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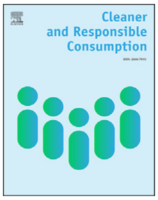

Life cycle assessment of pasture-based agrivoltaic systems: Emissions and energy use of integrated rabbit production

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ABSTRACT

Agrivoltaic systems, which deliberately maximize the utility of a single parcel of land for both solar photovoltaic (PV) electricity production and agriculture, have been demonstrated as a viable technology that can ameliorate competing land uses and meet growing energy and food demands efficiently. The goal of this study is to assess the environmental impacts of a novel pasture-based agrivoltaic concept: co-farming rabbits and solar PV. A life cycle assessment (LCA) quantified the impacts of 1) the integrated agrivoltaic concept in comparison to conventional practices including 2) separate rabbit farming and PV production and 3) separate rabbit farming and conventional electricity production. The impact assessment methods employed to determine the environmental impacts were IPCC 2013 global warming potential 100a V1.03 and fossil energy demand V1.11. The results indicate that the pasture-based agrivoltaic system produces the least amount of greenhouse gas emissions (3.8 million kg CO_2 equivalent) and demands the least amount of fossil energy (46 million MJ) per functional unit of cumulative MWh output of electricity and cumulative kg of meat over 30 years in comparison to the two other scenarios under study. The pasture-based agrivoltaic system features a dual synergy that consequently produces 69.3 % less emissions and demands 82.9 % less fossil energy compared to non-integrated production. The potential for agrivoltaic systems to significantly reduce environmental impacts revealed by this LCA demonstrates that integrated solar and pasture-based agricultural systems are superior to conventional practices in terms of their comparatively lower emission and energy intensity. These findings provide empirical support for increased agrivoltaic system development more broadly.

1. Introduction

The Energy Information Administration forewarns that by 2050, global energy demand is expected to increase by nearly 50 % compared to 2019 (EIA, 2019), which challenges current energy systems. Increasing energy demand combined with growing recognition of the environmental impacts associated with fossil fuels prompts an urgent need to reduce reliance on finite fossil resources. Solar photovoltaic (PV) technology represents one of the fastest growing (IEA, 2020) and most promising (environmentally and economically) methods to reach a sustainable energy system (Pearce, 2002). Because utility-scale PV farms are rapidly growing and necessitate large surface areas (Denholm and Margolis, 2008), there is considerable potential for land use conflicts between energy generation and food production (Nonhebel, 2005; Calvert et al., 2013; Dias et al., 2019). With the world population increasing at the rate of 1.15 % per year (UN, 2014), the Food and Agriculture Organization of the United Nations projects that food production will have to increase by 70 % between 2005 and 2050 to feed a burgeoning global population of 9.1 billion (FAO, 2009). This suggests an increase in the foreseeable tensions between land use for agriculture versus energy production. Historical examples of conversion of crop lands to energy production for ethanol have driven up the cost of food and increased world hunger (Ford and Senauer, 2007; Tenenbaum, 2008; Brown, 2008); yet this food versus fuel debate is avoidable given recent advances in PV technology and applications that allow land to be leveraged for both purposes (e.g., Riaz et al., 2019; Weselek, 2019). Meeting growing

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energy and food demands in alignment with Sustainable Development Goals 2, 8, 12 and 13 will require innovative and synergistic uses of land, specifically the co-location of solar PV with agriculture (Agostini et al., 2021).

Agrivoltaics, the strategic development of a single parcel of land for both PV and agricultural production, provides a technically viable solution to mitigate competing land uses (Adeh et al., 2019; Santra et al., 2017), establish security in both energy and food production (Dinesh and Pearce, 2016; Mavani et al., 2019), and increase global land productivity by 35–73 % (Dupraz et al., 2011). The emerging agrivoltaic technology can be applied in various contexts but was first introduced to plant-based agriculture such as wheat (Dupraz et al., 2011), corn and maize (Amaducci et al., 2018; Sekiyama and Nagashima, 2019), lettuce (Marrou et al., 2013; Elamri et al., 2018), aloe vera (Ravi et al., 2016), and grapes (Malu et al., 2017). Experimental research has confirmed improved crop yield (Marrou et al., 2013; Barron-Gafford et al., 2019), increased land use efficiency (Dupraz et al., 2011; Mavani et al., 2019) and potential economic yield (Dinesh and Pearce, 2016) resulting from the co-location of solar PV and agriculture. Further, research conducted by Bousselot et al. (2017) has found that protection from solar irradiance provided by PV arrays can reduce temperature fluctuations and consequently increase late season plant cover in green roof applications. Agrivoltaics has expanded to include livestock production with sheep (Ouzts, 2017; Mow, 2018), lamb (Andrew, 2020), emu (REW, 2014), rabbits (Lytle et al., 2020) and fish in aquavoltaics (Pringle et al., 2017). Aquavoltaics can also be used to harvest plants (Pringle et al., 2017) as well as salt (Kim et al., 2020). The viability and profitability of these systems all appear promising as there are synergistic benefits of increased yield for some shade-tolerant crops, as well as a more sustainable (environmentally and economically) form of vegetative maintenance for solar developers hosting livestock-based agrivoltaic systems. A study by Proctor et al. (2021) found an upper-bound land requirement of only 0.94 % of farmland is required to meet 20 % of U.S. electric generation, which further demonstrates the potential for agrivoltaics to conserve arable land while meeting food and energy demand efficiently. The diversity of possible agrivoltaic applications presents ample opportunity for creative agricultural co-location that reflects local community interests (Pascaris et al., 2020, 2021, 2021), mitigates land use conflict (Adeh et al., 2019), and increases the economic value of farms deploying such systems (Mavani et al., 2019).

Agrivoltaic systems also appear promising from an environmental perspective, although only a few life cycle assessments (LCA) have been conducted. Agostini et al. (2021) performed an economic and environmental assessment of agrivoltaic systems and found that the environmental impacts are commensurate to that of a traditional PV system, yet agrivoltaics provide added values of reduced impact on land occupation and crop production stabilization. By employing LCA methodology, Agostini et al. (2021) demonstrated that agrivoltaic systems have similar environmental performance in areas such as resource consumption, eutrophication, and climate change compared to traditional operations but generate valuable auxiliary benefits, which suggests co-located systems are environmentally superior. Ott et al. (2020) conducted LCA of a crop-based agrivoltaic system involving cabbage and beets grown beneath traditional c-Si PV modules. LCA results show reduced evapotranspiration of crops due to panel shading effects, consequently decreasing water consumption by 14–29 % in comparison to conventional crop production (Ott et al., 2020). Ott et al.'s (2020) assessment included field operations such as chemical fertilizers and agricultural machinery, resulting in a scenario in which the agrivoltaic global warming potential was higher compared to traditional PV; this study identifies areas for improving the environmental performance of agrivoltaic systems in terms of GHG emissions potential and reduced reliance on intensive field operations. Leon et al. (2018a, 2018b) have made contributions to the LCA methodology itself in the context of agrivoltaic applications, developing a "solar allocation" method and proposing new functional units to understand environmental impacts more comprehensively. Despite the dearth of agrivoltaic LCA studies, existing empirical research is beginning to show that co-locating PV and agriculture is an environmentally advantageous approach to traditional production practices, with consideration of the type of application (crop verses livestock) and system size contributing greatly to overall system performance (Ott et al., 2020).

To advance the agrivoltaic LCA literature, this study investigates the environmental performance of rabbit-based agrivoltaic systems. Rabbits are of interest because of their small-stature, high stocking density, grazing capabilities, and low carbon footprint in comparison to other sources of meat (Lytle et al., 2020). Application of LCA to a rabbit agrivoltaic system is intended to determine the environmental impacts of the concept in comparison to conventional practices of rabbit farming and production of electricity. The specific goal and scope of this study is to help stakeholders in land management and agricultural operations assess if integrating rabbit meat production with solar PV effectively minimizes the greenhouse gas emissions and fossil energy demand associated with these endeavors, compared to a scenario where these processes were operated independently. As relevant to the rabbit-based agrivoltaic pilot test study associated with this research project, three scenarios based in the state of Texas in the U.S. are analyzed. These scenarios are shown graphically in Figs. 1–3: 1) agrivoltaic integration of pasture-fed rabbits with PV; 2) independent solar PV and conventional rabbit production; and 3) independent conventional electricity and rabbit production. It should be pointed out that this is not a serial process but that all three scenarios are being compared in parallel. The assessment results are compared for greenhouse gas emissions and fossil energy demand, and are discussed in the context of sustainable development.

2. Methodology

ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b) establish the leading international standards for performing a Life Cycle Assessment (LCA), including a regulatory framework, principles, requirements, and guidelines. The LCA presented here was conducted in accordance with these guidelines.

2.1. Modeled scenarios

The goal and scope of this LCA study is to illustrate the differences in environmental impact between integrated agrivoltaic production of rabbits and electricity, compared to conventional production systems, as described above. Three separate systems have been designed to model the same level of service across both main system outputs (rabbit meat and electricity) but through different means. Based on the parameters established by Lytle et al. (2020), each system has been designed to achieve 1.57 MW energy generation with potential rabbit meat production constrained to the productive capacity of 2 ha (5 acres) of pasture. The first scenario is the baseline study that represents an agrivoltaic system, in which solar PV is directly integrated with pasture-fed rabbits (Fig. 1). The stages modeled include product fabrication, manufacturing, maintenance, and use (water). The second scenario features both a solar PV facility and conventional rabbit farming occurring independent of one another as shown in Fig. 2. The stages modeled include product fabrication and manufacturing, use (lawn mowing, herbicide application, feed, water, and building maintenance), and feed transport. The third scenario models Texas conventional electricity generation and conventional rabbit farming (Fig. 3). The stages modeled include product fabrication and manufacturing, use (electricity, feed, water, and building maintenance), and feed transport. All scenarios are designed to achieve the same multiple-output functional unit of 412,596 MWh (1.57 MW installed peak power) and 7200 rabbits (approximately 19,440 kg of rabbit meat) as allowed by the capacity of the baseline scenario over its lifetime of 30 years. It should be pointed out here that this is not the standard approach, but the multi-component functional unit is appropriate in this case, where modeling the integrated production of two

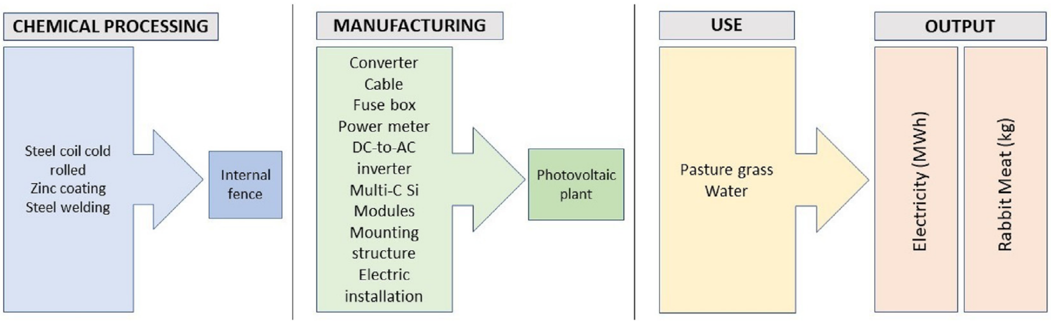

Fig. 1. Modeled scenario 1 (Rabbit Agrivoltaic System).

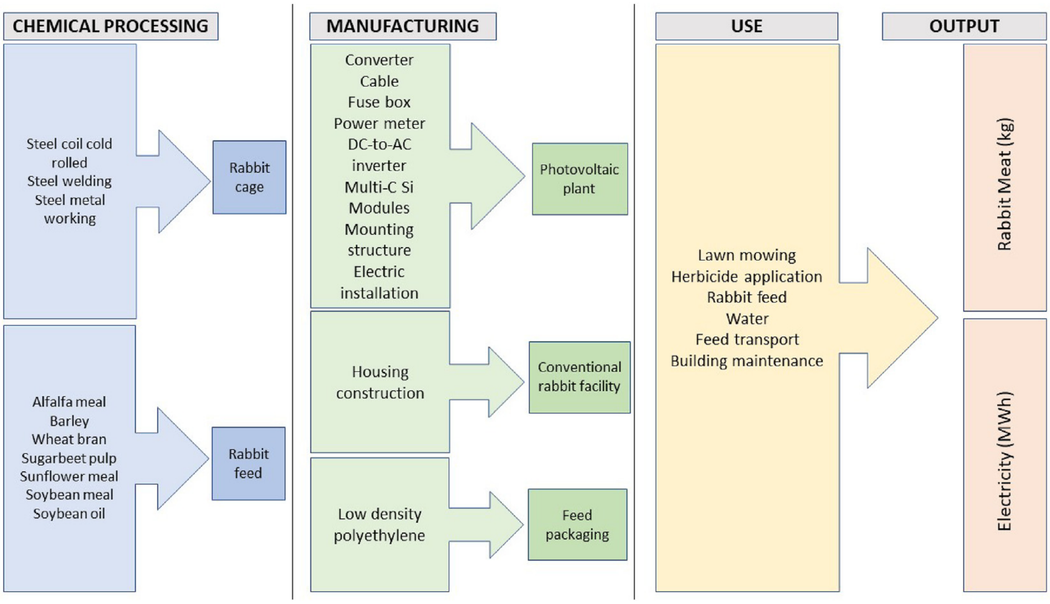

Fig. 2. Modeled scenario 2 (Independent Solar PV and Conventional Rabbit Production Systems).

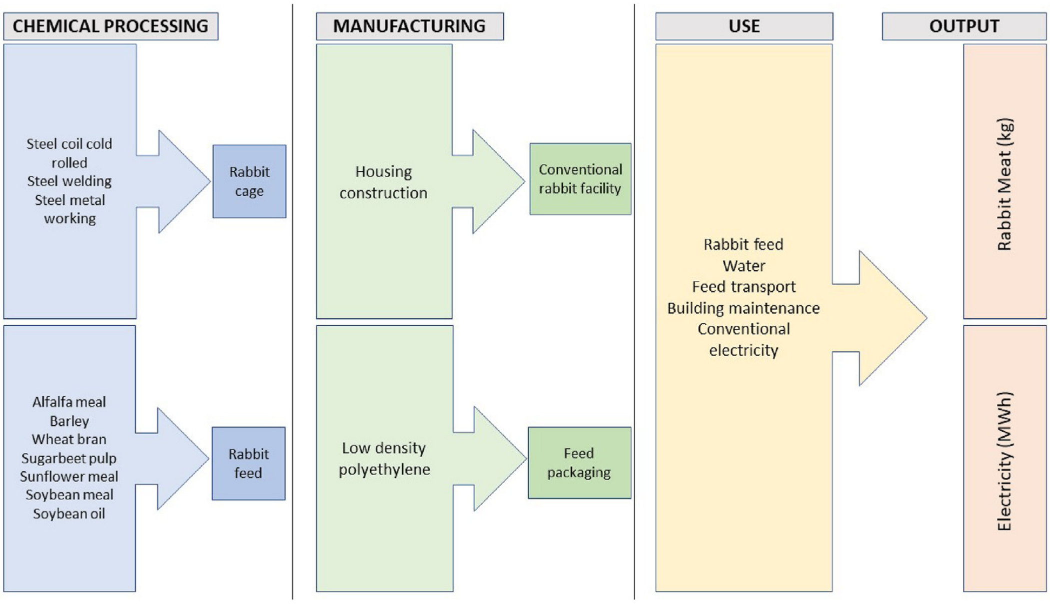

Fig. 3. Modeled scenario 3 (Independent Conventional Electricity & Rabbit Production Systems).

distinct services in the main agrivoltaic case, in comparison to scenarios where each of the services had to be produced independently. In this case complications due to allocation are avoided, because the combined environmental impacts are reported from producing both main products (rabbit meat and electricity) in each scenario. So, in Scenarios 2 and 3 where the products were being produced independently, effectively there were two separate LCAs performed, and the sum of the environmental impacts from both LCAs are reported.

2.2. System boundary

Data collection for this study is limited both spatially and temporally. The three modeled scenarios are investigated under a cradle-to-gate scenario, in which the energy and rabbit production systems are modeled from their conception to the end of the useful life of a typical solar array, assumed to be 30 years. The cradle-to-gate approach effectively excludes end-of-life disposal of the electrical and agricultural facilities, as these processes as modeled in this study have been found to be negligible for the environmental impacts of interest (GHG emissions and Fossil Energy Demand) and are likely to be commensurate for all scenarios under study, given similar system infrastructure. Considering these points, it is asserted that exclusion of the disposal scenario for electrical and agricultural infrastructure is neither consequential nor biased towards any one scenario over another. Additionally, the same quantity of organic waste output is assumed for all scenarios as they are modeled to produce the same amount of rabbit meat and has thus been excluded from the system boundary. The purpose of this study is to assess opportunities for integrated production of energy and agriculture; therefore, the focus is on the earlier stages of the life cycle rather than disposal or end-of-life impacts. Lastly, the systems are assumed to be located in the state of Texas, U.S. as related to the pilot test study associated with this project and because this region is characterized by grasslands and prairies, making it an ideal location for productive livestock grazing (USDA, 1995). By virtue of the intention to combine land uses for dual production, the study uses a multiple-output functional unit that satisfies two service requirements: cumulative MWh output of electricity and cumulative kg of rabbit meat.

2.3. Life cycle inventory development

For the purpose of modeling simplification, the following assumptions have been made for all three scenarios under study. The solar PV array is considered grid-tied and therefore does not require a battery backup. The rabbit facility infrastructure (building, equipment) is assumed to require 5 % total maintenance over the lifetime of the system. The lawn care required to maintain a conventional PV site has been included but does not account for the manufacturing or maintenance of the mowing equipment. Further, to simplify the modeling of rabbit farming, only the fattening (also known as juvenile) stage has been considered exclusive of the breeding process. It is assumed mature meat rabbits are slaughtered at ~2.7 kg (Cesari et al., 2017). Lastly, seasonality is not taken into account.

2.3.1. Scenario 1: rabbit agrivoltaic system

The conceptual design for rabbit-based agrivoltaics provided by Lytle et al. (2020) established a 1-acre, 314 kW solar farm building block. The outer perimeter is 65.7 m long and 60.1 m wide. This 1-acre building block has been scaled up by a magnitude of 5 to provide a full-time rabbit farmer with a realistic operation of 5 full acres and a total 1.57 MW of PV electric capacity. Ecoinvent (version 3) (Ecoinvent Centre, 2016) provided a pre-packaged ground-mounted photovoltaic plant modeled for a global scenario. All relevant balance of system components are included, as well as electric installation and fencing. Unlike a conventional solar array, an agrivoltaic system designed to host pasture-fed rabbits requires additional internal fencing to prevent escape. Based on Lytle et al.'s (2020) conceptual design, 40 stationary fences 63.5 m long each and 20 movable fences 7.7 m long each have been included in this scenario, necessitating a total of 2694 m of internal fencing needed for a 5-acre system. The internal fencing is based on a steel welded wire rabbit fence provided by Home Depot (Everbilt, 2020) that is 15.24 m in length per panel, requiring a total of 177 internal fencing panels for this system. A 5 % total maintenance of the internal fence has been assumed and included in the scenario. As per the Everbilt product, there is no significant packaging associated with the internal fencing and therefore has not been included.

Lytle et al. (2020) estimate 15–33 rabbits/acre/year in a purely pasture-based system. Mather details that 1 cohort of pasture-fed rabbits requires 26–28 weeks to mature, providing an average of 27 weeks (189 days) to reach slaughtering weight (2.7 kg). The study presented here overlooks seasonal restrictions to equate the potential meat output from both indoor and outdoor systems, and thus it is assumed that 2 rabbit cohorts can be sustained per year under all scenarios. An average of 24 rabbits/cohort/acre/year is thus obtained and scaled up to 2 ha (5 acres) over 30 years to produce a total system output of 7200 rabbits. Although pasture-based rabbits are typically supplemented with feed to increase growth rates (Lytle et al., 2020), this study is interested in observing pasture-fed livestock production in strict comparison to conventional production and therefore assumes the rabbits produced in the agrivoltaic system are solely pasture-fed. A sensitivity analysis that considers the impacts of including supplemental feed is provided in section 3.3.

Further, a pasture-fed rabbit consumes about 0.27 kg of grass per day (Meyer et al., 2021), resulting in 50 kg of grass per rabbit over its life span and a total of 181,000 kg of grass over the entire lifetime of the system. This scenario assumes that the pasture grass is generated on site and therefore is included but not modeled from an external source. A 2.7 kg rabbit consumes 0.05 L of water per kg of its body weight per day (Meyer et al., 2021*)*. Over its entire lifetime (189 days) one rabbit requires 25.5 L of water, resulting in a total system water demand of 183,700 L.

2.3.2. Scenario 2: independent solar PV and conventional rabbit production system

Both Scenario 1 and 2 include the pre-packaged ground-mounted photovoltaic plant modeled for a global scenario provided by Ecoinvent (version 3) (Ecoinvent Centre, 2016). All parameters are held equal for both solar PV systems (Scenario 1 and 2), excluding internal fencing for the independent facility. The major distinction between Scenario 1 and 2 in terms of the solar system is the use stage, in which the conventional facility requires continued vegetative maintenance rather than relying upon rabbits to graze the grass down to an acceptable height. An average solar array requires two mows per year and six herbicide applications (Lytle et al., 2020). Scaled to the modeled scenario's specifications, this requires a total of 120 ha of mowing and 816 kg of herbicide over the lifetime of the system (Ozkan, 2018). Herbicide packaging has been calculated accordingly and is included in this scenario.

Conventional rabbit farming has been modeled for feed inputs (including packaging and transport), as well as the housing system with cages and building operation (includes lighting, heating, and water per Ecoinvent). Rabbit feed ingredients were adapted from Cesari et al. (2018) and designed to model a typical 22.7 kg (50 lb.) bag (Tractor Supply Co, 2020). Respective percentages of each feed ingredient were provided by Purina Mills Rabbit Product Guide (2018). According to Purina Mills (2019), the daily feeding amount for a medium breed rabbit (1.4 kg–2.7 kg is about 0.09 kg–0.20 kg, informing an average of 0.14 kg per day for a typical rabbit. As per Ecoinvent, the raw material input needed to produce rabbit feed is produced in the Netherlands but is modeled to be transported from a Texas-based Purina Mills feed store via freight truck to Lubbock, Texas over a rough distance of 403.5 tkm. This calculation is based on the transport of 16,425 bags (22.7 kg each) of rabbit feed transported 16 km from the feed store to the rabbit facility over the lifetime of the system. It is assumed that the feed modeled from the Netherlands is a reasonable representation of U.S. animal feed as the production of relevant feed inputs are based on a mechanized and intensive form of agricultural production, and therefore can be appropriately interchanged for modeling purposes.

This scenario utilizes a pre-designed housing system provided by Ecoinvent that is intended for pig farming to model the rabbit facility, based on the assumption that the materials for manufacturing are commensurate. The housing system is assumed to require 5 % total maintenance. The pre-designed system does not include cages, however, and therefore required the modeling of cage manufacturing for this scenario. Based on a modular wire rabbit cage provided by KW Cages (2020), approximately 18 cages are needed to satisfy the housing requirements (7 rabbits per cage) of 2 separate 120-rabbit cohorts per year (Smith, 2020).

2.3.3. Scenario 3: independent conventional electricity & rabbit production system

The rabbit production facility for Scenario 3 is identical to Scenario 2. To account for electricity generation, 412,596 MWh output has been modeled from conventional energy sources in Texas. Energy data is current as of March 2018 and represents Texas Regional Entity low voltage electricity, provided by U.S. EPA (2020). This effectively makes all three scenarios equal in terms of their service of energy and meat output, allowing for comparison of environmental impacts as they are derived through different means.

Tables 1–3 detail the input data for each modeled scenario. Obtained values represent total system lifetime unless otherwise stated as a per unit calculation. Input items were modeled using Ecoinvent v3 ecoprofiles unless otherwise noted.

2.4. Impact assessment

The impact assessment methods employed to determine environmental impacts using SimaPro modeling software were IPCC 2013 Global Warming Potential (GWP) 100a V1.03 and cumulative energy demand (CED) V1.11. The IPCC GWP method calculates the greenhouse gas (GHG) emissions associated with a modeled scenario in terms of kilograms carbon dioxide (CO_2) equivalent, accounting for climate change factors within a 100-year time frame. The CED method provides a calculation of energy consumption in Mega Joules (MJ) for every stage of the life cycle under study, including both direct and indirect uses of energy. A subcomponent of the CED method is the fossil energy demand (FED), which is of particular interest to this study as quantification of non-renewable energy use provides a distinction between renewable and fossil energy sources, as relevant to the various scenarios under consideration. These two mid-point assessment methods were selected based on their ability to provide insight into the emissions and energy intensity associated with the systems under study. Offering more certainty in describing impacts than available end-point assessment methods, the IPCC GWP and FED methods can quantify the emissions and fossil energy demand associated with each modeled scenario and therefore allow a comparative environmental assessment of the various systems. The ultimate intention of using these two methods is to determine if integrating pasture-fed rabbits directly with solar PV in an agrivoltaic system causes a reduction in GHG emissions and fossil energy demand compared to conventional practice of separate production.

Table 1
Rabbit agrivoltaic system inputs.

Scenario 1			
Unit	Materials & Processes	Required Inputs	Source
Photovoltaic Plant	Includes: Multi-crystalline Si panels, mounting structure, inverter, electric installation (Fuse box, electric cables, electric meter), and external fence	Three 570 kWp photovoltaic plants	This amount of PV infrastructure input is required to generate 412,600 MWh of electricity, Ecoinvent v3
Internal Fence Manufacturing and Maintenance	Steel coil	5.8 kg per fence panel	HomeDepot, 5 % total maintenance requirements assumed
	Zinc coating	0.4 m^2 per fence panel	
	Welding	2.4 m per fence panel	
Pasture grass generated on site	Grass	362,000 kg	Meyer et al. (2021)
Water	Water	183,000 kg	Meyer et al. (2021)

3. Results & discussion

The GHG emissions and fossil energy demand associated with the 3 modeled scenarios are summarized in Table 4 and shown graphically in Figs. 4 and 5. The results reveal that the pasture-fed rabbit agrivoltaic system produces the least amount of GHG emissions (3,880,000 kg CO_2 equivalent) and demands the least amount of fossil energy (46,000,000 MJ) in comparison to the two other scenarios under study. These findings indicate that integrated solar and pasture-based agricultural systems are environmentally superior to conventional practices of separate production in terms of their comparatively lower emission and fossil energy intensity.

3.1. Main point of divergence

Both PV systems, with and without integration of farming, have substantially reduced GHG emissions and fossil energy demand compared to conventional grid electricity. While this has been amply demonstrated by prior research (e.g., Sims et al., 2003), the findings of this study further underscore the consequence of energy production choices while highlighting an opportunity for increased mitigation through combined production methods. Despite the enormous discrepancy in environmental impacts between the PV and conventional grid electricity scenarios modeled here, of most interest to this study is a comparison between scenarios 1 and 2, as it provides insight into the distinctions between an integrated animal agriculture and solar energy system versus standard separate production. The comparative assessment between scenarios 1 and 2 reveals that the pasture-based agrivoltaic system (scenario 1) is environmentally superior, producing 69.3 % less emissions and demanding 82.9 % less fossil energy than non-integrated production of solar PV electricity and meat (scenario 2). As shown in Figs. 4 and 5, the “Use Stage” of the life cycle is the main point of divergence in emissions and energy intensity, identifying where environmental burdens are of most concern. The Use Stage of scenario 2 features conventional rabbit feeding and vegetative maintenance of the solar array, including mowing and herbicide application. In scenario 2, 99 % of the emissions produced and fossil energy demanded during the Use Stage are related to the commercial rabbit feed production, associated packaging, and transport. This operation results in high environmental impact in comparison to the Use Stage of scenario 1 that only entails grass grazing and water provision.

The divergence between scenario 1 and 2 based on the Use Stage of the life cycle demonstrates the synergy generated by hosting grazing livestock on a solar array. Pasture-feeding rabbits under scenario 1 not only maintains no reliance on external feed but also that mowing and herbicide application to the PV array is unnecessary. Although herbicide application was found to be insignificant for the impact assessment methods under investigation, it is important to consider the associated environmental affects beyond GHG emissions and fossil energy demands, such as ecosystem toxicity, soil erosion, and water contamination (e.g., Liu et al., 2016; Siemering et al., 2008; Kortekamp, 2011). By foregoing the most environmentally impactful unit process required of scenario 2, the agrivoltaic system consequently produces less CO_2 emissions and

Table 2
Independent solar PV and conventional rabbit production system inputs.

Scenario 2			
Unit	Materials & Processes	Required Inputs	Source
Photovoltaic Plant	Includes: Multi-crystalline Si panels, mounting structure, inverter, electric installation (Fuse box, electric cables, electric meter), and external fence	Three 570 kWp photovoltaic plants	This amount of PV infrastructure input is required to generate 412,596 MWh of electricity, Ecoinvent v3
Lawn Mowing	Mowing by motor mower 2 times per year	120 ha	Lytle et al. (2020)
Herbicide Application	Six ten-pound applications per year	816 kg	Lytle et al. (2020)
Herbicide Packaging	Polyethylene packaging	0.36 kg	–
Rabbit Feed	Alfalfa meal	2.04 kg per bag	Cesari et al. (2018), Purina Mills (2019), Tractor Supply Co.
	Barley	3.62 kg per bag	
	Wheat bran	3.40 kg per bag	
	Sugarbeet pulp	3.40 kg per bag	
	Sunflower meal	3.40 kg per bag	
	Soybean meal	3.40 kg per bag	
	Soybean Oil	3.40 kg per bag	
Feed Packaging	Packaging film, low density polyethylene	166.2 kg	–
Feed Transport	Freight, truck, from within Lubbock, Texas	403.5 tkm	–
Cage Manufacturing	Steel Welding	5 kg per cage	KW Cages
	Steel (metal working)	0.6 m per cage	
		5 kg per cage	
Housing System and Maintenance	Pig, fully-slatted floor	N/A	Ecoinvent v3, 5 % total maintenance requirements assumed
Building operation	Includes lighting, ventilation, heating, and water	N/A	Ecoinvent v3

Table 3
Independent conventional electricity & rabbit production system inputs.

Scenario 3			
Unit	Materials & Processes	Required Inputs	Source
Electricity Generation	Conventional energy sources in Texas	412,596 MWh	Ecoinvent v3
Rabbit Feed	Alfalfa meal	2.04 kg per bag	Cesari et al. (2018), Purina Mills (2019), Tractor Supply Co.
	Barley	3.62 kg per bag	
	Wheat bran	3.40 kg per bag	
	Sugarbeet pulp	3.40 kg per bag	
	Sunflower meal	3.40 kg per bag	
	Soybean meal	3.40 kg per bag	
	Soybean Oil	3.40 kg per bag	
Feed Packaging	Packaging film, low density polyethylene	166.2 kg	–
Feed Transport	Freight, truck, from within Lubbock, Texas	403.5 tkm	–
Cage Manufacturing	Steel Welding	5 kg per cage	KW Cages
	Steel (metal working)	0.6 m per cage	
		5 kg per cage	
Housing System and Maintenance	Pig, fully-slatted floor	N/A	Ecoinvent v3, 5 % total maintenance requirements assumed
Building operation	Includes lighting, ventilation, heating, and water	N/A	Ecoinvent v3

demands less fossil energy. This dual synergy created by grazing livestock on a solar array illustrates the environmental benefits of the pasture-based agrivoltaic concept in comparison to conventional separate production.

3.2. Improvement analysis

For continued GHG emission mitigation and conservation of finite fuel and land resources, these findings suggest that agrivoltaics should become a mainstream approach to enhance the environmental performance of ground-mounted solar PV development. Conventional PV facilities require ongoing vegetative maintenance that includes the use of fossil-fuel powered mowing equipment, which can add to embodied emissions due to module breakage. In addition, vegetative maintenance often entails the application of herbicides, which have potential to cause compounding environmental damage such as ecosystem toxicity. These processes partially counter the environmental advantages of solar power generation, adversely contributing to the total life cycle impacts of a conventional array. Based on the results of this analysis, it is suggested that in instances where it is practical to do so, forthcoming ground-mounted PV systems should incorporate grazing livestock to maintain vegetation rather than employ current emissions and energy intensive practices of mowing and herbicide application. It is further recommended that existing PV facilities consider design modifications to accommodate an agricultural function of the land beneath the panels to reduce vegetative maintenance costs, livestock feed demands, and the associated environmental impacts.

Given the ability of LCA methodology to delineate unit processes and allocate environmental burdens, future research should investigate potential design modifications that could refine agrivoltaic systems according to the most intensive stages of the life cycle identified by this study. Specifically, the use of alternative materials in production of the fences is suggested to improve system efficiency. To enhance the environmental profile of agrivoltaic systems, a fence composed of material less intensive than steel (e.g., wood) could be utilized. To compensate for this material modification, the external fence could be designed to be electrified and powered directly by the on-site PV generation (only a small PV system is needed for this and there are existing commercial products that fill this need). Also, the pre-modeled PV system included in scenarios 1 and 2 are based on multi-crystalline Si (mc-Si) panels rather than single-crystalline Si (c-Si), which indicates room for improvement of power production efficiency.

Additionally, an average rabbit (6lbs.) produces about 0.1–0.2 kg of manure per day (Evander, 2020), which would result in approximately 309,272 kg maximum waste output over the duration of the modeled systems. Future livestock-based agrivoltaic LCA should expand the

Table 4
Impact assessment results.

	GHG Emissions (kg CO₂ eq)			Fossil Energy Use (MJ)		
Scenario	1	2	3	1	2	3
Infrastructure						
Fencing[a]	3330	–	–	36,500	–	–
Building[a]	–	1560	1560	–	14,300	14,300
Solar system	3,880,000	3,880,000	–	46,000,000	46,000,000	–
Key Operations						
Rabbit feed[b]	–	8,777,000	8,777,000	–	223,050,000	223,050,000
Herbicide	–	13,800	–	–	186,000	–
Mowing	–	2170	–	–	34,000	–
Electricity generation	–	–	256,000,000	–	–	3,570,000,000
Pasture use stage	103	–	–	1190	–	–
Total	3,883,000	12,667,000	264,771,000	46,037,000	269,234,000	3,793,064,000
Percent savings from conventional	98.5 %	95.2 %	NA	98.8 %	92.9 %	NA

[a] Includes maintenance.
[b] Includes rabbit feed, packaging, and transport.

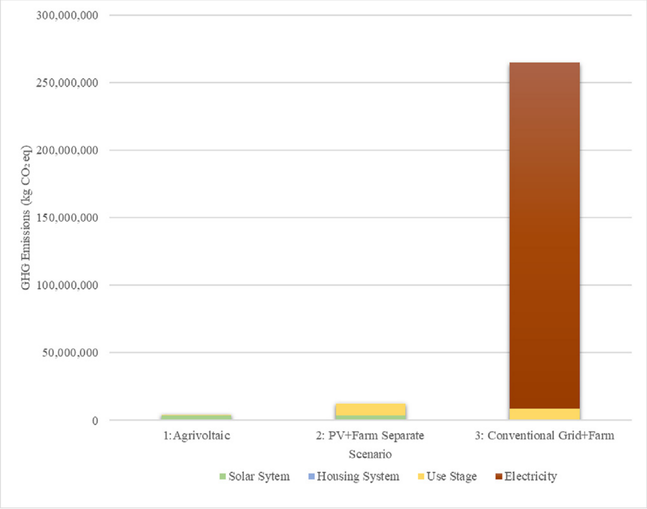

Fig. 4. Comparative assessment of GHG emissions across scenarios.

system boundary to include disposal scenarios to account for organic waste output and consider the associated impacts or benefits. There may be a possibility that manure in the pasture-based system could be used more effectively as a fertilizer to stimulate future growth of the pasture on which the rabbits depend, but there may also be a possibility of changes in potential agricultural runoff and associated environmental impacts between the conventional and pasture-raised systems. Because this study assumed the burdens or benefits from the organic waste output are equal across all modeled scenarios, continued work is needed to assess the potential for organic waste to be leveraged as an asset. By considering organic waste as an opportunity for industrial symbiosis in adjacent farm applications (e.g., Alfaro and Miller, 2014), future research could quantify the avoided use of fertilizers, decreased costs, and reduced environmental impacts that are made possible by re-purposing the waste created by livestock-based agrivoltaics.

Lastly, future research may consider the possible differences in labor requirements for agrivoltaic systems versus conventional practice and the associated impact on economic performance or job creation. Further work is also needed to determine the LCA optimum grazing livestock (some livestock do not require internal fencing as pasture-fed rabbits do) and to explore the potential synergy of simultaneous water provisioning for livestock and cleaning of PV modules, for example. Lastly, a comparative assessment between rabbit and sheep-based systems can be evaluated, as sheep have become the most common livestock-based agrivoltaic application in the U.S. (REW, 2014; Ouzts, 2017; Andrew, 2020).

3.3. *Sensitivity analysis*

Scenario 1 assumed that the pasture-fed rabbits did not require supplemental feed, which is contrary to standard pasturing practice. To investigate the inclusion of supplemental feed in a pasture-based agrivoltaic system, an additional scenario has been modeled to assess changes in environmental impacts. A scenario in which rabbits are supplemented external feed to satisfy 25 % of their daily feed requirements has been considered and results reveal no significant difference GHG emissions or fossil energy demand. Comparing a purely pasture-based agrivoltaic system with one that includes supplemental rabbit feed, fossil energy demand increased by 500,000 MJ (1.1 %) and GHG emissions increased by 200,000 kg CO₂ eq. The effect is a 4.8 % increase in emissions as a direct result of incorporation of rabbit feed in a pasture-based system. This minor increase in emissions can help inform decision-making about rabbit grazing practice for agrivoltaics as it has been demonstrated that either approach (purely pastured versus supplemented) produces nearly equivalent environmental impacts in performance areas of GHG emissions and fossil energy demand. Overall, the sensitivity analysis did not impact the selection of the most environmentally friendly option: integrated PV and pasture-based farming in a full agrivoltaic system. It is expected that similar results would be observed with other agrivoltaic systems, however, future work is needed to verify this for other animal species like sheep.

3.4. *Limitations*

As is standard among researchers employing LCA methodology (e.g., Gentil et al., 2010), a set of modeling assumptions were included. The cradle-to-gate system boundary established in this study limited the investigation of end-of-life impacts. Because disposal is beyond the focus to assess opportunities for integrated production, the end-of-life environmental impacts associated with the modeled scenarios has been overlooked for the purpose of this study. To properly consider the full life cycle impacts of an agrivoltaic system, future research should consider the decommissioning of the array and the recycling of the modules and other hardware components (e.g., McDonald and Pearce, 2010; Lunardi et al., 2018; Deng et al., 2019; Mahmoudi et al., 2019). Future LCA work is needed to investigate a broader range of environmental impacts including ecosystem toxicity and land occupation for agrivoltaic systems. Although it should be pointed out that in general and from a recent interview-based study of farmers (Pascaris et al., 2020), the vast majority of farmers using a pasture system to raise rabbits do not engage in a regular program of fertilization. It is also possible to use some of the PV-generated electricity to produce nitrogen fertilizer on site (Du et al., 2015).

Further, experimental trials are needed to produce known yields of rabbit meat output. Considering this study overlooked seasonality in the

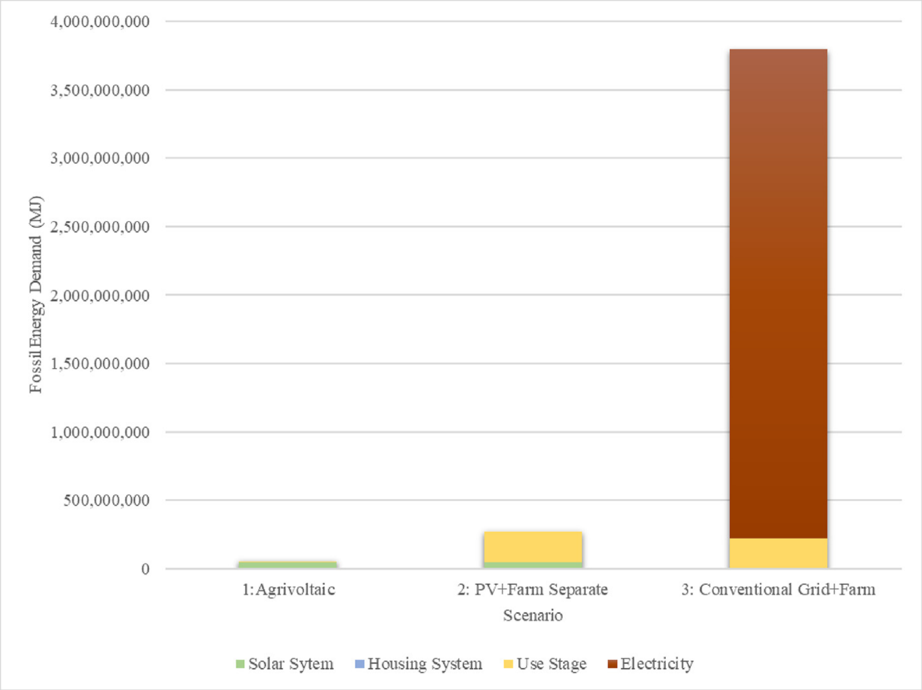

Fig. 5. Comparative assessment of fossil energy demand across scenarios.

pasture-based scenario, future research should 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. Finding an optimal balance of grass/crop-available solar radiation and PV module density will be a key consideration in the continued development of agrivoltaic systems, therefore subsequent LCA studies should assess scenarios of varying panel spacing and height as well as consider the use of semitransparent PV modules.

3.5. *Agrivoltaic systems in the context of sustainable development*

The findings presented here strengthen the argument that agrivoltaic systems are superior to traditional ground-mounted PV arrays in terms of their ability to leverage a single plot of land for dual purposes and consequently reduce the environmental impacts associated with each enterprise, which may be key in positively influencing social acceptance of solar development on agricultural land. Energy-focused social science research has proven that social acceptance of an energy development is a pivotal determinant of project success (Wüstenhagen et al., 2007; Devine-Wright et al., 2017; Sovacool and Ratan, 2012; Batel et al., 2013); projects that deliberately uphold community interests and are designed with participation from residents to be locally appropriate have shown higher levels of acceptance (Simpson, 2018). Pascaris et al. (2021) found that U.S. solar industry professionals consider social acceptance and public perception issues to be the most considerable barriers to developing photovoltaic systems, further emphasizing the importance of societal concerns about environmental and community impacts of solar development for the diffusion of innovation. As agrivoltaic systems start to proliferate agricultural communities, localized resistance to development rooted in place-protective action is to be expected (Boyd and Paveglio, 2015; Devine-Wright, 2009; O'Grady, 2020; Pascaris et al., 2021). Because farmer adoption of agrivoltaic technology is shaped by concerns about potential effects on long-term land productivity and compatibility with current practice (Pascaris et al., 2020), continued research is needed to verify the relatively benign land impacts of PV (e.g., Fthenakis, 2003; Turney and Fthenakis, 2011) and the environmental advantages of agrivoltaics, quantify the increased rural employment opportunities (Proctor et al., 2021), and identify the potential food, energy, and water synergies to be harnessed (e.g., Macknick, 2019). Social acceptance and farmer adoption will have implications on the increased deployment of agrivoltaics, therefore designing systems that not only generate technical and environmental benefits, but social benefits as well will be imperative.

In the broader global context, the UN forecasts the burgeoning human population will impose natural resource constraints, with increasing concern focused on agriculture and energy sectors (UN, 2021). The latest World Population Prospects (UN, 2019) asserts that the equivalent of nearly three planets worth of natural resources will be needed to sustain current lifestyles, making the need for integrative, efficient, and synergistic uses of land vital to the future of human life on Earth. Agrivoltaic system development represents a practical solution to growing concerns over resource constraints and has been demonstrated by this study and others (e.g., Agostini et al., 2021; Ott et al., 2020) to provide invaluable environmental advantages compared to non-integrated production. Research that continues to demonstrate the technical, environmental, economic, and social benefits of agrivoltaic systems can support the realization of many sustainable development goals (SDGs) established by the UN, such as SDG12 (Responsible Consumption and Production), that is founded upon the need to maximize resource efficiency in our transition to low-carbon economies (SDG13 Climate Action). In addition, the economic advantages of agrivoltaics (Dinesh and Pearce, 2016) can be used to fuel SDG8 (Decent Work and Economic Growth) because these systems remain relatively labor intensive compared to PV-only development and have been shown to be economically viable in rural areas (Ravi et al., 2016; Proctor et al., 2021). The enhanced yield (e.g., Bousselot et al., 2017), increase in late season biomass (Bousselot et al., 2017; Hassanpour et al., 2018), and greater soil moisture retention (Hassanpour et al., 2018) observed in some studies from the partial shading of PV arrays also points to a path to lower the cost of food and increase plant resilience to drought stress in a changing climate (Barron-Gafford et al., 2019), which directly supports SDG2 (No Hunger). Thus, the emerging agrivoltaic innovation may serve as an indispensable technology to achieve these SDGs.

The results presented here are of use to solar developers, farmers, land use planners, municipal governments, and policy makers when considering the value of land optimization through the use of innovative solar PV technologies. As the viability of agrivoltaic systems continues to be validated (Weselek et al., 2019), consideration of integrated solar energy and food production as a vital component of future sustainable land use practices is warranted. Based on the environmental advantages of agrivoltaic systems demonstrated by this study and their ability to support sustainable development (Proctor et al., 2021), it will be critical for policymakers to design financial mechanisms to incentivize and support the long-term adoption of this technology among solar developers and farmers.

4. Conclusions

Three scenarios were modeled to achieve the same multiple-output functional units of cumulative MWh of electricity and cumulative kg of rabbit meat. The LCA was limited to emissions and FED. The comparative assessment reveals that the pasture-based agrivoltaic system is environmentally superior, producing 69.3 % less emissions and demanding 82.9 % less fossil energy than non-integrated production of solar PV electricity and meat. By foregoing the most intensive unit process required of conventional farming practice (animal feeding and its associated packaging and transport) and PV array maintenance (mowing and herbicide application), the pasture-based agrivoltaic system features a dual synergy that generates a significant reduction in greenhouse gas emissions and fossil energy demand. Compared to conventional meat and electricity production, the agrivoltaic system modeled here produces 98.5 % less emissions and demands 98.7 % less fossil energy. Although given the limitations discussed of this study, these findings demonstrate that solar PV generated electricity is remarkably less environmentally damaging than traditional fossil energy mixes, and points to agrivoltaic applications as a strategy for continued emissions and energy demand reductions. Mitigation of the environmental impacts associated with conventional energy and livestock production practices is made possible by the integrative synergies generated by agrivoltaic systems. The findings of this LCA further validate the viability of combined solar energy and agriculture production techniques and provide empirical support for increased agrivoltaic system deployment as a pathway to sustainable development.

5. Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Declaration of competing interests

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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