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Evaluation of the energy and comfort performance of a plus-energy house under Scandinavian winter conditions

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ABSTRACT
A plus-energy house was studied in terms of indoor environmental conditions and energy balance, during Scandinavian winter conditions. The studied building, EMBRACE, is a single-family detached dwelling of 59 m^2 with two floors. The house also integrates a semi-outdoor space, covered by a glazed envelope, whose thermal environment has been investigated. The house is located in Nordborg, Denmark and was undergoing a year-round measurement campaign, of which are hereby presented the results from 16/11/2015 to 04/03/2016. During this period, the house was operated in heating mode, with five different cases investigated, combining different set-points (20 to 22°C) and ventilation heat recovery settings.
The thermal comfort indoors proved to be satisfactory, depending on the chosen set-point. Up to 92 and 98% of the time was reported within the range 21-25°C (Category I of EN 15251) respectively on the ground and first floors when the set-point was 22°C. The electrical energy balance resulted to be negative, with a photovoltaic (PV) production of 432 kWh and a consumption from the mechanical systems of 1521 kWh during the studied winter period of almost four months. Put into perspective with the summer evaluation, these results show an encouraging trend towards achieving an annual positive energy balance as designed for this plus-energy house. The thermal environmental conditions in the semi-outdoor space resulted more comfortable than the outdoors, with reduced wind velocity, protection from rain, and temperature increase of up to 2-3°C during sunny days, which increases the possibilities of occupancy in this area.

KEYWORDS
Plus-energy house, Energy performance, Indoor Environmental Quality, Sustainable housing.

INTRODUCTION
With the recast of the Energy Performance of Buildings Directive (European Commission, 2010), all new constructions in Europe will have to progress towards the performance of nearly Zero Energy Buildings (nZEBs) by 2020. Even though the definition of nZEB can vary in different geographic locations, the design guidelines generally include increasing the level of insulation of the envelope, improving the air tightness, integrating passive design strategies and efficient ventilation heat recovery. In regions where heating is the predominant need compared to cooling, those rules enable to efficiently reduce the energy demand of a building. But does this reduction induce a deterioration of the comfort indoors? Are nZEBs truly capable of maintaining a satisfactory indoor environment with minimal energy use, or is the energy performance improved at the cost of the occupants' comfort?
In order to answer these questions, the present study evaluates the energy balance and indoor environmental quality of an actual building designed for plus-energy targets, i.e. meaning it should produce more energy from renewable resources than it imports from external sources in a given year (European Commission, 2009). The study case, EMBRACE, is a single-family

house constructed for the purpose of the Solar Decathlon 2014 competition, and currently situated in Nordborg, Denmark, where it is undergoing a year-round measurement campaign. The results from the summer period were previously reported by Péan et al. (2016) and stated the achievement of the plus-energy target while maintaining a comfortable indoor environment. The present study focuses on the winter period, from 16/11/2015 to 04/03/2016.

Description of the house and its mechanical systems

EMBRACE is a detached dwelling of 59 m^2 floor area, designed to host two to three occupants. It was conceived to be placed on top of existing buildings of two to three storeys, in the frame of a refurbishment process and in order to densify cities by occupying these unused spaces. However the house now stands at ground level in the same way as a standard detached dwelling. The thermal envelope of the house is divided into four modules, and is highly insulated with a U-value of 0.08 W/m^2K for the walls (glasswool insulation). It is covered by a second skin envelope formed by glazing, and which is referred to as the "Weather Shield". Part of the space below this weather shield consists of a sheltered garden which is not actively conditioned. The Weather Shield protects the structure from rain and wind and contains monocrystalline photovoltaic cells for the production of electricity, which are split into two categories: opaque panels above the house and semi-transparent panels above the sheltered garden (Figure 1). The total power of the installed panels amounts to 6.4 kWp, however only 4.7 kWp were operational during the studied period.

Figure 1. Outside view of the house from South-East (left), and inside view of the experimental setup with the thermal dummies (right).

The main terminal unit for heating and cooling is a dry-radiant floor system, covered with ceramic tiles. The heated or chilled water is produced by an air-to-water heat pump, and stored in a 800 litres tank. A pumping and mixing station then circulates the water in the floor circuit which consists of six different loops (four on the ground floor and two on the first floor). Mechanical ventilation is also installed in the house with active and passive heat recovery. It is set to a constant air change rate of 0.7 h^{-1} for the sole purpose of providing fresh air. Further details on the house's structure and mechanical systems can be found in (Péan and Gennari, 2014; Team DTU, 2014).

Winter operation of the house

The house was in heating mode during the studied period. Five different combinations of set-points and ventilation settings have been investigated, which are summarized in Table 1. The set-point of the radiant floor corresponds to the indoor operative temperature goal, set in four individual room thermostats located in different rooms. For the ventilation setting, "active and passive heat recovery" means that the Air Handling Unit (AHU) first circulated the intake air into the crossflow heat exchanger (passive); if the air temperature then remained too low, a small heat pump cycle was activated in order to increase the air temperature (active).

Table 1. Studied cases during winter 2015/2016.

Case	Start date	End date	Number of days	Set-point room operative temperature [°C]	Set-point heat pump [°C]	Ventilation heat recovery
1	16-11-2015	16-12-2015	30	22	35	Passive
2	16-12-2015	12-01-2016	27	21	30	Passive and active
3	12-01-2016	01-02-2016	20	20	35	Passive and active
4	01-02-2016	17-02-2016	16	20	35	Passive
5	17-02-2016	04-03-2016	16	21	30	Passive

The house was not occupied since it is located in a science-themed park that was closed to visitors during the winter period. To simulate the occupancy of two people as designed for the house, thermal dummies were used: two in the upstairs bedroom (average power of 102 W each), two at the ground floor level (average of 80 W each, Figure 1). Because of technical limitations, their power could not be reduced to 72 W usually considered for occupants at 1.2 met. The two couples of dummies were activated alternatively with timers, according to the schedule presented in Figure 2. An additional dummy of 99 W (1.7 W/m^2) represented the equipment constantly switched on (fridge, electronic equipment, devices in sleep mode etc., in green on Figure 3).

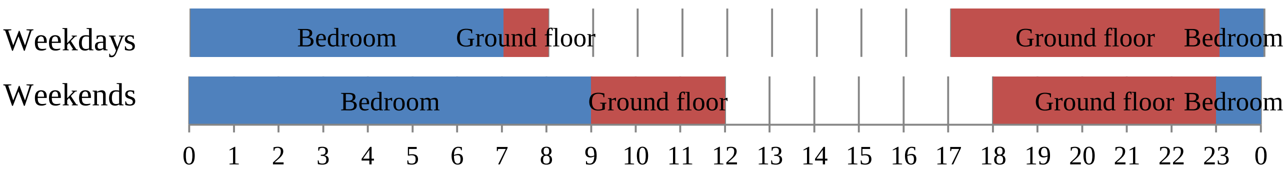

Figure 2. Operation schedule of the thermal dummies.

METHODS

Indoor Climate

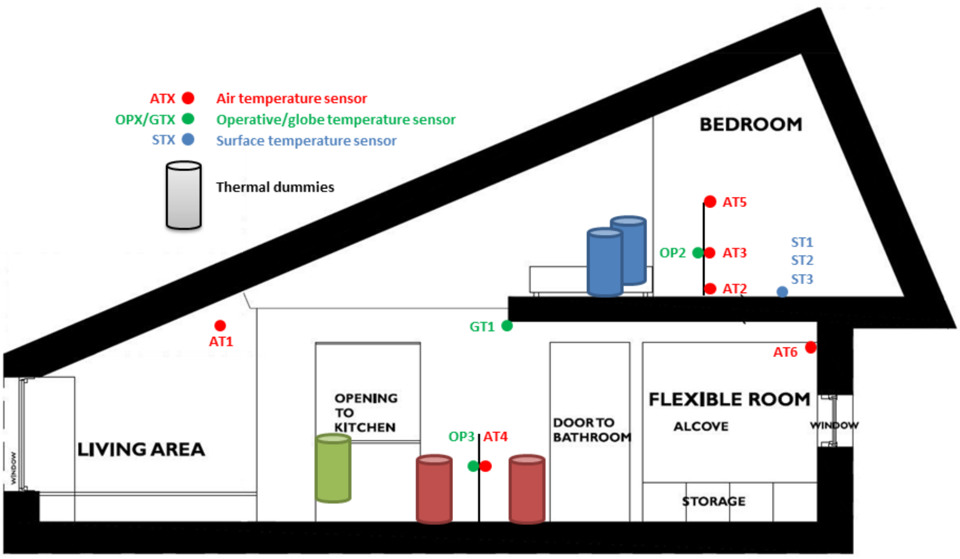

Figure 3. Experimental setup with location of thermal dummies and temperature sensors.

To assess the indoor thermal comfort, operative temperature was measured by PT100 sensors enclosed in Ø40 mm globes, calibrated in a climate chamber, with a resulting accuracy of ±0.3°C. One of these sensors was placed on the first floor, another one on the ground floor, both at 0.6 m heights. A third one of these globe temperature sensors has been placed hanging from the first floor, at ceiling height (2.5 m from the ground floor), to compare with measurements from the summer period (Péan et al., 2016). Air temperature was measured either by multi-sensor modules (accuracy of ±0.5°C) or by shielded PT100 sensors (accuracy of ±0.3°C). The locations of all sensors are presented in Figure 3, with sensors AT3, AT4 situated at 0.6 m height, AT2 and AT5 at 0.1 m and 1.7 m heights respectively. Additionally, three surface temperature sensors PT1000 were placed on the bedroom floor to record the temperature at the surface of the tiles.

A weather station placed on the roof recorded the outdoor conditions (accuracy of ± 0.5°C for the air temperature, ± 3% for the relative humidity and ± 1 m/s for the wind speed). Another weather station of the same model was placed in the sheltered garden to measure the difference between the climate under the weather shield and above it.

Energy use and production

The electricity use and energy produced by the heat pump was measured directly from the energy meter integrated in the heat pump. A heat meter is also installed in the circuit between the tank and the radiant floor pumping station. It measures the flow with an uncertainty of less than ± 5 %, and the temperature difference with an accuracy of ± $(0.15+2/\Delta T)$ % with ΔT the temperature difference between inlet and outlet.

Electricity use of the AHU was measured with an individual electric meter for Cases 3, 4 and 5. Mechanical ventilation accounted for an observed daily use of 7.2 kWh/day, and 7.4 kWh/day when active heat recovery was set. The difference is negligible and thus it is assumed that active heat recovery was rarely activated, even during the coldest period (Case 3). Similar values are adopted (7.2 and 7.4 kWh/day) for Cases 1 and 2 respectively.

The electricity use of the pumping, mixing and controlling station of the radiant floor has not been directly monitored, but Kazanci and Olesen (2014) reported in this matter a rather similar case. The house they studied was equipped with the same radiant floor system (Uponor), and the electrical use for the heating operation cases ranged from 0.1 to 0.6 kWh/day, with set-points of 20 to 21°C. Even though some bias could be introduced due to the different layout, a value of 0.6 kWh/day has been considered a safe hypothesis for the present case of EMBRACE.

RESULTS

Indoor Climate

Figure 4 presents the indoor operative temperature measurements, along with the outside air temperature (because of technical issues, data loss occurred between the 23rd of November and the 1st of December). The results show that the mechanical systems of the house were able to maintain the imposed indoor conditions; the difference between set-point and average temperature never exceeded 0.4°C in all cases. Only in two occasions, it was observed that the operative temperature on the ground floor dropped around 1°C below the set-point: on the 22nd-23rd of November and on the 2nd-5th of January, when a sudden decrease in the outside temperature was simultaneously monitored. Apart from these two episodes, the indoor temperature proved to be notably stable, since the standard deviation from the average temperature ranged from 0.2 to 0.4°C. The average temperature on the first floor was generally higher than on the ground floor, by 0.1 to 0.5°C depending on the studied case, and due to the thermal stratification in the open volume of the house.

The repartition of the time between the different indoor climate categories defined in EN 15251 (CEN, 2007) is shown in Figure 5. The results are satisfactory and correspond to the expectations given the set-points assigned for each case. With a set-point of 22°C (Case 1), 92% and 98% of the time is observed within the range of Category I, respectively in the ground and first floors. The thermal comfort is generally better in the first floor compared to the ground floor, because of the slightly warmer temperatures observed due to thermal stratification. A set-point of 20°C (Cases 3 and 4) appears to be too close to the limit, resulting in a significant proportion of time in Category III (between 9 and 25% of the time in Category III, i.e. with temperatures below 20°C).

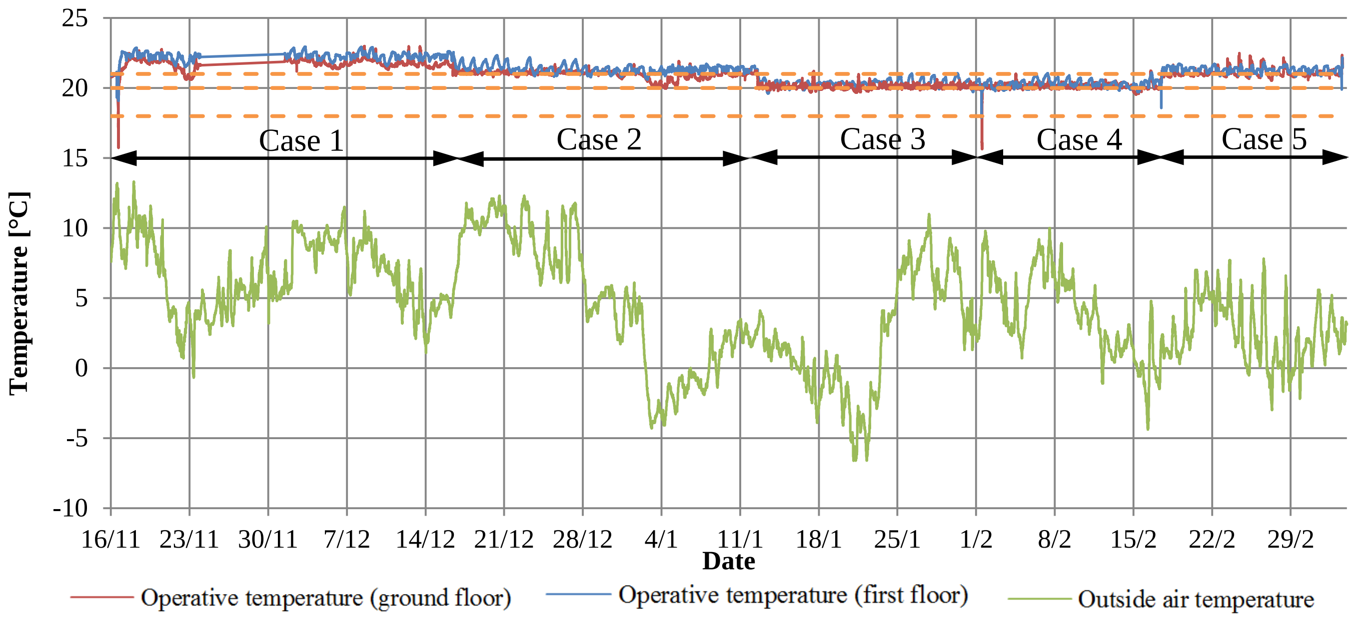

Figure 4. Operative and outside air temperatures (November 2015 – March 2016).

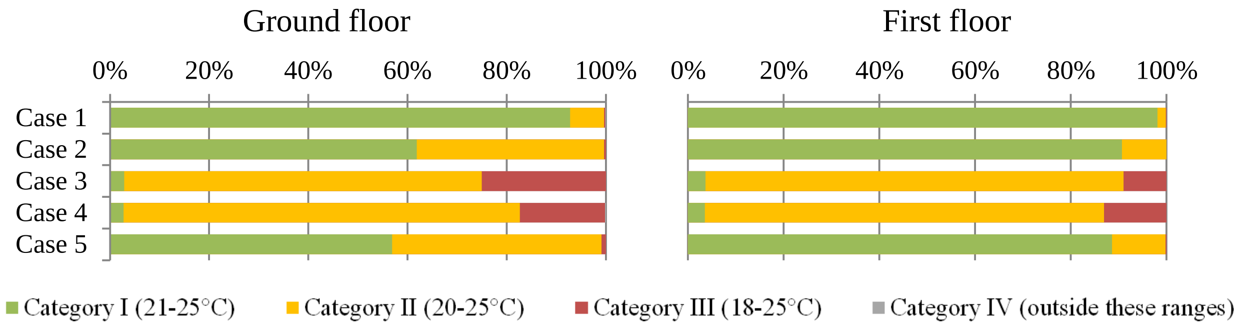

Figure 5. Repartition of the time between the different indoor climate categories.

HVAC systems

The daily heating energy provided to the radiant floor is presented in Figure 6, along with the outside air temperature. A clear relation between the outdoor air temperature and the heat provided to the space is visible. The highest values of 27 to 29 kWh/day were observed on Nov. 22nd, Jan. 3rd/4th, and Feb. 15th. The peak load was measured on Jan. 4th at 1.4 kW (29.5 W/m^2). Considering the additional internal loads of approximately 300 W, this value is slightly higher than the dimensioning case (1.6 kW or 34 W/m^2) which did not include internal loads and was calculated with an outside temperature of -12°C. This range of heating demand remains low for an individual dwelling, due the high level of insulation of the envelope. The heat output from the floor was measured on the first floor based on the surface temperature measurements. Results showed a peak heat output of 29 W/m^2 (radiant floor area) which is lower than the design case (50 W/m^2, Péan and Gennari, 2014). It is however assumed that the heat flux to the room was not uniformly distributed among the two floors: as the bedroom on the first floor was already partly heated from the warm air coming from downstairs, the heating demand was lower in that part of the house.

During January, which was the coldest month of the studied period, the water temperature averaged to 26.4°C for the supply, and 25.8°C for the return. These values are close to the indoor desired temperature. It thus confirms the low-temperature heating possibilities of a radiant floor terminal, which enables to produce the heated water at a lower temperature and hence a higher efficiency. The COP of the heat pump ranged from 1.6 (Case 3) to 2.2 (Case 1) during the studied period, which is lower than the manufacturer values in a similar setup (Daikin Europe N.V. 2015). However, the COP calculated here includes the electricity use of the pumps and the regulation system, not only the compressor.

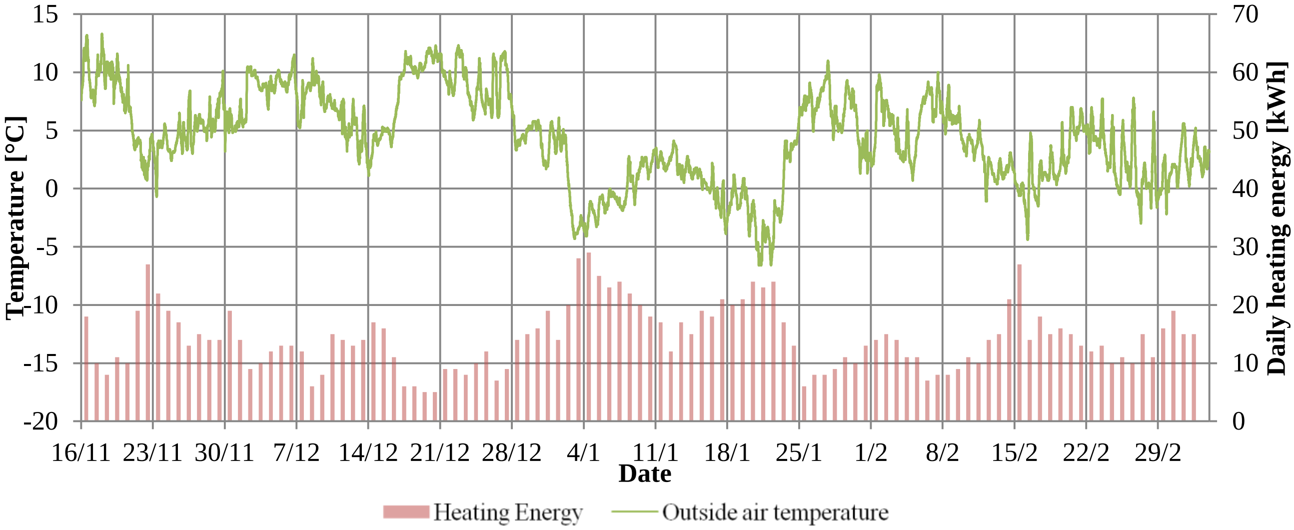

Figure 6. Daily heating energy measured by the heat meter.

Energy balance

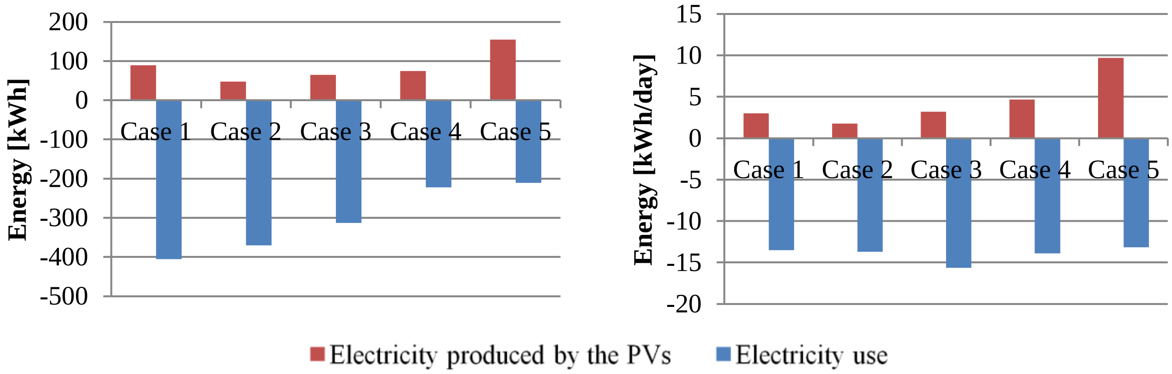

Figure 7. Electricity use and production for each case (left), and daily average (right).

For the energy balance of the house, the electricity use of the mechanical systems (heat pump, radiant floor and mechanical ventilation) has been compared to the electricity produced by the PVs. During the covered period of almost four months, EMBRACE produced 432 kWh of electricity while using 1521 kWh. The data detailed per case are presented in Figure 7, both the summed values and the daily average, which is more representative given the different durations of the cases.

The house used the most energy per day during Case 3, which was also the coldest (average outdoor air temperature of 1.8°C). Case 5 presented the closest equilibrium between electricity supply and demand: the PVs daily production reached almost 10 kWh in average thanks to particularly sunny weather conditions during this period, covering 73% of the demand during this case. The peak production was achieved on Feb. 26th at 17.3 kWh while on Jan. 2nd the weather conditions prevented the production of any electricity at all.

Semi-outdoor space

The sheltered garden constitutes a semi-outdoor space which transitions between outdoors and indoors. Even though it is not closed, the climate in this zone slightly differs from the outside weather. By means of the two weather stations placed above and below the shield, it was possible to compare both sets of climates. A temperature increase in the sheltered garden of up to 3°C was already reported by Péan et al. (2016) in September 2015. Similar differences have been observed over the winter (Figure 8, right), but it should be noted that this improvement only occurs during particularly sunny days. In cloudier weather conditions, the temperatures above and below the glazed weather shield remained equal (Figure 8, left).

The wind velocity is reduced in the semi-outdoor space, but still can reach up to 1.8 m/s in case of strong outside winds (up to 11 m/s above the roof). The wind protection is thus not perfect, but the weather shield also provides shelter from the rain.

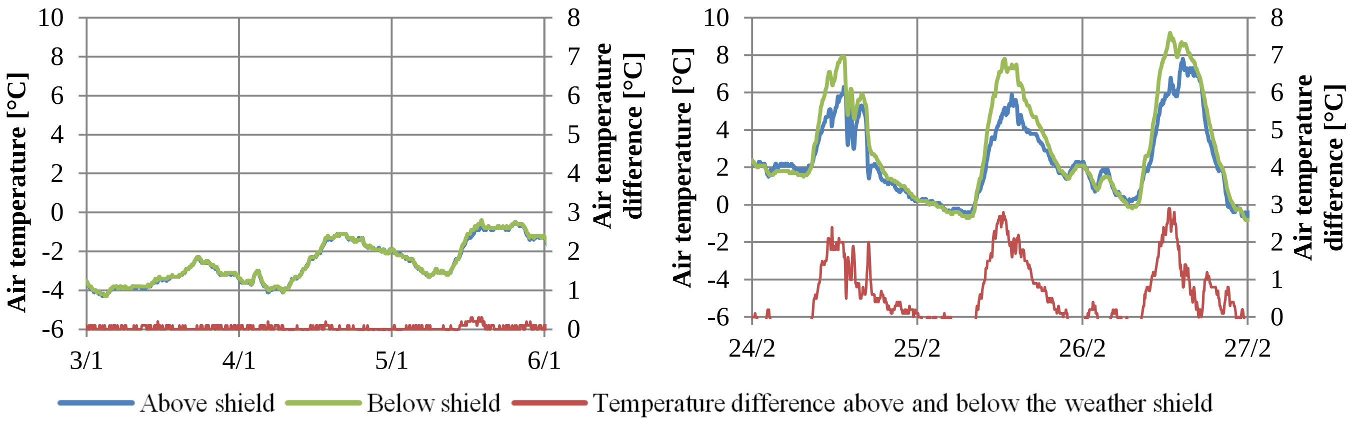

Figure 8. Comparison between the air temperature outside and in the sheltered garden, during cloudy days (left) and sunny days (right).

DISCUSSION

The results of the measurements show that the EMBRACE house was able to provide a comfortable indoor climate during a Scandinavian winter, also when the outside temperature was as low as -5°C. The occupancy was simulated by means of heated dummies, which represent the internal heat gains from occupants. It is expected that in the case of a real occupancy, the stability observed here in the temperature curves would be affected, notably through door and window openings and enhanced air mixing. The house's performance was however particularly satisfactory in terms of indoor thermal environment, and closer to reality than the results of the summer evaluation period, where occupancy was not controlled (Péan et al., 2016).

The energy used for heating exceeded the forecasted values, probably because of heat losses occurring through infiltration and thermal bridges. The house suffered from poor tightness due to its repeated assembly and disassembly. The electrical energy balance proved to be negative with a deficit of 1089 kWh during the studied period, which was an expected result due to the high heating demand and low solar resource usually encountered in a Scandinavian winter. The energy balance should be put in perspective on an annual basis: the summer evaluation from June to September 2015 showed on the opposite a surplus production of 1230 kWh (Péan et al., 2016). It is expected that the house would perform as a plus-energy building on a yearly basis, given that part of the PV panels were not operational during the summer period, which lowered the overall production.

The weather shield proved to protect the semi-outdoor space from rain, to reduce significantly the wind speed, and to increase the temperature by 2 to 3°C during sunny days, compared to the colder outdoors. Those results show a possibility for comfortable occupancy during a considerable amount of time (Papachristou et al., 2016). They also strengthen the initial design idea which consisted in conceiving a relatively small house, but with an additional semi-outdoor space usable a large part of the year. The reduction of the winter heating demand is another benefit of the weather shield design, and was studied besides by (Foteinaki et al., 2016).

CONCLUSION

The EMBRACE house was able to maintain a stable and comfortable thermal indoor environment during winter 2015-2016 in Denmark (up to 98% of the time in Category I of EN 15251). Even though the thermal comfort was satisfactory in winter, such a highly-insulated building could cause issues for the indoor conditions in summer. However, the evaluation previously carried out in the house showed that overheating did not result to be an issue, at least under the specified experimental setup and the Scandinavian climate of summer 2015 (Péan et al. 2016).

Overall, the house showed a deficit of electricity use during the winter period (-1089 kWh), but the surplus production observed in the summer period (+1230 kWh) balances this observation on the annual evaluation. These combined results show that EMBRACE was able to achieve the yearly positive energy balance of a plus-energy house, as it was initially designed, while providing a thermally comfortable indoor environment for the occupants.

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