

Life cycle efficiency of solar shading systems: a proof-of-concept

Nazanin Rezaei Oghazi^{1,2}, Thomas Jusselme¹, Elise Barri¹, Sergi Aguacil Moreno³, Marilyne Andersen²

¹Energy Institute, University of Applied Science of Western Switzerland (HEIA-FR, HES-SO), Fribourg, Switzerland

²Laboratory of Integrated Performance in Design (LIPID), Ecole polytechnique fédérale de Lausanne (EPFL), Switzerland

³Building2050 group, Ecole polytechnique fédérale de Lausanne (EPFL), Fribourg, Switzerland

Abstract

Solar control strategies are essential for the glare control and decreasing cooling needs or overheating risks (in the absence of active cooling system), however, they come with their own embodied energy. With the carbon neutrality objective looking at the 2050 horizon, life-cycle assessment (LCA) approach is needed to evaluate the impact of decisions made on the different building components, including solar shading systems. To that end, this paper applies a relatively new concept defined as the Life-Cycle Efficiency Ratio (LCER) to quantify the trade-off between operational and embodied energy. Results based on a low-carbon case study suggests that adding solar shadings does not reduce the life cycle carbon emissions of this project. Also, analyses show that the ratio between operational benefits and embodied impacts of external fabric blind is the highest, while this ratio is the lowest for the internal fabric blinds in this case study.

Key Innovations

- Highlighting the life-cycle impact of solar shading
- Quantifying the carbon footprint of solar shading systems with the LCER metric
- Revealing the impact of integrating photovoltaic (PV) systems in solar shading systems on their life cycle carbon performance

Practical Implications

The ultimate aim of introducing a life cycle-based methodology applicable to solar shading systems is to enable practitioners to evaluate and compare whole life cycle efficiency of different solar shading options under carbon budget constraints.

Introduction

The combination of sun course specifics and cloud cover variability result in changes in outdoor temperature over the course of the day and the year. With a fluctuating need for and availability of solar gains over time and across the globe, maintaining good comfort conditions indoors (thermal and visual environment) requires a careful trade-off between comfort objectives and energy use. While glare, overheating and/or conduction exchanges concerns may tend towards a minimization of window size,

windows serve many other purposes such as the provision of views through a connection to the outside, which has its own value (Turan et al., 2020), and of abundant and naturally varying (day)light, under which we evolved and that is necessary for our health and well-being (Andersen, 2015; Lockley, 2010). In most climates, solar control systems offer a way to at least partially solve this dilemma and positively contribute to visual comfort while mitigating overheating risks and thus decreasing cooling loads or ventilation needs.

Previous studies have mostly focused on assessing the potential of solar control systems based on their operational energy benefits and the expected increase in indoor environmental quality. Amongst other findings, exterior shadings have been found to reduce operational carbon emissions (Karlsen et al., 2016; Li & Tsang, 2008). However, how significant this reduction is very much depends on their heat conductivity, colour, tilt angles, climate context, and other factors (Grynning et al., 2017; Skarning et al., 2017; Nielsen et al., 2011; Tzempelikos et al., 2010). But while there is a growing body of knowledge dealing with the energy-saving potential of solar control systems, very few studies have so far considered both their embodied and operational carbon emissions. Considering the latest international agreements about carbon neutrality at the 2050 horizon (IPCC, 2018), it is high time that life cycle analysis (LCA) approaches become the norm when it comes to evaluating the overall energy performance of buildings or their components i.e. both their operational energy and embodied carbon footprint.

Assessing the carbon emissions of solar control strategies requires to resort to an appropriate LCA method (ISO 14040, 2006; Weißenberger et al., 2014) i.e. one that would be applicable to solar shading systems. As solar shading is used to control daylight penetration, this will effectively require to embed daylighting performance considerations when evaluating carbon footprint, a bridging of topics that has – to the authors' knowledge – never been performed so far. The present paper proposes a proof-of-concept methodology based on the adaptation of existing LCA approaches to evaluate the performance of solar control systems according to their so-called LCER, i.e. their Life-Cycle Efficiency Ratio, a performance indicator that was first introduced in 2018 for ventilation and thermal inertia (Brambilla et al., 2018).

Existing approaches

The impact of shading techniques on operational energy consumption has been studied quite extensively. For instance, Niu's study on high-rise residential buildings concluded that exterior shadings covering the entire glass surface area can reduce solar heat gains up to 80% (Niu, 2004). Another study on 35 commercial buildings in Hong Kong demonstrated that solar shading devices together with appropriate daylight design, glazing type, building area, building orientation and colour of external surface finishing can save up to 30% of the total electric lighting energy while also reducing cooling loads (Li & Tsang, 2008). On the other hand, Karlsen, et al developed a solar shading strategy for office buildings in cold climates which leads to satisfying compromises between indoor environmental performance and annual energy consumption (Karlsen et al., 2016). Skarning and co-workers assessed the energy, daylighting and thermal comfort potentials of static and dynamic shadings, and reported that for glazing-to-floor ratios of up to 15%, dynamic shading can improve overall comfort and may give 750–1'000 hours more daylighting than when using large solar control coated glazing (Skarning et al., 2017).

The embodied impact of solar control systems has generally, however, been largely overlooked so far, except for a few studies. One of them conducted in Hong Kong (Huang et al., 2012) focused on analysing the energy and CO₂ emission payback periods of external overhang shading and concluded that overhang systems had an overall tendency to increase green-house gas (GHG) emissions in low latitudes like that of Hong Kong, due to the structurally more resistant building materials used and low annual benefit on energy conservation. Another one from South America (Invidiata & Ghisi, 2016) used life-cycle cost analysis to determine to most energy-efficient and the most economically feasible shading strategy. They concluded that within the subtropical Brazilian climate, 3 out of the 4 analysed shading strategies, i.e. punctured concrete blocks, aluminium double sliding shutters, PVC roller shutters and wooden double open shutters, had a positive impact on the overall building life-cycle, with the PVC roller shutter having the highest positive energy balance. A third study conducted in North America (Babaizadeh et al., 2015) compared the life-cycle impacts of wood, aluminium and PVC shadings for five different climate zones in the United States. The authors concluded that for most scenarios, the use of exterior shading devices on windows would typically reduce fossil fuel consumption, while carrying a negative impact on environmental impact categories.

These examples highlight the urgent need for a life-cycle approach adapted to solar control systems and that would be able to reveal somewhat systematically whether it has a positive or negative energy and carbon impact overall. Of particular importance here is the ability to weigh the operational benefits enabled by a given solar shading against its additional embodied carbon impact, which is the point of this study. In particular, this paper evaluates the LCER of 8 solar shading scenarios and investigates

how integrating a PV system would impact these scenarios' carbon performance.

Methodology

The scope of this paper is to propose a proof-of-concept methodology allowing us to analyse and weigh operational benefits against embodied impact for different solar shading system choices. The proposed methodology relies on a performance metric introduced in 2018 and called LCER (Brambilla et al., 2018), which stands for Life-Cycle Efficiency Ratio and shows great promise for applicability to solar control systems.

Life-Cycle Efficiency Ratio (LCER)

The calculation of a Life-Cycle Efficiency Ratio relies on the outputs of a Life Cycle Assessment (LCA). The life-cycle impact of a building is the sum of an operational impact (OI), resulting from its operational phase, and embodied impacts (EI), resulting from material production, construction, replacement and end of life. This can be summarized in Equation 1:

$$I_{LC} = OI + EI \quad (1)$$

In the context of decision-making and especially in the early phases of design, one will typically aim at performing a simplified yet reliable LCA. To that end, the life-cycle stages and their specific modules must first be specified. According to the CEN standard (EN 15978, 2011), building has different life cycle stages, i.e. production, construction, use and end of life. This standard proposes to break down each stage into a separate LCA evaluation stage (or LCA module) as well: raw material supply, transport, manufacturing, etc., and indexed as A1, A2, A3, ..., C3 and C4 (see Figure 1). In our case, OI embeds the Operational energy use (B6), while EI embeds the following modules: Raw material supply (A1), Production Transport (A2), Manufacturing (A3), Construction Transport (A4), Replacement (B4), Demolition (C1), Transport (C2), Waste processing (C3) and Disposal (C4) that are highlighted with blue in Figure 1.

	Production			Construction		Use phase							End of life			
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4
Raw material supply																
Transport																
Manufacturing																
Transport																
Construction																
Use																
Maintenance																
Repair																
Replacement																
Refurbishments																
Operational energy use																
Operational water use																
Demolition																
Transport																
Waste processing																
Disposal																

Figure 1. Building life cycle assessment stages based on CEN standard. The highlighted parts show the considered life cycle modules in this study

According to Jusselme et al. (Jusselme et al., 2016) the embodied impact consists of multiplying the material volume (M_j) by the carbon impact conversion factor of the material ($IF_{E,j}$), which comes from a life cycle inventory database. The sum must be multiplied by the ratio

between the building reference study period (RSP_B) and the components' lifetime (LM_j). To calculate the embodied impacts per year per square meter (which is compatible with SIA 2040 performance units), the sum is divided by building reference study period (RSP_B) and energy reference area (ERA) (Jusselme et al., 2016), as expressed in Equation 2:

$$EI = \sum_j (M_j \cdot IF_{E,j} \cdot \frac{RSP_B}{LM_j}) / RSP \cdot ERA \quad (2)$$

Now, in order to weigh the operational benefits of a given solar shading against its additional embodied carbon impact, we use the LCER metric, which has been introduced by Brambilla et al. as follow: the difference between the operational carbon emissions of the reference and an analysed scenario divided by the difference between the embodied carbon emissions of an analysed scenario and the reference scenario (Brambilla et al., 2018). Accordingly, the LCER can be calculated as follows (Equation 3):

$$LCER = \frac{OI_{ref} - OI}{EI - EI_{ref}} \quad (3)$$

where

OI_{ref} : Operational carbon emissions of the reference scenario (kg CO₂-eq/m²y)

OI : Operational carbon emissions of the analysed scenario (kg CO₂-eq/m²y)

EI_{ref} : Embodied carbon emissions of the reference scenario (kg CO₂-eq/m²y)

EI : Embodied carbon emissions of the analysed scenario (kg CO₂-eq/m²y)

If LCER is negative, it means that the detrimental impact due to the embodied carbon of a given design option is higher than the beneficial impact of all anticipated operational energy savings induced by adding it, compared to a reference scenario. When it is lower than 1, it means the investigated design option does not bring more benefits than the reference choice. The greater the LCER, the higher the life-cycle benefits of a design choice. The advantage of using the LCER approach is that the LCA analysis can be restricted exclusively to building components that *differ* between a reference case and a considered alternative.

The proposed methodology is structured in three phases, developed around a relevant reference case. These three phases can be articulated as follows:

1. Phase I: Analysis and modelling of the reference case
2. Phase II: Definition of design scenarios
3. Phase III: Simulation hypotheses and LCER calculations

Description of the reference case

A low-carbon case-study, the Smart Living Lab building in Fribourg, is used to evaluate the LCER more accurately and specifically within the Swiss context. The case study is an exemplar research centre that will be built in 2021-2022 for the Smart Living Lab (SLL) (SLL, 2021), whose

core research focus revolve around the future of the built environment. The SLL building – currently in the last stages of design development – will be located in Fribourg (Switzerland) and presents a mix of different programs (offices spaces, experimental zones, laboratories and technical research facilities) distributed over 4 floors above a basement, with a total area of about 5'000 m². The local climate in Fribourg is characterised by cold and dry winters, and warm but rather dry summers, and comfortable mid-seasons.

One of the objectives of the SLL building is to meet the 2000-Watt Society targets defined by the SIA 2040 (SIA 2040, 2017) with a maximum GHG emissions of 13 kgCO₂/m².year (for office buildings), accounting for the environmental impact of construction, operation and end of life phases. To reach such ambitious targets, it is crucial to carefully select each of the building components as the choice made for some of these components, such as the shading devices, could have a significant influence on the whole energy performance of the building. During the design phase, a wood-based, modular façade structure was planned, with different design possibilities in terms of solar protection so as to guarantee visual comfort while avoiding summer overheating. Three main options were considered at the time by the design team: (a) install vertical and/or horizontal sunscreens, (b) install interior and/or exterior solar devices and (c) have no-solar protections but use glazing with a low solar-gain coefficient. To evaluate these options against one another, different types of simulations (pertaining to energy use, solar gains and environmental impact) are needed to evaluate their operational benefits as well as the embodied carbon emissions.

Phase I: Analysis and modelling of the reference case

To evaluate the value of OI, which is based on the energy consumption of a building, energy simulation with hourly time-steps were conducted using the EnergyPlus (US Department of Energy, 2018) simulation engine.



Figure 2. (a) Building-Energy Model, (b) Solar Energy Model and (c) Potential active surfaces (in blue)





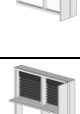
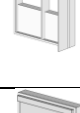



A first Building Energy Model (BEM) was built using the DesignBuilder (DesignBuilder, 2019) v6 software, and was based on a coarse definition of the building envelope (see Figure 2a), but accounting for the actual HVAC systems chosen for the building and the urban context surrounding it. A second calculation model, called the Solar Energy Model (SEM) was built in parallel with a higher level of detail using Rhino 3D (Robert McNeel & Associates, 2019). (Figure 2b), so as to evaluate on-site electricity production by the photovoltaic installation. The

latter was calculated using the DIVA for Rhino (Solemma LCC, 2018) plugin.

Phase II: Definition of design scenarios

All the shading scenarios envisaged within the options (a) or (b) mentioned above are listed as scenarios 2 to 9 in Table 1. They are to be confronted to scenario 1, i.e. no solar shading device, and in the LCER calculation will be considered as the reference scenario. Note that the scenarios involving fixed shading devices and external adjustable venetian blinds (4 and 5) actually correspond to the current status of the design concept (fall 2020). To explore what impacts the brightness of solar shadings may have on the resulting LCER, each scenario is evaluated for two colours, i.e. light grey and dark grey.

Table 1. Shading device scenarios

Sc.	Shading device	Image
1	No-solar device (Reference scenario)	
2	External adjustable venetian blinds (light grey)	
3	External adjustable venetian blinds (dark grey)	
4	Vertical and horizontal fixed sun shading (with photovoltaics elements) and external adjustable venetian blinds (light grey)	
5	Vertical and horizontal fixed sun shading (with photovoltaics elements) and external adjustable venetian blinds (dark grey)	
6	External fabric blind (light grey)	
7	External fabric blind (dark grey)	
8	Vertical and horizontal fixed sun shading (with photovoltaics elements) and interior adjustable venetian blinds (light grey)	
9	Vertical and horizontal fixed sun shading (with photovoltaics elements) and interior adjustable venetian blinds (dark grey)	

Phase III: Simulation hypotheses and LCER calculations

For both types of simulations (energy consumption and on-site electricity production), weather data were taken from the official weather station in Liebefeld (Bern) as defined in the SIA 380/1:2016 (SIA 380, 2016). An EnergyPlus Weather file (i.e. based on the “epw” format with hourly step-time data) was generated using the Meteororm (Meteororm, 2019) software by including historical data from 1991 to 2010.

Building-energy model (BEM) hypotheses

Most of the thermal zones of the building correspond to an office activity (individual or open-space). The energy-model was thus set using the standard parameters defined in SIA 2024:2015 (SIA 2024, 2015). Table 2 presents a summary of the main assumptions made.

Table 2. Summary of the main assumptions for building energy modelling

Parameter	Settings
General schedule	Working day from 8 am to 6 pm
Occupation	0.07 people/m ²
Metabolism	70 W/person (light work)
Heating setpoint	21°C
Cooling setpoint	26°C
Natural ventilation	User control (hypothesis T>24°C)
Office equipment	3 W/m ²
Lighting	7.3 W/m ²

As the building envelope of the building mainly consists of a wood-framed structure, it presents a lower thermal transmittance (U-value) compared to the minimum legal requirements defined by the SIA 380/1:2016 (SIA 380, 2016). The building will also have a green-roof that improves indoor thermal comfort and improves the PV panels’ performance by 3% to 16% thanks to the evapotranspiration effect (Weaver, 2012). The main characteristics that were hence defined for the building envelope’s model can be found in Table 3.

Table 3. Building envelope’ properties (including openings)

Component	Settings
Flat roof	U-value 0.12 W/m ² .K
External wall	U-value 0.12 W/m ² .K
Indoor partitions	U-value 0.67 W/m ² .K
Ground floor	U-value 0.17 W/m ² .K
Glazing (triple pane)	U-value: 0.67 W/m ² .K, Solar Transmittance: 50%, Light Transmittance: 75 %
Window frames	U-Value: 3.60 W/m ² .K
General building envelope air tightness	0.3 ACH

Regarding active heating and cooling, the building will be connected through two heat exchangers to a new district heating system relying on local geothermal heat-pumps,

which is characterised by a relatively high coefficient of performance of 5.

District heating will provide water for heating needs at 35°C and water for cooling needs at 12°C. Given the fact that the domestic hot water demand will be very small, the building will produce the DHW using electric tanks. The main features of the HVAC system and of the PV installation that were defined in the model are shown in Table 4. As for solar shading devices, their main characteristics are shown in Table 5 with a reference to the scenarios they apply to from Table 1.

Table 3. Heating, Ventilation and Air conditioning (HVAC) settings

Component	Settings
Heating system (Geothermal heat-pump)	Power: 320 kW; coefficient of performance: 5.00
Cooling system (Geothermal heat-pump)	Power: 180 kW; coefficient of performance: 5.00
Mechanical ventilation system with heat recovery	Nominal recovery-efficiency: 70%
Photovoltaic installation (Mono-Si cells)	Power: 139 kWp; efficiency cells with 21%.

Table 4. Solar device features and the used scenario

Component	Settings	Sc
External adjustable venetian blinds (light-coloured).	Solar reflexion: 75%	2,
	Light reflexion: 84%	4
External adjustable venetian blinds (dark-coloured).	Solar reflexion: 10%	3,
	Light reflexion: 7%	5
External fabric blind (light-coloured)	Solar reflexion: 57%	6
	Solar transmittance: 20%	
	Light transmittance: 18%	
External fabric blind (dark-coloured)	Solar reflexion: 4%	7
	Solar transmittance: 4%	
	Light transmittance: 4%	
Internal fabric blind (light-coloured)	Solar reflexion: 67%	8
Internal fabric blind (dark-coloured)	Solar reflexion: 6%	9
	Light transmittance: 4%	

Solar-energy model (SEM) hypotheses

This study proposes to consider all blue-coloured surfaces in Figure 2c as the possible areas, on which photovoltaics can be installed (Aguacil et al., 2019). The maximum power production of installed photovoltaics on the envelope is thus 203 kWp (according to the Standard Test Conditions – STC), and represents about 1'082 m² with a total electricity production of 173 MWh/year.

Considering the architectural characteristics of the project, the potential for photovoltaic installation is distributed in four areas: (1) South-oriented standard panels using the flat roof with 15° of inclination, (2) Flexible and low-weight PV elements fully embedded in the sunscreens, (3) Transparent PV panels with defined patterns of mono-Si solar cells on the winter garden façades (South, East and West) and the atrium's roof, and (4) Coloured PV elements on the bottom (opaque) part of

the facade. For all four groups, the same PV technology (based on mono-Si solar cells) is considered, with 20% of global efficiency. The colour of PV panels in field four is customized by adding a coloured film layer on the top of the solar panels (Solaxess, 2021). This results in 20% loss of efficiency of the mono-Si cells. For all PV fields, an additional 10% loss is applied to account for the DC/AC conversion and the efficiency losses due to the temperature of the solar panels (which is in general 0.7%/°C, for the temperature above 25°C according to STC).

Results

Energy

The simulated energy consumption of the building vs. its electric production is summarized in Figure 3 for each of the envisaged scenarios listed in Table 1.

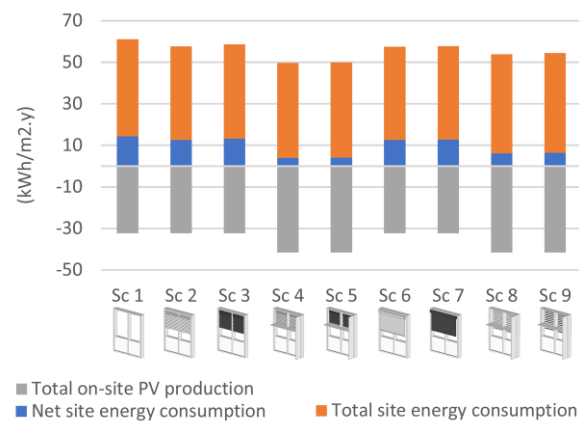


Figure 3. Electricity consumption, on-site PV production and total net balance expressed in kWh/m².year, considering a Reference Energy Area of 4'160 m²

Operational Impact (OI)

The OI was calculated from results of energy consumption and production. The calculation method used corresponds to the SIA 2032 standard (SIA 2032, 2010) and uses the KBOB Conversion Factors (CF), which are as follow: (1) CF for grid electricity is 0.102 kgCO₂/kWh, (2) CF for electricity produced and exported by the photovoltaic installation is 0.081 kgCO₂/kWh and (3) additional CF for electricity stored in the battery (and used) is 0.021 kgCO₂/kWh (KBOB, 2016). Figure 4 summarises the results of the operational impact (OI) for three possible cases: (1) without PV; (2) with PV; and (3) with PV and battery.

Embodied Impact (EI)

The only elements that actually vary from one scenario to another are the solar shading systems themselves and, in the case of non-mobile shading, their embedded PV panels. It is, therefore, possible to simplify EI calculations by assuming that the EI of the reference scenario without solar protection is 0 kgCO₂/m²y and to consider only the EI of the solar protection and the solar panels. Based on

this approach, the outcomes of the LCA calculations (using the KBOB database) are shown in Table 6.

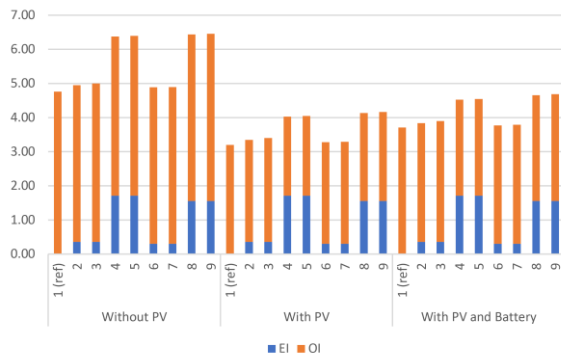


Figure 4. Operational Impact (OI) due to the electricity consumption and production of the building, considering a Reference Energy Area (REA) of 4'160 m². Scenario 1 (Sc1) represents the reference scenario (OI_{ref})

Table 5. Embodied impacts (EI) of the scenarios based on KBOB database (EI_{ref}=0)

Scenario No.	2	3	4	5
EI (kgCO ₂ /m ² y)	0.36	0.36	1.71	1.71
Scenario No.	6	7	8	9
EI (kgCO ₂ /m ² y)	0.31	0.31	1.56	1.56

Life-Cycle Efficiency Ratio (LCER)

LCER was evaluated based on OI and EI. Figure 5 depicts the resulting LCER for the three envisaged cases mentioned above: (1) without PV; (2) with PV and (3) with PV and battery.

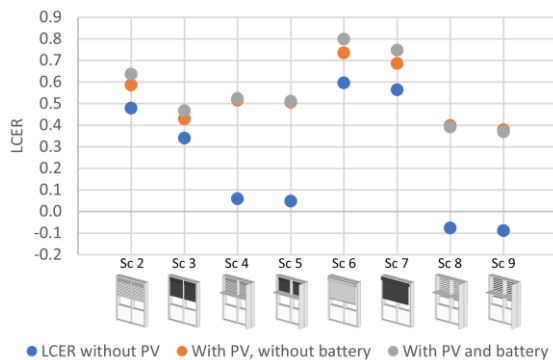


Figure 5. LCER of all scenarios according to the three possible cases (without PV, with PV and with PV and battery)

Analysis outcomes

As illustrated in Figure 4, sums of OI and EI of all scenarios are always higher than the reference case, which demonstrates that in this project adding solar shadings never lower life cycle carbon emissions. As shown in Figure 5 presenting LCER values for all scenarios with or without PV, all LCERs are less than 1 (LCER_{Sc 2-9}<1), which means that “investing” on embodied impact of sun shadings does not benefit this project. Given that the Smart Living Lab building has a highly efficient

geothermal heating system (whose coefficient of performance is equal to 5) the operational energy saving of the solar shadings is low. In fact, the more energy-efficient a building is, the more difficult it is to make the added embodied energy profitable. Our case study is already an energy-efficient building and therefore, the operational benefit of adding solar shadings was always negative.

By looking at Figure 5, one can observe that the LCER of scenarios with PV and battery (grey dots) are higher than scenarios with PV but without battery (orange dots), and that the LCER of scenarios without PV are the lowest. The reason is that in scenarios without PV panels, all the electricity consumed comes from the grid and each kWh consumed has an impact of 0.102 kgCO₂-eq (KBOB, 2016). In the other two cases with photovoltaic panels, almost half of the electricity consumed by the building comes from the grid while the other half is provided by PV panels, which has a lower impact: 0.081 kgCO₂-eq per kWh consumed (see Table 7). As the electricity production of scenarios with PV is the same, adding sun shadings reduces the OI and therefore, exports more electricity to the grid.

The OI_{ref} for scenarios with PV are lower than that of without PV because the impacts of delivered electricity to the grid has been subtracted from the operation impact of the reference case without PV. Also, the OI of scenarios with PV is lower than without PV due to lower conversion factors and thus lower carbon emissions (based on Table 7). However, the operational benefit (i.e. OI_{ref} - OI) of the scenarios with PV is higher than no PV, which makes their LCER somewhat higher (see Figure 6).

Table 6. Share of energy supply for grid, PV system and battery and their correspondent conversion factor

	Grid	PV	Battery
Share of energy delivery	0.49	0.51	0.13
KBOB conversion factor (kgCO ₂ -eq/kWh)	0.102	0.081	0.021

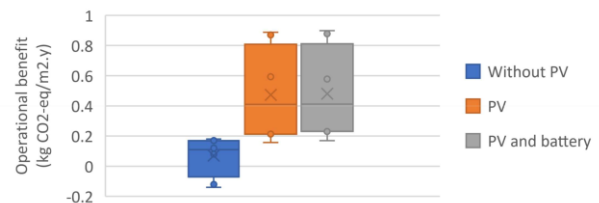


Figure 6. Distribution of the operational benefit

As illustrated in Figure 5, scenarios 6 and 7 (external fabric blinds) show the highest LCER of all. While they have a low operational benefit, their EI is also the lowest due to the low embodied impacts of the fabric used in roller blinds. When comparing scenarios 2 and 3 (external adjustable venetian blinds) with scenarios 4 and 5 (vertical and horizontal fixed sun shading with photovoltaics elements and external adjustable venetian blinds), one observes that adding PV elements to the external adjustable venetian blinds reduces the LCER

significantly because the added embodied impacts of PV elements surpasses their operational benefits. For similar reasons, scenarios 8 and 9 (vertical and horizontal fixed sun shading with photovoltaics elements and interior adjustable venetian blinds) indicate the poorest LCER because both the PV elements and the interior venetian blinds add a high EI without improving operational benefits. Another conclusion drawn from Figure 5 is that the scenarios with the light grey colour always show higher LCER compared to dark grey ones.

Although the battery implies an additional EI, it allows to use a greater part of the produced electricity and therefore less power is drawn from the grid. It also reduces the part that is returned to the grid which, according to our method, has a favourable impact. However, the battery increases the LCER of the most of the scenarios except for the scenario 8 and 9. According to our analyses on these 9 scenarios, all considered solar control systems are unsatisfactory for our case study given that their LCER is less than 1, with variant 6 (external fabric blind) with a light colour obtaining the best ratio among the studied scenarios.

Limitations and discussion

In this study, the life cycle efficiency of different solar shading systems was evaluated for a specific context in Fribourg, Switzerland. The analyses were performed based on global solar irradiation statistics relevant to that region, which are obviously highly dependent on location. The results are thus so far applicable only on the studied context, as solar irradiation impacts both indoor comfort and operational energy needs and, consequently, will also affect life cycle efficiency ratios.

As explained in the method section, the LCA was performed using the KBOB database. This database contains three types of solar shadings: dynamic projection blinds with motors, venetian blinds with motors and motorised roller shutter with wind protection, though the latter are usually not implemented into an office building). The database is limited in that it does not offer a lot of variety in solar shadings but also does not specify their physical characteristics, such as material, colour, dimensions, shapes, etc., even though these properties will affect their respective life-cycle carbon emissions. The data coming from KBOB can thus often only approximate actual systems used, as was the case for the Smart Living Lab building. To obtain more meaningful results, it would be necessary to have a higher diversity of materials in the KBOB database, or to perform accurate LCA per alternatives, which is very time consuming.

On the other hand, each solar control scenario was applied in this paper to the entire building at once, although solar gains are quite different from one orientation to another and would benefit from an independent control. Also, the modelled control system activates the adjustable shadings once the interior temperature reaches 24°C. The benefit of this threshold temperature is that it allows to anticipate the activation of the solar shading system before reaching the set point temperature, in this case 26°C, above which the

cooling system would be activated (see Table 2). The limitation is that glare may still happen when the temperature is below 24°C and the user might then need to close the shadings. Accordingly, considering visual comfort priorities (especially avoidance of glare) as well as zoning per orientation to control solar shadings in future investigations would bring the analysis to be more realistic.

Conclusion

This preliminary study is the first to propose a methodological framework that can hopefully be used for other building components affecting both operational and embodied carbon emissions. This work also aims to pave the way towards ultimately giving design guidance when it comes to choosing efficient solar control systems under carbon budget constraints.

This article used LCER as a metric to compare different solar control systems and answered whether adding sun protections and embedding PV systems in them was generally profitable in terms of carbon emissions for a variety of shading approaches applied a case study by relying on building performance simulations with Energy Plus. What emerged from the analysis is that the more energy-efficient a building is, the more difficult it is to make additional shading control profitable from an overall energy standpoint due to its added embodied energy. Overall, LCER results showed that although the LCER of all scenarios was below 1 (not beneficial overall i.e. when accounting for both operational and embodied energy), scenarios with PV system showed better overall performance. Indeed, a building with solar shading equipped with PV has higher LCER compared to one without PV because it offsets a part of the operational impacts by producing electricity.

The approach adopted in this paper might be helpful for practitioners in that it raises awareness about the need to weigh the operational benefit of a solar control system against its added embodied impact, thanks to quite manageable calculations relying on the LCER metric. The proposed method showed that using solar shadings in buildings that already have a low energy consumption in use phase may not improve their overall life-cycle efficiency, as was demonstrated for the chosen case study. Also, adding PV elements on solar shading and/or resorting to mobile interior venetian blinds significantly decreases the LCER as they significantly increase the embodied carbon emissions.

Beside life-cycle energy and carbon balance of buildings, solar control systems also impact the visual comfort of occupants. Further investigation is thus required to evaluate solar control scenarios also accounting for on visual comfort requirements and glare avoidance.

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