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Solar efficiency index of building envelopes and load matching in low energy buildings

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ABSTRACT
Net-zero energy buildings oftentimes rely on solar-based building integrated technologies to offset energy use and achieve their goals. However, the value of a particular system is difficult to assess given that these technologies often bring about complex interactions with the indoor environment, and building energy management systems. The approach chosen in this study was to propose and test a simple index called the *Solar Efficiency index (SE index),* which makes it possible to characterize the performance of building envelopes with integrated solar systems. The index was used to investigate the effect of different configurations of a PV integrated shading device on an office building in Norway. The results provided by the index allowed estimating how much solar energy was converted and how useful that energy was to the building in terms of load matching. This provided a picture of the building's energy autonomy.

KEYWORDS
Low Energy Buildings; Parametric Analysis; Load Matching; Solar Efficiency Index; Building Envelope.

INTRODUCTION
Sustainable building concepts such as net-Zero Energy Buildings (net-ZEB) or Zero Emission Buildings (ZEB) have increasingly become part of European building policies (D'Agostino et al., 2016). By definition, in order to reach a net zero balance, ZEBs and net-ZEBs must feed as much excess energy back into the grid as they purchase from the utility (Sartori et al., 2012). This design strategy is based on combining highly energy efficient building envelopes (Justo Alonso et al., 2015) with systems allowing to harvest and store renewable energy sources (RES). But reduced energy use and on-site production of heat and electricity, may lead to a seasonal load mismatch in the balance of energy use vs energy converted (Lindberg et al., 2016). This issue is especially critical in Nordic climates where solar radiation is relatively abundant during the summer while energy use is low, and the reciprocal during the winter.

As net-ZEBs and ZEBs become more popular, there is an increasing need to develop strategies in early design phase to improve load management and grid interactions. Increased energy autonomy can be achieved through energy storage, but isn't currently an economically viable option at single building scale given the techno-economic context (McKenna et al, 2017). Other approaches have been to optimize building systems such as heat pumps, or RES technology size and placement to best cover the energy loads (Dar et al., 2014). From a broader energy management point of view, load matching is an important topic of discussion, and fosters concern regarding the capacity of electric grids to adapt to future needs. In response to this need the International Energy Agency (IEA) in the Annex 67 created an energy flexibility indicator (Grønborg Junker et al., 2018). Previously, the IEA in the task 40 had reviewed Load Matching and Grid Interaction (LMGI) indicators and distributed them into four categories (Salom et al.,

2011). The findings showed that LMGIs are highly dependent on the timescale considered and more often than not, a shorter time step will improve their accuracy (Voss et al., 2011).
Designing low-energy buildings with RESs is not a straightforward task and requires careful balancing of parameters; this is because different uses of solar energy may have antagonistic purposes (e.g. visual comfort vs thermal comfort). The study presented in this paper deals with the development and testing of a new metric called the Solar Efficiency index (SE). The utility of the SE index is to characterize the extent to which different RES building envelope designs are able to utilize available solar radiation to reduce the building's energy use, while still maintaining high-quality indoor environments in terms of thermal and visual comfort. The goals of this study are: (i) define a new indicator called the solar efficiency index of the building skin; and (ii), to test the indicator on different envelope configurations in a Nordic climate by assessing its suitability to communicate the performance of the building in terms of solar energy use and load matching.

METHODS

This work was based on numerical simulations carried out in the dynamic building performance simulation tool IDA ice. The SE index was used to evaluate the simulation results of a case study based on a parametric analysis of the possible configurations for a PV integrated shading device (PVSD). The index was used to evaluate the amount of energy converted and how useful that energy was to the reference building in terms of hourly load matching.

Description of the reference building model

The reference model used for this study is a conceptual ZEB office building developed by (Dokka et al., 2013). The simulations were run using an EPW file for Trondheim, Norway. The inputs for the HVAC system, internal loads and domestic hot water demand were taken from the Norwegian Standard NS3031:2016 and Norwegian Passive House standard NS3701. A proportional control strategy for artificial lighting based on measured daylighting levels was used in peripheral zones during operation hours to ensure a minimum average of 500 lx at 0.8m from the floor level. Specifics about the building and energy systems are given in Table *1*.

Table 1. Characteristics of the base case building model used in the study

Element	Area	Value
Heated floor area/volume	1 980 m^2/ 7 128 m^3	
Building envelope	2 306 m^2	
External walls	860 m^2	U= 0.12 W/m^2K
External roof	495 m^2	U= 0.09 W/m^2K
Floor against cellar	495 m^2	U= 0.11 W/m^2K
Windows and doors	WWR 14%	U= 0.75 W/m^2K
Normalized thermal bridge value		Ψ''=0.03 W/m^2K
Air tightness		N_{50}<0.3 ach@50 Pa
Heat exchanger efficiency		86 %
Specific fan power		1.00 $kWh/m^3/s$
Heat pump coefficient of performance for heating/ cooling		3 /4.5

Description of the different building envelope configurations investigated

Using a common basic building geometry, 7 scenarios were defined as case studies where the changing parameters were the presence or not of a photovoltaic shading device (PVSD), its design configuration in terms of spacing between the louvre-blades and angles, the orientation of the building site and the window to wall ratio (Table *2*). The PVSD was modelled according to Taveres-Cachat et al. (2017). The conversion efficiency was assumed 15% after accounting for all the system losses, including self-shading and DC to AC conversion.

Table 2. Description of the scenarios investigated in the study

Case	Description
0	Base model with no shading system installed
1	Base model where all the south facing windows are equipped with an external shading system without PV coating. Inter-blade distance 132 mm, tilt angle 15°.
2	Base model where all the south facing windows are equipped with an external PVSD. Inter-blade distance 132 mm, tilt angle 15°.
3	Base model where all the south facing windows are equipped with an external PVSD. Inter-blade distance 111 mm, tilt angle 15°.
4	Base model where all the south facing windows are equipped with an external PVSD. Inter-blade distance 95 mm, tilt angle 0°.
5	Base model where all the south- and north facing windows are equipped with an external PVSD shading system. Inter-blade distance 132 mm, tilt angle 15°, WWR = 22%.
6	Case 1 with the building orientation changed by 90° and PVSD on east and west facing windows

Description of Solar Efficiency (SE) index

The models were first simulated in a theoretical context without solar radiation (neither direct nor diffuse), giving the hourly energy use $E_{0\ net}$ (kWh/m^2). The simulations were run a second time with solar radiation which yielded the energy use defined as $E_{sun\ net}$ (kWh/m^2).
These quantities were defined as follows:

$$E_{0\,net} = \int_{t1}^{t2} e_0(t)dt \quad (1)$$

$$E_{sun\,net} = \int_{t1}^{t2} \left(e_{sun}(t) - i(t)\right)\, dt \quad (2)$$

Where $e_{sun}(t)$ [W] and $e_0(t)$ [W] were respectively the electrical power demand required for heating, cooling and lighting for the building with and without the contribution of solar radiation at the instant t. $i(t)$ [W] was the amount of electric power being converted at the instant t.
The solar efficiency index was defined as:

$$SE_{index} = \frac{E_{0\,net} - E_{sun\,net}}{E_{0\,net}} \quad [-] \quad (3)$$

The solar efficiency index was calculated with hourly steps over the period of one year. Index values in the]0; 1] interval indicated that the building efficiently used solar radiation to lower its energy use compared to a situation with no solar radiation. An SE index value of one meant the building was completely self-sustaining (perfect load match) and any value above one meant excess energy was being sold back to the grid. An SE index value equal to zero implied that either no solar radiation was available, or the building was not able to use solar radiation to reduce its energy demand. Index values below zero indicated that the building had to use more energy to operate when there was solar radiation available than if there was not any.

RESULTS AND DISCUSSION

The SE index was calculated for all seven cases. The resulting SE index values are plotted as cumulated hourly frequency distributions to help visually assess the performance and identify both situations of under- and over energy production in Figure 1. Horizontal bars delimiting SE = 0 and SE = 1 highlight the different SE index value intervals. For all cases the SE index line crossed the lower threshold SE = 0 before the 0.15 marker, meaning that all configurations partially used solar energy to reduce energy use at least 85 % of the time. As anticipated, cases

0 and 1 performed the worst; crossing the lower threshold last and never yielding an SE index value above 0.7 because of the absence of energy conversion. Case 3 and 5 were seemingly the most efficient at using solar radiation with higher average SEs, but led to an energy surplus 15-20 % of the time. Cases 2 and 4 performed almost identically and provided the least conversion surplus. However, despite this, the values yielded were on average below those of other PVSD cases. Lastly, case 6 had satisfying SE index values with less energy surplus.

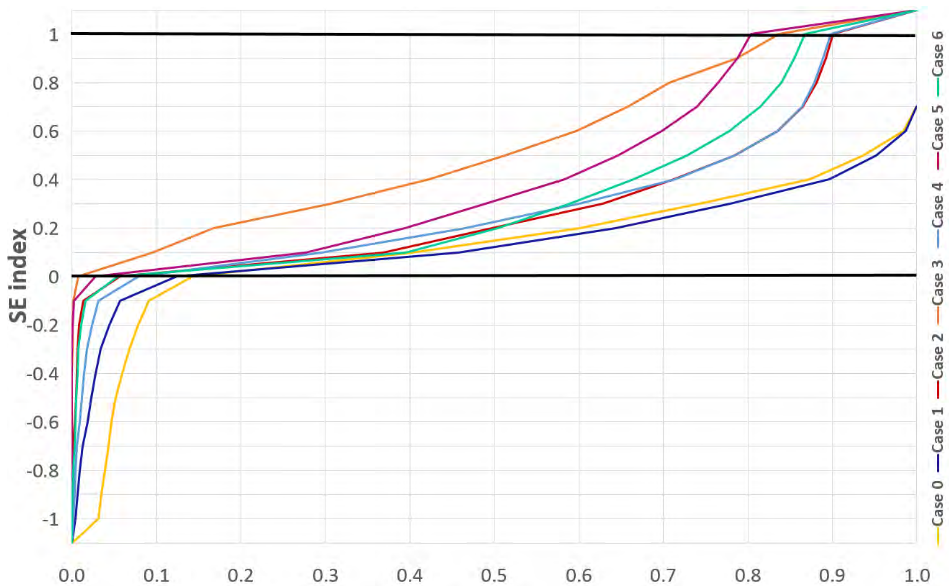
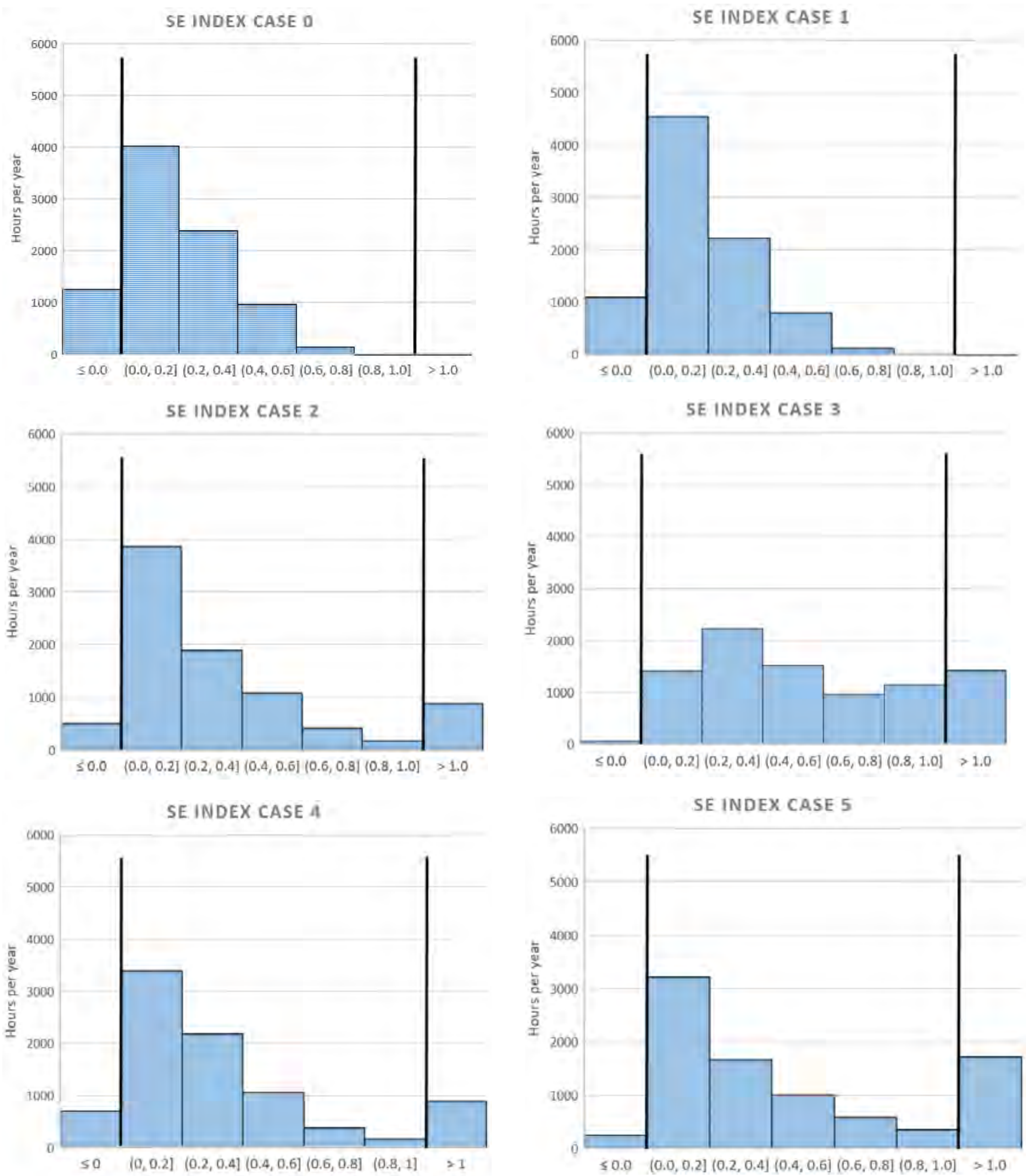
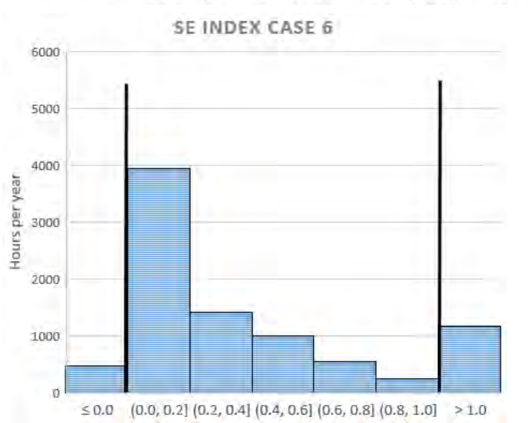


Figure 1 SE index for all cases as a cumulated frequency

The SE index results are analyzed further using the individual frequency distributions shown in Figure *2*. The comparison of cases 0 and 1 shows that the increase in energy use due to lower solar gains did not outweigh the benefits of a reduced cooling demand, despite the study being in a heating dominated climate. Moreover, the results for cases 2-6 highlight that adding PV conversion was immediately sufficient to reduce the number of hours with negative values. However in case 2, the introduction of PV conversion seemed to have mainly shifted hours from the SE < 0 to the SE > 1 bracket. This occurred without significantly improving the rest of the hourly distribution when compared to case 1; suggesting that the energy converted was most often insufficient to cover the building load. Similarly, only small improvements were achieved in case 4, as the increase in energy use due to reduced solar gains counteracted the benefits of the additional PV material. Case 5 benefited from increased PV capacity and daylight availability thanks to a higher WWR. It yielded a relatively better SE index than the base cases but had the largest amount of hours with energy conversion surplus. Case 6 provided good SE index values, but showed that east and west facing PVSDS configurations are unlikely to be competitive with south facing systems at equal number of equipped windows. Finally, as previously suggested, case 3 which was an intermediate configuration in terms of louver-blade count, achieved the best performance with the highest mean SE index value for a WWR = 14%, and the most hours in the $0.6 \leq SE \leq 1$ range.

These findings supported the conclusion that the relationship between higher SEs and increased amounts of PV installed is not a linear. Thus, adding more PV material in the shading system using a larger count of blades was beneficial up to a certain point, beyond which the benefits of additional PV conversion no longer outweighed the additional energy use due to low solar gains.





Case	SE mean	Standard deviation
0	0.1	0.4
1	0.1	0.2
2	0.5	0.9
3	0.8	1.2
4	0.4	0.9
5	1.1	2.6
6	0.7	1.9

Figure 2 SE index values plotted as frequency distributions for each case.

CONCLUSION

The SE index was used to evaluate seven different design configurations of a building with PVSD through a parametric analysis. The SE index was successfully able to capture the differences between the cases investigated, and highlighted the most promising configuration. This scenario corresponds to the best balance between increased PV conversion and solar gains reduction, without raising significantly energy use for heating and lighting. Other parameters that could influence SE index results are the load profile of the building (energy use timing), and the total energy use for the building. Refining the index with smaller value intervals might also be useful in some cases, because two scenarios may perform very similarly in reality but may not appear to do so in the result visualization depending on how the thresholds are set. Plotting the cumulated frequency is therefore an important first step. Overall, the SE index is proposed as a simple approach to help communicate and compare the benefits of implementing different solar RESs aiming to increase energy autonomy. SE index results can be improved with control strategies in the building envelope or if integrated energy storage solutions are implemented. The SE index can also be combined with other existing load matching indicators as well as life cycle cost analysis to obtain a holistic view of the building's performance.

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