

Answers to the reviewer's comments

We would like to thank both reviewers for providing useful comments to improve our paper. Please find our replies below each comment. New paragraphs in the manuscript have been referenced here as well.

Reviewer #1: The paper assesses greenhouse gas emissions of an adaptive solar façade system that combines shading with photovoltaic electricity generation. The authors also investigate how different design aspects affect the GHG emissions profile of the system.

The paper is relevant since it evaluates the environmental profile of a building-integrated photovoltaic system addressing energy efficiency in the built environment, and interesting because the authors examine a prototype rather than a hypothetical system. However, three major issues prevent me from recommending the paper for publication: the lack of multi-functionality considerations and proper system boundaries delimitation between the shading function and the PV electricity generation function; the inconsistency of geographical representativeness of data used for the electricity mix (i.e. use of average European electricity mix data instead of the Swiss mix data in the base case scenario) has a significant impact on the results, which convey a misleading message; the poor description of LCA methodology at basic level. These three major points are elaborated below followed by significant but lower priority (minor) comments.

A.1. The system under study combines a shading function with a PV electricity generation function, as the authors accurately describe right from the beginning in the Abstract, as well as later in Discussion and Conclusion. The choice of the functional unit suggests that the scope of the LCA study is the PV function. However, this is not reflected when deriving the system boundaries and modelling of the system. My argument is that the shading effect is a co-product that arises from the PV function, but it can exist in isolation from the PV function i.e. we can have an adaptive shading system with a panel and not necessarily a PV panel. This lack of multi-functionality (termed 'allocation' in ISO 14044:2006 [1]) considerations ascribes full environmental impacts (positive and negative) to the PV function, and, in my opinion, does not allow a fair and accurate assessment of the environmental performance of the PV function, especially when comparing with other PV systems.

We agree with this point. First of all, we do an assessment of an electricity producing system, as reflected by the functional unit. Therefore, the results are presented at first without taking the shading effect into account. For instance, in the first paragraph of the discussion page 23 we clearly highlight the advantages of a fixed system over an adaptive system. In Figure 13 we also compare first the PV without the benefits of shading, and then have the system expansion in blue.

Only in a second step we perform a system expansion (according to ISO 14044). We deemed this two-step analysis necessary in order to account for the multi-functionality of the ASF. Also, we tried to be careful and not mislead the reader by illustrating the benefits due to shading separately, as it is seen in figure 13.

In order to make this fact more clear we also made the following changes:

- **Abstract, Page 1. Added a line for the multi-functionality**
- **Introduction, Page 3. Shows the system expansion as a separate analysis**
- **Section 2.1, page 6, . Under 4-Interpretation we added a sentence describing the system expansion**
- **Figure 10 Page 18. We split the waterfall chart into the baseline case, and the system expansion. The system expansion is marked with text and a dotted line to separate it from the baseline case**
- **Figure 14, Page 23: We changed the colour of the bars so that the orange colour fits the theme of the system expansion. This is to avoid confusing the reader**
- **Conclusion, Page 25. Made the first paragraph clearer to address that the system performs worse than traditional systems. However with the system expansion, allowing for multi-functionality, it performs better.**

A.2. The use of European electricity mix data gives inaccurate results, and conveys a misleading message. Since the authors assume that the system is located in Switzerland (and, for that reason, make correct use of Swiss weather file and solar irradiation data), the choice of European electricity mix data is inconsistent and flawed (p.11, l.32). As explained in the ILCD Handbook [2], "the geographical coverage of the LCI data should represent the smallest, appropriate geographical unit, depending on the goal of the LCI/LCA study and the intended applications. If e.g. the use of an energy-using consumer product in France would be the scope of the data set, the corresponding electricity market consumption mix (which is not automatically France) and French product use conditions were to be considered, i.e. not European or Global average conditions." Otherwise, there is a risk of producing inaccurate and misleading findings, as in this case where results differ significantly when Swiss mix data is used, as shown in Figure 8. Again as explained in [2], "the use of data from one geographical area or specific supplier to another one is appropriate only if the differences in the environmental impacts have no or little relevance for the overall representativeness of the inventory."

Thank you for pointing this out. During our first submission, we also were discussing this point, and chose the EU electricity mix as Switzerland is part of the European electricity network. We tried to

address this point by showing the sensitivity of the electricity mix. Thanks to your review, we will now use the German electricity mix as the default and we amended this by expanding it to three separate regions: Germany, Switzerland and Spain, where each region uses its own respective electricity mix. Furthermore, we ran additional simulations using localized climate data (addressing also comment B.2d).

These changes are detailed in

- **Section 3.3 paragraph 1, page 19**
- **Figure 12, page 21**
- **Section 2.4, bullet point 2, page 14**

A.3. Description of the LCA methodology is flawed at basic level. For example, p.4, l.52-53 read: "the life cycle assessment is performed in three stages 1) goal, 2) scope definition, and 3) assessment." Overall, the whole paragraph (p.4, l.39-47) and section 2.1 present fundamental errors, and do not comply with ISO 14044:2006 [1], which stipulates that "there are four phases in an LCA study: a) the goal and scope definition phase, b) the inventory analysis phase, c) the impact assessment phase, and d) the interpretation phase".

Thank you for this point. We have done the analysis according to ISO 14044:2006, but failed to describe it properly. We have reverted our text to an earlier iteration which discusses each of the four phases individually. Please see Section 2.1, pages 5-7 which detail this change.

Minor comments:

B.1. The paper does not justify the exclusion of other environmental impacts categories from the scope of the study. The holistic nature of the LCA methodology allows quantifying potential environmental impacts and avoiding environmental burden-shifting. Unfortunately, limiting the scope of the study to assessing GHG emissions happens too often in LCAs despite evidence in the literature that GHG accountings are not sufficient indicators for environmental sustainability [3]. In principle, all relevant environmental impact categories should be considered; otherwise, it should be clearly stated and discussed [1]. Moreover, characterising your findings as 'environmental impact/performance' is a bold generalisation that should be avoided, since the authors have limited the scope of their work to climate change impacts only.

Agreed. We added 6 ReCiPe midpoint results to Figure 8 based off the analysis by Ortiz et al [1].

B.2. Several points need to be reported clearly and transparently:

a. An accurate description of the end-of-life stage is missing. For example, p.5, l.41 mentions that "the cut-off approach is used for the allocation of recycling and landfill disposal", whereas a simple internet search

shows that direct landfilling is not allowed in Switzerland (<http://www.bafu.admin.ch/abfall/01495/01496/index.html?lang=en>).

By 'landfill disposal', we actually meant 'disposal' in general. Thank you for noticing the wording. Our analysis for the disposal in Switzerland actually uses municipal incineration, not landfill disposal. This was a mistake from our side.

Furthermore, we realize that our wording was not overly clear and we changed the description in 2.1. We use the *cut-off system model* of ecoinvent as described here:

<http://www.ecoinvent.org/database/system-models-in-ecoinvent-3/cut-off-system-model/allocation-cut-off-by-classification.html>

We changed Section 2.1 'Goal and Scope Definition', page 5,6 accordingly. Furthermore, we described the major contributions to the disposal in Table 9 to the Annex Section 7.2, page 29 which specifies each process used.

b. It is not justified why benefits from recycling credits are not taken into account (p.5, I.43), while recycling is central to the reduction of environmental impacts (particularly metal depletion and toxic effects) and scaling up the availability of BOS metal components in future PV systems [4-6].

This may be a misunderstanding and we tried to make our wording more clear (see B2a). The ecoinvent cut-off system model implies that recycled materials leave the system boundary (cf. <http://www.ecoinvent.org/database/system-models-in-ecoinvent-3/cut-off-system-model/allocation-cut-off-by-classification.html>). See also our changes in B2a (Section 2.1 'Goal and Scope Definition')

We could do another system expansion and give credits for recycled material, but we expect no substantial changes in the results. That means the benefits would be in the same order of magnitude for both systems. Also we believe that this is beyond the scope of this study

c. The "cut-off approach" is not explained (p.5, I.20, I.42) i.e. the cut-off criteria are not reported neither is the assumption that defines and quantifies them (see paragraph 4.2.3.3.3 [1]).

Thank you for the input. Concerning the background system, we added a reference to the ecoinvent database, as described in B2a. Concerning the foreground system, the system boundary should (at least now) describe the cut-off criteria sufficiently.

We have made some amendments to the scope, page 5 'Goal and Scope Definition' to make this more clear

d. The sensitivity analysis of the electricity mix (p.13, l. 45-55) does not clearly describe the geographical coverage of your LCI data. In other words, when data for the German electricity mix is used, it is not clear whether appropriate weather file and solar irradiation data for Germany are used too. If not, the geographical coverage of the LCI data is inconsistent as highlighted earlier in A.2.

Thank you for pointing this out. It has been amended alongside point A.2. We ran additional simulations with the appropriate climate data.

B.3. A number of the Journal's requirements are not met, as described in the 'Guide for Authors' (<https://www.elsevier.com/journals/solar-energy-materials-and-solar-cells/0927-0248/guide-for-authors#40100>).

a. The graphical abstract image should be readable at a size of 5×13cm using a regular screen resolution of 96 dpi, which is not the case here. That said, I do not review the content of the graphical abstract.

A new graphical abstract has been created which is readable at a size of 5x13 using a screen resolution of 96 dpi.

b. The highlights exceed the maximum 85 characters, including spaces, per bullet point. Again, I do not review the content of the highlights.

Thank you for pointing this out. Somehow we misunderstood this as being 85 characters excluding spaces. We will shorten our highlights to fit the guidelines.

c. All sections should be numbered as explained in the 'Guide', which is not true for all subsections within section 2.1 (p.4, l.50), 2.2 (p.5, 40) and 2.3 (p.9, 37).

The headings within section 2.1, 2.2 and 2.3 are not meant to be subsections but rather a description. We will be happy to create sub-subsection headings if necessary.

d. Plus, there is a discrepancy between the title on the abstract page ("Life cycle analysis of...") and the title on p.1 of the manuscript ("Life cycle assessment of...").

Well picked up, we realized this upon submission. Thank you for noticing. The correct title is 'Life Cycle Assessment', this will be clarified in our review submission.

[1]: Ortiz, Oscar, Francesc Castells, and Guido Sonnemann. "Sustainability in the construction industry: A review of recent developments based on LCA." *Construction and Building Materials* 23.1 (2009): 28-39.

