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Exploring the potential of combining diffuse ceiling and double-skin facade for school renovations

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ABSTRACT

With the aim to offer an alternative renovation concept for schools and thus contribute to a better indoor environmental quality and reduced energy consumption, a system combining diffuse ceiling and double-skin facade with an existing exhaust ventilation (I-DIFFER) was proposed in a previous work by the authors. The initial analyses of the novel system were promising, showing a potential 11 % reduction in primary energy consumption compared to a traditional renovation where the facade was insulated, windows were replaced and a balanced ventilation system was installed. Consequently, this work further investigates the performance of I-DIFFER under different boundary conditions using BPS. The influence of orientation, thermal mass and reflectance of the existing classroom facade, future climate change, extreme weather conditions, and varying occupant densities are studied. The results show that I-DIFFER can compete with the traditional renovation approach for all investigated orientations but north and leads to superior results for southern orientations (SE, S, SW). It was found that a high thermal mass facade with low reflectance is favourable for the classroom facade. For forecasted future climate conditions and climates with mild winters and mild to hot summers, I-DIFFER showed superior results compared to the traditional renovation. An equal performance was seen for a varying occupant density. With this study, I-DIFFER can be confirmed as a competitive alternative to a traditional renovation and thus contributes to improving not only the energy efficiency but also the IEQ of schools.

1. Introduction

The building sector of the European Union (EU) contributes today with 40% to the total energy consumption and is responsible for 36% of the energy-related greenhouse gas emissions [1]. In light of the recently announced “2030 Climate Target Plan” of the EU, which increases the EU’s ambition to reduce greenhouse gas emissions, the need for the building sector to act becomes evident. Consequently, the existing building stock comes to the fore, as 85% to 95% of today’s buildings, of which 85% were built before 2001, will still be used in 2050 [1]. Therefore, renovations become an essential tool to achieve future climate targets. Despite this importance, the energy renovation rate remains at a low of about 1% [1]. Thus, the need to increase this low retrofitting rate is apparent if the decarbonisation of the EU is to succeed. In Denmark, there are 1989 schools [2], of which more than 80% were built before 1982 [3], and a large share of these buildings still require refurbishment [4]. Thereby schools can play a vital role for two reasons. They can initiate an experience and knowledge transfer via the pupils to their parents if pupils perceive the positive effect of “good” renovation approaches in their schools [5]. Moreover, it is well known that schools’ indoor environmental quality (IEQ) directly affects pupils’ performance [6–9] and health/well-being [10,11]. Not only the well-being of students but also from teachers can be adversely affected by the IEQ [12]. Despite this knowledge, past studies have shown that a significant share of classrooms in Denmark have an unsatisfactory

Abbreviations: ACH, air change rate per hour (h^{-1}); BPS, building performance simulation; CW, calendar week; DCV, diffuse ceiling ventilation; DSF, double skin facade; E_{ref}, energy balance for windows calculated according to §258 of BR18 [41] (kW/m^2); g, solar factor; HY, hysteresis; I-DIFFER, Integrated Solution-Double Skin Facade and Diffuse Ceiling Ventilation for School Renovation; IAQ, indoor air quality; IEQ, indoor environmental quality; n, number of simulations; ORM_{30}, outdoor running mean temperature over the last 30 days excluding the current day; PE, primary energy; SFP, specific fan power ($kW/(m^3\,s)$); T_{air}, air temperature (°C); T_c, thermal neutral temperature (°C); T_{ext}, external air temperature (°C); T_{op}, operative temperature (°C); I_{sun}, solar irradiation on facade (W/m^2); U_f, U-value window frame ($W/(m^2\,K)$); U_g, U-value window glazing ($W/(m^2\,K)$); VAV, variable air volume; λ, thermal conductivity ($W/(m\,K)$); τ, visible light transmittance

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IEQ, [13–15] which agrees with findings from researchers in other countries [16,17]. Further, it could be shown that this decrease in performance due to insufficient IEQ leads to considerable negative socio-economic consequences [18].

In 2020, the Danish government announced an increase in investments in the building sector to renovate schools and nursing homes and carry out energy renovations [19]. This initiative is followed by the Danish building industry, which has developed a guide to ensure good indoor environmental quality in schools to avoid a narrow-minded target of the energy frame as a sole goal in school renovations [3].

Given these points, the need for school renovations is undeniable, and the financing is also given. Yet, the renovation rate of the school buildings is still behind, and the uptake is yet to come. When it does, the building industry and the public sector stand weak with few renovation alternatives on the market, which in general terms include full or partial insulation/replacement of the building envelope, installation of balanced mechanical ventilation, installation of solar-shading devices, and acoustic panels, renovation/replacement of the heating and lighting systems [20–22]. Often these actions impose specific problems such as the disturbance of school life through noise and debris, the high space demand for ventilation system ducts [23], and limitations in the use of the external shading devices due to e.g., high wind velocities.

In our recent work [24], we proposed a solution to overcome several of these limitations, I-DIFFER (Integrated Solution - Double Skin Facade and Diffuse Ceiling Ventilation for School Renovation), which combines a Double Skin Facade (DSF) with a Diffuse Ceiling Ventilation (DCV) and utilises the exhaust ventilation system which is currently used in every fifth Danish school building [14]. A short description of the I-DIFFER system is provided in the following section (Section 2.1.2). Previously, we demonstrated through building performance simulation (BPS) that I-DIFFER can archive a lower primary energy (PE) consumption (by 11%) compared to a traditional renovation for a south-facing classroom while providing a satisfying IEQ [24].

While the principal feasibility of the system was demonstrated, its performance under deviating boundary conditions remains unknown. For this reason, this work studies the effect of the classroom orientation, classroom facade material, extreme and future weather conditions, and occupant density to obtain more in-depth knowledge about the performance of I-DIFFER.

The first aspect, the building/classroom orientation, is naturally highly influential as the intensity and angle of solar irradiation changes. This was confirmed by recent research [25–28] which studied the performance of DSFs for various orientations. Experimental investigations further showed that solar irradiation highly influences naturally ventilated DSFs, which supports the importance of orientation [29–31]. Thus, while existing literature highlights the importance of the orientation, it also shows that the optimal orientation is case-specific and dependent on, for example, the internal loads, heating-to-cooling demand ratio and climate. For this reason, it was decided to investigate I-DIFFER's performance for eight cardinal directions (N, NE, E, SE, S, SW, W, and NW).

The classroom facade material was chosen as it is expected that this is likely to vary between different existing school buildings. The effect of the inner facade material is not well studied for DSFs, but the sparse existing literature confirms that a high thermal mass in warm climates can reduce the cooling demand [25]. Investigating the effect of phase change material (PCM) in shading blinds in DSF, it was demonstrated that PCM which has high thermal inertia, decreases and stabilises the DSF cavity temperature [32,33]. Thus, overall confirming the general idea that high thermal mass within the DSF can reduce possible cooling.

However, as our previous study of I-DIFFER [24] showed that the energy demand for heating is more significant than the one for ventilation, it remains unknown if a low thermal mass could be beneficial for I-DIFFER in winter to reduce the heating demand. Similarly, the reflectance/colour of the facade could influence the performance. Consequently, it was decided to study both the influence of thermal mass and the reflectivity of the classroom facade material.

Independent of the system are the aleatory uncertainties related to the operation of the building and the outdoor environment. Reduction of this kind of uncertainty is impossible as occupant patterns or future weather cannot be predicted with certainty. Still, it can be better classified by conducting more investigations [34]. Weather, with its fast-changing nature, is highly unpredictable and can thus significantly influence the energy consumption of a building [34]. Systems like I-DIFFER, whose performance depends on the weather conditions, have, therefore, the potential to perform differently than initially anticipated.

Thereby in the context of climate change, recent works have shown the importance of considering both the general effect of climate change and the increased frequency and intensity of extreme weather events, as otherwise, the energy demand and the IEQ can be greatly miss-predicted [35–37]. Thus, highlighting the need to not only rely on weather files, such as typical meteorological year (TMY) or design reference year (DRY), which due to their averaging nature, lead to an underprediction of extreme weather conditions. Based on this, it was decided to investigate the future climate's influence and further analyse the systems' performance during extreme weather conditions.

The second investigated aleatory uncertainty is the classroom occupancy density [34]. Even though classroom schedules seem repetitive and predictable as school hours and holidays are known, occupant density varies between classrooms and schools and between different regions, e.g., city and countryside. In Denmark, for example, the number of students per classroom varies between public and private schools or primary and secondary schools [38]. The change in occupancy load is expected to have a significant influence on heating as well as ventilation consumption. Thereby it is anticipated that the heating consumption increases with decreasing occupant density, whereas the ventilation energy decreases with decreasing occupant density. For an increasing occupant density, the opposite is expected. Taking this into account, this paper investigates five different occupant densities from 17 to 25 people per classroom.

Thus, this work aims to provide more knowledge on how I-DIFFER performs under varying conditions. Such knowledge can be vital for the real-life application of the concept to assess for which cases the system is suitable, and what variation can be expected. Additionally, the results obtained from the analyses can provide general insight into the performance of a DSF for varying orientations, and thermal masses, reflectance properties of the inner façade, particularly for the latter two where existing literature is scarce.

2. Methodology

This work focuses on five main aspects: the influence of the orientation and the classroom facade material on I-DIFFER's performance, the effect of future and extreme conditions and at last the influence of varying occupant density. As in our previous work on I-DIFFER [24], BPS (IDA-ICE 4.8 SP2 [39]) is used. In order to assess the performance of I-DIFFER under the varying condition a case study classroom is used, and the results are compared against a traditional/conventional renovation. In the following, first the case study classroom, the traditional renovation and the renovation using I-DIFFER is first briefly outlined before the used BPS model, the evaluation criteria, and the studied parameters are presented.

2.1. Case study

The used case study classroom is based upon the one used in Bugenings et al. [24]. It is a typical classroom ($8\,\text{m} \times 6.25\,\text{m} = 50\,\text{m}^2$) for a Danish one-storey school building from the 1960s with an attached hallway (Fig. 1). The classroom has a window to floor ratio of 0.25, is equipped with an exhaust ventilation system and 20 students and 1 teacher are assumed as normal occupancy. Deviating from Bugenings

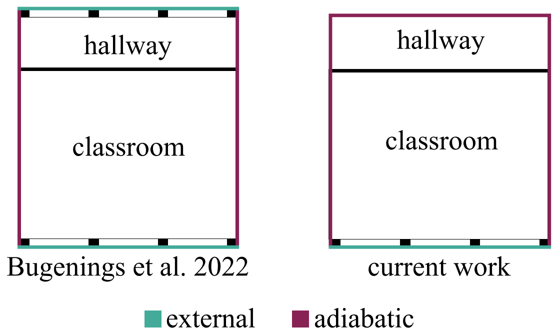

Fig. 1. Schematic model illustration including boundary conditions of the model in this publication (right) compared to the model of Bugenings et al. [24] (left). Only the wall of the hallway was modified.

et al. [24], it is assumed that the hallway does not face exterior but that the building has classrooms on both sides of the hallway. This change was made to allow to analyse different orientations while minimising the influence of the hallway. For a more thorough description of the case study, including detailed description of the construction, the interested reader is referred to Bugenings et al. [24].

2.1.1. Traditional renovation

As mentioned before, the performance of I-DIFFER is compared against a traditional renovation. The traditional renovation is identical to the one used in the previous study of I-DIFFER [24], but to easy the understanding the most importance aspects are briefly outlined. The idea of the traditional renovation is to represent a “standard” renovation commonly performed nowadays. Consequently, it is assumed that the existing exhaust ventilation system is replaced with a balanced ventilation system (heat recovery efficiency = 73%, specific fan power (SFP) = $1.8\,\mathrm{kW/(m^3\,s)}$) with variable air volume, controlled by the classroom CO_2-concentration and air temperature (minimum airflow: $1.26\,\mathrm{m^3/(h\,m^2)}$; maximum airflow: $18\,\mathrm{m^3/(h\,m^2)}$ (ACH = 6.67)), that the windows are replaced and that the exterior wall and roof are additionally insulated. To be less dependent on a specific renovation, the combination of three different wall insulation levels ($0.18\,\mathrm{W/(m^2\,K)}$, $0.14\,\mathrm{W/(m^2\,K)}$ and $0.10\,\mathrm{W/(m^2\,K)}$) and ten different window glazing (Table A.9) are used, summing up to 30 different combinations. The roof is for all variations insulated to $0.12\,\mathrm{W/(m^2\,K)}$.

2.1.2. I-DIFFER renovation

To ease the understanding of the results of the conducted investigations, in following, the renovation with I-DIFFER, as presented in Bugenings et al. [24], is briefly outlined. The interested reader is referred to the before-mentioned reference for a more thorough description.

I-DIFFER consist of two individual components, DSF and DCV. The DSF is thereby a transparent outer layer in front of the existing facade. This creates a cavity between glazing and the existing facade, which is subdivided into two cavities — one large in front of the existing window and one smaller, called bypass, on top. A venetian blind, controlled by the solar radiation on the facade and the airflow mode, is located within the cavity. The second component, the DCV, consists of a permeable ceiling which separates the classroom from a small plenum similar to a suspended ceiling. Furthermore, the system is combined with the upgraded existing exhaust ventilation system, providing the necessary airflow to the classroom. The system is operated in four different modes:

- transparent insulation: exhaust ventilation - off; all openings in cavity and bypass - closed.
- preheating: exhaust ventilation - on; bottom DSF cavity opening - open; top DSF cavity opening to plenum - open; bypass openings and top opening in DSF cavity to exterior - closed; airflow path: bottom opening cavity - top cavity opening to plenum - permeable ceiling - classroom
- cooling: exhaust ventilation - on; all openings but top DSF cavity opening to plenum - open; airflow path (mechanically driven): bypass - permeable ceiling - classroom; natural ventilation in DSF cavity due to wind and buoyancy
- cooling no vent: exhaust ventilation - off; all openings to exterior open; natural ventilation in DSF cavity and bypass due to wind and buoyancy

A schematic of the modes can be seen in Fig. 2. Consequently, the airflow in the classroom is always mechanically driven by the exhaust ventilation system and thus easily controllable. The mode's control is based on the operative room temperature and state of occupancy. The control logic can be found in the Appendix A.1 (Fig. A.12).

For the case study, as mentioned, the existing exhaust ventilation system is upgraded to be sufficiently sized and as the traditional renovation to be controlled by the classroom CO_2-concentration and air temperature with the same minimum and maximum air flow (and SFP). The roof is, as for the traditional renovation, insulated to $0.12\,\mathrm{W/(m^2\,K)}$. Additionally, as in [24] the combination of five different DSF cavity thicknesses (0.32 m, 0.43 m, 0.65 m, 0.81 m and 1.08 m) and ten different exterior glazing of the DSF (Table A.10), hence a total of 50 combinations are used for the evaluation.

2.2. BPS model & evaluation criteria

2.2.1. BPS model

For all conducted investigations, the BPS (IDA-ICE) model is derived from the model used in Bugenings et al. [24]. Only the before-mentioned change of the hallway boundary condition (Fig. 1) was implemented. Hence, all windows were modelled using the detailed pane-by-pane model. Further also, the same modelling strategy for I-DIFFER was used, which means the DSF is represented using a thermal zone and the openings between DSF and DCV plenum, and Bypass and DCV plenum were modelled using a leak component with a defined volume flow as the airflow through this openings is always know, as it is driven by the exhaust ventilation system.

2.2.2. Evaluation criteria

Two evaluation criteria are used for I-DIFFER and the traditional renovation variation. The first criterion is the global thermal comfort evaluated based on the operative classroom temperature according to ‘method A’ as stated in CEN/TR 16798-2:2019-05, whereby 93.5% (rounded to 94%) of all occupied hours (2088 h) must satisfy the comfort criteria. The respective upper and lower limits follow for the cooling season the adaptive thermal comfort (cat. II), whereas for the heating season they follow EN ISO 7730:2006-11. The clothing level follows the correlation on the 4-day outdoor running mean (including the current day) proposed by Mors et al. [40]. Thus, it is to be noted that for the investigation of the different future and extreme conditions (Section 2.3.3), the adaptive thermal comfort limits and the clothing level change accordingly for each climate condition. Secondly, I-DIFFER's primary energy (PE) consumption is compared against the PE consumption of the traditional renovation, whereby I-DIFFER is not allowed to have a higher PE demand than the worst traditional renovation. The total PE contains heating, ventilation, and lighting. Further, for the traditional renovation (as I-DIFFER does only have an exhaust ventilation system), the PE for the ventilation energy does not contain the energy used to preheat the supply air, this energy is included in the heating energy. The primary-energy factors used for electricity and district heating are 1.9 and 0.85 [41]. Another criterion which is usually used to assess the IEQ in a classroom is the CO_2-concentration (critical threshold 1000 ppm). As both renovations, the traditional renovation and the renovation with I-DIFFER achieved this criterion for all simulations, it is not shown in this study.

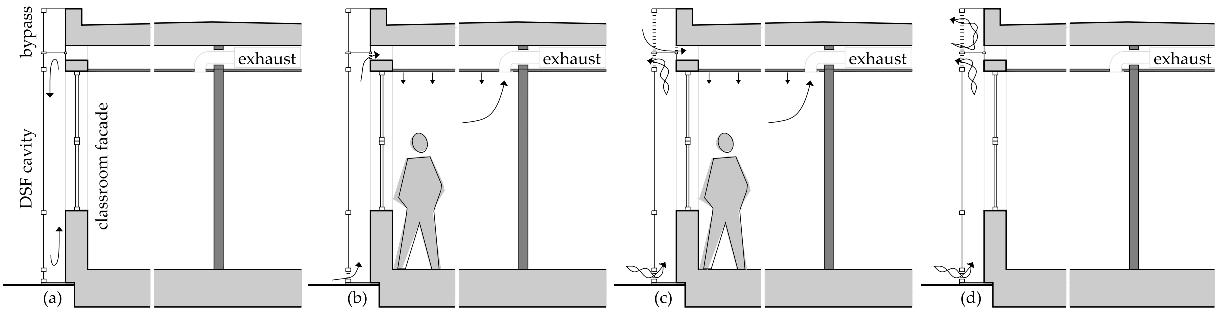

Fig. 2. Operation modes: (a) transparent insulation (classroom unoccupied), (b) preheating (classroom occupied), (c) cooling (classroom occupied/unoccupied) and (d) cooling no ventilation (classroom unoccupied). Based on Bugenings et al. [24].

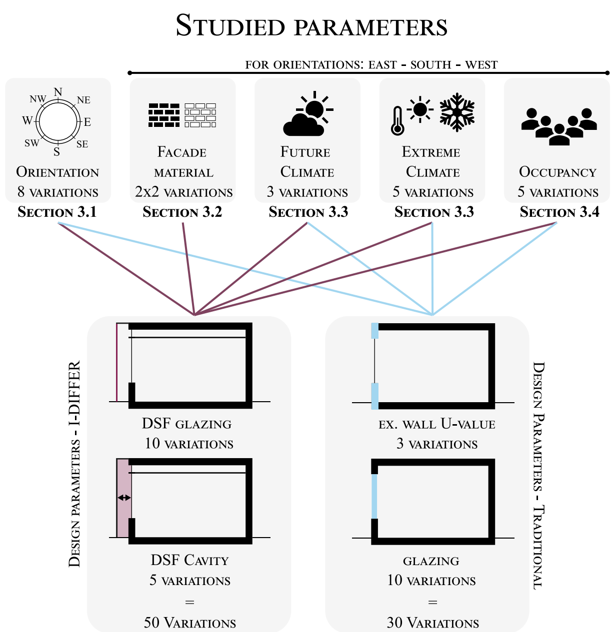

Fig. 3. Simulation scheme showing the combinations of design parameters and parameters investigated. The sections refer to the respective result sections for each parameter.

2.3. Studied parameters

In the following all five different studied parameters (orientation, facade material, future climate, extreme climate, occupant density) are outlined. For each of these parameters the in Sections 2.1.1 and 2.1.2 mentioned design parameters are varied for the traditional renovation and I-DIFFER respectively. Consequently for the traditional renovation 30 simulations and for I-DIFFER 50 simulations were conducted (Fig. 3)

2.3.1. Classroom orientation

To investigate the performance of I-DIFFER for various cardinal directions, a classroom facing eight different compass directions (N, NE, E, SE, S, SW, W, and NW) are analysed. The south orientation is included, as the model used in this work assumes a classroom on both sides of the hallway (Section 2.2.1). Thus, the included south orientation allows relating the results of this work to the prior investigation of I-DIFFER [24]. All design parameters as described in Section 2.2.1 are varied for each compass direction, and for each direction, I-DIFFER's performance is compared against the traditional renovation.

Table 1
Main properties of the used facade cladding for the four investigated cases. Rf = shortwave reflectance. Brick dark is the material used for all other investigations, and our prior investigation of I-DIFFER [24].

	d [m]	ρ [kg/m^3]	c [J/kg K]	Rf
Metal bright	0.001	2700	900	0.750
Metal dark	0.001	2700	900	0.107
Brick bright	0.120	1800	900	0.750
Brick dark (ref.)	0.120	1800	900	0.107

2.3.2. Facade material

Next to the orientation, the influence of the external classroom facade's thermal mass and reflectance (colour) is studied. Therefore a metal and a brick facade, representing a low and high thermal mass inside the DSF, both in light and dark colour (Table 1), are compared against one another. The dark brick facade equals the facade used for I-DIFFER in all other investigations. The reflectance is adapted to be equal for both materials. As the influence of these parameters on the traditional renovation is expected to be minor — as the facade faces outdoors, the performance of I-DIFFER is compared only against itself. This investigation is conducted for a classroom facing the three-compass directions east, south, and west. These three directions were selected based on the results of the classroom orientation study as elaborated in Section 3, which showed that changes between the orientations are predictable. Hence, it is assumed that results for non-studied directions can be easily derived from east, south, and west results.

2.3.3. Climate conditions

The influence of both future and extreme conditions is investigated again for the three compass directions east, south, and west. This is done as different building orientations can change the effect various climate conditions have on the building.

Extreme climate

Four extreme climate files representing a Danish hot, cold, sunny and cloudy year developed by Wittchen and Jønsson [42] are used to investigate the influence of extreme climate conditions. For each of these four conditions, the performance of I-DIFFER is compared against the traditional renovation and the performance using the Danish design reference year (DRY), which must be used for building permit calculation and is used for all other investigations in this work and was used in our previous analysis of I-DIFFER [24]. The main characteristics of the four extreme conditions used are summarised in Table 2. These four years are composed of the respective extreme months measured between 2001 and 2019 at a weather station near Denmark's capital Copenhagen. Thus, as these extreme years are assembled from actual weather data, the relation between, i.e. solar radiation and temperature is not independent. Consequently, as shown in Table 2, the hot year has, e.g. also, a relatively high solar irradiation.

Table 2
Temperature and global horizontal irradiance (GHI) for the design reference year(DRY)(2001–2010), the extreme years and future climate — based on Wittchen and Jønsson [42].

	DRY	Hot	Cold	Sunny	Cloudy	2050	2090
Average temperature [°C]	8.1	11.7	5.8	8.0	8.2	9.7	11.3
Maximum. temperature [°C]	27.7	31.2	26.3	30.1	28.2	30.0	29.7
Minimum temperature [°C]	−15.0	−10.0	−17.3	−17.3	−8.7	−8.8	−8.5
GHI [kWh/m^2]	1030.1	1137.2	856.1	1265.7	786.2	998.2	909.0

Table 3
Change in internal heat gains for the different cases at an air and mean radiant temperature of 22 °C, humidity ratio of 0.01 kg/kg and the clothing of 0.5 clo.

	Number of occupants				
	17	19	21	23	25
Occupants heat gains [W]	2080.80	2325.60	2570.40	2815.20	3060.00
Total heat gains (occ. + equipment) [W]	2777.80	3052.60	3327.40	3602.20	3877.20
Total gains per room area [W/m^2]	55.56	61.05	66.55	72.04	77.54
Total gains per room volume [W/m^3]	20.58	22.61	24.65	26.68	28.72

Future climate
Next to the previously described extreme conditions, the influence of the predicted future climate on I-DIFFER's performance is analysed. Therefore, the climate forecasts for the same measurement station as the extreme conditions for 2050 and 2090 [42] based on climate data of IEA EBC Annex 80 'Resilient Cooling of Buildings' are used. The summary of the main characteristics of the used future climates is shown in Table 2. Again the performance of I-DIFFER under these conditions is compared against the traditional renovation and the performance under the DRY climate condition.

2.3.4. Occupancy density

Next to the different climate conditions, the effect of varying occupancy density is investigated. Again, as for the climate conditions, the influence is studied for a classroom facing east, south, and west. The number of students is changed to 17, 19, 23 and 25, and the results are compared for both the traditional renovation and I-DIFFER against the reference case of 21 students. For each case, the equipment load per occupant (15 W per student, constantly assuming one teacher) is also adjusted. It is to be noted that according to Danish building regulation [41], at least 6 m^3 room volume are required per person in a classroom, thus limiting the number of people in the used case study classroom (135 m^3 room volume) theoretically to 22.5. Thus, 25 persons can be seen as the worst case, which should not occur for extended periods. A summary of the internal gains for each case is given in Table 3.

3. Results

3.1. Classroom orientation

Following, the results of the different orientations are presented. The thermal comfort is shown within the three left diagrams of Fig. 4(a–c), occupied hours within category II, underheating and overheating. Under- and overheating were defined as hours below respectively above the thresholds for category II. Invalid simulations (below 93.5% of the occupied time within category II) are marked in grey. The energy consumption is shown within the three right diagrams of Fig. 4(d–f), total PE including heating, ventilation and lighting, the heating PE and the ventilation PE. The PE for lighting is due to its minor magnitude and, consequently subordinate importance is not shown separately.

In the following, the wording *valid* is used to refer to results of simulated cases which either not fulfil the thermal comfort (thermal comfort not valid), only fulfil the thermal comfort criteria (valid thermal comfort & not valid energy) or fulfil the thermal comfort and have a total PE which is at maximum as high as the highest PE of the traditional renovation (valid thermal comfort & valid energy). For thermal comfort, it can be seen that for the traditional renovation, the occupied hours within category II (Fig. 4a) increase from south-eastern orientations towards northern ones. Thereby, SE, S and E show in mean the lowest number of hours inside the comfort category II, caused by overheating, which reaches above 8% for SE (Fig. 4c). In contrast, the hours of underheating remain relatively constant and below 0.5% for all orientations (Fig. 4b).

The occupied hours within category II of I-DIFFER (Fig. 4a) decrease from the northern orientations towards the south-eastern ones. Again, overheating (Fig. 4b) is the main determining factor for simulations being valid or not valid. However, the overheating trend is shifted more towards E and SE compared to the traditional renovation, with values up to 6%. The underheating (Fig. 4c) shows considerable variation for I-DIFFER, with the highest values for N, NW, and NE, where it reaches above 3%. Additionally, for the underheating, it can be seen that each orientation is split up into two groups. The upper groups consist solely of all single-glazing configurations. This can be traced back to the lower cavity (and thus inlet) temperature, which causes a problem on cold mornings when occupancy starts. The same effect was already seen and in more detail elaborated by Bugenings et al. [24].

Comparing the traditional renovation and the renovation with I-DIFFER, it can be said that for northern orientations, the traditional renovation shows higher thermal comfort values and a minor variation. In contrast, for the southern orientations, I-DIFFER is favourable as it causes less overheating. In terms of valid simulations, the traditional simulation has 100% valid simulations for N, NE, W and NW. The lowest number of simulations has the south orientation. For I-DIFFER, N, S, SW, W and NW reach 100% valid simulations. The remaining orientations have all two invalid simulations (Table 4), the ones with the highest number of hours above the upper comfort limit, namely the combination with glazing S-A1 and the two thinnest cavities. Glazing S-A1 has the highest g-value (g = 0.88) of all DSF glazing.

Regarding the PE consumption, the traditional renovation shows less sensitivity to the orientation than I-DIFFER (Fig. 4d). The slight decrease towards S can be led back to the reduction of PE for heating while the PE for ventilation remains relatively stable for all orientations, with its highest values for E.

For I-DIFFER, the orientation influences the PE consumption drastically. Further, as in the previous investigation of I-DIFFER [24], the PE of heating (Fig. 4e) is, on average, about four times higher than the one of the traditional renovation while the ventilation PE (Fig. 4f) is only about 40% of the traditional renovations'. The lowest total consumption for I-DIFFER can be seen for S. In contrast, the highest is seen for N. The reason is the heating consumption which increases by around 1000 kWh from S to N. The clear separation into two groups for the PE of heating can be traced back to single and double glazing of the DSF, with the upper consisting only of single glazing. The ventilation PE is in contrast relative stable across the orientations, with a slight increase from N towards SE.

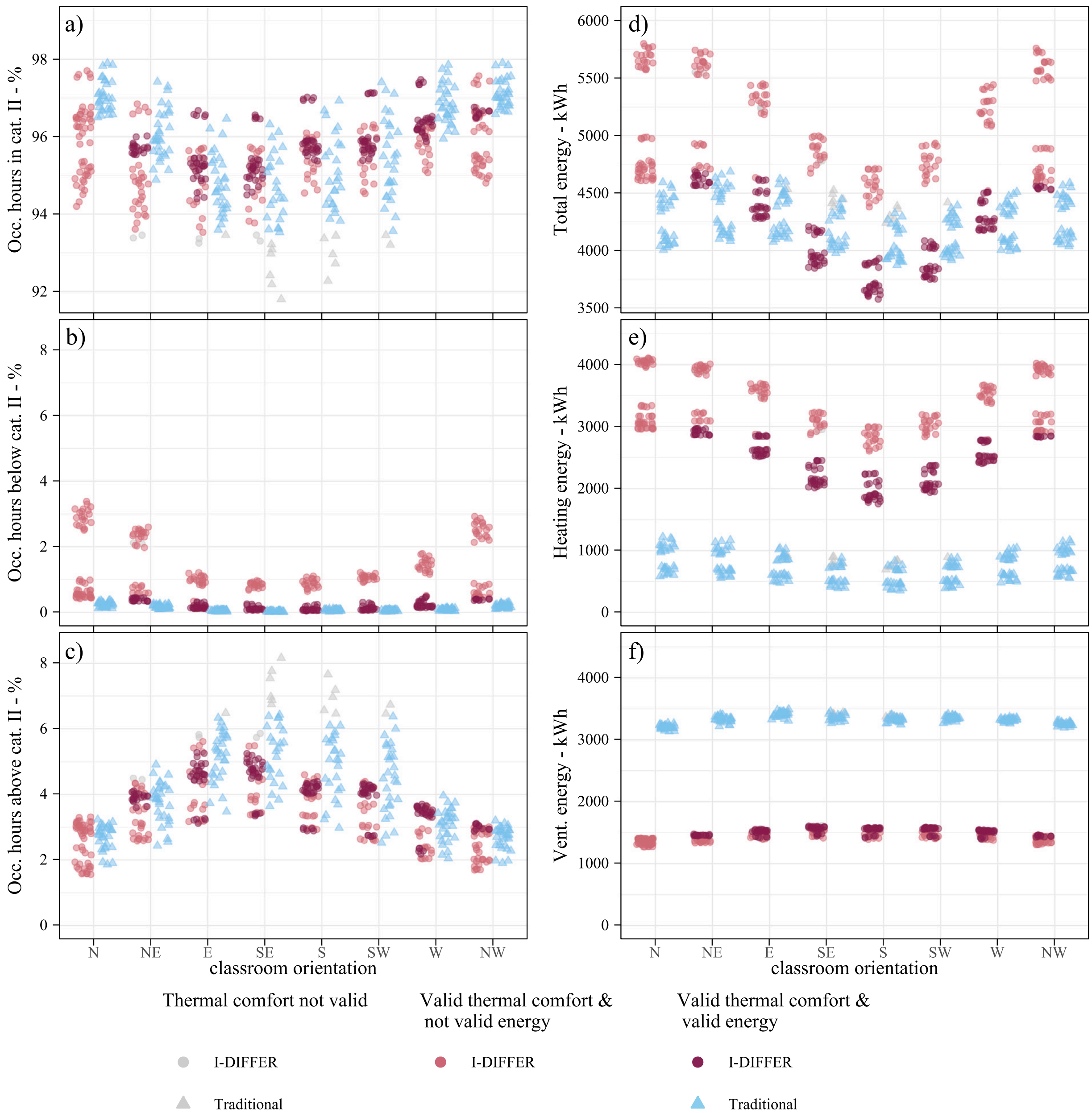

Fig. 4. Orientation: Occupied hours inside cat. II, occupied hours below cat. II, occupied hours above cat. II, total PE, PE heating and PE ventilation. Traditional n = 30; I-DIFFER n = 50 (per orientation).

In simulations with both a valid thermal comfort and an equal or better energy consumption than the worst traditional renovation, no simulations remain for N, whereas 60% remain for SE, S and SW (Table 4). Decisive is thereby the heating consumption. Overall, I-DIFFER can be used for all investigated orientations but N, while only for SE, S, and SW a lower total PE than for the best traditional renovation can be achieved.

3.1.1. Detailed analysis

In addition to the general analysis of the different orientations, a detailed study is conducted to understand better how different orientations affect I-DIFFER in detail. Therefore, three days in summer and winter were selected. For better comparability to previous results, the same three days as in Bugenings et al. [24] were chosen. Only simulations with valid thermal comfort and a valid total PE were included in this analysis. The main focus was set on the east-facing classroom as this leads to the most overheating hours, and Bugenings et al. [24] has already presented a detailed analysis of a south-facing classroom. Nevertheless, the results are then related to the other orientations, with the main emphasis on south and west, for which the detailed diagrams can be found in the Appendix A.3 (Figs. A.13–A.16). The diagrams for all other orientations but N, which does not have any valid energy simulations, are provided in the supplementary materials.

Winter period

Fig. 5 shows the selected three days in winter, where the 3rd day (Tuesday the 21st of December) is the coldest day of the year. It is to be noted that shading and mode in Fig. 5 represent all shown solutions above each other. Thus, in this case, where n = 29/50, it shows 29 lines above each other. All boxplots represent hourly mean values of the respective quantity.

For periods in transparent insulation mode with little to no solar radiation (and no occupants), the cavity temperature ranges between 5 and 9 °C and the outdoor temperature has little influence. Furthermore, it can be seen that during this time, the heating power is relatively

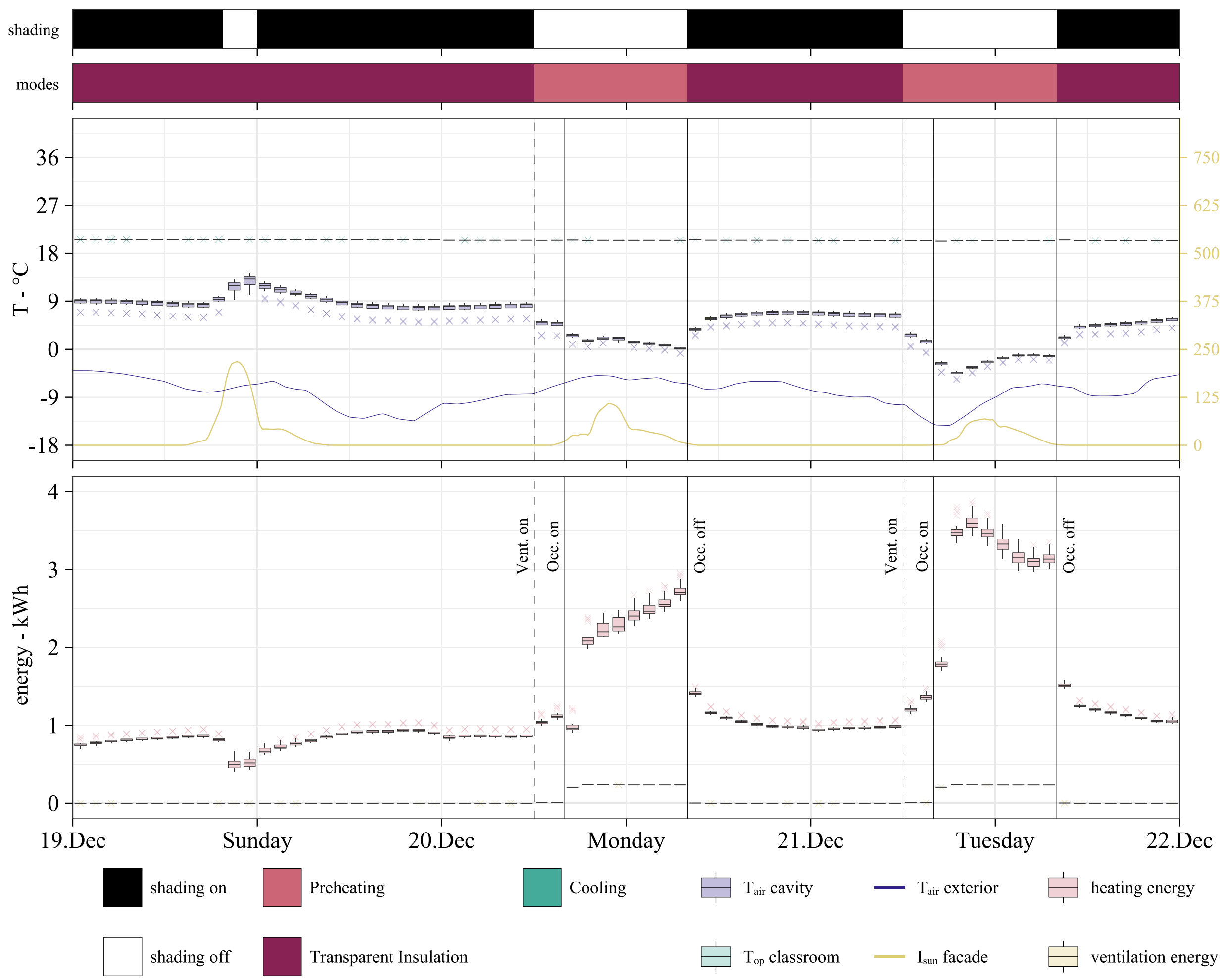

Fig. 5. CW (calendar week) 52 east: Hourly averages of heating power, ventilation power cavity and classroom temperature. Instantaneous values for modes, shading, solar irradiation on the facade and outdoor temperature over all thermal comfort and energy valid variations (n = 29/50). Modes and shading represent all variations as lines above each other. This means that, in this case, where n = 29/50, 29 lines are stacked above each other.

Table 4
Orientation: Valid thermal comfort (TC) simulations for the traditional renovation and the renovation with I-DIFFER and the simulations for I-DIFFER, which have a valid TC and an equal or lower energy consumption than the highest traditional renovation.

	TC - Traditional	TC - I-DIFFER	TC+Energy - I-DIFFER
North	30/30	50/50	0/50
Northeast	30/30	48/50	20/50
East	29/30	48/50	29/50
Southeast	24/30	48/50	30/50
South	25/30	50/50	30/50
Southwest	28/30	50/50	30/50
West	30/30	50/50	29/50
Northwest	30/30	50/50	10/50

stable at around 1 kWh. When solar radiation occurs, but occupants are still absent (Sunday), and the shading is off, the cavity temperature increases along with the increasing solar radiation, which also causes the heating power to decrease by about half. For days where occupants are present, and thus the cavity is ventilated, the cavity temperature decreases to slightly above 0 °C which is still more than 5 °C above the outdoor temperature. The solar radiation seems to have only a minor influence during that time as the increase in cavity temperature seen for the unoccupied day can no longer be spotted. Instead, the cavity temperature follows the outdoor temperature — so does the heating power in mirrored shape. By Bugenings et al. [24], it was seen in the detailed analysis for a south-facing classroom that the heating power changes rapidly at the beginning and end of the occupancy. This is also seen for the east-facing classroom. Comparing the south-oriented classroom to the east-oriented classroom, it can be said that the heating power is slightly higher for the east-oriented case, which can be related back to a lower cavity temperature. In addition, it is to be noted that all but four simulations show a similar cavity temperature and heating power. (These four are indicated as outliers of the boxplot.) Those four simulations with a constantly lower cavity temperature and a higher heating power are combinations with glazing D-D1, the glazing with the highest U-value of the shown simulations.

Relating these results to the other orientations (S - Fig. A.13; W - Fig. A.15; other orientations in supplementary materials), it can be said that, in principle, all orientations show the same trend with the expected deviations due to the changed solar irradiation. So has SE, S, and SW a higher solar irradiation on the facade and is consequently more substantially influenced by it, particularly on Sunday. In the same manner, have NE and NW hardly any solar irradiation on the facade and are therefore unaffected by it. Additionally, it can be said that the south orientation shows similar results as the one presented in Bugenings et al. [24], thus demonstrating that the, in this work used, model leads, despite the made changes, to similar results.

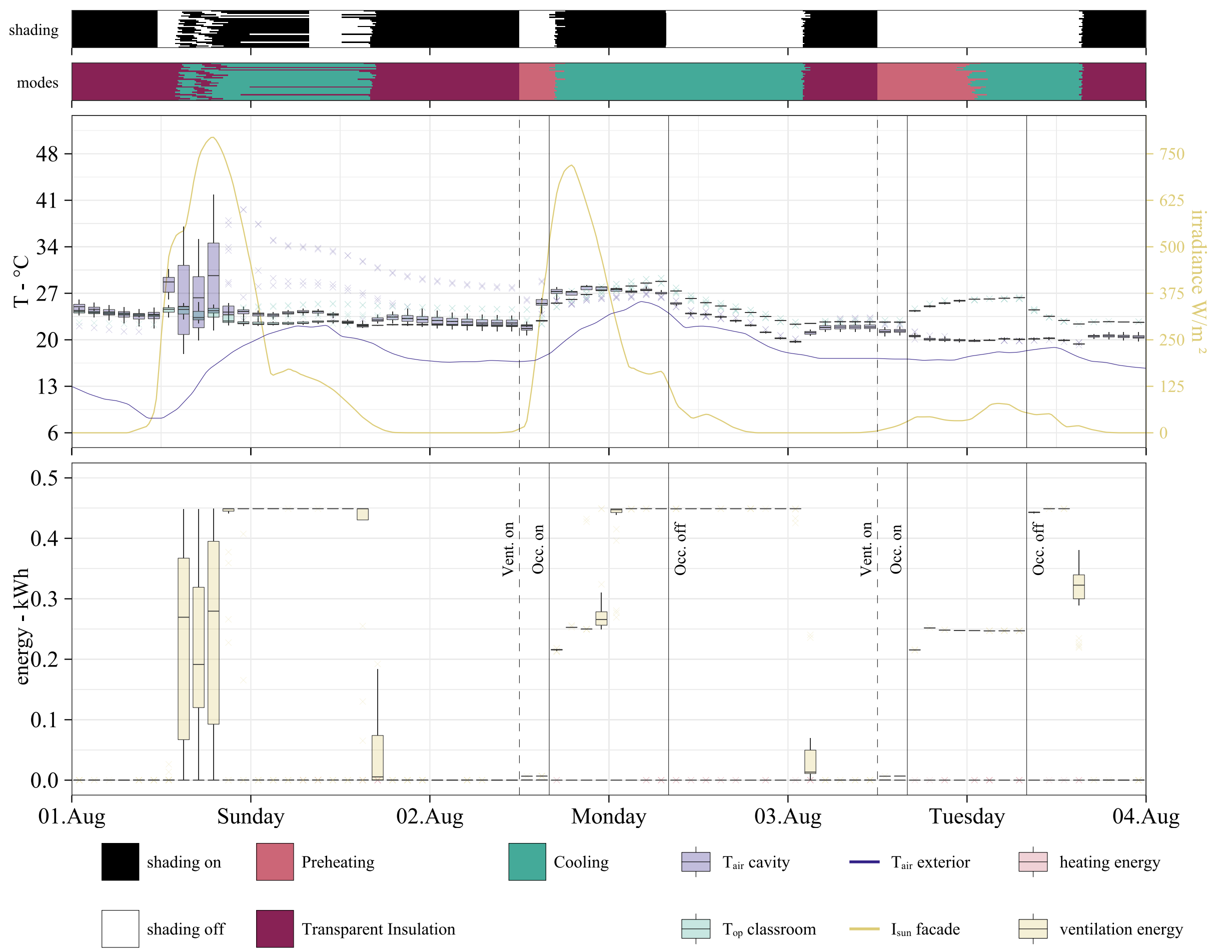

Fig. 6. CW 32 east: Hourly averages of heating power, ventilation power cavity and classroom temperature. Instantaneous values for modes, shading, solar irradiation on the facade and outdoor temperature over all thermal comfort and energy valid variations (n = 29/50). Modes and shading represent all variations as lines above each other.

Summer period

Fig. 6 shows the three selected summer days. For Sunday, the influence of the high solar irradiation is visible. The cavity temperature increases significantly till the mode switches from transparent insulation to cooling. Accompanying this, the ventilation is increased to the maximum. This leads, despite the high solar irradiation and exterior temperatures, to a decrease in the classroom temperature close to the exterior air temperature in the afternoon. The increased spread of the cavity temperature on that day can be explained by the fact that not all simulations switch to cooling mode respectively switch back to transparent insulation mode as the classroom temperature reaches the defined lower limit.

For both occupied days, it can be seen that at 6:00, when the ventilation starts, preheating mode is activated following the defined control as the classroom temperature is in an acceptable range. During the day, the solar irradiation's strong influence becomes apparent, and the cooling mode is activated due to the rising classroom temperature. Thereby, it can be seen, particularly for Thursday, that switching between preheating and cooling modes does not affect the cavity temperature significantly but seems to flatten the temperature increase.

Comparing this to the other orientations (S - Fig. A.14; W - Fig. A.16; other orientations in supplementary materials), as for winter, the overall trend is for all orientations similar with the expected deviations due to the orientation. Thereby, it can also be seen that the "earlier" high solar irradiation for east and SE causes higher temperatures throughout the day, which explains why these directions have more hours of overheating compared to, e.g. south. This effect becomes particularly evident when comparing NE with NW, where NE uses cooling mode on Sunday while NW does not. It can also be seen for all orientations that there is, as expected, little to no difference on Thursday when the solar irradiation is low. Finally, as for winter, S shows results very similar to the ones shown in Bugenings et al. [24] confirming that the here used model is despite the changes similar to theirs.

3.2. Facade properties

For all subsequent analyses, the investigation was only conducted for east, south, and west, based on the results of the study of different orientations (Section 3.1). These three directions were chosen as the number of valid thermal comfort and energy simulations exceeded 50% for those orientations. Additionally, the results of this investigation have shown that changes between the orientations are as expected. Hence, it is assumed that results for non-studied orientations can be easily derived from east, south, and west results.

For the investigation of the facade properties, only I-DIFFER's performance is presented as it is expected that the performance of the traditional renovation is only minorly affected by the varied facade properties as they the facade faces the exterior. For reference, the total PE of the traditional renovation, as introduced in Section 3.1, is used. The results are shown in Fig. 7.

The material of the facade has minor importance on the overall performance, thermal comfort (Fig. 7e1,s1,w1) and energy consumption

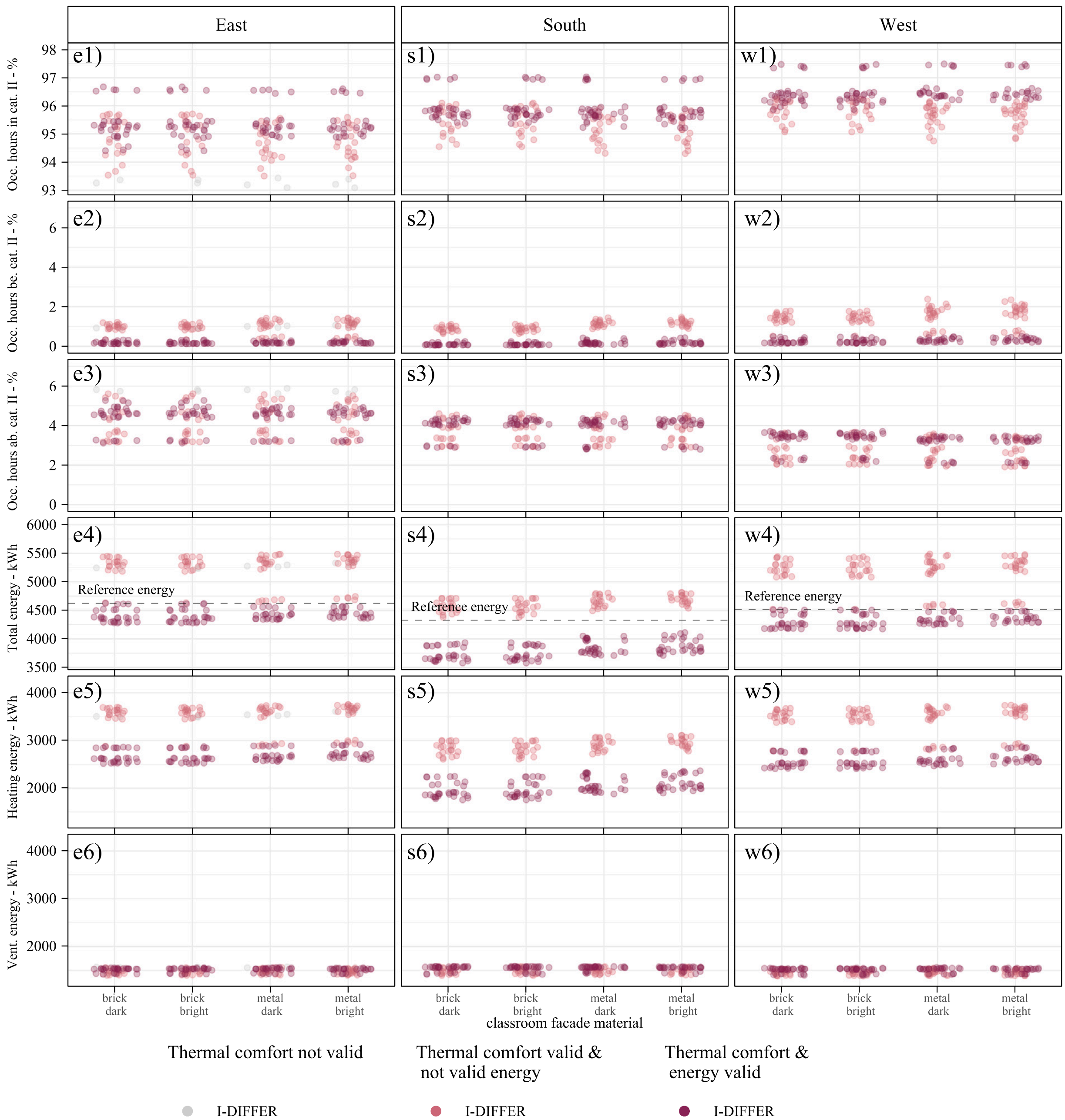

Fig. 7. Facade properties: Occupied hours inside cat. II, occupied hours below cat. II, occupied hours above cat. II, total PE, PE heating and PE ventilation. I-DIFFER n = 50.

(Fig. 7e4,s4,w4) and the difference between bright and dark facades is not reflected in the valid simulations (Table 5). The results further illustrate, for example, that even though those minor differences in terms of material brick/metal might have significant implication for the dynamic performance of the system (Fig. 8) as the high thermal inertia damps the dynamic of the system. Consequently this may ease the control of the system and could be also beneficial to decrease the risk of overheating. As a result, it can be said that the dark brick (used for the reference) delivers the best results in terms of energy consumption which is dominated by the heating PE and hours below the thermal comfort limits.

Table 5
Facade properties: Valid thermal comfort (TC) simulations for the renovation with I-DIFFER, and the simulations for I-DIFFER with a valid TC and an equal or lower energy consumption than the highest traditional renovation (dark brick).

	TC - I-DIFFER			TC+Energy - I-DIFFER		
	East	South	West	East	South	West
Brick dark (ref)	48/50	50/50	50/50	29/50	30/50	29/50
Brick bright	48/50	50/50	50/50	29/50	30/50	29/50
Metal dark	47/50	50/50	50/50	25/50	30/50	25/50
Metal bright	47/50	50/50	50/50	25/50	30/50	25/50

3.3. Climate conditions

3.3.1. Extreme climate

The studies extreme weather conditions strongly influence the thermal comfort (Fig. 9e1, s1, w1). The most decisive influence on the thermal comfort has the hot year. All variants stay thereby below the desired 93.5% for east and south. Only three traditional renovations achieve the minimum thermal comfort requirement for west. The sunny year shows a similar but more favourable trend for both renovations.

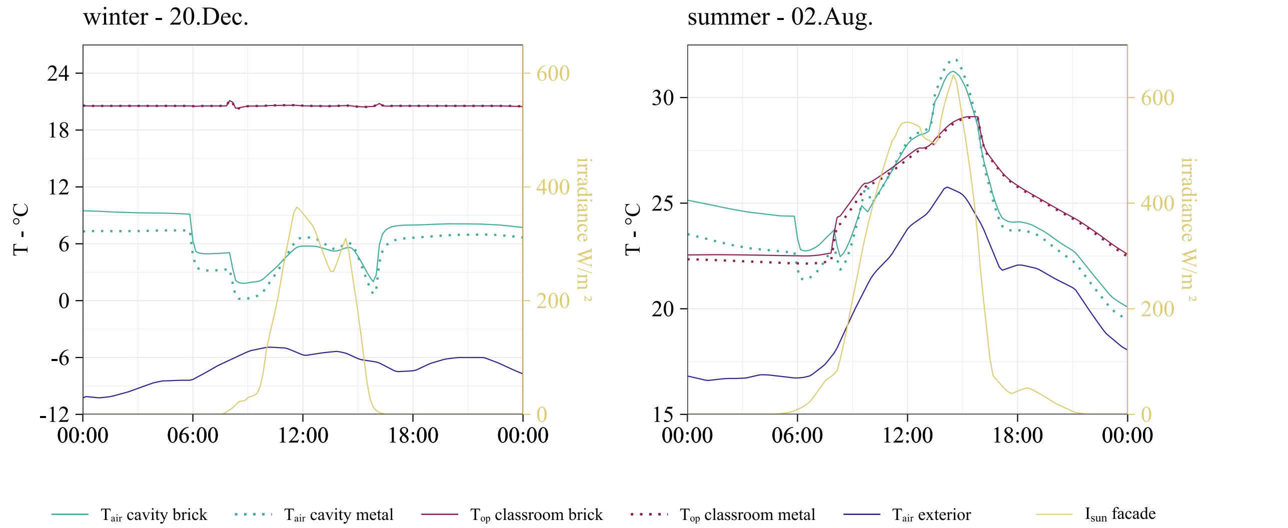

Fig. 8. Facade properties: Cavity temperature for brick and metal facade for one summer and one winter day. Glazing D-D1, widest cavity and low reflectivity (Rf = 0.107).

The spread over the variants is most significant for the eastern orientation and most minor for the western orientation, whereby I-DIFFER decreases its spread and thus sensitivity to the varied parameters already for the southern orientation. The opposite trend is shown by the cold and cloudy year, where all simulations improve their thermal comfort compared to the reference.

The main reason for the change of hours inside the comfort limits is that the hours above the comfort limits increase for the hot and the sunny year and decrease for the cold and cloudy years (Fig. 9e3, s3, w3). The traditional renovation stays as low as the reference case for hours below the comfort limits (Fig. 9e2, s2, w2). In contrast, I-DIFFER increases its hours slightly for the cold and cloudy years and decreases its hours for the hot and sunny years. The two simulation groups, already seen for the reference climate, can still be seen for the cold, cloudy, and sunny years. Thereby, the upper group consists of all single glazing. Only for the hot year, single glazing shows similar low values as double glazing.

In terms of valid thermal comfort simulations (Table 6), no valid simulations remain in the hot and sunny years for both renovation strategies. On the opposite is the cold and the cloudy year, where all simulations are valid, which is an increase compared to the reference climate.

The results of the PE show that the weather condition does not only have a significant influence on the magnitude of the total PE but also on the spread of the data. The total PE significantly reduces for I-DIFFER for the hot year, whereas it rises for the traditional renovation (Fig. 9e4, s4, w4). For I-DIFFER, this can be led back to the heating PE (Fig. 9e5, s5, w5), which was reduced by nearly half compared to the reference. Even though there is an increase in ventilation energy (Fig. 9e6, s6, w6), the reduction in heating energy overcompensates this rise. Different from this is the traditional renovation where the enlargement of the total PE can be led back to the increase of the PE ventilation by around 1000 kWh. Even though the PE heating decreased by roughly one-third, the ventilation is the main driving force for the total PE rise. This effect of heating PE on I-DIFFER and ventilation PE on the traditional renovation was already seen by Bugenings et al. [24] and gets more significant with extreme conditions.

Comparing the sunny year to the reference, the total PE for I-DIFFER falls, whereas the traditional renovation rises. A trend that was already seen for the hot year but to a lesser extent. The reason for this can also be traced back to the ones previously discussed for the hot year.

For the cold year, the effect is less compared to what was seen before for the hot year. For the traditional renovation, the total PE falls to its overall low, which can be led back to the decreased PE

Table 6
Extreme climate: Valid thermal comfort (TC) simulations for the traditional renovation and the renovation with I-DIFFER, and the simulations for I-DIFFER with a valid TC and an equal or lower energy consumption than the highest traditional renovation.

	TC - Traditional			TC - I-DIFFER			TC+Energy - I-DIFFER		
	East	South	West	East	South	West	East	South	West
Ref.	29/30	25/30	29/30	48/50	50/50	48/50	29/50	30/50	29/50
Cloudy	30/30	30/30	30/30	50/50	50/50	50/50	30/50	30/50	17/50
Cold	30/30	30/30	30/30	50/50	50/50	50/50	0/50	20/50	0/50
Hot	0/30	0/30	3/30	0/50	0/50	0/50	0/50	0/50	0/50
Sunny	0/30	1/30	12/30	0/50	0/50	5/50	0/50	0/50	0/50

for ventilation. At the same time, I-DIFFER increases to the highest consumption compared to other extreme weathers and further enlarges its spread over the variants. The heating PE causes the increase in both spread and the upper limit.

For the cloudy year, it can be seen that the total PE for traditional renovation and renovation with I-DIFFER decreases. This is due to the reduced heating and the reduced ventilation PE. It is to be noted that this behaviour can be not only led back to reduced solar radiation, which reduces the ventilation energy needed in the summer period, but also to the relatively high temperature in winter, which decreases the heating. The lower temperatures in summer decrease the ventilation during summer.

Regarding simulations with valid thermal comfort and a total PE consumption lower than the highest traditional renovation, 20 remain for the cold year facing south (Table 6). For east and west, no simulations are valid, which is caused by the decrease of PE by the traditional renovation. For the cloudy year, 30 remain for east and south. In contrast, only 17 remain for west. No valid simulations exist for all orientations for the hot and sunny years because no simulation has a valid thermal comfort. For the extreme cold weather, the models with double glazing, except double glazing D-D1 and D-E1, the uncoated glazing and the double glazing with the lowest g-value, led to valid results. No single glazing is valid. Hence showing a favourable trend for glazing with low thermal losses and high solar gains. For the cloudy weather, all double glazing can lead to valid results.

Overall, I-DIFFER shows favourable results for the total PE consumption for the sunny and hot years, while the traditional renovation is superior for the cloudy and cold years. However, as for the traditional renovation, none of the analysed variations is valid for the hot and the sunny year, indicating an overheating problem in summer for both renovations.

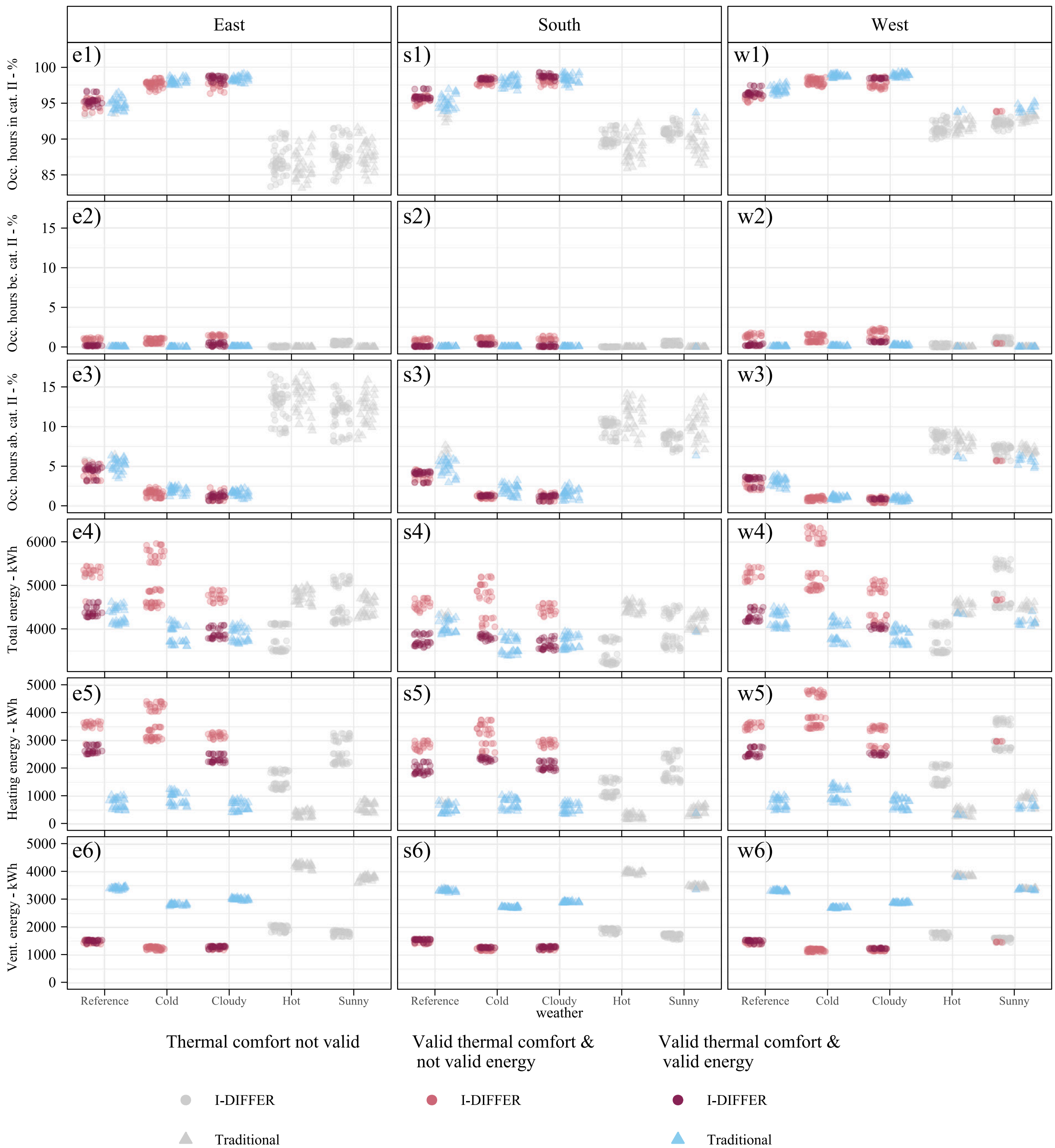

Fig. 9. Extreme weather: Occupied hours inside cat. II, occupied hours below cat. II, occupied hours above cat. II, total PE, PE heating and PE ventilation. Traditional n = 30; I-DIFFER n = 50.

3.3.2. Future climate

Further, the results of the future climate are presented (Fig. 10). Here, it can be seen that the change in thermal comfort from the reference (Danish design reference year) to 2050 and 2090 is small (Fig. 10e1, s1, w1). The thermal comfort decreases for the traditional renovation for 2050 for east. In contrast, it remains on the same level as the references for south and west. Reason for this is the increase in overheating in 2050 for east. In comparison, I-DIFFER increases its thermal comfort from the reference to 2050 for east but also remains at the reference level for south and west. Reason for the increase in thermal comfort for east is the reduction of hours below the comfort limit of the single-glazing due to increased temperatures during winter (Fig. 10e2, s2, w2). The trend of decreasing hours below the comfort limit is also seen for south and west. For the year 2090, the traditional renovation increases its thermal comfort increases for east, decreases it for south and remains at the same level as the reference case for west. For east, this change is attributed to the reduction in hours above the comfort limit (Fig. 10e3, s3, w3). For south, the hours above the comfort limit increase. This trend can be traced back to the general temperature and solar radiation development. The solar radiation decreases when the temperature increases for 2050 and 2090 (Table 2). Thus, lower solar radiation and higher temperatures seem less critical for east-facing classrooms than for south-facing ones. For I-DIFFER, the thermal comfort increases from 2050 to 2090 for all orientations, which can be led back to the further reduction of hours below the comfort limit. The hours above the comfort limit remains at

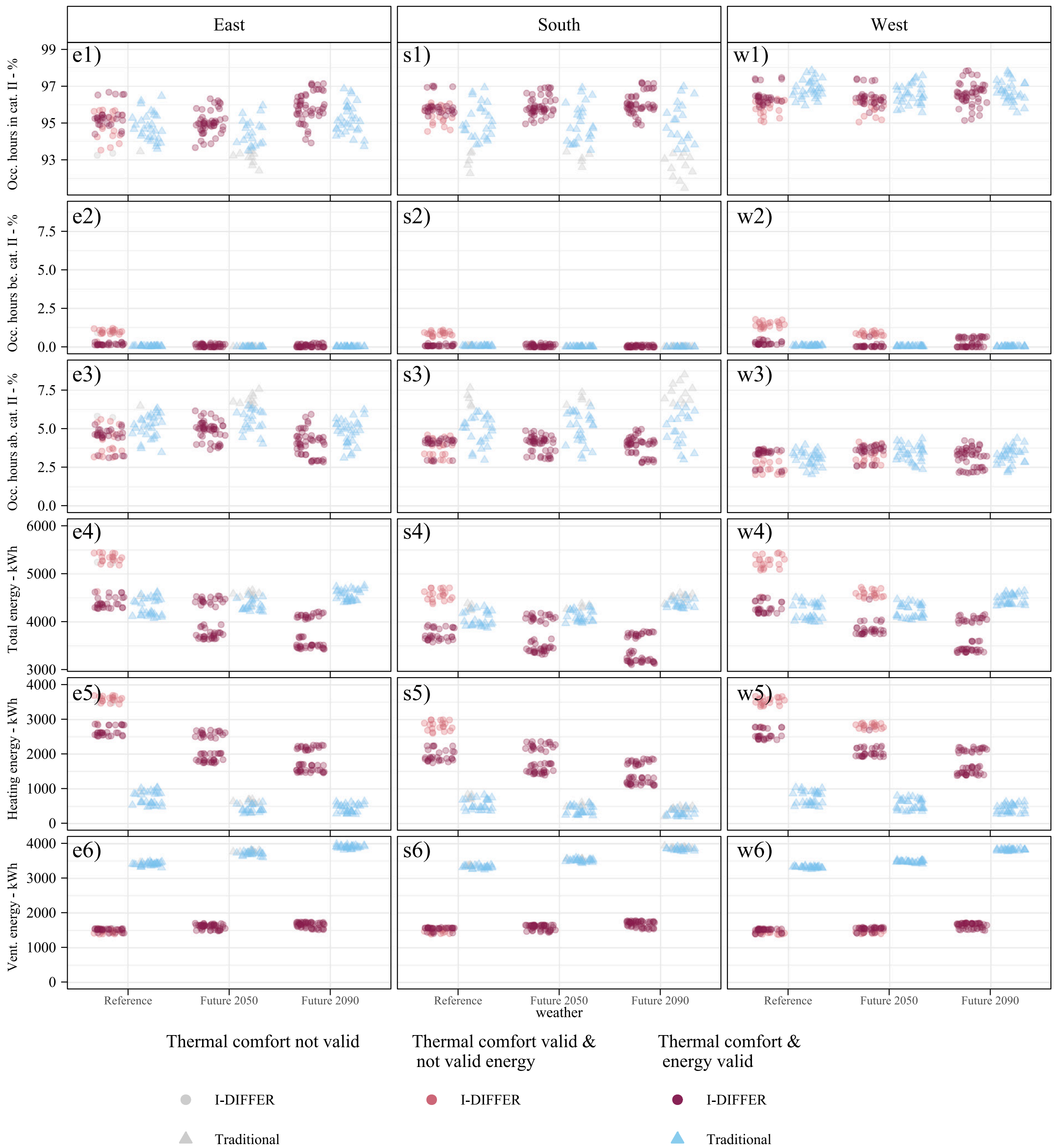

Fig. 10. Future climate: Occupied hours inside cat. II, occupied hours below cat. II, occupied hours above cat. II, total PE, PE heating and PE ventilation. Traditional n = 30; I-DIFFER n = 50.

a similar level as 2050. The trends described above accompany with the thermal comfort valid simulations for all orientations (Table 6).

Focusing on the total PE (Fig. 10e4, s4, w4), the traditional renovation shows an increasing trend from the reference over 2050 to 2090 for all orientations. The main reason for this is the rise in ventilation energy (Fig. 10e6, s6, w6) which can be led back to the increase in outdoor temperature. The rising outdoor temperature is also the reason for the heating energy decrease for the traditional renovation (Fig. 10e5, s5, w5). Still, the heating decrease is too slight to balance the ventilation energy increase. In contrast stands I-DIFFER, which shows a decreasing total energy consumption. The main reason for this overall decrease is that the reduction of heating PE outbalances the rise in ventilation PE.

The trend of the increasing valid thermal comfort and energy simulation can be seen in Table 6. All simulations of the east and south-facing case are valid for both 2050 and 2090, which means that even the simulations with the single-glazing achieve an energy consumption equal to or better than the worst traditional simulation. For west, the simulations with single-glazing remain invalid for 2050 as the reduction in I-DIFFER's total energy is slightly lower than for the east-facing case.

Overall, I-DIFFER shows superior results for the future climate forecast compared to the traditional renovation (see Table 7). For thermal comfort, I-DIFFER shows a constant or slight increase trend in occupied hours within the comfort limits. The traditional renovation shows a continuous or decreasing trend except 2090 for east. Even more noteworthy is the difference for total PE, there I-DIFFER shows a significant reduction for 2050 and again for 2090, while the results for the traditional renovation show an increase for both years.

Table 7
Future climate: Valid thermal comfort (TC) simulations for the traditional renovation and the renovation with I-DIFFER, and the simulations for I-DIFFER with a valid TC and an equal or lower energy consumption than the highest traditional renovation.

	TC - Traditional			TC - I-DIFFER			TC+Energy - I-DIFFER		
	East	South	West	East	South	West	East	South	West
Ref.	29/30	25/30	30/30	48/50	50/50	50/50	29/50	30/50	29/50
2050	20/30	25/30	30/30	50/50	50/50	50/50	50/50	50/50	31/50
2090	30/30	19/30	30/30	50/50	50/50	50/50	50/50	50/50	50/50

Table 8
Occupant density: Valid thermal comfort (TC) simulations for the traditional renovation and the renovation with I-DIFFER, and the simulations for I-DIFFER that have a valid TC and an equal or lower energy consumption than the highest traditional renovation.

	TC - Traditional			TC - I-DIFFER			TC+Energy - I-DIFFER		
	East	South	West	East	South	West	East	South	West
17	30/30	30/30	30/30	50/50	50/50	50/50	30/50	30/50	30/50
19	30/30	30/30	30/30	50/50	50/50	50/50	30/50	30/50	30/50
21	29/30	25/30	30/30	48/50	50/50	50/50	29/50	30/50	29/50
23	17/30	12/30	30/30	39/50	50/50	50/50	20/50	30/50	25/30
25	6/30	4/30	30/30	21/50	46/50	50/50	0/50	30/50	25/50

3.4. Occupancy density

Analysing the varying occupancy density, Fig. 11 shows the thermal comfort and PE consumption for the varying number of occupants for east, south and west. It can be seen for both renovations and all three orientations that the hours inside the limits decrease with an increasing number of occupants (Fig. 11e1, s1, w1). While I-DIFFER shows a relatively constant and smaller spread within the variations, the spread for the traditional renovation increases with an increasing occupancy density. At the same time, the rate of change between the different occupancy loads is more significant for the traditional renovation than for I-DIFFER. Compared to the reference, the traditional renovation and I-DIFFER increase their thermal comfort to only have simulations above the set comfort limit of 93.5% for both lower occupants densities. The traditional renovation decreases its valid simulation for the higher number of people and east and south (Table 8). I-DIFFER remains at the same level as the reference for south and 23 occupants but decreases to 46 valid simulations. For east, both high number of occupants (23 and 25) reduces the thermal comfort valid simulations. For west, the traditional renovation and I-DIFFER have no invalid simulations for all occupant densities.

From this analysis, it can be concluded that while for higher occupant densities, I-DIFFER is less prone to overheating than the traditional renovation, it is slightly more prone to underheating for lower occupant densities.

Overall for the total PE (Fig. 11e4, s4, w4), it can be seen that both renovations and all orientations, the traditional renovation and I-DIFFER change linearly with the altered number of occupants, and the magnitude of change agrees well between both. A lower occupancy density leads to decreased total PE consumption, while an increased load leads to the opposite. Further, I-DIFFER shows a significantly larger spread over all simulations, caused mainly by the single glazing of the DSF. It is also to be noted that the rate of change is nearly symmetrical around the reference case. Thus, a decrease or increase of the occupants' density loads seems to have the same magnitude of effect on the total PE consumption.

To further understand the change in total PE, the individual PE for heating and ventilation is analysed. For the heating PE, the trends seen for traditional renovation and I-DIFFER are opposite (Fig. 11e5, s5, w5). Where the heating energy of I-DIFFER decreases with decreasing occupant density, the PE for the traditional renovation rises. This behaviour of I-DIFFER is surprising as one would expect a decrease in PE for heating with increasing internal heat loads. The opposite trend seen is caused by the demand-controlled ventilation (Fig. 11e6, s6, w6). With increasing occupant density, the ventilation flow rate increases the same way as for the traditional renovation due to the higher CO_2 production and the VAV ventilation system. However, compared to the traditional renovation, the heating needed to compensate for the ventilation losses of I-DIFFER is far higher as the supply temperature is lower. Thus, the ventilation losses of I-DIFFER, caused by the ventilation rate needed per person, overcomes the heat gains per person. Therefore, additional occupants increase the heating demand counter-intuitively. The PE for ventilation shows, in contrast, a similar trend for both renovations, which is equal to the one for the total PE consumption — falling PE with decreasing number of occupants and increasing PE with an increasing number of occupants. The traditional renovation shows the significant absolute change between the different occupancy loads but I-DIFFER the larger relative one.

These analyses show that the number of valid combinations in terms of comfort and energy increases with decreasing occupant density for I-DIFFER. Further, it was seen that a lower g-value is favoured with increasing occupant density. With the highest tested occupant density, only the double glazing with the lowest g-value remains as only valid glazing. This also indicates that double glazing is still necessary to achieve a low enough energy consumption to be at least equal to the traditional renovation despite higher internal gains. Additionally, a similar behaviour for the traditional renovation and I-DIFFER could be seen, indicating that neither of them seems more robust than the other if the occupants' density varies.

4. Discussion and conclusion

In the previous investigation of I-DIFFER [24], it was shown that this concept has the potential to become a serious alternative to traditional school renovation if the facade faces south. This work further explored the novel renovation concept for schools which combined diffuse ceiling ventilation and double skin facade with an (existing) exhaust ventilation system. The influence on I-DIFFER's and the traditional renovation's thermal comfort and energy consumption was investigated for eight cardinal directions, addressing the majority of the potential renovation cases. Based on this, eastern, southern and western orientations were further analysed regarding their performance when the facade material changes. At last, their resilience to future and extreme climate and occupant density was investigated.

The orientation study showed that I-DIFFER can compete with the traditional renovation approach for all investigated orientations but north. Nevertheless, I-DIFFER showed for the PE consumption a much greater sensitivity to the orientation. The energy consumption increased for I-DIFFER in relation to the traditional renovation for non-southern orientations. Only south-east, south, and south-west I-DIFFER can achieve a lower total PE consumption than a traditional renovation. Thus, the application of the I-DIFFER concept for an entire building renovation, including the north-oriented facades, must be carefully evaluated. A detailed analysis of three summer and winter days showed that the trend across the orientations is, in principle, similar with the expected influence of each orientation. It could also be shown that the model used in this investigation leads despite the changes to similar results as the model used in our earlier investigation of I-DIFFER [24]. These results also agree with existing literature, which highlights the great importance of solar irradiation and thus orientation for DSFs [25–27,29–31].

The analyses of a high and low thermal mass classroom facade (metal and brick), each with high and low reflectance, showed that a low reflectance facade with high thermal mass leads to the best results (lowest PE demand and highest thermal comfort) while a low thermal mass facade with high reflectance leads to the worst results. However, the overall change between the four investigated configurations is minor. Thus, it can be concluded that the classroom facade material is of subordinated importance to the overall performance of I-DIFFER. The detailed analyses showed that the high thermal mass of the brick façade

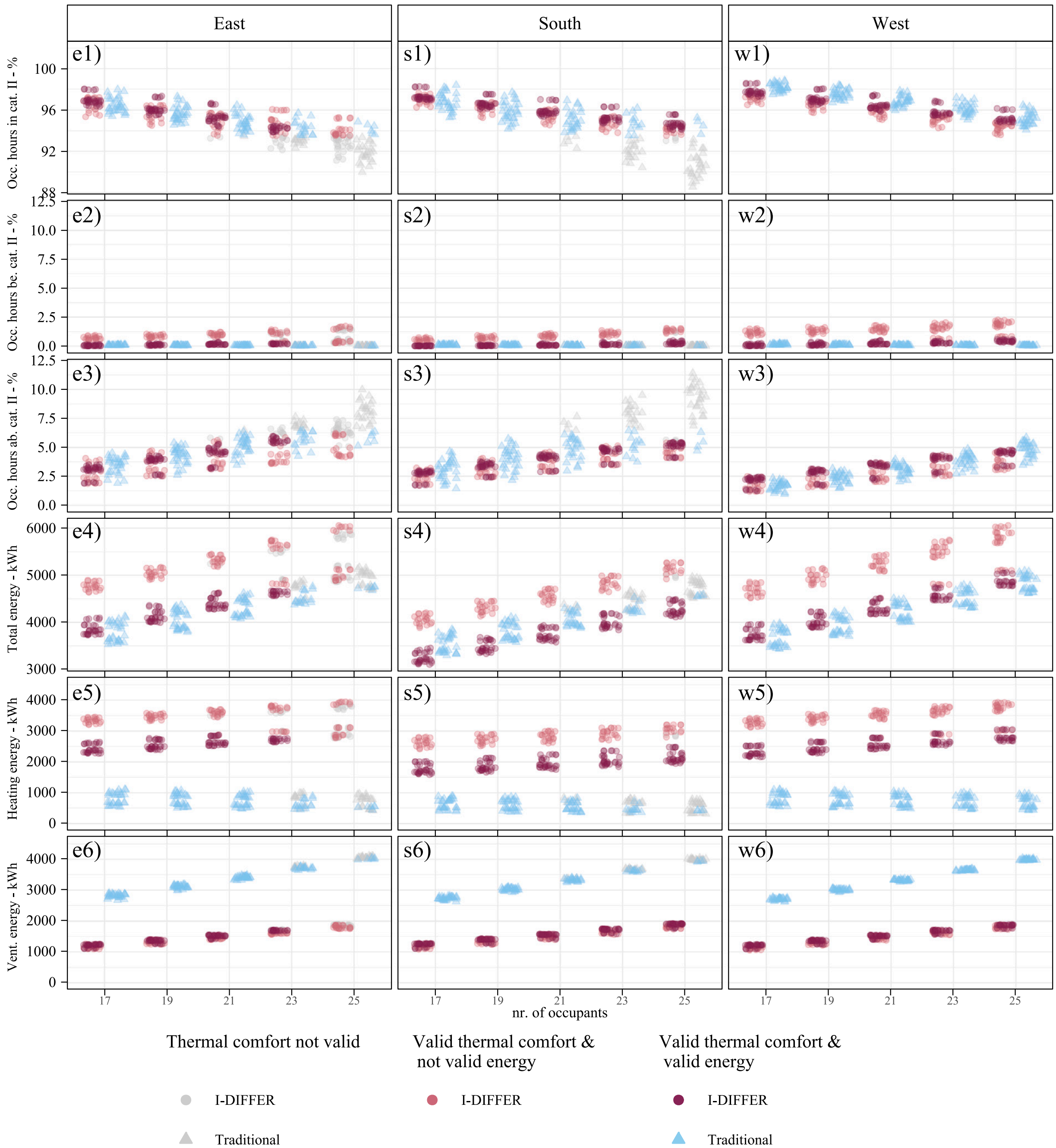

Fig. 11. Occupant density: Occupied hours inside cat. II, occupied hours above cat. II, occupied hours below cat. II, total PE, PE heating and PE ventilation. '21 occupants' is the reference case. Traditional n = 30; I-DIFFER n = 50.

has a stabilising effect on the DSF cavity air temperature, and thus leads to lower cavity air temperatures in periods of high solar irradiation which agrees with the principal findings of recent studies [32,33], which analysed the effect of PCM in shading blinds, and thus a high thermal mass inside the DSF.

The analysis of extreme climates indicated for all but the cold climate that I-DIFFER could consistently perform at least on an equal level as the traditional renovation. For extreme cold conditions, the traditional renovation outperforms I-DIFFER. In contrast, for extreme hot and sunny conditions, where an equal thermal comfort level as for the traditional renovation is achieved, I-DIFFER leads to a lower PE consumption. A trend which also pursues for the forecasted future climate conditions were not only a favourable trend for the PE consumption but also for the thermal comfort can be seen for I-DIFFER. Overall, I-DIFFER shows a high potential for climates with mild winters, increased availability of solar irradiation and mild to hot summers.

For varying occupant densities, I-DIFFER shows a similar trend for the total PE than the traditional renovation, increasing with an increasing number of occupants. For the east, however, it was seen that I-DIFFER has a higher PE demand for the highest occupant density (25 - occupants) than the worst traditional renovation. Additionally, it was found that counterintuitively the heating PE increased for I-DIFFER with an increasing number of occupants, as the higher ventilation rate, combined with the cold inlet temperature, outbalances the heat gains per person. For the thermal comfort overall, similar trends

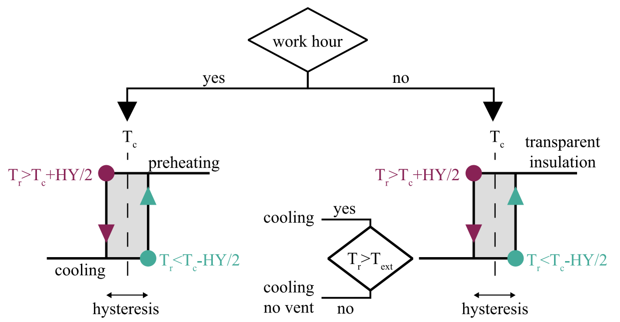

Fig. A.12. Outline of airflow-pattern control for I-DIFFER: HY = hysteresis (summer: 4 °C; winter: 2.5 °C); T_{ext} = ambient air temperature; T_c = thermal neutral temperature dependent on season (summer: T_c = T_c-0.5 °C; winter: T_c = T_c), T_{op} = classroom operative temperature. Based on Bugenings et al. [24].

were observed for I-DIFFER and the traditional renovation, decreasing with increasing occupant density. However, I-DIFFER showed slightly superior performance in terms of overheating. Thus, no significant difference between I-DIFFER and the traditional renovation could be observed.

This study confirmed that I-DIFFER is a competitive alternative to a traditional renovation, thus widening the range of renovation concepts. Thus, contributing to the aim to improve not only the energy efficiency but also the IEQ of schools. Additionally, the study gives further insight into the performance of a mechanical driven DSF under varying boundary conditions and can thus increase the general applicability of such DFSs also outside the I-DIFFER concept.

While this study has further investigated the potential of I-DIFFER, some aspects remain unknown. The performance over the whole life cycle in terms of cost and environmental impact should be addressed by future research. Further, a more detailed analysis by experiment or computational fluid dynamics could allow for valuable insight into I-DIFFERS performance on a higher resolution as possible with BPS.

CRediT authorship contribution statement

Markus Schaffer: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Laura Annabelle Bugenings:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Olena Kalyanova Larsen:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Chen Zhang:** Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Table A.9
Traditional renovation glazing, E_{ref} calculated according to BR18 [41]. All glazing properties but for Triple A1 are taken from Saint-Gobain Glass [43]; Triple A1 properties are taken from Nippon Sheet Glass Co., Ltd [44]. U_g based on EN 673:2011-02 [45]; g and τ based on EN 410:2011-02 [46]; U_f based on EN ISO 10077-2:2017 CEN [47]. Based on Bugenings et al. [24].

Name	U_g [W/(m² K)]	g	τ	E_{ref} [kWh/(m² a)]
Double-glazing - U_f = 1.9 W/(m² K)				
Double A1 (D-A1)	0.9	0.52	0.71	1.83
Double B1 (D-B1)	1.0	0.62	0.82	14.33
Double B2 (D-B2)	1.2	0.62	0.82	0.05
Double C1 (D-C1)	1.1	0.71	0.83	24.87
Double C2 (D-C2)	1.4	0.71	0.83	3.45
Triple glazing - U_f = 1.0 W/(m² K)				
Triple A1 (T-A1)	0.5	0.33	0.61	10.14
Triple B1 (T-B1)	0.5	0.47	0.70	37.64
Triple B2 (T-B2)	0.7	0.47	0.70	23.36
Triple C1 (T-C1)	0.5	0.60	0.77	63.17
Triple C2 (T-C2)	0.7	0.60	0.77	48.90

Table A.10
I-DIFFER DSF glazing. Glazing properties are taken from Saint-Gobain Glass [43]. U_g based on EN 673:2011-02 [45]; g and τ based on EN 410:2011-02 [46]; U_f based on EN ISO 10077-2:2017 CEN [47]. Based on Bugenings et al. [24].

	U_g [W/(m² K)]	g	τ
Single-glazing - U_f = 5.0 W/(m² K)			
Single A1 (S-A1)	5.8	0.88	0.91
Single B1 (S-B1)	5.7	0.70	0.67
Single C1 (S-C1)	5.8	0.57	0.51
Single D1 (S-D1)	5.8	0.44	0.37
Double-glazing - U_f = 1.5 W/(m² K)			
Double B1 (D-B1)	1.0	0.62	0.82
Double B2 (D-B2)	1.2	0.62	0.82
Double C1 (D-C1)	1.1	0.71	0.83
Double C2 (D-C2)	1.4	0.71	0.83
Double D1 (D-D1)	2.7	0.80	0.83
Double E1 (D-E1)	1.0	0.33	0.70

Data availability

Data will be made available on request.

Appendix

A.1. I-DIFFER details

The system is controlled according to the schematic in Fig. A.12. Here the thermal neutral temperature is based on EN 16 798-1:2019-05 [48]. The summer is defined as $ORM_{30} \geq 10$ °C (outdoor running mean temperature over the last 30 days) whereas the winter is defined as $ORM_{30} < 10$ °C. A hysteresis was introduced to avoid cycling around the thermal neutral temperature.

A.2. BPS model parameter

In the following two tables (Tables A.9 and A.10), the different glazing variations for both the traditional variation and I-DIFFER are outlined. These are based on the previous investigation by Bugenings et al. [24].

A.3. Orientation - detailed analysis

See Figs. A.13–A.16.

Appendix B. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.buildenv.2023.110199.

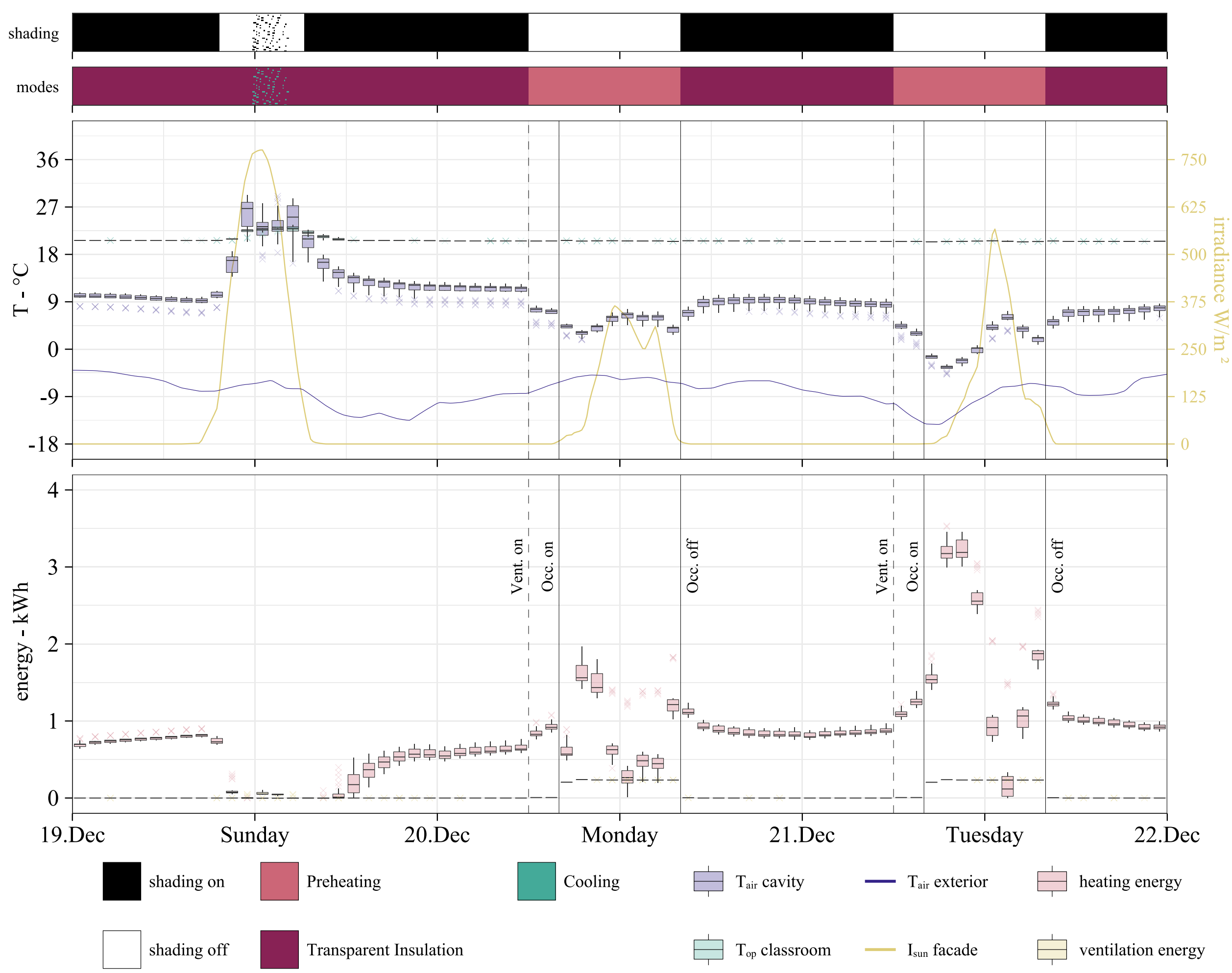

Fig. A.13. CW 52 south: Hourly averages of heating power, ventilation power cavity and classroom temperature. Instantaneous values for modes, shading, solar irradiation on the facade and outdoor temperature over all thermal comfort and energy valid variations (n = 30/50). Modes and shading represent all variations as lines above each other.

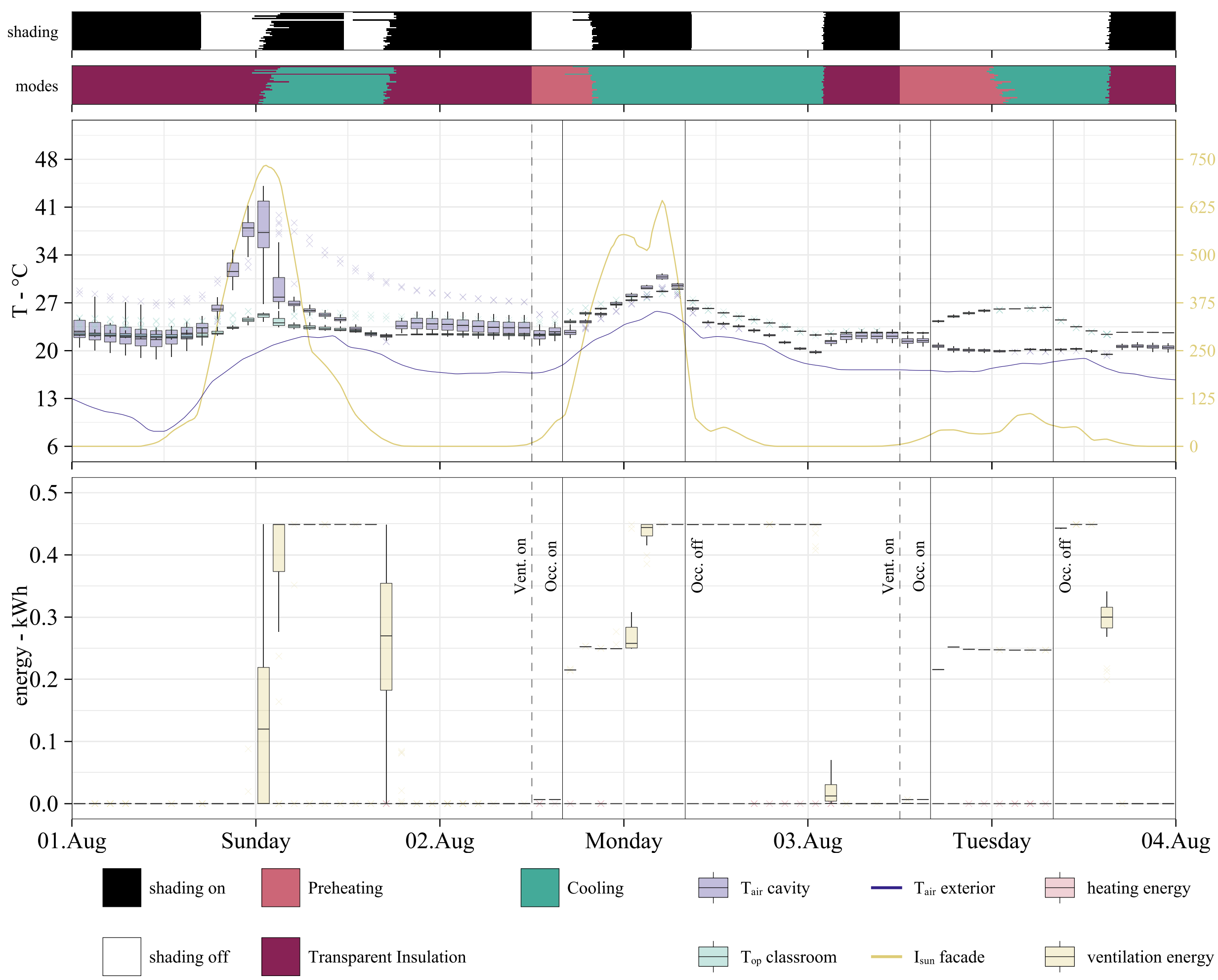

Fig. A.14. CW 32 south: Hourly averages of heating power, ventilation power cavity and classroom temperature. Instantaneous values for modes, shading, solar irradiation on the facade and outdoor temperature over all thermal comfort and energy valid variations (n = 30/50). Modes and shading represent all variations as lines above each other.

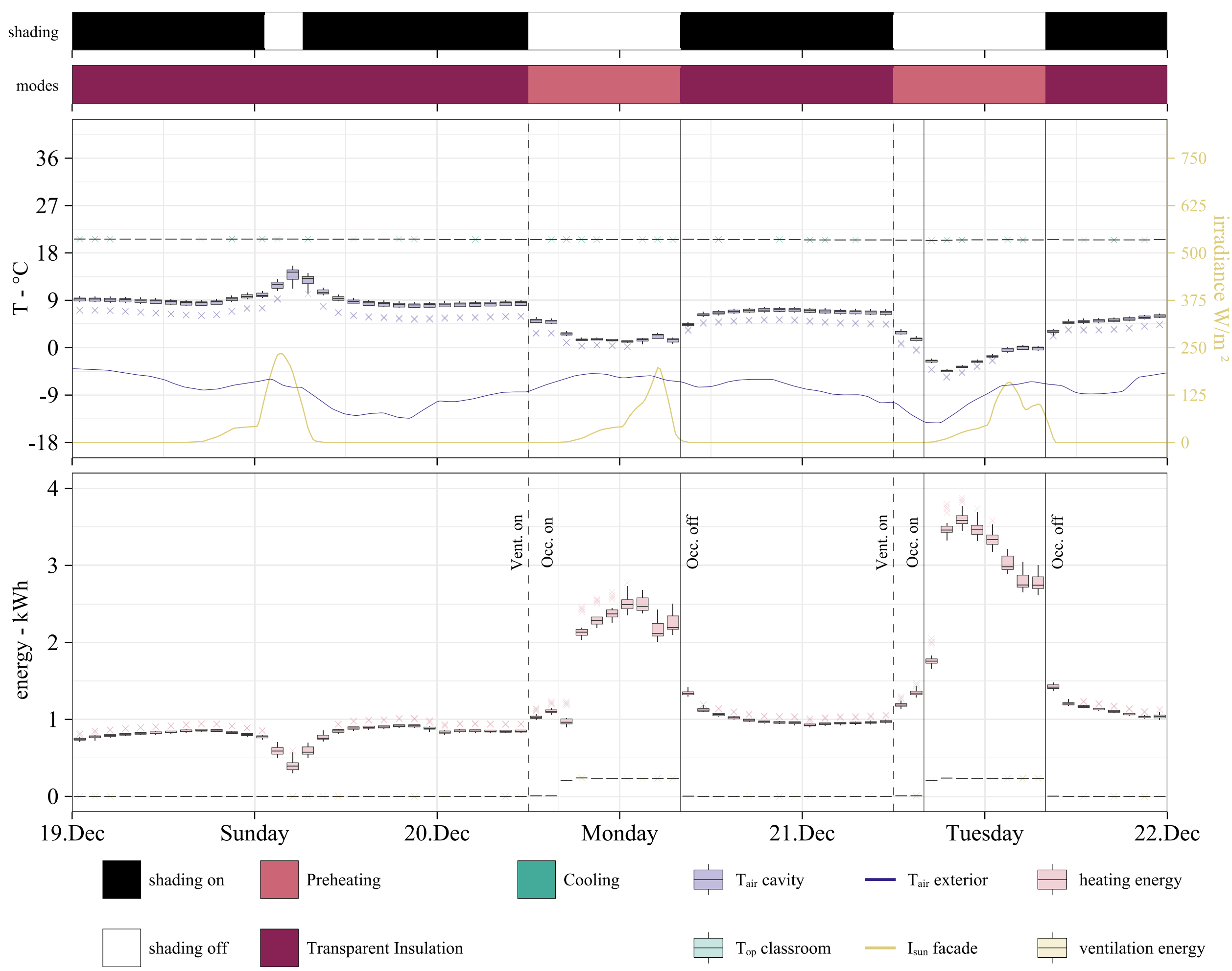

Fig. A.15. CW 52 west: Hourly averages of heating power, ventilation power cavity and classroom temperature. Instantaneous values for modes, shading, solar irradiation on the facade and outdoor temperature over all thermal comfort and energy valid variations (n = 29/50). Modes and shading represent all variations as lines above each other.

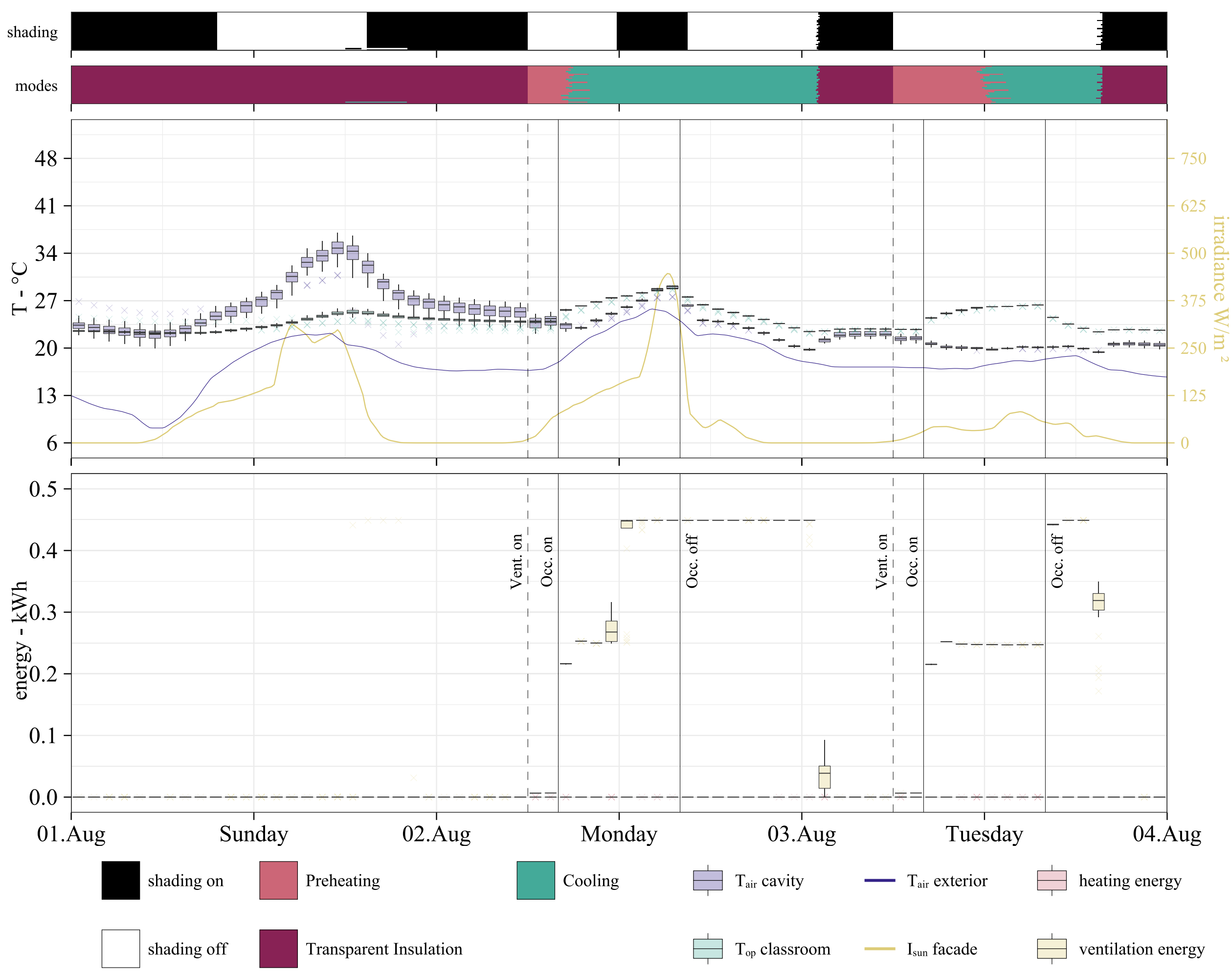

Fig. A.16. CW 32 west: Hourly averages of heating power, ventilation power cavity and classroom temperature. Instantaneous values for modes, shading, solar irradiation on the facade and outdoor temperature over all thermal comfort and energy valid variations (n = 29/50). Modes and shading represent all variations as lines above each other.

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