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Influence of allocation methods on the LC-CO_2 emission of an agrivoltaic system

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ABSTRACT

Agrivoltaic systems are multi-output systems where both solar power and crops are produced on the same land. Unlike other land-based photovoltaics (PV), the agrivoltaic PV modules are ground mounted between crops at some height with a certain tilt. Alternatively, PV modules replace part of a greenhouse or are partially set either below or above a covering material. The system could become an important mitigation option for climate change. However, power generation by PV reduces sunlight transmittance and therefore reduces agricultural yield. An allocation method that will address the potential interference of PV with crops is required for life cycle assessment (LCA) to evaluate greenhouse gas mitigation. This study aims to develop a new allocation method (i.e., solar allocation) and compare the LCA results of the new and traditional allocation methods (i.e., system expansion and economic allocation). The partition rate of the solar allocation is derived from the ratio of the active area covered by PV to the greenhouse surface area and light transmittance. These methods were applied to an agrivoltaic tomato production system using protected horticulture with the introduction of organic photovoltaics as a case-study of a system in Japan.

The allocation methods considered in the present study could serve as potential methods in assessing life cycle − CO_2 emissions. Above all, the solar allocation method can be used for many crops that will be influenced by PVs. Further improvement of the allocation method is required in cases where crop growth is less influenced by PVs (e.g., shadow-tolerant crops or transparent PV).

1. Introduction

Limiting the global temperature increase to less than 2 degrees above the pre-industrial levels during this century was agreed upon by 195 nations at the Conference of Parties 21 (United Nations Framework Convention on Climate Change; UNFCCC, 2015). Renewable energy is gaining interest because of its potential benefits for reducing non-renewable energy use and mitigating climate change. Approximately one-fifth of the global energy consumption in 2014 depended on renewable energy (Ren 21, 2016). The world photovoltaic (PV) capacity in 2015 was 227 GW, which has increased by approximately 10-fold in the last 10 years (Ren 21, 2016).

An agrivoltaic system in which power generation by photovoltaics (PV) and food production are combined (Dupraz et al., 2011) is attractive because sunlight is used in multiple ways on the same land. The system has different terminologies. The term agrivoltaic system is used by Dupraz et al. (2011), Marrou et al. (2013), and Dinesh and Pearce (2016). Alternatively, the term PV greenhouse is used when a PV or semi-transparent PV-module (Emmott et al., 2015) replaces or is installed partly on top of or below the covering material. Moreover, some other studies used neither of these terminologies but discussed the same concept (Ureña-Sánchez et al., 2012). The agrivoltaic system will become a potential method for mitigating climate change, especially for protected horticulture, where heating accounts for a large portion of the total LC − CO_2 emissions. In the case of a tomato greenhouse, heating accounts for over 65% of total LC − CO_2 emissions (65%, Theurl et al., 2014; 71–84 %, Röös and Karlsson, 2013; 85%, Hendricks, 2012). Underneath agrivoltaic systems, despite the potential benefits, heavy shadows influence crop growth. Verification studies observed the varying influence of PVs, which depends on the crop and arrangement of the PV. The yields of rice decreased by 20% as the shade increased by 20% (Homma et al., 2016). Marrou et al. (2013) observed that lettuce yield was reduced as the amount of shadow increased. In contrast, Ureña-Sánchez et al. (2012) observed no influence of the solar panels on tomato yield and income despite the negative impact on size and color of fruits when 9.8% of the roof area of the greenhouse was

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covered with PV.

Life cycle assessment (LCA) is one of the primary methods of evaluating agrivoltaic systems. Because agrivoltaic systems are multi-output processes, allocating $LC-CO_2$ emissions between crop production and power generation is required. In the LCA, the traditional allocation methods have been defined by the International Organization for Standardization (ISO) 14044 (2006) as follows: expanding the system boundary or subdividing certain processes to avoid or minimize physical allocation or other allocation methods (e.g., economic value). Although ISO recommends system expansion or sub-division to avoid allocation, there are limitations to these methods. In system expansion, as discussed in attributional and consequential LCA, the environmental impacts vary depending on the scenarios and selection of the marginal process. The divergent results in LCA studies are attributed to speculative assumptions (i.e., what happens and what would have happened, Heijungs and Guinée, 2007). Fruergaard et al. (2009) reported a large variation in average data on electricity provision among European countries because of differences in fuels and efficiencies among countries. Ekvall and Finnveden (2000) mentioned that there are too many potential fuels that can replace the energy from waste paper in a case when waste paper is recycled. Subdivision is a limited method that can be used only when the multifunctional processes are physically separated, and inventory data are available (Ekvall and Finnveden, 2001). This method is not a suitable option when crop growth is influenced by PV. The use of economic allocation is recommended when the other allocation methods are not suitable (ISO 14044, 2006). Despite this recommendation, economic allocation has been widely used because of its simplicity and ability to illustrate complex systems, despite price variations and the minor relationship between price and physical flow (Ardente and Cellura, 2012).

None of these methods address the potential influence of power generation by PV on intercepting sunlight and therefore on agricultural yield. Accordingly, a new allocation method that will address the potential interference of PV with crops is urgently required for achieving a more sustainable agricultural production based on better decision making and better environment assessment. For this, a proportion of solar radiation could be used as an allocation method (hereafter, solar allocation).

The present study has two goals: (1) to estimate a partition rate for solar allocation and (2) to apply the traditional (ISO 14044, 2006) and the new allocation methods to an agrivoltaic tomato production system using protected horticulture with organic photovoltaics (OPV). To achieve a comprehensive understanding, the present study considered life cycle CO_2 ($LC-CO_2$) emissions among a wide range of environmental impacts. The methods considered could be applied to other potential environmental impacts.

2. Material and methods

2.1. Goal, scope, system boundary and functional unit

The LCA is carried out following the ISO 14040 (2006) and 14044 (2006) guidelines as well as the International Energy Agency's (IEA) methodological guidelines for PV LCA (Frischknecht et al., 2015). The goal is to carry out an LCA of agrivoltaic systems in a tomato greenhouse where tomatoes and power are produced. The results of the LCA provide sufficient information on the influence of the choice of allocation methods on LCA results. The results will be used by farmers and policy makers for decision making. The system boundary in the present study was limited to a cradle to gate for crop production, and a module production to use phase for OPV (Fig. 1), leaving the end-of-life stage for future research.

Due to a potential mismatch in the time of day needed for electricity supply and demand (i.e., in a protected horticulture system, the electricity demand is high at night for heating, whereas power is generated during the day), it was assumed that electricity was supplied to the grid. However, system expansion in the attributional LCA (ALCA) is not able to credit the avoided emissions in the studied system when electricity is sold to the grid due to the requirement that the sum of the emissions allocated into a subsystem is equal to a non-allocated system (ISO 14044, 2006). In contrast, the consequential LCA (CLCA) describes the consequences of actions (European Commission - Joint Research Centre – Institute for Environment and Sustainability, 2010). The system is expanded by including all processes that could be influenced by actions (Schmidt and Weidema, 2008) and the allocation is avoided (Ekvall and Weidema, 2004). Because the CLCA is used to model forecasted consequences of decisions and allocation is not carried out, the CLCA is not a suitable method to address the off-set credit nor to assign the environmental burden between crop production and power generation in the studied system. To account for the offset credit in the studied system, the present study applies the product system expansion method (Blonk et al., 2010). That is, the system boundary is expanded before allocation is performed so that the studied system receives the credit for the electricity co-product, which avoided emissions from the comparable product. This was done by Blonk et al. (2010), who performed an allocation in a case where electricity and tomatoes were produced in a greenhouse with a combined heat and power (CHP) system. The authors expanded the product system to compare environmental impact with/without CHP and to present the benefit of CHP to tomato production at a system level. Petroleum-fired power generation is regarded as the replaced/avoided process in the present study. For crop production, 1 kg of crop production is defined as the functional unit of $LC-CO_2$ emissions. Moreover, an area (1 ha) is defined as the functional unit to present the changes in total $LC-CO_2$ emissions when the number of PV in a cropland is increased (i.e. from conventional tomato field to PV only field).

2.2. Allocation methods

A sensitivity analysis is required (ISO 14044, 2006) if several allocation methods are relevant. This study investigated 3 different allocation methods: system expansion, economic allocation and solar allocation.

In a system expansion, tomato is a main product, whereas electricity is a co-product. The $LC-CO_2$ emission of the main product, tomato, is obtained by subtracting avoided emission by co-products from the total impacts (Cherubini et al., 2011). For the co-product, the present study defined petroleum-fired power generation as the replaced/avoided process. In Japan, petroleum-fired power generation is used as the peak load supply and has the highest cost among the other sources.

For economic allocation, a partition rate, D, is obtained as follows:

$$D = \frac{\text{Price of crop}}{(\text{Price of crop} + \text{Price of power generation})} \tag{1}$$

where D is the partition rate for the economic allocation for crop production, price of crop is the price for 1 kg of crop and price of power generation is derived by multiplying the purchase price under the Feed-in-Tariff (FIT) scheme by the power generation (kWh) in association with 1 kg of crop production (i.e., the total power generation in a greenhouse is divided by the crop yield).

Solar allocation is used to address the interference of OPV with the crop. The partition rate is obtained as follows, assuming it was equivalent to the solar radiation assigned to the crop production:

$$E = 1 - \left[\left(\frac{\text{Area covered by OPVs}}{\text{Greenhouse surface area}} \right) \times (1 - \text{Light transmittance}) \right] \tag{2}$$

where E is the partition rate for solar allocation for crop production, area covered by the OPVs is the active area of OPV, and light transmittance is the ratio of light that goes through the OPVs. The OPV used in this study does not select wavelength. It is assumed that incoming