Life Cycle Assessment of Dynamic Building Integrated Photovoltaics

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Abstract

We assess the environmental impact of dynamic, adaptive, building integrated photovoltaic (BIPV) systems. Such systems combine the benefits of adaptive shading with facade integrated solar tracking, thus reducing the building energy demand, and simultaneously generating electricity on-site. The inventory for the life cycle assessment (LCA) was acquired using production data, and Energy Plus simulations to calculate the building energy demand. The impact assessment was conducted according to ISO 14040 and ISO 14044 standards using the Eco-invent database and openLCA as an analysis tool. The embodied environmental impact of a dynamic BIPV solution is higher than a static solution due to the added control system, electronics, actuators, and additional supporting structure. However the added savings through adaptive shading to the building's heating, cooling and lighting loads offsets the entire embodied environmental impact. This demonstrates the advantage of using the PV material, especially when used as a building element for adaptive shading. We also conduct a sensitivity analysis to investigate modifications to the actuator type, and the control system and find that none of the investigated parameters overturn the key findings. The analysis ultimately enables us to provide design recommendations for future dynamic BIPV installations.

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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 [1]. Within this strategy, building integrated photovoltaics (BIPV) has the potential of providing a substantial segment of a building's energy needs [2]. Even the photovoltaic (PV) industry has identified BIPV as one of the four key factors for the future success of PV [3].

Recent developments regarding efficiency and costs of thin film BIPV technologies, in particular, CIGS, have brought new design possibilities [4] [5] [6] [7]. Their lightweight nature and customisable shapes allow for easier and more aesthetically pleasing integration into the building envelope. In addition, less power is required to actuate them, thus facilitating the development of dynamic envelope elements [8].

Dynamic buildings envelopes have gained interest in recent years because they can save energy by controlling direct and indirect radiation into the building, while still responding to the desires of the user [9]. This mediation of solar insolation offers a reduction in heating / cooling loads and an improvement of daylight distribution as seen in Figure 1 [8]. Interestingly the mechanics that actuate dynamic envelopes couples seamlessly with the mechanics required for facade integrated PV solar tracking. The use of light weight PV as an adaptive envelope material enables it to also benefit from on-site energy production. Furthermore, it 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 behind the envelope [10]. We have proposed one possible combination of these technologies as an Adaptive Solar Facade (ASF) [11]. An example of an ASF can be seen in Figure 2.

The design of an ASF comes at an added cost. The additional electronics, actuators, and supporting structure adds further embodied CO_2 to the

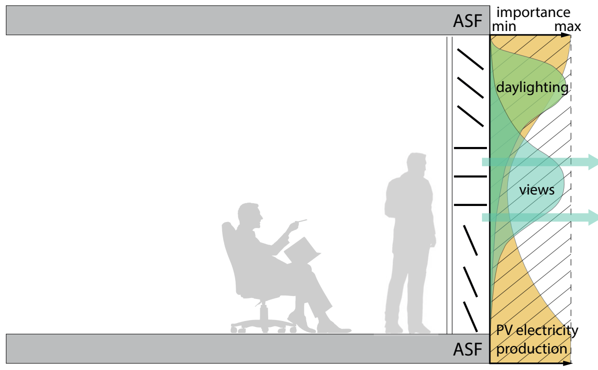

Figure 1: The facade acting as a mediator between the interior and exterior environment, while fullfilling various functions [11]

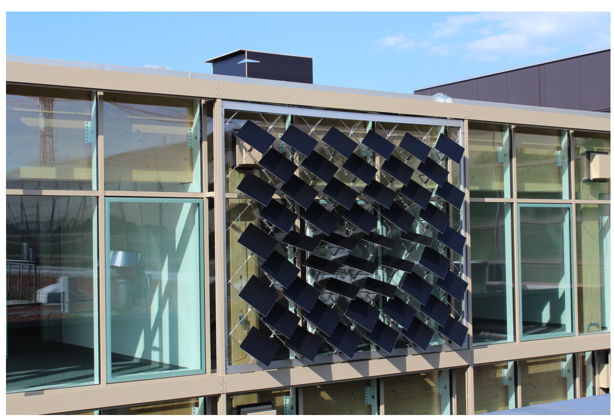

Figure 2: An example of an ASF constructed at the House of Natural Resources [11]

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 actuator, control system, and location of operation can have a significant impact on its environmental performance.

The state of the art assesses existing photovoltaic technologies [12] [13] [14], and the balance of systems (BOS) which includes all other components of a photovoltaic system [15]. This has not however, been expanded to dynamic BIPV systems, and in particular, systems that combine the benefits of adaptive shading and electricity production.

In this paper, we investigate the environmental performance of an ASF and compare it to existing static photovoltaic systems. We also investigate 1) Design variations of the ASF, 2) the operational emissions of a building, with and without an ASF, and 3) the sensitivity of the LCA to its location and design.

The remainder of the paper is organized as follows. The next section introduces the ASF and the used LCA methodology. In Section 3, we present the results of the LCA analysis. Section 4 discusses the results and provides design guidelines. Section 5 concludes the paper.

2. Methodology

In this section, we detail the inventory, Energy Plus simulation methodology, important assumptions, and the LCA evaluation method. The assessment considers the environmental impacts of the production, operation, and disposal of an ASF. We assume a lifetime of 20 years based on the product warranty of the PV panels. The impact assessment is performed according to the ISO 14040 and ISO 14044 [16], using the IPCC 2007 methodology [17] for global warming potential (GWP) assessment.

2.1. Impact Assessment

The life cycle assessment is performed in three stages 1) goal, 2) scope definition, and 3) assessment.

1. **Goal:** This paper assesses carbon emission reductions. The global warming potential (GWP) impact category is therefore used. This analysis

will also touch on the regional distributions of GWP and terrestrial acidification to give a complete picture.
The functional unit is the electrical power production of the system in kWh.

2. **Scope:** The scope of the assessment is summarised in Figure 4. We analyse the manufacture, dynamic actuation, maintenance, disposal and the energy savings through adaptive shading. The scope comprises of a cradle-to-grave approach, where transport to and from site is taken into account. For the database, the cut-off approach is used. This implies that benefits from recycling are out of the scope of this paper. As the analysis is done in Switzerland we assume irradiation on the Facade of 966kWh/m^2/year.

3. **GWP Assessment:** The assessment is based on the IPCC 2007 methodology [17]. The GWP assessment is performed using the OpenLCA assessment tool [18]. In the assessment, we compare the emission factor (EF) of an ASF with other PV systems. The emission factor is expressed as

$$EF = \frac{GWP}{\mathrm{G}} \qquad [\frac{kgCO_{2-eq}}{kWh}] \tag{1}$$

where (G) is the electricity production in (kWh).

2.2. Embodied Life Cycle Inventory

The Ecoinvent v3.1 database is used as the main LCA database [19]. 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.

The mechanical components of an 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 are also additional electronics which exists off the facade in a separate control box. Theses five components along with the assembly, are the main product systems in the manufacture of an ASF as seen in Figure 4. The inventory quantities are given in SMQ (specific mass quantity), which is the mass in kg of the specific materials.

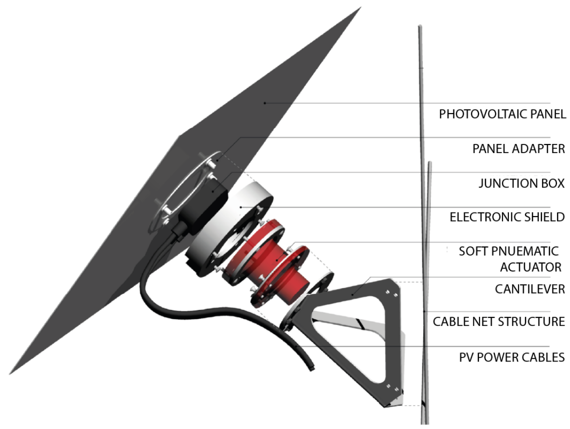

Figure 3: Exploded view of an ASF module mounted on a cable net supporting structure

PV Panel

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. The technology also needs to be on the market with high module efficiency. CIGS PV panels were 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 [20].

Material description	SMQ
CIGS PV film	0.569 m^2_{PV}/m^2_{facade}
Aluminum sheet	1.593 kg/m^2_{facade}
Chromium steel panel adapter	1.422 kg/m^2_{facade}
Polyethylene for junction box	0.036 kg/m^2_{facade}
Diode, glass for junction box	0.011 kg/m^2_{facade}

Table 1: Inventory of the top five input flows to the PV manufacturing process

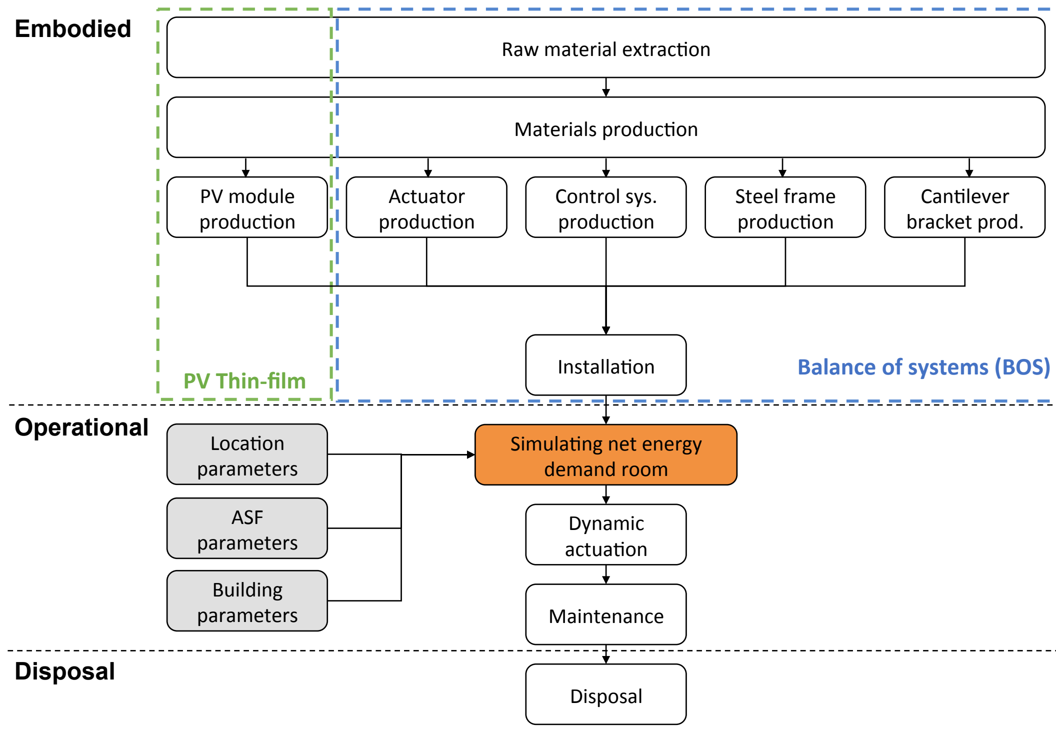

Figure 4: Breakdown of the ASF into five embodied product components, installation, operation, and disposal

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[21]. The soft robotic actuators however are still in development and have an estimated lifetime of five years. They will therefore require three rounds of maintenance during the lifetime of the ASF. For the purpose of this analysis we will analyse both servo motors and soft robotic actuators.

Material description	SMQ
Chromium steel rings	1.0665 kg/m^2_{facade}
Electronics, for control, 2-2way valves	0.0130 kg/m^2_{facade}
Silicone chambers	0.8887 kg/m^2_{facade}
Polyurethane tubes	0.0933 kg/m^2_{facade}
Air compressor, screw type, 0.75kW	1.7281 kg/m^2_{facade}

Table 2: Inventory of four main input flows to the soft robotic actuator manufacturing process

Cantilever

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

Material description	SMQ
Chromium steel bracket	1.4220 kg/m^2_{facade}
Chromium steel fixing clamp	0.0284 kg/m^2_{facade}

Table 3: Inventory of main input flows to the Cantilever manufacturing process

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 existing adaptive solar facade [11]. This design consists of a steel cable-net that spans a steel supporting frame. The steel frame is then mounted on the building facade.

Material description	SMQ
Chromium steel frame	6.9928 kg/m^2_{facade}
Chromium steel swaged external thread	0.2897 kg/m^2_{facade}
Chromium steel wire rope WC	0.1593 kg/m^2_{facade}

Table 4: Inventory of the four main input flows to the manufacturing process of the Supporting Structure

Control System and Electronics

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

Material description	SMQ
Inverter 1.25kW	0.6090 kg/m^2_{facade}
PV cable	3.1995 kg/m^2_{facade}
Electronics control[1]	0.0419 kg/m^2_{facade}
Electronics control[2]	0.0097kg/m^2_{facade}

Table 5: Inventory of the four main input flows to the manufacturing process of the Control System

Assembly

There are many assembly options available. From past experience, an installation of an equivalent ASF required a hydraulic hoist which was in operation for eight hours [10].

Material description	SMQ
Hoist, diesel <18.64kW, idling	0.5267 h/m^2_{facade}

Table 6: Inventory of main input flows to the Assembly Process

2.3. Operational Life Cycle Inventory

The operational inventory is categorised as 1) energy consumption of an office room 2) electricity consumption through dynamic actuation, and 3) maintenance.

Building Energy Consumption:

An adaptive shading system, when mounted over a glazed facade, has an impact on the energy consumption of the building as described in Section 1. More specifically, it has an impact on the heating cooling and lighting loads. Previously conducted simulations compared three scenarios: 1) facade with no shading, 2) a facade with a static shading system, optimally angled at 45° to the horizontal axis, and 3) an adaptive solar facade [10].

The simulation was conducted on a south facing office room. The room, 7.0 meters in length, 4.9 meters wide and 3.1 meters high was modeled using Rhinoceros 3D CAD Package [22]. Grasshopper [23] was used to model the orientation of each photovoltaic panel. The geometrical input is imported to Energy Plus [24] though the DIVA [25] 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 MATLAB [26].

The simulations show a total energy saving of 25% compared to static panels at 45° and 56% compared to a case with no facade shading [10]. These results are sumarised in Figure 5.

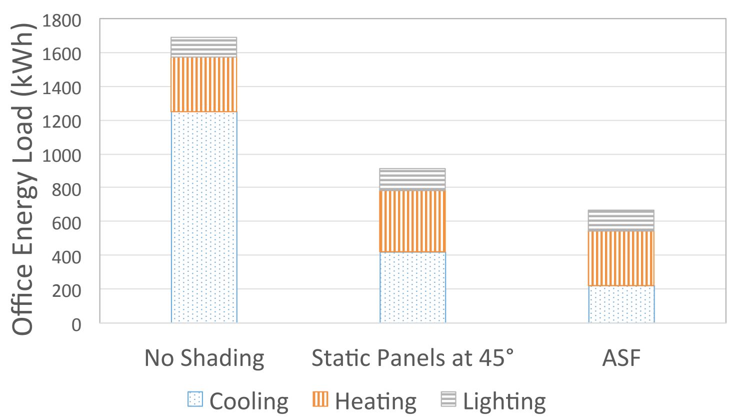

Figure 5: Breakdown of operational energy consumption for a system with a) no shading, b) with louvers at 45° and c) with an ASF – not including onsite electricity production.

Dynamic Actuation: The energy required for actuation is also taken into account. It takes 0.31Wh to fully open a single actuator. Based on the assumption of four full openings and closings per day per actuator, we approximate the combined energy requirement to be 489kWh in its 20 year lifetime.

Maintenance: Soft robotic actuators currently have a lifetime of five years, and therefore will need to be replaced three times during the 20 year lifetime of an ASF. No other maintenance efforts are considered.

Building Settings	
Office Envelope	Roof: Adiabatic
	Floor: Adiabatic
	Walls: Adiabatic
	Window: Double Glazed (e=0.2) 3mm/13mm air
Thermal Set Points	Heating: 22° degrees Celcius
	Cooling: 26° degrees Celcius
Building System	Hydronic Heating: COP=4
	Hydronic Cooling: COP=3
Lighting Control	LED Lighting
	Lighting Load: 11.8W/m2
	Lighting Control: 300 lx 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 (067000IWEC)
Electricity Mix	ENTSO-E [27]
Average Solar Radiation	966kWh/m^2/year
Maintenance	
Actuator Changes	Every 5 years
ASF Settings	
Full open and closes per day	4 per day

Table 7: Summary of main assumptions for the calculation of operational emissions

2.4. Sensitivity Analysis

In order to evaluate the impact of varying parameters on the LCA, we performed a sensitivity analysis on the following assumptions

- The GWP of the electricity mix
- A static version of the ASF, where panels are optimally orientated to 45°

- The type of actuation system (servo motors compared to soft robotic actuators)
- The complexity of the control system

3. Results

We present the results of the LCA analysis in relation to the 1) embodied GWP, 2) a calculation of the emission factor, 3) sensitivity of the LCA to design and location, and 4) a comparison to other PV technologies.

3.1. LCA of the Adaptive Solar Facade Manufacture

A breakdown of the embodied global warming potential (GWP) can be found in Figure 6. The largest embodied GWP contribution in the ASF comes from the solar panels, the electronics and the supporting structure.

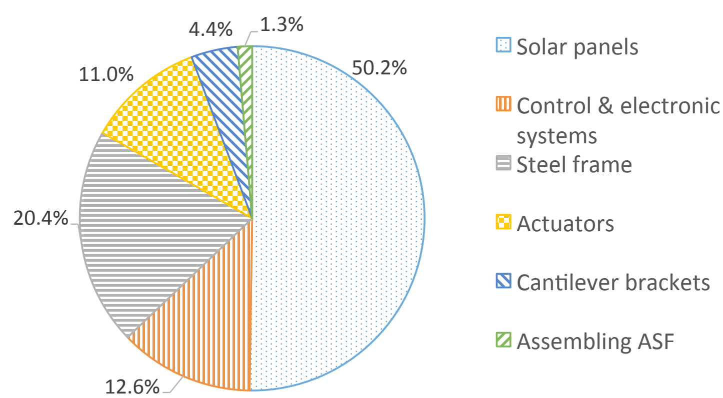

Figure 6: Breakdown of greenhouse gas emissions due to material production. The total is GWP is 2676 kg CO_{2-eq}

3.2. Calculation of Emission Factor

The combined GWP of main inputs to the ASF, previously described in Figure 4, can be built up using a waterfall chart as shown in Figure 7.

This gives us a total GWP of -6229.6 kg CO_{2-eq}. We calculate a total electricity production of 518kWh per year, resulting in an emission factor of -601.1 gCO_{2-eq}/kWh.

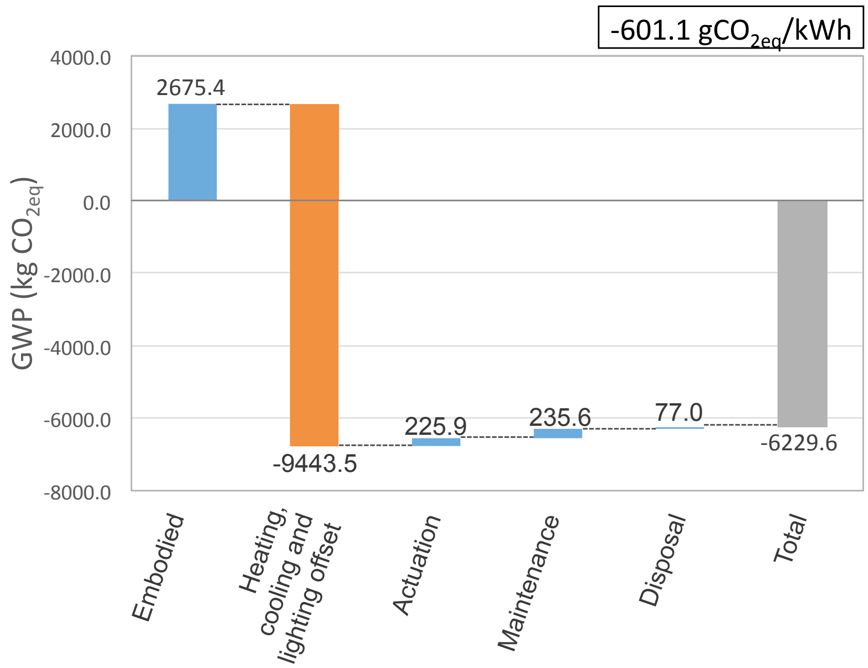

Figure 7: Waterfall diagram of GWP of the ASF. The far left bar details the embodied carbon emissions. The second bar details the emission reduction of the building through adaptive shading. The third, fourth and fifth bar shows the effect of dynamic actuation, maintenance, and disposal respectively. This leaves us with a final emissions value (grey bar). When we apply this value to Equation 1, we obtain an emission factor per kWh of -601.1 gCO_2-eq./kWh. Note that the waterfall chart itself doesn't show PV electricity generation. This is taken into account in the emission factor.

3.3. Sensitivity Analysis

The sensitivity analysis is shown in Figure 8. The GWP savings from adaptive shading is dependent on the electricity mix as explained in Section 2.3. Changing our assumption from the European ENTSO-E mix to a country specific mix brings interesting results. In Switzerland, the mix is dominated by hydro and nuclear power which has a very low GWP potential[27]. This would then increase the emission factor of the ASF to 70.6 gCO_{2-eq}/kWh. The German mix on the other hand has a higher GWP mix than the ENTSO-E mix due to their high share in coal fire plants. This then reduces the emission factor of the ASF to -792.9 gCO_{2-eq}/kWh. This difference arises as the greenhouse gas emission savings of adaptive shading are dependent on the emission factor of the grid mix.

We also present a case where we remove the actuators and necessary control system for a dynamic system. Instead, we have panels that are optimally orientated at 45° to the horizontal axis. This reduces embodied greenhouse gas emissions by 12.1% from the baseline highlighted in Figure 6. However the reduction in electricity production, and savings through adaptive shading, result in a higher emission factor of -507 gCO_{2-eq}/kWh.

The choice of actuator has a small impact on the embodied carbon emissions. Changing a single Soft Robotic Actuator (including the air compressor, tubing, and maintenance) to a classical servo motor increases the total embodied GWP from 2675.4 kg CO_{2-eq} to 3251.2 kg CO_{2-eq}. However, the lower emissions from actuation and maintenance for servo motors cancels out this increase, resulting in an ASF with servo motors having an emission factor of -588.4 gCO_{2-eq}/kWh.

The control system design should be carefully thought out due to the high embodied GWP of electronic components, these systems contribute to 13% of total embodied GWP. However limiting the individual actuation of panels to rows does not result in a significant difference. The control system required for an ASF where each panel can be independently actuated has an emission factor of -599.5 gCO_{2-eq}/kWh. A system which actuates only rows, has an emission factor of -601.1 gCO_{2-eq}/kWh. This 0.3% difference is insignificant.

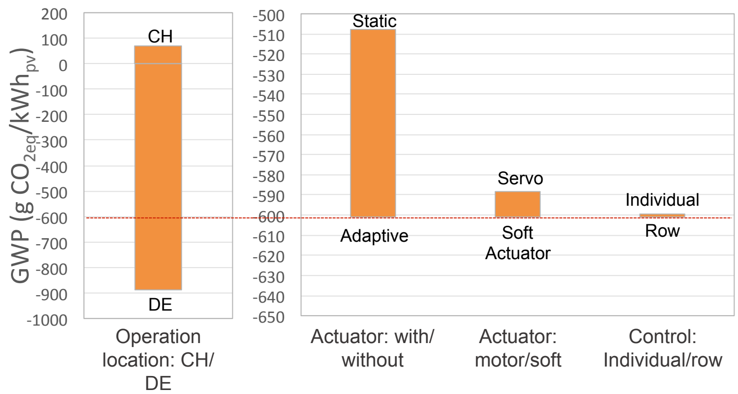

Figure 8: Sensitivity analysis of the emission factor based on electricity mix, actuation system, and control system

3.4. Comparison to existing PV technologies

Comparison of the ASF to other PV technologies and the ENTSO-E electricity mix is highlighted in Figure 9. This comparison is conducted in Switzerland with an average irradiation of 966kWh/m2/year.

The orange bars detail systems with no added shading benefits. Here we present the ASF, a static optimally orientated facade as detailed in Figure 8, and three classical flat facade installations. The blue bars detail systems built over glazed surfaces which also bring energy savings to the building. Because the GWP savings through adaptive shading offsets the entire embodied GWP, we have a system with a negative emission factor.

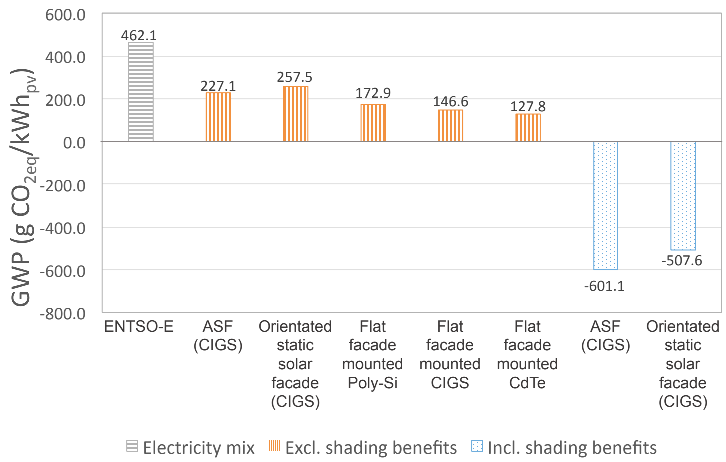

Figure 9: Comparison of facade installations in Switzerland with an average irradiation of 966kWh/m2/year. We compare an ASF to an optimally orientated static facade, and classic flat facade mounted PV solutions. The blue bars include energy savings through shading.

4. Discussion

An adaptive solar facade, purely as a solar tracking and electricity generation technology is inferior to simple flat mounted static solutions in terms of life cycle emissions. Its emission factor is approximately 30% and 55% higher than Poly-Si and CIGS solutions respectively. This is due to the additional greenhouse gas emissions, caused by the material required for the control system, supporting structure, actuators, and the energy required for actuation. An optimally orientated static facade also performs poorly. The added PV electricity harvested through optimising the angle does not compensate the GWP of the added structural support required.

However when we also consider the energy savings to the building through adaptive shading we have a system that yields a negative emission factor of -601.1 gCO_{2-eq}/kWh. This is because the savings to the building system in terms of heating, cooling, and lighting offsets the embodied GWP three-fold. This demonstrates the advantage of using the PV material, not only as an electricity generation unit, but also as a building material for adaptive shading systems. In this analysis we also present a static ASF where all panels were orientated at an optimal angle of 45° to the horizontal axis. Although this solution performs well, it sacrifices user comfort. The users can not open the facade to suit their desires.

The GWP savings through adaptive shading however are sensitive to the GWP of the electricity mix. A country with a low GWP electricity mix will result in lower operational GWP savings than a country with a high GWP electricity mix. For example, an ASF installed in Switzerland only has an emission factor of 70.6 gCO_{2-eq}/kWh. Germany on the other hand would have an emission factor for the ASF of -887.5 gCO_{2-eq}/kWh.

Although it is favorable to install an ASF in Germany, it still has benefits in countries such as Switzerland. For instance, with an emission factor 44% less than the standard mix, it contributes to a nuclear free energy mix. Furthermore, it provides interesting design options for architects where they can install PV in locations which were previously not possible. Thus increasing BIPV potential.

When designing an ASF architects and engineers may consider:

- The trade-off between soft robotic actuators and servo motors for actuation. Although a soft robotic actuator has an embodied GWP three times lower than a servo motor, it requires three times more energy to actuate. Purely from an LCA perspective, if more than 6 actuations are required a day, servo motors would be the preferred solution.

- Control system electronics cost 27.5$kgCO_{2-eq}$/kg and therefore should be carefully designed. However increasing the resolution of the control system to allow each panel to be independently actuated only increases the emission factor by 1.6gCO_{2-eq}/kWh.

- The structural support system in our current analysis used a stainless steel frame representing 20.4% of our total embodied carbon emissions. Using plain steel, or an alternative material with a lower GWP should be considered.

- If the ASF is installed over an opaque building surface then the advantages of adaptive shading are not present. In this case, a static, flat mounted system is a preferred design choice.

One limitation of the LCA is that the locations are bound to the climate of where the energy simulation was conducted. In our case, the simulation was conducted in Geneva, Switzerland. This restricts our LCA to similar temperate climates on the same latitude. Conducting the simulation in Spain, the MENA region, or a tropical climate may lead to different results and conclusions. Furthermore the analysis focuses on a single office room. Expanding the analysis to the entire building, or urban level may yield different results. The LCA also assumes that the user will not override the system. In practice the facade will adapt to the desires of the user. The LCA also excludes other aspects of building system such as the downsizing of heating and cooling appliances, the use of DC electricity on-site, and the increase in user comfort.

5. Conclusion

The environmental performance of the ASF has been shown to be favorably competitive with a classic BIPV installation. Even though the total embodied GWP for the ASF is high, this can be offset through energy savings by adaptive shading. This combination of adaptive shading with photovoltaic generation brings new advantages to solar as it effectively has a negative emission factor of -601.1 gCO_2/kWh. These advantages however, will not be present if the ASF is installed over an opaque building surface. It is therefore preferable to install static systems over opaque facades, and keep the adaptive system for glazed facades only.

The design of an ASF naturally can greatly influence the results. Varying factors such as the choice of actuators, the complexity of the control system, and the structural support can change the emission factor. The largest variable however is the emission factor of the grid electricity mix. The building operational savings in heating, cooling, and lighting will have a CO_2 saving based on the grid electricity mix.

Future research will validate the assumptions to building energy consumption through experimentation, and test the users response. This will be conducted on the ETH House of Natural Resources living lab where an example of an ASF has already been constructed [11]. Further numerical simulations of the ASF on different building typologies, building systems and climates will enable us to specifically target the best application scenario. An application of the ASF in Spain for example could yield even larger energy savings compared to a temperate climate like Switzerland.

To conclude, we demonstrated that BIPV systems and adaptive shading elements complement each other successfully. We see an improvement in environmental performance of the PV technology, and create new architectural possibilities for the aesthetic integration of PV panels over glazed building surfaces, thus expanding BIPV potential.

6. Acknowledgments

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7. Appendix

7.1. Electricity production of different PV Systems

	ASF	Orientated Solar Facade	Flat CIGS	Flat CdTe	Flat PolySi
Total Irradiation (kWh/m2/year)	966.0	966.0	966.0	966.0	966.0
Utility Factor (m2/m2)	0.69	0.69	0.69	0.69	0.69
Losses from sub optimal angle	0.00	0.30	0.38	0.38	0.38
Irradation of active PV (kWh/m2/year)	670.8	469.6	412.8	412.8	412.8
Efficiency	0.11	0.11	0.11	0.10	0.07
Self Shading Losses	0.40	0.40	0.00	0.00	0.00
Losses due to sub optimal tracking angle	0.77	1.00	1.00	1.00	1.00
Total Power (kWh/year)	518.2	471.1	690.1	627.4	439.2

Table 8: Total PV production for the ASF, a static version of the ASF in an optimal orientation for building shading and PV production, and classical flat facade mounts of CIGS, CdTe and PolySi panels

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