument provides an economic incentive to generate electricity from renewable energy sources. This instrument can take several forms. The rate is generally guaranteed for a specific period and calculated by the cost of energy production plus a profit margin for the producer. FiTs are a straightforward mechanism and have a demonstrated ability to promote investment in renewable energy (Kulichenko 2012, Haghi, Raahemifar, and Fowler 2018, Dijkgraaf, van Dorp, and Maasland 2018). FiTs can have varied design characteristics within the tariff agreement. The tariff rate may be flat or change during times of the day (e.g. higher FiT during peak demand), called a Time-of-Use tariff. Tariffs can wind-own over time to encourage innovation and energy storage. FiTs have been the preferred renewable energy incentive in European countries such as Germany, Italy and Spain (Comello and Reichelstein 2017, Grizzetti et al. 2016, Markard 2018).

Net metering can influence the economic returns of renewable energy installation (Perez et al. 2016). The policy of net metering allows operators of residential- and commercial solar PV systems to sell surplus electricity back to their utility at the going retail rate, as opposed to a flat rate (Comello and Reichelstein 2017). California, an early implementer of net metering, accounted for 55% of all net metering customers within the

USA in 2008 (Energy Information Administration 2008) and had interconnection policies favourable for renewable energy (Beckman and Xiarchos 2013).

Infrastructure innovation is required alongside policy incentives, organisational and technology change to support the successful transition of renewable energy (Markard 2018, McCarthy, Eagle, and Lesbirel 2017). Markard (2018) outlines two clear phases of energy transition. The first phase is characterised by innovation and adoption of new technologies and public policies supporting renewables (e.g. FiT and renewable portfolio standards). The second phase of transition is characterised by a decreasing support of generation and increasing support to complementary technologies such as batteries and smart grids, innovation in functionality such as distribution, transmission and storage, and a decline in established generation.

Functional grid innovation and investment is required to reduce the risks of relying on intermittent generation. Innovations may include 'super grids' to connect populous regions or countries to each other, balancing systems and resources, or microgrids in sparsely populated areas to facilitate intermittent renewable penetration (IRENA 2019). A stronger grid with a larger capacity can theoretically connect a higher volume of renewables. Infrastructure in regional Queensland's large distribution network that contains long stretches of sparsely populated areas, remains an investment challenge.

The emergence of low emission renewable hydrogen energy technology from renewable energy as a diverse energy carrier has reignited policy settings in developed countries. Hydrogen can be created and stored from otherwise wasted un-met energy from renewable generation. This fuel source is both a direct energy source via a fuel cell to drive machinery or it can generate electricity for grid export. Haghi et al (2018) investigated hydrogen's role in distributed generation in Canada and found it to be a cost effective inclusion for smaller agricultural loads with other components (e.g. solar PV and diesel generators) connected in a microgrid. Hydrogen policies in Queensland are new and, given the current high production costs from renewable sources, are focused on research and development to overcome electrolyser capital cost, storage safety and logistics rather than focusing on providing adoption incentives to consumers (Queensland Government 2019).

4.4. Australia and Queensland's Energy Policy Landscape

Decarbonisation of the Australian economy is closely tied to global energy policy, and market and technology shifts. Initiatives from individuals, civil society, companies and investors can make a major difference, but the most significant capacity to shape an energy landscape typically lies with governments' actions and policies (IEA 2019). Energy technology shifts occur through the allocation of capital as directed by investors seeking opportunities in energy transition and to avoid market risks.

Under the Paris Agreement, governments have committed to limit temperature increases to well below two degrees above pre-industrial levels. Australia has formulated domestic energy policies to reduce dependence on fossil fuel and increase use of renewable energy. The Australian Government's carbon and energy policies have two main levers; the Renewable Energy Target (RET) and the Emissions Reduction Fund (ERF). The ERF operates alongside the RET and is the centrepiece of the Australian Government's climate change policy to help achieve the Paris emissions reduction target of a 26% reduction on 2005 levels by 2030 (DOE 2020). Energy retailers offer a FiT for renewable generation sold back into the grid; however, connection policies in each Australian state impact the effectiveness of encouraging uptake. Finance concessions like low-interest loans and subsidies can contribute to end-users shifting towards renewable generation technology. An individual's location, retail competition and network constraints can limit the level of a FiT and thereby weaken the incentive to adopt renewable energy technologies (Davis 2018b). This section provides a more detailed examination of policy incentives available to Queensland sugarcane irrigators.

Renewable Energy Target (RET)

The RET is an established policy instrument accessible to businesses and households. It is designed to reduce Australia's emissions growth in the electricity sector and encourage the additional generation of renewable energy using financial incentives (Clean Energy Regulator 2016). The RET requires 33,000 gigawatt hours of additional renewable electricity generation by 2030 (Clean Energy Regulator 2016). There has been a RET in some form since 2001 (formally called the Mandatory Renewable Energy Target). Under the RET, certificates are divided into small and large certificates. Small certificates can be administered upfront by the equipment supplier upon the purchase and installation of renewable energy, such as solar panels or wind turbines. The rebate is deducted from the capital cost, reducing the upfront cost of the investment. Creating large certificates involves a more detailed set of criteria than small certificates and has greater administrative requirements (Australian National Audit Office 2018). A registered power station can create large certificates only once generation can be measured by a registered meter, only until the end of the scheme in 2030. Large certificates are fully subscribed already, which means that supply will exceed demand and prices will fall (Clean Energy Regulator 2019). Benefits are uncertain and quite possibly low.

Most irrigation pumps in the sugarcane industry fall in the smaller certificate range, under 100 kW (Attard 2017), so rebates from small certificates are relevant when integrating solar PV installations. Australia has the highest rate of small-scale solar PV adoption in the world (Best, Burke, and Nishitateno 2019, Zander et al. 2019). However irrigated sugarcane farmers have been slow to adopt this technology. The study using

ADOPT (Chapter 3) identified the key barriers for irrigated sugarcane farmers were the impact regulatory frameworks had on the profit advantage and the difficulty in calculating the economic benefit of renewable energy due to their variable seasonal demand loads. Renewable technology can fit irrigation systems, lower costs and achieve economic hurdle rates - as demonstrated by solar PV case study sites at Bundaberg (BRIG 2020). These findings are consistent with Chapter 2 where solar was found to be the best renewable energy fit to lower irrigation costs and emissions. Yet an industry survey (Welsh and Powell 2017) of irrigated cane farmers and advisors found only 9% understood the support offered for capital purchases of solar PV through either small or large certificate rebates, potentially reflected in the low uptake of solar PV by the industry. The ease of administration for payment and the stable pricing structure of small certificates has contributed to record levels of domestic investment in rooftop solar (Zander et al. 2019). However, only marginal uptake exists in agriculture on a ‘small industrial’ scale – between domestic and utility-scale (30-200 kW), which is the focus of this review. The RET is set to wind up in 2030, meaning both small and large certificates will no longer be traded beyond this date. Access to RET rebates will be unavailable after 2030.

Emissions Reduction Fund

The Emissions Reduction Fund (ERF) is the Australian Government’s centrepiece to deliver emissions reduction as a part of Australia’s 2030 target. The ERF is a voluntary scheme that provides incentives for a range of organisations and individuals to adopt new, low-cost practices and technologies to reduce carbon emissions. Approved projects are credited with Australian Carbon Credit Units (ACCUs) for each tonne of carbon dioxide equivalent (CO_2e) reduction achieved. The Clean Energy Regulator runs a reverse auction process whereby the Government purchases ACCUs at the lowest available cost (Clean

Energy Regulator 2020a). Two energy efficiency methods apply to irrigated sugarcane farmers, the 'Industrial Electricity and Fuel Efficiency' method and the 'Aggregated Small Energy Users' method (Clean Energy Regulator 2020b). Both methods share a requirement that any measured emission reductions from a business as usual situation are eligible to generate ACCUs. Equipment such as a variable speed drive installed on a pump would be an eligible activity, however, minimum abatement levels exclude these types of energy efficiency investments. ERF applications require scale and aggregation better suited to large scale business for ease of data collection, to recoup auditing costs and administration fees.

Research by CottonInfo and NSW DPI (2017), found that available methods were not suitable for farm-scale projects, due to the minimum 2,000 t / CO_2e abatement requirements. With the average Australian sugarcane farm comprising 125 hectares (Nelson, Xia, and Agbenyegah 2019), it is highly unlikely that participation in energy-related ERF methods will eventuate. Businesses that participate in the RET for site-specific infrastructure cannot register an energy efficiency method, due to double-dipping. The ERF is part of a newly branded 'Climate Solutions Fund' aimed at delivering a third of Australia's greenhouse gas reductions by 2030. This policy was due for review at the end of 2020 (Department of Environment 2019).

Grid policy

Grid policies capture networks, retail and wholesale energy markets and can vary between jurisdictions and their different requirements for embedded generation of any kind. Grid policy can have a strong influence on the feasibility of integrating solar PV into pump sites as noted in Chapter 2. Australia currently runs a two-part electricity tariff structure, whereby end users pay a fixed connection charge, demand tariff, as well as a variable consumption charge. Consumers are encouraged to cross-shift energy demand to off-peak periods via a Time-of-Use tariff structure. End-users that are unable to shift electricity use to off-peak periods to obtain maximum yields, such as sugarcane irrigators, relying on electricity for water pumping during summer months, face higher energy input costs. Where Time-of-Use tariffs and plant agronomics allow, irrigators that can load shift to daytime use and solar PV, can potentially reduce this input cost pressure.

In Australia, some state governments mandate the FiT floor price (cents per kWh) for electricity fed into the grid. For example, the Victorian government has set a minimum Time-of-Use FiT of 9.1c, 9.8c and 12.5c per kWh for off-peak, shoulder and peak times (Energy Victoria 2020). Retailers are not obligated to set the FiT at these levels and in a competitive energy retail market, values can be much higher. Price checks by Solar Choice (2020) found rates as high as 16 c/kWh in the state of New South Wales. By comparison, in regional Queensland, there has been uncertainty in FiT's which keep being reduced. In 2020, monopoly retailer Ergon Energy offered cane farmers a flat 7.14c/kWh for systems with inverter sizes 30 kW or less (Ergon Energy 2020). The government oversees the Queensland Competition Authority or other authorities' recommendations for 'fair and reasonable' FiTs pricing annually. The recommendations take into consideration the wholesale electricity price, avoided network losses, and avoided market fees. Industry lobby groups continue to pressure the Australian Energy Market Commission (who determines the rules) to change outdated electricity pricing structures, based on the centralised distribution from large power stations. Ergon's export limits are set a maximum 30 kW. For example, a solar PV system may have a capacity of 39 kW but is only permitted a maximum export of 30 kW at any one time. The regulatory framework that applies to distribution networks does not incentivise them to upgrade or procure network support to deal with renewable energy distribution issues, instead the consumer is faced with export constraints. Revenue regulation encourages the networks to choose the cheapest alternative (KPMG 2018).

Business-to-business trading of energy via public infrastructure can encourage decarbonisation and allow a more direct market for smaller generators. Trading platforms are established in some countries (Brinker and Satchwell 2020) and are being trialled in some Australian states (NSW Dept of Planning 2020). A trial in the Byron Bay Shire Council achieved mixed results; profitability could occur under a theoretical 'private wire' distribution scenario (separate from the Essential Energy public network) due to the high fees associated with accessing the public grid. Low-cost solar PV and back-up generation were also key drivers of local electricity trading success (Rutovitz et al. 2016).

Finance incentives

Two main-stream federally funded, and state-based initiatives exist to incentivise would-be purchasers of renewable energy equipment to execute commercial proposals. The Clean Energy Finance Corporation is a national initiative providing debt finance subsidies to established clean-energy technologies to address the lower level of private-sector finance in the industry. By providing finance in collaboration with the private sector, the Clean Energy Finance Corporation can offer a 0.7% discount on equipment finance for loans for eligible clean-energy investments, such as solar for irrigation (CEFC 2020a). A state-based government low-interest loan facility is available for irrigators to improve their sustainability. The Queensland Rural and Industry Development Authority (2020) provides finance up to AU$1,300,000 to assist a more productive and sustainable enterprise, including renewable energy installations. Loans for up to 20 years at the base lending rate can be fixed for a period and interest-only terms are available for five years (QRIDA 2020). While leasing and Power Purchase Agreements are also options, a cash purchase with an interest subsidy offers the highest lifetime Net Present Value (Welsh and Powell 2019). These initiatives aim to assist farmers to reduce energy costs by supporting an accelerated adoption of improvements in on-farm energy use.

4.5. A qualitative review of policy options

Industry survey data and case study results were obtained from a three-year Sugar Research Australia project (2017-2020) that investigated energy technology options for sugarcane irrigators. The project's research results were examined to underpin a qualitative assessment of applicable policies. The project's data, for example, showed feedback from farmers that highlighted the importance of energy in irrigated cane production. Surveys collated from cane farmer engagement activities (Curraro (2019) found mitigating high energy prices, information on batteries and disconnecting from the grid as key priority areas. More recent energy adoption surveys (see Chapter 3) identified that economic benefits were limited by high upfront costs; and capped FiTs were the leading impediment to renewable energy adoption. These findings are consistent with other industry and energy workshop surveys that identify high transaction costs, lack of installer competition and complex engineering language as reasons for not adopting renewable energy technology (Welsh and Powell 2017).

The qualitative analysis in this present study examined adoption levels, renewables penetration, transaction costs, and public costs and benefits. Literature review findings helped identify public costs, for example price paid per tonne of CO_2e. Perceived public benefits were deemed a proxy for emissions abatement and improved environmental sustainability. Table 9 synthesises a summary of findings.

Table 9 A qualitative assessment of policy effectiveness in Queensland

Policy lever	Ease of adoption	Irrigator transaction costs	Public cost	Public benefit (if executed)	Primary Reference
RET small certificate rebates	High	Nil	Moderate	High	(Powell, Welsh, and Farquharson 2019)
RET large certificate rebates	Difficult	High	Low	High	(Welsh and Powell 2017)
Feed-in-tariff	High	Nil	Moderate	Moderate	Chapter 2
Net metering	High	Nil	Moderate	Moderate	Chapter 2
Preferential loans	Moderate	Moderate	Low	Low	Welsh and Powell (2019)
Emissions Reduction Fund energy method	Difficult	High	Low	High	CottonInfo and NSW DPI (2017)

The results show a trade-off between ease of adoption and public costs among policy levers with each option showing shortcomings. Policy options with higher public costs (on a $ / t / CO2e measure) were those more easily adopted. The policy incentives with lower public costs only offered higher public benefits when or if participation occurs. In sugarcane irrigation, survey data revealed all policy levers suffer low participation, and adoption of renewable energy remains low.

4.6. Opportunities for policy change

As large generators are replaced by a range of technology types and smaller generators in the energy system, the transmission landscape will change; load curves will shift, prices will adjust, and utility companies will respond with changing business models. For these changes to occur, policy mechanisms will also need to adapt to be both proactive and reactive.

Renewable energy represents a key priority of the Queensland Government, with a target to have 50% of Queensland's energy generation coming from renewable sources by 2030, to reduce emissions, create new jobs and diversify the state's economy (Trade and Investment Queensland 2020). These goals are challenging when applied to sugarcane irrigation where profit margins are shrinking and per hectare yields have plateaued (Nelson, Xia, and Agbenyegah 2019). A survey of various agricultural industries (CBA (2018) found that 95% of cane farmers cited energy costs as their biggest concern, a higher percentage than for any other industry. Therefore, domestic and regional energy policy settings are critical determinants of agricultural productivity as they shape farmers' incentives and capacity to innovate and improve productivity. This section explores three potential opportunities for policy reform to deliver greater adoption of renewable energy technologies.

Grid policy innovation

Due to the coastal location of most irrigated sugarcane farms, where many urban communities also reside, access to the national electricity market has led to around 90% of irrigation pumps being grid-connected. In Queensland, where the Transmission Service Provider and retailer are a monopoly provider and government-owned, grid and retail policy continue to be an area for potential reform. Access to higher FiT rates (flat or Time-of-Use (TOU)) and increased competition for end-user markets in regional Queensland would provide additional income and economic incentive to install renewable energy.

Tariffs can promote demand-side management. TOU FiTs – such as those currently in operation in other states with higher peak period rates - are designed to reward load-shifting and grid sell-back from solar PV systems These tariffs may help to utilise the vast and plentiful solar resource in cane-growing areas, smooth load demand curves, reduce carbon emissions, and lower pumping costs jointly.

Business-to-business trading platforms, such as those in operation in California have the potential to unlock savings for sugarcane irrigators. While transmission service provider (line rental) fees make up a large proportion of energy costs borne by Queensland irrigators, the levelised cost of energy to produce small-scale solar PV systems is around 5c per kWh. Unused or surplus generation on a seasonal load such as an irrigation pump can therefore be on-sold to consumers capturing additional revenue. The intermittent supply of solar PV can also be smoothed to irrigation pump loads through inclusion of battery storage in a decentralised group of electricity sources referred to as a micro grid. Support of systems by policy makers to include storage is an example of Markard (2018) phase II innovation suggestions that transition electricity systems towards sustainability. Therefore, there remains potential for grid policy reform to increase adoption of renewable energy aligned with various state, national and industry strategic plans.

Merging water and energy policy for targeted irrigator incentives

Increasing water productivity and improving energy-use efficiency are critical to reducing the environmental footprint of agricultural production (Mushtaq et al. 2015). The adoption of best-management approaches for land and other resources, such as water and energy, is an integral component of sustainable agriculture. Therefore, the thesis that water and energy departments may be effective at delivering policies to advance innovation and adoption is a valid one. Opportunities to weave in incentives for renewable energy and subsequent emissions abatement exist with solar PV pump installations; and require interaction with the government-owned water service provider, Sunwater who control fixed and variable rates charges. In a similar policy initiative for drought-hit farmers in New South Wales, the state Department of Agriculture waived all Local Lands Services rate notices to help lift the cost burden on farmers. For example, a farmer with

2,500 hectares could save $3,000 per year by not having to pay rates (Local Lands Services 2020). Theoretically, an example of an energy / water policy mix could include provision for Sunwater fees to be waived for grid-connected pumps supplemented by solar PV. A subsidy, or rebate to further encourage adoption could be administered by demonstrating a feed-in-tariff by National Meter Identifier – a simple and easily assessable form of retail documentation. With over 15,000 irrigation pumps estimated to be in the Burdekin region, financial incentives in addition to those currently available, such as the RET and CEFCs could have a significant impact on adoption of solar PV systems. Merging water and energy incentives offers another pathway to meet Queensland's 50% renewable energy target by 2050, however additional cost benefit modelling is required to calculate public costs and benefits.

Expanding the small certificate threshold

The Small Renewable Energy Scheme creates a financial incentive for households, small businesses, and community groups to install eligible small-scale renewable energy systems such as solar PV systems. It does this by legislating demand for STCs. These are created for systems at the time of installation, according to the amount of installation. Calculations are determined by the amount of electricity they are expected to produce or displace in the future (Department of Industry 2020). Each Net Metering Identifier can claim a maximum of one 100 kW system. Solar PV arrays over this size are grouped into the 'large market' utility-scale system sizes producing large certificates, a free market and unregulated pricing structure with significant administration requirements.

Many irrigation pumps fall into the 'small industrial' 10 kW-100 kW range and could be suitable for solar PV systems over 100 kW. Communicating pricing structures to irrigators (i.e. upfront rebate vs claiming large certificates in arears) becomes a complex message for extension agents. Large certificates claimable after the energy is produced via metering, in contrast to an upfront subsidy for small certificates accrued on PV panels upon installation, with the latter administered by the installer. Price protection and risk management of large certificates involves forward pricing, power station registration, as well as third-party advice ancillary to a solar PV installation. Complexity and ambiguity therefore exist in messaging for those adopting solar PV systems for pumps, potentially creating a deterrent for larger systems. If the threshold for small certificates was extended from 100 kW to 200 kW, it is plausible that small industrial loads such as irrigation pumps may attract new renewable energy investment from improved economic feasibility and administrative simplicity. While these are clear benefits to irrigators in this category, extending the STC rebate for systems >100 kW equates to an additional public cost, which would need to be accounted for in future costing analyses.

4.7. Conclusion

Countries around the world have successfully managed the integration of variable renewable energy into their power systems via a range of policies and incentives. Notably, some countries have managed 100% dependence on renewables for short periods, meaning electricity networks can achieve low-emissions grid scenarios (IRENA 2019b). Using a combination of incentives, government policies can have a substantial impact on delivering practice change through affecting adoption of new technologies such as solar PV systems. While Australia boasts high penetration of domestic rooftop PV, in the case of sugar cane irrigation (small scale industrial), the uptake of solar PV systems for water pumping is currently low. This study reviews the policy settings that can potentially increase irrigators' adoption of PV systems and explores several policy reform opportunities.

Queensland, where most of Australia's sugar cane is produced, has a government-imposed 50% renewable energy target to enhance the uptake of energy technologies that displace traditional fossil fuel sources. This policy intersects with other industry and state objectives to improve current rates of adoption of renewable energy, including solar PV systems. The Sugar Research Australia's strategic plan, the Queensland hydrogen initiative and various sub-policies within the Renewable Energy Target and Emissions Reduction Fund aim to incentivise commitment and acceptance of renewable technologies. Grid policy settings, through export limits and feed-in-tariff pricing, can improve the feasibility of combining solar PV into grid-connected seasonal loads. Collaboration between water and energy government departments also offers an alternative design of incentives for sugarcane irrigators, by offering rebates for water pumping from micro grids with a renewable component. Finally, the ease with which the small certificate rebates can be administered and the success of the Small Renewable Energy Scheme since inception would suggest (when combined with improved export limits and FiT incentives) greater irrigator participation in renewables, if future policies could lift thresholds from 100 kW to 200 kW. Under this scenario, those pumps 55 kW and above would be relieved of current administrative and risk exposure required under the large certificate trading scheme. Refining current policies to target incentivisation for irrigated cane farmers to adopt solar PV and battery storage systems could lower farm energy costs whilst simultaneously improving productivity and reducing emissions.

5. Discussion and conclusion

The aim of this thesis was to understand the economic feasibility of commercially available energy and storage solutions for irrigators in the Australian Sugar industry. This knowledge was gained so renewable energy could potentially be promoted by the industry to improve sustainability via simultaneously reducing the cost of energy and reducing the carbon footprint.

The thesis concluded in Chapter 2 that commercially available renewable energy and storage solutions have the potential to reduce emissions and lower the cost of pumping for Australian sugarcane irrigators (<100 MW per annum). However, economic feasibility is just one influence on levels and rates of adoption, so Chapter 3 further explored the other factors influencing the level and rate of adoption.

Policy and distribution network service provider (DNSP) rules were identified in Chapter 2 to be a key influence of economic feasibility and also in Chapter 3 as an influence on the level of adoption. Chapter 4 concluded that existing energy policies influencing the adoption of renewable energy by Australian sugarcane irrigators could be refined to increase adoption rates of renewable energy and storage options.

Several key findings were identified, contributing to the knowledge of energy and storage solutions applied to irrigation in the Australian sugarcane industry. This knowledge can be applied to small-scale (<55 kWh load) pumping scenarios across other industries. Some general findings and themes may be applied broadly, however the specific tariff and DNSP rules within the study were for regional Queensland's provider Ergon Energy, making the results most applicable to regional QLD.

The results of Chapter 2 indicated that the cost of energy could be reduced by up to 26%, saving 1303 t/CO_2e, by using a combination of solar PV and electricity grid energy supply. These results were influenced by the seasonal demand load and DNSP rules.

An estimated 90% of Australian sugarcane irrigation pump sites are connected to the national electricity grid. This study investigated which combinations of energy generation (grid, wind turbines, solar PV, and diesel generators) and battery storage could reduce the cost of energy in sugarcane production. Solar PV and an existing grid connection were identified to have the lowest net present cost across all three case studies, even when subject to thorough sensitivity testing. Solar PV was identified as the most economically feasible energy generation combination or microgrid and became the focus of the adoption study in Chapter 3.

Off-grid, microgrid solutions offset the most emissions however these systems also had higher levelised cost of energy. The reduced economic feasibility was due to seasonal loads and limited demand-side management. The energy demands of seasonal irrigation are tied to crop water requirements, meaning there was, in many cases, limited flexibility to shift the load pattern. Where irrigation scheduling could be shifted to daylight hours (when energy is generated by solar PV) the economic feasibility of any solar scenario (both on or off grid) was improved. This finding, which was consistent with previous studies, highlights the importance of a load profile matching energy supply.

The seasonality of the load profile was a factor in batteries not being selected as an optimal component. The cost of a battery, sized to cover the entire energy load for night-time pumping, could not be justified. Even when the cost of the battery was decreased by 60%, the energy from an existing grid connection resulted in a lower levelised cost of energy to supplement solar PV during sunlight hours.

Another finding in Chapter 2 was that connection policies created an economic disincentive for renewable installations by limiting embedded generation to a 30 kW inverter. This factor is also linked to seasonal irrigation, as the pump sites did not use enough renewable energy to offset the cost of the solar PV installation unless energy generated outside irrigation periods could be exported and a feed in tariff (FiT) received. When export limits and FiT were sensitivity tested, the optimal size of the solar PV array within the microgrid increased (for sites that had energy demands over 30 kW/h) as export limits increased. Larger solar PV arrays resulted in more grid energy being offset by renewable energy, increasing emissions abatement, and reducing the levelised cost of energy.

Chapter 3 is thought to be the first study to use the ADOPT framework to analyse the various influences on the adoption of renewable energy technology; in this case specifically solar PV. The findings fill a knowledge gap on the drivers of adoption for renewable technology applied to agricultural irrigation. The policies and rules identified in Chapter 2 that reduced the economic benefits and limited the abatement potential of solar PV were also identified in Chapter 3 as a factor limiting the potential level of adoption.

The key factors influencing the level of adoption were those that contributed to how the technology affected farm profit. Grid and connection policies have the greatest influence on the economic feasibility of embedded renewable energy, changes to these policies could potentially increase the adoption level up to 90%. The factor most influencing the rate of adoption was the ability of sugarcane farmers to understand the technology and the relative advantage it provided. The unique energy demands of each pumping site combined with a rapidly evolving technology and changing policy environment make calculating the economic feasibility of solar PV a challenge.

Australia’s renewable energy policy is focused on encouraging investment in lower-emission energy technologies. However, in the case of customers in regional

Queensland, the DNSP export limit of 30 kW is limiting investment in embedded generation. Limits are in place due to out-dated distribution networks and the regulatory framework does not incentivise the DNSP to upgrade the network. Where increases to export limits are not feasible, providing certainty in FiTs and potentially refining the FiT system towards Time-of-Use FiTs could incentivise embedded renewable energy while also smoothing load demand curves. An additional policy incentive for renewable energy in irrigation may be a reduction in water usage fees for water pumped using renewable energy. The policy findings in Chapter 4 contribute to knowledge on specific strategies that can target the irrigation sectors adoption of renewable energy and may be useful for policy makers and advocacy groups.

The results obtained from this thesis provide knowledge to those influencing investment in renewable energy for the application of water pumping. Additionally, the findings can help policy makers and advocacy groups assess likely impacts on farmers' adoption choices of changes in government policy and practice. The findings from this study can aid future extension strategies in irrigated industries, and potentially influence Australian or international government energy and industry policy design to ensure industry economic and sustainability goals are achieved. Increased adoption of solar energy can directly improve farm productivity, lower emissions and may indirectly improve on farm water use efficiency through increased investment in the more energy intensive technologies that improve water use efficiency.

Co-benefits of improved sustainability metrics (CO_2e per unit output) have flow-on effects for irrigators seeking to meet expectations of more environmentally aware consumers and can help irrigators gain access to premium agricultural export markets.

The cost benefit analysis in Chapter 2 and adoption analysis in Chapter 3 was limited to componentry prices, tariff structures and government policy at the time of investigation. Sensitivity testing was performed. However, further research into the effects of uncertainty on investment behaviour would be useful. Over the 25-year life of a renewable energy investment, high levels of uncertainty remain with DNSP tariffs and connection policy, in addition to rapidly improving technology pricing and performance. These factors are primary influences on the economic feasibility and adoption rate of a renewable investment. Real options analysis could reveal further findings about the optimal timing of a renewable energy investment.

Industry surveys suggest that in some cases, the amount of water applied to a cane crop is being limited and is below optimal crop requirements due to the high cost of energy for pumping. Further analysis into the flow-on effects of increased irrigation from the reduced cost of energy may indicate changes to whole-farm profitability. Including Life Cycle Assessment relating to the manufacture and disposal of solar PV systems at the end of life also would present more robust emission abatement estimates.

A potential policy identified to incentivise the adoption of renewable energy was the merging of water and energy incentives. However additional cost benefit modelling is required to calculate the public costs and benefits of this potential policy and is an option for further research.

6. References

ABARES. 2015. Australian sugarcane farm businesses. Financial performance, 2013-14. In *Research report 15.14*, edited by H. Valle and P. Martin. Canberra: Australian Bureau of Agricultural and Research Economics.

Abdullah, F.A., and B.A. Samah. 2013. "Factors impinging farmers use of agriculture technology." *Asian Social Science,* 9 (3):1911-2025. doi: 10.5539/ass.v9n3p120.

ACIL Allen consulting. 2017. "Report: Victorian Feed in tariff: estimate of energy value." Victorian Government, Last Modified 18 December 2017, accessed 7 December https://www.esc.vic.gov.au/wp-content/uploads/2017/12/victorian-feed-in-tariff-fit-estimate-of-energy-value-acil-allen-report-to-essential-service-commission-20171219.pdf.

Agri Insights. 2018. Exploring energy use and investment in the Australian agribusiness sector,. In *Agri Insights Report*, edited by CommBank.

Allen, R.G., L.s. Pereira, D. Raes, and M. Smith. 2006. "Report: FAO Irrigation and Drainage Paper." accessed 8 December. https://www.kimberly.uidaho.edu/water/fao56/fao56.pdf.

Amutha, W. Margaret, and V. Rajini. 2016. "Cost benefit and technical analysis of rural electrification alternatives in southern India using HOMER." *Renewable and Sustainable Energy Reviews* 62:236-246. doi: 10.1016/j.rser.2016.04.042.

Andrew, R., J. Makindara, S.H Mbaga, and R. Alphonce. 2019. "Ex-Ante Analysis of Adoption of Introduced Chicken Strains Among Smallholder Farmers in Selected Areas of Tanzania." International Conference on Social Implications of Computers in Developing Countries.

Arist von, Schlippe, and Frank Hermann. 2013. "The Theory of Social Systems as a Framework for Understanding Family Businesses." *Family Relations* 62 (3):384.

ATO. 2020. "Instant asset write-off for eligible businesses." accessed 20 August. https://www.ato.gov.au/Business/Depreciation-and-capital-expenses-and-allowances/Simpler-depreciation-for-small-business/Instant-asset-write-off/.

Attard, S.J. 2017. "Pumps in the Burdekin region." 5 December 2017.

Australian Bureau of Meteorology, the. 2017. "Climate data online." accessed 16 November. http://www.bom.gov.au/climate/data/.

Australian Energy Council. 2017. "Electricity prices around the world – What is the impact of renewable charges?", accessed 11 Nov.

Australian Energy Regulator. 2018. "About Energy Bills." Australian Government, accessed 17 November. https://files.energymadeeasy.gov.au/About-energy-bills.pdf.

Australian Institute of Petroleum, the. 2018. "Regional Queensland Diesel Price average." accessed 7 October 2018. https://www.aip.com.au/pricing/Diesel/QLD/queensland-regional-average.

Australian National Audit Office. 2018. "Administration of the Renewable Energy Target." ANAO, accessed 14 August. https://www.anao.gov.au/work/performance-audit/administration-renewable-energy-target.

Australian Renewable Energy Agency. 2018. "ARENA - projects." Australian Government, accessed 30 October. https://arena.gov.au/projects/?project-value-start=0&project-value-end=500000000.

Bahramara, S., M. Parsa Moghaddam, and M. R. Haghifam. 2016. Optimal planning of hybrid renewable energy systems using HOMER: A review.

Baumgart-Getz, A., L. Prokopy Stalker, and K. Floress. 2012. "Why farmers adopt best management practice in the United States: A meta-analysis of the adoption literature." *Journal of environmental management* 96 (1):17-25. doi: 10.1016/j.jenvman.2011.10.006.

Beaton, C., P. Jain, Mini. Govindan, V. Garg, R. Murali, Dimple. Roy, A. Bassi, and G. Pallaske. 2019. Mapping Policy for Solar Irrigation Across the Water– Energy–Food (WEF) Nexus in India. edited by IISD. online.

Beca. 2015. OPPORTUNITIES FOR RENEWABLE ENERGY IN THE AUSTRALIAN WATER SECTOR,. edited by ARENA. https://arena.gov.au/assets/2016/01/Opportunities-for-renewable-energy-in-the-Australian-water-sector.pdf.

Beckman, Jayson, and Irene M. Xiarchos. 2013. "Why are Californian farmers adopting more (and larger) renewable energy operations?" *Renewable Energy* 55:322-330. doi: 10.1016/j.renene.2012.10.057.

Berril, T. 2016. "The Renewable Energy Revolution - Making it happen in the Sunshine State." Last Modified June 2016, accessed 19 November. https://trevolution.com.au/images/stories/presentations/Sustainable_Queensland_50_RE_issues_paper_submission_July_2016_Updated.pdf.pdf.

Best, Rohan, Paul J. Burke, and Shuhei Nishitateno. 2019. "Evaluating the effectiveness of Australia's Small-scale Renewable Energy Scheme for rooftop solar." *Energy Economics* 84:104475. doi: 10.1016/j.eneco.2019.104475.

Borchers, A. M., I. Xiarchos, and J. Beckman. 2014. "Determinants of wind and solar energy system adoption by U.S. farms: A multilevel modeling approach." 106.

BRIG. 2020. "Adapting renewable energy concepts to irrigated sugarcane at Bundaberg,." BRIG, accessed 4 April. http://brig.org.au/.

Brinker, Laura, and Andrew J. Satchwell. 2020. "A comparative review of municipal energy business models in Germany, California, and Great Britain: Institutional context and forms of energy decentralization." *Renewable and Sustainable Energy Reviews* 119:109521. doi: 10.1016/j.rser.2019.109521.

Brinsmead, T.S., J. Hayward, and P. Graham. 2014. Australian electricity market analysis report to 2020 and 2030. edited by CSIRO.

Bureau of Meteorology. 2018. "Koeppen Climate classification of Australia." accessed 10 May. http://www.bom.gov.au/jsp/ncc/climate_averages/climate-classifications/index.jsp?maptype=kpn#maps.

Burr, Chrystie. 2014. "Subsidies, tariffs and investments in the solar power market." *University of Colorado-Boulder Working Paper*.

Campana, Pietro Elia, Hailong Li, and Jinyue Yan. 2013. "Dynamic modelling of a PV pumping system with special consideration on water demand." *Applied energy*.

Carley, Sanya, Elizabeth Baldwin, Lauren M. MacLean, and Jennifer N. Brass. 2017. "Global Expansion of Renewable Energy Generation: An Analysis of Policy Instruments." 68:397-440. doi: 10.1007/s10640-016-0025-3.

Carroquino, Javier, Rodolfo Dufo-López, and José L. Bernal-Agustín. 2013. "Introducing Off-Grid Renewable Energy Systems for Irrigation in Mediterranean Crops." *Applied Mechanics and Materials* 330 (1):198.

Carroquino, Javier, Rodolfo Dufo-López, and José L. Bernal-Agustín. 2015. "Sizing of off-grid renewable energy systems for drip irrigation in Mediterranean crops." *Renewable Energy* 76:566-574. doi: 10.1016/j.renene.2014.11.069.

Castaneda, Monica, Sebastian Zapata, Judith Cherni, Andres J Aristizabal, and Isaac Dyner. 2020. "The long-term effects of cautious feed-in tariff reductions on photovoltaic generation in the UK residential sector." *Renewable Energy*.

CBA. 2018. Exploring energy use and investment in the Australian agribusiness sector. In *CommBank Agri Insights.*, edited by CBA. online.

CEFC. 2020a. "No-fuss solar helps farmer cut pumping costs,." CEFC, accessed 20 April. https://www.cefc.com.au/case-studies/no-fuss-solar-helps-farmer-cut-pumping-costs/.

CEFC. 2020b. "Where we invest: agribusiness." accessed 20 August. https://www.cefc.com.au/where-we-invest/sustainable-economy/agribusiness/.

Chandel, S. S., M. Nagaraju Naik, and Rahul Chandel. 2015. "Review of solar photovoltaic water pumping system technology for irrigation and community drinking water supplies." *Renewable and Sustainable Energy Reviews* 49:1084-1099. doi: 10.1016/j.rser.2015.04.083.

Chen, Guangnan, Craig Baillie, and Paul Kupke. 2009. "Evaluating On-farm Energy Performance in Agriculture." *Australian Journal of Multi-disciplinary Engineering* (1):55.

Chen, Guangnan, Gary Sandell, Talal Yusaf, and Craig Baillie. 2013a. Evaluation of alternative energy sources for cotton production in Australia. Engineers Australia.

Chen, Guangnan, Gary Sandell, Talal Yusaf, and Craig Baillie. 2013b. Evaluation of alternative energy sources for cotton production in Australia. Engineers Australia.

Clean Energy Regulator. 2016. "About the Renewable Energy Target." accessed 14 August. http://www.cleanenergyregulator.gov.au/RET/About-the-Renewable-Energy-Target/History-of-the-scheme#:~:text=Renewable%20energy%20has%20an%20important,cent%20renewable%20energy%20by%202020.&text=In%202009%2C%20this%20was%20increased,electricity%20(41%20000%20GWh).

Clean Energy Regulator. 2018a. "Auction June 2018." Australian Government, accessed 14 October. http://www.cleanenergyregulator.gov.au/ERF/Auctions-results/june-2018.

Clean Energy Regulator. 2018b. "REC Registry - What is a renewable energy certificate?", accessed 14 October. https://www.rec-registry.gov.au/rec-registry/app/public/what-is-a-rec.

Clean Energy Regulator. 2019. "2020 Large-scale RET capacity achieved." accessed 14 August. http://www.cleanenergyregulator.gov.au/RET/Pages/News%20and%20updates/NewsItem.aspx?ListId=19b4efbb-6f5d-4637-94c4-121c1f96fcfe&ItemId=684#:~:text=The%20Clean%20Energy%20Regulator%20has,will%20be%20met%20in%202020.

Clean Energy Regulator. 2020a. "About the Emissions Reduction Fund." accessed 10 April. http://www.cleanenergyregulator.gov.au/ERF/About-the-Emissions-Reduction-Fund.

Clean Energy Regulator. 2020b. "Energy efficiency methods." Australian Government, accessed 12 April. http://www.cleanenergyregulator.gov.au/ERF/Choosing-a-project-type/Opportunities-for-industry/energy-efficiency-methods.

Clean Energy Regulator, the. 2018c. "Renewable Energy Certificates calculator." accessed February. https://www.rec-registry.gov.au/rec-registry/app/home.

Comello, Stephen, and Stefan Reichelstein. 2017. "Cost competitiveness of residential solar PV: The impact of net metering restrictions." *Renewable and Sustainable Energy Reviews* 75:46-57. doi: 10.1016/j.rser.2016.10.050.

Cotton Australia. 2018. Irrigators - the flow-on benefits of regionally embedded generation,. edited by Cotton Australia. Energy Consumers Australia.

CottonInfo and NSW DPI. 2017. ERF: Industrial electricity and fuel efficiency method. edited by the Cotton Research and Development Corporation. online.

Crago, Christine Lasco, and Ilya Chernyakhovskiy. 2017. "Are policy incentives for solar power effective? Evidence from residential installations in the Northeast." *Journal of Environmental Economics and Management* 81:132-151.

CSIRO. 2019a. "ADOPT: Adoption Diffusion Outcome Prediction Tool,." accessed 7 October 2019. https://www.csiro.au/en/Research/Farming-food/Innovation-and-technology-for-the-future/ADOPT.

CSIRO. 2019b. "What is ADOPT?", accessed 23 October. https://www.csiro.au/en/Research/Farming-food/Innovation-and-technology-for-the-future/ADOPT.

Curraro, A. 2019. Sugar Research Australia Burdekin grower and advisor survey. No published.
Davis, Georgina, ed. 2018a. *The Energy-Water-Climate Nexus and Its Impact on Queensland's Intensive Farming Sector*, *The Impact of Climate Change on Our Life, the question of sustainability*: Springer.
Davis, Georgina. 2018b. "The Energy-Water-Climate Nexus and Its Impact on Queensland's Intensive Farming Sector." In *The Impact of Climate Change on Our Life*, 97-126.
de Arce, Miguel Pérez, and Enzo Sauma. 2016. "Comparison of incentive policies for renewable energy in an oligopolistic market with price-responsive demand." *The Energy Journal* 37 (3).
Department of Energy and Water Supply. 2017. "Decision regulatory impact statement - Queensland's statutory voltage limits." Queensland government, accessed 5 December. https://www.dews.qld.gov.au/__data/assets/pdf_file/0005/1279571/decision-ris-qld-statutory-voltage-limits.pdf.
Department of Environment. 2019. "Climate Solutions Package." Australian Government, accessed 18 April. https://www.environment.gov.au/system/files/resources/bb29bc9f-8b96-4b10-84a0-46b7d36d5b8e/files/climate-solutions-package.pdf.
Department of Industry, Science, Energy and Resources,. 2020. "The Renewable Energy Target Scheme." accessed 29 April. https://publications.industry.gov.au/publications/climate-change/climate-change/government/renewable-energy-target-scheme.html.
Department of the Environment and Energy. 2017. "National Greenhouse Accounts Factors." Australian Government, accessed 17 December. https://www.environment.gov.au/system/files/resources/5a169bfb-f417-4b00-9b70-6ba328ea8671/files/national-greenhouse-accounts-factors-july-2017.pdf.
Department of the Environment and Energy. 2018a. "Australian Energy Statistics." accessed 30 October. https://www.energy.gov.au/publications/australian-energy-update-2018.
Department of the Environment and Energy. 2018b. "The Renewable Energy Target Scheme,." accessed 30 May. http://www.environment.gov.au/climate-change/government/renewable-energy-target-scheme.
Dept of Energy and Water Supply. 2017. Decision regulatory impact statement - Queensland's statutory voltage limits. edited by D. online: Queensland government.
Dhehibi, B., M.B. Salah, A. Frija, A. Aw-Hassan, Y.M Al Raisi, I. Al, S.A.A Bousaidi, S Al Sobahi, and K. Al Shoaili. 2018. "Predicting Farmers' Willingness to Adopt Liquid Pollination and Polycarbonate Drying House Technologies: A Case Study from the Date Palm Growers in the Sultanate of Oman." *Sustainable Agriculture Research* 7 (4):18-30.
Dijkgraaf, Elbert, Tom P van Dorp, and Emiel Maasland. 2018. "On the effectiveness of feed-in tariffs in the development of solar photovoltaics." *The Energy Journal* 39 (1).
Dvorak, P., S. Martinat, D. Van der Horst, B. Frantal, and K. Tureckova. 2017. "Renewable energy investment and job creation; a cross-sectoral assessment for the Czech Republic with references to EU benchmarks." *Renewable and sustainable energy reviews.* 69 (March 2017):360-368.
EC. 2018. "Directive (EU) 2018/2001 of the European Parliment and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources." accessed May. http://data.europa.eu/eli/dir/2018/2001/oj.
Energy Information Administration. 2008. "Annual electric power industry report.". http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html.
Energy Victoria. 2020. "Minimum Feed-in-taiffs." accessed 14 April. https://www.energy.vic.gov.au/renewable-energy/victorian-feed-in-tariff/current-feed-in-tariff.

Ergon Energy. 2016. "Understanding Network Tariffs." Last Modified June 2016, accessed 5 December. https://www.ergon.com.au/__data/assets/pdf_file/0009/348066/Understanding-Network-Tariffs-More-than-100MWh-SAC-Large.pdf.

Ergon Energy. 2020. accessed 19 April. https://www.ergon.com.au/retail/residential/tariffs-and-prices/solar-feed-in-tariff.

Essential Energy. 2018. "Metering and Micro Embedded Genrators,." Essential Energy, accessed 22 October. https://www.essentialenergy.com.au/at-home/metering-and-renewable-generation-systems.

Eyre, D, J Alexandra, R Richards, and E Swann. 2014a. The Water & Energy Nexus: a Multi-Factor Productivity Challenge. NSW FA website.

Eyre, D, J Alexandra, R Richards, and E Swann. 2014b. "The Water & Energy Nexus: a Multi-Factor Productivity Challenge." accessed 10 June. http://www.nswfarmers.org.au/__data/assets/pdf_file/0019/46027/The-Water-and-Energy-Nexus-A-multi-factor-productivity-challenge.pdf.

Farquharson, R., and J.M. Welsh, eds. 2017. *The Economics and Perspectives of Site Specific Irrigation Management,*. Edited by S.M Pederson and K.M. Lind, *Precision Agriculture: Technology and Economic Perspectives*. Gewerbestrasse, Switzerland: Springer.

Fedrizzi, Maria Cristina, Fernando Selles Ribeiro, and Roberto Zilles. 2009. "Lessons from field experiences with photovoltaic pumping systems in traditional communities." *Energy for Sustainable Development* 13 (1):64-70. doi: 10.1016/j.esd.2009.02.002.

Foley, J.P., G.R. Sandell, P.M. Szabo, M. Scobie, and, and C.P. Ballie. 2015. Improving energy efficiency on irrigated Australian cotton farms: Benchmarking report. edited by National Centre for Engineering in Agriculture. http://www.cottoninfo.com.au/sites/default/files/documents/EnergyBenchmarkingReport_June2015.pdf.

Food and Agriculture Organisation. 2019. "FAO and the 2030 Agenda for Sustainable Development." FAO, accessed 14 August. http://www.fao.org/3/ca5299en/ca5299en.pdf.

Gamarra, Carlos, and Josep M. Guerrero. 2015. "Computational optimization techniques applied to microgrids planning: A review." *Renewable and Sustainable Energy Reviews* 48:413-424. doi: 10.1016/j.rser.2015.04.025.

García-Álvarez, María Teresa, Laura Cabeza-García, and Isabel Soares. 2018. "Assessment of energy policies to promote photovoltaic generation in the European Union." *Energy* 151:864-874. doi: 10.1016/j.energy.2018.03.066.

Garnaut, R. 2011. "Garnaut Climate Change Review - Electricity transformation." accessed 5 November. http://www.garnautreview.org.au/update-2011/garnaut-review-2011/chapter11.html.

Graham, Paul W., Thomas Brinsmead, and Steve Hatfield-Dodds. 2015. "Australian retail electricity prices: Can we avoid repeating the rising trend of the past?" *Energy Policy* 86:456-469. doi: 10.1016/j.enpol.2015.07.022.

Green Energy Markets. 2018. "STC Market Prices." accessed 14 October 2018. http://greenmarkets.com.au/resources/stc-market-prices.

Grizzetti, B., C. Liquete, P. Antunes, L. Carvalho, N. Geamănă, R. Giucă, M. Leone, S. McConnell, E. Preda, R. Santos, F. Turkelboom, A. Vădineanu, and H. Woods. 2016. "Ecosystem services for water policy: Insights across Europe." *Environmental Science & Policy* 66:179-190. doi: 10.1016/j.envsci.2016.09.006.

Haghi, Ehsan, Kaamran Raahemifar, and Michael Fowler. 2018. "Investigating the effect of renewable energy incentives and hydrogen storage on advantages of stakeholders in a microgrid." *Energy Policy* 113:206-222. doi: 10.1016/j.enpol.2017.10.045.

Heath, R, L Darragh, and A. Laurie. 2018. "The impacts of energy costs on the Australian agricultural sector." Last Modified August 2018, accessed 27 November. http://farminstitute.org.au/publications/research_report/energy.

Holden, J., and P. McGuire. 2014. Irrigation of Sugarcane Manual. In *Technical Publication MN1 4002*. http://elibrary.sugarresearch.com.au/bitstream/handle/11079/14553/Irrigation%20of%20Sugarcane%20Manual.pdf?sequence=1.

Hybrid Optimisation of Multiple Energy Resources. 2018. "HOMER optimisation design software." accessed January-May. https://www.homerenergy.com/.

IEA. 2019. World Energy Outlook - Executive Summary. edited by International Energy Agency. online.

International Renewable Energy Agency. 2017. Electricity Storage and Renewables: Costs and markets to 2030. website.

IPCC. 2014. Summary for Policymakers. . In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by IPCC. online.

IRENA. 2018. Renewable Energy Policies in a time of Transition. online.

IRENA. 2019. Global energy transformation: The REmap transition pathway (Background report to 2019 edition). edited by International Renewable Energy Agency. Abu Dhabi.

IRENA. 2019b. Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables. edited by International Renewable Energy Agency. Abu Dhabi.

Jaramillo, A. 2018. "Irrigation pumps in the Burdekin region." 15 April 2018.

Katzman, M.T, and R.W. Matlin. 1978. "The economics of adopting solar energy systems for crop irrigation,." *American Journal of Agricultural Economics* 60:648-654.

Knowler, Duncan, and Ben Bradshaw. 2007. "Farmers' adoption of conservation agriculture: A review and synthesis of recent research." *Food Policy* 32 (1):25-48. doi: 10.1016/j.foodpol.2006.01.003.

Koech, R. K., R. J. Smith, and M. H. Gillies. 2014. "A real-time optimisation system for automation of furrow irrigation." *Irrigation Science* 32 (4):319-327. doi: 10.1007/s00271-014-0432-6.

KPMG. 2018. Optimising network incentives. In *Alternative approaches to promoting effecient network investment*, edited by KPMG. online: KPMG.

Kuehne, G., R. Llewellyn, D. Pannell, R. Wilkinson, P. Dolling, J. Ouzman, and M. Ewing. 2017. "Predicting farmer uptake of new agricultural practices: A tool for research, extension and policy." *Agricultural Systems* 153:115-125.

Kuehne, Geoff, Cam Nicholson, Michael Robertson, Rick Llewellyn, and Cam McDonald. 2012. "Engaging project proponents in R&D evaluation using bio-economic and socio-economic tools." *Agricultural Systems* 108:94-103. doi: 10.1016/j.agsy.2012.01.009.

Kulichenko, Natalia. 2012. *Concentrating solar power in developing countries regulatory and financial incentives for scaling up*. Edited by Jens Wirth, *World Bank Studies*. Washington, D.C: World Bank.

Land and Water Australia. 2020. "The Economic Benefits of Irrigation to National and Regional Economies." accessed 14 August, 2020. http://lwa.gov.au/node/2326#:~:text=Irrigation%20contributes%3A,saving%20%244%20billion%20in%20imports.

Li, Shin-Je, Ting-Huan Chang, and Ssu-Li Chang. 2017. "The policy effectiveness of economic instruments for the photovoltaic and wind power development in the European Union." *Renewable Energy* 101:660-666.

Local Lands Services. 2020. "Frequently asked questions about Local Lands Services rates." accessed 27 April.

https://www.lls.nsw.gov.au/__data/assets/pdf_file/0005/849848/2020-Rates-External-FAQ-document.pdf.
Love, G. 2005. "Impacts of climate variability on regional Australia." Climate Session Papers, Canberra.
Markard, Jochen. 2018. "The next phase of the energy transition and its implications for research and policy." *Nature Energy* 3 (8):628-633. doi: 10.1038/s41560-018-0171-7.
Martin, Nigel, and John Rice. 2018. "Solar Feed-In Tariffs: Examining Fair and Reasonable Retail Rates Using Cost Avoidance Estimates." *Energy Policy* 112:19-28.
Maurya, V.N., G. Ogubazghi, B.P. Misra, A.K. Maurya, and D.K Arora. 2015. "Scope and Review of Photovoltaic Solar Water Pumping System as a Sustainable Solution Enhancing Water Use Efficiency in Irrigation " *American Journal of Biological and Environmental Statistics* 1 (1):1-8. doi: 10.11648/j.ajbes.20150101.11.
McCarthy, Breda, Lynne Eagle, and Hayden Lesbirel. 2017. "Barriers to the diffusion of renewable energy in Queensland." *Rural Society: SPECIAL ISSUE: SUSTAINABLE ECONOMIC GROWTH FOR REGIONAL AUSTRALIA 2016 CONFERENCE* 26 (3):210-224. doi: 10.1080/10371656.2017.1364480.
Md Asaduzzaman, S., and G.M. Shafiullah. 2018. "Renewable energy integrated islanded microgrid for sustainable irrigation - A Bangladesh perspective." *Energies* 11 (5):1-19.
Mushtaq, S., T. N. Maraseni, K. Reardon-Smith, J. Bundschuh, and T. Jackson. 2015. "Integrated assessment of water–energy–GHG emissions tradeoffs in an irrigated lucerne production system in eastern Australia." *Journal of Cleaner Production* 103:491-498. doi: 10.1016/j.jclepro.2014.05.037.
NASA. 2018. "Surface Meteorology and Solar Energy." accessed 18 March. https://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi?email=wctauber@aol.com.
National Irrigators Council. 2014. Agricultural Competitiveness. In *Australian Government Green Paper*. http://agwhitepaper.agriculture.gov.au/GP%20Submissions%20for%20publication/GP295%20National%20Irrigators'%20Council.pdf.
Nelson, R., C. Xia, and B. Agbenyegah. 2019. Prospects for the Australian Sugar Industry. edited by Department of Agriculture and Water Resources: ABARE.
NSW Dept of Planning, Industry and Environment. 2020. "Case study: Businesses share solar power to save money and reduce emissions." accessed 14 April. https://energy.nsw.gov.au/media/1896/download.
Oliva H, Sebastian, Iain MacGill, and Rob Passey. 2016. "Assessing the short-term revenue impacts of residential PV systems on electricity customers, retailers and network service providers." *Renewable and Sustainable Energy Reviews* 54:1494-1505. doi: 10.1016/j.rser.2015.10.094.
Parliament of Australia. 2018. "Feed In Tariffs." Australian Government, accessed 10 May 2018. https://www.aph.gov.au/About_Parliament/Parliamentary_Departments/Parliamentary_Library/Browse_by_Topic/ClimateChangeold/governance/domestic/national/feed.
Pearl, J. 2018. Seasonal Forecasting adoption: ADOPT summary report.
Perez, Richard, Karl R. Rábago, Mike Trahan, Lyle Rawlings, Ben Norris, Tom Hoff, Morgan Putnam, and Marc Perez. 2016. "Achieving very high PV penetration – The need for an effective electricity remuneration framework and a central role for grid operators." *Energy Policy* 96:27-35. doi: 10.1016/j.enpol.2016.05.016.
Peters, B.G., G. Capano, M. Howlett, I. Mukherjee, M-H Chou, and P. Ravinet. 2018. *Designing for Policy Effectiveness: Defining and Understanding a Concept. Elements in Public Policy.* : Cambridge University Press.
Pick, J.B. 2017. *Renewable Energy: Problems and Prospects in Coachella Valley, California*. Vol. 52. https://inspire.redlands.edu/oh_books/52: Springer.

Powell, J. W., J. M. Welsh, and R. Farquharson. 2019. "Investment analysis of solar energy in a hybrid diesel irrigation pumping system in New South Wales, Australia." *Journal of Cleaner Production* 224:444-454. doi: 10.1016/j.jclepro.2019.03.071.

Powell, J.P., J.M. Welsh, and R. Farquharson. 2018. "Investment analysis of solar energy in a hybrid diesel irrigation pumping system in New South Wales, Australia. ." *Journal of Cleaner Production,* (Under Review).

Powell, J.W., and J.M. Welsh. 2016a. Grid connected solar: Irrigation case studies. Available at; http://www.cottoninfo.com.au/sites/default/files/documents/Cotton%20Energy_GRID%20CONNECTED%20SOLAR.pdf.

Powell, J.W., and J.M. Welsh. 2016b. Solar Energy – policy setting and applications to cotton production. In *CottonInfo reports and analyses*, edited by CottonInfo. website.

Powell, J.W., and J.M. Welsh. 2016c. "The sums add up for solar powered irrigation." *The Australian Cotton Grower* October-November:22-25.

QFF. 2020. "Energy Savers Program." Queensland Farmers Federation, accessed 5 April https://www.qff.org.au/projects/energy-savers/information-resources/.

QRIDA. 2020. "Sustainability Loan Program." accessed 25 April. https://www.qrida.qld.gov.au/entity/primary-producer/Sustainability-Loan-Primary-producer.

Queensland Government. 2018. "Feed-in-tariffs for regional Queensland." accessed 10 May. https://www.qld.gov.au/housing/buying-owning-home/feed-in-tariff-regional-queensland.

Queensland Government. 2019. "Queensland Hydrogen Industry Strategy." accessed 14 July 2020. https://www.dsdmip.qld.gov.au/resources/strategy/queensland-hydrogen-strategy.pdf.

Queensland Rural and Industry Development Authority. 2020. "Sustainability Loan - Primary producer." accessed 19 April. https://www.qrida.qld.gov.au/entity/primary-producer/Sustainability-Loan-Primary-producer.

Ratnam, Elizabeth L., Steven R. Weller, and Christopher M. Kellett. 2015. "Scheduling residential battery storage with solar PV: Assessing the benefits of net metering." *Applied Energy* 155:881-891. doi: 10.1016/j.apenergy.2015.06.061.

Renouf, M.A., and M.K. Wegener. 2007. "ENVIRONMENTAL LIFE CYCLE ASSESSMENT (LCA) OF SUGARCANE PRODUCTION AND PROCESSING IN AUSTRALIA " Proc. Aust. Soc. Sugar Cane Technol.

Rizi, Atefeh Parvaresh, Afshin Ashrafzadeh, and Azita Ramezani. 2019. "A financial comparative study of solar and regular irrigation pumps: Case studies in eastern and southern Iran." *Renewable Energy* 138:1096-1103. doi: 10.1016/j.renene.2019.02.026.

Roocke, Neroli. 2014. "Smart phone means smart irrigation." *Australian Canegrower* (13 Oct 2014):20.

Roth, Guy, Graham Harris, Malcolm Gillies, Janelle Montgomery, and David Wigginton. 2013. "Water-use efficiency and productivity trends in Australian irrigated cotton: a review." *Crop & pasture science* 64 (12):1033.

Rubio-Aliaga, Á, M. S. García-Cascales, J. M. Sánchez-Lozano, and A. Molina-García. 2019. "Multidimensional analysis of groundwater pumping for irrigation purposes: Economic, energy and environmental characterization for PV power plant integration." *Renewable Energy: An International Journal* 138:174-186. doi: 10.1016/j.renene.2019.01.077.

Rutovitz, J., A. Atherton, L. McIntosh, S. Teske, and E. Langham. 2016. "Virtual Trial of local network credits and local electricity trading: Byron Shire Council." University of Technology, Sydney, accessed 18 April. https://www.uts.edu.au/sites/default/files/LNCLET_Trial_Case_study_Byron_final_v3.pdf.

Schultz, Bart, Avinash Tyagi, Somkiat Apipattanavis, Zhanyi Gao, Yunxin Zhang, Lihui Gao, and Ruoxi Li. 2018. "Progress on Solar Photovoltaic Pumping Irrigation Technology." *Irrigation and Drainage* (1):89. doi: 10.1002/ird.2196.

Sen, Rohit, and Subhes C. Bhattacharyya. 2014. "Off-grid electricity generation with renewable energy technologies in India: An application of HOMER." *Renewable Energy* 62:388-398. doi: 10.1016/j.renene.2013.07.028.

Sinden, J.A., and D.J. Thampapillai. 1995. *Introduction to benefit-cost analysis*. Melbourne: Longman.

Solar Choice. 2020. "Which electricity retailer is giving the best solar feed-in tariff?", accessed 15 April. https://www.solarchoice.net.au/blog/which-electricity-retailer-is-giving-the-best-solar-feed-in-tariff/.

Srinivasan, Sunderasan, and Vamshi Krishna Reddy Kottam. 2018. "Solar photovoltaic module production: Environmental footprint, management horizons and investor goodwill." *Renewable and Sustainable Energy Reviews* 81 (Part 1):874-882. doi: 10.1016/j.rser.2017.08.031.

Suess-Reyes, Julia, and Elena Fuetsch. 2016. "The future of family farming: A literature review on innovative, sustainable and succession-oriented strategies." *Journal of Rural Studies* 47 (Part A):117-140. doi: 10.1016/j.jrurstud.2016.07.008.

Trade and Investment Queensland. 2020. "Queensland renewable energy - a state of opportunity." accessed 27 April. https://www.tiq.qld.gov.au/download/business-interest/invest/19007-MRE-TIQ-Renewables-brochure_v5.pdf.

Trinasolar. 2018. "Products and solutions, monocrystalline datasheets." accessed 6 August. https://www.trinasolar.com/us/resources/downloads#TSM-DD05A-08-2.

Turner, James A., Kelly Rijswijk, Tracy Williams, Tim Barnard, and Laurens Klerkx. 2013. "Challenges to effective interaction in the New Zealand agricultural research and extension system: An innovation systems analysis." *Extension Farming Systems Journal* 9 (1):89.

United States Environmental Protection Agency. 2016. "Direct Emissions from Mobile Combustion Sources." accessed 10 September. https://www.epa.gov/sites/production/files/2016-03/documents/mobileemissions_3_2016.pdf.

Vick, B. D., and L. K. Almas. 2011. "Developing Wind and/or Solar Powered Crop Irrigation Systems for the Great Plains." *Applied engineering in agriculture* 27 (2):235-245.

Vick, Brian D., and R. Nolan Clark. 2009. "Determining the optimum solar water pumping system for domestic use, livestock watering or irrigation." *Solar 2009 : Buffalo/Niagara, May 11-16, 2009 : proceedings of the 38th ASES National Solar Conference, proceedings of the 34th National Passive Solar Conference, proceedings of the 4th Annual Renewable Energy Policy, Advocacy and Marketing Conference / edited by R. Campbell-Howe*.

Vick, Brian D., and Byron A. Neal. 2012. "Analysis of off-grid hybrid wind turbine/solar PV water pumping systems." *Solar Energy* 86:1197-1207. doi: 10.1016/j.solener.2012.01.012.

Welsh, J. 2016. Solar pumping: economic and environmental rewards. In *Grower fact sheets - energy efficiency*, edited by CottonInfo. website.

Welsh, J.M., and J.P. Powell. 2019. The funding options for innovative energy in sugarcane irrigation. edited by Ag Econ. online: Sugar Research Australia.

Welsh, J.M., and J.W. Powell. 2017. Opportunities for energy innovation in Australian irrigated sugarcane. In *Sugar Research Australia Report.* Burren Junction, NSW, Australia: Ag Econ.

Wheeler, S., A. Zuo, and H. Bjornlund. 2013. "Farmers' climate change beliefs and adaptation strategies for a water scarce future in Australia." *Global Environmental Change* 23 (2):537-547. doi: 10.1016/j.gloenvcha.2012.11.008.

Wu, X., M. Howlett, and M. Ramesh. 2017. *Policy Capacity and Governance: Assessing Governmental Competences and Capabilities in Theory and Practice.*: Springer.

Zander, Kerstin K., Genevieve Simpson, Supriya Mathew, Rabindra Nepal, and Stephen T. Garnett. 2019. "Preferences for and potential impacts of financial incentives to install residential rooftop solar photovoltaic systems in Australia." *Journal of Cleaner Production* 230:328-338. doi: 10.1016/j.jclepro.2019.05.133.

Zhou, Deyi, Abdullah, and Fatih Yildiz. 2017. "The acceptance of solar water pump technology among rural farmers of northern Pakistan: A structural equation model." *Cogent Food & Agriculture* 3 (1).

Zulfiqar, Farhad, Raza Ullah, Muhammad Abid, and Abid Hussain. 2016. "Cotton production under risk: a simultaneous adoption of risk coping tools." *Natural Hazards* 84 (2):959-974. doi: 10.1007/s11069-016-2468-9.