Life Cycle Assessment of Adaptive Building Integrated Photovoltaics

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Abstract

Text
@Zoltan, we are thinking about possibly deleting the blue text as the introduction is quite large and we need to simplify it. Could you comment on this as well

Keywords: Adaptive, Solar Facade, Life Cycle Analysis, Multi Functional Envelope, BIPV

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1. Introduction

Buildings are at the heart of society and currently account for 32% of global final energy consumption and 19% of energy related greenhouse gas emissions [1]. Nevertheless the building sector has a 50-90% emission reduction potential using existing technologies, and widespread implementation could see energy use in buildings stabilise or even fall by 2050. Within this strategy, building integrated photovoltaics (BIPV) has the potential of providing a substantial segment of a buildings energy needs [2]. Even the

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photovoltaic (PV) industry has identified BIPV as one of the four key factors for the future success of PV [3].

The PV industry is currently dominated by crystaline silicon photovoltaic cells due to their high efficiency and low processing costs [4]. However these technologies are often difficult to integrate in a way that maintains the architectural expression of the building [5]. This combined with their intrinsic weight restricts their large scale implementation to roofs where they are out of sight. However, in the last decade, there has been interesting developments in second generation thin film technologies [6]. In particular, Cu(In,Ga)Se_2 (CIGS) is reaching competitive levels of efficiencies [7] and manufacturing costs [8] [9].

This development has brought new BIPV design possibilities. Their light weight nature and customisable shapes allows for easier and more aesthetically pleasing integration into the building envelope. Furthermore, this technology can be easily actuated and used as an adaptive building envelope, because ... [10].

Adaptive buildings envelopes have gained interest in recent years because they can save energy by controlling the flow of direct and indirect radiation into the building, while still responding to the desires of the user [11]. This mediation of solar isolation offers a reduction in heating / cooling loads and an improvement of daylight distribution [10]. Interestingly the mechanics that actuate adaptive envelopes couples seamlessly with the mechanics required for facade integrated PV solar tracking. This enables a adaptive envelope to also benefit from on-site energy production, and also provides a new way of aesthetically integrating PV panels onto buildings. The balance of electricity production, and adaptive shading can in some cases offset the entire energy demand of an office space behinf the envelope [12]. We have proposed one possible combination of these technologies as the Adaptive Solar Facade (ASF) [13].

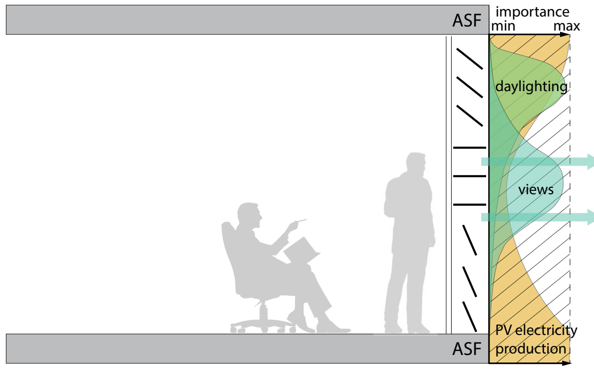

Figure 1: The facade acting as a mediator between the interior and exterior environment, while fullfilling various functions [13]

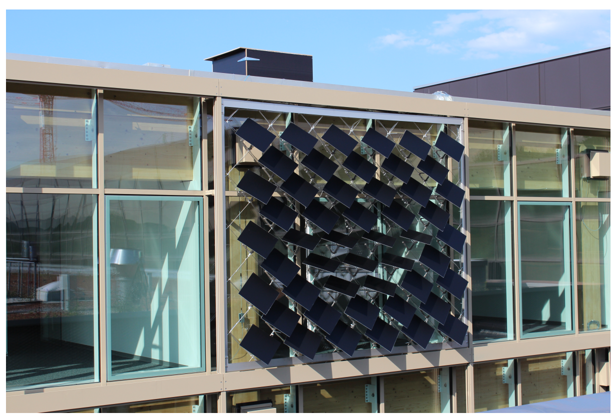

Figure 2: Building Scale Prototype Constructed at the House of Natural Resources [13]

The design of an ASF comes at an added cost. The additional electronics, actuators, and supporting structure adds further embodied CO_2 to the product. It is therefore important to conduct a life cycle impact assessment (LCA) to analyse whether the carbon savings during operation offsets the increased embodied carbon emissions in manufacture. It is also important to see how variations in design can alter the GHG reduction potential of the technology. Aspects such as the chosen PV material, actuator, and even location of operation can have a significant impact on its environmental performance. There has already been work conducted on static photovoltaic systems [14], however this has not yet been expanded to adaptive BIPV systems.

In this paper we investigate the aforementioned trade-off between added material and on-site energy production, along with other benefits such as adaptive shading. We assess a. the ASF system with possible design variations, b. the operation of a building with an ASF, c. its global and local environmental impact, d. the sensitivity of the LCA to the design and location, and e. a comparison with existing static PV technologies.

In the next section we describe the inventory of the ASF and the LCA methodology used for analysing this adaptive system. In Section 3 we will present the results from the LCA and look at the major sources of embodied carbon, along with the operational performance. In this section we will also compare the results of the LCA with other technologies and its performance in different regions. In Section 4 we discuss the results and provide design recommendations for future adaptive building integrated photovoltaic installations.

2. Methodology

The assessment looks into the environmental impacts of production, operation, and disposal of an Adaptive Solar Facade (ASF).

2.1. Life Cycle Inventory and Assumptions

The mechanical components of the ASF can be broken into four parts: a PV panel, actuator, cantilever, and a cable net supporting structure. The PV panel, actuator and cantilever combine to form a dynamic PV module, which is then mounted on a cable net supporting structure. An exploded view of these components can be seen in Figure 3. There also the additional electronics which exists off the facade in a seperate control box. Theses five components are the main product systems in the manufacture of the ASF as seen in Figure 4.

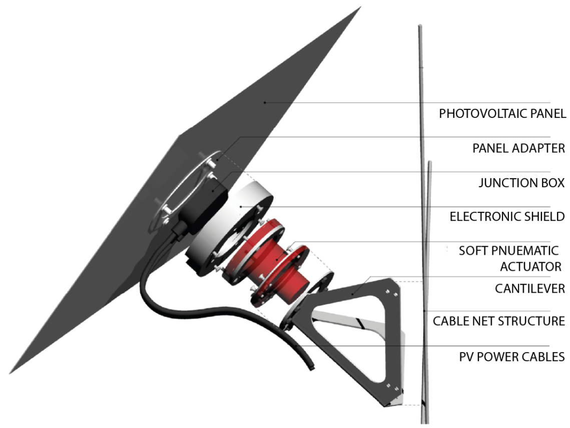

Figure 3: Exploded view of an ASF module mounted on a cable net supporting structure

@Zoltan: Should this be pushed to an Annex, or shall we leave it as is

PV Panel

(It is nice to explain the inventory step by step, but this will take a lot of space... We might have to reconsider later.) Weight is the primary restriction when selecting a PV panel. Any technology that requires glass encapsulation or a heavy substructure can therefore not be used. This limits us to CIGS and amorphous silicon panels.

CIGS PV panels was selected as the thin film panel of choice due to its high efficiency, low cost, and ability to be deposited on a polymer or aluminium substrate [15]. A less efficient thin film amorphous silicon panel could also be used and will also be discussed in this analysis.

(Not sure if it makes sense to provide the entire inventory here. If so, we would probably also need to give expected lifetimes, etc.)

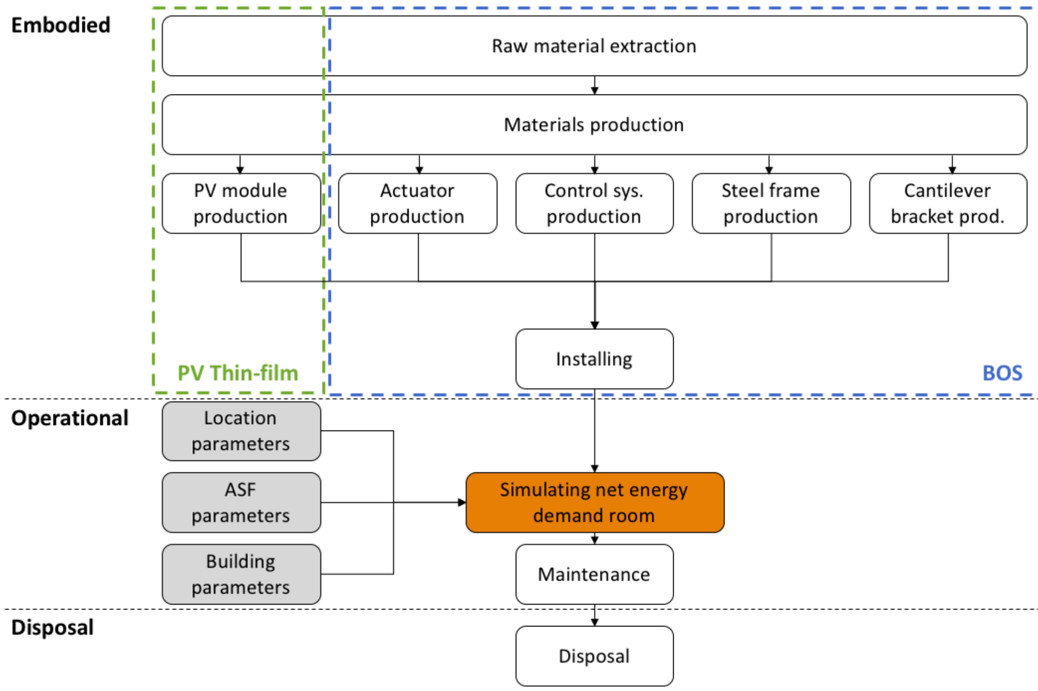

Figure 4: Breakdown of the ASF into five embodied product components and installation costs, operational costs, and disposal

Panel Type	SMQ	η
CIGS	0.7036 $\mathrm{m}^2_{\mathrm{panel}}/\mathrm{m}^2$	YY%
a-Si	0.7036 $\mathrm{m}^2_{\mathrm{panel}}/\mathrm{m}^2$	YY%
Aluminum sheet	x kg/m^2	

Table 1: Possible PV technologies for an ASF [Ref required]

CIGS	xx g/m2
Junction Box	
Power Cables	

Table 2: Inventory of main input flows to the PV manufacturing process [ref required]

Actuator

Traditionally photovoltaic actuation is done through the use of servo motors. Servo motors however become a limiting factor for adaptive facades due to their high upfront costs, and instability in heavy winds. Soft robotic actuators on the other hand are cheaper and more resilient to harsh environmental conditions[16]. For the purpose of this analysis we will analyse both servo motors and soft robotic actuators.

Compressor	xxg/unit
Tubes	xxgCO2/m
Silicone	xxgCO2/yy

Table 3: Inventory of main input flows to the Actuator manufacturing process [ref required]

Cantilever

The cantilever is a steel connection point between the PV panel and the supporting structure.

Steel	xxgCO2/yy
xxxx	xxgCO2/yy
yyyyy	xxgCO2/yy

Table 4: Inventory of main input flows to the Cantilever manufacturing process [ref required]

Supporting Structure

The supporting structure is the connection point between the array of photovoltaic modules and the building itself. Many different designs are possible, however we will base our analysis of an adaptive solar facade that has already been constructed [13]. This design consists of a steel cable-net that spans a steel supporting frame. The steel frame is then attached to the building itself.

Steel	xxgCO2/yy
xxxx	xxgCO2/yy
yyyyy	xxgCO2/yy

Table 5: Inventory of main input flows to the manufacturing process of the Supporting Structure[ref required]

Controls and Electronic System

The control system is required for the actuation of panels and the regulation of photovoltaic electricity production.

Steel	xxgCO2/yy
xxxx	xxgCO2/yy
yyyyy	xxgCO2/yy

Table 6: Inventory of main input flows to the manufacturing process of the Control System[ref required]

Installation

The installation of the ASF to the building requires a hydraulic hoist which needs to be in operation for eight hours based off previous construction experience [12].

Steel	xxgCO2/yy
xxxx	xxgCO2/yy
yyyyy	xxgCO2/yy

Table 7: Inventory of main input flows to the Assembly Process[ref required]

2.2. Operational Emissions and Assumptions

The potential savings are based off previously completed numerical simulations [12]. The simulation was conducted on a south facing office room. The room xx meters in length, xx meters wide and xx meters high was modeled using Rhinoceros 3D CAD Package [17], shown in Figure XX. Grasshopper [18] was used to model the dynamic aspects of the ASF which consists of an array of 400mm CIGS solar panels. The geometrical input is imported to Energy Plus [19] though the DIVA [20] interface. A single zone thermal analysis was conducted for each possible geometrical configuration of the ASF for each hour of the year. The results were then post processed in Python [21] with the NumPy [22], and pandas [23] plug-ins.

Based on the assumption of XX full openings and closings per day, we approximate the energy requirement to actuate the ASF to be YY kWh in its lifetime.

Building Settings	
Office Envelope	Roof: Adiabatic Floor: Adiabatic Walls: Adiabatic Window: Double Glazed LoE (e=0.2) 3mm/13mm air Floor Area: 21.7m2
Thermal Set Points	Heating: 22 degrees Celcius Cooling: 26 degrees Celcius
Lighting Control	Lighting set point: 11.8W/m2 Lighting Control: 300 Lux Threshhold
Occupancy	Office: Weekdays from 8:00-18:00 People set point: 0.1 persons/m2 Infiltration: 0.5 per hour
Location Assumptions	
Weather File	Geneva, Switzerland
Electricity Mix	UCTE
Maintenance	
xxxx	xxxx
ASF Settings	
Full open and closes per day	yy

Table 8: Summary of main assumptions for the calculation of operational emissions [ref required]*(Put me into Annex?)*

2.3. Evaluation Method

The life cycle analysis is performed according to the ISO 14040 and ISO 14044 guidelines. The analysis is therefore divided into goal and scope definition, inventory analysis, impact assessment and interpretation

This paper assesses carbon emission reductions, therefore the impact category used is the global warming potential (GWP*[IPCC 2013 reference - let me know if you need it]*). This is described as the emissions of $CO_2 - \text{eq}$ in kilograms divided by the functional unit. The functional unit needs to be based on the primary function of the technology. For adaptive building integrated photovoltaics this function can be twofold. When the adaptive BIPV acts as a shading system in front of a glass facade area the functional unit of m^2 is used, while a comparison with static facade mounted photovoltaic systems requires the functional unit of electricity produced in kWh. *(We should discuss the functional unit again. It should be defined more precisely / comprehensively.)*

According to International Energy Agency (IEA) [REF REQUIRED], the calculation of energy (kWh) produced *G?* needs to be based on the conversion efficiency η, performance ratio PR, irradiation I, lifetime (service life) LT and area A of the module. Equation 1 gives the exact formulation:

$$G = \frac{\text{GWP}}{\text{I} \cdot \eta \cdot \text{PR} \cdot \text{LT} \cdot \text{A}} \tag{1}$$

The scope of the LCA comprises of the embodied, operational, and disposal global warming impact of the respective system. Figure 4 illustrates the system boundaries of the process flows. The supporting structures are also included in the system boundaries. The reason for this is that technologies within the building envelope also change the design of the supporting structures. The supporting structure of solar panels is referred to as balance of systems (BOS).

The inventory data was obtained through technical drawings, research papers describing the technology and expert judgement. The Ecoinvent v3.1 database is used as the main LCI database [24]. To keep assumptions consistent, only data from this database is used. *(Is that so? Didn't we add a CIGS dataset?)* Furthermore, the cut-off approach is used for the allocation of recycling and landfill disposal. This means that recycling does not generate any credit for the product and resulting benefits are not taken into account. Furthermore the use of recycled products do not bear the burden of processes higher up the chain.*(We don't do any system expansion?)*

For the impact assessment the ReciPe midpoint (H) indicator is used [25]. *(This is a little inconsistent. We should consistently use the term environmental impact as opposed to carbon content, etc.)* The impact assessment is performed using the OpenLCA impact assessment tool [26].

Things which should be addressed (in more detail):

- service life of components
- In case we do a comparative LCA, also the "conventional" system needs to be described.
- Do we give benefits / credits for injecting electricity into the grid? What is being substituted and how?

3. Results

3.1. LCA of the Adaptive Solar Facade

A breakdown of the embodied carbon emissions can be found in Figure 5. It can be seen that the largest embodied global warming potential (GWP) contribution in the ASF comes from the solar panels, the electronics and the steel frame.

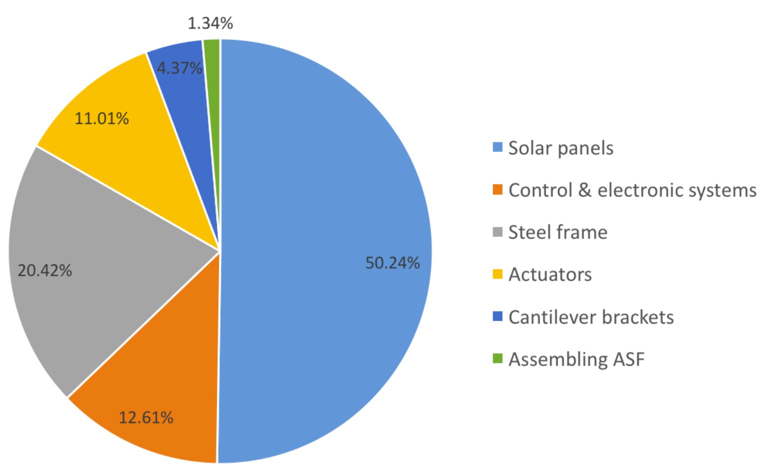

Figure 5: Breakdown of the embodied carbon emissions, it can be seen that xxxx has the greatest GWP contribution

The operational energy consumption of the office space was obtained through an energy plus simulation as explained in Section 2. The office space behind the ASF was compared to a case with a static louvered based shading system at 45° and a case with no shading at all. We calculated a total energy saving of 25% compared to louvers at 45° and 56% compared to a case with no facade shading [12]. These results are sumarised in Figure 6. Note that this figure does not include on site electricity generation.

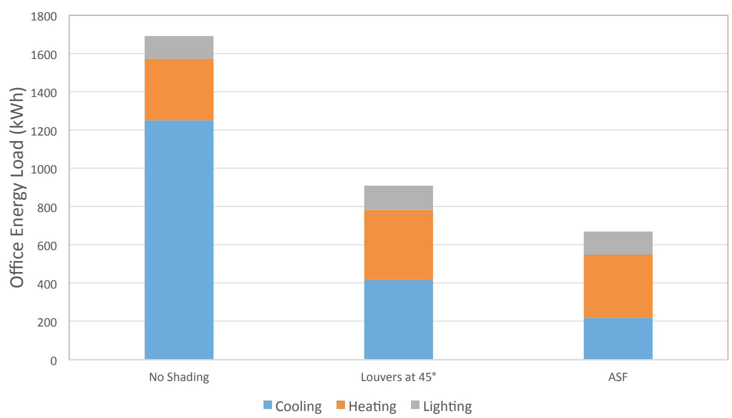

Figure 6: Breakdown of the opperational carbon emissions for system with a. no shading, b. with louvers at 45° and c. with an ASF – not taking on-site electricity production into account.

The total GWP of the ASF can be built up using a waterfall chart, Figure 7. To calculate the emission factor (gCO_2-eq./kWh) we subtract the total embodied energy by the savings through adaptive shading. *Also this should maybe be described in the methodology section or at the beginning of this chapter in more detail.)*. We then add the GWP values for maintenance and disposal to achieve a total GWP over the 20 year life time of the ASF. This total is then used to calculate the emission factor of electricity produced by the ASF (126.8 g CO_2-eq./kWh).*(This seems high...?)*

It can be seen that the embodied GWP of the ASF is greater than a classical PV installation, however most of that initial investment is offset through the reduction of heating, cooling and lighting loads. Maintenance and disposal takes up roughly 10% of all total carbon emissions.

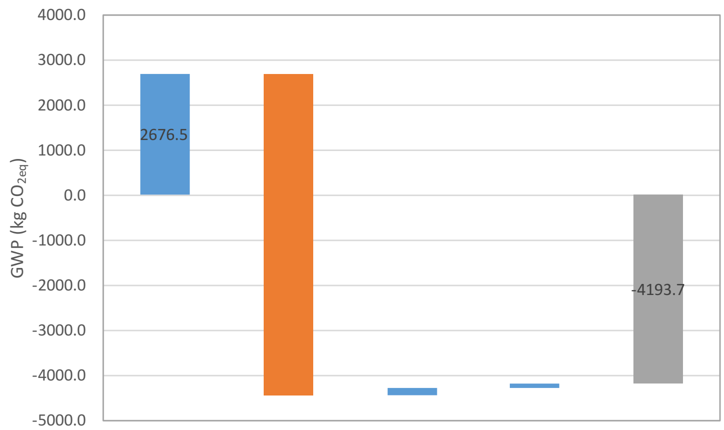

Figure 7: Waterfall diagram of GWP of the ASF. The far left column details the embodied carbon emissions. The second bar details the emission reduction of the building through the smart shading algorithms of the ASF. The third column shows an increase of emissions through maintenance. The fourth column shows an increase in emissions in the disposal. This leaves us with a final emissions value. When we apply this value to Equation 1, we obtain an emission factor per kWh of 126.8 g CO_2-eq./kWh.

3.2. Global Distribution of GWP and Terrestrial Acidification

(This is nice, but may be a bit out of scope of this article. I think we have enough to explain and our readers will probably not so much care about the regionalised impacts...)

The global distribution of embodied GWP emissions is focused in Europe, specifically Germany and Switzerland as most of the manufacturing is done in this region. It can be see however that emissions occur globally due the sourcing of primary materials from many locations around the world. Terrestrial acidification however is more interesting as it has a local impact compared to carbon emissions. It is interesting to note that China carries the greatest burden of terrestrial acidification from the ASF production.

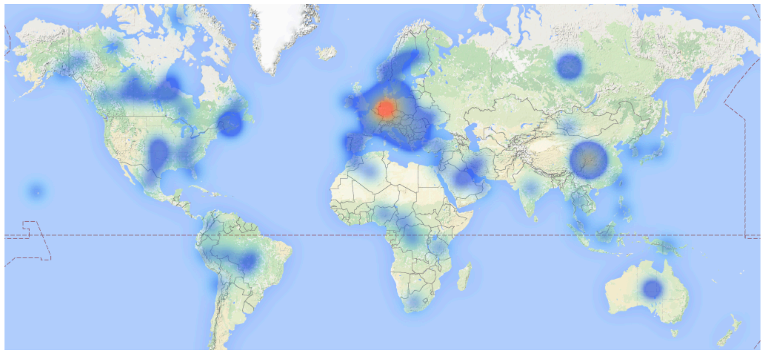

Figure 8: Global distribution of embodied GWP emissions

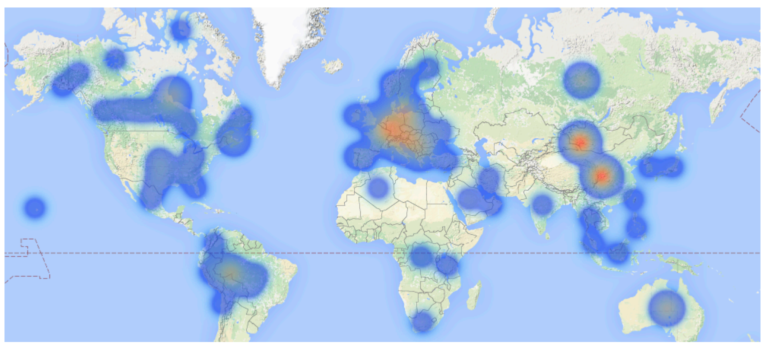

Figure 9: Global distribution of terrestrial acidification

3.3. Sensitivity Analysis

Changing the assumptions can have a significant impact on the LCA result. Four key assumptions were evaluated in the sensitivity analysis: electricity mix being substituted by on-site energy production, uncertainty in the eco-invent background system (Monte Carlo analysis), type of PV material, and the type of actuation system. The inputs are summarised in Table 9 with the results shown in Figure 10.

It can be seen that the substituted electricity mix has a significant impact on the environmental impacts. In Switzerland, we see a 6% reduction compared to the average electricity mix. This is because the Swiss electricity mix is dominated by hydro and nuclear which has a very low GWP potential [citation needed*ecoinvent?*]. In Germany on the other hand, the ASF has a

Assumption	Case A	Case B
Operation Location	Switzerland	Germany
PV Panel type	a-Si	CIGS
Actuator Type	Servo Motor	Soft Robotic Actuator

Table 9: Inputs to the Sensitivity Analysis Conducted

81% reduction in carbon emissions as the emission factor of the electricity grid is roughly five times higher compared to Switzerland [citation needed] due to the relatively high share in coal-fired power plants.

The actuators and Pv panel type had a ...

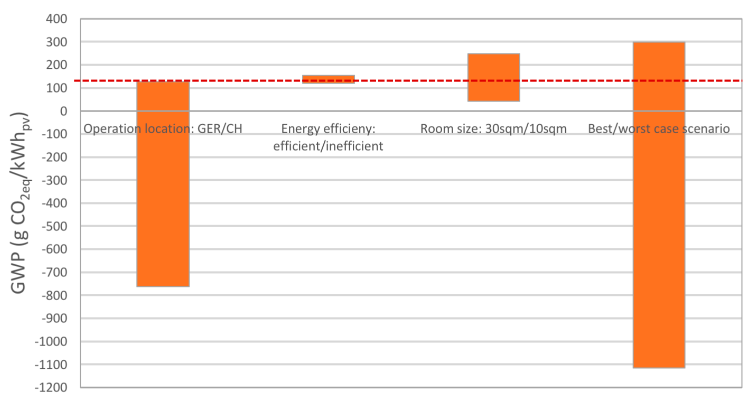

Figure 10: Sensitivity analysis of the emission factor based on location of use, panel type, and actuator type (Wrong Figure)

3.4. Comparison to existing PV technologies

Comparison of the ASF to other PV technologies and the UCTE electricity mix is highlighted in Figure 11. We can see in this figure that the ASF without shading benefits is inferior to all other technologies. It is only with the added shading benefits that we really see the advantages of the adaptive system. We can also see that the utilisation of the ASF in an area where the electricity mix has low GWP intensity such as Switzerland also has disadvantages. It is capable of out performing Silicone based technologies but is still inferior to simply mounted CIGS panels. Note that even the panels themselves of the ASF, without the BOS, is still lower that the CIGS installation. This is due to the added inefficiencies as the panels are not always at the optimum position to the sun.

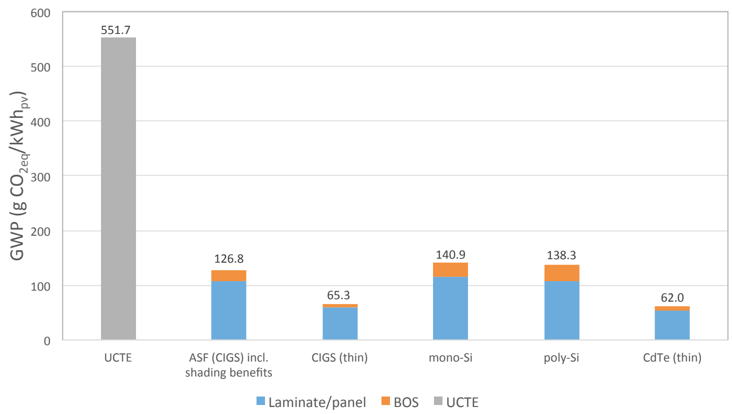

Figure 11: Comparison of thin-film and BOS to other PV technologies. I would add some extra columns, one without shading, one with the ASF in Switzerland, one with the ASF in Europe

4. Discussion

- When is the ASF advantages, when is it not
- Would it be better to just have a optimally angled static system?
- Limitations of the study
- Nuclear power in France and Switzerland
- No need to purchase land, advantage of facade integration
- What should designers of adaptive solar facades keep in mind
- Other advantages of the ASF that are not clear in the LCA analysis, such as daylighting and user centered control
- Have a technology where you can put PV where you normally can't put PV

-It is interesting to note that the choice of actuation system for an ASF can have a significant / minimal impact on the embodied emissions. [Elaborate further when results come in]

5. Conclusion

- xxx% of Embodied emissions of the photovoltaic BOS can be offset through smart shading
- This multi functionality brings about new advantages/disadvantages for solar as it has a reduced/increased the emissions per kWh by xxx%
- Higher embodied CO2 compared to a classic photovltaic retrofit. However reduction can be made through x y and z
- Results are highly sensitive to x y and z
- Have a technology where you can put PV where you normally can't put PV

6. Acknowledgments

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