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Life Cycle Assessment of an Exemplary Agrivoltaic System in Thuringia (Germany)

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Abstract. Agrivoltaic systems create numerous synergies between the aspects of agriculture, climate protection, climate change adaptation, land use and energy. For this reason, the present study examined the environmental impact of this technology using the life cycle assessment approach. Three scenarios were developed: An APV scenario with combined production of electricity and potatoes on one field (scenario 1), a PV scenario with separate production of PV electricity and potatoes (scenario 2) and a scenario in which electricity production is covered by the German electricity mix (scenario 3). All three scenarios showed the same output in energy production (500.13 kWp) and in potato production (307.87 dt/a or 9,236 dt/30 years). The results show that APV systems have similar impacts as open-space PV systems and achieve significantly better performances than the German electricity mix. In half of the impact categories examined, the environmental impacts were caused by potato production, in the other half by electricity production. Due to current developments in system design and solar module development, it can be expected that the life cycle impact of APV systems will continue to improve in the future.

Keywords: Agrivoltaic, Life Cycle Assessment, Environmental Impact

1 Introduction

Anthropogenic climate change represents one of the greatest challenges of the 21st century. For this reason, numerous countries have decided to significantly reduce the relevant greenhouse gas (GHG) emissions as part of the Paris Climate Agreement. In Germany, the aim is to achieve savings of 65% by 2030 [1] and GHG neutrality by 2045. In a climate protection program set up for this purpose, a large part of this saving was planned through the use of renewable energies [2].

A large proportion of GHG emissions are caused by the agricultural sector. Globally, the food-related emissions are calculated at around 49 billion t CO_2 eq per year. Accordingly, they account for around 33% of all emissions [3]. GHG emissions contribute to climate change, which in turn leads to more frequent and more intense extreme weather events such as heavy rain or heat waves [4-6]. Extreme temperatures, including prolonged periods of drought, mean that soil water reserves cannot be replenished over the long term. However, extreme weather events such as storms, heavy rain and hail also increase the production risk for farmers and, in the worst case, lead to total losses [7]. In Germany, losses in agriculture due to climate extremes to the value of around 500 million Euros per year, an average of the years 1990-2013, is observed [8]. Agriculture, thus, not only contributes to climate change, but is also strongly influenced by it [9-14].

One approach to reducing GHG emissions is the implementation of solar energy through photovoltaic systems. However, the introduction of ground-mounted systems leads to potential land use conflicts, also with agriculture [15]. For this reason, an intelligent solution is required that combines multiple uses and can create synergies between the fields of energy, agriculture and land use [16].

The concept of agrivoltaic (APV) creates synergies between the areas of energy, agriculture and land use. Especially with regard to climate change, this technology represents a possible contribution to climate protection and climate adaptation. APV creates synergy effects by protecting the areas covered by the solar modules from, for example, wind erosion [17] or drying out [18, 19], and protects the crops from adverse weather events [20]. In addition, the production of solar power contributes to the reduction of GHG emissions and, thus, APV shows increased land use efficiency, which counteracts the ongoing problem of competition for land.

In order to promote APV, the Federal Council of Germany proposed to set tender volumes specifically for APV as part of the draft of the German Renewable Energy Law (Erneuerbare Energien Gesetz, EEG) in 2021 and the later approved tender of a volume of 150 MW included APV systems in the so-called "special solar systems" [21, 22]. In summer 2022 a special sector to specifically support APV is going to be implemented in the EEG. However only a few studies on the environmental effects of APV have been published to date [23, 24], including a recent review [20], and a gap exists especially with regard to the life cycle assessment (LCA) of this technology. Thus, specifically an LCA of different plant designs like high-mounted systems without tracking has not been published yet. This research gap is intended to be closed with this study.

2 Materials and Methods

In this study, the LCA of a planned APV plant in Thuringia, Germany, with an expected installed capacity of 500,13 kWp was conducted (plant design type: pilot project APV RESOLA in Baden-Wuerttemberg, by Fraunhofer Institute for Solar Energy).

A LCA analyzes the input and output flows of a product system and the resulting environmental impacts over the entire life cycle. This can be used to show improvement options from raw material extraction to disposal ("cradle to grave"). In order to introduce uniform international standards when assessing the life cycle impact of production systems, the procedure for LCAs was defined by the International Organization for Standardization in the standards DIN EN ISO 14040 [25] and DIN EN ISO 14044 [26]. This standardization should help to make the results of LCA comparable. DIN EN ISO 14044 defines four phases for this, which are to be examined and presented in a LCA: Defining the goal and the scope of the assessment, the inventory analysis, the impact assessment and the evaluation and interpretation. In the following, these steps are explained on the basis of the above mentioned APV system.

2.1 Goal and Scope

The aim of this LCA is to assess the life cycle impact of the products of an exemplary APV plant in Thuringia, Germany. The generation of electricity and the production of potatoes were selected as outputs. The results were compared with the impacts of two systems in which the outputs are not generated on the same area.

For this purpose, three scenarios were developed: an APV system with combined potato and electricity production (scenario 1), a system with spatially separated potato and photovoltaic (PV) electricity production (scenario 2) and a potato scenario in which the respective electricity purchase was covered by the German electricity mix (scenario 3).

All three scenarios show the same outputs in energy production (500.13 kWp) and in potato production (307.87 dt/a or 9,236 dt/30 years). The potato yields were determined based on the harvest yields in the state of Thuringia in the years 2014 to 2019 [27]. According to Weselek et al. (2021) [28] improved potato yields under PV modules of around 11 % during extreme dry periods can be expected. Due to the persistent dry summer periods in Germany, the potato production of scenario 1 was therefore set at +5 % compared to the calculated average (2014-2019). The system boundaries were defined in both electricity and potato production according to the cradle-to-gate principle. In the case of potato production, the post-harvest processes such as washing the potatoes, packaging, storage and transport were therefore defined as cut-off criteria. In the area of electricity production, the aspects end of life, the commute to and from the system and activities in the areas of administration, marketing, research and development were not taken into account.

2.2 Life Cycle Inventory

The life cycle inventory described here is based on exemplary data for PV electricity and potato production from various databases. With regard to the data sets for electricity production, the LCA guidelines for PV systems of the IEA PVPS Task 12 [29, 30], updated by Hengstler et al. (2021) [31], were used. The guidelines take the following components into consideration: PV modules, inverters, the mounting structure and electrical cables. The data used is available in the EcoInvent database [32]. Depending on the component, they were adapted to each scenario. According to the IEA PVPS Task 12 [30] a 500 kW inverter was assumed for both PV scenarios (scenarios 1 and 2). In addition, the night-time power consumption was calculated at 394.2 kWh per year and set to be covered by the German electricity mix.

The life cycle inventory data from PVPS Task 12 were used for the mounting structure of both PV scenarios (scenarios 1 and 2), which relate to a 1 m² module area and a regular open-space PV system. The steel consumption was based on the PVPS Task 12 for scenario 2. Due to the significantly higher mounting structure in an APV system (scenario 1), the specification concerning the steel production in the PVPS Task 12 was adjusted based on the information from the Heggelbach plant in Germany. Furthermore, instead of concrete foundations, 60 spin anchors were selected for scenario 1, which resulted in an additional steel consumption of around 134.85 kg per spin anchor. The electrical lines were modeled based on Hengstler et al. (2021) for a system output of 1 kWp and then extrapolated to the output of scenario 1 and scenario 2. For the solar modules, c-Si PV modules manufactured in China were assumed. As no PV system was considered for scenario 3, an electricity input covered by the German electricity mix was assumed. The background data for the electricity mix was taken from the EcoInvent database.

With regard to potato production, the Agri-footprint 5 database [33] for Germany was used and adapted to the conditions of the three scenarios. In comparison to scenario 1, lower crop yields were assumed for scenario 2 and scenario 3 (see Chapter 2.1). The background data for the impact assessment covers the years 2011 to 2018. The geographic coverage largely includes Thuringia and Germany.

2.3 Impact Assessment

The life cycle impact was calculated for 16 impact categories which can be divided into the following four root categories: The climate-relevant group includes e.g., the categories climate change, ozone depletion and photochemical ozone formation. The health-related group includes the impact categories particulate matter, human toxicity (non-cancer) and human toxicity (cancer). The categories acidification, eutrophication (freshwater) and eutrophication (marine) and others were summarized as ecosystem-related categories and land use, water use, resource use (fossils) and resource use (minerals and metals) were grouped under the root category of resource-relevant categories. The impact assessment was calculated using the software SimaPro [34]. According to the "Product and Organization Environmental Footprint" (PEF) [29], these impact categories are recommended for LCA for PV systems. The results were dimensioned to a functional unit of 1 kWh of electricity and 1 kg of potatoes.

3 Results and Discussion

Due to the higher material consumption of the high mounting structures, the lowest environmental impacts were caused by scenario 2, but the APV scenario (scenario 1) also achieved significantly fewer impacts in comparison to scenario 3.

In half of the impact categories, a large part of the impacts is caused by potato production, especially in the health and ecosystem-relevant impact categories. This circumstance results from fertilization and the use of pesticides, as the release of ammonia contributes to the formation of particulate matter emissions [35, 36]. In the climate and resource-relevant categories, PV power production achieves a higher proportion of the environmental impact. For scenarios 1 and 2, the majority of the environmental impacts in these impact categories result from the manufacture of the modules and the steel consumption in the production of the mounting structure.

In general, up to 94 % fewer emissions could be calculated in scenarios 1 and 2 compared to scenario 3, especially for the climate-relevant environmental impacts. For example in the category of climate change, scenario 1 caused only 30 % of the CO_2 eq compared to the environmental impacts from scenario 3 (Figure 1). The APV system (scenario 1) only found higher environmental impacts than scenario 3 in the case of the consumption of minerals and metals. This circumstance results from the increased steel consumption, since the mounting structure of the APV scenario is significantly higher in order to provide enough space for agricultural machines. Here, scenario 3 only achieves 16 % of the environmental impacts of Scenario 1. In the Land Use impact category, scenario 1 achieves the lowest environmental impacts. The environmental impacts from scenario 1 account for 63 % of the environmental impacts from scenario 3.

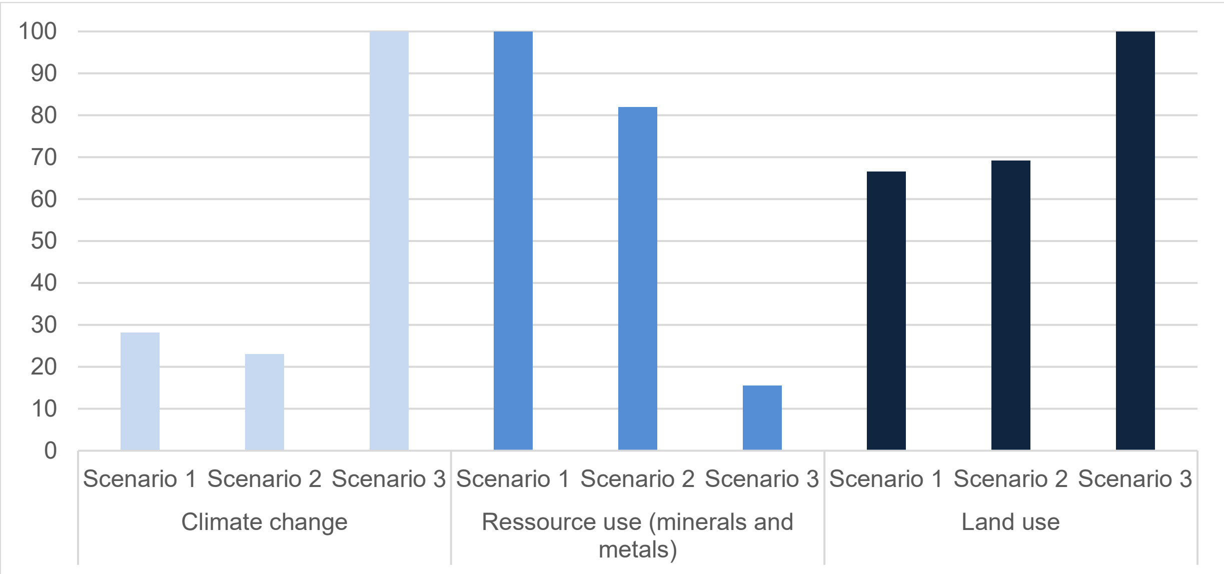

Figure 1. Ratio of the environmental impacts of scenarios 1, 2 and 3 for the selected impact categories climate change, resource use (minerals and metals) and land use in %.

The results show that the environmental impact of APV systems can be compared with those of open-space PV systems and achieve significantly better performances than the German electricity mix in most impact categories. This result is also reflected in the results of life cycle assessments in which other forms of APV systems were examined [23, 24].

Additionally, for a comprehensive estimation of LCA of APV it has to be considered that various forms of APV with respect to mounting structure (lowly mounted, foldable, rope systems, etc.) and numerous module technologies are being used in commercial and pilot studies, which mostly reduce the LCA, compared to the pilot APV system analyzed in this study. The results obtained here provide a general assessment of the environmental impact of APV and show mostly positive effects. Although the PV scenario (scenario 2) mostly caused lower impacts, it can be assumed that with the further development of APV technology, life cycle impacts of APV systems will improve significantly in the future.

Data availability statement

The data presented here are constituents of a publication [37]. They can presently be provided on request.

Author contributions

Christin Busch: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Visualization, Writing – original draft. Kerstin Wydra: Methodology, Supervision, Validation, Writing – review & editing.

Competing interests

The authors declare no competing interests.

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