Agrivoltaic grazing systems in Queensland

The potential, challenges, and opportunities for the co-existence of grazing and solar power plants in Queensland

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Queensland Government

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The Department of Agriculture and Fisheries proudly acknowledges all First Nations peoples (Aboriginal peoples and Torres Strait Islanders) and the Traditional Owners and Custodians of the country on which we live and work. We acknowledge their continuing connection to land, waters and culture and commit to ongoing reconciliation. We pay our respect to their Elders past, present and emerging.

Executive summary

This report provides a review of the potential, challenges, and opportunities for the co-existence of grazing systems and utility-scale solar energy production in Queensland. The land area under solar power plants is expected to increase 7.4-fold over the coming years, with 84 new plants proposed for development. These developments are expected to occur close to the primary transmission network in eastern Queensland. Many of these developments are likely to occur on land currently used for agriculture.

Solar power plant developers are motivated to maximise profit per ha from energy generation and this appears likely to vastly exceed returns possible from agriculture on the same land area. There are a current lack of incentives to motivate solar power plant developers to prioritise agrivoltaics if the arrays are more costly to deploy than traditional ground-mounted photovoltaic systems.

However, the costs incurred on vegetation control and landscape management by solar power plant operators appear to be significant. As a consequence, the power plant operators are likely to consider the potential cost savings associated with grazing livestock on solar power plants as a method of vegetation control. It is likely that solar power plant operators will not be skilled in livestock operations and will therefore look for livestock owners to stock the plants. Depending upon the level of cost saving expected by the solar power plant operators, they are likely to offer incentives to livestock owners, including offering free agistment, with conditions. The solar power plant operator may not want livestock on the power plant all of the time and the livestock may have to be applied at a high stocking rate to significantly reduce biomass. Therefore, the agistment comes with risks for the livestock owner. Furthermore, it is likely that significant up-front capital will be required to enable grazing of solar power plants by livestock. Which party supplies this additional capital will influence the nature and length of grazing contracts and could determine whether agrivoltaics is pursued by solar power plant operators.

An economic analysis from the perspective of the livestock owner indicated that, when agistment is free and additional development costs are low to moderate, there appears to be value in grazing either beef cattle or meat sheep on solar power plants in the following circumstances:

1) The plant is located on either high or medium productivity land types, and
2) The reduction in stocking rate due to solar infrastructure is minimal.

Additionally,

1) Under circumstances where no additional capital investment, other than livestock capital, is required by the livestock owner, short term grazing contracts would be viable; however,
2) Where low to moderate levels of capital investment are required by the livestock owner, only long term grazing contracts would be viable (i.e. up to the 30 years applied in this analysis).

In the analysis, grazing beef weaner steers or a meat sheep flock gave similar investment returns for equivalent levels of 1) reduction in stocking rate and 2) additional development cost. However, the cost of setting up a solar power plant for cattle grazing is expected to be significantly greater than setting up the same solar power plant for grazing by a flock of meat sheep. It is therefore considered unlikely that cattle, even weaner steers, will be used to graze solar power plants due to the additional capital required when compared to a meat sheep enterprise. This latter statement may not hold true if investment in an exclusion fence is required to successfully graze meat sheep. Further work is required to assess relevant scenarios. Economics of size will be important to the livestock owner as the expected benefits of grazing a small solar power plant may not cover the additional labour and management effort incurred. Furthermore, for the grazing activity to be worthwhile, the annualised returns have to be greater than the value of the annual labour and management required for the solar grazing activity, as these were not included in the analysis.

Investment returns for solar grazing projects decreased as land productivity, and associated livestock carrying capacity, decreased. Solar power plants on low productivity land were assessed as unlikely to be profitable for grazing by the majority of livestock owners, even with no reduction in stocking rates and nil development cost. As expected, investment returns decreased in line with 1) reductions in stocking rate due to solar panel projects and 2) with increases in additional development costs.

This preliminary review and analysis indicates that solar power plants and livestock grazing need not be mutually exclusive. There has been a lack of uptake of cattle co-grazing in Australia (and internationally) and further work is required to identify the particular impediments that apply and whether these can be overcome. Flocks of meat sheep are relatively rare in the regions of eastern Queensland where the majority of solar power plants are proposed for development. Further work is required to identify whether flocks of meat sheep can be established and expanded in these regions to undertake the amount of grazing likely to become available on solar power plants (i.e. ca. 100,000 ha).

Recommendations resulting from this review include:

1) Conduct more detailed and extensive analysis to identify how it may be possible to incentivise investment, in additional solar project infrastructure costs, to enable co-existence with grazing, particularly cattle.

2) Conduct field research to improve knowledge and understanding of how solar grazing could optimally occur, for both cattle and sheep grazing at representative sites across Queensland. To provide useful data for economic feasibility studies, paired solar and non-solar sites that are representative of key regions targeted for REZ development should be established to provide data sets and insights on:

    - The most suitable forage species (grass and legume) adapted to growth under partial shading in a range of environments and soil types.
    - Pasture biomass growth and forage quality of the most suitable adapted species (grass and legume) to partial shading.
    - Grazing management for optimal pasture and livestock productivity.
    - Effects of PV arrays on livestock health, diet quality and productivity.
    - The economic efficiency of livestock enterprises co-located with utility-scale solar power plants.

3) Analysis to examine the feasibility of zoning and development of primary production processing plants in the regions, which could utilise power off-take from solar plants. The objective would be to value-add to (or offset negative regional and agricultural consequences of) solar plant locations on agricultural land.

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1. Background

The *Queensland Energy and Job's Plan* (The State of Queensland 2022a, 2023b) has set a target to achieve 50% renewable energy by 2030, 70% by 2032, and 80% by 2035, by connecting 22 gigawatts (GW) of new wind and solar generation. The Queensland Government has outlined the optimal infrastructure pathway in the *Queensland SuperGrid Infrastructure Blueprint* with a proposed backbone transmission line down the east coast of Queensland (The State of Queensland 2022a). New Queensland laws are under development to establish the framework for declaring and developing Queensland Renewable Energy Zones (REZs; The State of Queensland 2023a).

Developments within the REZs will be supported by regional plans which are statutory, long-term strategic documents that guide decision-making and investment for state and local governments (The State of Queensland 2023c). These regional plans identify Priority Agricultural Areas (PAAs) which contain strategic clusters of the most significant agricultural production areas with designated Priority Agricultural Land Uses (PALU; e.g. broadacre cropping, horticulture, intensive animal husbandry, plantation forestry and terrestrial aquaculture). Any non-agricultural resource activity seeking to operate in these areas will not be supported unless they can co-exist with the PALUs for mutual benefit and without compromising the PALU's current or future ability to operate. The PAAs and PALUs are defined terms under the *Regional Planning Interests Act 2014* (The State of Queensland (Office of the Queensland Parliamentary Counsel) 2014-2024a) and the *Planning Act 2016* (The State of Queensland (Office of the Queensland Parliamentary Counsel) 2014-2024b). The most recently updated regional plans, North Queensland Regional Plan March 2020 and Wide Bay Burnett Regional Plan 2023, state that establishment of renewable energy systems for off-grid or site-specific uses may be supported within PAAs, where they directly support on-site agricultural production and processing activities (The State of Queensland 2020, 2022b).

By inference, it would appear that REZ developments in Queensland will occur on lands currently utilised for grazing cattle in eastern Queensland (as sheep grazing primarily occurs in western Queensland). Pasture lands are designated 'Agricultural Land Class C' (The State of Queensland 2015) and do not fall within the PAA and PALU categories protected from development.

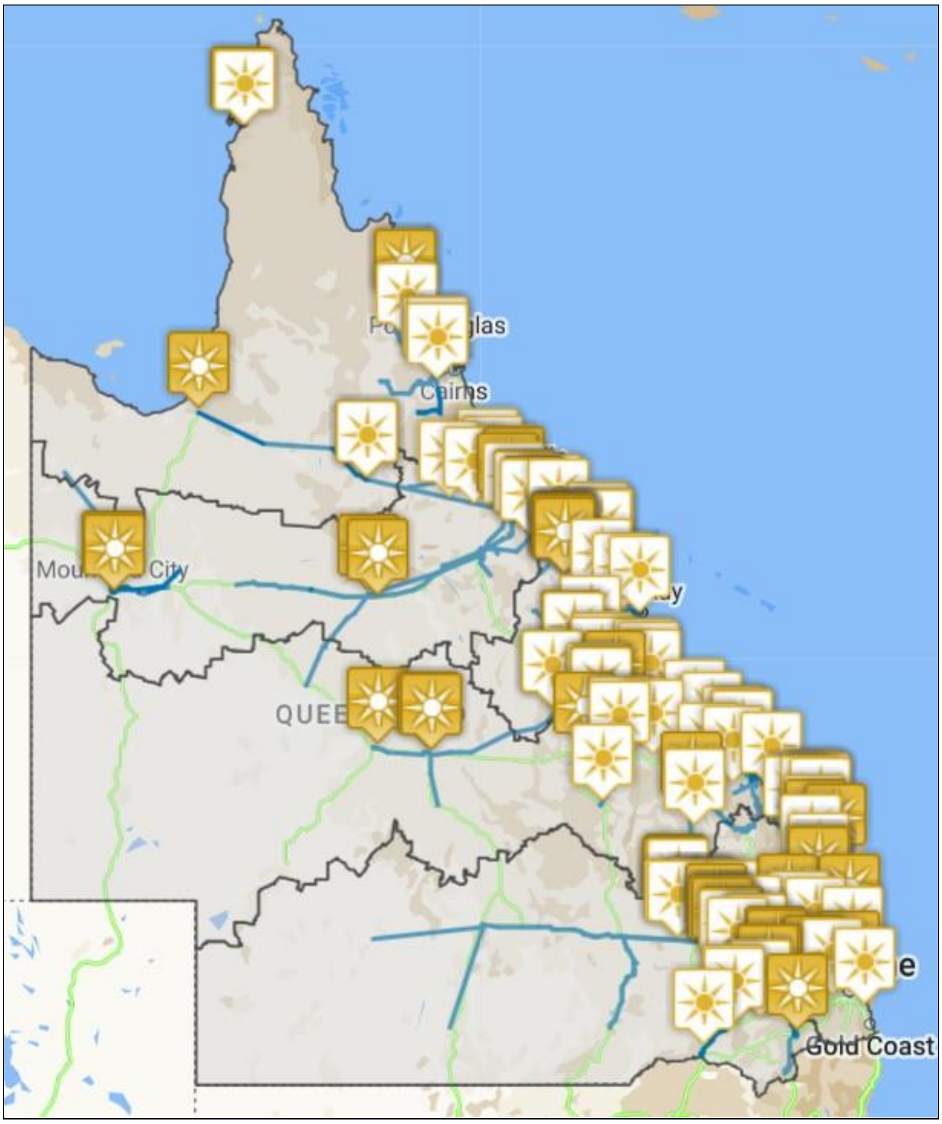
Agrivoltaics (also referred to as 'agrisolar') is the simultaneous use of areas of land for both agricultural production systems and solar panel projects. An investigation of the potential for agrivoltaics in Queensland is a priority given the anticipated growth in renewable energy projects over the next decade in Queensland. Furthermore, an investigation of the potential for co-existence of livestock grazing with utility-scale solar projects (i.e. 'solar grazing'), is of most importance given the likelihood that much of this development will occur on grazing lands currently used for beef cattle production.

2. Current status

2.1 Characteristics and location of solar power plants in Queensland

Australian solar power plants generally use one of the following technology types: fixed arrays, single-axis trackers, or dual-axis trackers (The State of Queensland 2018). Fixed arrays are set at a position calculated to provide optimal power output. Single-axis trackers follow the sun as it crosses the sky in one direction. Dual-axis trackers track the sun across the sky as well as adjusting for seasonality. The single-axis trackers achieve more output than fixed arrays and may use less land area than dual-axis trackers which require larger spacing. In Queensland, there are currently 131 existing and proposed solar power plants identified, with a total capacity of 25,035 megawatts (MW), (Figure 1). These are comprised of 43 existing (3,248 MW), 4 under construction (130 MW), and 84 proposed (21,656 MW) solar plants (The State of Queensland 2023d). Based on the expected energy generating capacity of the proposed power plants, this equates to 7.4-fold increase in land area under solar power plants in Queensland.

Figure 1 Location of the 131 identified solar power plants in Queensland with yellow boxes signifying power plants either existing or under construction and white boxes identifying proposed solar plants. The regional Ergon distribution network is identified as blue lines (The State of Queensland 2023d; downloaded 05/02/2024; https://electricity-generation-map.epw.qld.gov.au/)



The *Queensland Solar Farm Guidelines* indicate that ca. 2-3 ha of land is required per 1 MW of power generation (The State of Queensland 2018). However, development areas may have watercourses or other exclusion areas which are not suitable for solar panel infrastructure, necessitating a larger land area per MW. An example of a solar power plant layout is provided in Figure 2 and Figure 3 for Lilyvale Solar Farm, located in central Queensland near Tieri, 50 km north-east of Emerald. The area of the farm is 387 ha, with a contracted capacity of 100 MW (frv 2023a; The State of Queensland 2023d). If the Lilyvale Solar Farm is assumed to be broadly representative of other solar developments likely to occur in Queensland, then an area of 3.87 ha is required to produce ca. 1 MW capacity. The *Queensland Energy and Jobs Plan* (The State of Queensland 2022a) indicates that ca. 13.5 GW capacity is anticipated to be supplied by solar photovoltaic (PV) technology by 2039-40. Based on the MW output per land area for Lilyvale Solar Farm as an example, this indicates that a minimum 52,245 ha of land will be required for solar farm development across Queensland with additional areas required for supporting infrastructure and transmission lines. However, working on the same estimate of land area required per MW output (i.e. 3.87 ha per 1 MW), an area of ca. 96,882 ha will be under solar power plant infrastructure in coming years if all proposed power plants currently identified for development by The State of Queensland (2023d), proceed. Thus the target of 13.5 GW solar output by 2039-40 will be exceeded by 1.85-fold (25 GW total capacity identified with existing and proposed plants). It is likely that there will be some efficiency improvements in solar panel output over time. Regardless, the estimates above provide an indication of the potential solar plant footprint.

Figure 2 Lilyvale Solar Farm in central Queensland near Tieri (Google earth imagery; downloaded 06/02/2024)

Figure 3 Closer view of panel arrangement and spacing at Lilyvale Solar Farm in central Queensland, near Tieri (Google earth imagery; downloaded 06/02/2024)

2.2 Solar grazing in Australia

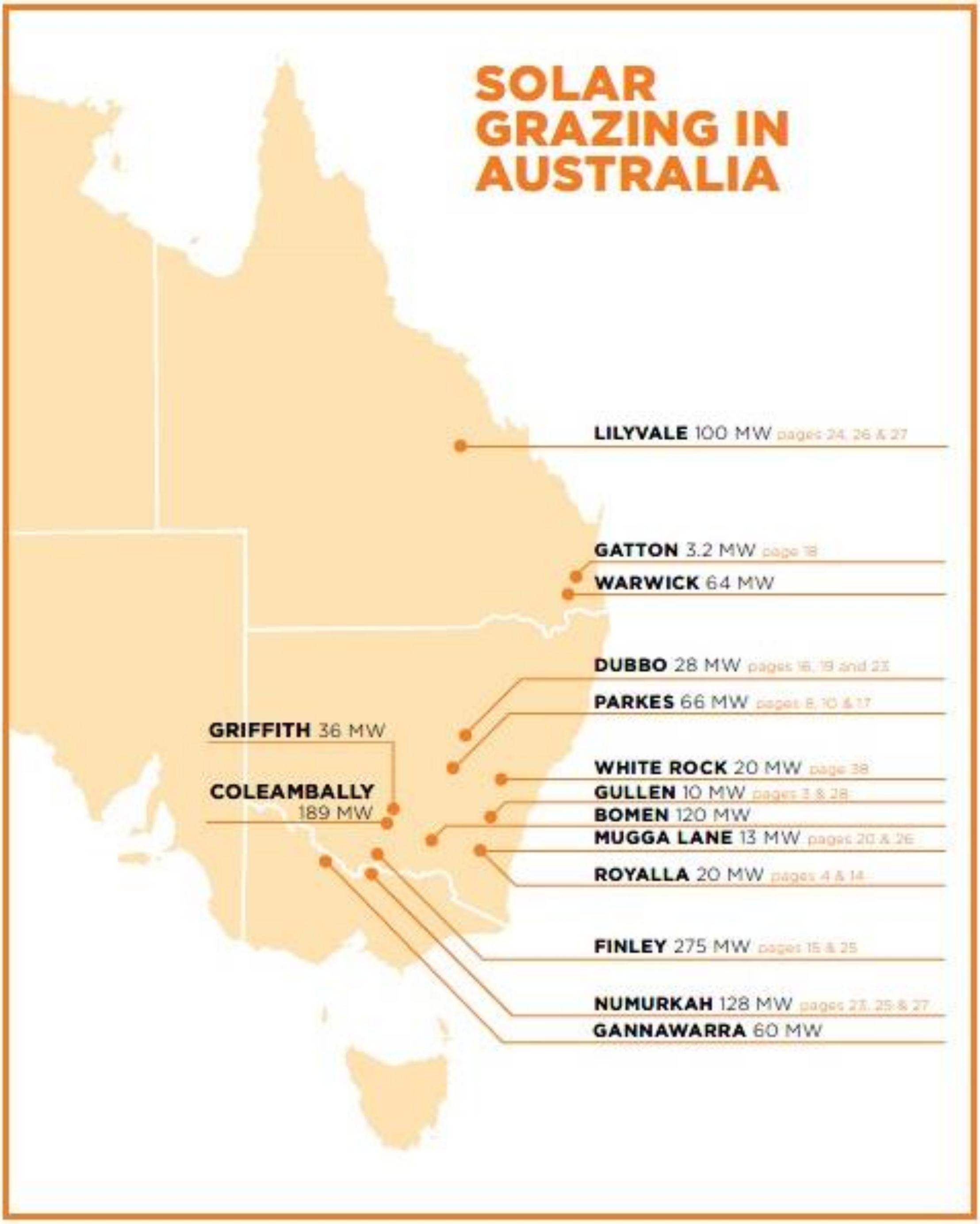
In Queensland, landowners have the option to sell or lease part or all of their property to solar power plant developers. Unlike gas and resources developments, landholders have no obligation to negotiate or proceed with an agreement if they do not wish to (Queensland Farmers Federation 2023). However, the Queensland Department of Resources advise that freehold is considered the most appropriate tenure for renewable energy projects. Leaseholders can apply to convert their lease to freehold but need to meet certain conditions and pay a conversion price. The existence of Native Title is also a factor in whether a conversion is possible for term leases. Where a leaseholder of agricultural land doesn't convert their lease to freehold, they may apply under the *Land Act* to have an additional purpose of renewable energy to be added to the lease conditions.

In Australia, agrivoltaics in general, including solar grazing, has seen very slow adoption (Stark and Bomm 2023). The Clean Energy Council (2021) stated that 15 sites across Australia had solar grazing in operation (3 in Queensland, 10 in New South Wales and 2 in Victoria); (Figure 4). However, Stark and Bomm (2023) reported on anecdotal evidence that not all of these sites were still in co-existence with grazing at the time of publication of their report.

Merino or merino-cross sheep, particularly wethers, are the most common livestock type involved in solar grazing on Australian solar power plants (Clean Energy Council 2021). However, the dorper breed has also been grazed on solar power plants in Australia and the USA, despite a reputation for being livelier and for rubbing against objects to help shed their wool. Internationally, sheep grazing on solar power plants has been conducted in England for at least a decade and subsequently has commenced in many countries across Europe and the Americas. The American Solar Grazing Association (2024) state that sheep solar grazing operations occur in North Carolina, Florida and New York. Currently there is little evidence of co-existence, of utility-scale solar plants, with cattle grazing in Queensland, Australia or internationally. The consensus in Australia and internationally appears to be that sheep production is the most feasible grazing enterprise to be co-located with solar facilities. The American Solar Grazing Association explicitly recommend sheep as the best-suited livestock for co-existence with solar power plants and do not recommend goats, cows, pigs or horses for the safety of the traditional low-mount solar arrays (American Solar Grazing Association 2024). The Australian

Clean Energy Council (2021) also states that cattle and goats are usually deemed inappropriate for large-scale solar power plants due to size (cattle) and behaviour (goats).

Figure 4 Location of solar grazing in Australia as reported in Clean Energy Council (2021), p. 16.



A review of published literature, media articles, internet sites, and anecdotal reports has identified a number of examples of solar grazing in Queensland and other Australian states. These examples are summarised below with some key insights, where available.

2.2.1 Queensland

2.2.1.1 Sheep grazing

1) The Clean Energy Council (2021) reported that the University of Queensland's Gatton Solar Farm has grazed sheep in partnership with its Veterinary School since 2016. Dorper and merino sheep are grazed on a 10 ha site at an average stocking rate of 10 sheep per ha. Three types of solar arrays were trialled: fixed-tilt arrays (stationary panels), single-axis trackers, and dual-axis trackers. The Clean Energy Council (2021) reported that even with purchase of yard equipment, installation of water access and partition fencing, the costs saved from mowing under the solar arrays were approximately $100,000 per year. However, this figure seems substantial for a 10 ha site given quotes for slashing on solar farms range from $320-640/ha per event. Prior to the introduction of sheep, mowing was contractually required once per quarter (Clean Energy Council 2021). Some damage to panels occurred in fixed-tilt array paddocks where sheep attempted to push beneath the panels. However, this damage was stated to be minimal relative to damage to infrastructure (including panels) caused by mowing. The intention to develop a second solar farm near Warwick to allow the co-existence of sheep grazing, was stated.

2) Central Queensland grazier, Peter Cheal, grazes dorper meat sheep on a) Lilyvale Solar Farm near Tieri and b) Clermont Solar Farm, near Clermont under no-cost agistment arrangements (Clean Energy Council (2021) and P. Cheal, pers. comm.). There has been only minor damage to panels from sheep grazing and satisfactory grass growth at both locations (buffel grass (*Cenchrus ciliaris*) and/or native pastures). Ewes and lambs are grazed at both solar farms with wether lambs removed at weaning and grazed on a finishing paddock (i.e. not solar grazing) near Emerald prior to marketing locally as a 'paddock to plate' arrangement. The greatest challenge to sheep management on the solar farms has involved mustering difficulties which have been overcome with the use of a helicopter or drone. Wild dog incursions at one site also necessitated investment (by the livestock owner) in additional fencing.

2.2.1.2 Cattle grazing

1) Caitlin McConnel, 'Cressbrook Station' (ca. 400 ha total) near Toogoolawah, grazes cattle under 100 kW of solar provided by 14 solar panels, each with a concrete base of 1 m^2. The solar panels are used to provide a diversified income for the property through the rebate received for returning power to the main grid (Farmers for Climate Action 2024). It should be noted that this is a different scenario to grazing on utility-scale solar power plants which have a much denser arrangement of solar panels (Figure 5).

Figure 5 Configuration of solar panels on 'Cressbrook Station', Toogoolawah

2.2.2 Other Australian states

2.2.2.1 Sheep grazing

1) Tom Warren (Dubbo, New South Wales) claims benefits from merino sheep grazing below solar panels on land leased to the solar developer Neoen (Farm Renewables Consulting 2020; Stark *et al.* 2022). The identified benefits to the land and livestock owner include a) substantial income from lease of the land to the solar developer, b) free agistment of sheep, and c) additional grass growth beneath panels during drought periods due to concentration of dew on the panels overnight. Tom claims that the solar panels have increased the carrying capacity of the land by about 25% for merino sheep grazing (Stark *et al.* 2022). Approximately 150 sheep are grazed on the solar power operation (Clean Energy Council 2021).

2) The Pakes Pastoral, Agricultural and Horticultural Association (the Show Society) have trialled the grazing of merino wethers on the Parkes Solar Farm, New South Wales in 2019 (Clean Energy Council 2021). A total of 132 sheep were grazed on the site. Wool quality and sheep health was reported to be satisfactory.

3) Grazier, Damien Sexton, runs sheep on Finley Solar Farm, New South Wales and reports shearing the sheep every 12 weeks to prevent mortalities due to wool being caught in the motor drive shaft of the solar panels (Clean Energy Council 2021). The additional shearing costs amount to $20/head.annum.

4) Sheep grazed on Mugga Lane Solar Park, New South Wales, appear to seek shelter offered by the panels over the summer months (Clean Energy Council 2021).

5) frv (Fotowatio Renewable Ventures) published a news story indicating that a solar grazing agreement for 600 sheep was in progress for their 250-ha Winton Solar Farm 25 km south-west of Wangaratta, New South Wales. Neighbours to the solar farm were in discussions to secure the agistment agreement (frv 2023b).

6) Sheep were introduced to Numurkah Solar Farm, in northern Victoria by the former landowner, Eddy Rovers, after a phased trial (Clean Energy Council 2021; Clean Energy Regulator 2022). Merino sheep graze over 515 ha on the solar farm. Green strips of grass observed under the leading edge of the solar panels were attributed to the accumulation of dew moisture on the panels overnight which drips down to irrigate the grass beneath.

7) A media article reported that livestock owner, Greg Fowler, grazed 300 merino sheep on Gannawarra Solar Farm in northern Victoria (ABC News 2021). The sheep had been observed seeking shade under the panels on a hot day. The sheep were moved off the solar farm during periods when pasture became limiting. Internal fencing was added to facilitate management.

2.2.2.2 Cattle grazing

1) A trial of solar panels designed to accommodate dairy cows by an Australian company, Wynergy, was stated as planned for construction at Farrer Memorial Agricultural High School, Tamworth, New South Wales in 2021 (Clean Energy Council 2021). The panels were to have a 2.4 m clearance distance to the ground. A later update by Wyngery's director (Renew Economy 2023) indicated that the cost of installing the higher and more durable panels for cattle grazing was 160% greater than a ground-based tracking system. It was concluded that the added cost of installing solar farm infrastructure suitable for cattle grazing would likely make these systems unattractive for most developers.

3. Analysis

3.1 Review of published research papers with implications for solar grazing

It is well accepted that agricultural land is the primary target for utility-scale, ground-mounted solar energy development worldwide (Toledo and Scognamiglio 2021; Goldberg 2023; Gomez-Casanovas 2023). Engineering and design innovations can address issues precluding agrivoltaic adoption. However, there are a current lack of incentives to motivate solar energy developers to prioritise agrivoltaics which are more costly to deploy (Goldberg 2023; Gomez-Casanovas 2023). An economic study in Germany indicated that substantial policy support would be required to make agrivoltaics competitive with traditional ground-mounted PV (Feuerbacher *et al.* 2022). This finding is supported by a financial analysis of case study sites in New Zealand which indicated that overall returns to a beef and sheep farm from investing in utility-scale solar panel developments were greater when using a standard PV design focused on maximising solar generation cf. adapting the solar development to maintain original sheep carrying capacity (Brent *et al.* 2023). In the same analysis, investment in agrivoltaics for a dairy farm significantly reduced property-level returns due to (1) the relatively greater capital cost of the solar infrastructure required for cattle grazing and (2) the greater returns per ha from dairy farming, cf. sheep and beef enterprises (Brent *et al.* 2023).

However, the fire hazard created by unmanaged vegetation growth on solar power plants is well recognised (e.g. Vaverkova *et al*. 2022). To manage this risk, and to prevent panel shading, regular mowing of vegetation is recommended practice. There has been increasing interest internationally in the use of grazing sheep as an alternative method of vegetation management (The Australian Clean Energy Council 2021; American Solar Grazing Association 2024). At present, it appears that the primary incentive for solar power plant developers to engage in solar grazing is the reduction in site operating costs allocated to vegetation management (e.g. Kochendoerfer *et al*. 2019). However, it is interesting to the note the perspective of New Zealand authors that utility-scale solar farms should not claim 'agrivoltaic status' simply by grazing sheep underneath panels, but without making any adaptations to designs to reduce food production losses (Brent *et al.* 2023; Vaughan *et al.* 2023). These authors have labelled such practices by solar plant developers as ‘green-washing’.

To facilitate the optimisation of solar grazing systems, an understanding of the effect of agrivoltaic systems on energy, plant and animal production is required. International research studies have indicated that solar panels have significant effects on plant microclimate due to affecting soil temperature, soil moisture and vegetation growth. However, the results are inconsistent across studies, seasons, bioregions and climatic zones. For instance, Madej *et al.* (2022) reported that the effects on inter-row vegetation were influenced by the density of solar power plant infrastructure at sheep-grazed sites in France. However, the effects of solar panels in this study were inconsistent, indicating that research should be conducted on multiple sites and over several seasons and years to understand vegetation dynamics and animal production implications for solar grazing.

In another study, in semi-arid, C_3 grasslands in Colorado USA, an agrivoltaic array designed with row spacing intended to maximise energy production resulted in minimal effects on evapotranspiration, photosynthesis, and grassland productivity, despite large reductions in light availability (Kannenberg *et al.* 2023). At the same site, the PV array did not significantly reduce forage production or quality (Sturchio *et al*. 2024). The authors concluded that the results of these studies reflect the nature of the semi-arid environment, where water is more limiting than sunlight for plant growth. Modelling provided no evidence that the increased water retention within the PV array altered grassland resistance to drought (Kannenberg *et al.* 2023). The results of these studies may have some applicability to semi-arid and arid western Queensland environments, where sheep grazing is common (i.e. the Mitchell grasslands), although the perennial pastures in Queensland are predominantly C_4 rather than C_3 grasses.

In the Mediterranean climate of Oregon USA, with semi-arid pastures and wet winters, a study at an ungrazed PV site at Oregon State University Corvallis, showed a large increase in biomass production over the May-Aug (Spring) period due to increased water use efficiency in the shaded areas under PV panels (Hassanpour Adeh *et al.* 2018). In contrast, a subsequent study of sheep grazing at the same site found a negative effect of solar panels on pasture biomass production but a positive effect on forage quality (Andrew *et al*. 2021). The net result of the latter study was comparable lamb liveweight gain per head and per ha, between solar sites and open pastures, over two consecutive spring periods.

The only published study reporting tropical C_4 grass growth associated with PV systems, is a simulation modelling study. Effects of PV systems on growth of the subtropical pasture, Bambatsi Panic grass (*Panicum coloratum*) , was modelled using the APSIM (Agricultural Production Systems sIMulator) modelling framework (McCown 1996; Keating 2003) calibrated for tropical grass biomass production under three different PV installations on The University of Queensland Gatton Solar Research Facility (Mamun *et al.* 2023). The simulation results indicated that biomass production was greater under PV systems when compared to full sunlight conditions: 15.82, 13.53, 8.03% higher with fixed-tilt, single-axis tracking, and dual-axis tracking arrays, respectively. However, the efficacy of the simulations of agrivoltaic systems relies on data for factors that limit pasture growth in a range of environments and for a range of pasture species. The authors identified that to improve the accuracy of biomass modelling in agrivoltaic systems more data is required to improve model calibration. In particular, it was identified that biomass was overestimated in instances where soil moisture was limiting for plant growth indicating that field data is required to improve predictions of soil moisture under PV panels. Additionally, the fluctuation of soil nitrogen under different types of PV installations is poorly understood and is a current limitation to accuracy of modelled output.

A claimed benefit of agrivoltaic grazing systems is that the shade provided by solar panels can potentially reduce heat stress of grazing livestock in hot climates. However, those studies reporting data for shade benefits of solar panels for grazing livestock do not represent utility-scale power plant scenarios. Instead, the sites represent low-density PV installation designed to supplement the power requirements for an agricultural enterprise and/or provide income diversification through power supply to the grid. These studies have reported benefits of shading from solar panels in reducing heat load of grazing sheep (e.g. Fonseca *et al.* 2023) or dairy cattle (Sharpe *et al.* 2020; Heins *et al.* 2022; Faria *et al.* 2023). However, none have demonstrated associated benefits on dry matter intake, liveweight gain, fertility, or milk production. The majority of solar panel-related, shade benefit studies did not report on animal production effects. The exception was the study of Heins *et al.* (2022) where pastured dairy cows at the University of Minnesota West Central Research and Outreach Centre USA showed no effect due to solar panel shading in fly prevalence, milk production, milk fat or protein production, body weight, body condition score, drinking bouts, hock lesions or locomotion. The lack of a production response was observed despite shaded cows having lower afternoon respiration rates and lower body temperatures than unshaded cows.

Recent international reviews have concluded that there are critical gaps in knowledge of the impacts of agrivoltaic systems on energy, plant and animal production across a wide range of environments, soil types and plant species (e.g. Toledo and Scognamiglio 2021; Mamun *et al.* 2022; Gomez-Casanovas 2023). In particular, research has primarily been conducted in the northern hemisphere with a clear deficit of formal research or available case studies applicable to bioregions in Queensland. The only currently published Australian research with application to solar grazing is a modelling calibration exercise for pasture biomass growth at one existing agrivoltaic site (Mamun *et al.* 2023).

Targeted field research is therefore required to improve knowledge and understanding of how solar grazing could optimally occur, for both cattle and sheep, at representative sites across Queensland. To provide useful data for economic feasibility studies, paired solar and non-solar sites, that are representative of key regions targeted for REZ development, should be established to provide data sets and insights on:

1) The most suitable forage species (grass and legume) adapted to growth under partial shading in a range of environments and soil types.
2) Pasture biomass growth and forage quality of the most suitable adapted species (grass and legume) to partial shading.
3) Grazing management for optimal pasture and livestock productivity.
4) Effects on livestock health, diet quality and productivity.
5) The economic efficiency of livestock enterprises co-located with utility-scale solar power plants.

3.2 Challenges to co-existence of grazing with solar power plants in Australia

The Australian Agrivoltaics Research Centre identifies that one of the greatest risks to Australia's energy transition stems from land use conflict, where solar developments are contested over claims of reduced food security and the use of prime agricultural land for energy production (Stark and Bomm 2023). Other concerns raised by opponents of solar developments include erosion from grading and construction works, visual impacts, inadequately controlled weeds, impacts on neighbours and local economies and supply chains from loss of agricultural productivity. Potential chemical release following panel damage, and subsequent management of associated environmental impacts, has also been raised as a concern by some agricultural producers and requires investigation.

Factors which have hindered uptake of solar grazing opportunities have been identified by Stark and Bomm (2023) and include:

- A lack of knowledge and understanding.
- Technical and economical impediments.
    - The priority for developers is lowest cost construction and maximum output per dollar invested and thus unnecessary additional infrastructure costs are a disincentive if required to facilitate solar grazing. Typically, the height and strength of solar structures would need to increase, particularly for cattle grazing. Additionally, a greater area of land is likely to be required to facilitate efficient livestock grazing and management.
- Lack of trust in renewable energy proponents (developers).
- Poor planning and a lack of clear policy guidance at the development stage.
- The adoption by some insurers of a restriction on grass height to no >100 mm, albeit with some flexibility possible outside the fire season.
- Failed examples of solar grazing production systems due to retrofitting to operate within the constraints of the constructed array and poor suitability to the practicalities of grazing management. Examples of challenges experienced with existing solar power plant developments include:
    - Difficulties mustering livestock around panels,
    - Inadequate trafficability and holding areas available to enable efficient stock movement and handling,
    - Incursion of wild dogs causing livestock mortality (particularly sheep),
    - Limited hours of access to the site precluding swift animal health or other management interventions,
    - Limitations in managing pastures and weed control,
    - Use of chemicals by solar panel proponents that have chemical withholding period implications for livestock,
    - Capacity to provide adequate water sources for livestock.

Negotiations with solar power plant developers and site managers could allow many of the issues identified above to be overcome. Investment in suitable or modified infrastructure could address the identified constraints to grazing and livestock management. For example, locating livestock water sources within trap yards outside the solar paddock could overcome mustering issues. Alternatively, helicopters or drones can be used as a mustering aid and have been adopted by some commercial grazing operations on solar power plants. As another example, perimeter exclusion fencing to protect livestock from wild dog incursions can be erected at a cost of ca. $10,000+/km.

3.3 Potential benefits of co-existence of grazing with solar power plants in Australia

3.3.1 Claimed benefits for livestock owners

- Free or low-cost agistment.

- Provision of shade and shelter for livestock.

  - There are claims that temperatures under utility-scale solar panels can be up to 5 degrees lower during heat waves (Sun'Agri 2021; Stark *et al*. 2022). The number of annual 'emergency' heat stress days (temperature-humidity index ≥84) for beef cattle at Biloela, Queensland under a medium emissions scenario (Representative Concentration Pathway 4.5) is expected to increase by 33 days to 109 days by the 2050s, compared to the 1994-2023 average of 76 days (Climate Services for Agriculture 2023). Therefore, provision of shade may become increasingly beneficial for animal welfare during summer months. However, the lack of a production response to shade, in studies with high production dairy cows in the USA (Heins *et al.* 2022), indicates that provision of shade may be more important for animal welfare than for production of grazing livestock.

- Improved seasonal pasture quality/duration due to provision of shade, potential reduction of water use, and concentration of water runoff from panels.

  - These aspects require further research under Queensland conditions to understand the effects on soil parameters and pasture production. For example, if water runoff from panels is lost from the solar grazing paddock, this would not be of benefit for pasture growth on the power plant. However, if panels concentrate moisture, from small falls of rain or dew beneath the lower edge of panels, this may increase the effectiveness of grass growth.

- Potential for reduced frost damage to pastures as night-time temperature under solar panels can be between 1-4 degrees higher (Stark *et al.* 2022).

- Protection from predators due to secure perimeter fencing.

3.3.2 Claimed benefits for the proponents of the solar power plant developments

- Reduced costs of weed and grass management through reduced mowing and chemical application.

  - Quotes obtained from Queensland slashing contractors indicate that the cost of slashing around and under solar panels is likely to be in the range of $320-640/ha per event, which would be a substantial operating cost to the solar power plant business. Additionally, there are anecdotal reports of damage to panels and infrastructure occurring during slashing activities.

- Improved community and regional support for solar power plant developments.

3.4 Economic analysis of the value of grazing livestock on solar power plants in Queensland

3.4.1 Introduction

Beef cattle production is the most common grazing enterprise in eastern Queensland with the most profitable component of the breeding and growing enterprise being the young growing steers (Bowen and Chudleigh 2019; Bowen and Chudleigh 2021a,b). Therefore, the feasibility of grazing weaner steers on solar power plants is worthy of investigation in an economic analysis. However, the majority of examples of solar grazing in Queensland, Australia and internationally have been with sheep. Furthermore, livestock owners have expressed a preference for grazing ewes and lambs on solar power plants due to perceived benefits of finishing lambs under more controlled grazing and management environments than are currently possible on a solar power plant. Therefore, an economic analysis was conducted to examine the value of grazing solar power plants with either 1) growing beef weaner steers or 2) a meat sheep breeding flock producing weaner lambs for transfer to another property. The perspective was from that of the livestock owner who may be willing to contribute to some of the development costs required to facilitate grazing on commercial solar power plants, assuming that 1) agistment was provided at no cost, and 2) a long term contract for grazing rights could be established. An objective of this analysis was to identify how much a livestock owner could invest in additional development costs to allow either cattle or sheep co-grazing on solar power plants, across a range of productivity environments in eastern Queensland. A key assumption for this analysis was that the manager of the solar power plant will benefit through a reduction in land management (slashing/mowing) costs and that they will seek a livestock owner to run livestock rather than undertaking a livestock enterprise themselves. This perspective appears to reflect current practice in Australia.

3.4.2 Methods

The analysis assessed the profitability of grazing 1) beef cattle (weaner steers), or 2) meat sheep (breeding flock), on solar power plants in eastern Queensland. Livestock were grazed on a 100-ha solar power plant for a 12-month period. Given the lack of data to indicate:

1) the effects of solar PV infrastructure (panels, inverters and other supporting infrastructure) and high-traffic areas on grass production across the entire grazing area, and across a range of local environments and seasonal conditions, and

2) the level of additional development costs required to facilitate either sheep or cattle grazing,

a sensitivity analysis approach was taken. In total, 120 scenarios were assessed to examine the various combinations of:

1) livestock type (growing steers or meat sheep flock),

2) land productivity/carrying capacity (high, 1.54 ha/adult equivalent (AE); medium, 2.65 ha/AE; and low 9.43 ha/AE),

3) reduction in stocking rate across the entire grazing area due to solar PV infrastructure (0, 25, 50 and 75%), and

4) additional development cost ($0, $25,000, $50,000, $100,000, $200,000).

In line with what appears to be current practice in Queensland and Australia (Clean Energy Council 2021), the agistment was provided free of charge, by the managers of the solar power plant to livestock owners.

The productivity, costs and price basis for growing steer enterprises on three levels of land productivity were adapted from previously published and unpublished data and analysis of grazing beef cattle across Queensland bioregions (Bowen 2024; Bowen and Chudleigh 2021a); (Table 1 and Table 2). The productivity, costs and price basis for meat sheep flocks were adapted from Bowen and Chudleigh (2022), (Table 1 and Table 3). Livestock (weaner steers or meat sheep flock) grazed on the solar power plant for 12 months before sale of 1) feed-on steers or 2) male lambs, cull ewes and surplus young females. Cattle and sheep prices were based on expected values derived from consideration of long term records of market prices.

Table 1 Assumed forage and stocking rate parameters for land with high, medium and low productivity in eastern Queensland, prior to solar photovoltaic development

Biological parameter	Land type productivity		
	High	Medium	Low
Perennial pasture type	Sown/introduced	Sown/introduced	Native
Median, annual pasture biomass production (kg DM/ha)	5,100	3,000	1,500
Utilisation of annual biomass growth (%)	35	35	23
Median annual biomass available for consumption (kg DM/ha)	1,785	1,050	345
Average, annual diet dry matter digestibility for grazing cattle (%)	57	56.5	49.5
Average, annual steer liveweight gain (kg/head)	180	175	121
Carrying capacity of steers (ha/AE)[A]	1.54	2.65	9.53
Stocking rate of growing weaner steers over the 12-month period (ha/head)	1.53	2.79	7.55
Carrying capacity of meat sheep (breeding flock component; ha/DSE)[B]	0.18	0.32	1.13

[A]AE (adult equivalent) defined in terms of the forage intake of a 2.25 year-old, 450 kg *Bos taurus* steer at maintenance, consuming a diet of the specified dry matter digestibility and walking 7 km/day on level 1, gentle slope.
[B]DSE (dry sheep equivalent) defined in terms of the forage intake of a 45-kg wether sheep, with no fibre growth above that included in maintenance, requiring 8.7 MJ ME/day and with an AE:DSE ratio of 1:8.4.

The three alternative levels of grazing land productivity/carrying capacity selected (high, 1.54 ha/AE; medium, 2.65 ha/AE; low 9.43 ha/AE) were considered relevant to land types in eastern Queensland. Initially, the stocking rate and productivity of steers prior to solar PV development was determined for each level of grazing land productivity and was informed by previous published and unpublished data and analysis of grazing livestock across Queensland bioregions (Bowen 2024). The pasture and animal production associated with each of the three categories of land type productivity are given in (Table 1). The number of steers able to be grazed on 100-ha over each annual period was determined by estimating the average pasture dry matter intake of steer cohorts using the QuikIntake Excel spreadsheet calculator (McLennan and Poppi 2019) modified from the Australian ruminant feeding standards (NRDR 2007) to better predict intake for *B. indicus* content cattle and tropical diets (McLennan 2014). The average pasture dry matter digestibility, liveweight of the cattle (i.e. liveweight at the mid-way point of the grazing period) and the assumed average daily gain over the relevant period were used as key inputs. Appropriate pasture utilisation rates of annual biomass growth were applied to match the safe carrying capacity for either sown/introduced or native pastures growing on high, medium or low productivity land (The State of Queensland 2022c). Grazing pressure equivalence between livestock species was determined according to the recommendations of McLennan *et al.* (2020) where an AE or DSE rank is assigned to a grazing animal as the ratio of its metabolisable energy (ME) requirements for a particular level of production to that of a 'standard animal'. The standard animal for all species was defined as having zero weight change, walking

7 km/day on level ground and consuming pasture of 55% dry matter digestibility (7.75 MJ ME/kg DM). A standard bovine animal, representing one AE, was defined as a 450-kg, 2.25-year-old *Bos taurus* steer requiring 73 MJ ME/day. A standard ovine animal, representing one DSE was defined as 45-kg wether sheep, with no fibre growth above that included in maintenance, requiring 8.7 MJ ME/day. This corresponded to a 1:8.4 ratio of AE:DSE.

Table 2 Beef steer price and cost assumptions for a 12-month grazing period, for land with high, medium and low productivity in eastern Queensland

Parameter	Land type productivity		
	High	Medium	Low
Starting liveweight (kg)	200	228	179
Starting value ($/kg)	$3.83	$3.83	$3.88
Closing liveweight (kg)	380	403	301
Closing value ($/kg)	$3.47	$3.47	$3.65
Mortality (% year)	1	1	1
Husbandry and variable costs ($/head)[A]	$101	$104	$128

[A]Labour and management costs associated with the operation of the livestock grazing enterprise were not included in the estimate of husbandry and variable costs.

Table 3 Meat sheep flock price and cost assumptions for a 12-month grazing period, for land with high, medium and low productivity in eastern Queensland

Parameter	Value
Flock capital ($/DSE)	$79
Net sheep sales ($/DSE)	$60.51
Mortality (% year)	2
Husbandry costs ($/DSE)[A]	$1.06
Net ram replacement ($/DSE)	$6.17

[A]Labour and management costs associated with the operation of the livestock grazing enterprise were not included in the estimate of husbandry costs.

Four levels of stocking rate reduction (compared to a grass paddock in the same location but without solar PV infrastructure) were examined (0%, 25%, 50%, or 75% reduction). It was assumed that the solar power plant had suitable existing pastures for grazing (either native or sown/naturalised) and that the power plant was fenced to a basic standard. Five levels of additional investment by the livestock owner, to make the solar power plant suitable for grazing either cattle or sheep, were assessed ($0, $25,000, $50,000, $100,000, $200,000). This investment could include additional fencing costs (e.g. exclusion fence for meat sheep to provide wild dog protection), watering points and trap yards, or installing panels at a height and durability standard suitable for grazing cattle. It should be noted that the additional development costs did not include the cost of livestock capital required to stock the solar power plant. The livestock capital costs were accounted for separately in the analysis as part of the capital requirements for the investment.

The key economic criterion was net present value (NPV) at a discount rate of 10% to represent the relevant opportunity cost for funds invested in such an enterprise over a 30-year investment period. A 30-year investment period was chosen to reflect the expected economic life of the additional capital required by the enterprise. A positive NPV indicates that the return on funds invested in the solar grazing enterprise was better than 10%. The NPV is the sum of the discounted values of the future income and costs associated with the solar grazing project and was calculated as the net returns over the life of the investment, expressed in present day terms. The NPV thus represents the addition to the investor's (livestock owner's) current wealth above or below the gain if they had invested the capital involved in an alternative that earned at the real discount rate applied.

An annualised (amortised) NPV was calculated, at the discount rate (10%) over the investment period of 30 years, to assist in communicating the returns from investing in solar grazing and is the metric presented in this report. The annualised NPV can be considered as an approximation of the average annual profit over 30 years, resulting from investing in the solar grazing project. It is important to note that the costs of labour and management required for the solar grazing project were not included in the analysis. Therefore, for the investment to be worthwhile, the annualised NPV values would have to be better than the value of the annual labour and management required for grazing activity.

3.4.3 Results and discussion

The annualised NPV for investment to graze either 1) beef weaner steers, or 2) a meat sheep flock, on a 100-ha solar power plant over a 30-year period are given in Table 4 and Table 5, respectively. This analysis identifies that there appears to be value in grazing either beef cattle or meat sheep on solar power plants under long-term contracts (i.e. 30 years in this analysis) on either high or medium productivity land types, in situations where the reduction in stocking rates and the additional developments costs are low to moderate.

An important assumption in our analysis was that the agistment on the solar power plant was provided free of charge to the livestock owners. The high costs/ha to the solar power plant of mowing under solar panels (ca. $320-640/ha per event), and the anecdotal reports of solar power plant managers offering leases for free livestock agistment both in Australia and internationally, indicates that there is a significant cost-saving and thus an incentive for solar power plants to provide free agistment to livestock owners. This inference is supported by a case study on Cornell University Musgrave Research Farm which indicated that sheep grazing was a cost-effective approach for solar plant managers to control on-site vegetation (cf. mechanical mowing and trimming), (Kochendoerfer *et al.* 2019). However, the authors recommended multi-year contracts be adopted to encourage sheep farmers to agist on solar sites.

Grazing beef weaner steers or a meat sheep flock gave similar investment returns for equivalent levels of 1) reduction in stocking rate and 2) additional development cost. However, the cost of setting up a solar power plant for cattle grazing is expected to be significantly greater than setting up the same solar power plant for grazing by a flock of meat sheep (e.g. Brent *et al.* 2023; Renew Economy 2023). It is therefore considered unlikely that cattle, even weaner steers, will be used to graze utility-scale solar power plants due to the additional capital required compared to a meat sheep enterprise. This conclusion is broadly in accord with the lack of uptake of cattle co-grazing with solar power plants in Queensland, Australia and internationally. Whether or not an exclusion fence is required to successfully graze meat sheep will also be a critically important factor in the decision of a livestock owner to invest.

An additional consideration is that, for the investment to be worthwhile, the annualised NPV have to be greater than the value of the annual labour and management required to manage the solar grazing activity as these were not included in the analysis. The anticipated costs of labour and management requirements, in relation to solar grazing projects, would need to be estimated by individuals considering the investment in cattle or sheep solar grazing enterprises. This analysis was for a 100-ha project area, but it is important to note that labour and management effort is unlikely to increase proportionally with grazing area, making a larger project potentially more attractive to a livestock owner, dependent on associated development costs. This aspect reinforces the importance of the economics of size in assessing the value of such investments. Each grazing opportunity provided by a solar power plant would need to be assessed on its own merits.

Investment returns for solar grazing projects decreased as land productivity, and associated livestock carrying capacity, decreased. Low productivity land was assessed as likely to be unviable for solar grazing projects even with no reduction in stocking rates and nil development cost. Additionally, as expected, investment returns decreased in line with 1) reductions in stocking rate due to solar panel projects, and 2) with increases in additional development costs.

The results of the current analysis are broadly in accord with results from New Zealand case study sites representing either a 1) sheep and beef farm, or 2) dairy farm (Brent *et al.* 2023). The latter study had a different perspective to the current analysis in that the financial impact to the agricultural landowner, from investing in solar developments to provide an alternative income stream, was assessed. The study indicated that investing to install solar panel infrastructure, so that it was compatible with dairy cow grazing, was unviable. However, modifications to PV infrastructure to accommodate sheep grazing, on the sheep and beef farm, were feasible. Regardless, overall profit on the sheep and beef farm, including from power generation, was maximised when standard PV designs were used with no investment to prevent a reduction in sheep stocking rate. This result reflects the greater profit per ha from solar power generation cf. agricultural production.

It is important to note that the relative and absolute value of the calculated investment returns in this analysis are heavily influenced by the assumed livestock prices. A small change in the assumed livestock prices can have a disproportionately large impact on the net returns of the investment. Therefore, it is recommended that individual livestock owners considering a solar agistment activity apply prices and costs applicable to their specific situation and based on their knowledge, experience, and expectations of future livestock prices.

Table 4 Annualised net present value (NPV) for investment to graze beef weaner steers on a 100-ha solar power plant over a 30-year period

Beef cattle grazing (growing steers) – high productivity land types				
Additional development cost	**Reduction in stocking rate due to solar panels**			
	0**%**	25%	50%	75%
$0	$23,473	$17,605	$11,736	$5,868
$25,000	$20,821	$14,953	$9,085	$3,216
$50,000	$18,169	$12,301	$6,433	$564
$100,000	$12,865	$6,997	$1,129	-$4,740
$200,000	$2,257	-$3,611	-$9,479	-$15,348
Beef cattle grazing (growing steers) – medium productivity land types				
Additional development cost	**Reduction in stocking rate due to solar panels**			
	0%	25%	50%	75%
$0	$11,322	$8,492	$5,661	$2,831
$25,000	$8,670	$5,840	$3,009	$179
$50,000	$6,018	$3,188	$357	-$2,473
$100,000	$714	-$2,116	-$4,947	-$7,777
$200,000	-$9,894	-$12,724	-$15,555	-$18,385
Beef cattle grazing (growing steers) – low productivity land types				
Additional development cost	**Reduction in stocking rate due to solar panels**			
	0%	25%	50%	75%
$0	$2,500	$1,875	$1,250	$625
$25,000	-$152	-$777	-$1,402	-$2,027
$50,000	-$2,804	-$3,429	-$4,054	-$4,679
$100,000	-$8,108	-$8,733	-$9,358	-$9,983
$200,000	-$18,716	-$19,341	-$19,966	-$20,591

Table 5 Annualised net present value (NPV) for investment to graze a meat sheep flock on a 100-ha solar power plant over a 30-year period

Meat sheep grazing (ewes and lambs) – high productivity land types				
Additional development cost	**Reduction in stocking rate due to solar panels**			
	0%	25%	50%	75%
$0	$23,771	$17,829	$11,886	$5,943
$25,000	$21,119	$15,177	$9,234	$3,291
$50,000	$18,467	$12,525	$6,582	$639
$100,000	$13,163	$7,221	$1,278	-$4,665
$200,000	$2,556	-$3,387	-$9,330	-$15,273
Meat sheep grazing (ewes and lambs) – medium productivity land types				
Additional development cost	**Reduction in stocking rate due to solar panels**			
	0%	25%	50%	75%
$0	$13,837	$10,377	$6,918	$3,459
$25,000	$11,185	$7,725	$4,266	$807
$50,000	$8,533	$5,073	$1,614	-$1,845
$100,000	$3,229	-$230	-$3,690	-$7,149
$200,000	-$7,379	-$10,838	-$14,298	-$17,757
Meat sheep grazing (ewes and lambs) – low productivity land types				
Additional development cost	**Reduction in stocking rate due to solar panels**			
	0%	25%	50%	75%
$0	$3,850	$2,887	$1,925	$962
$25,000	$1,198	$236	-$727	-$1,689
$50,000	-$1,454	-$2,416	-$3,379	-$4,341
$100,000	-$6,758	-$7,720	-$8,683	-$9,645
$200,000	-$17,366	-$18,328	-$19,291	-$20,253

4. General Discussion

The land area under solar power plants is expected to increase 7.4-fold over the coming years, with 84 new plants proposed for development (The State of Queensland 2023d). These developments are expected to occur close to the primary transmission network in eastern Queensland (The State of Queensland 2022a). Many of these developments are likely to occur on land currently used for agriculture.

Solar power plant developers are motivated to maximise profit per ha from energy generation and this appears likely to vastly exceed returns possible from agriculture on the same land area. There are a current lack of incentives to motivate solar power plant developers to prioritise agrivoltaics if the arrays are more costly to deploy than traditional ground-mounted photovoltaic systems (e.g. Feuerbacher *et al.* 2022; Brent *et al.* 2023; Renew Economy 2023).

However, the costs incurred on vegetation control and landscape management by solar power plant operators appear to be significant. As a consequence, the power plant operators are likely to consider the potential cost savings associated with grazing livestock on solar power plants as a method of vegetation control (e.g. Kochendoerfer *et al.* 2019). It is likely that solar power plant operators will not be skilled in livestock operations and will therefore look for livestock owners to stock the plants. Depending upon the level of cost saving expected by the solar power plant operators, they are likely to offer incentives to livestock owners, including offering free agistment, with conditions (Clean Energy Council 2021). The solar power plant operator may not want livestock on the power plant all of the time and the livestock may have to be applied at a high stocking rate to significantly reduce biomass (Stark and Bomm 2023). Therefore, the agistment comes with risks for the livestock owner. Furthermore, it is likely that significant up-front capital will be required to enable grazing of solar power plants by livestock. Which party supplies this additional capital will influence the nature and length of grazing contracts and could determine whether agrivoltaics is pursued by solar power plant operators.

An economic analysis from the perspective of the livestock owner indicated that, when agistment is free and additional development costs are low to moderate, there appears to be value in grazing either beef cattle or meat sheep on solar power plants in the following circumstances:

1) The plant is located on either high or medium productivity land types, and

2) The reduction in stocking rate due to solar infrastructure is minimal.

Additionally,

1) Under circumstances where no additional capital investment, other than livestock capital, is required by the livestock owner, short term grazing contracts would be viable; however,

2) Where low to moderate levels of capital investment are required by the livestock owner, only long term grazing contracts would be viable (i.e. up to the 30 years applied in this analysis).

In the analysis, grazing beef weaner steers or a meat sheep flock gave similar investment returns for equivalent levels of 1) reduction in stocking rate and 2) additional development cost. However, the cost of setting up a solar power plant for cattle grazing is expected to be significantly greater than setting up the same solar power plant for grazing by a flock of meat sheep (e.g. Brent *et al.* 2023; Renew Economy 2023). It is therefore considered unlikely that cattle, even weaner steers, will be used to graze solar power plants due to the additional capital required when compared to a meat sheep enterprise. This latter statement may not hold true if investment in an exclusion fence is required to successfully graze meat sheep. Further work is required to assess relevant scenarios. Economics of size will be important to the livestock owner as the expected benefits of grazing a small solar power plant may not cover the additional labour and management effort incurred. Furthermore, for the grazing activity to be worthwhile, the annualised returns have to be greater than the value of the annual labour and management required for the solar grazing activity, as these were not included in the analysis.

Investment returns for solar grazing projects decreased as land productivity, and associated livestock carrying capacity, decreased. Solar power plants on low productivity land were assessed as unlikely to be profitable for grazing by the majority of livestock owners, even with no reduction in stocking rates and nil development cost. As expected, investment returns decreased in line with 1) reductions in stocking rate due to solar panel projects and 2) with increases in additional development costs.

5. Conclusions

This preliminary review and analysis indicates that solar power plants and livestock grazing need not be mutually exclusive. There has been a lack of uptake of cattle co-grazing in Australia (and internationally) and further work is required to identify the particular impediments that apply and whether these can be overcome. Flocks of meat sheep are relatively rare in the regions of eastern Queensland where the majority of solar power plants are proposed for development. Further work is required to identify whether flocks of meat sheep can be established and expanded in these regions to undertake the amount of grazing likely to become available on solar power plants (i.e. ca. 100,000 ha).

6. Recommendations

Recommendations resulting from this review include:

1) Conduct more detailed and extensive analysis to identify how it may be possible to incentivise investment, in additional solar project infrastructure costs, to enable co-existence with grazing, particularly cattle.

2) Conduct field research to improve knowledge and understanding of how solar grazing could optimally occur, for both cattle and sheep grazing at representative sites across Queensland. To provide useful data for economic feasibility studies, paired solar and non-solar sites that are representative of key regions targeted for REZ development should be established to provide data sets and insights on:

    - The most suitable forage species (grass and legume) adapted to growth under partial shading in a range of environments and soil types.
    - Pasture biomass growth and forage quality of the most suitable adapted species (grass and legume) to partial shading.
    - Grazing management for optimal pasture and livestock productivity.
    - Effects of PV arrays on livestock health, diet quality and productivity.
    - The economic efficiency of livestock enterprises co-located with utility-scale solar power plants.

3) Analysis to examine the feasibility of zoning and development of primary production processing plants in the regions, which could utilise power off-take from solar plants. The objective would be to value-add to (or offset negative regional and agricultural consequences of) solar plant locations on agricultural land.

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8. Glossary of terms and abbreviations

Table 6 Glossary of terms and abbreviations

Abbreviation/Term	Definition
AE	Adult equivalent. An AE is a standard animal unit used to describe and quantify grazing pressure imposed on pasture by foraging ruminants. An AE rating is applied to grazing ruminants which approximates their grazing pressure relative to a standard animal. A wide range of AE approaches, and definitions of a standard animal, are in use across Australia and internationally. The most commonly applied AE systems in northern Australia for grazing cattle include: 1) **Linear weight AE** where the liveweight of cattle classes are expressed relative to a standard animal, animal, often a 450 kg or a 455 kg (1,000 lbs) liveweight steer at maintenance, 2) **Metabolic weight AE** where the metabolic liveweight (liveweight to the power 0.75) of cattle classes are expressed relative to the metabolic weight of a standard animal, being a 450 kg liveweight steer at maintenance. 3) **Metabolisable energy (ME) requirement AE** where the ME requirement of cattle classes are expressed relative to the ME requirement of a standard animal. The standard animal is defined as a 2.25 year-old, 450 kg liveweight *Bos taurus* steer at maintenance, walking 7 km/day and consuming a diet of 55% dry matter digestibility (DMD; 7.75 MJ/kg DM) and therefore requiring 64.3 MJ/day and consuming 7.9 kg DM/day for cattle on tropical diets (72.6 MJ/day and 9.4 kg DM/day for temperate pastures); McLennan *et al.* (2020). **In this Agrivoltaics analysis** When calculating the equivalent grazing pressure and applied stocking rates on solar power plants, the **ME requirement AE** was applied. The spreadsheet calculator QuikIntake Version 6 (McLennan and Poppi 2019) was used to calculate daily cattle dry matter intakes (and AE rating) for (1) the specified average dry matter digestibility of each forage type and the (2) breed and (3) class of cattle grazing the pastures along with (4) their expected liveweight gain.
ALC	Agricultural Land Classes
Amortise	An amortised value is the annuity (series of equal payments) over the next *n* years equal to the present value at the chosen relevant compound interest rate.
Agrivoltaics	The simultaneous use of areas of land for both agricultural production systems and solar panel projects. Also referred to as 'agrisolar'.
DCF	Discounted cash flow. This technique is a way of allowing that when money is invested in one use, the chance of spending that money in another use is gone. Discounting means deducting from a project's expected earnings the amount which the investment funds could earn in its most profitable alternative use. Discounting the value of money to be received or spent in the future is a way of adjusting the future net rewards from the investment back to what they would be worth in the hand today.

Discounting	The process of adjusting expected future costs and benefits to values at a common point in time (typically the present) to account for the time preference of money. With discounting, a stream of funds occurring at different time periods in the future is reduced to a single figure by summing their present value equivalents to arrive at a net present value (NPV). Note that discounting is not carried out to account for inflation. Discounting would still be applicable in periods of nil inflation.
Discount rate	The interest rate used to determine the present value of a future value by discounting. This helps determine if the future cash flows from a project or investment will be worth more than the capital outlay needed to fund the project or investment in the present.
DM	Dry matter. DM is determined by oven drying pasture forage (or other organic material) in an oven until constant weight is reached (i.e. all moisture removed).
DSE	Dry sheep equivalent. This standard unit represents a 2-year old, 45 kg Merino sheep (wether, or non-lactating, non-pregnant ewe) at maintenance. To estimate grazing pressure equivalence between cattle and sheep in our analysis we adopted the approach of McLennan *et al.* (2020) where the energy requirements of a standard animal unit (defined AE or DSE) are assumed to represent equivalent grazing pressure. A ratio of DSE : AE of 8.4 : 1 was adopted.
GW	Gigawatt
kW	Kilowatt
ME	Metabolisable energy. The energy from a feed source remaining for use by a ruminant after losses in faeces, urine and methane gas are subtracted.
MW	Megawatt
NPV	Net present value. Refers to the net returns (income minus costs) over the life of an investment, expressed in present day terms. A discounted cash-flow allows future cash-flows (costs and income) to be discounted back to an NPV so that investments over varying time periods can be compared. The investment with the highest NPV is usually preferred. NPV was calculated at a 10% rate of return which was taken as the real opportunity cost of funds to the producer. Annualised NPV converts the Marginal NPV to an amortised, annual value. *The **annualised (or amortised) NPV** can be considered as an approximation of the **average annual change in profit over 30 years**, resulting from the management strategy.*
Opportunity cost	The benefit foregone by using a scarce resource for one purpose instead of its next best alternative use.
PAA	Priority Agricultural Areas
PALU	Priority Agricultural Land Use
PV	Photovoltaic
REZ	Renewable Energy Zone

Safe carrying capacity	A safe carrying capacity for a property is defined as a strategic, i.e. long-term (e.g. 20-30 years) estimate of livestock numbers that can be carried without any decrease in pasture condition and without accelerated soil erosion.