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

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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 >40 kW), 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 kW), reducing NPC of pumping from 12 to 25% and emission reductions ranging from 1245 t CO_2e to 1314 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.

1. Introduction

Most Australian electricity is generated from fossil fuels that produce carbon dioxide (CO_2) emissions (Department of the Environment and Energy, 2018). 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 et al., 2009; Foley et al., 2015), automation and application of new technology (Roth et al., 2013; Koech et al., 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. (2013) 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. (2014) 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

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Abbreviations

CO_2e	Carbon Dioxide equivalent
ERF	Emissions Reduction Fund
FiT	Feed-in tariff
genset	Diesel Generator
DNSP	Distribution Network Service Provider
kW	Kilowatts of power
LCOE	Levelised Cost of Energy
NMI	National Meter Identifier
PV	Photovoltaic
RET	Renewable Energy Target
STCs	Small Technology Certificates
TOU	Time of Use

Qinghai 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). In a review of solar PV systems for irrigation and community drinking water Chandel et al. (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, 2016b) 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 micro-grids 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 et al. (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 et al. (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 et al., 2018; Davis, 2018), this analysis focuses on sugarcane irrigators in a unique setting of the highly regulated regional Queensland electricity network and monopoly retail market.

2. 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 Fig. 1. HOMER decision support software is used to design optimised microgrid systems for each site (Hybrid Optimisation of Multiple Energy Resources, 2018). 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 Fig. 2), 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

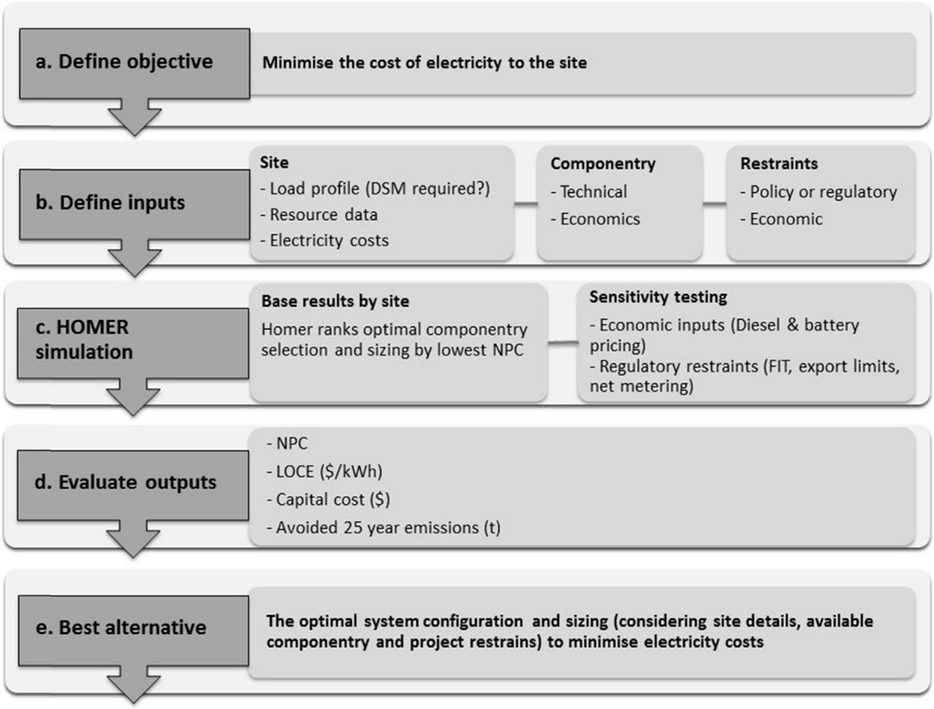

Fig. 1. Methodology framework.

Fig. 2. A map of the case study sites: Site A (Ayr), Site B (Marian) and Site C (Bundaberg).

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 et al. (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.

2.1. 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 Fig. 2).

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 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).

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.

2.2. 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.

2.3. 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 h. 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.

2.3.1. 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.

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

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[a]	1058 mm	1655 mm	1048 mm
Industry proportion of energy use for irrigation[b]	64%	8%	9%

[a] Australian Bureau of Meteorology (2017).
[b] Welsh and Powell (2017).

2.3.2. 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 h 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.

2.3.3. 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 h per day. Consumption and day-to-day variability details entered into HOMER decision support are summarised in Table 2.

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.

2.4. 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. Fig. 3 is the schematic system configuration for Site B, pivot pump house. All sites considered identical component costings, each with their own unique load profiles.

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.

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-W monocrystalline module has a 25-year lifetime, so required no

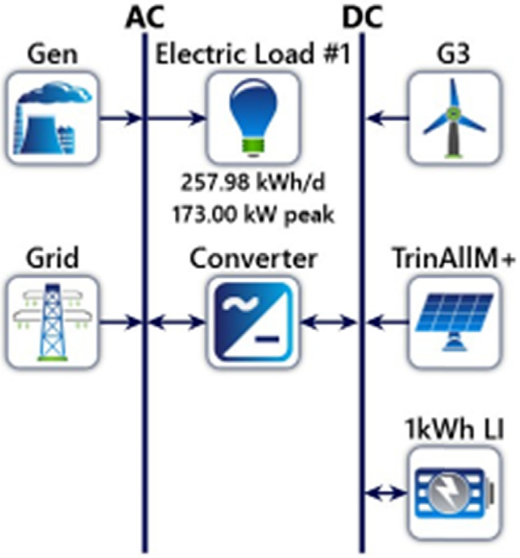

Fig. 3. HOMER example schematic for Site B – Pivot pump house.

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

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 h
Lithium-ion battery	$800/kWh	$10/kWh	15 years
System converter	$300/kW	$0	15 years

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. 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 2.8 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.

2.6. 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 system. A list of scenarios in the sensitivity analysis is shown in Table 4.

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.

2.7. 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.

2.8. 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’.

3. 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.

3.1. Optimisation results

The optimal componentry combinations for each site, based on

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

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

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 h 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.

The reduced cost of energy under these investment scenarios will lower production costs, improve enterprise gross margins, encourage more frequent irrigation practices and potentially lead to higher yields. 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.

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	1539	49%	892	$0.128	$0.273	$177,000	$238,000	1303
B	Partial shift	2354	9%	1503	$0.16	$0.299	$351,000	$400,000	1314
C	Not shifted	2108	15%	1270	$0.159	$0.318	$306,000	$381,000	1245

3.2. 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 Fig. 4) 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 Fig. 4). 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.

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. Fig. 5: Site B and Site C sensitivity analysis, LCOE, Figs. 5 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.

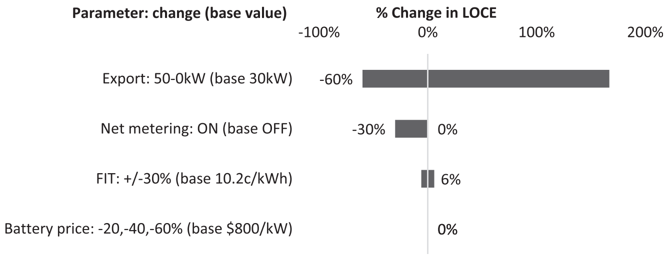

Fig. 4. Sensitivity analysis of the key input parameters for Site A LCOE.

A range of export limit scenarios (0–50 kW) for sites B and C were tested (Fig. 5). 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. Fig. 6 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 (Fig. 6) 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 et al. (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.

3.3. 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

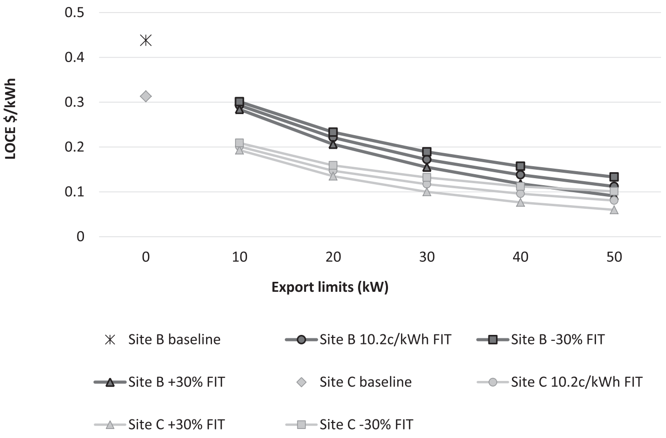

Fig. 5. Site B and Site C sensitivity analysis, LCOE.

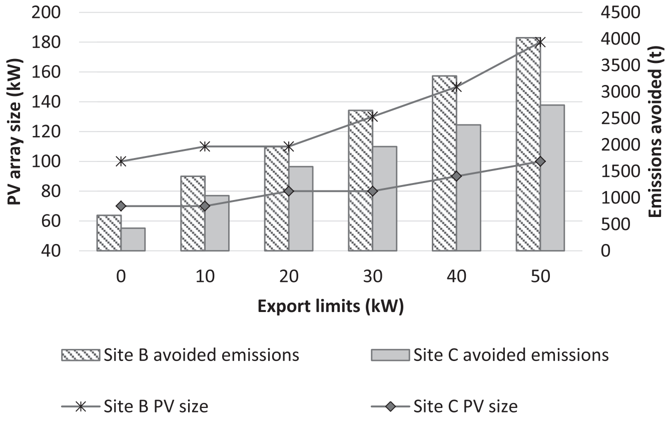

Fig. 6. Site B and Site C sensitivity analysis; export limits and avoided emissions.

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.

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 (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 is 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.

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 $/$CO_2$e				
			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

4. 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.118177.

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