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A Comprehensive Life Cycle Assessment Framework for Agrivoltaic Systems

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Abstract. This paper suggests a comprehensive life cycle assessment (LCA) framework for agrivoltaic systems – systems that integrate photovoltaic energy and agricultural production. Agrivoltaics propose a solution that provides additional land for meeting renewable energy goals while supporting agricultural production and water and land use efficiency. This study contributes to the assessment of the dynamic life cycle improvements associated with agrivoltaics installations by applying the framework to a case study at Jack's Solar Garden in Boulder, Colorado. We utilize the ReCIPe midpoint hierarchist method and leverage data from existing OpenLCA databases to evaluate the environmental and economic impacts of co-located crop production and solar energy generation. The results highlight the potential for reduced land and water use, underscoring agrivoltaics' role in managing land conflicts and water scarce environments. However, challenges such as increased material demands, limited open-source data, and the need for tailored configurations persist. Our framework aims to guide researchers, producers, and policymakers in making informed decisions on the adoption of agrivoltaics.

Keywords: Agrivoltaics, Life Cycle Assessment, Food-Water-Energy Nexus, Multiple Land Use

1. Introduction

Regional, state, and local political jurisdictions are pursuing ambitious renewable energy plans that require expanded reliance on solar energy resources. This transformation will necessitate more rapid and widespread redevelopment of electric grids, which, in turn, demands that locations suitable for solar deployment be carefully identified while considering current and future population, land use, and technological constraints.

As a result, there is increasing competition between agricultural land use and renewable energy production interests, which puts pressure on rural agriculture to simultaneously provide food and energy to urban centers. Agrivoltaics is an emerging, synergistic solution that combines solar photovoltaic-based renewable energy generation with agricultural production. Agrivoltaic applications are suitable for both rural and urban environments, where rooftop agrivoltaics can provide fresh food to urban residents and rural agrivoltaics can provide new economic opportunities for farmers and landowners [1]. Thus, agrivoltaics is uniquely situated to provide solutions across the food-water-energy nexus and to help bridge the urban-rural divide [2].

In addition, agrivoltaics have the potential to provide many direct benefits, including job creation in local communities through solar installation and maintenance, increased agricultural revenue for farm operators, and greater water use efficiency attributable to decreased evaporation from soil and plant transpiration [3]. Agrivoltaic systems benefit food production through optimized carbon uptake for crop growth, reproduction and shading. Energy capture efficiency may improve due to the co-location of transpiring plants that can cool photovoltaics panels [4]. Further, agrivoltaic installations can help political jurisdictions meet renewable energy goals while working to reduce climate and health impacts from burning fossil fuels.

Despite promising research suggesting the utility, efficiency, and feasibility of agrivoltaics systems, implementation has been limited, certainly in the United States, partly due to an incomplete understanding of the associated life cycle costs and impacts. Ideally, investments in agrivoltaics at the regional and farm level would be leveraged to support incremental improvements in farm and energy systems. While early research suggests that agrivoltaic installations result in lower net carbon emissions and less energy demand [5], these benefits often come at the cost of increased material requirements beyond those of conventional ground mounted solar installations [6]; and therefore, the viability of agrivoltaics projects from a purely economic standpoint may be in question.

Broadly, making the right agrivoltaics investment decisions and designing effective policies requires knowledge in three areas which our framework helps to address: (1) What are the dynamic life cycle improvements associated with agrivoltaic installations, specifically across field conditions and under varying photovoltaic (PV) installations? (2) What are the socio-economic underpinnings to consider when working to increase agrivoltaics adoption? (3) What broadscale benefits would agrivoltaics need to present to farmers and energy developers?

This research does not attempt to address all three questions but contributes to the capacity to address these questions. To date, no comprehensive framework has been available for assessing the collective improvements attributable to agrivoltaics across the full life cycle of energy and farm systems that can be used to direct investments and research, and to measure progress. Consequently, in this paper we present work on developing a framework for an agrivoltaics life cycle assessment (LCA) that is applicable to a variety of operational settings and that can be used by researchers, producers, and policy makers alike. This framework, including identification and alignment of the required data inputs, provides valuable decision knowledge that can be used to direct investment and policy decisions. This paper also specifically contributes to question #1 by applying this framework to a case study in Boulder Colorado, USA to assess the impact of agrivoltaic systems.

2. Existing LCA assessments of agrivoltaics

There is a limited number of assessments on the LCA of agrivoltaic systems. One study addresses the impact of additional material consumption used in the mounting of the photovoltaic panels [6]. Other studies address the impacts on crop production due to intermittent shading, noting that more data is needed to fully understand the relationship [7-8]. Leon and Ishihara [9] looked at two functional subsystems: one addressing the unique scenario of land use changes involved and one addressing the monetary aspect of creating two valuable products with one system.

Additional investigations have occurred on the methodologies of LCAs for food and agriculture systems that could inform the agricultural portion of agrivoltaics. In these studies, agricultural LCAs limit the system boundary to the production and transportation of inputs, and cultivation [10]. Applying this boundary to agrivoltaics assumes that the processing, distribution, consumption, and waste management are the same for both agricultural systems being compared. However, this assumption does not apply to the PV portion of agrivoltaic systems since the waste management of PVs is a substantive impact. A potential approach to reconcile boundaries may be to limit the flow of farm products to cultivation in LCAs but follow the flow of PVs through end of life. Another aspect of consideration is assessing the potential difference between urban and commercial farming schemes presented by agriyoltaics. Farmers with agrivoltaics may alter their crop choice to support more urban food demands, of which crop choice can greatly affect LCA inputs such as water consumption [11].

3. A Systems View of a Comprehensive LCA

Figure 1 illustrates a comprehensive Life Cycle Assessment framework in the context of agrivoltaics. The AV system and manufacturing phases involve land preparation, PV mounting, and panel production, leading to cost increases but reduced land-use pressures. In the production phase, AV systems influence crop cultivation, irrigation, and harvesting, with symbiotic relationships between crops and panels improving water-use efficiency and potentially enhancing crop output. The use-stage reflects renewable energy generation, economic benefits from dual land use, and farmer revenue growth. Additionally, job creation and innovation in farming methods contribute to social welfare improvements. Figure 1 also highlights system-of-system linkages, showing how changes in farming practices impact land use, economic returns, and social benefits.

This framework addresses the need to consider the entire system from a holistic, systems engineering perspective, emphasizing that the examination of the farm-to-energy and farm-to-social lifecycles is also crucial for evaluating the integrated impact of combining solar energy production with agricultural practices. This comprehensive framework further recognizes a systems-of-systems perspective and how each component, from the raw materials used in photovoltaic systems to the end-of-life disposal and recycling of these systems to the impact on changes in social systems, impacts the overall impact of the agrivoltaic systems. The framework necessitates a transdisciplinary approach through integrating subsystems representing engineering, agricultural science, economics, and social sciences to capture the complex interactions presented by agrivoltaic systems.

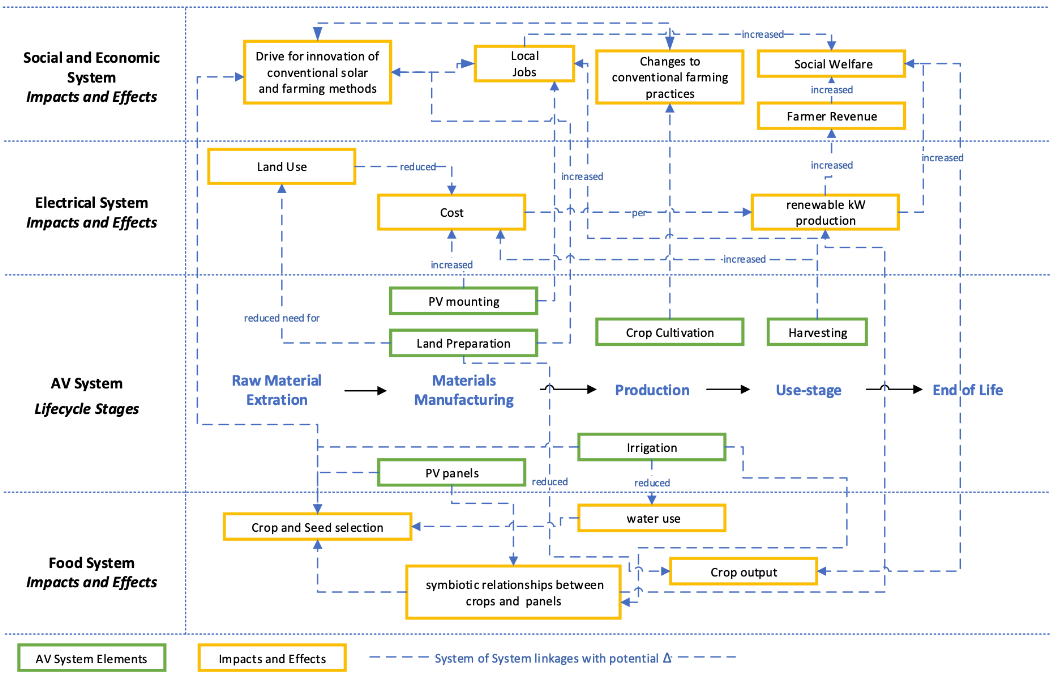

Figure 1. Systems of Systems view on a comprehensive life cycle framework for conducting assessments of Agrivoltaic systems

Because agrivoltaics is a relatively new concept to many farmers, energy industry representatives, and associated community stakeholders, there is a need to apply this assessment to answer how agrivoltaics may require changing or aligning farm operations with broader societal practices, values, and meaning. The proposed framework considers the various resources (e.g., social capital, infrastructure, human resources, financial capital, etc.) needed to deploy new technology on farms amongst differing cultural, tradition, and institutional norms. Incorporating these social perspectives into an LCA framework helps to better inform investment decisions and operational priorities, which can lead to expanded adoption of the technology. Although outside the scope of this paper, substantial research is occurring in the socio-economic factors of agrivoltaics [12-14].

Figures 2-4 depict the process flow diagrams of the unit system process of the *agrivoltaic subsystem component* compared to two conventional agricultural+solar farm systems. Each process diagram notes inputs and outputs to the system as well as the products being created. These diagrams visualize a cradle-to-gate approach for the agricultural elements and a cradle-to-grave approach for the energy production system, which is appropriate for agrivoltaics in which the LCA boundary ends after harvesting and operation as post farm product, such as delivery, use, and end of life, are outside the influence of agrivoltaics.

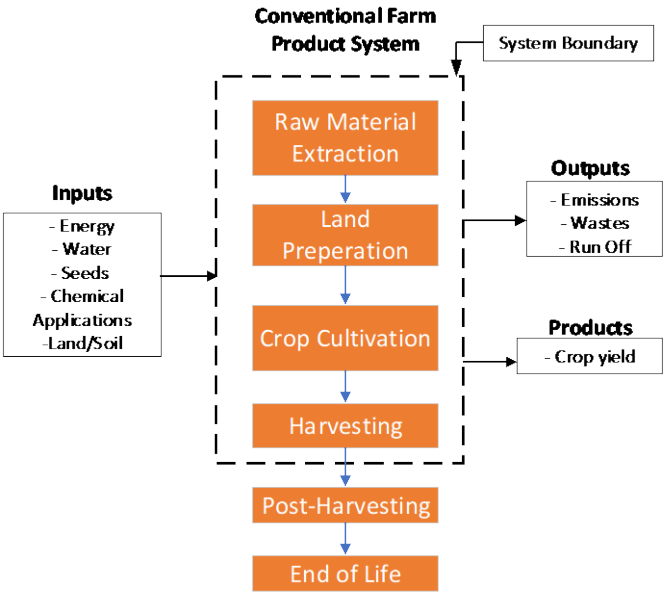

Figure 2. *The Life cycle process diagram for conventional farming*

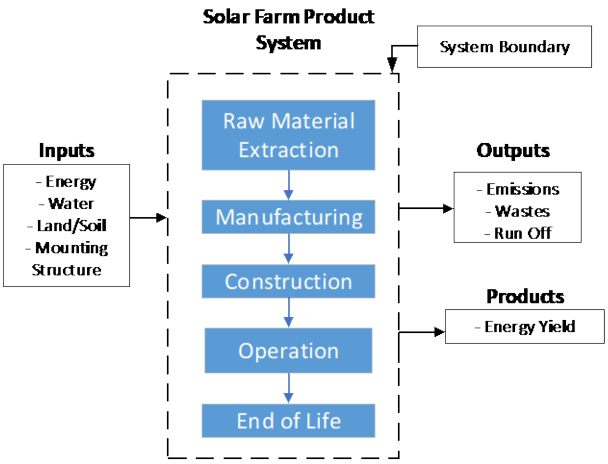

Figure 3. *Conventional solar farm process flow diagram with analysis boundary*

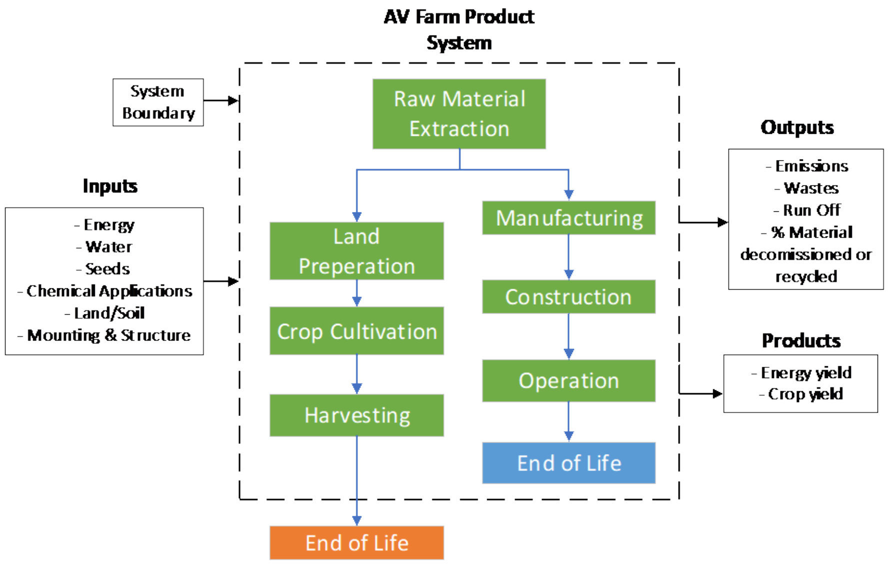

***Figure 4**. Agrivoltaic subsystem process flow diagram showing with required inputs and outputs*

4. Methods and Farm Context

To investigate the application of the LCA framework for the *agrivoltaic subsystem*, this study assessed the lifecycle impacts of an agrivoltaic system that mimics the dimensions at Jack's solar garden in Boulder, Colorado, USA. This system has3,276 6 ft and 8ft tall panels organized in rows that are 17ft on center. These use a 960kW-AC single axis tracking system that produces around 2.1 - 2.2 GWh/yr. Our investigation used the system deployed here to compare conventional methods of agriculture with solar farming (Figure 5). Jack's solar garden represents an agrivoltaic system that marries conventional urban farming/gardening with mounted photovoltaic panels for energy generation. The ‘traditional’ systems are that of conventional potato farming, and solar farms. Potatoes were chosen since data is readily available, they are commonly grown in Colorado, and yield a suitable nutritional content that mimics crops in a community garden [11]. We also limit our assessment to on-farm activities for the PV system as end-of-life data are not available.

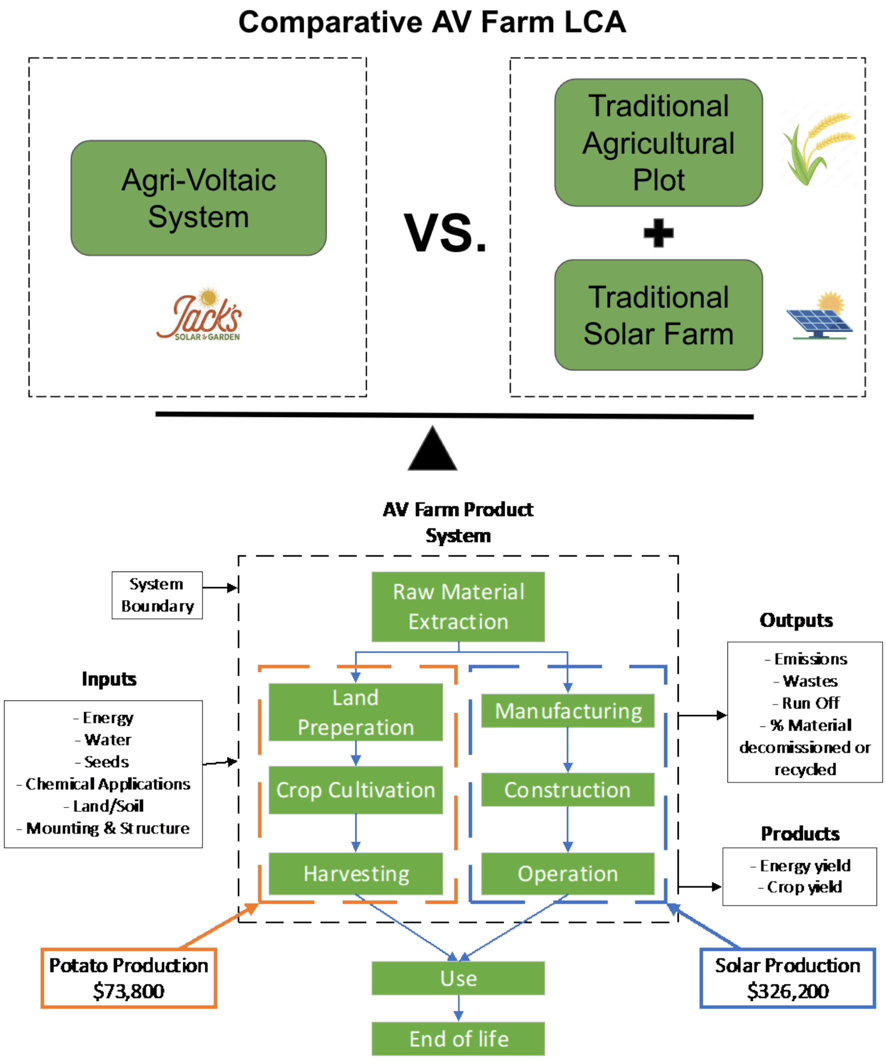

Figure 5. *A visual comparison of product systems included in the LCA case study*

A goal for our comprehensive framework is for it to be open and accessible. To explore this aspect, we conducted a comparative LCA using OpenLCA (v2.1.1) [15]. OpenLCA is a free LCA software with a broad range of available databases on products, systems, and applications. In OpenLCA we configured two systems illustrated in Figure 5. This process combined the inputs of electricity produced by ground mounted solar panels, and potatoes produced in the United States. Inventories were created to represent the systems using the ReCIPe Hierarchist LCIA method [16]. The results of this combined system were then adjusted to represent the impact of an agrivoltaic system. These adjustments were the removal of land occupation and water consumption values that are sourced from the photovoltaic energy from the solar panels. Results from OpenLCA were then compiled and assessed in Microsoft Excel.

Table 1 illustrates the study scope for our investigation. The development of the functional unit for this study across this scope introduced a unique challenge, specifically, how to properly address a multi-product system. Previous agrivoltaic studies historically focused on energy production and its corresponding impacts [8,17]. For this analysis, an emphasis is placed on both crops and energy being produced. To best mimic the output of Jack's, a summation of production for a complete year was estimated and given an economic value. Thus, the functional unit for this study is "one year of total production at Jack's." This analysis allows us to quantify energy and potatoes to be separately assessed as conventional systems. It also allows an important variation to be included--the difference in total crop yield in agrivoltaic systems.

Tables 2-3 describe the remaining functional units. Since solar arrays require space for the mounting systems, the amount of land was reduced, lowering total crop yield when compared to a conventional system with the same land use.

Table 1. *Study scope and functional unit breakdown*

Section	Details
Functional Unit	One year of total production at Jack's Solar Garden
Product Systems	There are two separate product systems that are considered in this project. The first being energy generated for public use. The second system is vegetable crops being grown for human consumption.
System Boundary	The boundary for this assessment strays from the typical studies being done on PVs. Due to data limitations this study will follow both product systems cradle-to-gate. Meaning that impacts will be followed from birth to farm gate. Since both systems being compared include the same type and value of solar panels, it is assumed the end-of-life impacts would be similar. Literature suggests that a large portion of environmental impacts come from the disposal of PVs, thus future studies should expand to include this data.
Inputs	Potato yield (lbs) & Electricity Production (kWh)
Outputs	1 year of production at Jack's Solar Garden
LCIA Methods	ReCIPe midpoint Hierarchist was the impact assessment method chosen for this project. This assessment method will give feedback involving more immediate impacts that are commonly involved in policy. The impact categories of interest calculated with this method are: land occupation, water depletion, resource depletion and global warming impact.
LCA Software	OpenLCA v2.1.1

Table 2*. System production matrix of an agrivoltaic system compared to a conventional farm*

	Size (acres)	Annual Potato Production (lbs/acre)	Annual Potato Yield (lbs)	Annual Solar Yield (kWh)
Jack's Solar Garden	4.1*	18,000	73,800	2.2E6
Conventional Potato Farm	3.69	20,000	73,800	2.2E6

**Sized for equivalent production assuming that more land is required to match conventional potato production*

Table 3*. Values used to derive input values based on functional unit*

	Potato	Solar
Price	0.96 ($/lb)	0.15 ($/kWh)
Jack's Solar Garden	$70,848	$330,000
Conventional System	$70,848	$330,000
Total	$400,848	

For our study we made several assumptions and adjustments to the data. First, data mimicking the products from Jack's were scaled to the level of production at Jack's (Table 2). Thus, the size (acres), solar yield (kWh), and crop type (potato) were selected to best represent a real world agrivoltaic system of 4.1 acres (the same size as Jack's), and the solar energy produced is based on wattage created by the number and type of panels at Jack's. Thus, the combined system is a 4.1 acre potato farm and a solar farm that would generate the same output at Jack's. The combined system represents two systems on two different land allotments. Data for these products were sourced from the Ecoinvent database (v3.4) for photovoltaic energy and combined with data from the Agribalyse (v3.0.1) for potatoes [18,19]. Both sources provide data quality metrics that help portray the quality of the data utilized.

We also examined the dynamics and uncertainty of the system through a Monte Carlo simulation. Data quality values were assigned to each input product (PV electricity and potatoes) and translated into uncertainty values within the OpenLCA software. Uncertainty for each product was calculated by taking an average of the data quality metrics within the original electricity and potato processes, as provided by the Ecoinvent and Agribalyse databases. Overall data quality indexes that were used are noted in Table 4, and we used a representative degree of uncertainty for potatoes and electricity as: *Potato - 1.2077, Electricity - 1.080*. A Monte Carlo simulation was run using these values and 1000 iterations to calculate average values for the impact categories of interest.

We then conducted a comparative analysis on the results calculated from both the initial values and the values that incorporated uncertainty. This included an assessment of hot spots shown in a Sankey diagram that represent large quantities of impacts flowing from their sources. The uncertainty associated with the project was calculated using a Monte Carlo simulation and the derived uncertainty value from the data quality metrics (Table 4).

***Table 4**. Qualitative data quality values based on LCA pedigree matrix used to calculate uncertainty in the monte Carlo analysis*

	Reliability	**Completeness**	**Temporal Correctness**	**Geographic Correctness**	**Further Technical Correctness**
Electricity	2	2	2	4	1
Potato	2	1	4	1	1

5. Agrivoltaic System Life Cycle Analysis Results

Table 5 illustrates the impact of an agrivoltaic system in the western region of the United States across the key LCA elements: land usage and water consumption. A full dataset of impacts is available upon request.

Table 5. *LCIA Results indicating the net changes (deltas) between conventional, combined solar and farming systems, and agrivoltaic systems*

	Conventional Farming Only	**Combined Systems**	**Jack's (AVS)**	**Delta between AVS and Combined System**
Agricultural Land Use (m^2 annually)	8776.4849	15037.89	8776.48	6397.4051
Natural Land Transformation (m^2)	0.77326	17.84	17.84	17.0664
Urban Land Occupation (m^2 annually)	136.88	60120.55	136.88	59983.67
Water Depletion (m^3)	3769.52	4304.83	3769.53	535.3

The most substantive difference between the agrivoltaic subsystem and the combined agricultural+solar systems was land occupation. This paper assumes that combined systems are not typically co-located causing more substantial impact than AV systems or systems that use adjacent land. Solar farms are very similar to crop-based farms in that they typically require large amounts of wide open, relatively flat, sunny land. Thus, these systems could potentially compete for a prime commodity: real estate.

We quantified two land uses using the ReCIPe midpoint hierarchist method: agricultural and urban. The conventional system requires large urban land usage due to the conventional PV system. With the integration into another land sector, this number is greatly reduced. The agricultural land occupation is reduced by a smaller margin due to the system still requiring agricultural land to cultivate crops. Figure 6 illustrates the relative land use difference between systems.

Land occupation is particularly relevant in this study as we replicate an agrivoltaic system. Jack's solar garden functions as a community or urban garden that grows crops to be sold locally, most likely located in a more developed area where real estate is more valuable and energy in higher demand. Thus, it's assumed that land occupied by a similar agrivoltaic system would require some amount of urban and agricultural land, making it an impact of interest. The combination of these systems allows for Jack's to maintain its proximity to consumers without requiring land for both solar and food crops.

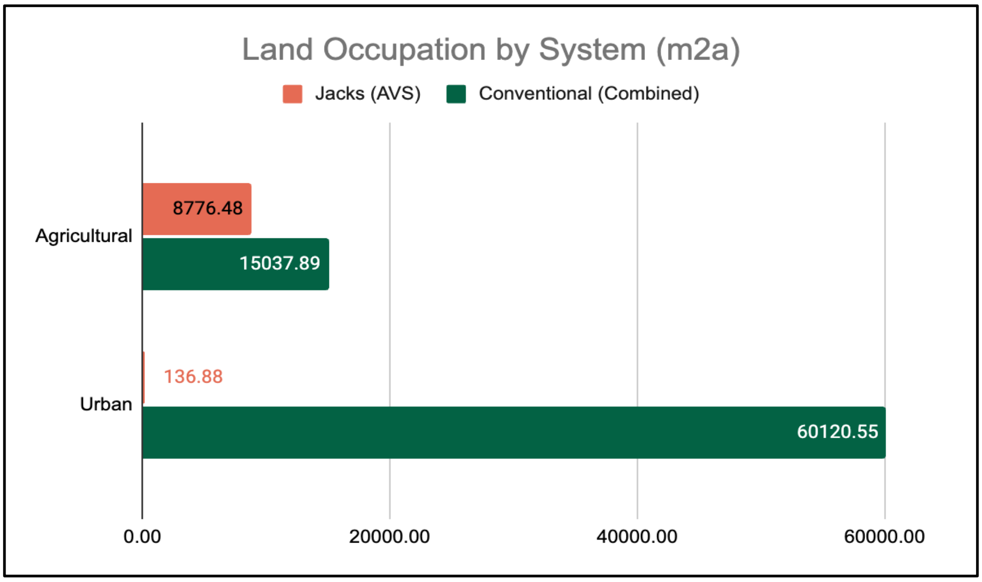

Figure 6. *Land occupation comparison*

Another important metric that affects crop cultivation in stressed areas of the world is water consumption. Figure 7 shows that the majority portion of water consumption in the agrivoltaic subsystem is used for potato production. Table 5 provides a comparative water use summary between a combined system and an agrivoltaic subsystem.

The data provided gave average life cycle inventory values for potato production across the United States, thus a more in-depth and geographically accurate study would be required to limit the investigation to water consumption in a particular location.

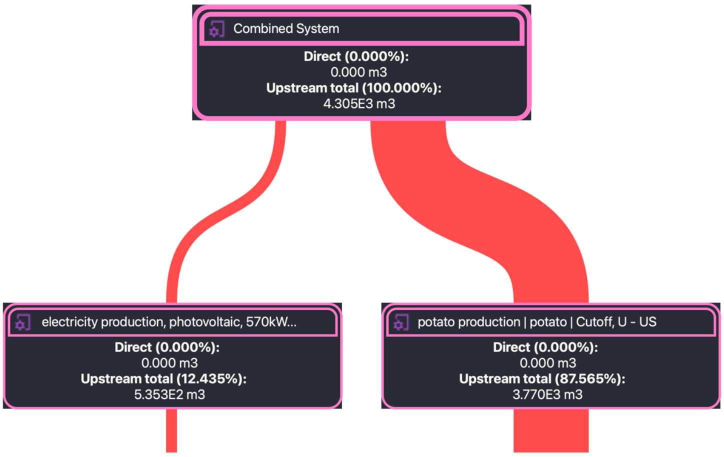

Figure 7*. Water depletion Sankey Diagram of water use for a combined system (conventional farming+solar farm) evaluated in OpenLCA*

The results of the 1000 Monte Carlo iterations indicated greater impact for each category, as shown in Figure 8. A 5% error range was added to the original data to provide reference of the percent change of different values after the simulation. All values from the Monte Carlo simulations were within these error bars. The biggest area of uncertainty according to the pedigree matrix (Table 4) is the poor temporal correlation with the potato data and the geographical correlation with the electricity. This indicates that the open-source data is likely out of date and not very specific to our chosen location (Boulder, CO). Despite this limitation we found that our uncertainty analysis shows relatively low levels of variation in the results.

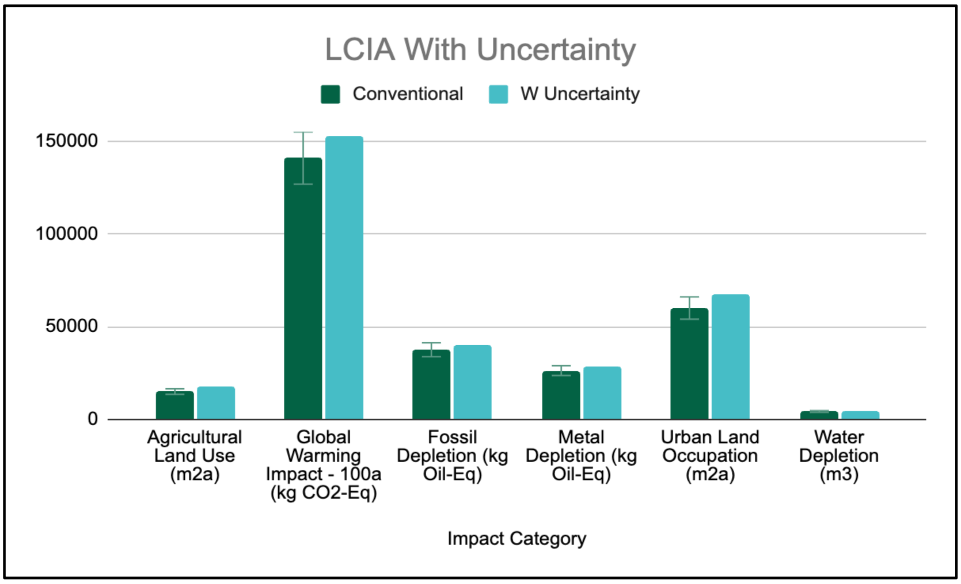

***Figure 8**. Monte Carlo results comparison for combined systems (agriculture+solar)*

6. Conclusion and Limitations

Future investigations could consider the addition of higher quality data in terms of recency and geographical relevance. The open access data sets use geographical averages for product outputs and only provide an estimated value for a farm system located in Colorado. These older datasets may also lack knowledge and impacts from improvements in photovoltaic technology as well as potential differences in crop production yields due to increased global temperatures. The implication being that as PV panels show efficiency losses between .1% and .5% per C above 25C [20], any reduction of temperature is worthwhile. However, the cooling efficiency effect and subsequent energy output was not available in accessible datasets. Therefore, the net benefit of this and other symbiotic relationships was not assessed.

It is also our hope that future agrivoltaic studies will assess the effects of agrivoltaics on water consumption given that studies have shown that the intermittent shade keeps soil moist longer, requiring less irrigated water throughout the growing season [8]. The additional understanding of the intermittent shading relationship is a key point that needs to be developed alongside temporally and geographically accurate crop data.

In terms of resource depletion and global warming potential, most metal flows are attached to the process for photovoltaic energy production. This potentially comes from the mining of materials to create the panels and their respective stands. Our study noted increased material consumption, emphasizing the need for new mounting designs that require less material [7]. Comparable greenhouse gas emissions were noted for the agrivoltaic subsystem and the combined systems, as indicated by our assumption that equivalent renewable energy production would offset similar greenhouse gas emissions. This is not fully accurate in that a considerable amount of fossil depletion flows from heavy machinery in the potato production process. No data was available that illustrated the impact of photovoltaic systems on harvesting methods. For instance, at Jack', substantial labor is done by hand, which reduces emissions from heavy machinery but also changes labor requirements. At a commercial scale, we might expect impact from greenhouse gases to be on similar order as organic systems as agrivoltaics also reduce large scale machinery use and require additional manual labor. Further investigation with updated data is required to accurately report the impact of differently configured agrivoltaic systems on emissions attributable to fertilizers, pesticides and other farm operational changes. Further research may also affect the understood values relating to crop production with intermittent shading from the photovoltaics. Changing these factors may create a more specific life cycle assessment that can be used to better evaluate agrivoltaic systems in Colorado and other locations.

In summary, the proposed LCA framework is designed to facilitate informed decision-making by providing a system level view of the overall lifecycle impacts of agrivoltaic systems. This study illustrates only part of the proposed comprehensive framework. By implementing all components of the LCA framework, decision makers could gain additional understanding of the environmental, economic, and social benefits and other impacts associated with agrivoltaics. Further data and update of this framework, to include assessing potential reductions in greenhouse gas emissions, improvements in land and water use efficiencies, and the socio-economic impacts on local communities, is required. A complete assessment would more thoroughly illustrate the benefits and impacts that arise when solar energy and agriculture systems are combined on the same land. Moreover, additional work with Jack's farm and other Colorado producers will see a completed framework and analysis in subsequent research.

Data availability statement

The datasets analyzed during the current study are available from the corresponding author on reasonable request. The data are stored in the Ecoinvent (v3.4) and Agribalyse (v3.0.1) databases and are subject to institutional review and approval. Access to the data can be granted by the authors in compliance with the associated organizations guidelines and with appropriate permissions.

Author contributions

Whiting, K.: *Writing - Original Draft Preparation*, *Formal Analysis* – K, Methodology. Whiting was responsible for drafting the original manuscript, performing the data analysis, and contributed to the conceptualization of the research.

Conrad, S.: *Supervision*, *Writing – Original, Review & Editing*, *Conceptualization*, *Methodology, Funding Acquisition* - S. Conrad provided leadership and supervision throughout the investigation, obtained funding to support the research, established the overarching research goals and methodology, contributed to the original draft and critically reviewed and edited the manuscript.

Bradley, T.: *Conceptualization*, *Resources, Writing - Review & Editing* - T. Bradley contributed to the conceptualization of the research, supporting resources for the investigation, and critically reviewed and edited the manuscript.

Coburn, T.: *Writing - Review & Editing*, *Conceptualization, Supervision* - T. Coburn contributed to the conceptualization of the research, participated in the critical review and editing of the manuscript, and provided mentorship to the core team.

Competing interests

The authors declare that they have no competing interests.

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