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Environmental impacts of electricity self-consumption from organic photovoltaic battery systems at industrial facilities in Denmark

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ABSTRACT

Organic photovoltaics (OPV) show promise of greatly improving the environmental and economic performance of PV compared to conventional silicon. Life cycle assessment studies have assessed the environmental impacts of OPV, but not under a self-consumption scheme for industrial facilities. We investigate the life cycle environmental impacts of electricity self-consumption from an OPV system coupled with a sodium/nickel chloride battery at an iron/metal industry in Denmark. Results show that an OPV system without storage could decrease the carbon footprint of the industry; installation of the battery increases climate change and human toxicity impacts. We discuss sensitive modelling parameters and provide recommendations.

1. Introduction

Photovoltaics (PV) are expected to play a key role in the race to mitigate climate change [1]. Self-consumption of PV-generated electricity has become more attractive than exporting it to the grid with fading feed-in tariffs and rising retail electricity prices at residential level [2]. Moreover, decreasing costs of small-scale battery systems have enabled increasing coupling of PV with battery storage, thus allowing for increased self-consumption [3]. In the long term, self-consumption based on PV battery systems may offer the most economical solution compared to PV alone or the grid [2]. In the context of manufacturing industries, on-site generation has become an alternative to conventional electricity grid supply, despite its operation management challenges [4].

Organic PV (OPV) is an emerging technology that shows promise of greatly improving the environmental and economic performance of PV compared to conventional silicon-based technologies. OPV belong to the thin-film PV technologies utilizing abundant, non-toxic organic/polymer materials to absorb light and convert it into electricity. They are typically built in multiple layers that are deposited on plastic foil by high-throughput printing and coating techniques [5]. Compared to conventional PV, OPV modules exhibit advantageous installation features such as thin design, low weight, material flexibility, semi-transparency (making integration into window or glass facades possible) as well as fast and easy (de) installation. Until now, shorter lifetimes and lower power conversion efficiencies have not allowed OPV module prices to compete with conventional PV at market level [6]. However, their low weight qualify them for installation on roofs of industrial facilities where the roofing cannot withstand heavy structures typically required for the heavier conventional PV. In addition, fast and easy (re)installation can overcome the shorter lifetimes of 2–5 years that represent the current state-of-the-art. Thus, in the near future, OPV could offer lower energy costs and decreased environmental impacts associated with electricity consumption based on own production to industrial facilities with limited structural capacity.

Previous publications have assessed the environmental impacts associated with electricity generation from OPV technologies based on life cycle assessment (LCA) studies (see review by Chatzisideris et al. [7]). Focus in these studies has been on impacts at technology level, under the assumption that all generated electricity is exported to the grid thus replacing grid electricity from other sources. The potential for reducing environmental impacts of industrial facilities through OPV for self-consumption has not been examined.

The purpose of this paper is to address this gap by assessing how industries from different branches in Denmark could potentially reduce the environmental impacts caused by their electricity consumption when implementing self-consumption of OPV-generated electricity with or without battery storage. The analysis was performed under Danish (DK) conditions, but the applicability of the approach to other regions is also discussed.

2. Methods

2.1. Modelling of OPV battery system self-consumption

A model was developed to simulate the electricity flows at an electricity consumer with an OPV battery system installation

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allowing for self-consumption. Time series data sets with hourly values of electricity consumption and solar irradiation over a typical year in Denmark were used as inputs to the model.

The electricity consumption time series data were modelled based on hourly load profiles developed by the Danish Energy Association, with measurement-based electricity consumption data of Danish electricity consumers from 2012 (http://www.elforbrugspanel.dk). In the study, focus is on the iron/metal industry as one of the most electricity intensive sectors of the Danish industry. To offer comparison, electricity consumption data was also modelled for three other important electricity consumers with different consumption patterns: the chemical industry sector, the retail sector and residential houses.

Solar irradiation data were taken from the Danish Meteorological Institute (http://irradiance.dmi.dk) based on a data set representing a typical year and specifically developed for computer simulations. Electricity generation from the OPV system was calculated as:

$$OPVoutput = solar\ irradiation \times PCE \times module\ area \times PR \quad (1)$$

The OPV system parameters were modelled based on the study by Espinosa et al. [8]. More specifically, an installation on a horizontal plane was assumed with a 5% module power conversion efficiency (PCE), a 5-year module lifetime, an 80% performance ratio (PR) and a system lifetime of 35 years.

Economic performance is highly dependent on volatile energy taxation or subsidies, and it was considered outside the scope of this study, so no optimal economic sizing of the OPV capacity was performed. Instead, a range of OPV capacity values were used, calculated as a ratio of the annual electricity generation to the annual load consumption (e.g. for an OPV system at 100% capacity size, its annual OPV generation is equal to the annual electricity consumption).

The coupling of the OPV system with battery storage was modelled based on sodium/nickel chloride batteries, which have been demonstrated to be suitable for industrial applications [9]. According to Scenario B of the study by Longo et al. [9], the roundtrip efficiency was assumed at 90%, the depth of discharge was taken at 95% and a useful lifetime of 2187 days was considered. Similar to the approach taken for PV capacity sizes, a range of battery storage capacity values of up to 0.2% were used, calculated as the ratio of storage capacity to annual OPV electricity generation. To put this figure into perspective, a rule of thumb for cost optimal sizing of residential PV batteries was found in the range of 0.1–0.15% capacity levels [10].

In our model, electricity flows were simulated by comparing OPV generation and electricity consumption values on an hourly basis according to the following rules:

- OPV system without battery storage: if OPV generation was lower than consumption, the deficit was supplied by the grid; if OPV generation was higher than consumption, the OPV surplus was exported to the grid.
- OPV system with battery storage: if OPV generation was lower than consumption, available stored electricity was used from the battery (discharge), and when the battery was fully discharged, the deficit was supplied by the grid; if OPV generation was higher than consumption, the OPV surplus charged the battery, and when the battery was fully charged, the OPV surplus was exported to the grid.

Based on this comparison, the total locally consumed OPV-generated electricity (directly from the PV or through discharge of the battery) was calculated over a typical year. This enabled to calculate the self-sufficiency, which is defined as the ratio of the total locally consumed OPV-generated electricity to the total electricity consumption of the facility over a year [2].

2.2. Scope of the environmental impact assessment

For the study of the electricity consumption of an iron/metal industry, the functional unit, expressing the basis of comparisons of the environmental impacts, was defined as the average supply of 1 kWh to the industry.

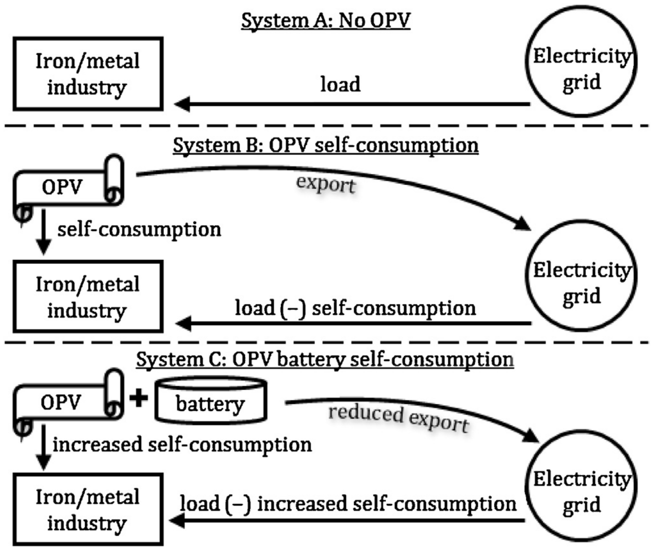

Fig. 1. Systems under study.

Fig. 1 shows the three different systems under comparison from an LCA modelling perspective. System A expresses the baseline situation where no OPV system is installed, and the DK grid satisfies electricity demand. In System B, an OPV system is installed for self-consumption, while the part of OPV-generated electricity that is not consumed locally is exported to the grid. In System C, battery storage is added for increased self-consumption. Thus, in Systems B and C, the environmental profile of the industry's electricity consumption was calculated based on the sum of locally consumed OPV-generated electricity and imported electricity from the DK grid, where the balance was indicated by the self-sufficiency calculation results. In addition, exported electricity was assumed to replace marginal electricity sources, and thus to save their associated environmental impacts.

The environmental profile of the OPV battery system was calculated based on results from previous LCA studies on an OPV system [8] and a sodium/nickel chloride battery [9]. Both studies used the International Reference Life Cycle Data System (ILCD) [11] life cycle impact assessment method. Two impact categories were selected as relevant for this study: climate change and human toxicity. When shifting electricity generation from fossil-based to renewable technologies, climate change impacts have been shown to co-vary with impact categories such as acidification and photochemical ozone formation but not with human toxicity and resource depletion [12]. Therefore, human toxicity was considered as a complementary impact category to represent toxicity-related impacts (incl. ecotoxicity impacts). For human toxicity, cancer and non-cancer effects were aggregated; the impact scores were expressed in comparative toxicity units for humans (CTU_h) reflecting the estimated increase in mortality and morbidity in the total human population as a result of the system implementation. Although resource depletion could also be relevant for investigation, it could not be assessed because the indicator was not reported for the battery in the study by Longo et al. [9]. Future studies should cover all impact categories to identify the most problematic ones, as shown by Chatzisideris et al. [7] for thin-film PV technologies.

The environmental impacts of the Danish electricity grid at medium voltage level were calculated with the ILCD v.1.08 LCIA method [11] in SimaPro v.8.2 with the ecoinvent 3.2 database [13] (reference year 2012). In the modelling of the electricity flows, the industry was assumed to consume electricity from the average Danish grid mix, as in the absence of OPV system, while exports of electricity from the OPV system to the grid were assumed to substitute marginal electricity sources, i.e. Danish wind power as a default scenario [13]. To address the uncertainty of this modelling