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Thermal, energy and life-cycle aspects of a transparent insulation façade: a case study

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Abstract. Research and development in the façade engineering field highlights the need for comprehensive system solutions integrating advanced materials and renewable energy use. Presented study focuses on implementation of Transparent Insulation Materials (TIMs) in a façade concept. The idea is based on sensible use of (renewable) solar energy to reduce the heating demand of buildings. The concept integrates TIMs into a Transparent Insulation Façade (TIF) based on more common "solar wall" or "Trombe wall" systems enhanced with selective absorber (SA) functionalities. The study presents analysis of thermal, solar energy and environmental performance of the concept on a case study basis. Firstly, thermal analysis based on standard calculation is introduced to describe thermal and solar performance of the concepts. Secondly, energy balance calculations are used to compare the concepts with conventional façade systems. Finally, a Life-Cycle Assessment (LCA) evaluating the environmental impacts of the façade concept is introduced. The results show that the proposed concept performs better in both energy consumption and environmental impacts compared to a common facade with external thermal insulation. The TIF has higher heating energy demand than a common façade, however this is offset by up to 178 kWh·m⁻²·a⁻¹ solar heat gains. The difference in environmental impacts (up to 80%) is also in favour of the TIF.

1. Introduction

Many contemporary buildings are constructed using combination of a load-bearing frame with prefabricated façade panels. The disadvantage of common façade panels is their focus on only some of the physical parameters (e.g. lighting, shading, thermal insulation, acoustics, fire protection, and moisture handling), and limited (if any) integration of renewable energy sources. That is why multifunctional [1, 2] and adaptive façade systems [3, 4] are designed to be incorporated in next generation of façade designs. Their advantage is especially higher utilization of renewable energy (e.g. passive solar gains, photovoltaics or hybrid-technologies). Research results suggest that switch to adaptable and dynamic building envelopes could improve building energy efficiency and indoor climate, [5]. Recently, a wide range of novel façade solutions directly utilizing the potential of solar energy gains has been described. However, there are still barriers (e.g. efficiency concerns) to overcome in order to promote widespread application of façade-integrated solar components [6]. Nevertheless, development and evaluation of different technical solutions and integration of new progressive materials in building facades is highly relevant issue.

Novel multifunctional façade concept evaluated in this paper integrates well-known solar wall principles [9] with modern transparent insulation material (TIM) and two different solar absorbers (with different emissivity). The reason for the integration is better thermal and energy performance,



which in turn reduces environmental impacts of a building in question. Previously, the integration of TIMs has been predominantly analyzed in solar thermal collectors [10]. However, the utilization of TIMs as a way for improving thermal parameters of other structures, i.a. walls has been also pursued [7]. Recent research and development even combines TIMs with active renewable energy generation, e.g. integrated photovoltaic cells [8].

This paper presents thermal, solar energy and environmental aspects of a transparent insulation façade (TIF) concept in the mild climate of Czechia in the middle of Europe. It also provides comparison with a common façade with external thermal insulation system (ETICS) to demonstrate key specifics of TIF application; e.g. need for protection against overheating.

2. Materials and methods

Thermal and energy parameters as well as environmental impacts of the façade assemblies are calculated using standard calculation methods described in following sub-sections.

2.1. Transparent insulation façade parameters

Two similar TIF assemblies represent the proposed façade concept in the paper. The assemblies differ in the applied solar absorbers: first has a selective absorber (SA) with low-e coating, while the second has a non-selective absorber (nSA) with high emissivity level. The load-bearing base structure for the TIF is made of 200mm concrete wall (with plaster finish in the interior) for the purpose of this paper. It serves as a load-bearing element and also provides thermal mass. The performance of both TIF assemblies is compared with performance of three reference case models comprising of the same concrete wall and ETICS with 80mm (RC1), 180mm (RC2) and 280mm (RC3) utilizing mineral wool insulation on the exterior side. Mineral wool was selected for the purpose of this comparison as it is applicable in most building types (from small detached houses to large office buildings) in Czechia. RC1 corresponds with recent Czech building practice, while RC2 and RC3 correspond with current and future energy efficiency targets in the EU following e.g. Directive 2010/31/EU [11]. The evaluated TIF concept utilizes commercially available TIM Kapilux TWD, which comprises of transparent honeycomb plastics (PMMA) enclosed with glazing and the structure is filled with krypton gas. There is an air cavity between the TIM component and concrete wall with installed SA or nSA solar absorber respectively. Figure 1 shows the TIF concept incorporated in a wooden frame for the purpose of ongoing experimental research. The figure illustrates materials and geometry of the concept. Calculations presented in this paper do not take into account the frame used in authors' previous work [12]. Total size of the evaluated models is 1.19 x 1.19m with 1.15 x 1.05m size of the TIM panel.

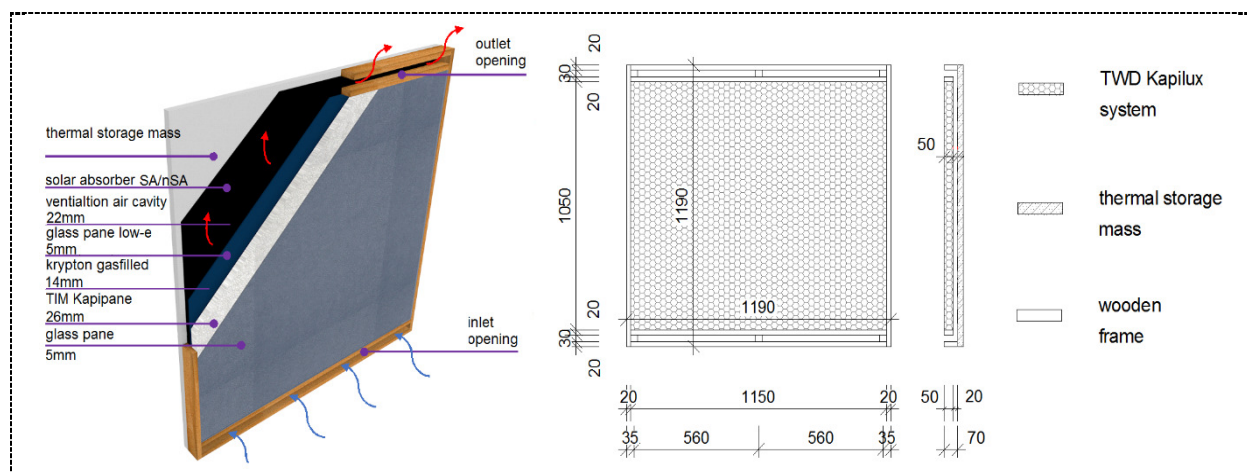


Figure 1. Experimental transparent insulation façade (TIF) model using two types of absorber, selective (SA) and non-selective (nSA) absorber [12], geometrical parameters, material specification.

The TWD has thermal transmittance U_{TWD} $0.7 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$, which corresponds to R_{TWD} $1.26 \text{ m}^2\cdot\text{K}\cdot\text{W}^{-1}$. Normal incidence and diffuse total solar energy transmittance or solar heat gain coefficients $g_{t,\perp}$ and $g_{t,h}$ are 58% and 46% respectively. Light transmissions τ_{\perp} and τ_{h} are 70% and 51% respectively.

2.2. Thermal and solar calculations

This sub-section presents the main aspects of the standard calculations employed to model performance of the presented TIF assemblies as well as the reference case assemblies. The energy performance of the evaluated assemblies is calculated using monthly average data. The performance of the TIF assemblies is calculated for different cardinal orientations.

2.2.1. Thermal performance.

Generally, the simplified procedure for the thermal performance characterization is to use the standard calculation method. Thermal resistance of a facade (or any other structure) is calculated as the sum of the thermal resistance of all solid layers R_s and thermal resistance of the airspaces R_g . One of the key variables in determination of the thermal resistance of the unventilated airspaces R_g is the emissivity of its both parallel surfaces. For the purpose of the R_g calculations the airspace is considered as an infinite number of parallel planes consisting of the radiative heat transfer (h_r) and the heat transmittance through the air by convection and conduction (h_a) according to the empirical equation given in ISO 6946 [13].

2.2.2. Solar heat gain.

Commonly, solar heat gains are understood as the solar energy passively absorbed by a building through transparent surfaces (e.g. windows). If this happens during the heating season, less energy is needed for heating. The amount of energy that can be obtained in this way can be calculated as a sum of the solar radiation intensity incident on the effective collector surface. Influencing factors include shading elements or the g -value of the transparent material (e.g. glass). Opaque (non-transparent) building elements such as envelope walls or roofs absorb solar energy as well. Simplified characteristic values for the calculation of solar heat gains of opaque elements are defined in ISO 52016-1 [14]. However these opaque solar heat gains normally play almost no role in the energy balance of the building. Here the solar heat gains through opaque elements can be calculated. Solar heat gain Q_{sol} is the amount of heat generated by the solar irradiance for opaque building part and is the sum of solar heat gains during the considered month or season with the time-average heat flow rate from solar heat source $\Phi_{sol,k}$ over the length of the considered period (daily, monthly, seasonally or annually). The heat flow generated by solar gains is calculated using the relation based on the effective solar collecting area of an opaque part of the building.

TIFs are a special type of opaque element. Integration of TIM to a façade allows the incident solar radiation transfer to the absorbing layer (SA or nSA in this study) and thus leads to increased internal wall temperature. Therefore, the effective collecting area for any orientation j and month m can be calculated in accordance to the relation (1) and the heat transfer coefficients of considered layers are needed for the calculations.

$$A_{s,j,m} = A \cdot F_S \cdot F_F \cdot \frac{U}{U_t} \cdot g_{t,j,m} \quad (1)$$

Combining with the effective collecting area of surface defined in ISO 52016-1 [14], a radiation absorption degree of a TIF can be determined as heat generated by the solar incident radiation on the opaque building element using a solar absorption coefficient of its opaque part $\alpha_{s,c}$ (2). This parameter can be directly used in (1) for calculation of the total solar heat gain of an opaque element.

$$\alpha_{s,c} = F_S \cdot F_F \cdot \frac{R_{se} + R_t + R_g}{R_{se}} \cdot g_{t,j,m} \quad (2)$$

R_{se} corresponds to the external surface heat resistance, R_t is the thermal resistance of TIM, R_g corresponds to the thermal resistance of air gap between the TIM and the opaque element. A variable parameter in relation (2) is the effective total solar energy transmittance of the transparent insulation product $g_{t,j,m}$ for any orientation j and month m in accordance to the relations (3). For the TIM with negligible solar transmittance (e.g. with a solar absorber directly integrated) the value shall only be modified to take account of the thermal resistance R_g of the air gap between the transparent insulation and the opaque element in terms of first equation. For a product with non-negligible solar energy transmittance, that is case of presented TIFs in terms of the second, the effective value is proportional to the absorptance of the opaque element behind transparent insulation:

$$g_{t,j,m} = \frac{R_{se}+R_t}{R_{se}+R_t+R_g} \cdot (g_{t,h} - c_{j,m} \cdot g_{t,\perp}) \quad \text{and} \quad g_{t,j,m} = \alpha \cdot (g_{t,h} - c_{j,m} \cdot g_{t,\perp}) \quad (3)$$

In equations (4) the calculation of the effective total solar energy transmittance depends on the type of the TIM taking the angle of incidence of direct solar radiation into account with the coefficients $c_{j,m}$. It considers extra heat flow due to thermal radiation to the sky from building element k , in accordance to the tabular values given in [14].

2.3. Life-Cycle Assessment

The environmental impacts of both TIF assemblies were calculated using Life-Cycle Assessment (LCA) framework defined in ISO 14040 [15], EN 15978 [16] and other concerned standards. The EN 15978 standard divides life cycle of a building element into four stages (Product stage, Construction process stage, Use stage and End of life stage), which are further divided into 16 modules. The assessment presented in this paper includes environmental impacts in all modules of the Product stage (A1-A3). Only materials necessary to produce the assemblies described in sub-section 2.1 are assessed in these modules. Any HVAC or other equipment are considered out of scope of this LCA. Construction process stage is represented by module A4 (Transport). Use stage is represented by modules B4 (Replacement) and B6 (Operational energy use). B4 stage includes only environmental impacts related with material production, their transport and final disposal. B6 stage covers heating energy demand based on heat losses of the façade assemblies (see sub-section 3.3). This should represent the difference in performance of common ETICS (reduction of heat losses) and TIF (utilization of energy gains). In case of TIF assemblies the solar heat gains are simply deduced from the heat losses to represent the total heating energy demand for the purpose of the presented LCA. Cooling energy needs are not considered, because these could be reduced with e.g. external shading system. End of life stage is represented by modules C2 (Transport) and C4 (Disposal). Landfilling is considered as the waste disposal scenario. It should represent a worst-case scenario with no reuse of the in-built materials. Moreover it is still a common waste treatment scenario (although receding) in Czechia [17]. Other modules are omitted, because it is expected that there will be none or negligible environmental impacts related with them.

The declared unit used for calculations and presentation of the environmental impacts is 1m^2 of the TIF or reference ETICS façade assemblies. The assessment covers a 50-year service life of the assemblies. This is a common design service life in Czechia. For the purpose of the assessment it is estimated that only the concrete load-bearing part of the wall would endure whole 50-year service life. It is assumed that all other materials would have to be replaced once (after approx. 25 years) due to lower durability.

The LCA is performed in GaBi software tool. Environmental impacts are calculated using CML2001 characterization model in version Nov. 10 (also known as v. 3.9). Normalization CML2001 EU 25+3 is applied for simplified presentation of the results due to space limitations in this paper. Ecoinvent 2.0 database was used as the source of data about environmental impacts of materials used in all assessed assemblies. Even though it is one of the largest databases, several simplifications are necessary during the LCA: i) There is no single process representing TIM in the database. Therefore it

is modelled using a combination of processes *RER: polycarbonate, at plant* and *RER: extrusion, plastic film* (honeycomb PMMA), *RER: flat glass, uncoated, at plant* representing (glass casing) and *RER: krypton, gaseous, at plant* (gaseous filling); ii) There is also no single process representing the selective solar absorber. Therefore it is modelled as a combination of processes *RER: aluminium, primary, at plant* (base material), *RER: sheet rolling, aluminium* (processing) and *SK: selective coating, aluminium sheet, nickel pigmented aluminium oxide* (coating); iii) Transport of raw materials and incomplete products during Product stage (especially module A2) is included in individual ecoinvent processes. A4 and C2 (partially also B4) modules describe transport of final products and wastes respectively. For the purpose of the assessment it is assumed that the materials and wastes are transported on road with a truck or lorry. This is represented by process *RER: transport, lorry 3.5-16t, fleet average*. The transport distances used in the assessment represent the distance between individual production facilities and Brno, Czech Republic. The distances vary between 4.8km (concrete) and 536km (TIM); iv) Electric energy in process *CZ: Electricity - low voltage, at grid* represents the energy consumed to cover heat losses of evaluated façade assemblies. The reason is that electricity is the most common heating energy source in Czechia, [18].

3. Result analysis

The thermal performance and the total solar heat gain of an opaque transparent insulation façade element were calculated for all cases as well as cardinal orientations respectively. Finally, a comparative thermal and solar energy performance is summarized to provide an overall efficiency.

3.1. Thermal performance

The following thermal transmittances according to the fundamental calculations given in Section 2 are calculated for the efficiency factor to be considered. Table 2 presents thermal characterization of two TIF concepts with (SA) and without a selective absorber (nSA) with three base case models of a conventional type. Thermal resistance R_{te} and transmittance U_{te} are calculated for solar effective layers prior to the solar absorbers.

Table 1. Thermal resistance and transmittance for individual layer and whole concepts.

| $m^2 \cdot K \cdot W^{-1}$ | R_t | R_g | R_i | R_{te} | R_c | U_c | U_{te} |
|----------------------------|-------|-------|-------|----------|-------|-------|----------|
| nSA | 1.26 | 0.18 | 0.126 | 1.48 | 1.736 | 0.58 | 0.67 |
| SA | 1.26 | 0.57 | 0.126 | 1.87 | 2.126 | 0.47 | 0.53 |
| RC1 | 2.00 | n/a | 0.126 | n/a | 2.296 | 0.44 | n/a |
| RC2 | 4.50 | n/a | 0.126 | n/a | 4.796 | 0.21 | n/a |
| RC3 | 7.00 | n/a | 0.126 | n/a | 7.296 | 0.14 | n/a |

Table 2. The monthly energy need for heating and cooling of the assessed facade assemblies in kWh.

| | Jan. | Feb. | Mar. | Apr. | May | June | Jul. | Aug. | Sept. | Oct. | Nov. | Dec. | H | C |
|---------------|----------------|-------|------|------|----------------|------|------|------|-------|----------------|------|-------|-------|------|
| [kWh] | Heating period | | | | Cooling period | | | | | Heating period | | | kWh | |
| θ_e °C | -1.8 | 0.4 | 4.6 | 9.9 | 14.9 | 17.9 | 19.6 | 19.2 | 15.2 | 9.8 | 4.3 | -0.3 | 3.86 | 17.4 |
| nSA | 12.89 | 11.59 | 9.11 | 5.97 | 3.02 | 1.24 | 0.24 | 0.47 | 2.84 | 6.03 | 9.28 | 12.00 | 66.88 | 7.81 |
| SA | 10.45 | 9.39 | 7.38 | 4.84 | 2.44 | 1.01 | 0.19 | 0.38 | 2.30 | 4.89 | 7.52 | 9.73 | 54.20 | 6.33 |
| RC1 | 9.78 | 8.79 | 6.91 | 4.53 | 2.29 | 0.94 | 0.18 | 0.36 | 2.15 | 4.58 | 7.04 | 9.11 | 50.74 | 5.92 |
| RC2 | 4.67 | 4.20 | 3.30 | 2.16 | 1.09 | 0.45 | 0.09 | 0.17 | 1.03 | 2.18 | 3.36 | 4.35 | 24.22 | 2.83 |
| RC3 | 3.11 | 2.80 | 2.20 | 1.44 | 0.73 | 0.30 | 0.06 | 0.11 | 0.69 | 1.46 | 2.24 | 2.90 | 16.14 | 1.88 |

As can be seen, the U -value of RC1 corresponds to the thermal performance of the TIF with SA. TIF with nSA has U -value 64% worse than RC2 (representing current thermal performance targets), while

the TIF with SA had U -value 55% worse. The difference between the TIFs is up to 18% due to different solar absorbers. This is specifically caused by low emissivity function of selective absorber. Thermal parameters described in Table 2 are used for calculation of the monthly need for heat values shown in Table 3, which is interpreted as seasonal heating requirements in Figure 2. The values could be used also for calculation of cooling energy need. Unsurprisingly, the obtained values reach the same percentage difference as thermal characterization of all considered models.

3.2. Solar energy performance

Table 4 presents solar heat gain characterization of both TIF assemblies using monthly and seasonal approach. The solar heat gains are presented for Southern (S), South-Eastern/Western (SE/SW), Eastern/Western, North-Eastern/Western (NE/NW) and Northern (N) orientation of the façade. Solar heat gains of reference models are negligible, therefore their results are not presented.

Table 3. Monthly and seasonal solar heat gains for both TIF assemblies (SA and nSA) in kWh.

| | j | Jan. | Feb. | Mar. | Apr. | May | June | Jul. | Aug. | Sept. | Oct. | Nov. | Dec. | H | C |
|-------|---------|---------|-------|-------|-------|---------|-------|-------|-------|-------|---------|-------|-------|--------|--------|
| [kWh] | | Heating | | | | Cooling | | | | | Heating | | | | |
| nSA | S | 10.63 | 14.95 | 20.14 | 20.08 | 27.05 | 25.35 | 25.63 | 28.42 | 30.59 | 19.52 | 11.55 | 9.95 | 106.82 | 137.05 |
| SA | | 11.03 | 15.45 | 20.76 | 20.70 | 27.84 | 26.10 | 26.39 | 29.24 | 31.47 | 20.13 | 11.97 | 10.34 | 110.38 | 141.05 |
| nSA | SE/SW | 7.15 | 10.88 | 16.36 | 19.77 | 31.75 | 30.71 | 31.16 | 31.87 | 29.50 | 14.60 | 7.91 | 6.43 | 83.08 | 154.99 |
| SA | | 7.46 | 11.28 | 16.90 | 20.38 | 32.65 | 31.59 | 32.05 | 32.77 | 30.35 | 15.09 | 8.24 | 6.72 | 86.08 | 159.41 |
| nSA | E/W | 3.91 | 7.09 | 12.93 | 19.15 | 31.19 | 32.33 | 32.00 | 29.10 | 21.56 | 9.65 | 4.10 | 2.97 | 59.80 | 146.19 |
| SA | | 4.15 | 7.40 | 13.38 | 19.76 | 32.08 | 33.24 | 32.91 | 29.94 | 22.22 | 10.02 | 4.34 | 3.18 | 62.23 | 150.40 |
| nSA | NE/NW | 2.69 | 4.59 | 8.00 | 12.55 | 22.65 | 25.20 | 24.07 | 19.55 | 12.44 | 5.27 | 2.48 | 1.77 | 37.36 | 103.90 |
| SA | | 2.90 | 4.85 | 8.34 | 13.00 | 23.33 | 25.95 | 24.78 | 20.16 | 12.88 | 5.54 | 2.69 | 1.96 | 39.26 | 107.11 |
| nSA | N | 2.33 | 3.89 | 5.97 | 8.19 | 15.54 | 17.14 | 15.95 | 13.88 | 9.31 | 4.12 | 2.10 | 1.57 | 28.17 | 71.81 |
| SA | | 2.53 | 4.12 | 6.26 | 8.53 | 16.06 | 17.70 | 16.47 | 14.35 | 9.67 | 4.36 | 2.30 | 1.75 | 29.85 | 74.25 |

3.3. Comparative thermal and solar energy analysis

Figure 2 shows a comparison of energy demands of all evaluated façade assemblies (Figure 2a) and the total solar heat gain of transparent insulation façade concepts exposed to different orientations (Figure 2b). It shows that TIF assemblies have up to 64% and 76% higher heating energy requirements. However this is offset by significant solar heat gains (see Figure 2b). It also shows that difference between SA and nSA is only approx. 3% for both heating and cooling periods.

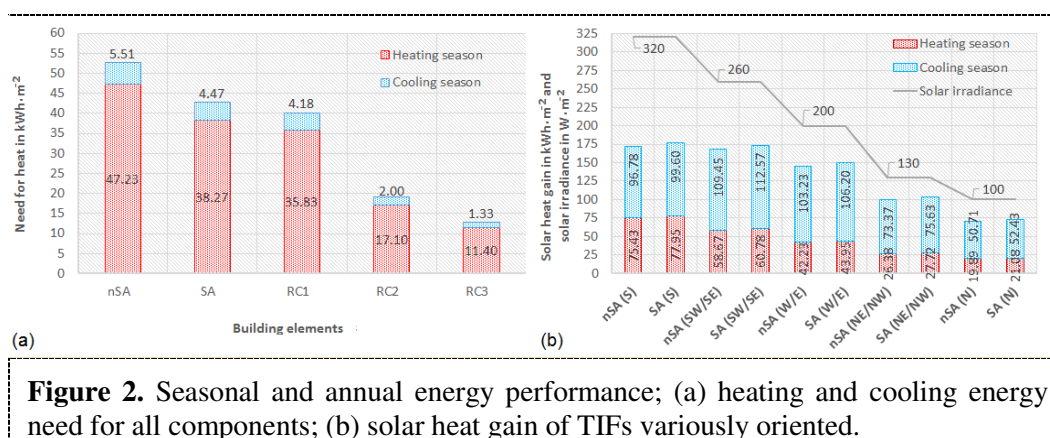
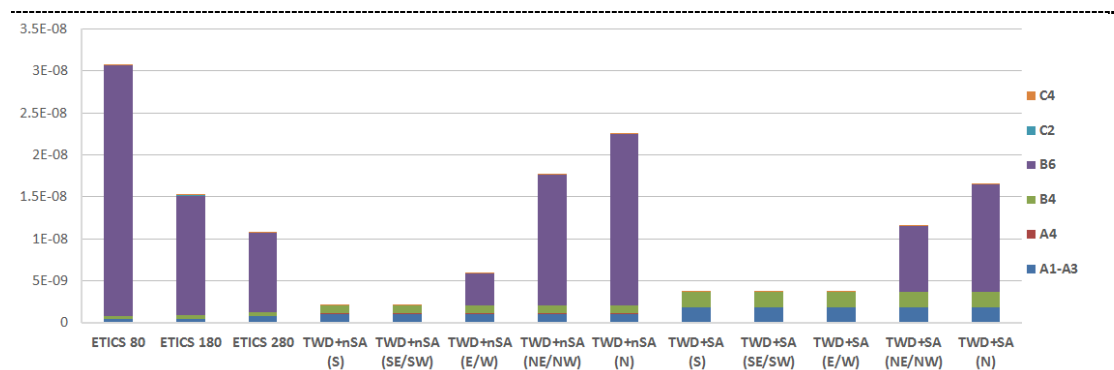
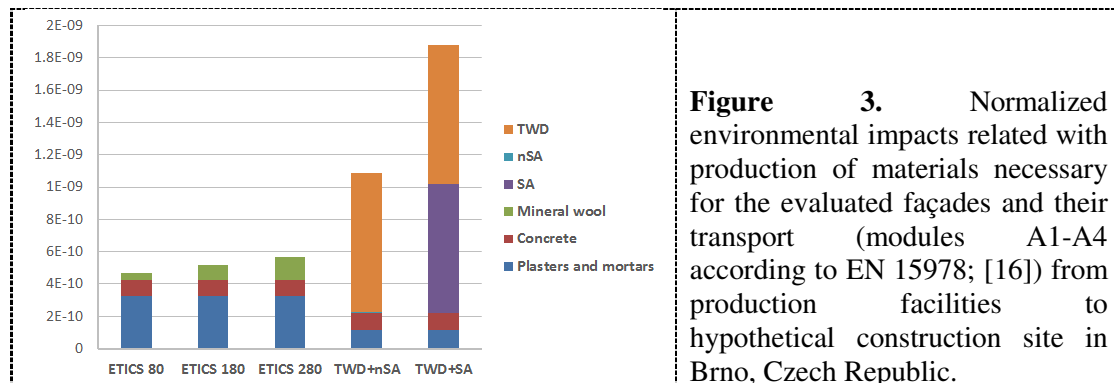


Figure 2. Seasonal and annual energy performance; (a) heating and cooling energy need for all components; (b) solar heat gain of TIFs variously oriented.

3.4. Environmental impact analysis

LCA was performed following the boundary conditions defined in sub-section 2.3. Normalized results of the LCA are presented in Figures 3 and 4. Figure 3 shows that under these boundary conditions the

environmental impacts related with materials used for the proposed TIF concepts are much higher than environmental impacts of a common ETICS façade. This is due to high environmental impacts related with the modelled TIM and solar absorbers. However this is outweighed by the energy performance of these façade concepts during the modeled 50-year service life. Figure 4 shows that integration of TIFs on façades facing in general Southern direction (East-South-West) brings between 65 and 80% lower total environmental impacts (under specified boundary conditions) compared even to the thickest evaluated ETICS façade. It should be highlighted that the level of difference is significantly influenced by specified climate conditions and heating energy source.



4. Conclusion

Presented paper compares two variants of a newly developed TIF concept with three reference case façade assemblies utilizing common ETICS. Thermal, solar energy and environmental aspects were evaluated. Based on the calculated thermal performance it is possible to say that the TIF with SA has the biggest potential to replace conventional façades with ETICS. This statement could seem on the contrary to the calculated heat losses. It is true that the developed TIF concept with SA does not meet even contemporary heat loss requirements (U-value). However, this is offset by utilization of significant solar heat gains. Contemporary opaque facades have negligible solar heat gains, while the proposed TIF concept has theoretical solar heat gains up to $178 \text{ kWh}\cdot\text{m}^{-2}\cdot\text{a}^{-1}$. TIF concept with nSA has shown 18% worse thermal performance and 3% higher solar heat gains compared to TIF with SA. From the environmental point of view, it can be said that the proposed TIF concept is an effective solution for reduction of heating energy demand in buildings (in mild Czech climate). The LCA results show that higher environmental impacts related with the production of materials are more than offset by the heat gains through the structure. The biggest limitation of the performed LCA is the fact that

shading devices or a cooling system were not considered. Incorporation of such systems is the aim of the future research.

Acknowledgments

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