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Greener sheep: Life cycle analysis of integrated sheep agrivoltaic systems

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ABSTRACT

Solar photovoltaic (PV) growth can be stalled due to social acceptance. Agrivoltaics can improve social acceptance by enabling dual use of land. The most popular type of agrivoltaics in North America is grazing sheep under conventional PV farms. The environmental benefits of this integrated agrivoltaic system are unknown, so this ISO-compliant life cycle assessment study investigates the environmental performance of sheep-based agrivoltaic systems. This study investigated agrivoltaics to produce a combined output of electricity and agricultural goods, in comparison to conventional methods (various electric grid generation mixes in the U.S. and plane pastures) for producing that same quantify of service in both categories. Agrivoltaics is twice as land use efficient as providing sheep and PV services separately. In addition, the global warming potential of agrivoltaics was found to be 3.9% better than conventional PV and sheep grazing separately, and represents two orders of magnitude improvement (280%-894%) over conventional grids in the U.S. and sheep production. Only considering emission reductions from shifting sheep to PV farms for grazing, the U.S. could conserve 5.73E8 kg CO_2 eq per year from sheep raising, which is equivalent to removing 117,000 average automobiles from the road. To house the current national 5.2 million domestic sheep in agrivoltaic systems, the U.S. has the potential to expand utility scale PV by a factor of four. The results of this study provide further evidence that agrivoltaic systems are superior to conventional ground-mounted PV systems because they have dual purposes and reduce the environmental impacts associated with producing food and electricity. It is clear that encouraging sheep grazing on all appropriate conventional PV systems is warranted.

1. Introduction

Solar photovoltaic (PV) technology is the fastest growing energy source (Li, 2021), energy industry (Feldman et al., 2021) and most environmentally promising methods to obtain a sustainable energy system (Pearce, 2002). Large utility-scale PV farms demand large surface areas (Denholm and Margolis, 2008), which can create land use conflicts between energy generation and agriculture (Dias et al., 2019), which threatens food production (Nonhebel, 2005). In addition, there is a conflict between bioenergy crops and PV (Calvert & Mabee, 2015), which demands high-quality information (Calvert et al., 2013). This conflict is becoming larger because the 1.15% annual world population growth rate (UN, 2014), demands a 70% increase in food production between 2005 and 2050 to feed an expected 9.1 billion people (FAO, 2009). Past conversion of crop lands to ethanol energy production increased food costs (Brown, 2008) and exacerbated world hunger (Tenenbaum, 2008) – literally starving the poor (Ford & Senauer, 2007). Fortunately, using the UN's Sustainable Development Goals 2, 8, 12 and 13 guides us to use innovative and synergistic uses of land (Agostini et al., 2021), specifically the co-location of solar PV with agriculture known as agrivoltaics (Weselek, et al., 2019; Santra et al., 2017).

Less than 1% farmland is required for agrivoltaics to meet 20% of U.S. electric generation (Proctor et al., 2021). This makes agrivoltaics a technically viable solution to land use conflicts (Adeh et al., 2019) as it provides an economic method (Dinesh & Pearce, 2016) of higher land use efficiency (Mavani et al., 2019) using land in a new way (Dupraz et al., 2011). Agrivoltaics has potential for use with a wide variety of food types including: aloe vera (Ravi et al., 2016), corn (Sekiyama & Nagashima, 2019)/ maize (Amaducci et al., 2018), grapes (Malu et al., 2017), lettuce (Marrou et al., 2013)/ irrigated lettuce (Elamri et al., 2018), and wheat (Dupraz et al., 2011). Synergies realized in agrivoltaics such protection from solar irradiance provided by PV arrays can reduce temperature fluctuations (Bousselot et al., 2017), increased water use efficiency (Hassanpour Adeh, et al, 2018) from a beneficial microclimate (Marrou et al., 2013) can even increase crop yields (Barron-Gafford et al., 2019). Agrivoltaics has also shown promise in both coldframes (Pearce, 2021), greenhouses (Toledo & Scognamiglio, 2021) and smart greenhouses (Minanda, et al., 2021); again by improving the mi-

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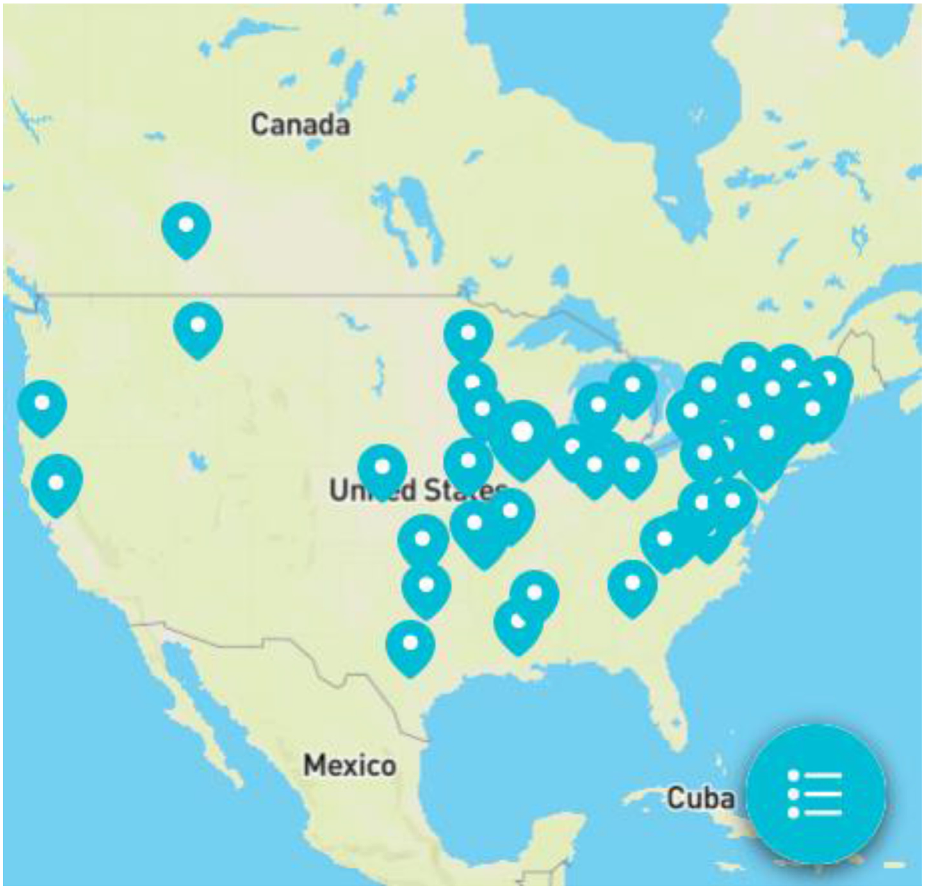

Fig. 1. Solar PV companies and solar graziers requesting collaboration on 11/8/2021 in Canada and the U.S. (Solar Grazing Map, 2021).

croclimate (Fatnassi, et al. 2015). In addition, agrivoltaics can be used on water to be aquavoltaics to harvest plants (Pringle et al., 2017) and salt (Kim et al., 2020) in salt farms (Kang et al. 2021).

In addition, agrivoltaics includes raising animals like emu (REW, 2014), rabbits (Lytle et al., 2020) and grouper fish (Hendarti, 2021) and other fish in small-scale (Hsiao, et al., 2021) or large scale aquavoltaics (Pringle et al., 2017) . The most mature livestock production in agrivolitacs is with lamb (Andrew, 2020) and sheep in North Carolina (US) (Ouzts, 2017) and throughout the U.S. (Mow, 2018), This approach has been shown to particularly good for pasture production (Andrew et al., 2021a;2021b). Both shepherds (Pascaris, et al., 2020) and solar PV industry (Pascaris, et al., 2021a) see benefits for themselves and have a growing experience with sheep-based agrivoltaics. Andrew et al. found that although solar pastures produced 38% lower herbage than conventional unshaded open pastures due to the relatively low pasture density in fully shading beneath the solar farm PV modules, this was offset by higher forage quality, resulting in similar spring lamb production to open pastures (2021a). Land productivity can be greatly increased because the sheep grazing is constant while substantially more value is generated by the PV. The PV systems also provide benefits for the animals by offering shading from PV (and there is anecdotal evidence better wool from the sheep) and the animals prefer PV-cast shade (Maia, et al. 2020). There is also some evidence that it curries favor with the general public for large-scale solar because it eases concerns that rural communities may have about displacing traditional land-uses for new energy development as agrivoltaics retains the agricultural features of the landscape (Pascaris et al., 2022). It is an established enough practice, that the American Solar Grazing Association has been established to promote grazing sheep on solar installations (American Solar Grazing Association 2021). A snapshot of the map on 11/8/2021 of sheep-based agrivoltaic activity with solar companies and solar graziers looking for partnerships is shown in Figure 1 (Solar Grazing Map, 2021).

The viability and profitability of these systems all appear promising, although only a few life cycle assessments (LCA) have been conducted to determine if this is environmentally beneficial. LCA is a standardized method of quantifying environmental impacts or products and services, and has been used to understand the impacts of different operating assumptions in a variety of agricultural settings (e.g., Lares-Orozco et al. 2016) and renewable energy systems (e.g., Burkhardt et al., 2012). Environmental impacts of agrivoltaics are found to be similar to a traditional PV system, yet they provide added values of reduced impact on land occupation and crop production stabilization (Leon & Ishihara, 2018a, 2018b) as well as economic benefits (Agostini et al., 2021). Agrivoltaics also reduce evapotranspiration of crops due to module partial shading, which decreases water consumption compared to conventional crops, but LCAs makes it clear that the intensiveness of farming plays a greater role in overall environmental performance (Ott et al., 2020). Finally, Pascaris, et al. (2021b) found a rabbit pasture-based agrivoltaic system produces 69.3% less greenhouse gas emissions and demands 82.9 % less fossil energy compared to non-integrated rabbit/PV production. Rabbits, despite their greenhouse gas emission efficiency as a source of meat protein (Cesari et al, 2018) (particularly with distributed production (Meyer et al., 2021)) are not a common food in North America and under present market conditions have limited scaling potential without substantial education of the public and a shift in food preferences. For more common animals used for food that have already shown potential for agrivoltaics like sheep there is a dearth of appropriate LCAs. Studies are currently lacking to help quantify the environmental benefits of this integrated agrivoltaic system in a systematic, holistic manner using realistic and scalable animals.

To fill this knowledge gap, this study investigates the environmental performance of sheep-based agrivoltaic systems for the first time. Using sheep to graze underneath conventional solar PV farms has several potential benefits. First, in respect to the PV system, sheep can take the place of regular maintenance operations, reducing or even eliminating

Table 1
Summary of scenarios evaluated and functional unit baskets for LCA study.

Location	Production system(s) used		
	Agrivoltaic	Conv Solar / Conv Sheep	Conv Grid / Conv Sheep
NY	216429 MWh electricity 376800 kg sheep meat	216429 MWh electricity 376800 kg sheep meat	216429 MWh electricity 376800 kg sheep meat
TX	317727 MWh electricity 376800 kg sheep meat	317727 MWh electricity 376800 kg sheep meat	317727 MWh electricity 376800 kg sheep meat
WY	288400 MWh electricity 376800 kg sheep meat	288400 MWh electricity 376800 kg sheep meat	288400 MWh electricity 376800 kg sheep meat

the use of herbicides, lawnmowers and weed-eaters, which have negative impacts on the environment and can also damage PV systems. In regards to the sheep production aspect of agrivoltaics, yield has been reported to stay the same in agrivoltaic systems as in conventional pasture systems (Andrew et al. 2021a), which means that additional costly and environmentally impactful grain-based commercial feeds can be reduced or avoided. The significance of this study is that it quantifies the environmental benefits or tradeoffs of sheep-based agrivoltaic system using an LCA approach. The LCA study is set up in a manner that is comparable with Pascaris et al. (2021), to evaluate the agrivolatic system, producing renewable electricity and agricultural goods, to alternative systems producing the same quantity of agricultural goods and electricity from different processes. This study was conducted to be consistent with ISO guidelines for life cycle assessment (ISO, 2006). The goal of the LCA is to understand the environmental impacts of sheep-based agrivoltaic systems in their ability to produce a combined output of electricity and agricultural goods, in comparison to other methods for producing that same quantify of service in both categories. The scope of this study will be cradle to gate in nature, including the production of infrastructure and materials required for the generation of electricity and raising of sheep, but ending at the point where the electricity has been produced and sheep have been raised, without considering further impacts of processing or food preparation. The results will be discussed in the context of the necessary scaling of the PV industry.

2. Methods

The agrivoltaic production system is designed around a model agricultural field of 30 acres, over a time period of 30 years. Interviews with sheep farmers in the U.S. (Pascaris, 2021) indicated that a field of this size could support 200 sheep annually, with rotational grazing. Using an assumption of 62.8 kg of meat per sheep per year from the Ecoinvent version 3.3 (Ecoinvent Centre 2016) life cycle inventory database (Weidema et al. 2013), this equates to 376,800 kg of sheep meet produced over the 30-year time horizon of the study. If this field were also equipped with solar PV to support an agrivoltaic operation, guidance suggests a PV module density of 4.5 acres per MW of PV (Horowitz et al. 2020), so the model 30-acre field could support a 6.67 MW solar system. Different regions of the U.S. would be expected to produce different levels of electricity from the same land area devoted to PV, due to differences in daylight, cloud cover, and other factors. To explore this variation and also to illustrate the importance of baseline electricity grid mix, the study focused on three examples locations: Syracuse, New York (NY), Lubbock, Texas (TX), and Cheyenne, Wyoming (WY). The PVWatts calculator (NREL, 2021) was used to estimate the potential annual production at each of these locations, and the lifetime electricity production over the 30-year time horizon of this study was also calculated, assuming a 0.5% efficiency loss per year, a conservative assumption consistent with the results found by Jordan & Kurtz (2013).

The functional unit of this study is established similar to Pascaris et al. 2021b, with a basket of two products, equivalent to the 30-year production of sheep meat and electricity in each system (Table 1). It should be stressed here that the integrated agrivoltaic system uses exactly half of the land area of the separate system made up of isolated units of conventional solar and conventional sheep pasture. For each location, the electricity service included in the functional unit can either be provided by the integrated agrivoltaic system, a conventional stand-alone solar PV system, or the conventional electric grid. The required amount of sheep protein service in the functional unit can either be satisfied through an integrated agrivoltaic system, or through conventional grazing of sheep in a pasture system. Because the solar installations in different locations can produce different amount of electricity, the specified quantity of electricity service in the functional unit is different for each location. Assessing these different locations will help to explore the relative benefits of agrivoltaic systems versus stand-alone sheep and solar operations, and also compared to the conventional gird electricity available in each location. Scenarios that will be assessed in this study are summarized in Table 1.

All items are modeled using inputs from the Ecoinvent version 3 database unless otherwise noted. A brief summary of the systems under study follows, and a summary table of input data can be seen in Table 3.

2.1. Conventional Sheep System Description

The conventional sheep agriculture system is scaled to the demand for sheep meat described above and in Table 1, and is based on an Ecoinvent version 3 profile, where sheep are raised in the U.S. primarily for their meat production, with a small amount of associated wool harvest at the time of processing. Sheep feed is supplemented approximately 20% with a mixture of corn grain and soybean meal, and the rest of the caloric requirements of the sheep are assumed to come from pasture. Water is provided from an irrigation pump, and a small amount of NPK fertilizer is added to stimulate new pasture growth each year. Biogenic methane emissions are accounted for in addition to CO_2 and N_2O. External fencing for the 30-acre sheep pasture is provided from sturdy welded wire fencing (0.83 kg fence /m), and the internal fencing used to create separate areas for rotational grazing is assumed to be lighter-duty welded wire fencing. The lifetime replacement requirements for both internal and external fencing is assumed to be 25%.

2.2. Conventional Solar PV System Description

Conventional solar PV is scaled to be consistent with the 6.67 MW system described above, and is modeled using the Ecoinvent profile for a ground-mounted silicon PV plant, which includes solar modules, racking, inverters, and external fencing. No maintenance to the solar PV system hardware is assumed over the 30-year life of the system, although the panels are assumed to lose 0.5% electricity production efficiency every year as stated above. The conventional solar PV system will need to have a management system in place for the grass that is growing around the PV panels – a gasoline-powered industrial mowing Ecoinvent profile is used to model this service, assuming 4 mows per year for the life of the system. Glyphosate weed treatment around the PV where mowing is not possible is also assumed at a rate of 1 kg/acre, also 4 times per year.

Table 2
Electricity generation mix summary for grid subregions in the study. Data from U.S. EPA (2020).

	Generation mix (%)						
	Coal	Natural Gas	Other Fossil	Nuclear	Wind	Solar	Other Renewables
TX - ERCOT	18.6	51.1	0.5	9.9	18.3	1.0	0.6
NY – NEWE	0.5	49.3	0.3	29.8	3.7	1.5	14.9
WY - RMPC	42.5	26.5	0.0	0.0	16.9	1.8	12.2

Table 3
Summary of life cycle input data for LCA study.

Item	Amount (30-year timeframe)	Comments / Ecoinvent profile name
Agrivoltaics Scenarios		
Sheep cultivation	376800 kg	Sheep for slaughtering, live weight, for meat, U.S., with all soy meal and corn grain inputs removed
Internal fencing	1480 m	Zinc-coated steel wire mesh fencing
Photovoltaic plant	11.7 units	570 kW(peak) solar PV installation, ground-mounted silicon panels.
Conventional Solar / Conventional Sheep Scenarios		
Sheep cultivation	376800 kg	Sheep for slaughtering, live weight, for meat, US
External fencing	1740 m	Zinc-coated steel wire mesh fencing, heavy duty
Internal fencing	1480 m	Zinc-coated steel wire mesh fencing
Photovoltaic plant	11.7 units	570 kW(peak) solar PV installation, ground-mounted silicon panels.
Herbicide	3600 kg	Glyphosate
Mowing	3600 acres	Gasoline mower, 1.9 m working width
Conventional Grid / Conventional Sheep Scenarios		
Sheep cultivation	376800 kg	Sheep for slaughtering, live weight, for meat, U.S.
External fencing	1740 m	Zinc-coated steel wire mesh fencing, heavy duty
Internal fencing	1480 m	Zinc-coated steel wire mesh fencing
Electricity	216429 MWh (NY) or 317727 MWh (TX) or 288400 MWh (WY)	U.S. electricity, low-voltage Ecoinvent data, modified with appropriate grid mix.

2.3. Conventional Grid Electricity System Description

The conventional electric grid was modeled in each of our three representative locations by adapting the standard U.S. medium voltage electricity profile available in Ecoinvent, with the embedded generation efficiencies for each fuel type and transmission losses. The profile was modified by changing the grid mix to be consistent with the grid mix present in each grid region considered in our study for NY (NEWE grid region), TX (ERCOT grid region) and WY (RMPA grid region), according to data available from the U.S. EPA eGrid database (U.S. EPA, 2020). Table 2 briefly illustrates the differences in generation mix for all three grid subregions evaluated in the study. The largest difference between the grid areas is related to the adoption of natural gas over coal, which is happening much more quickly in TX and NY than in WY. The NY grid also has a great abundance of low-GHG emissions nuclear power, hydropower, and biomass (Other Renewables in Table 2). Texas has a large amount of wind power and natural gas, while the RMPC grid subregion that includes Wyoming includes much more coal-based electricity.

2.4. Agrivoltaics System Description and Inputs

The integrated agrivoltaics system is set up as described above and modeled in the same manner as the conventional PV system, with a 6.67 MW system on a 30-acre field, that is also grazed with 200 sheep annually. The field perimeter is fenced similar to the conventional solar PV system, and also has internal movable fencing to accomplish rotational grazing. (It should be noted that this is sometimes used to allow different parts of the pasture to regenerate in a systematic way but is only a minor impact on the LCA.) No mowing or herbicide treatment are used in this system, because the sheep satisfy the need for grass management in the agrivoltaics systems. Sheep are assumed to have their caloric and nutritional needs met from the growth of the pasture (Pascaris, 2021), so the sheep production Ecoprofile in Ecoinvent is modified in this case to remove all corn and soy feed inputs, but other requirements like water and periodic pasture fertilizer inputs are still included.

2.5. Impact Assessment

Life cycle assessment modeling was performed in SimaPro version 9. Two environmental impacts were assessed. The effect of greenhouse gas emissions produced during the life cycle of the systems as evaluated with the IPCC 100a global warming potential method, which measures the cumulative CO_2-equivalent (CO_2eq) greenhouse effect of all climate-active gas emissions involved in the life cycle. The general effect on ecosystems was evaluated with the Ecotoxicity indicator from the U.S. EPA TRACI method, measured in cumulative toxicity units (CTUs) (Bare, 2011).

3. Results and Discussion

Table 4 summarizes the LCA results over the 30-year lifetime of the facilities being studied. For purposes of comparison, the baseline case was assumed to be agrivoltaic sheep production, which can be compared to any of the other scenarios, because the amount of solar electricity produced from the panels would vary according to the location. Therefore, the corresponding grid-based electricity required in the 'Conv Grid' scenarios is adjusted to be comparable with the predicted solar electric output in that location. For the Global Warming Potential impact factor, it is apparent that electricity production is the most significant cause of GHG emissions, between 10-100 times more impactful than the meat production service that is provided by these scenarios. Solar PV systems appear to be roughly 10 times less impactful than the conventional electricity grids evaluated for this study. The differences between the agrivoltaics system and an equivalent system operating in any of the grid regions studied is quite large. In Wyoming, an agrivoltaic system of the size described in this study would be expected to produce 288,400 MWh over

Table 4
LCA results for all scenarios.

Item	Global Warming Potential (kg CO_2eq) Agrivoltaic	Conv Solar Conv Sheep	Conv Grid (NY) Conv Sheep	Conv Grid (TX) Conv Sheep	Conv Grid (WY) Conv Sheep
Electricity Production	1.61E+07	1.62E+07	6.57E+07	1.59E+08	1.76E+08
Meat Production	1.85E+06	2.47E+06	2.48E+06	2.48E+06	2.48E+06
Total	1.80E+07	1.86E+07	6.81E+07	1.61E+08	1.78E+08
Item	**Ecotoxicity (CTU)**				
Electricity Production	8.03E+08	8.04E+08	1.36E+09	3.84E+09	4.40E+09
Meat Production	1.20E+06	4.87E+06	4.87E+06	4.87E+06	4.87E+06
Total	8.04E+08	8.09E+08	1.36E+09	3.84E+09	4.41E+09

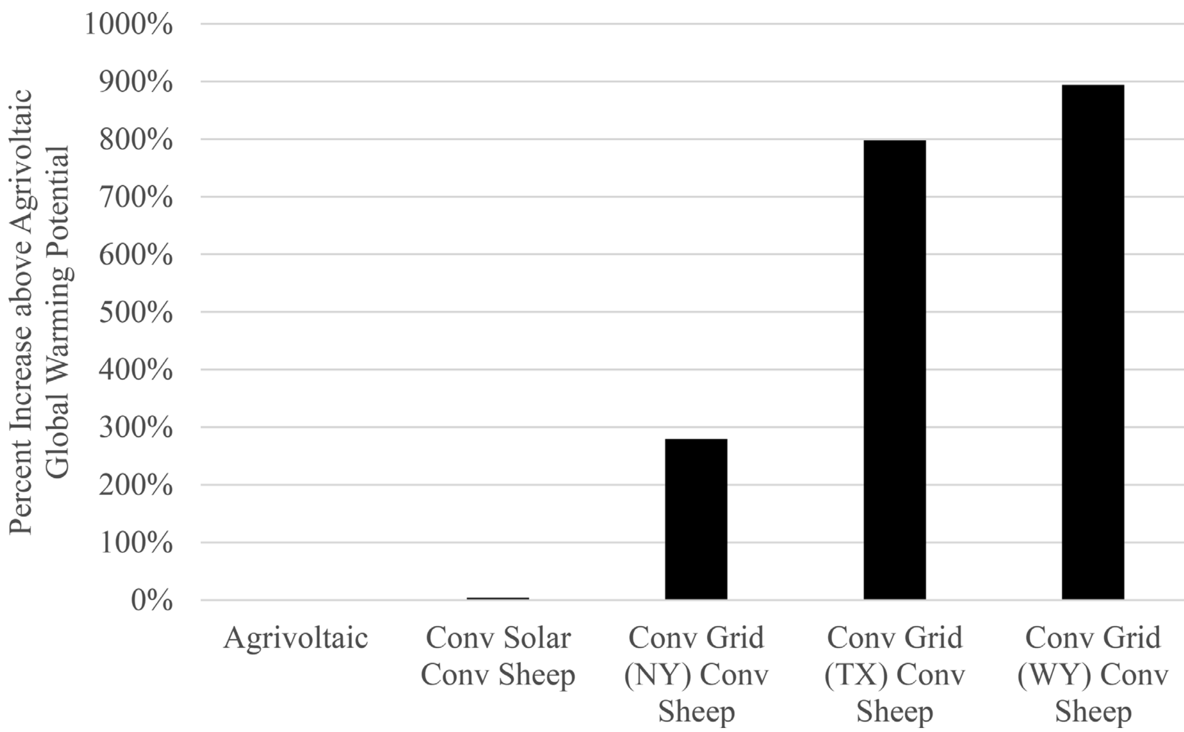

Fig. 2. Percent increase above agrivoltaic system for Global Warming Potential (kg CO_2eq).

the 30-year time horizon of the study, and producing that much electricity from the WY grid results in an overall emissions profile that is almost 9 times worse. This indicates that from an environmental perspective agrivoltaic systems should be encouraged in the most polluting electrical grid (i.e. coal burning) regions.

The comparison between the agrivoltaic sheep and conventionally-produced sheep reveals that the agrivoltaic sheep have an emissions burden that is roughly 25% better than conventional sheep, which is due to the absence of corn and soybean feed in the agrivoltaic system. As an added benefit to the agrivoltaic system, the sheep replace the requirements for mowing and herbicide application in the conventional solar system, but the avoidance of those grass management activities amounts only to ∼ 70,000 kg CO_2 eq (1.61 E07 vs. 1.62 E07 kg CO_2eq in Table 4), so feed reduction appears to be the biggest benefit of the integrated agrivoltaic production system. This improvement is somewhat dwarfed by the scale necessary to show the carbon emissions and ecotoxicity of the grid in Figures 2 and 3. Overall, this amounts to about a 4% improvement in the GHG emissions profile of the agrivoltaic system compared to the separated conventional solar and conventional sheep production systems. This alone would be a great benefit for using the agrivoltaic approach, but it should be pointed out that agrivoltaics may be what makes a PV system acceptable to the local population at all and thus the appropriate comparison is agrivoltaics to conventional sheep and the grid. It appears clear in Figures 2 that the largest GHG emissions benefit would obviously be the transition from grid electricity to solar PV systems. If agrivoltaic systems provide extra economic or social incentives for the co-production of animal products and electricity, then perhaps those incentive to transition to solar-based electric systems is their biggest potential enhancement to environmental outcomes.

Similar trends are observed in the Ecotoxicity indicator, where the changing impacts due to electricity production are more important than the meat production service under study here. Notably, the transition from conventional sheep production to agrivoltaic sheep production reduced the ecotoxicity of the meat cultivation by 75%, due to the removal of grain feeds from the sheep's diet. Removing the use of glyphosate herbicide resulted in a relatively minor change in cumulative ecotoxicity (8.04 E8 vs. 8.03 E8 CTU from Electricity Production in the Conv Solar / Conv Sheep scenario vs. Agrivoltaic scenario, respectively), compared to the effect of changing sheep diet.

The percent increase above the agrivoltaic system is shown for global warming potential and ecotoxicity in Figures 2 and 3, respectively. Figures 2 and 3 shows clearly that although integration in pasture-based agrivoltaics decreases the environmental impact slightly, the far more

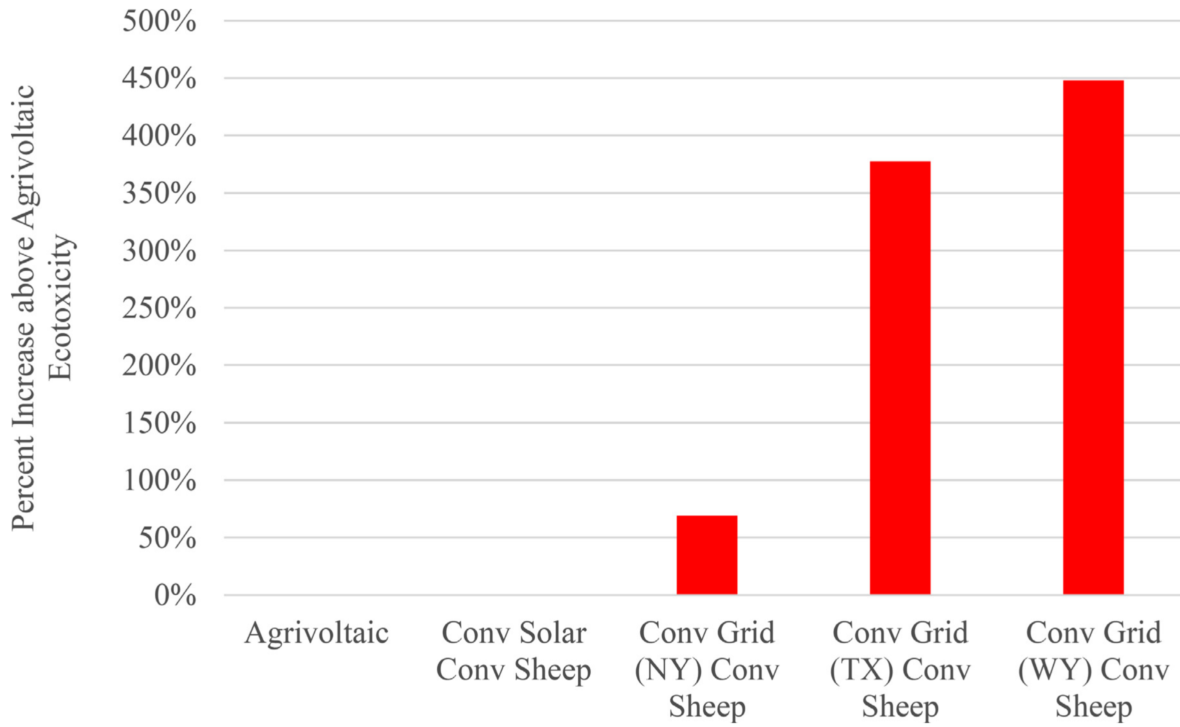

Fig. 3. Percent increase above agrivoltaic system for Ecotoxicity (CTU).

important metric is the replacement of fossil-fuel burning power plants with PV.

3.1. Limitations and Future Work

Like all LCAs (Gentil et al., 2010), this analysis demanded some assumptions. First, this was a cradle-to-gate investigation, which did not consider the end-of-life impacts. The end-of-life environmental impacts associated with the modeled scenarios could be included in a future study of the full life cycle impacts of the sheep-based agrivoltaic system. This would entail obtaining the end-of-life values for the conventional grid in the targeted locations as well as the environmental impact of decommissioning the PV system (Mahmoudi et al., 2019) and the recycling (Deng et al., 2019) of the modules (Lunardi, et al., 2018), wires, electronics and racking that may demand policy interventions to obtain (McDonald and Pearce, 2010). These latter stages of the life cycle would likely not improve the comparison between conventional sheep or solar power and their agrivoltaic counterparts, because the downstream process for sheep produced conventionally or through agrivoltaics is likely to be the same, as an example. Second, future LCA investigation is needed in the full range of environmental impacts including ecosystem toxicity, soil development, and the impact on sheep pasture value (Barlow, 1985) for sheep pasture-based agrivoltaic systems. Finally, secondary effects should be included such as the impact of sheep agrivoltaics on pasture methane emissions (Dengel et al., 2011), if adequate emissions data is available for animals exposed to different diets. A life-cycle cost assessment could also be performed on the competing systems in order to make the economic case for agrivoltaic operations, which could make a clear financial motivation to pursue this integrated agricultural approach, with or without considering the monetary impacts of environmental improvements facilitated by agrivoltaics.

Although sheep-based agrivoltaics is already widespread as shown in Figure 1, to further increase knowledge in the area openly published experimental trials are needed to produce yields of sheep meat and wool output. Future agrivoltaic research can also analyze the impact of climate and regional variability as well as the shading effects of panels on pasture grass growth rate for livestock-based agrivoltaics. In this study, the PV module density of 4.5 acres per MW from Horowitz et al. (2020), was used, but there are two factors that could impact optimal density. The impacts of the PV shading on the pasture and thus overall agricultural production are important, but from a total greenhouse gas emissions perspective the carbon intensity of the local grid can play a major role. For example, increasing the packing density of PV above the point that losses in agricultural production may be justified in carbon-intensive grid locations. The optimal agrivoltaic system is not a static value. In general, as renewable energy continues to offset fossil fuel production, the optimal packing factor of PV will decrease from maximum PV generation to obtain more balance with agricultural production. Simultaneously, as climate change increases raising temperature and thus heat stress on crops/pastures (Dupraz, et al., 2011; Barron-Gafford, et al, 2019; Schindele, et al., 2020), PV may provide shading that will protect plants and thus increase yields. Finally, the environmental impact of the PV systems themselves is also dynamic and improving as their production is somewhat dependent on the energy mix during their manufacture, their efficiency and the materials for their racking. For example, wood-based racking (Vandewetering, et al., 2022a, b) can reduce economic costs and may reduce environmental impact as well. Finding an optimal balance of solar radiation controlled by PV module density as well as potentially percent transmission of the PV module (e.g. controlling cell density within a module) can be used to optimize agrivoltaic system design for specific locations. Thus, future LCA studies should assess scenarios of varying module row spacing and geometry as well as consider the use of semitransparent PV modules (Husain, et al., 2018).

3.2. Agrivoltaic Systems in the Context of the UN's Sustainable Development Goals

The results of this study provide further evidence that agrivoltaic systems are superior to conventional ground-mounted PV systems because they have dual purposes and reduce the environmental impacts associated with producing food and electricity. The environmental impacts were slightly 'greener' (more environmentally friendly) than the systems working separately (and used half the land area to deliver the same level of service), which is also expected to increase social acceptance of solar development on agricultural land (Pascaris, et al., 2022). Previous, energy-themed social science research has shown that social acceptance is a pivotal determinant of large-scale energy project success including low-carbon energy projects (Batel et al., 2013), renewable energy projects (Wüstenhagen et al., 2007), energy storage (Devine-Wright et al., 2017), and solar and wind energy (Sovacool & Ratan, 2012). In the U.S., solar industry professionals consider social acceptance and public perception the largest barriers to developing large-scale PV systems (Pascaris et al., 2021a). Agrivoltaics with sheep, which have greater land efficiency and lower environmental impact, while also contributing in part to local employment (Proctor et al., 2021) and providing a local food (Pollan, 2010) would all be expected to increase social acceptance. Social acceptance will have implications on the increased deployment of PV and the concomitant environmental benefits including a reduction of air-pollution-based mortality (e.g. replacing the remaining coal-fired power plants with PV would reduce premature deaths in the US by more than 50,000 per annum (Prehoda, & Pearce, 2017)). Encouraging sheep grazing on all appropriate conventional PV systems is a first step, but future work can investigate how to further optimize the agrivoltaic systems as a whole (Chamara & Beneragama, 2020). For example, solar can be used for water pumping (Periasamy, et al., 2015) by directly coupling PV to the pumps (Chandel, et al., 2017) to provide water for the sheep, to use solar power for farm equipment (Gorjian, et al., 2021), or to use onsite PV to to provide grain drying (Rein, et al., 1982) and produce nitrogen fertilizer (Du et al., 2015) to increase pasture growth rate. Finally, additional work is needed to investigate different agrivoltaic array geometries (Riaz et al., 2019).

The dual use of the same land becomes even more important when considering the UN's Sustainable Development Goals (SDGs) (UN Assembly, 2015) in the context of the increasing population (UN, 2019) taxing both the energy and agricultural sectors (UN, 2021). This study has shown that the sheep-based agrivoltaic system represents a practical, economic, and environmentally superior solution to these growing concerns. Further research that continues to demonstrate the technical, environmental, economic, and social benefits of other agrivoltaic systems can support several SDGs: i) SDG12 (Responsible Consumption and Production), which is needed to maximize resource efficiency, ii) SDG13 (Climate Action) directly helps our transition to low-carbon renewable-energy-based economies by offsetting fossil fuel energy production by solar-generated electricity, iii) SDG8 (Decent Work and Economic Growth) because agrivoltaics encourages local employment and has an economic advantage over both conventional agriculture and PV per acre per year (Dinesh & Pearce, 2016), iv) SDG2 (No Hunger) is supported because land used for PV can also produce food to reduce food prices and world hunger. Grazing is particularly good for this as it can produce food in areas that are not suitable for more intensive farming.

3.3. Scaling Sheep-based Agrivoltaics

In the U.S. there were about 5.2 million head of sheep and lambs as of 2020 (Statistica. 2021). The results of this study showed that each sheep that is converted to a solar sheep raised on pasture in an agrivoltaic system prevents about 103 kg CO_2 eq per year. Thus, if the U.S. went to only agrivoltaic sheep raising, 5.73E8 kg CO_2 eq per year would be conserved. This is roughly equivalent reduction in GHG emissions to removing 117,000 average automobiles (U.S. EPA, 2016) from the road. On the other hand, the U.S. Energy Information Administration (2021) reports that the U.S. housed over 46 GW of utility scale PV in 2020. Thus, with the grazing density used in this study only about a quarter of the current U.S. sheep production has the potential now to move to solar farms. This is rapidly changing as the PV industry continues to grow with over 26 GW of additional utility PV projects already announced (SEIA, 2021). Range and pasture lands are available in most places. For example, in the U.S. they are located in all 50 states (U.S. Department of Agriculture, 2021), and it appears likely that the solar industry in the U.S. will easily grow to be able to accommodate all of the sheep demand in the nation in the next decade.

3.4. Policy to Support Agrivoltaics

Although the results of this agrivoltaic LCA will be of use to solar developers and land owners for making their cases to install PV systems, they are of most use to land use planners, municipal governments, and policy makers as they can guide in maximizing value of a given parcel of land sustainably. Policy makers should take into consideration integrating solar PV electricity generation and food production as a core component of future sustainable land use practices (Gorjian, et al., 2022; Pearce, 2022). Based on the environmental advantages of the grazing-based agrivoltaic systems demonstrated by this rigorous LCA study and thus agrivoltaics ability to support sustainable development, it is important for policymakers to design regulations that encourage rather than discourage agrivoltaic deployment and incentives to support the long-term adoption of this technology among solar developers and shepherds. One area that needs particular attention in the U.S. is for agrivoltaic systems to be continued to be zoned for agriculture. PV system operators that are continue to use land for environmentally-superior sheep production should not be economically penalized.

4. Conclusion

A life cycle assessment study was conducted in order to explore the impacts of integrated agrivoltaic systems involving sheep pasture cultivation. The expected benefits of the agrivoltaic system in comparison to a conventional solar or conventional sheep agricultural operation are a reduction in sheep feed, combined with a synergistic reduction in solar PV maintenance activities, all while maintaining equivalent yields of a stand-alone sheep agricultural or PV system. The results show modest environmental benefits of this type of agrivoltaic system compared to conventional solar (1.61 to 1.62E7 kg CO_2eq) production and better still for sheep production (1.85 to 2.47E6 kg CO_2eq). The environmental benefits of an agrivoltaic system are much larger in comparison to scenarios where conventional grid-provided electricity are used to provide electricity in absence of the agrivoltaic system (e.g. up to orders of magnitude in kg CO_2eq depending on the grid). The significance of these results is clearly that even this relatively light form of agrivoltaics should be encouraged on any existing grazing land and the concept as a whole should be used whenever possible to offset grid electricity in regions with high fossil fuel use. The synergistic benefits of integrated sheep management and solar PV electricity production are observed in the LCA data when comparing to conventional sheep and PV systems operated independently, although these differences are small in comparison to the benefits gained when grid electricity is replaced with solar PV. In this sense, if agrivoltaics can serve as a potential economic and social motivator to increase the adoption of more PV production capacity on the grid, this would be the biggest source of environmental benefit from this technology system.

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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