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Agrivoltaics for small ruminants: A review

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ABSTRACT

The mitigation of climate change will require the large-scale uptake of renewable energy generation, in particular wind and solar. Utility-scale solar photovoltaics (PVs), or solar farms, will necessitate the transformation of agricultural land. Agrivoltaics is the dual land-usage solution with the integration of solar PV arrays with ongoing agricultural production. The farming of ruminants, especially sheep, is particularly suited for agrivoltaics in that little modification of the infrastructure is required to accommodate sheep grazing beneath and between the PV arrays. However, many uncertainties remain and this review paper provides more insights into the technology, the role of small ruminants, the potential impacts on agriculture productivity and the land, as well as other sustainability aspects of agrivoltaics. Previous and ongoing research suggests there are (potentially) mutual benefits for both operations to occur on the same land – if the integration is designed well. The sheep aid solar farm operators with maintenance aspects, specifically vegetation management and associated costs. The PV arrays influence the microclimate conditions on the farm in terms of wind speed (and direction), temperature and humidity, including rain distribution, providing for better animal welfare in terms of heat stress and protection against harsh weather – especially in the face of climate change. The construction process does have a negative impact on the soil, but the land can be restored in a short period of time. Once operational, the soil is positively impacted with better moisture retention and vegetation growth improves in hotter months. The widespread shading also means (potentially) a better distribution of urination events with less overloading on the land and lower leachate, although more field trials are required. Overall, the available evidence suggests that the environmental performance of agrivoltaics is positive. Apart from the impact on the land, the life cycle of the systems have low material and carbon footprints, with short carbon and energy payback periods, emphasising the role of agrivoltaics in the energy transition. Further quantifications of many aspects are needed with longitudinal data from different climate contexts around the world.

1. Introduction

The International Energy Agency published a comprehensive report (International Energy Agency IEA, 2021) on how the transition to a net zero (carbon emissions) energy system may be achieved, while "*ensuring stable and affordable energy supplies, providing universal energy access, and enabling robust economic growth*". The cost-effective and economically productive pathway that is set out clearly shows a clean, dynamic and resilient energy economy that is dominated by renewables, most notably wind and solar (see Fig. 1). The variable generation of wind and solar means that they will need to be complemented with other renewables, such as hydropower, and different storage options to reach a net zero carbon emissions power system.

The IEA (2023) projects that the global capacity for utility-scale solar photovoltaics (PVs) – or solar farms – will reach between 1.5 and 1.8 TW of electricity generation capacity by 2028. The analyses of Bolinger and Bolinger (2022) indicate that the current power density of typical commercial installations – fixed-tilt or single-axis tracking (see Section 2) – is between 0.54 and 1.01 MW_{DC} per hectare, which implies that 1.5–3.3 million hectares of land will be used for solar farms by 2028. While this required land area is small in comparison with the total global agricultural land for livestock farming – around 4 billion hectares (World Economic Forum, 2019), utility-scale solar farms do require reasonably flat land in regions with good solar energy resources, which implies potential land use competition. In the US, the American Farmland Trust estimates that 7.5 million additional hectares of agricultural

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land may be lost between 2016 and 2040 if current development trends continue (Hirtzer, 2023). On the other hand, with typical commercial solar farm designs the lowest points of the PV arrays are installed to make them more suitable for small ruminant grazing, although herding can be more challenging. Indeed, the use of sheep to maintain the vegetation around and beneath the PV arrays has become common practice across the globe. The American Solar Grazing Association, for example, estimated in 2023 that about 5000 sheep maintained solar farms across the US (Hirtzer, 2023) with the results of a comprehensive census to be released in late 2024. However, Ross (2023) points out several challenges with conventional solar farms. In some regions there is strong opposition to converting productive agriculture land to intensive solar farms with some grazing, as there are concerns of damage to local environments, economies and culture, as well as the (potential) decline in adjacent property values. Also, shepherds indicate that many existing solar sites are not purposefully constructed to cater for the needs of sheep – water, routine care, food, and shelter – and the associated logistics that are required for vegetation management with sheep comes with significant costs.

Agrivoltaics, introduced in the early 1980s (Goetzberger and Zastrow, 1982), address these challenges with the effective combinations of agricultural production (as a first priority) and electricity generation (for secondary income) on the same land. The concept is receiving much attention globally as a viable alternative to conventional large-scale solar farms – to create mutual benefits for each sector (Macknick et al., 2022). Agrivoltaic systems differ from conventional ground-mounted solar arrays in that the panels are typically given more ground clearance and are spaced further apart (Trommsdorff et al., 2020). This provides enough space for farming equipment to operate and allows light to reach the crops below. A change in crop yield can be expected due to the shadows under module arrays, but the amount depends on the climate as well as the shade tolerance of the specific crop (Cuppari et al., 2021). For example, lettuce, sweet potatoes, eggplants, soybeans, and peanuts, thrive in shady or low-light environments (Kumpanalaisatit et al., 2022). If agrivoltaic systems are designed well, land productivity could rise by 60–70 % compared to maximising solar electricity generation alone (Kumpanalaisatit et al., 2022), which could address the concerns, in some countries, of converting arable land with extensive solar farms. Cuppari et al. (2021), for example, demonstrate substantial increases in revenues relative to farm-only scenarios for alfalfa and soybeans in Oregon, and soybeans and strawberries in North Carolina. Additionally, agrivoltaic systems have been used in pastoral lands, with added shelter to protect livestock against heat stress and adverse winter weather. Sheep-based agrivoltaics has been shown to be particularly good for pasture production, and both shepherds and the solar PV industry recognise the benefits of designing appropriate agrivoltaic systems (Handler and Pearce, 2022). Schoeck (2023) reports that the US industry expects an annual growth rate of over 10 % to capitalise on these benefits.

Although the agrivoltaics concept is gaining traction, many uncertainties remain that are being researched. The objectives of this review paper is to provide more insights into: 1) the current status with respect to the technology, 2) the role of (appropriate) small ruminants in agrivoltaics, 3) the potential impacts of agrivoltaics on agriculture productivity and the land, and 4) other sustainability aspects.

2. Method

The primary method for undertaking the research was that of a traditional, or narrative, review, which is defined as "*a scholarly summary along with interpretation and critique*" (Greenhalgh et al., 2018). The co-authors are experts in different aspects of agrivoltaics, namely: solar photovoltaic technologies, ruminant agriculture production, and environmental impacts. They then focussed on the specific objectives separately and undertook a combination of a hermeneutic review – to create a deeper, interpretative understanding of the various aspects of agrivoltaics – and a realist review – to gain a better understanding of the causality in terms of the implications of agrivoltaics. The key term 'agrivoltaic' was used to scan the wider literature and identify research papers specific to the separate objectives.

3. Overview of agrivoltaics technology in use

Many different solar array configurations are being applied for agrivoltaic systems, manifesting in different typologies (see Fig. 2). For sheep-based agrivoltaics open, overhead mounting structures are typically used. Of key importance for optimal electricity generation are the mounting structure configurations and module orientations, the type of PV modules, and the solar array layout in terms of spacing – all affecting the techno-economics.

3.1. Mounting structure configurations and module orientations

The feasibility of an agrivoltaic system depends on the mounting structures, as different panel arrangements can affect agricultural operations and how much light reaches the crops (Trommsdorff et al., 2020). There are two prevailing arrangements of the panels – a straight-line or checkerboard pattern (see Fig. 3). The checkerboard pattern distributes solar radiation more heterogeneously, but generates less electricity per area of land, and so straight-line structures are the most common in practice.

The mounting structures accommodate fixed tilt (facing the equator), or north-south aligned tracking systems – to follow the sun (see Fig. 4). With fixed tilt systems the panels are usually about 2–3 m above

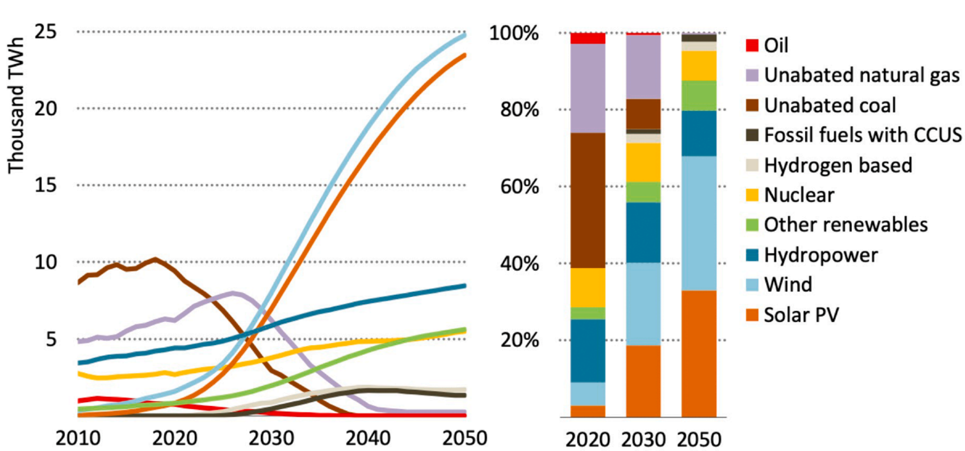

Fig. 1. Global electricity generation by source in a net zero carbon emissions scenario (International Energy Agency IEA, 2021).

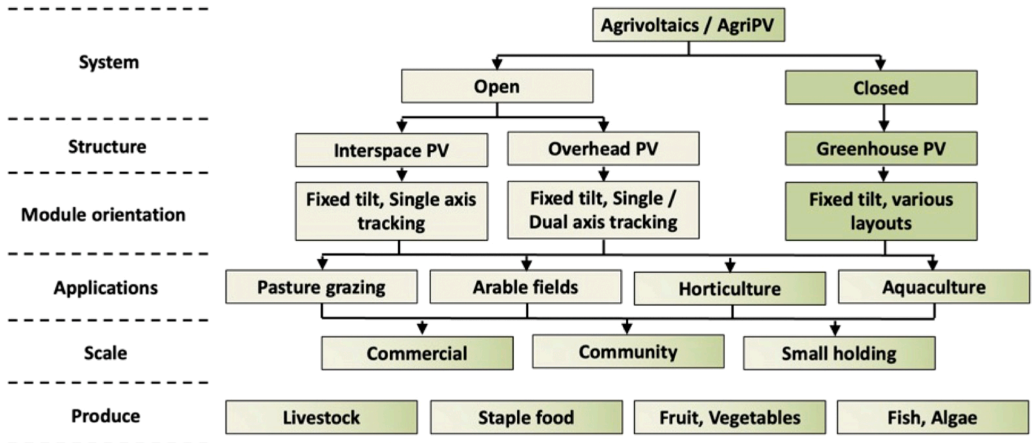

Fig. 2. Typologies of agrivoltaic systems (adapted from Trommsdorff et al., 2022).

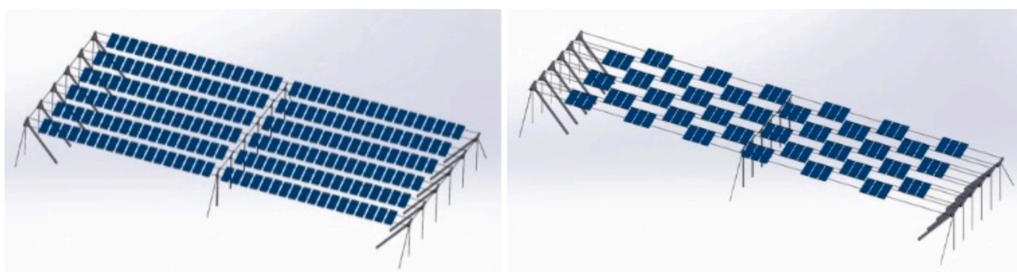

Fig. 3. Conventional panel arrangements – straight line (left) and checkerboard (right) (Trommsdorff et al., 2020).

Fig. 4. Fixed-tilt (a) and single-axis tracking (b) agrivoltaic systems.

ground level (at the centre), with distances between rows at least three times the height of the modules (to achieve a reasonably uniform solar radiation on the ground). Higher stilted agrivoltaics are possible, with more than 4 m in some commercial systems (Toledo and Scognamiglio, 2021), but low height mounting structures are preferred to minimise wind shear and the associated costs for strengthening the structures. A number of foundation options are utilised, depending on the geology of the location (Solarport Systems, 2024). Most projects use driven piles, and for specific soils anchors (for reclaimed ground or shallow embedment) or ground screws (high clay content). No concrete is needed in these applications. In exceptional cases ballast systems on top of the ground may be used. The optimal tilt for a fixed system varies with location and is ideally similar to the latitude of the location (Patel et al., 2019).

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

A benefit with the mounting structure is the microclimate that is created underneath the panels with, for example, better soil moisture retention (see Section 5.5).

3.2. Type of PV modules

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

Bifacial panels are becoming the industry standard as they can capture the reflected light from the ground (Sojib Ahmed et al., 2022). Although roughly 10 % more expensive, they have the same order of gains over monocrystalline modules (Deline et al., 2019). Especially in periods of the year with low insolation levels – as shown for specific locations in Vietnam, Bangladesh, China, India and Brazil – they can offer a better return of investment (Sojib Ahmed et al., 2022).

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

3.3. Solar array layout

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

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

The German standard for agrivoltaic systems may be a reasonable benchmark (Lettenmeier et al., 2021). This states that the agriculturally unusable land must not exceed 10 % for category I farming (overhead systems, >2.1 m high).

4. The role of small ruminants in agrivoltaics

A particularly important element of agrivoltaics is ensuring that not only do the solar panels remain in good condition, but also the wider solar farm environment. Alongside the energy production purpose of solar panels, there are beneficial effects on agriculture production and vegetation management (Kampherbeek et al., 2023).

In typical solar farms, with no grazing, vegetation around panels tends to be managed through the use of herbicides, manual labour and mowing. The use of grazing livestock is a much more time effective and efficient approach. It can provide forage for livestock to support their growth and production ability, whilst also maintaining vegetation for farmers and lessening their manual labour demand (Nordberg et al., 2021). Andrew et al. (2021) note that small ruminants can be used, "*in targeted grazing systems*" to control pasture production and overgrowth without the intervention of machinery, or with less reliance on machinery, which has both financial and environmental benefits. Furthermore, persistent use of chemicals for vegetation management has lasting effects on biodiversity, which would be costly to reverse (Nordberg et al., 2021). Maintenance with herbicides could also result in run-off, potentially polluting adjacent natural systems.

Successful agrivoltaic grazing system design relies on the careful consideration of solar PV design and layout, selection of appropriate livestock, and establishment and maintenance of suitable pasture or grazing crops. These factors help to ensure that agrivoltaic systems are well suited to the environment (Nordberg et al., 2021).

Agrivoltaics is particularly beneficial when working alongside small ruminant farming industries because, unlike cattle, sheep are small enough to fit underneath ground mounted solar panels, eliminating the risk of damage to them (Kampherbeek et al., 2023). As sheep are small enough to fit under the panels, this allows for easy installation and there is generally no need to adjust the photovoltaic panels (Andrew et al., 2023). Goats are not well suited because they are predisposed to chewing wires or jumping on panels (Kampherbeek et al., 2023). Therefore, using sheep can be a cost-effective way of utilising all that solar panels have to offer both in an agriculture and commercial sense.

5. The potential impacts of agrivoltaics on agriculture productivity and the land

5.1. Livestock well-being and behaviour

The review of Biswal et al. (2021) found that heat stress conditions significantly affect the growth, production, milk yield, feed intake, reproductive performance, and other biological functions of small ruminants – especially in tropical and sub-tropical areas with high humidity levels and temperatures above 30°C. They argue that climate change will exacerbate these effects.

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

Marcone et al. (2021) concluded that sheep can experience heat stress in moderately warm conditions. Their research found 54 % of woolly ewes will seek shade when the average air temperature exceeds 19°C in a high-latitude country (Estonia). Under shade, sheep were observed panting less, and eating and ruminating more. Additionally, Sevi and Caroprese (2012) found that in Mediterranean countries lactating sheep that experience temperatures above their thermoneutral zone (25°C) decrease their feed intake, milk yield, and quality. Similarly, in a trial of beef cows in Aotearoa New Zealand, the provision of shade resulted in more time spent grazing (Betteridge et al., 2012). While this study did not conclude more grazing resulted in higher production, it does offer an indication as to the benefits of giving animals access to shade.

Sheep have been shown to spend 38 % of their time under photovoltaic panels and this increased to 70 % of their time when solar radiation was equal or greater than 800 W/m^2 in a study based near Sao Paulo, California, USA (Maia et al., 2020). (Fonsêca et al., 2023) found that ewes had 30 % less radiant heat load when under the shade of solar panels, compared to when they were exposed to the sun. During the period of April and May in Oregon, USA, lambs grazing in pastures with solar panels spent 96.1 % and 96.5 % of their "*idling time*" in the shade of the solar panels, respectively. The grazing time itself remained the same, with approximately 43.5 % of their time spent under the solar panels grazing, noting that this did not differ across different times of the day (Andrew et al., 2021). This contrasts with Kampherbeek et al. (2023), who found, for a solar farm in California, that the rate that sheep grazed increased in the solar panel treatment group compared to the native rangeland group. It is noted, however, that grazing time may not be a good metric of the benefits, as it can be affected by, for example, the kind of forage (see Section 5.3).

The panels can provide shelter from the rain, protecting grazing animals from the elements and supporting higher animal welfare (Andrew et al., 2021; Clean Energy Council, 2021). Modelling by Gill et al. (2024) based on conditions in Victoria, Australia, suggests that in cooler climates, lamb survival may be improved due to the significant reduction in wind speed and protection from rain. The fencing of solar sites also offers protection from predators in environments where predation of livestock is an issue (Gill et al., 2024).

Anthelmintic resistance is an increasing issue globally in ruminant management (Charlier et al., 2022). Grazing management is recognised as a valuable non-chemical tool in the management of gastrointestinal parasites in sheep. Grazing management strategies include the cross-grazing of different ruminant species, as well as cropping and/or pasture renewal for both improved nutrition and decontamination purposes (Bricarello et al., (2023). Given the significant financial investment in PV setup, some solar farm operators are reluctant to allow larger ruminants to graze under panels, or for larger machinery required for cropping to be used in the vicinity of PV panels. In addition, if the sites are used consistently for grazing lambs that are receiving regular chemical anthelmintic treatments, the risk of anthelmintic resistance is likely to significantly increase (Leathwick, 2014). Whilst this concern regarding panel damage may be justified with existing PV design, it does potentially limit the long-term feasibility of lamb finishing on solar grazing, particularly in areas in which gastrointestinal parasites are an existing major challenge to sheep production systems. There are currently trials underway in several states in the USA with cattle grazing under elevated PV panels (Sharpe et al., 2021). In addition, anecdotal evidence – from Australia, USA and the UK –suggests that as relationships are established and strengthened between solar energy businesses and farmers, there is increased acceptance of the use of farm machinery between panels and other farming activities for pastoral care (Our Land and Water, 2024), and those developing their own PV systems (as opposed to grazing land belonging to a third party) will have the ability to design accordingly for larger livestock and machinery if required – to maximise the use of the land.

5.2. Livestock productivity

There is a lack of research investigating livestock productivity when grazed under solar panels. However, in one of the few published articles to date, Andrew et al. (2021) noted a comparable growth in lambs grazed under solar panels in Oregon, USA, compared to those grazed on open pasture, despite lower herbage on offer in the pastures under solar panels. This may be attributable to the reduced heat stress that lambs experienced when in solar panel pastures. Consequently, it is likely that the lambs would have better food intake and less breathing to regulate their body temperatures, which reduces production losses (Andrew et al., 2021). This has been supported by earlier studies where Pent et al. (2020) recorded that lambs spent about 90 % of daylight hours in the shade in summer – in Virginia, USA, and Cloete et al. (2000) noting that lambs born in shaded paddocks were heavier than those born in open pastures – in the Western Cape Province of South Africa.

5.3. Forage

Various plants can successfully be grown under solar panels without being negatively affected by higher levels of shade, compared to open pastures (Mamun et al. 2022).

The literature shows under a full shade system, forage production is reduced through moisture constraints and plants intercepting less solar radiation. An experiment assessing the effect of permanent shade on a white clover and perennial ryegrass mix showed a reduction in production in line with increasing shade (Ehret et al., 2015). The findings are similar to Andrew et al. (2021) who reported a significant reduction in herbage yield in fully shaded areas.

Partial shade – with sunlight distribution between the panels – offers the benefits of shade such as slower evapotranspiration and lower soil temperatures while not comprising growth. Partial shading could allow adequate exposure to sunlight required for photosynthesis and plant growth, and minimise the harm caused by over exposure (Sekiyama and Nagashima, 2019). Improved yields have been observed in shade intolerant species under a low module density solar array in Colorado, USA compared to a control (no modules) and high module density. This indicates the crop does not need to be shade-loving to maintain production under a partially shaded system (Beatty et al., 2017; Kumpanalaisatit et al., 2022). The pastural system in Aotearoa New Zealand, for example, has traditionally been based on ryegrass and white clover. Perennial ryegrass has significant reductions in production and quality at temperatures above 20°C (Kauffman et al., 2007). Hassanpour Adeh et al. (2018) found that pasture grasses in partial shade grew significantly more biomass with greater water efficiency than those in full sun – in Oregon, USA. The study attributed this to plants being exposed to less solar radiation and thus slower drying of stored water.

In some trials, agrivoltaics integration has been shown to improve water use efficiency while potentially not impacting yield. Payne and Norton (2011) discuss that plants that experience periods of shade have greater available water in soils and foliage – in a dry region of Aotearoa New Zealand. The shade leads to lower evapotranspiration, which reduces water demands of vegetation (Macknick et al., 2022; Sekiyama and Nagashima, 2019). In arid and semi-arid environments, plants under solar arrays have been shown to benefit from the shading by reducing the level of solar radiation and reducing water losses (Weselek, 2019). The review of Yavari et al. (2022), across different climate regions, supports this noting that water efficiency is maximised under shaded areas, which helps to increase biomass by reducing evapotranspiration losses. This is also supported by Semeraro et al. (2024) who observed, in southern Italy, higher production under solar panels in the low water input treatment compared to the high-water input treatment and they suggest that this could offer economic benefits with less reliance on irrigation. However, moisture availability directly under the panels can become a limiting factor (Macknick et al., 2022). Beatty et al. (2017) indicate that any area under panels greater than 0.5 m from the edge may receive limited water from rain.

Efficiency can be enhanced by tactically selecting suitable plants. The review of Mamun et al. (2022) notes that grasses and legumes grow well together and in doing so improve the long-term health of the soil and encourage the ready growth of the following seasons' crops. They also note that sheep pasture, perennial rye-grass, lemongrass, France grass, Sonamukhi and rye are suitable in moist conditions on agrivoltaics farms. The study of Loan et al. (2022) in central France found that species in the Poaceae family would have high chances of prominent growth but not for Fabaceae plants because they have a low shade tolerance.

The design of the solar farm is a major determinant of agrivoltaics system success, reducing issues around land competition (Bowen, 2024). For example, the area shaded is influenced by the area and height of the panels. As the height of panels increases, the shaded area decreases (Toledo and Scognamiglio, 2021). Marrou et al. (2013), Montpellier, France, show with panels 1.6 m apart lettuce yield was 48 % less than those under full sun, whereas at 3.2 m the yield was hardly affected. Design also impacts the ease of cultivation and ability to use machinery between the rows (Marrou et al., 2013). Yavari et al. (2022) note that the way the solar panels were tilted could have an impact on how water was distributed and minimise water interception. Low mounted panels are the most common design, which have consequences to forage quality and the ability for efficient pasture production as shown from a study in Brazil (Maia et al., 2020). A concern is the ability for plants to grow with the trampling effects from sheep. This is attributable to the amount of time sheep spend under the panels, which prevent the plants from seeing and absorbing light and space to grow (Maia et al., 2020). Forage growth can also be impacted by the way the panels are shaped, their size and the direction they are pointing in relative to where the plants are supposed to be growing (Loan et al., 2022).

Kampherbeek et al. (2023) investigated the quality of forage by comparing a solar panel site to a native rangeland area in California, USA. The way that a photovoltaic system is structured is influential in the growth and quality of the forage beneath the panels (Andrew et al., 2021). Solar panels are beneficial in the sense that they can create, "*microclimates*" (see Section 5.6) by providing shade and withholding moisture in the soil. As a result, there are higher protein quantities in the forage that grows beneath the panels, particularly on the edge (Kampherbeek et al., 2023), and lower carbon to nitrogen rations, resulting in improved quality and digestibility of the pasture. In a semi-arid, C3-pasture dominant environment in Colorado, with row spacing designed to maximise energy production, neither pasture quality nor production were significantly impacted compared to the open pasture control (Sturchio et al., 2024).

Loan et al. (2022) raised a concern that persistent grazing under solar panels may penalise biomass production in France. However, the study of Sturchio et al. (2024) in Colorado has suggested that grazing has beneficial effects on forage growth.

Perna et al. (2019) conclude that well designed agrivoltaics systems – in California and Texas – can optimise power output and forage production and quality.

5.4. Stocking density

Stocking density is highly related to forage production, so as described in Section 5.3 above, changes in stocking density will be highly site specific.

Kochendoerfer et al., (2022) suggest, based on their research in the US Northeast, that forage production in panel shaded areas may be up to 2.5 times less than unshaded areas and stocking density should be adjusted accordingly. Vaughan et al. (2023) modelled a 30 % reduction in stocking density for a solar farm site with a tracking design with 9 m row spacing. This reduction reflected the total panel to land cover ratio of 28.9 %.

Improved vegetation management outcomes may be achieved by rotational grazing at a higher stocking density (Kamperherbeek et al. (2023). The authors suggest that this will result in the pasture being grazed more evenly, a greater number of species grazed, and therefore animals become less selective.

5.5. Soil impacts

The construction of PV power plants will change the original landscape and affect the ecological functions of soil hydrology, carbon and vegetation dynamics, and biological activities (Yousuf et al., 2022). Under normal conditions, affected land surfaces may require extensive periods to recover. However, the study of Luo et al. (2024) demonstrates that a well-designed agrivoltaic system, with cropping, can significantly enhance the soil quality within two years of operation with "*a noteworthy enrichment in soil organic carbon, nitrogen, phosphorus, and potassium nutrients*". It is noted, however, that the control was barren land in a warm climatic zone. Nevertheless, if existing pastoral land is used, it can be expected that the soil should recover from the construction process within two growing seasons.

The integration of grasses in solar fields reduces soil erosion and drift, and the impact extends to hydrology. Hydrologic processes have been found to be affected by solar farms as evident in the difference in mineral quantities in the soil. In the US it was found that on solar farms "*basal respiration and microbial biomass*" quantities are lower in solar farms compared to "*reference land covers*", and carbon and nitrogen quantities have also been found to be lower in solar panel soils (Yavari et al., 2022). There may also be variations in water processing within the solar farm depending on where the panels are placed. For example, a study completed in Colorado found that the presence of unsaturated hydraulic conductivity was higher directly beneath the panels compared to the space between them or the edges (Yavari et al., 2022).

The behaviours of ruminants, discussed in Section 5.1, is an important factor. Betteridge et al. (2012) found that 50 % of urination events happened in 10 % of the paddock where animals are camped near water and shade. They discuss that these zones cause soils to become overloaded, increasing leachate. However, no studies have investigated this impact in the context of agrivoltaics where the area of shade is greater and therefore camping may (potentially) be more evenly distributed across the land.

5.6. Microclimate

Solar PV arrays change the local microclimate in terms of air and soil temperatures, and humidity levels. As discussed in Section 3.3, the array layout affects solar irradiance levels across the soil, as well as different patterns in rainwater run-off.

A significant finding of Luo et al. (2024) is that the presence of a PV array in a dry-hot valley in southwest China reduced soil evaporation, as discussed in Section 5.5, due to the wind-blocking effect, while vegetation coverage and root absorption contribute to enhanced soil moisture retention through a positive plant–soil moisture feedback process. They also show significant lower wind speeds and different wind directions close to the ground, as well as lower temperatures directly under the panels, when comparing the meteorological variables from a station in the centre of an agrivoltaic system (with measurement at different heights), and a station in an adjacent control site. Studies in Colorado show that soil under solar panels have lower soil temperatures than those in full sun (Barron-Gafford et al., 2019; Marrou et al., 2013). The lower air temperatures increases the performance of the solar PV modules (Barron-Gafford et al. 2019). Hence the importance of integrating these systems to improve performances for both electricity generation and biomass production.

6. Other sustainability aspects

Concerns have been expressed about the water overrun caused by the angle of solar panels where water drips down the sides and causes an uneven water distribution. As a result of this, stormwater management needs to be considered. In US states with solar farms, recommendations are made regarding the construction of the solar arrays to promote efficiency, sustainability and prevention of stormwater wastage (Yavari et al., 2022). Capturing runoff from stormwater by designing space between solar array rows to catch the water, or installing infiltration basins are amongst these recommendations (Yavari et al., 2022). Water can be recycled by attaching water channels along the edges of the arrays to drain into barrels where overrun water can be stored. This water could then be used to clean the panels or for forage irrigation (Mamun et al., 2022).

Integrating agrivoltaic systems on farms offers income from both energy production and crop production (Kumpanalaisatit et al., 2022). However, there is still limited understanding and quantification of how and to what extent agrivoltaics will impact the yield of different pastures and crops, and how this will vary across different climates and soil types. Nevertheless, a case study of Vaughan et al. (2023) of a sheep farm in Aotearoa New Zealand demonstrates that, if normal operations can continue, even at reduced stocking density, the financial benefits for the farmer are substantial (see Appendix A).

Another consideration is the environmental performances of the solar PV systems, which requires a more holistic approach in the form of life cycle, or cradle-to-grave, assessments. Life cycle assessments (LCAs) have been undertaken for utility-scale solar farms. Since little modification of the solar PV structures are required for the integration with ruminant farming the outcomes of the LCAs are then useful to understand the environmental implications, typically in relation to the metrics of material intensity, and carbon and cumulative energy demand (and payback). Pimentel Pincelli et al. (2024) undertook a comprehensive LCA of a constructed solar farm in Aotearoa New Zealand. They found the carbon footprint to be around 26 gCO_{2eq}/kWh of electricity generated, which includes the upstream mining and processing of materials, the manufacturing of the components around the globe, transportation to the solar farm site, construction, operation and maintenance over 30 years, and decommissioning and end-of-life management. The carbon and energy payback is less than 1 year with the displacement of other generators on the national grid. Overall their analyses, and their review of previous LCAs, indicate an overall net positive implication for the energy transition with utilising these systems.

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

7. Conclusions

Agrivoltaic systems are gaining more traction as part of the energy transition to allow dual land usage for solar photovoltaic electricity generation and agricultural production. Small ruminants, specifically sheep, will likely play a key role in most agrivoltaic systems, as they can aid solar operators with vegetation management. For sheep farmers the solar arrays offer protection for livestock with, potentially, productivity gains in terms of animal welfare and water usage. Evidence is emerging that if integrated agrivoltaic systems are designed well, taking into consideration spacing between solar array rows and water runoff management, among others, there are multiple benefits in terms of the microclimates that are created, soil impacts, and vegetation growth. Nevertheless, pastural yields with ruminant behaviours need further investigation in different (climate) contexts with many research efforts underway across the globe. Further evidence, and improved regulations around agrivoltaics, will support greater social acceptance.

In general, it can be concluded from this review that the sustainability implications of integrating well-designed agrivoltaics with ruminant farming are largely positive from environmental, economic and social perspectives.

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Anna Vaughan and Alan Brent: Conceptualisation, literature analysis, writing, review and editing.

CRediT authorship contribution statement

Alan Brent: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Anna Vaughan:** Writing – review & editing, Writing – original draft, Project administration, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.smallrumres.2024.107393.

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