Bæredygtige Energi-plus Huse: Part 2
Sustainable Plus-Energy Houses: Part 2

Slutrapport – Final Report
Projekt nr. 346-037

Af/by

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Summary

The present document is the final report of project 346-037 from ELFORSK, titled "Bæredygtige energy-plus huse: Part 2 – SDE 2014" (Sustainable Plus-Energy houses: Part 2 – SDE 2014).

The project focuses on a plus-energy house, EMBRACE, which was designed and built by a team of students from DTU in order to compete in an international competition, Solar Decathlon 2014. After that event, the house was disassembled and later rebuilt in Denmark (Sønderjylland), where it underwent a one-year long measurement campaign focused on its energy and indoor environment performance. This work was a continuation of project 344-060, which studied another plus-energy house, developed by DTU for the 2012 edition of the Solar Decathlon competition. The previous house, FOLD, was rebuilt in Jutland where it went through a similar measurement campaign of one year.

Further than the house itself, a particular technology was investigated in the frame of this project: nocturnal radiative cooling with solar panels. This technology was implemented in the EMBRACE house as a means of providing passive cooling, but the tests during the Solar Decathlon competition were not sufficient to state on the potential of such a system. Therefore, an experimental facility was built at DTU with two types of solar panels, in order to study further their possibilities with regards to nocturnal radiative cooling.

Following these two main topics, the present report is structured as follows. Chapter I describes the EMBRACE house, its architectural concepts and some details of its mechanical systems. Chapter II relates the Solar Decathlon competition in June-July 2014 and the performance of EMBRACE during this event. In Chapter III, the measurement campaign carried out in Denmark is recounted, from the experimental setup to the analysis of the recorded data. Chapter IV details the studies performed on nocturnal radiative cooling and the publications produced on this topic. Eventually, discussions and conclusions are drawn about the outcome of the project. A final chapter presents the dissemination activities carried out in the frame of the project: master and bachelor thesis, presentations, publications in journals and conferences.

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Abbreviations

AHU	Air Handling Unit
DF	Daylight Factor
DHW	Domestic Hot Water
DTU	Technical University of Denmark, name of the team participating in SDE2014
HVAC	Heating, Ventilation, Air-Conditioning
ICIEE	International Centre for Indoor Environment and Energy (DTU)
NRC	Nocturnal Radiative Cooling
nZEB	Net-Zero Energy Building
PCM	Phase Change Material
PV/T	Photovoltaic/thermal
SDE	Solar Decathlon Europe

Introduction

The European Union has fixed ambitious goals for reducing the amount of energy used by buildings. By 2020, the Energy and Performance of Buildings Directive (EPBD) states that all new constructions should meet the standards of net-zero energy buildings, also known as nZEB (European Commission, 2010). A further goal consists in designing new residential dwellings as plus-energy houses, i.e. houses that produce more energy from renewable energy resources than they import from external resources in a given year, according to the definition given by the European Commission (2009). These ambitions have set the expectations at a high level, but some questions arise when it comes to the realization of these plans.

First of all, the feasibility of plus-energy houses could be questioned. Our growing needs for improved comfort and living standards lead to increased energy use. In this context, can a single house still produce enough energy for itself, simply with a photovoltaic system not larger than its own roof? Some prototypes have already been evaluated and proved the possibility of achieving the plus-energy target (Kazanci and Olesen, 2014), but more examples of such buildings should be brought forward. If more study cases show evidence of the feasibility to meet such high standards, the industry will more likely move forward in this direction.

Secondly, the comfort in passive houses has gotten bad press among the general public. A lot of people have come to believe that the achievement of a passive or plus-energy house is made at the cost of the occupants' comfort. The problem is that this public opinion can slow down the large-scale deployment of such sustainable buildings. Do these statements rely on scientific facts? Can plus-energy houses truly provide a comfortable environment with a minimal energy use? Or is the energy performance improved at the cost of the inhabitants' comfort? Those questions need to be answered, and their answers spread to a large audience, to raise the general awareness in favour of sustainable buildings.

Finally, one issue of sustainable buildings in general is the realization of the design goals. During the conception phase of any building, numerous calculations are performed to estimate its future energy use or its comfort level. These simulations already contain some level of errors. Furthermore, few verifications are generally carried out once the building is completed, to check for example if the building works have been executed in the desired way. These uncertainties can lead to considerable differences between the estimated performance of a building and its actual performance (Maivel et al., 2015).

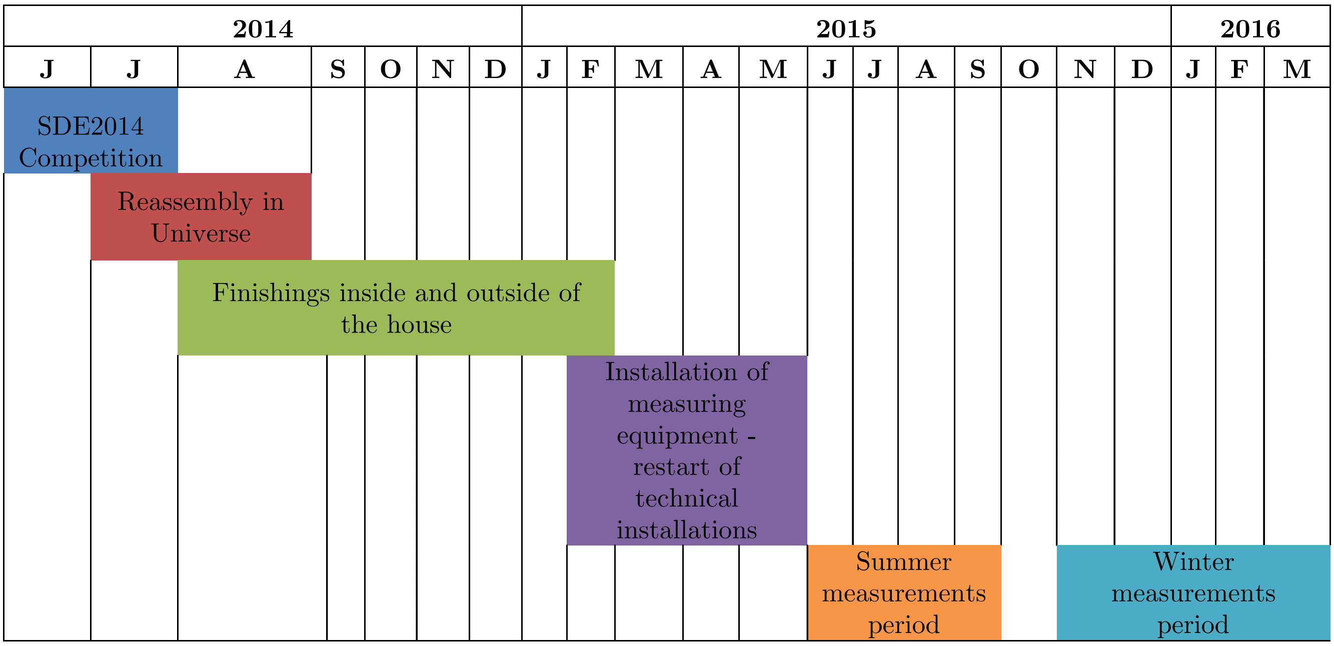
In relation to these identified issues, an actual house was studied: EMBRACE, which had been designed as a plus-energy house. The objectives of the project were to verify if EMBRACE can reach a positive energy balance over the course of one year, to evaluate the level of comfort of its indoor environment, and to compare the projected performance of the house with its actual performance.

EMBRACE was designed and built by DTU students for the Solar Decathlon event in Europe in 2014. Solar Decathlon is an international competition in which 20 teams of students from all around the world gather in one place to erect their prototype house. The 20 houses are then evaluated: as the name *decathlon* suggests, ten subcontests form the competition and each one comprises a certain amount of available points. Some of the subcontests are evaluated by monitoring (measurements performed inside the houses), and others by competent juries. The European edition of Solar Decathlon took place in Madrid in 2010 and 2012, and in Versailles, France, in 2014. DTU participated in 2012 with the house

FOLD and in 2014 with the house EMBRACE. The former was rebuilt in Bjerringbro while the latter was rebuilt in Universe, a science-themed park situated in Nordborg, also in Denmark.

One specific technology was implemented in the EMBRACE house in order to reduce its energy use in summer: nocturnal radiative cooling. It simply consists in utilizing solar panels at night in order to cool water through radiation heat exchange towards the cold nocturnal sky. This concept has gained interest in the recent years, notably with the extension of radiative cooling also to daytime (Raman et al., 2014). However, the literature on the topic is relatively limited, therefore this technology has been considered worth investigating with further in-depth studies. Experimental and simulation works have been carried out in this objective during the project, and are the subject of part of the present report.

The timeline of the EMBRACE project is presented in Figure 1, and some photos in Figure 2. Two main measurement periods were performed, in summer 2015 and winter 2015-2016. Some measurements were also gathered during the remaining periods but were not the subject of detailed analysis or publications.



2014							**2015**												**2016**		
J	**J**	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**
SDE2014 Competition																					
	Reassembly in Universe																				
		Finishings inside and outside of the house																			
								Installation of measuring equipment - restart of technical installations													
												Summer measurements period					Winter measurements period				

Figure 1. Timeline of the Solar Decathlon project.

Figure 2. Photos of the EMBRACE house, during SDE2014 (left), and back in Denmark (right).

I. The EMBRACE house

1. General description of the house

EMBRACE is a dwelling designed for a two people family, brought to life by combining passive architectural solutions and active technological solutions in one building. It comprises two floors summing up to 59 m^2. EMBRACE was conceived as an addition to be installed on the rooftop of an existing building, in order to densify the cities and occupy these unused spaces. In the course of a refurbishment process, EMBRACE could be added on top of the building, and enter in symbiosis with the existing construction: for instance the excess electricity production from the PVs of EMBRACE could be redistributed, or the heat recovered from the central ventilation system could be used to heat the EMBRACE rooftop house. The motto of the project is summarized in three S-words:

SMART SAVE **SHARE**

SMART for designing and operating the house in an intelligent and efficient manner; SAVE to emphasize the potential energy and financial savings of such a building; SHARE to incite the occupants to share facilities or energy production within the community and the building beneath.

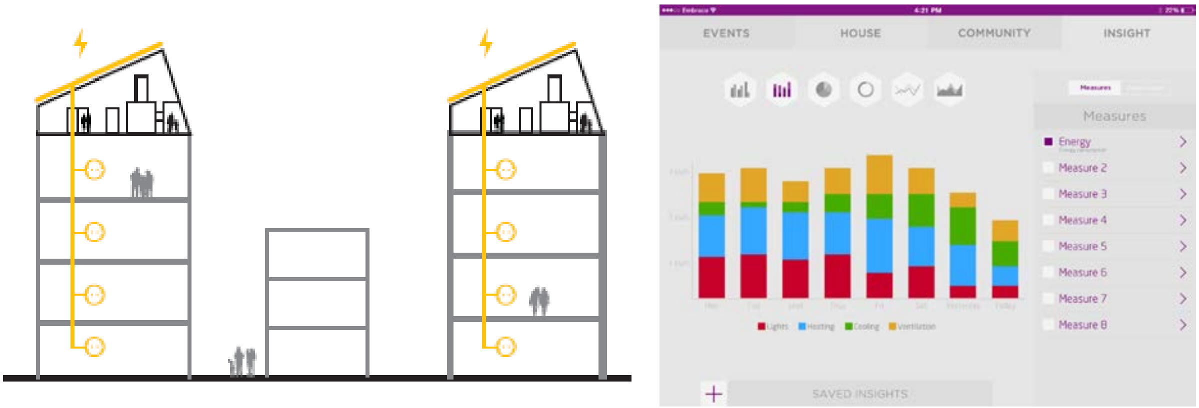


Figure 3. Rooftop concept of EMBRACE (left), and app designed to control the house (right).

Figure 3 shows the example of the rooftop addition and electricity redistribution (left), as well as the app designed to control the house's systems (lights, windows, heating, cooling, ventilation...) and give detailed feedback to the users about their electricity consumption so that they could react upon it.

1.1. Weather Shield and semi-outdoor space

The concept behind the name "EMBRACE" relies on the splitting of the building envelope in two different parts: the Thermal Envelope and the Weather Shield. The Thermal Envelope refers to the conditioned dwelling unit and the Weather Shield is a glazed second skin, "embracing" and protecting the underneath space from water, wind, direct radiation and snow. The shield overhangs from the dwelling and creates a covered outdoor area - the

Sheltered Garden, which is not actively conditioned. This design strategy consisted in keeping the inhabitable Thermal Envelope relatively small since the Sheltered Garden provides an additional space that is comfortable a major part of the year. It thus encourages people to live in smaller dwellings, reducing the heated or cooled area. Additionally, the Weather Shield enables to build the Thermal Envelope and the Sheltered Garden with simpler and different materials that would normally be used only for indoor constructions.

As the house was to perform during the Parisian warm summer, it was decided not to completely close the Sheltered Garden, to let the air flow through it so that to avoid overheating due to the greenhouse effect. The intention was to close the semi-outdoor space when the house was erected again in Denmark, but this project was not brought to fruition due to a lack of funding.

Figure 4. Second skin concept (left); Realization: Sheltered garden and Weather Shield in Versailles (middle), occupancy by kids in the Universe theme-park (right).

1.2. Thermal envelope and modular design

The first step of designing a plus-energy house obviously consists in reducing its heating demand by increasing the insulation level. For this reason, the external walls of EMBRACE comprise around 40 cm of glasswool insulation, resulting in a U-value of 0.08 W/m^{2}K. The roof and external floor have a similar level of insulation with U-values of 0.085 and 0.1 W/m^{2}K respectively. The chosen windows and glazed doors are made of triple-glazing which enables very low U-values of 0.8 W/m^{2}K. The construction of the thermal envelope is divided in four modules to enable easy transportation and assembly, as can be seen in Figure 5.

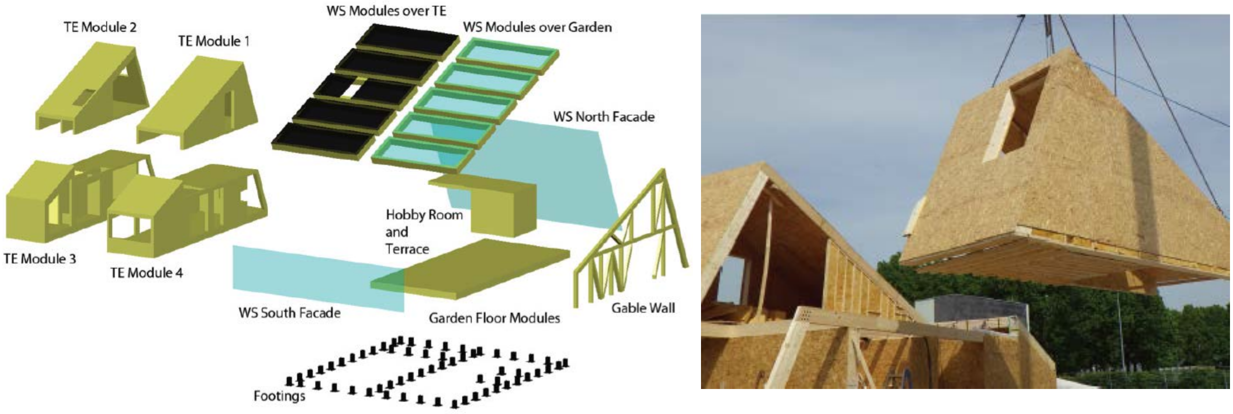


Figure 5. Construction of the house (left) and assembly at DTU in May 2014 (right).

2. Systems

In this section, the different mechanical systems chosen and implemented in EMBRACE are described. For further details, see Gennari and Péan (2014).

2.1. Solar collectors

For hot water production (DHW), flat plate solar collectors have been mounted on the upper part of the weather shield, with connection pipes going down to the technical room. Two copper collectors of 2.2 m^2 each have been installed, summing up to 4.4 m^2 absorber area. They were integrated in the weather shield, below the glazing panels and above an insulation layer of 10 cm of glass wool. The system includes an expansion vessel of 20 litres and does not allow drain back.

Given the unpredictability of the solar production, other systems were implemented for the hot water production. The ventilation unit (Compact P from Nilan) includes a small compressor, which acts as active heat recovery and can transfer heat from the exhaust air to the DHW tank. Furthermore the DHW tank is equipped with a backup electric heater. The DHW was also used to supply directly the washing machine, dishwasher and dryer.

Once the house has been reassembled in Denmark the solar collectors have been disconnected. In fact EMBRACE was not inhabited in Universe, therefore no hot water tapping was planned, and it would furthermore have caused issues with the safety rules of the park when the house was open to the public.

Figure 6. View of the flat-plate thermal collectors before their mounting on the Weather Shield (left), and the unglazed collectors for cooling on the ground (right).

Other collectors of a different type (unglazed) have been laid down on the ground in the north side of the house during SDE2014. Those panels were used only at night, in order to exploit the nocturnal radiative cooling (see chapter IV). They were cooling the water of the storage tank, which was then used by the radiant floor for space cooling during daytime. This technology was not implemented back in Denmark, due to the reduced cooling demand.

2.2. Terminal unit for heating and cooling: radiant floor

The main provider of heating and cooling to the space of the house is a dry-radiant floor system. It has been chosen because it is a water-based, low temperature heating and high temperature cooling system. The heated or chilled water needed to operate a radiant floor has a temperature closer to indoors, compared to other systems, and therefore it can be produced at higher efficiencies (by a heat pump for example).

The radiant floor system has been sized according to the load calculations and the methods of EN 1264 (CEN, 2008). The main results for the dimensioning cases are presented in Table 1, and they have been corroborated with a 2D heat transfer model (HEAT2). It has to be noted that the cooling and heating dimensioning cases are based on different climates due to the competition requirements, which is a rather unusual design method.

For the floor covering above the radiant system, ceramic tiles have been chosen over a solution of chipboard plate with linoleum. Ceramic tiles were easier to mount on the floor during the repeated reassemblies of the house, and they provide a higher heat flux to the room thanks to their higher conductivity. Even though the chosen ceramic tiles included a thin rubber layer beneath to enable them to adhere to the floor, it has been verified that the whole system was able to cover the heating and cooling needs. The radiant floor system is made out of six different loops, two on the first floor and four on the ground floor.

Table 1. Dimensioning cases.

	HEATING **Copenhagen (-12°C)**	**COOLING** **Paris (30°C)**
Design load (indoor 21°C/25°C)	1600 W	1500 W
Design heat flux to the room	50 W/m^2	40 W/m^2
Design supply temperature	28.5°C	16°C

2.3. Heat pump

To produce the heated or chilled water necessary for the radiant floor operation, an air-to-water heat pump was installed. The chosen model, Daikin Altherma, consists of an indoor module with the control and pumping station, and an outdoor module with the fan, both linked by the refrigeration cycle. The main characteristics of the chosen product can be found in Table 2.

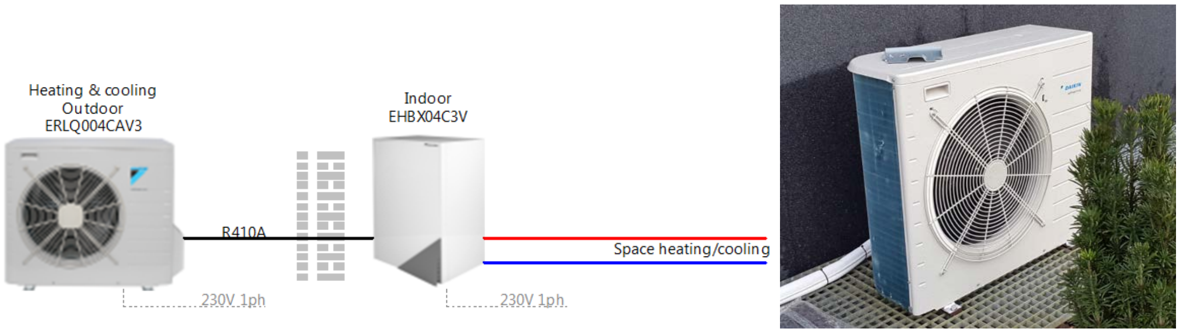


Figure 7. Principle scheme of the heat pump (left), external module placed on the West wall of the house (right).

Table 2. Principal characteristics of the heat pump.

Heat Pump overview – Daikin Altherma ERLQ004CAV3	
Nominal heating capacity	4,31[1]/3,50[2]kW
COP	4,72[2]/3,81[3]
Operation range heating	-25,0 / 25,0°C (ambient condition, wet bulb)
Nominal cooling capacity	7,04[3]/4,98[4] kW
EER	3,21[4] /2,58[5]
Operation range cooling	10,0 / 43,0°C (ambient condition, dry bulb)
Refrigerant	R410A

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[1] Entering water 30°C;Leaving water 35°C; ambient conditions: 7°C dry bulb/6°C wet bulb

[2] Entering water 30°C;Leaving water 35°C; ambient conditions: 2°C dry bulb/1°C wet bulb

[3] Entering water 23°C;Leaving water 18°C; ambient conditions: 35°C dry bulb

[4] Entering water 12°C;Leaving water 7°C; ambient conditions: 35°C dry bulb

2.4. *Mechanical ventilation*

Mechanical ventilation is provided through the Nilan Compact P unit which is equipped with a counter flow heat exchanger for passive heat recovery (85%), and a small heat pump cycle which enables to reach even higher percentages through active heat recovery. Fresh air is supplied in the flexroom, staircase and bedroom floor, and exhausted in the bathroom, bedroom and through the kitchen hood (see Figure 8). The DHW tank of 180 litres is included in this unit, and can be heated also via the active thermodynamic cycle.

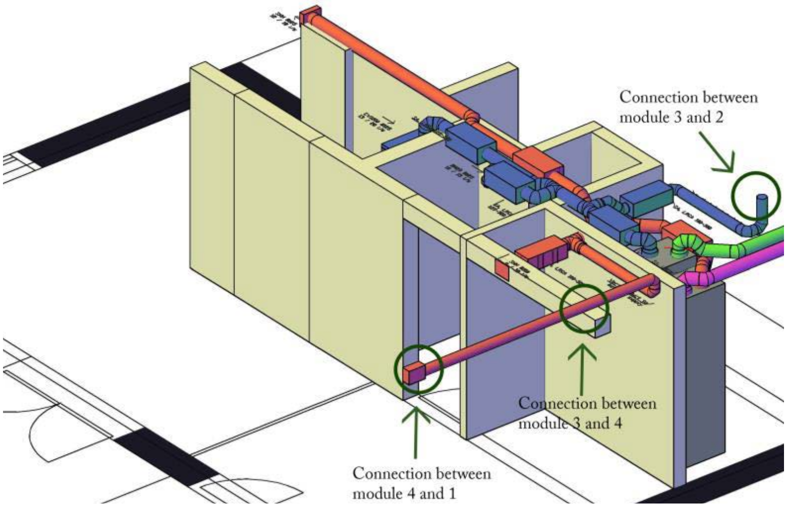

Figure 8. Mechanical ventilation in EMBRACE.

The mechanical ventilation in the house was designed for energy savings via different air flow steps for maximum, minimum and unoccupied requirements set by current standards (Haagensen, 2014). The normal mode is the basic ventilation rate, corresponding to around 0.7 h^{-1} (see Table 3), and it is the ventilation mode chosen for the operation of the house in Universe. Another "away mode" was intended when the occupants are not present in the house, but the current regulations do not formally allow a lower air change rate, regardless of occupancy. Additionally, the air flows were meant to be individually controlled per room, so that the maximum air flow is not imposed to the whole house if there is pollution in only one room. These approaches were part of the larger Intelligent Home Control (IHC), which unfortunately had never been fully functional.

Table 3. Ventilation rates in EMBRACE

	Normal mode	Forced mode
Room	Supply	
Bedroom	8 l/s	8 l/s
Living room	12 l/s	21 l/s
Flexroom	9 l/s	16 l/s
	Exhaust	
Bedroom	7 l/s	7 l/s
Kitchen	11 l/s	20 l/s
Bathroom	8 l/s	15 l/s

2.5. *Photovoltaic installation*

The electricity is produced in EMBRACE through monocrystalline PV cells integrated in the glazed Weather Shield, divided in two parts: opaque panels situated above the house, and semi-transparent tiles above the sheltered garden, arranged in a more scattered pattern in order to let the light through to the garden (see Figure 9, top). Around 2/3 of the electricity is produced by the opaque panels, and the remaining third by the semi-transparent panels. The total installed power sums up to 6.8 kWp, however because of the limits set by the competition, two rows of panels were never connected to the inverter (see Figure 9). Additionally, a dysfunction occurred some time in 2015 in one of the semi-transparent panels, shutting off this whole part of the system. As it was not possible to fix the issue, the defective row was simply excluded from the circuit on Nov. 16th 2015, so that the rest of the semi-transparent panels could still produce electricity.

Table 4. Different successive states of functioning of the PV panels.

	Opaque panels kWp	Semi-transparent panels kWp	**TOTAL kWp**
Installed power	4.6	2.2	**6.8**
SDE 2014 competition	2.9	2.2	**5.1**
Universe, spring and summer 2015	2.9	0	**2.9**
Universe, from 16/11/2015	2.9	1.9	**4.7**

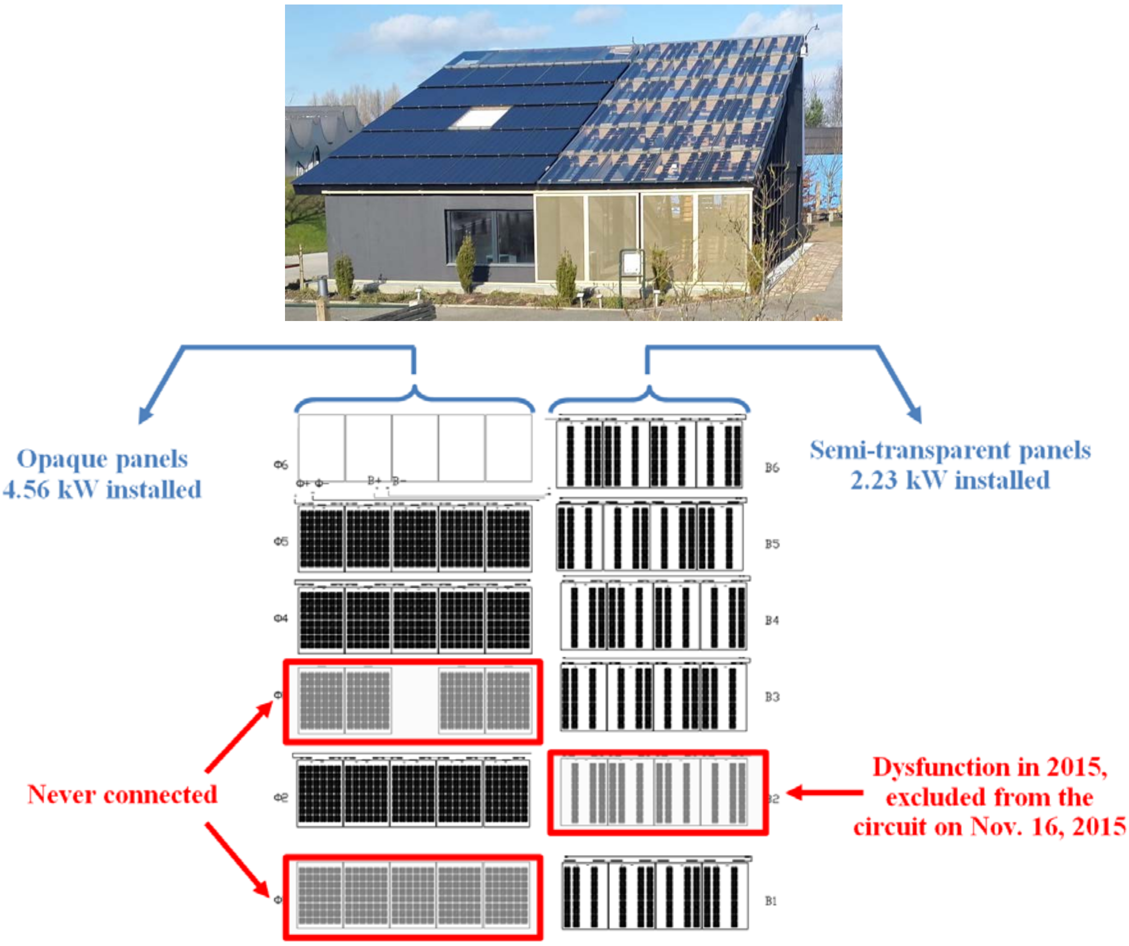

Figure 9. View of the PV roof (top), and scheme of the PV panels (bottom).

3. *Control of the heating and cooling systems*

The systems described in the previous sections were laid out according to the hydraulic scheme of Figure 10. In cooling mode, the unglazed collectors[5] would produce cold water at night through radiative cooling, which would be stored in the tank. If the temperature in the tank was not cold enough at the end of the night, the heat pump could cool the water further down. The Uponor control system would then decide to operate the different loops of the radiant floor, based on the set-point, the actual indoor temperature and relative humidity recorded by the thermostats, the return water temperature and the available water temperature in the tank.

The systems are operated in a similar way during heating mode, except that the heat pump is then the only source of heating in the storage tank. The heat pump controls the temperature in the storage tank by checking at regular time intervals, and by activating the refrigeration cycle if the measured value does not meet the set-point. Previous calculations had determined a set-point of 28°C for the heating case and 16°C for the cooling case to be input to the heat pump (Gennari and Péan, 2014).

The control strategy presented here had been simplified from the initial design, and it separates the demand side (radiant floor) from the supply side (heat pump), by the use of an intermediate storage tank. A demand-based control could be a better strategy, matching directly the production to the demand, but it was not possible to implement it because of the complication level and the time issues.

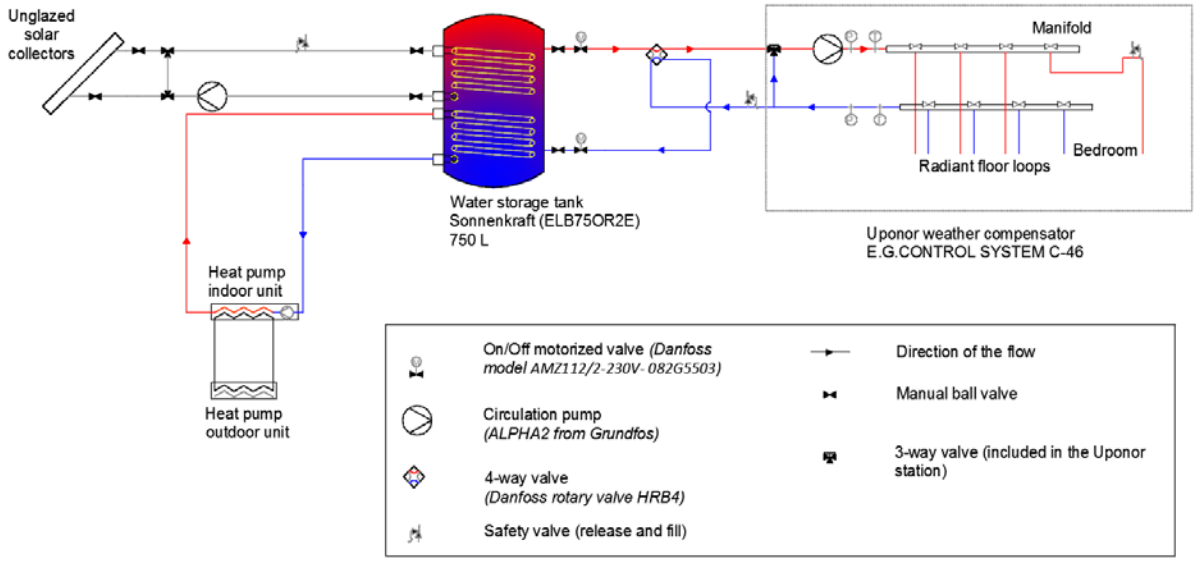

Figure 10. Hydraulic scheme of the systems in EMBRACE, here in heating mode.

4. *Comparison and improvements from FOLD*

Team DTU had previously participated in the Solar Decathlon competition in 2012: the house FOLD competed in Madrid and was brought back to Denmark (Bjerringbro), where it underwent a similar year-round measurement campaign. This constituted a chance to benefit from our previous experience and improve the house design based on past mistakes. The designs of the two houses can be seen on Figure 11.

The thermal envelope of FOLD was "folded" on itself to form a unique large space in the house. Two large glazing facades delimited the space on the South and North sides. This

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[5] The unglazed collectors were not reinstalled when the house was rebuilt in Denmark.

design proved to be costly in terms of energy use, both for heating in winter and cooling in summer due to high heat losses and solar gains, respectively. Even though this concept was architecturally pleasing, it was not kept for EMBRACE where only few glazing doors and windows were implemented. The sheltered garden actually acted as a buffer zone to reduce the need for heating in winter for example.

Figure 11. Comparative designs of FOLD and EMBRACE.

The organization of the space has also been improved. FOLD presented a unique space which gave little opportunity for privacy. EMBRACE also has an open space, but it is more divided, firstly with the two different floors, and secondly between the different rooms, with the bathroom and kitchen spaces better delimited.

Another problem encountered in FOLD was the high energy consumption of the control systems. In addition to the different sensors and control units, a computer was placed and constantly turned on for the systems to operate correctly. It resulted in a high electricity use for this part (up to 39% of the total electricity consumption, Kazanci and Olesen, 2014). For EMBRACE, it was decided to decentralize this electricity use by using a cloud service: the data was sent and processed by a server situated outside, where the energy use was better managed, and therefore a part of the electricity use was not directly accounted for in the house.

The last major change concerned the integration of the photovoltaic panels: FOLD was covered with PV/T which produced both hot water and electricity in a unique system. In EMBRACE, it was chosen to split between solar thermal collectors and photovoltaic cells. This decision relied mainly on the still excessive cost of the PV/Ts, and the increased individual efficiency of separated systems compared to a joint system. Furthermore, some transparency was needed above the sheltered garden, therefore hot water production was not possible on that part of the Weather Shield. The final decision could still be discussed as PV/Ts have advantages and were well integrated in the roof of FOLD (Team DTU actually received a prize to reward this particular aspect of the design) but they increase the overall cost of the house significantly, which is also not to be neglected.

II. Solar Decathlon Europe 2014

1. Competition

Solar Decathlon Europe 2014 took place in Versailles, France, during the months of June and July 2014. The 20 teams had approximately 10 days in June to erect their prototypes, and the competition started officially on June 30th, for 12 days. The organizers of the competition monitored several parameters constantly such as the indoor operative temperature, relative humidity, CO_2 concentration, electricity production and consumption, temperatures in appliances such as fridge, freezer and oven. The monitoring was active during the whole period, but the public opening hours of the houses were discarded for the point awarding. Jury presentations took place in the house for the subcontests that were not based on monitoring, such as architecture or communication for example.

Team DTU encountered several problems during the assembly period, mainly because of delays in the delivery of the house's modules to Versailles, and an accident during the mounting of one panel of the weather shield. However, EMBRACE was completed on time and stood ready on June 30th to start competing with the 19 other prototype houses.

Figure 12. Cité du Soleil and EMBRACE under construction.

2. Comfort Conditions subcontest

The main task for the Comfort Conditions subcontest consisted in keeping the indoor operative temperature within the limits imposed by the competition (65 points out of 120). The organization was publishing each day the set-point to be achieved during the day with a tolerance of ±1°C. This set-point was derived from the running mean outdoor temperature of the previous days, and could result in relatively high values (around 24-25°C). The temperature in July in Paris is not necessarily warm (temperature can drop down to 10-15°C at night), therefore it could have become problematic to keep the set-point also at night. In fact, heating would probably have been needed during the summer nights, which would have been totally paradoxical for houses that aim to be passive and energy-efficient. For these reasons, the organization introduced a night setback, allowing the indoor temperature down to 18°C from 0.00 until 8.00 every night (see the red lines showing the limits in Figure 13).

The temperature requirements are strict: a range of indoor temperature of 2°C is relatively narrow, and it can result difficult to stabilize the temperature within this range, given the fluctuating outdoor conditions and internal gains, especially because of the public tours taking place in the house. The recorded temperature curves are presented on Figure 13, along with the outside conditions and range imposed by the competition. The weather was remarkably cold during the considered period, therefore overheating did not result to be an issue (only on July 3rd temperatures exceeded the maximum limit). Given that cooling was obviously not needed, the team actually decided to shut down the heat pump, to save on the electricity use and gain more points on that other subcontest. Keeping the temperature above the minimum limit posed more issues: the mechanical ventilation was capable of warming the supply air, but this again used energy. The team therefore tried to benefit from the internal gains generated by the mandatory House Functioning tasks, for example by turning on the oven in the mornings.

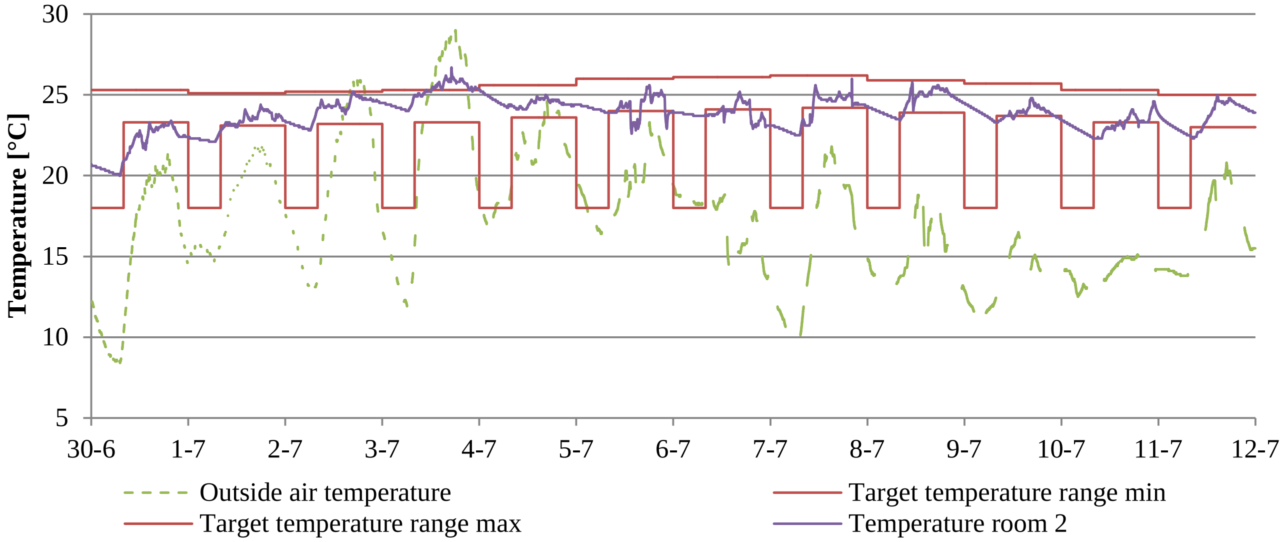

Figure 13. Official operative temperature measurements during SDE2014.

Overall the house performed very satisfactorily in this subcontest. 62.05 points out of 65 were awarded to Team DTU for this temperature contest. The indoor temperature stayed within the organization range during between 62 and 73% of the time. It should be considered that a lower set-point (thus for heating) is usually not taken into account in summer, when cooling constitutes the main demand. If only the upper limit (cooling set-point) is considered, these percentages are higher: the indoor temperature stayed below the upper limit between 83 and 96% of the time.

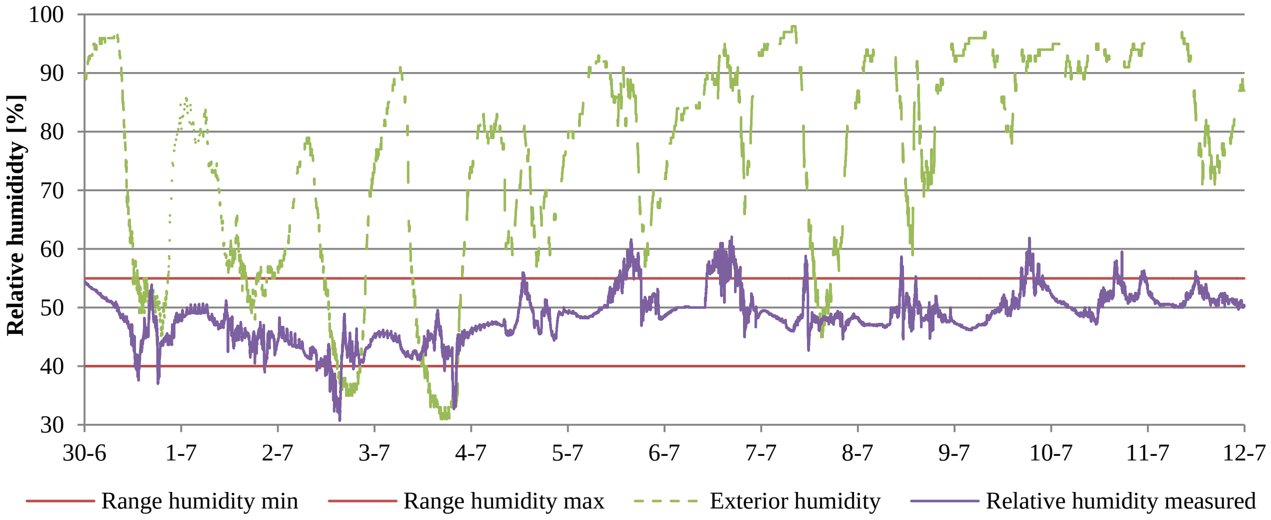

Figure 14. Official RH measurements during SDE2014.

The relative humidity contest had simpler rules and less points available for the teams (10 points out of the 120 for the Comfort Conditions). The target range was constant: the indoor humidity had to stay between 40 and 55%. The indoor humidity was indirectly managed through natural and mechanical ventilation, without any equipment for humidification or dehumidification. The humidity curves are presented on Figure 14. The high target indoor temperatures made the goal easily reachable for the EMBRACE house: with a remarkably stable relative humidity indoors, Team DTU was awarded 9.94 points out of 10 for this subcontest, which was the best score among all the other teams.

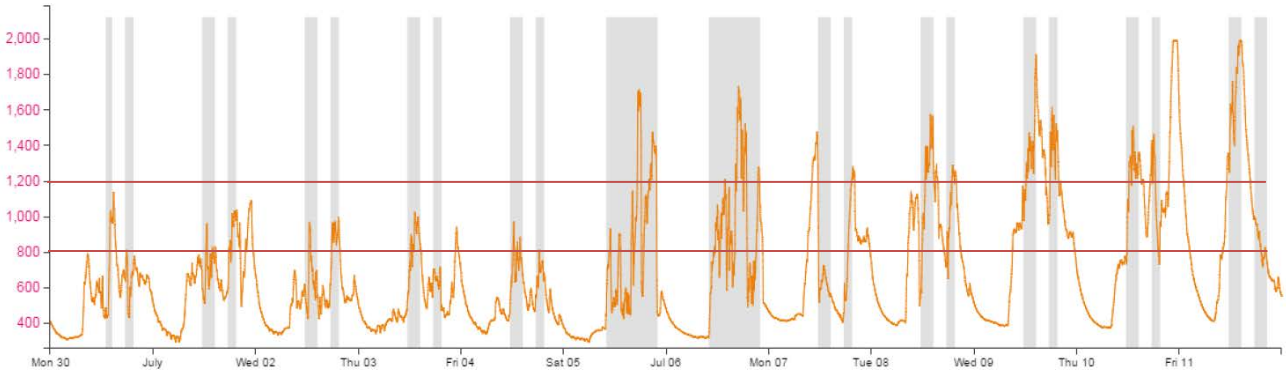

Figure 15. Official CO_2 measurements during SDE2014.

5 points were available for the CO_2 measurement contest. The CO_2 concentration had to stay below 800 ppm to gain full points, and in the range 800-1200 ppm for reduced points. The CO_2 curve is presented on Figure 15. Though some high peaks of CO_2 concentration were observed, they mainly occurred during the public tours of the house, when several occupants were present indoors, without any increased ventilation rates. Those periods were not accounted in the final point awarding (they are highlighted in grey on Figure 15), and Team DTU finally gained 4.46 points out of 5 in this subcontest.

20 points were available for the acoustics measurements. Thanks to the acoustic panels placed all over the ceiling of the house, and the sound absorption boxes integrated in the ventilation ducts, EMBRACE performed well in this category. In fact the reverberation time proved to be remarkably low at 0.3 second, considering that the maximum of 5 points could be earned with up to 0.9 second. The sound level of HVAC and active system was also measured at a relatively low level, with $L_{Aeq} = 20$ dB(A) (up to 25 dB(A) was accepted to get the maximum 5 points). The field measurement of airborne sound insulation of the façade elements ended up less satisfactory. The measurements revealed some weaknesses in the structure which let the sound go through, therefore Team DTU received only 5.8 points out of the 10 points available in this category. Overall, the score of 15.8 points out of 20 is considered good for the Acoustics subcontest.

15 points were available for the daylight measurements. This subcontest revealed a relatively poor daylight factor inside EMBRACE. During the design of the house, the team members preferred to emphasize a highly-insulated thermal envelope, which induces small openings and thick walls that hinder the penetration of natural light into the indoor space. Furthermore, the Weather Shield provides shadow, and therefore the daylight is reduced through the glazing openings that give onto the sheltered garden. Some efforts have been put into

improving the daylight, by installing a skylight above the kitchen, which provides direct light into the cooking workplace. It seems that these efforts have not been rewarded, since none of the 16 daylight measurements locations was situated in the kitchen, and the architectural jury also emphasized the lack of daylight inside EMBRACE. In addition, the chosen covering materials inside (Troldtekt acoustic panels, wooden boards) are poorly reflective and did not help improving the daylight. The measured daylight factor ranged from 1.3% in the living room to 6.1% close to the South Window, with an average of 2.7%. Given the high requirements of the competition to get maximum points (DF>4%), Team DTU only received 2 points out of 15 for this subcontest, arriving at rank #12.

3. Electrical Energy Balance subcontest

Contest n. 4 evaluated the electrical energy balance of the houses, by monitoring both the load and production powers of every prototype. During the competition time in July in Versailles, the HVAC systems of EMBRACE were estimated to consume energy mainly for space cooling, heating of DHW, plus the additional consumption of circulation pumps, lights and ventilation fans. The cooling was to be produced partly by nocturnal radiative cooling with the unglazed solar collectors (see chapter IV), partly by the heat pump. The majority of the hot water for draw-offs and appliances were expected to be produced by the solar collectors.

The weather was unusually cold in the second competition week, which meant low cooling demand and very low solar heating production. The solar collectors also had leakage problems, which means this source was completely unavailable for part of the competition period. Instead, the high temperature set-point, imposed by the SDE2014 Organization, meant heating demand. The team members decided not to switch the heat pump in heating mode, which would have required a considerable amount of energy to warm up the entire storage tank, and rather rely on a change of weather. Thus heating could only be covered by warmed supplied air from the Nilan ventilation unit. As well, the hot water demand had to be covered by the same unit. The team had decided to operate the house in cooling mode, which means the storage tank was filled with cold water. During the second week, the outside temperature was exceptionally low, which means the cooling demand was inexistent. The radiant floor did not need to be used, and neither did the Daikin heat pump, so they were simply switched off.

The graphs of the electricity consumption are shown on Figure 16. The official monitoring of SDE organization only splits the consumption between the home electronics and the appliances (Figure 16, left). Team DTU recorded its own data, but it is to be taken with caution since some data loss and technical problems occurred (Figure 16, right).

The home electronics (TV, computer, DVD player) consumed a small amount of energy thanks to the very efficient devices chosen. Because of the imposed schedule of the in-house tasks, the team had to run regularly all appliances in order to earn points. Despite the energy-efficient labelled products chosen, the appliances have been the most energy consuming devices of the house during the competition. Because of its multiple functions (DHW and ventilation), the Nilan Compact P is the unit that has the largest energy consumption among the HVAC systems. The energy devoted to cooling was limited to 7% of the total due to the low cooling needs as previously explained, and the consequent switching off of the heat pump.

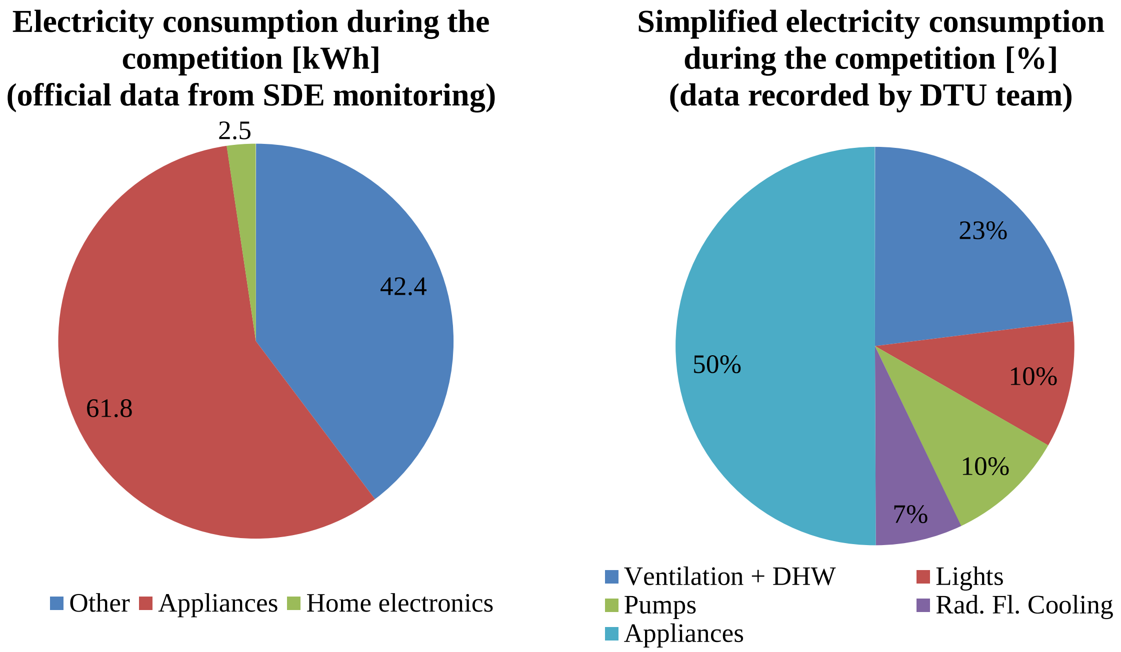

Figure 16. Repartition of the electricity consumption (left). Subdivision of the electricity consumption during the competition (right).

The daily production and consumption of the house is presented on Figure 17. The large roof surface available and the south orientation enabled an optimized production of electricity. Despite the poor weather conditions (cloudy during most of the second week), EMBRACE produced in total 235 kWh, to be compared to its total consumption of 107 kWh during the same period. The house proved to be an actual plus-energy building, producing more than twice its consumption during the competition. Only on July 10th the consumption was higher than the production, given the low available solar radiation, and therefore the low electricity generation. Team DTU gained 79.22/120 points in the Electrical Energy Balance subcontest, arriving at rank #7 among the other teams.

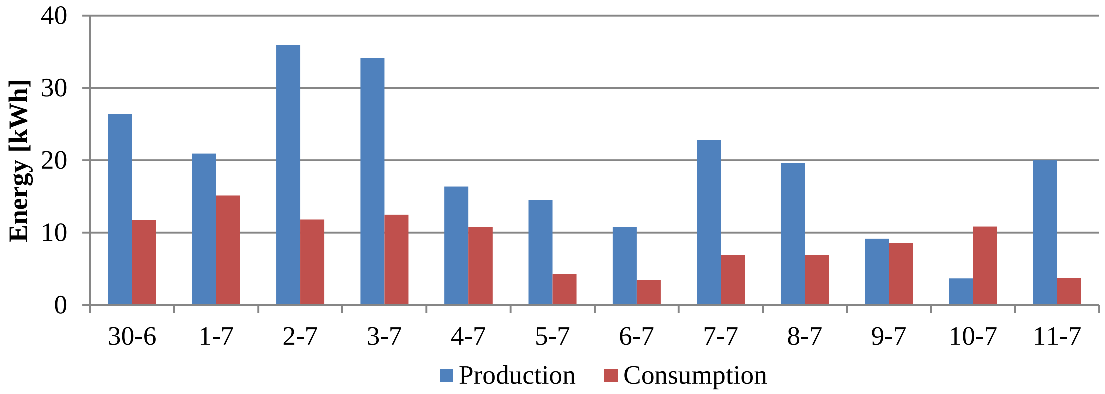

Figure 17. Energy production and consumption per day during the competition.

4. Summary of the competition results

Regardless of the results, the Solar Decathlon project has been a fantastic experience for all the students involved. EMBRACE finally ranked #8 out of the 20 teams, with 780 points out of the 1000 points available. The ranking was improved from the 2012 edition where FOLD arrived #10, which shows the previous experience has been partly beneficial. The 2014 edition was won by the University of Rome and their project RhOME for DenCity. The detailed ranking is presented on Figure 18, and the points on Table 5.

Table 5. Results of Team DTU in SDE2014.

Sub-contest	**Points earned by DTU**	**Ranking of Team DTU**
Architecture	78 / 120	#12
Engineering and Construction	69.6 / 80	#8
Electrical Energy Balance	79.22 / 120	#7
Energy Efficiency	71.84 / 80	#9
Comfort Conditions	99.23 / 120	#8
House Functioning	90.66 / 120	#11
Communication and Social Awareness	64 / 80	#8
Urban Design, Transportation, Affordability	101.64 / 120	#4
Innovation	59.81 / 80	#9
Sustainability	68 / 80	#6
Penalties	-2	-
TOTAL	**780.01 / 1000**	**#8**

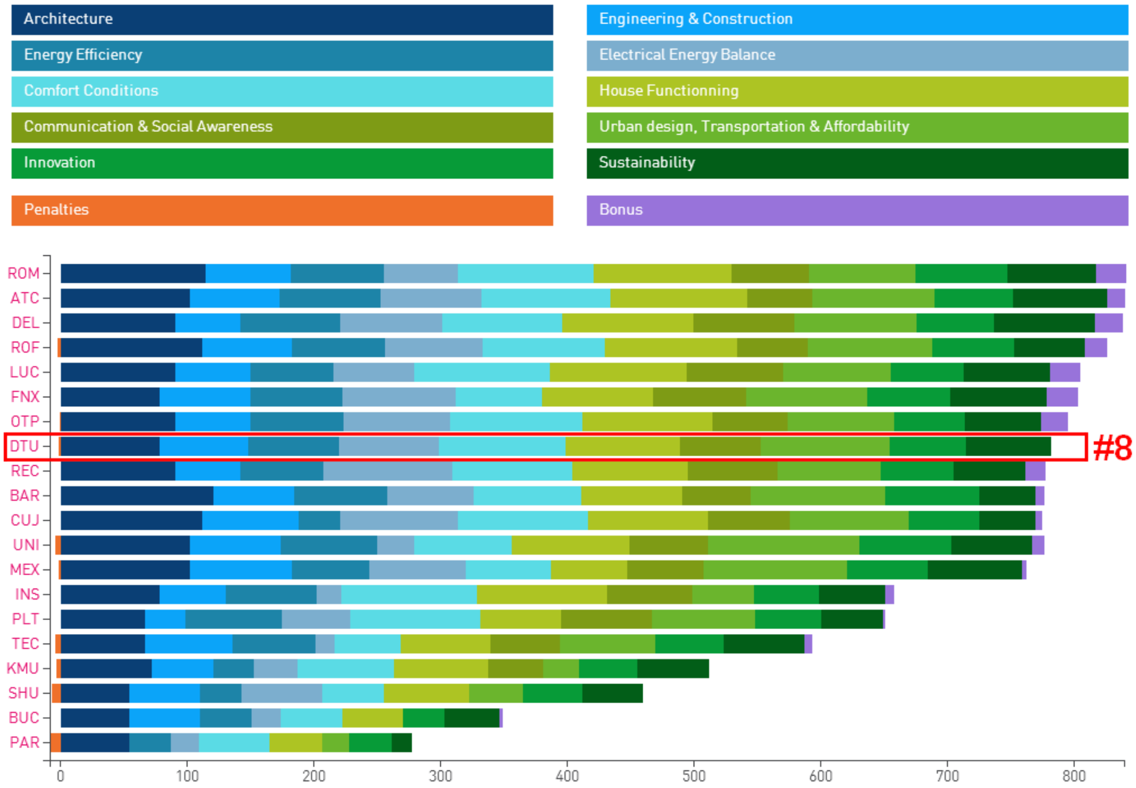

Figure 18. Final SDE2014 Ranking.

These results are rewarding the great amount of work dedicated by the team members. The best subcontest ranking was achieved in “Urban Design, Transportation and Affordability” where the team arrived #4, which also rewards the design ideas and concepts developed for EMBRACE. The monitored results of the “Comfort Conditions” and “Electrical Energy Balance” have proven to be very satisfying given the hastily circumstances in which the house has been built, the difficult weather conditions and the complexity of the control systems.

III. Measurement campaign in Universe

1. Introduction

The investigations made during Solar Decathlon were carried out in a very specific context, which is the one of the competition. The daily schedule was strictly regulated, the public tours caused occupancy peaks of dozens of visitors in the house, and the students were keeping a constant look at the house monitoring to adapt the control to the current environmental conditions and achieve the best performance at all times. Furthermore, the competition took place in France while EMBRACE was normally designed to be implemented in the context of Nordhavn, the harbour district of Copenhagen. For these reasons, once the house was repatriated in Denmark, it underwent a year-round measurement campaign to evaluate its performance in a more realistic environment.

EMBRACE was reassembled in the Universe park situated in Nordborg, Sønderjylland. Universe is a science themed park originally affiliated to the Danish company Danfoss, and conceived in the purpose of raising children's interest into scientific topics. EMBRACE was installed within the "Energy" section of the park, where it is used as a medium to explain about solar energy and energy management in general. Videos recorded by the team members of the team were broadcasted on three screens inside the house to popularize the main concepts of EMBRACE.

In this new location, the house was used to carry out several investigations of its performance in terms of indoor environment and energy. The summer period presented some inconvenience for the measurements since the park was open to the public. The main datalogging equipment was thus placed on the first floor which was not accessible to visitors, with several devices also installed on the ground floor, but out of reach from children misbehaviour. During winter, the park was closed to the public, therefore it was possible to implement a more controlled occupancy through the use of thermal dummies, and to have more sensors on the ground floor.

Figure 19. Location of the Universe park (left), and map of the park's attractions (right).

2. Experimental setup of the house in Universe

The first measurement campaign in the Universe park took place from 01/06/2015 until 30/09/2015, evaluating the house under summer conditions. The results were reported in

(Péan et al., 2016a). The second measurement campaign took place from 16/11/2015 until 04/03/2016, evaluating the house under winter conditions. The results have been reported in (Péan et al., 2016c). In between these periods, some data were gathered but did not constitute the subject of any publication.

The measurements in EMBRACE mainly focused on indoor climate and electrical energy balance. The experimental setup of the house and description of the measuring equipment is presented in details in section 2.1. for the summer period, then the adjustments made for the winter period are described in section 2.2.

2.1. Summer measurement campaign

Studied cases and operation of the house

During summer 2015, four study cases were investigated (S1 to S4), corresponding to the months of June, July, August and September. The settings of each case are summarized in Table 6. The house was in cooling mode during July and August with an indoor operative temperature set-point of 24°C, and in heating mode the rest of the time (June and September) with a set-point of 20°C. Mechanical ventilation was always set to a constant air flow rate of 0.7 h^{-1}, for the sole purpose of providing fresh air (i.e. not for conditioning the space). Occupancy was not controlled, but visitors could access only the ground floor of the house during the opening hours of the park (10 til 18 every day).

Table 6. Summer measurement cases.

	Case S1 June	**Case S2 July**	**Case S3 August**	**Case S4 September**
Date beginning	01-06-2015	01-07-2015	01-08-2015	01-09-2015
Date end	01-07-2015	01-08-2015	01-09-2015	30-09-2015
Number of days	30	31	31	30
Operating mode of the house	HEATING	COOLING	COOLING	HEATING
Indoor operative temp. set-point [°C]	20	24	24	20
Heat pump leaving water temp. set-point [°C]	30	15	15	30
Ventilation heat recovery setting	Passive	Passive	Passive	Passive
Average outdoor air temperature [°C]	15.2	16.6	18.4	14.0

Indoor climate measurements

Operative temperature was measured by PT100 sensors mounted in Ø40 mm globes, calibrated in a climate chamber, with a resulting accuracy of ± 0.3°C. Two of these sensors were placed in the first floor, at 0.6 and 1.1 m heights. As it was not possible to place a sensor tripod on the ground floor because of the presence of visitors, one of these globe temperature sensors has been placed hanging from the first floor, at ceiling height (2.5 m from the ground floor).

Air temperature was measured either by multi-sensor modules (Netatmo, accuracy of ± 0.5°C) or by shielded PT100 sensors (accuracy of ± 0.3°C). Those sensors were placed on a tripod at the first floor at 0.1, 0.6, 1.1 and 1.7 m heights, and on two locations of the ground floor. Additionally, three surface temperature sensors PT1000 were placed on the bedroom floor to record the temperature at the surface of the tiles. All sensors' locations can be seen on the elevation of the house in Figure 20.

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, but it was recording data only from September 2015.

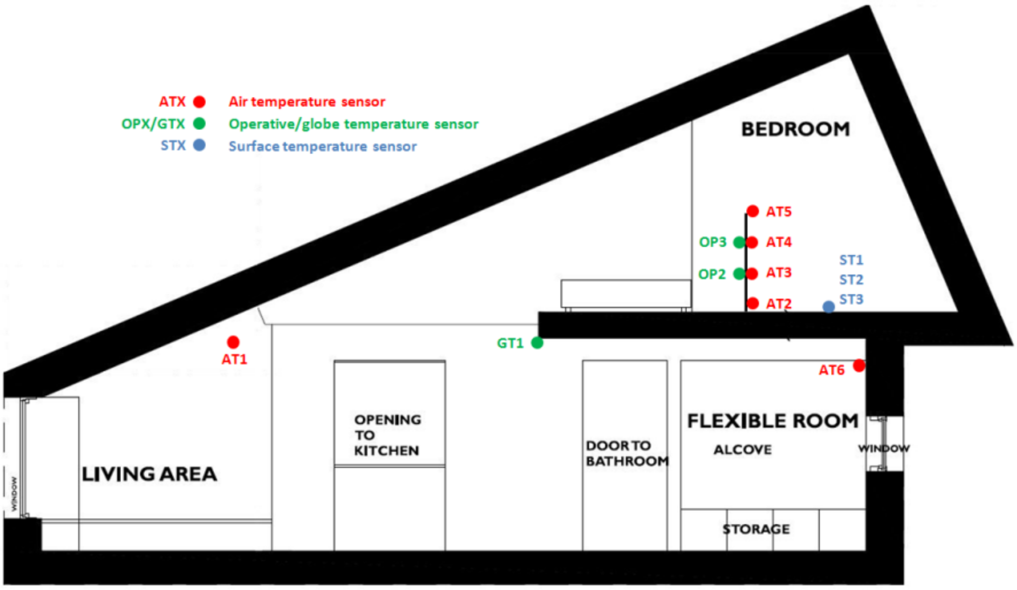

Figure 20. Elevation of the EMBRACE house with locations of sensors during summer.

Energy measurements

The PV electricity production was monitored monthly from June 2015, and daily from August 2015. The energy produced and electricity use of the heat pump was collected directly from the energy metering device of its console. Because of some uncertainty in these measurements, a heat meter (Kamstrup Multical 302) was also installed in the hydraulic circuit before the radiant floor, to measure the heating or cooling input into the terminal unit. It measures the flow with an accuracy of less than ± 5 %, and the temperature difference with an accuracy of ± (0.15+2/ΔT) % with ΔT the temperature difference between inlet and outlet. The monthly maximum heating or cooling power, average supply and return temperatures, and volume circulated were also recorded by the heat meter. The monthly energy values for heating or cooling can then be converted into electricity used by the heat pump, using calculated COP and EER values. The electricity use of the radiant floor component and the mechanical ventilation unit has not been directly measured, but estimated based on the FOLD measurements which took place in very similar setup (Kazanci and Olesen, 2014; Péan et al., 2016a). In FOLD, the same radiant floor unit was implemented (dry system from Uponor), as well as the same ventilation unit (Nilan Compact P). Even though the setup was not precisely the same (only one floor, different number of loops in the radiant floor), hypothesis have always been considered to stay on the safe side (i.e. overestimating the energy use).

2.2. Winter measurement campaign

Studied cases and operation of the house

During winter 2015-2016, the Universe park was closed to visitors, therefore more flexibility was allowed in the deployment of the measuring equipment. Several sensors were brought down on the ground floor, and thermal dummies installed to simulate occupancy. Five study cases were investigated (W1 to W5); their respective settings can be found in Table 7. 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 improve the heat recovery (active).

Table 7. Winter measurement cases.

	Case W1	**Case W2**	**Case W3**	**Case W4**	**Case W5**
Date beginning	16-11-2015	16-12-2015	12-01-2016	01-02-2016	17-02-2016
Date end	16-12-2015	12-01-2016	01-02-2016	17-02-2016	04-03-2016
Number of days	30	27	20	16	16
Operating mode of the house	HEATING	HEATING	HEATING	HEATING	HEATING
Indoor operative temp. set-point [°C]	22	21	20	20	21
Heat pump leaving water temp. set-point [°C]	35	30	35	35	30
Ventilation heat recovery setting	Passive	Passive & active	Passive & active	Passive	Passive
Average outdoor air temperature [°C]	6.6	4.8	1.8	3.8	2.5

Indoor climate measurements

One air and one operative temperature sensors were brought down to the ground floor. All other sensors stayed in the same place than for the summer period, as can be seen on Figure 22.

To simulate occupancy, two thermal dummies were placed in the upstairs bedroom (average power of 102 W each), two at the ground floor level (average of 80 W each). 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 21. 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 22).

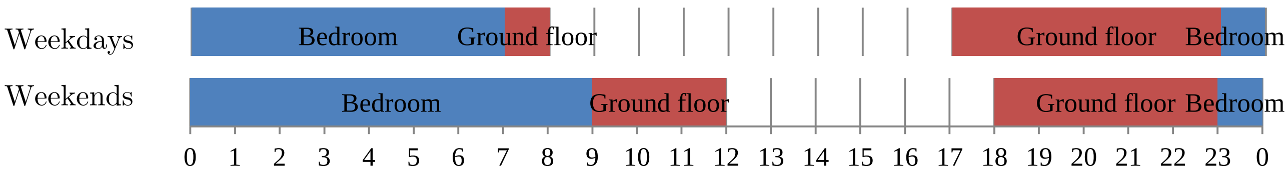

Figure 21. Operation schedule of the thermal dummies.

Energy measurements

The same measuring equipment and calculation methods were used than in the summer period. In addition to these data, the electrical energy use of the mechanical ventilation unit was available for the three last cases, from an electrical meter. These values were used to estimate the electricity use of the first two cases.

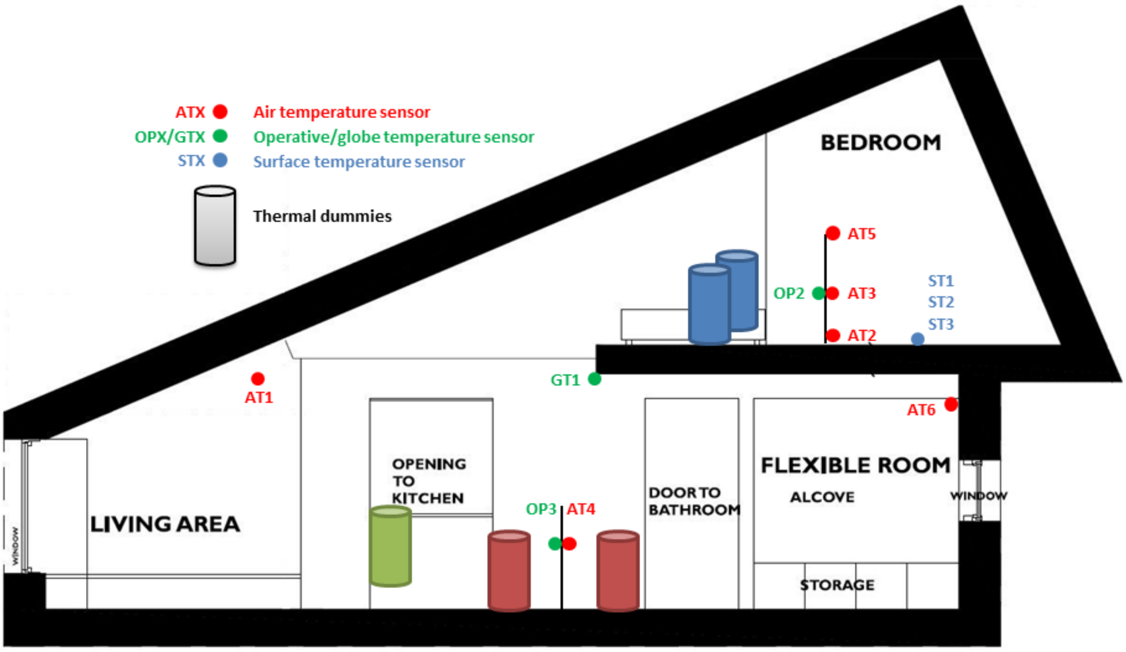

Figure 22. Elevation of the EMBRACE house with locations of sensors during winter.

Figure 23. Experimental setup during winter on the ground floor (left) and first floor (right).

3. Results of the summer measurement campaign

Indoor climate

The operative temperature measurements are displayed on Figure 24, along with the outside air temperature (because of technical issues, data loss occurred between the 25th and 31st of July). The repartition of the operative temperature between the indoor climate categories defined by EN 15251 (CEN, 2007) is shown on Figure 25.

The house showed satisfactory results in terms of indoor thermal environment during summer: the operative temperature was above 26°C for 58 hours on the first floor and for only 15 hours on the ground floor during the four studied months. These values stay below the limit of 100 hours recommended by the Danish standard DS 469 (DS, 2013). Overheating did not result to be an issue, even with the effects of the second-skin envelope, but the operative temperature sometimes dropped below the heating limit of 20°C even in summer.

This was caused by a combination of door openings by visitors and cold outside weather conditions.

The indoor climate was quantitatively better during the heating operation periods, than during the cooling operation period: indoor climate Category II was met for more than 95% of the time in June and September, and for more than 66% of the time in July and August. The standard deviation from the average temperature was also higher during the cooling operation period: between 1.3 and 1.7°C, compared to between 0.6 and 0.9°C during the heating operation period. This means that the indoor temperature has been fluctuating more during July and August. These results question the choice of operating the house in cooling mode under a Scandinavian climate. It appears that the installation of a cooling system in such a house could even have been avoided, but it should be noted that the cooling system was implemented for the house to perform under the French summer climate during the Solar Decathlon Europe 2014 competition.

The surface temperature of the floor always stayed within the range 19-29°C usually considered optimal for comfort and to avoid condensation (CEN, 2008).

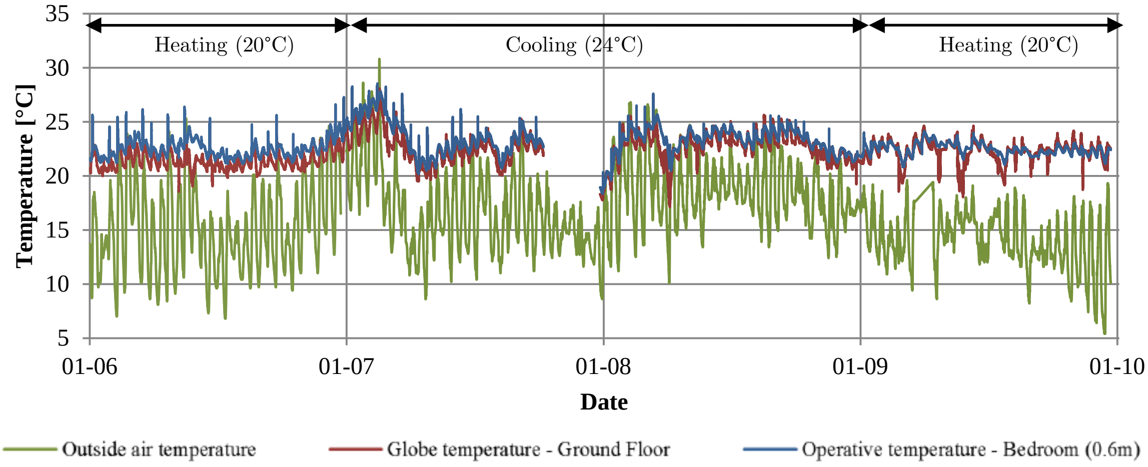

Figure 24. Operative and outside air temperature curves (June-September 2014).

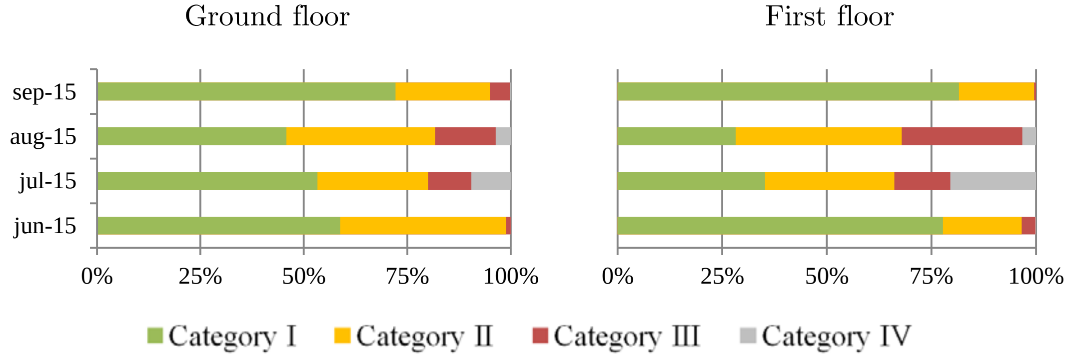

Figure 25. Repartition of the time between the different Indoor Climate Categories.

<u>Energy balance</u>

For the energy balance, the electricity used by the mechanical systems (heat pump, radiant floor system, mechanical ventilation) is reported along with the electricity produced by the PV panels. For the considered four months, the house produced 1563 kWh of electricity while using 333 kWh; the balance is therefore positive for the summer period. Figure 26 shows the monthly detailed data. As explained in section III.6, the electricity production could have been doubled if a dysfunction in the PV system did not occur.

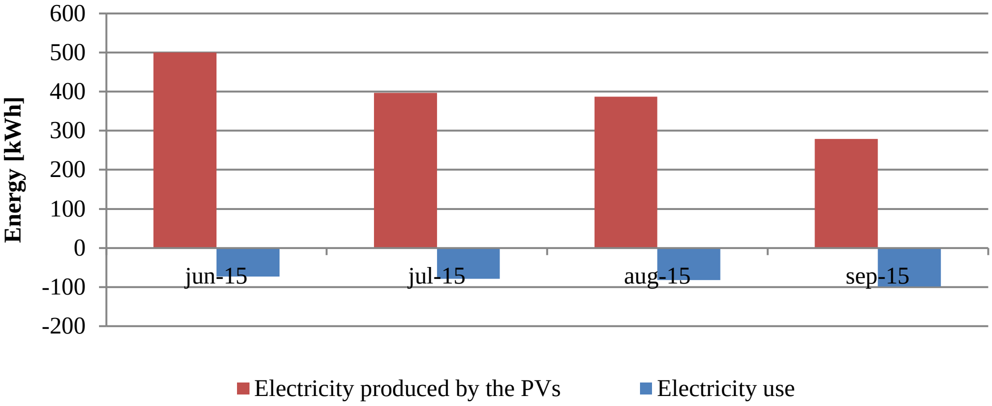

Figure 26. Electricity use and consumption during the period June-September 2015.

HVAC systems

The maximum cooling load observed during the summer season was 0.7 kW. This value is lower than the expected 1.3 kW estimated by simulations by Gennari and Péan (2014) during the design phase. This can be explained by the fact that the house was not in normal operation: it was open to the public, and visitors could enter during the opening hours of the park where it is placed. This means that doors could have been left open, resulting in high natural ventilation rates that helped cooling the indoor space. Additionally, no internal heat gains such as cooking activities, presence of occupants at night or use of electronic devices occurred during the measurement period, which lowered the need for cooling. Finally, the high air infiltration (see III.5.) could have contributed to the cooling through natural ventilation.

Case S4 (September) presented the highest energy use. This can be explained by the fact that the heat pump had to warm the whole storage tank of 800 litres on the first day of this case. Previously, the house was run in cooling mode, therefore the water in the tank was kept at 15°C. Switching to heating mode required to heat the water up to 30°C.

Summary and conclusion

The previously mentioned energy balance only covers the summer season, and is therefore not representative of an annual evaluation which would include the large electricity use due to heating in the winter season (see next section III.4. for the winter measurements results). Nevertheless, it shows the capability of the house to produce a great amount of excess electricity during the period where the solar resource is the highest: the excess electricity was around 1230 kWh in these four months.

The measurements presented some degree of inaccuracy since the house was not normally occupied, and several assumptions had to be made regarding the energy use of the systems. However, safe hypothesis have always been made to provide reliable conclusions on the energy balance.

The indoor climate has proved to be satisfactory, especially during the periods where the house was in heating mode. During the cooling operation months (July and August), it is assumed that the park was also more visited, which caused more instability in the indoor climate of the house because of numerous visitors going in and out.

Table 8 presents summarized values for all summer cases S1 to S4.

Table 8. Summarized data for the summer cases.

	Parameter		Unit	Case S1	Case S2	Case S3	Case S4
				June 2015	July 2015	Aug. 2015	Sept. 2015
	Number of days			30	31	31	30
	Mode			Heating	Cooling	Cooling	Heating
	Ventilation heat recovery setting			Pass.	Pass.	Pass.	Pass.
PVs	Electricity produced by the PVs		kWh	500	397	387	278.78
	Daily electricity production average		kWh	-	-	10.6	9.5
	Daily runtime average		hours	-	-	13:53	12:11
Heat	Heating/cooling energy supplied to the radiant floor		kWh	43	50	62	203
	Volume circulated in the radiant floor		m3	264	875	926	526
HP	Set-point of the heat pump		°C	30	15	15	30
	Electricity consumed by the heat pump		kWh	39.8	44.8	48.0	64.9
El. use	Electricity consumed by AHU		kWh	18	18.6	18.6	18
	Electricity consumed by radiant floor		kWh	15.3	15.8	15.8	15.3
	Electricity consumption total		kWh	73.1	79.2	82.4	98.2
	Electricity consumption per day		kWh/day	2.4	2.6	2.7	3.3
Temperatures & indoor climate	Average outside temperature for the period		°C	15.2	16.6	18.4	14.0
	Average temperature in the garden		°C	15.2	18.3	19.6	14.4
	Indoor operative temperature set-point		°C	20	24	24	20
	Mean operative temperature	Gr. Floor	°C	21.4	22.7	22.6	22.2
		1st floor	°C	22.5	23.5	23.2	22.5
	Standard deviation Operative temperature	Gr. Floor	°C	0.8	1.5	1.4	0.9
		1st floor	°C	0.8	1.7	1.3	0.6
	Number of hours with Top>26°C	Gr. Floor	-	0	15	0	0
		1st floor	-	0	58	0	0
	Percentage of time in Category I	Gr. Floor	%	58.8%	53.3%	45.8%	72.2%
		1st floor	%	77.8%	35.3%	28.2%	81.6%
	Percentage of time in Category II	Gr. Floor	%	98.9%	80.0%	81.8%	95.0%
		1st floor	%	96.6%	66.2%	67.9%	99.6%
	Percentage of time in Category III	Gr. Floor	%	100.0%	90.5%	96.3%	99.8%
		1st floor	%	99.8%	79.5%	96.7%	100.0%

4. Results of the winter measurement campaign

Indoor Climate

Figure 27 presents the indoor operative temperature measurements in the winter cases, 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.

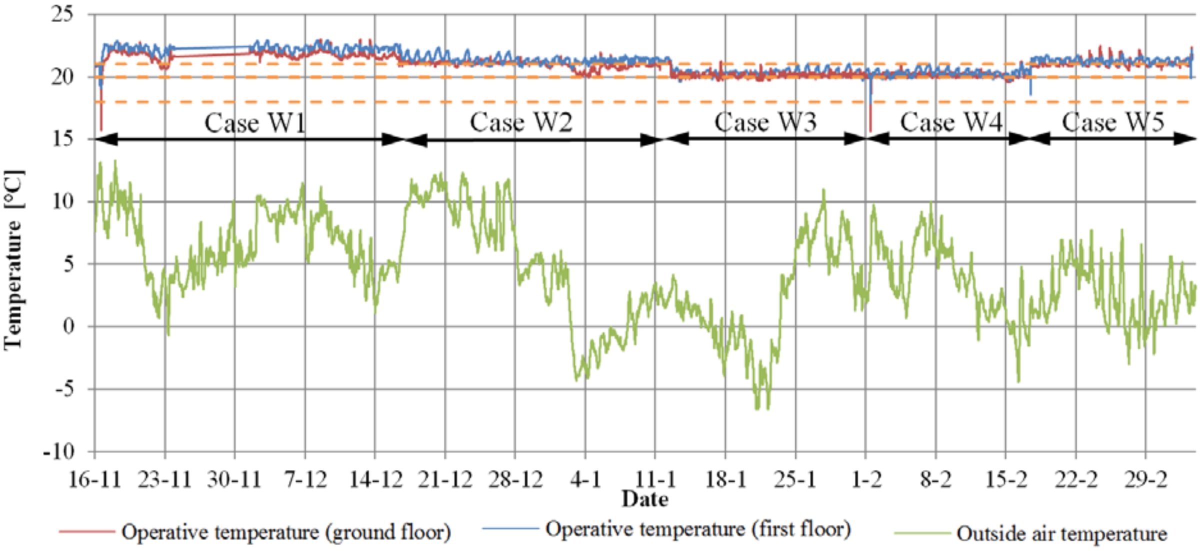

Figure 27. Operative and outside air temperature curves during winter.

The repartition of the time between the different indoor climate categories defined in EN 15251 (CEN, 2007) is shown in Figure 28. 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 W1), 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 W3 and W4) 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). This observation was also reported in FOLD (Kazanci and Olesen, 2014).

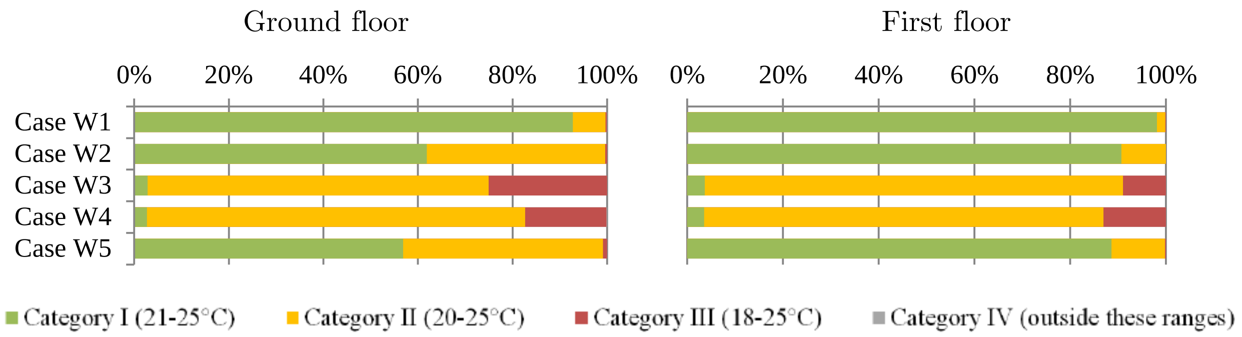

Figure 28. Repartition of the time between the different indoor climate categories.

Energy balance

Similarly than for the summer evaluation, 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 balance is here negative, with a deficit of 1089 kWh that needed to be taken from the grid. The data detailed per case are presented in Figure 29, both the summed values and the daily average, which is more representative given the different durations of the cases.

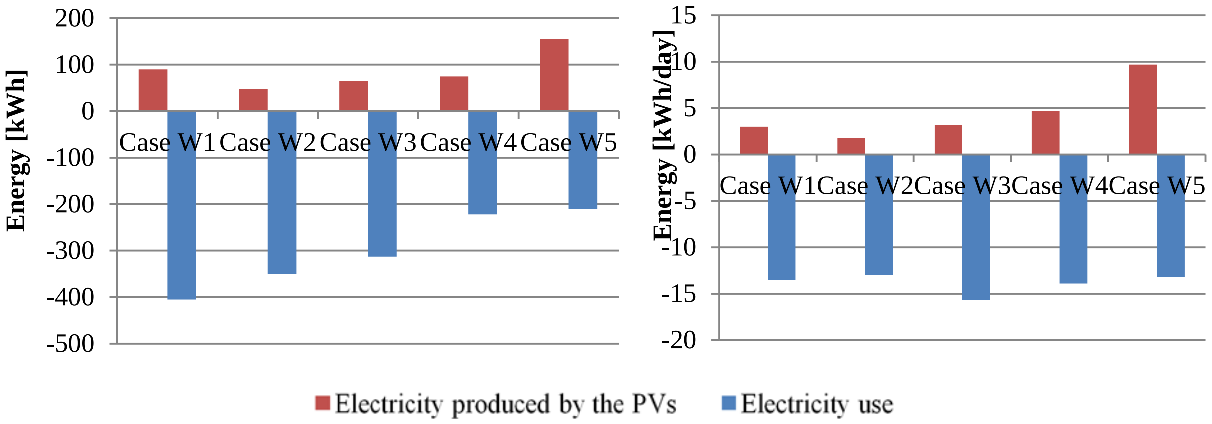

Figure 29. Electricity use and production for each case (left), and daily average (right).

The house used the most energy per day during Case W3, which was also the coldest (average outdoor air temperature of 1.8°C). Case W5 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.

HVAC systems

The daily heating energy provided to the radiant floor is presented in Figure 30, 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. It appears that a set-point of 35°C for the heat pump was not necessary (Cases W3 and W4), 30°C would have been sufficient during the whole winter. The COP of the heat pump ranged from 1.6 (Case W3) to 2.2 (Case W1) during the studied period, which is lower than the manufacturer values in a similar setup (Daikin Europe N.V. 2015).

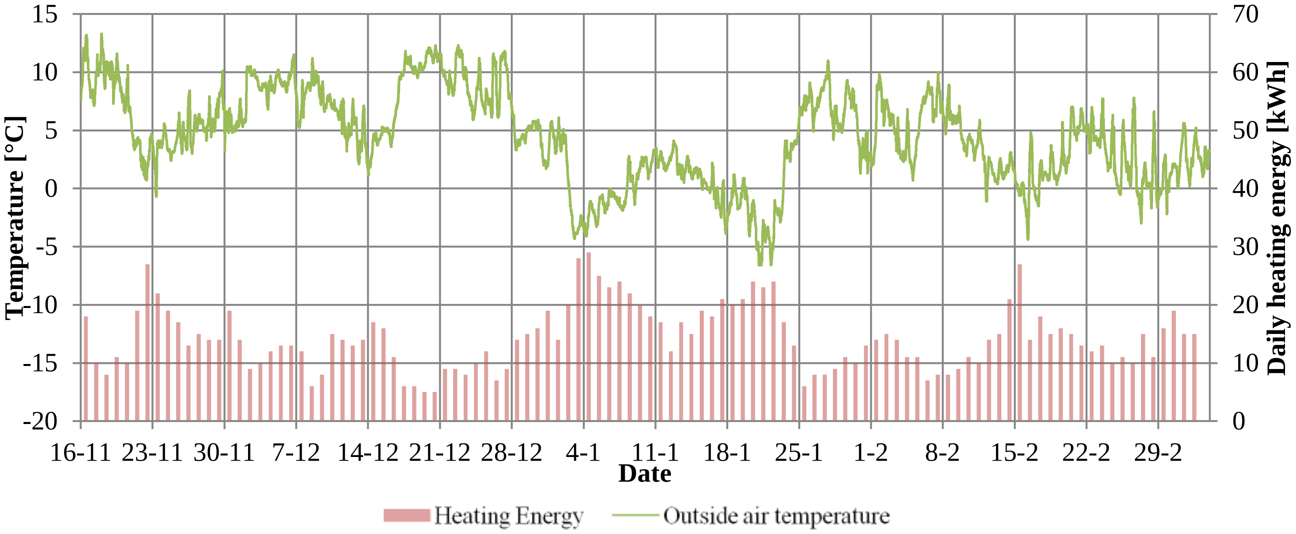

Figure 30. Daily heating energy measured by the heat meter.

For the ventilation, the datalogging from the AHU (Nilan Compact P) was only available from September 1st, 2015, therefore mainly for the winter evaluation. It recorded the different temperatures at several points of the duct system, but the resolution of these measurements (1°C) does not present a high accuracy. The results are presented in Figure 31 for the worst case (Case W3, which was the coldest, with an average outdoor temperature of 1.8°C). The AHU was set to keep the air temperature of the house at 18°C; however since the set-point of the hydraulic radiant floor system always stayed above 20°C, the unit rarely needed to switch on the active heat recovery to heat the inlet air. This corresponds to the desired operation of the house: providing the house conditioning with a water-based system (therefore more efficient), and use the mechanical ventilation only for refreshing the indoor air and remove the pollutants. The AHU can work as a support for heating only in extremely cold cases.

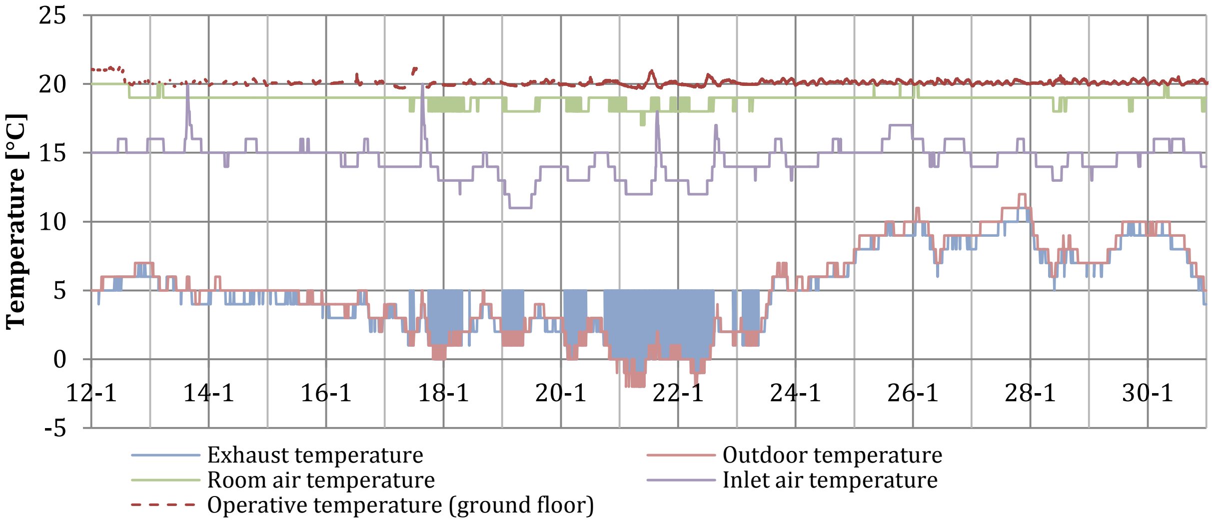

Figure 31. Temperatures recorded by the AHU.[6]

This strategy proved to work efficiently during case W3: even though the inlet air temperature dropped at the lowest point to 11°C, the passive heat recovery was sufficient to provide an inlet air flow at around 15°C most of the time. The operative temperature was maintained at the desired set-point despite the sometimes low air supply temperature. The benefits of the radiant floor can be clearly seen here: even though the air temperature in the space was around 19°C, the operative temperature stayed above 20°C most of the time thanks to the radiation effect of the floor system. The supply temperatures of the different cases are presented in Table 9.

Table 9. Summary of the AHU air temperatures.

Case		**W1**	**W2**	**W3**	**W4**	**W5**
Minimum supply temperature	**[°C]**	14.0	12.0	11.0	12.0	12.0
Maximum supply temperature	**[°C]**	36.0	24.0	20.0	24.0	20.0
Average supply temperature	**[°C]**	18.2	16.8	15.0	16.0	16.2

Summary and conclusion

During the studied winter period, EMBRACE was capable of maintaining a remarkably comfortable and stable indoor climate. The energy balance is negative during the period of almost four months, with an electricity deficit of 1089 kWh. This should be compared with the excess production of 1230 kWh observed in the summer months.

The measurements were more realistic than in the summer period, since the occupancy was simulated by means of thermal dummies. This still does not reflect a real occupancy, where opening of doors and windows, indoor activities such as cooking would affect both the energy balance and the indoor environment. However, the results are considered reliable enough to state on the performance of the house in winter.

Table 10 summarizes the measurements carried out in winter for all cases W1 to W5.

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[6] The frequent rises in exhaust temperature correspond to the defrosting mode, when the air temperature was too close or below the freezing point.

Table 10. Summarized data for the winter cases.

	Parameter		Unit	Case W1	Case W2	Case W3	Case W4	Case W5
	Date beginning			16/11/2015	16/12/2015	12/01/2016	01/02/2016	17/02/2016
	Date end			16/12/2015	12/01/2016	01/02/2016	17/02/2016	04/03/2016
	Number of days			30	27	20	16	16
	Mode			HEATING				
	Ventilation heat recovery setting			Pass.	Pass. & act.	Pass. & act.	Pass.	Pass.
PVs	Electricity produced by the PVs		kWh	89.6	47.6	64.6	74.8	155.0
	Daily electricity production average		kWh	3.0	1.8	3.2	4.7	9.7
	Daily runtime average		hours	6:48	6:40	7:27	8:47	10:08
Heat	Heating Energy supplied to the radiant floor		kWh	422	401	309	209	224
	Volume circulated in the radiant floor		m^3	832.08	660.62	451.31	337.16	386.24
Heat pump	Set-point of the heat pump		°C	35	30	35	35	30
	Electricity consumed by the heat pump		kWh	171	154	161	102	87
	Energy produced by the heat pump		kWh	367	308	251	179	173
	COP calculated for the heat pump		-	2.1	2.0	1.6	1.8	2.0
El. use	Electricity consumed by AHU		kWh	217	181	148	117	114
	Electricity consumed by radiant floor		kWh	18	16.2	4	3.2	9.6
	Electricity consumption total		kWh	405.6	351.2	313.0	222.2	210.6
	Electricity consumption per day		kWh/day	13.5	13.0	15.7	13.9	13.2
Temperatures & indoor climate	Average outside temperature for the period		°C	6.6	4.8	1.8	3.8	2.5
	Average temperature in the garden		°C	6.6	4.8	2.2	3.9	2.7
	Indoor operative temperature set-point		°C	22	21	20	20	21
	Mean operative temperature	Gr. Floor	°C	21.7	21.0	20.1	20.2	21.1
		1st floor	°C	22.2	21.4	20.3	20.3	21.3
	Standard deviation Operative temperature	Gr. Floor	°C	0.4	0.3	0.2	0.3	0.3
		1st floor	°C	0.4	0.3	0.3	0.3	0.3
	Percentage of time in Category I	Gr. Floor	%	92.8%	61.9%	2.9%	2.7%	56.9%
		1st floor	%	98.1%	90.7%	3.6%	3.5%	88.6%
	Percentage of time in Category II	Gr. Floor	%	99.6%	99.6%	75.0%	82.7%	99.1%
		1st floor	%	99.9%	100.0%	91.0%	86.9%	99.7%
	Percentage of time in Category III	Gr. Floor	%	99.9%	100.0%	100.0%	99.9%	100.0%
		1st floor	%	100.0%	100.0%	100.0%	100.0%	100.0%

5. *Air tightness*

Air tightness was expected to be an issue in this house, since it has been first erected in Denmark, disassembled and transported to Versailles where it was rebuilt for the competition. After the end of Solar Decathlon, EMBRACE was torn down again and shipped to southern Denmark, where the 4 modules of the house were assembled for the last time. Even though some attention has been paid to reconnect each time the vapour barrier and air tightness membranes, these repeated assembly/disassembly processes caused tightness issues in the building envelope. In order to quantify these, a blower door test has been carried out in the house on 15/04/2015, completed by the take of thermographic images both from inside and outside the house, in order to identify potential leakages.

The fan pressurization test has been performed in accordance with DS/EN 13829 (CEN, 2001). The terminal devices of the mechanical ventilation system were sealed prior to the test, and a membrane was installed in the flexroom floor, where an existent leakage was already known (the hole was designed to access and connect pipes below the floor between modules). Wind conditions, temperatures inside and outside were recorded, as well as the baseline (zero-flow) pressure differences before and after the test. Since the average of these values stayed below 5 Pa, the results of the test are considered valid. Both pressurization and depressurization tests were performed, with the air-blowing equipment (blower-door) installed in the entrance door. A smoke pen was utilized when the house was pressurized to identify the leakages' locations. The results are presented in Figure 32 and Table 11.

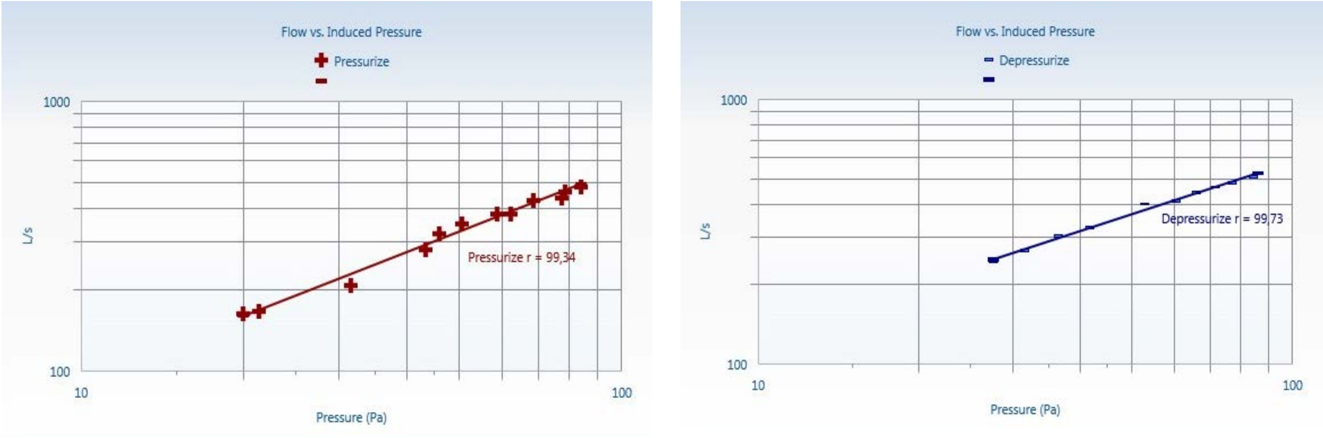


Figure 32. Pressurization and depressurization test curves.

Table 11. Results from the pressurization tests.

		Pressurization test	Depressurization test
Air flow exponent, n	[-]	0.78	0.66
Air flow coefficient, C_{env}	[$l/s/Pa^n$]	15.6	28.2
Air leakage coefficient, C_L	[$l/s/Pa^n$]	15.6	28.2
Air leakage at 50Pa, V_{50}	[l/s]	328	367
Air changes at 50Pa, n_{50}	[h^{-1}]	8.62	9.65
Air permeability at 50Pa, q_{50}	[$l/s/m^2$]	1.93	2.16
Specific leakage rate at 50Pa, w_{50}	[$l/s/m^2$]	5.56	6.23

The Danish Building Regulation states that the air leakage through the envelope must not exceed 1.0 $l/s.m^2$ heated floor area in the case of low-energy buildings, when tested at a pressure of 50 Pa (Danish Enterprise and Construction Authority, 2010). The average from pressurization and depressurization tests shows a specific leakage rate at 50 Pa $w_{50} = 5.9$ $l/s.m^2$, which is therefore around 6 times the maximum allowable. These results highlight the poor air tightness expected in the envelope of EMBRACE. The leakages identified with the smoke pen are shown in the different photographs of Figure 33, and their position in the elevation of Figure 34.

Figure 33. Identification of air leakages with smoke pen during pressurization.
Top-left: hole in the staircase between the bedroom and the technical room.
Top-right, middle-left and middle-right: frame of the upstairs bedroom.
Bottom-left: Floor of the alcove in the flexroom.

It can be noted that important leakages are observed at the junctions between the different modules. The repeated assembly and disassembly processes are the main cause for these leakages, since the modules might not have been replaced properly on top of each other, or the membrane and vapour barriers not taped. The door of the 1st floor going from the bedroom to the terrace is also subject to important leakages, notably on its bottom frame (which is also the connection between top and bottom modules). The framing of the door had not been thoroughly sealed, therefore a silicone joint has been added during the spring of 2015, but this measure did not totally solve the issue.

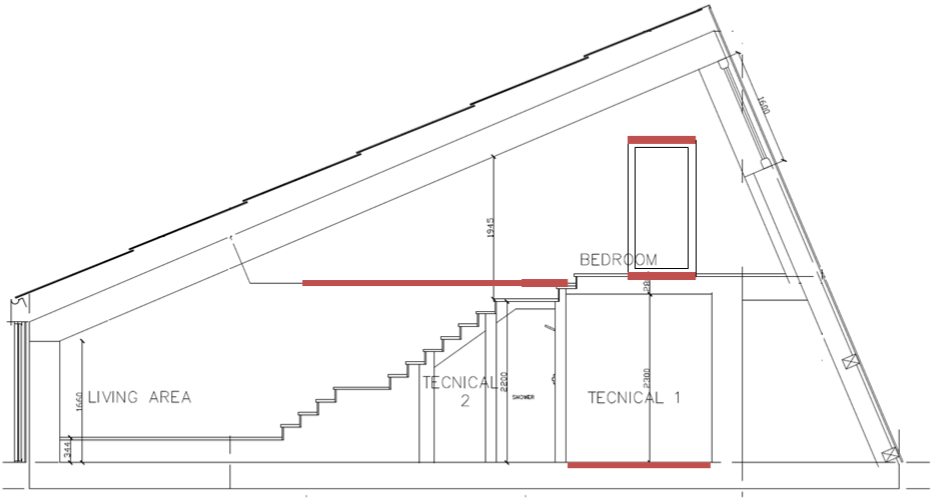
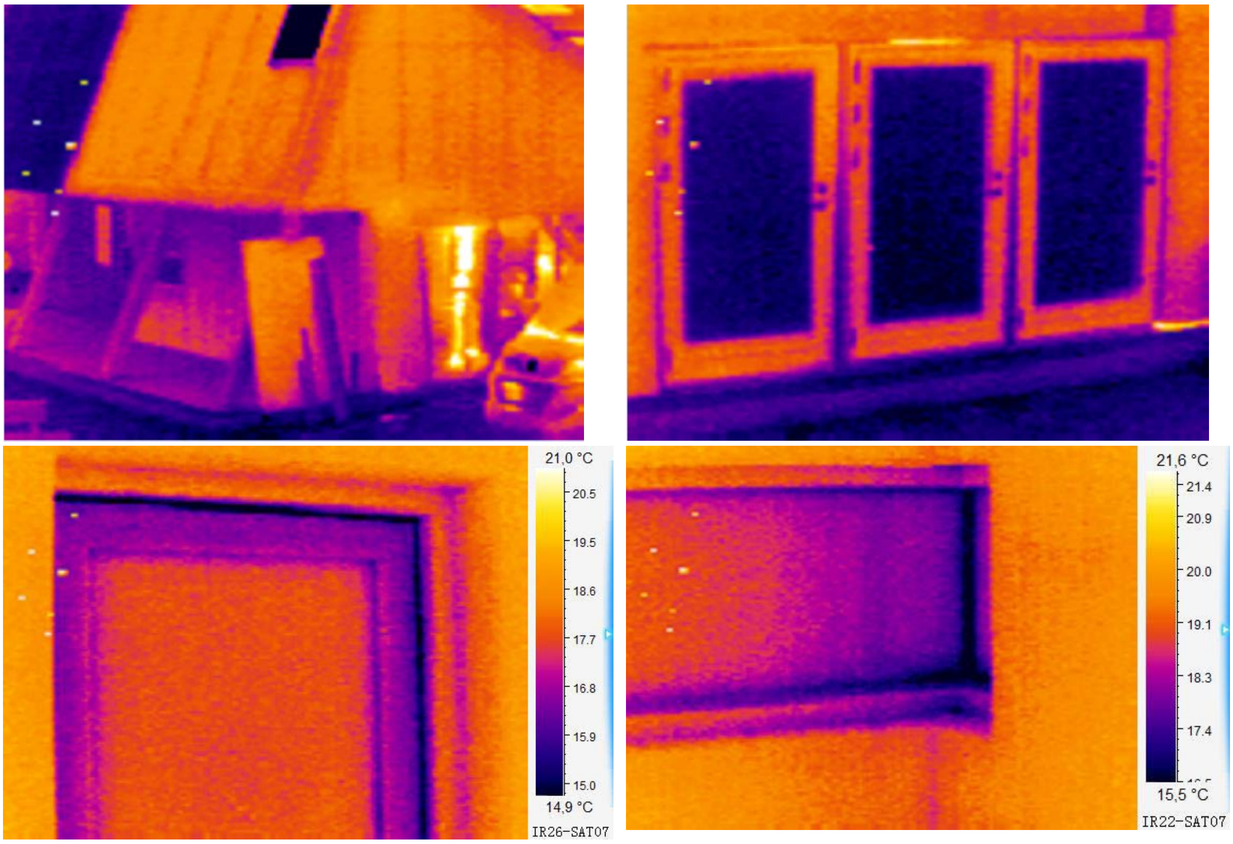


Figure 34. Position of leakages in the house.

In addition to the smoke pen, thermographic images were taken to corroborate the identified leakages. These are mainly meant to identify relative temperature differences. The hole in the staircase (bottom right picture) between the bedroom and the technical room may not have been an issue if the technical room placed afterwards had been sealed properly. Unfortunately this is not entirely true, as can be seen on the top-right picture, some leakages or thermal bridges are found on top of the doors for example. The rest of windows and doors seem to be correctly tight, except the bedroom door, where a yellowish tongue is clearly visible on top of the frame (bottom left picture). It is an evident sign of air leakage in this door frame, as previously seen with the smoke pen test.



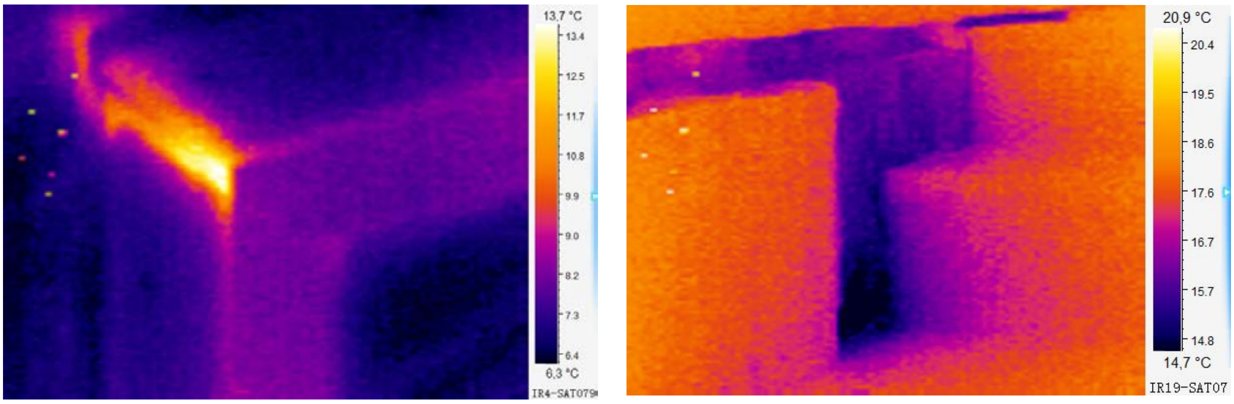


Figure 35. Thermographic images.
Top row: exterior views, whole view from NW (left), technical room doors (right).
Middle row: inside views, entrance door (left), north window (right).
Bottom row: identified leakages, top of the bedroom door from outside (left), hole in the staircase from inside (right).

A major issue related to the untightness of the house is the increased energy use for heating, due to an increased infiltration. A standard infiltration rate used for building simulation is 0.13 l/s.m^2. When the results of a pressurization test are available, as is the present case, the infiltration I is given by the following formula:

$$I = 0.04 + 0.06 \cdot w_{50}$$

which results in an infiltration rate of 0.37 l/s.m^2 in the case of EMBRACE, thus considerably higher than the standard value. Energy simulations have been carried out in IDA-ICE by Wohlenberg (2015) for her bachelor thesis in order to estimate the increase in energy use due to this higher infiltration rate. Results showed that an increased infiltration from 0.13 to 0.37 l/s.m^2 caused an increase of around 35% in the annual energy use of the house. This is very significant and highlights the fact that more attention should have been drawn on the building works during the successive assemblies of the house.

6. Electricity production

The electricity production was monitored daily from the 12th August 2015 until the end of March 2016. Unfortunately, a dysfunction occurred in one semi-transparent panel during Spring 2015, therefore the whole semi-transparent panels' circuit was shut down. The issue was resolved on the 16th November 2015 when the defective row was excluded, enabling the rest of the semi-transparent panels to produce electricity again from that date.

The daily electricity production is plotted against the daily available solar energy on Figure 36. The periods before and after the 16th November 2015 (date of repairs) have been separated in this graph. A proportional relation is clearly visible for both sets of data. The proportional coefficient is approximately doubled from before the repairs (3024 Wh/(Wh/m^2)) to after the repairs (6130 Wh/(Wh/m^2)). This means that the electricity production was reduced by half, and it is a safe estimation to consider that the production in Spring and Summer 2015 could have been doubled during this period, if the dysfunction did not occur. These considerations are important when stating on the ability of the house to meet its plus-energy targets.

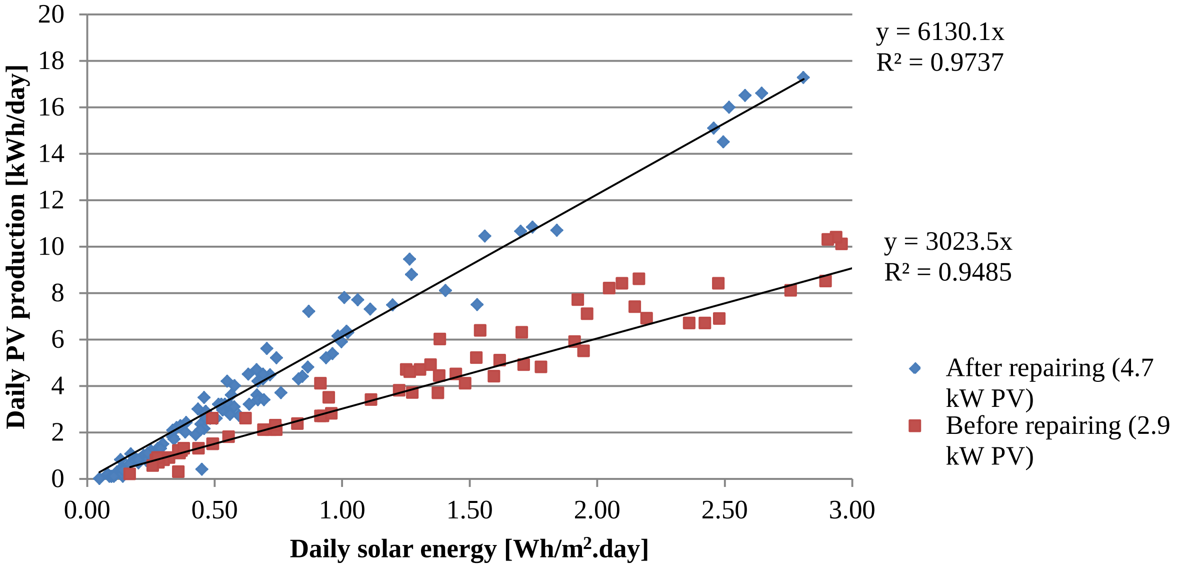


Figure 36. Relation between solar resource and production.

The daily electricity production is presented on Figure 37, from 12/08/2015 until 06/03/2016. The change between before and after the 16th of November 2015 is not clearly visible since the production was low at that moment. However, it can be noted that the production in February 2016 reached similar levels to the ones of August 2015.

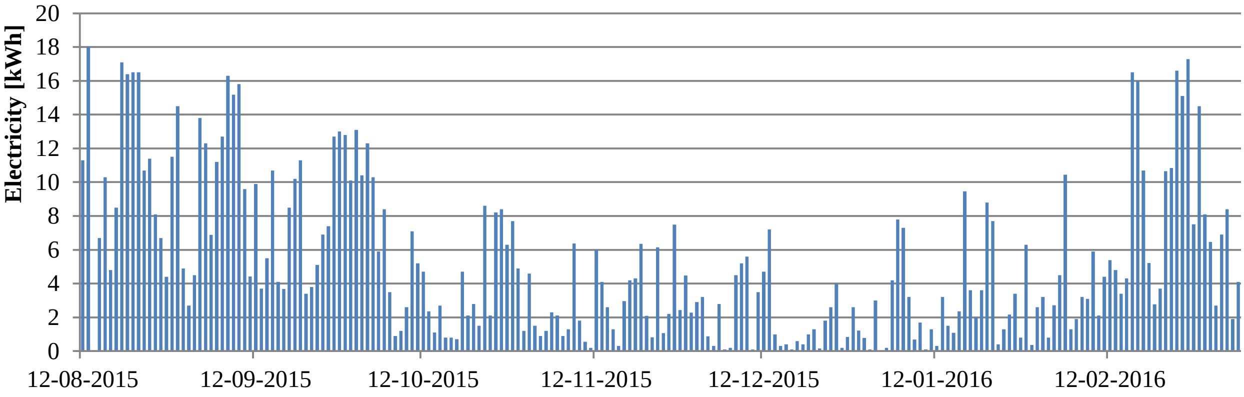


Figure 37. Daily PV production from 12/08/15 until 06/03/16.

7. Climate in the semi-outdoor space

As mentioned in paragraph I.1.1, the major concept of EMBRACE relied on the construction of a glazed Weather Shield above the house, which creates a semi-outdoor space underneath, known as the sheltered garden. This space was intended to be closed, but not actively conditioned. In practice and because of a lack of funds, it was not possible to completely close it, therefore the Eastern gable wall is completely open, and air circulates freely in the space. Even though it is not sealed, 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. During autumn and winter, a temperature increase in the sheltered garden of up to 3°C has been observed frequently (Figure 38, 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 38, left).

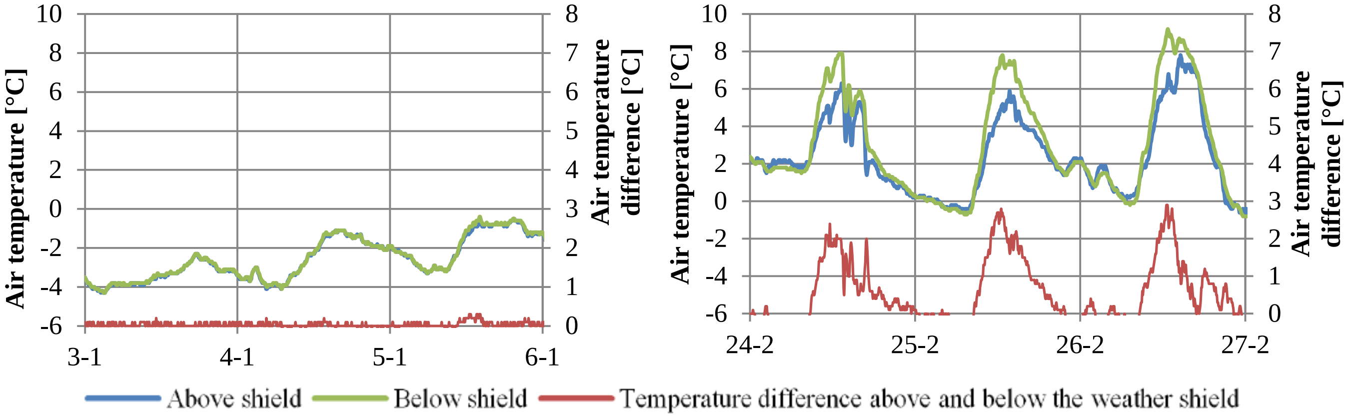


Figure 38. Comparison between the air temperature outside and in the sheltered garden, during cloudy days (left) and sunny days (right).

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), see Figure 39. The wind protection is thus not perfect, but the weather shield also provides shelter from the rain.

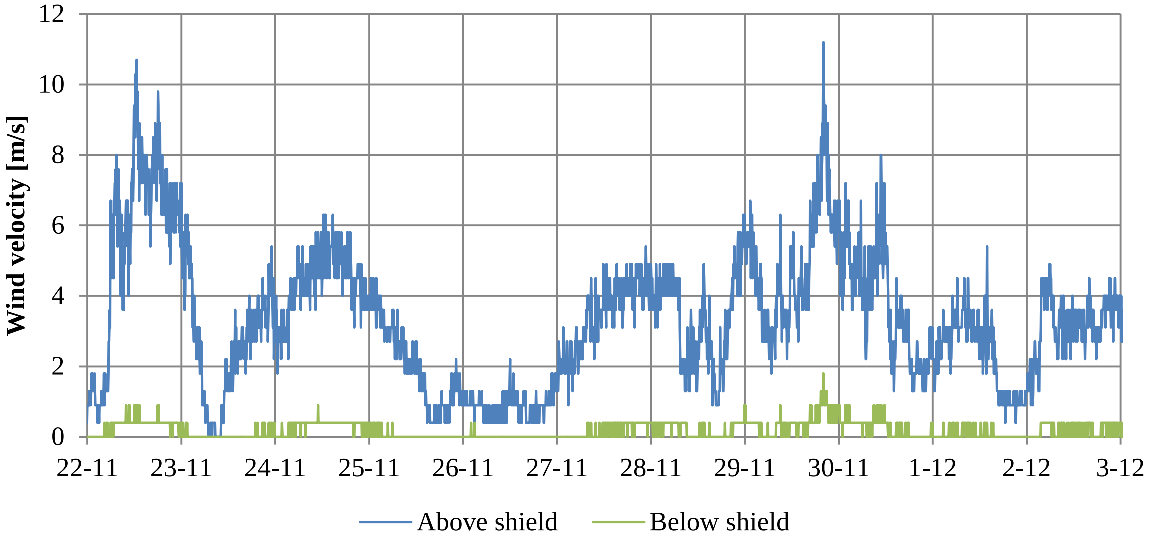


Figure 39. Wind velocity above and below the weather shield.

The semi-outdoor space has been studied theoretically as a concept by C. Papachristou and K. Foteinaki for their master thesis and two conference papers (Papachristou and Foteinaki, 2015; Papachristou et al., 2016; Foteinaki et al., 2016). Their studies have taken EMBRACE as an example of this concept, also used to carry out energy and indoor climate simulations, but considering that the sheltered garden was then closed. The outcome of these studies showed that the peak heating load and annual heating energy of the house were slightly reduced (by around 3%) by the addition of the weather shield, since the sheltered garden acts as a buffer zone between indoor and outdoor. The cooling load was increased because of the weather shield (by 25%), but by implementing natural ventilation in the sheltered garden, the cooling load could finally be reduced by 30% and the annual cooling energy by 15%.

Regarding possible occupancy of the semi-outdoor space, the studies have considered the hours in which a thermally comfortable environment was achieved, i.e. with $-1<PMV<1$. The simulations in IDA-ICE showed that this criterion was met for 2670 hours per year in the sheltered garden of EMBRACE. It corresponds to 45% of the whole year which compared to the 1100 hours annually that an outdoor space can be used, is more than doubled. A risk of overheating in summer is identified, but it can be avoided by efficient natural ventilation in the space. However, this type of construction is more suited to northern climates; in southern climates such as the Mediterranean area, it is expected that overheating issues would overcome the benefits of the second skin concept.

Both experimental and simulation results validate the initial design ideas which were at the basis of the design of EMBRACE. It appears that the benefits of the second skin are limited on the heating or cooling energy used annually, but the sheltered garden offers a comfortable space which is usable most of the year. The house was designed relatively small in order to save materials and energy for operation, but since the semi-outdoor space can still be occupied most of the time, it extends the limited space available in the thermal envelope itself. An identified issue comprises the risk of having the occupants trying to heat the semi-outdoor space in inefficient ways such as with convectors, which would drastically impact the energy balance of the house.

8. Conclusion on the annual evaluation

Globally, the measurement campaign in Universe showed positive results about the performance of the house. Some inaccuracies could have influenced the outcome, since the house was never truly occupied by a family. Instead, visitors randomly entered in the house during opening hours in summer; during winter the occupancy was simulated by static thermal dummies, which only accounted for the thermal contribution of the occupants to the indoor climate, but not for their pollution, movements, indoor activities etc. However, the authors have taken any possible precautions in the data elaboration to make the evaluation results reliable enough for further analysis.

The energy balance has been calculated separately for both the summer and the winter measurement campaign. In the first case, an excess electricity production of 1230 kWh was observed, while in the second case a deficit of 1089 kWh occurred. The studied summer and winter periods, both of approximately four months, represented respectively the most favourable and least favourable cases for energy balance. The balances of these two periods can be added, to have an overview of the performance during the 8 considered months: a slight electricity excess of 141 kWh is then observed. It is estimated that the remaining periods would not affect this balance in a negative way: spring and autumn would probably stay close to equilibrium between electricity supply and demand in the house, since for example in February already 73% of the demand was covered by the PV production. Furthermore, if a dysfunction in the PV system did not occur, the electricity produced during spring and summer would have been at least doubled (see paragraph III.6.); and if the house envelope had been tightened in a better way, the heating consumption would have been decreased (see paragraph III.5.). It is therefore entirely safe to state that EMBRACE fulfils the plus-energy target fixed in its design.

The indoor thermal environment proved to be remarkably stable and comfortable, especially during the periods where the house was in heating mode, since the indoor environment was then better controlled. The mechanical systems were able to maintain the indoor climate in Category I of EN 15251 for up to 92 and 98% of the time (respectively in the ground and first floors) with a set-point of 22°C (Case W1), and without spending excessive amounts of energy. This is a great achievement that proves the feasibility of a comfortable plus-energy house. The sheltered garden also provided a comfortable environment, and forms an area that can be occupied a large part of the year, extending the available space in the house. Even though the sheltered garden is not closed as expected, the design goals in this matter have been achieved.

Regarding the operation of the systems themselves, even though they performed in the desired way, some conclusions can be drawn from this measurement campaign. Operating the house in cooling mode in a Scandinavian summer could probably have been avoided. Overheating did not appear to be an issue: the second skin enabled to provide shadow to the house, limiting the solar gains. On the other hand, the greenhouse effect was reduced because the sheltered garden was not completely closed, therefore natural ventilation was provided to this space. The authors would recommend to try running the house passively during next summer, and investigate if overheating (i.e. operative temperature $>$ 26°C) would still occur for less than 100 hours per year. This objective is considered easily reachable, especially if efficient natural ventilation strategies are implemented.

Another debatable point is the presence of the storage tank in the hydraulic circuit: its presence is not necessarily justified. It was implemented for storing cold water produced through radiative cooling at night for use the next day. Since nocturnal radiative cooling technology and solar heating are both not utilized anymore in the house, the heat pump is the only source of heating/cooling for the space conditioning, therefore it could have been connected directly to the radiant floor circuit. The heat pump is inverter-controlled and would be capable of providing the right water temperature for the radiant floor to operate correctly. Removing the tank would reduce the installation costs and release available space in a house that is already relatively small.

IV. Nocturnal radiative cooling

1. Introduction

1.1. Literature review

The world economies are gradually draining the earth's resources in fossil fuels, which means that the need for renewable and sustainable sources of energy is becoming more and more urgent. Simultaneously the desires for improved living standards are always spreading, which results in a global increase in energy needs. More specifically, the need for cooling is rising, partly due to the new building standards that impose always tighter and better insulated building envelopes. Natural and free sources of cooling need to be found in order to address these issues.

Several natural heat sinks exist for dispersing the heat stored in buildings, such as the ambient air or the ground. Another one, which is yet not exploited to its full potential, is the sky, which can exchange heat with objects through longwave radiations. Especially at night, the effective temperature of the sky can drop far below the air temperature, creating favourable conditions for radiative heat exchange. This phenomenon has been exploited in the past using roof ponds that store heat during the day and release it at night, or by movable insulation removed at night to expose the building directly to the cold sky.

Nowadays, the research on radiative cooling focuses on radiators installed on the roofs, in which water is circulated and cooled by exploiting the sky as a natural heat sink. Those radiators can be specially designed for this purpose, or they can be existing solar panels, already facing the sky for the purpose of daytime water heating, and that can be used as well during nighttime for cooling applications. Some literature on the topic is summarized in the following table, with the achieved cooling power for the different type of panels.

Table 12. Summarized literature review.

Authors	**Type of panels**	**Cooling power**	**Location**
Erell and Etzion, 2000 (Israel)	Flat plate radiator	80 W/m^2	Desert areas
Anderson et al., 2013 (New Zealand)	Unglazed solar collectors	50 W/m^2	New Zealand and Australia
Eicker and Dalibard, 2011 (Germany)	PV/T	60 to 65 W/m^2	Madrid (Spain) /Shanghai
Hosseinzadeh and Taherian, 2012 (DTU & USA)	Unglazed flat plate collector (copper and iron)	23 to 52 W/m^2	Babol (Iran)
Dobson, 2005 (South Africa)	Radiator panels	60.8 W/m^2	Namibia
Yong et al., 2015 (China)	Solar heating and cooling panel	87 W/m^2 (clear nights in hot season)	China
Xu et al., 2015 (China)	Flat plate collector	26 W/m^2	China
Raman et al., 2014 (US)	Photonic radiative cooler	40.1 W/m2 (under direct sunlight)	Stanford (California)

It seems like the topic of radiative cooling has gained interest over the last couple of years. The latest technological breakthrough came from the United States, where a team of researchers from Stanford developed a special radiator panel, which surface could exploit radiative cooling also during daytime, even under direct sunlight. Their results, reported in Nature (Raman et al., 2014), showed a capability of this photonic panel to reflect the incoming solar radiation while improving the longwave radiation towards the sky thanks to the selective emittance properties of its surface. The tested panel was therefore able to cool water nearly five degrees below ambient temperature under direct sunlight conditions. A company has even been created to commercialize the panels developed at Stanford. This research has revived the worldwide interest in radiative cooling: only in China in 2015 for example, at least three articles have been published describing different systems exploiting this phenomenon.

In the US, the Department of Energy (DOE) ordered an extensive report that was published in November 2015, and which estimates the energy savings potential of radiative cooling (Fernandez et al., 2015). This report considered a standard three storey office building, which would be normally conditioned with an air VAV system. By implementing radiant floor slabs indoors and radiative cooling panels on the roof, it was estimated that between 24 and 103 MWh of electricity could be saved per year, depending on the location in the US. It represents between 45 and 68% of the electricity used for cooling with the normal VAV system. The percentage of the cooling load addressed by radiative cooling has also been calculated for 5 cities in the US, as seen in Figure 40. In the coldest 5 months of the year, the radiative cooling technology can cover 100% of the cooling needs in Chicago, Los Angeles or Las Vegas, which shows evidence of the potential of this technology.

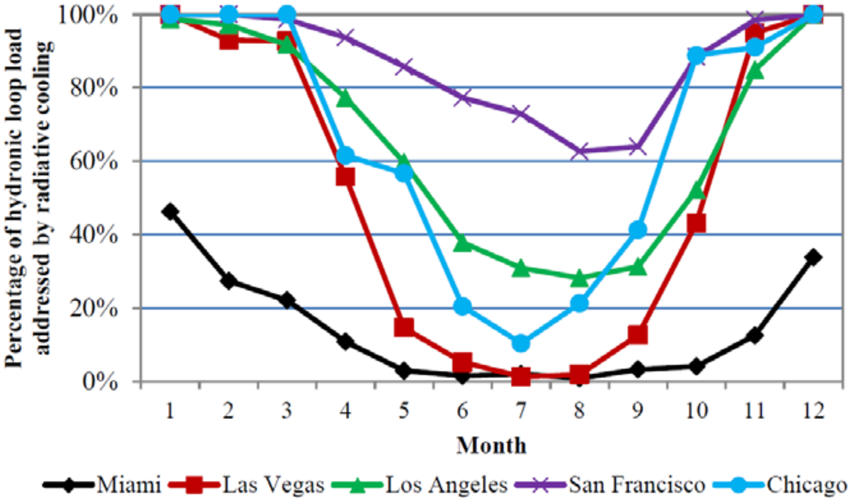


Figure 40. Percentage of cooling load addressed by radiative cooling in five U.S. cities.

The DOE also carried out a market analysis in its report, and identified the potential barriers for the adoption of radiative cooling in the market. This research is needed if radiative cooling products are to be commercialized, and it shows the strong interest of the DOE into this technology. The potential market barriers identified are:

- Poorly suited to retrofit buildings
- Complexity and holistic design
- Installation cost
- Limitations on building suitability by shape
- Space concerns
- Familiarity and customer acceptance level
- Climate constraints

1.2. Topics of the present research

In the present research, two types of panels have been investigated with regards to nocturnal radiative cooling: unglazed collector and photovoltaic/thermal panels (PV/T). Unglazed collectors are a low-tech type of device, typically used for heating swimming pools in summer. This type of panel is cheap and can therefore answer to the identified barrier #4 relative to the cost of such an installation. Unglazed collectors were installed in EMBRACE during the Solar Decathlon 2014 event for cooling the water of a storage tank at night, and using it for space cooling the next day. The weather during the competition did not actually require any cooling, and few data were recorded at that time. Those results are however recounted in section IV.2.

Photovoltaic/thermal panels are found at the other end of the market: they consist of a high-tech combination of photovoltaic cells and a water circuit for solar heating. The water circuit enables to cool down the PV cells, improving their efficiency, and warming water at the same time. Extensive research has been carried out on PV/Ts, but few focused on their potential for radiative cooling. Even though PV/Ts are still expensive due to their position in a niche market, they are still mentioned by DOE as a mean to reduce the installation costs (barrier #4). In fact, the combined production of heating, cooling and electricity reduces significantly the return on investment rate.

The present project has studied both types of panels with regards to nocturnal radiative cooling. The compared results in terms of cooling capacity have been reported by Péan et al. (2015a). The experimental setup has then been improved, with a connection to two storage tanks in the building underneath (one for hot water, one for cold water) and the possibility to use the chilled water for discharging phase-change material ceiling panels installed in a climate test chamber. The results of these studies are reported by Bourdakis et al. (2016a and 2016b).

Finally, given the fluctuation of the radiative cooling resource depending on the weather, a parametric analysis has been carried out to understand better the impact of the environmental conditions on the cooling capacity. This last research enables to address the identified barrier #7 about climate constraints and weather dependency of radiative cooling technology.

2. Tests during SDE2014

The radiative cooling technology was implemented in EMBRACE, in order to provide free cooling to the house during the SDE2014 competition. For this purpose, four strings of unglazed collectors have been laid down on the ground in the north side of the house, and connected to the storage tank (Figure 41). Unfortunately, as recounted in section II, the weather was exceptionally cold during the competition, therefore the need for cooling was inexistent and the radiant floor system was shut down. Therefore the cold water in the tank was not used by the radiant floor terminal unit.

Figure 41. Photos of the unglazed collector in SDE2014.

Some measurements were however performed, but they contain a high level of inaccuracy. The first method focused on the water side: two Vortex Flow Sensors (VFS) were installed at the supply and return of the panels, measuring the flow $\dot{q}$ and the temperature difference ΔT. These measurements enabled to calculate a first cooling power by means of the following formula:

$$q_1 = c_w \cdot \rho \cdot \Delta T \cdot \dot{q} / A_{collectors}$$

where c_w and ρ are respectively the water heat capacity (4200 J/kg·K) and density.

The second method focused on the side of the water tank: temperature sensors were installed to measure the water temperature at the bottom and top of the storage tank. The drop of temperature in the tank over the night has been used to determine the effective cooling gained q_2.

Finally, a third method considered the theoretical model described in IV.3.2. This model considered that the panels had a top surface temperature equal to the mean between the supply and the return water temperatures (measured by the VFS). From that surface temperature, the heat exchanges by convection and radiation have been calculated, and summed to form the third cooling power q_3. The results for the three methods and the 6 considered nights are presented on the following table.

Table 13. Average cooling powers during SDE2014.

Night	q_1 (W/m^2)	q_2 (W/m^2)	q_3 (W/m^2)
02/07/14	57	70	95
03/07/14	60	20	60
04/07/14	37	41	89
05/07/14	46	42	83
07/07/14	48	67	115
08/07/14	17	59	84

As can be seen from Table 13, the results show a high degree of inconsistency. The reason behind it is the uncertainties of the measurements: the VFS have a high error in the temperature measurement (±2°C), and the theoretical model was based on inaccurate weather data retrieved online from a station not placed at the exact same location than

EMBRACE. However, a temperature drop was observed during the night in the tank; for example during the night of 02/07/2014, the temperature went down from 21 to 16.5°C. This shows evidence that the panels were effectively cooling the 800 litres of water of the storage tank over the night. The cold water was never actually used for cooling the house, therefore at the end of the period, on the 09/07/2014, the water in the tank had reached 13°C. The cooling power of the panels ranged from 17 to 115 W/m^2 but could not be determined precisely, therefore more accurate measurements were performed at DTU afterwards.

3. Experimental measurements at DTU

3.1. Initial experiment setup

The further experiments have been carried out on the roof of building 412 at the Technical University of Denmark, Kgs. Lyngby (55°47'02.5"N 12°31'19.9"E), during August 2014. The experimental setup is presented in the schematic layout of Figure 42. The subject panels are three PV/T panels mounted in series (Solarzentrum, 1.3 m^2 each) and one unglazed collector (2.4 m^2), tilted 45° towards South. Data were recorded every ten seconds and time averaged for five minute time steps. The total water flow rate was 3.3 L/min, split in two branches: 2 L/min were supplied to the PV/T panels and 1.3 L/min were supplied to the unglazed collector. The balancing has been made with the balancing valves, so that the flow rate per surface area of collector was equal in both branches, with a value of 0.5 L/min-m^2. The pump was running 24 hours per day, meaning that during the day, the panels were warming up the circulated water, which was stored in a 1 m^3 tank. At night, the water of the tank was then cooled by the panels. Because of this operation, the supply temperature was not the same every night, depending on the daily solar radiation.

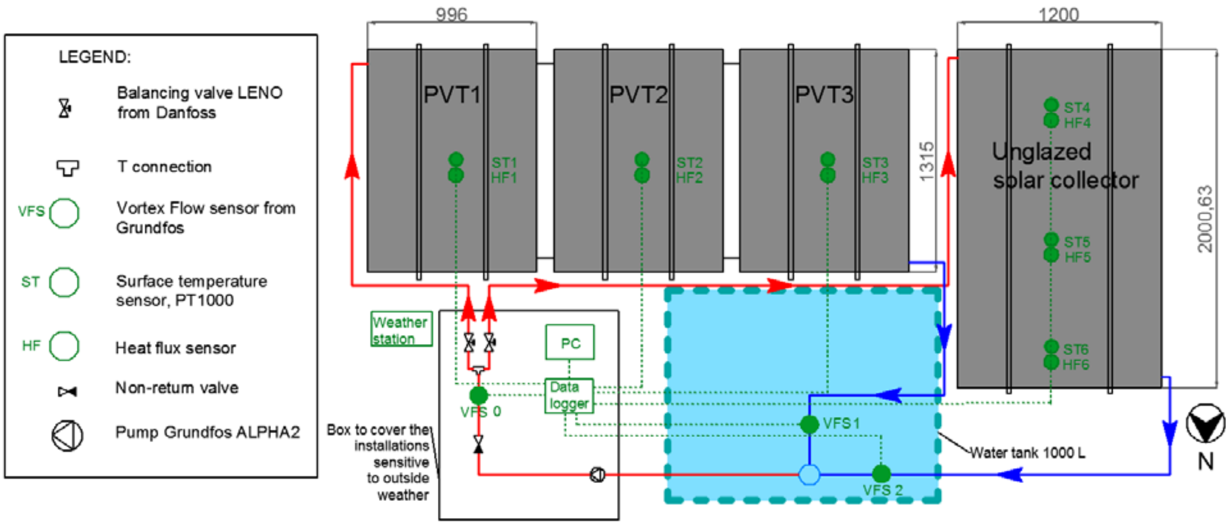


Figure 42. Schematic layout of the experiment

Figure 43 presents two photographs of the experimental setup, as of August 2014. On the left picture, the black unglazed collector as well as the three PV/Ts can be seen.

Figure 43. Front and back views of the experimental facility.

3.2. Methods

Similarly to the measurements carried out during SDE2014, the cooling power of the panels was measured through three different methods, which are described in details in the following paragraphs.

First method: water side (VFS)

The first method is similar to the tests of SDE2014: VFS sensors were installed at the common supply and at both returns of the two types of panels. The flow $\dot{q}$ was thus measured as well as the temperature difference ΔT. The same equation was then applied to those values: $q_1 = c_w \cdot \rho \cdot \Delta T \cdot \dot{q}/A_{collectors}$ $[W/m^2]$ which gives a first estimation of the cooling power per area of collector. Since an inaccuracy was previously observed in the temperature measurements (±2°C), verifications were realized with a more accurate thermometer, enabling to bring down the inaccuracy to ±0.4°C.

Second method: surface heat flux

The second method consisted in measuring directly the heat flux occurring at the surface of the panels. Micro foil heat flux sensors were attached to the surface of the panels with thermal paste, and measured directly the heat exchange q_2 $[W/m^2]$ between the panel and the environment. Those sensors were placed in the middle of each panel (see Figure 42).

Third method: theoretical model

The third method applied the theory of convective and radiative heat exchange between the panels and the environment. The surface temperature of the panels T_r $[K]$ was measured by PT1000 sensors, and the environmental parameters were recorded by a weather station placed on the experiment site (air temperature T_a $[°C]$, relative humidity [%], wind speed [m/s]).

The radiative component of the heat loss was then obtained through the following equation:

$$q_{3,rad}=\varepsilon_r \sigma\left(T_r^4 - T_{sky}^4\right) \ [W/m^2]$$

with σ the Stefan–Boltzmann constant, ε_r the emissivity of the panels' surface. The effective sky temperature T_{sky} $[K]$ is the most important parameter of the radiative cooling heat exchange. It was measured by a handcrafted sensor, which was made of a circular aluminum plate facing the sky and a PT1000 temperature sensor attached to it. The same theory was applied to the sensor, in order to determine the sky temperature, and the results have been corroborated with those of a pyrgeanometer placed nearby.

The convective component was obtained with the following equation:

$$q_{3,conv} = h_c \cdot (T_r - T_a)\ [W/m^2]$$

The convective heat loss coefficient h_c was calculated based on natural and forced convection occurring at the panels' surface, and included the wind speed and the air temperature recorded by the weather station (Péan et al., 2015). Both convective and radiative cooling components were then added to obtain the total cooling power $q_3 = q_{3,rad} + q_{3,conv}\ [W/m^2]$.

4. *Cooling power*

The average cooling power for the three methods is presented in Table 14. The average of the three methods is then used for further analysis. In the case of PV/Ts, because of the notable difference in the cooling power obtained with the VFS and the values obtained with the other methods, the first value has been discarded in the calculation of the average cooling energy per night. The cooling energy produced over the night is obtained by integration of the cooling power curves from 19:00 to 07:00. In order to analyze the efficiency of the system, the coefficient of performance (COP) is used. The COP is the ratio of the cooling energy obtained by the energy used by the pump. The circulation pump had an average power of 8 W, which consumes 96 Wh during a night of 12 hours. The COP has been obtained based on the total cooling energy produced by PV/T and unglazed panels since one pump was used to supply both of them. It is therefore mentioned as "COP - Overall" in Table 14.

The cooling energy produced by both types of panels is represented on Figure 44 (values based on the average of three methods). It is important to note that the cooling energy depends on several parameters other than the weather. One of those is the temperature of the water supplied to the panels, which directly affects the surface temperature of the panels and varied every night, depending on the daily radiation. Since the water supply temperature, the surrounding air temperature and the plane radiant temperature faced by the panels affect the most the cooling output, those values have also been plotted on Figure 44. The resulting cooling energy is simultaneously in function of all three parameters, therefore they cannot be read independently.

Table 14. Summarized data during the experiment period, from 12/08/2014 till 25/08/2014.

Date	q_1		q_2		q_3		**COP**
	W/m^2		**W/m^2**		**W/m^2**		**-**
	PV/T	Unglazed collector	PV/T	Unglazed collector	PV/T	Unglazed collector	Overall
12/08/2014	111.8	68.1	77.4	73.9	71.6	73.7	58.8
13/08/2014	93.1	68.1	68.9	67.3	64.6	69.7	56.6
14/08/2014	100.8	75.8	77.0	74.8	61.1	65.9	58.8
16/08/2014	78.8	38.9	42.2	43.9	30.2	32.2	32.5
17/08/2014	52.8	11.6	32.4	22.6	23.3	24.6	19.0
18/08/2014	76.5	38.8	52.0	49.6	42.5	42.0	37.2
19/08/2014	104.6	72.3	65.7	67.2	55.4	61.8	53.2
20/08/2014	104.5	67.3	62.4	66.1	57.4	65.5	52.5
21/08/2014	106.5	63.9	65.2	69.6	48.2	55.0	49.7
22/08/2014	79.3	35.9	47.5	45.2	28.3	33.0	31.5
23/08/2014	88.2	70.7	68.0	75.3	56.7	69.1	55.4
24/08/2014	89.0	56.7	55.5	60.0	49.7	56.7	45.1
25/08/2014	79.1	54.0	56.4	63.3	48.2	58.9	45.5

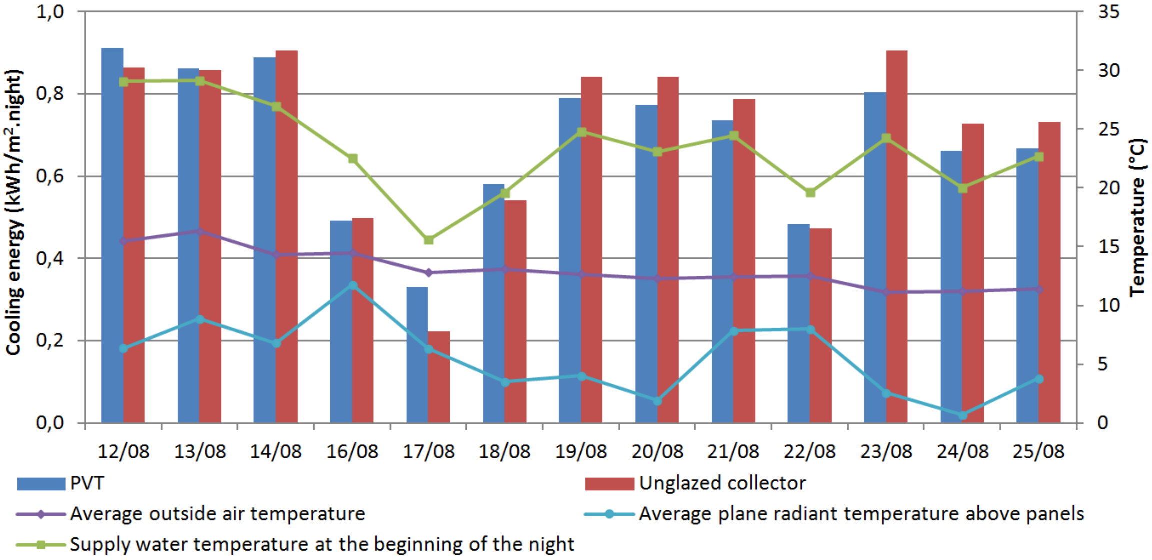


Figure 44. Comparison of the cooling obtained by the PV/T and the unglazed collector per night, from 12/08/2014 to 25/08/2014 (the energy is an average of the outputs of the three adopted method; the supply water temperature at the beginning of the night is averaged from 19:00 until 20:00; outside air and plane radiant temperatures are averaged from 20:30 till 7:00).

It can be seen that the difference of production between PV/T and unglazed collector is negligible. It was expected that the PV/T panels would produce less cooling than the unglazed collector, mainly because of the glazing that hinders the heat transfer, shielding the infrared radiation. The results show that this difference was slight, always less than 0.1 kWh/m^2.night between the two types of panels.

5. Combination with PCM

After the measurements carried out in summer 2014, the experimental facility was upgraded. Instead of using a simple tank placed on the roof, two insulated tanks were installed inside the building underneath, for the separate storage of hot and cold water. The panels were connected to a heat exchanger which would redirect the output water flow, to the hot water tank during the day to produce heating, or to the cold water tank during the night to produce cooling. Furthermore the cold water tank was connected to ceiling panels which embedded phase-change materials (PCM). Those panels, installed in a climatic chamber, could be discharged using the water from the cold tank. Finally, only the PV/T panels were utilized during this period because of some leakages that occurred in the unglazed collector loop. The final experimental setup is presented in Figure 45.

This upgraded experimental facility was used to perform several experiments during summer 2015, in order to estimate the performance of the coupling between PCM panels and radiative cooling with PV/T. The global output from PV/T was also investigated, considering the heating and electricity produced during the day and the cooling energy produced at night.

The first series of full-scale measurements took place in June 2015. Three different cases of one week each were then investigated, with variations of the water flow rates, both in the PCM loop and in the PV/T loop. The results are reported by Bourdakis et al. (2016a). They showed that the highest flow rate (210 l/h) in the PCM loop provided the best thermal environment in the climate chamber, with 92% of the occupancy time in Category III defined by standard EN 15251 (CEN, 2007). The lowest flow rate in the solar panels' loop resulted in the highest cooling power, but due to significant variations in the weather between the three cases, it was not possible to conclude safely on the influence of the flow rate on the cooling output. The PV/T panels could cover from 68 to 87% of the electrical energy use of the chamber.

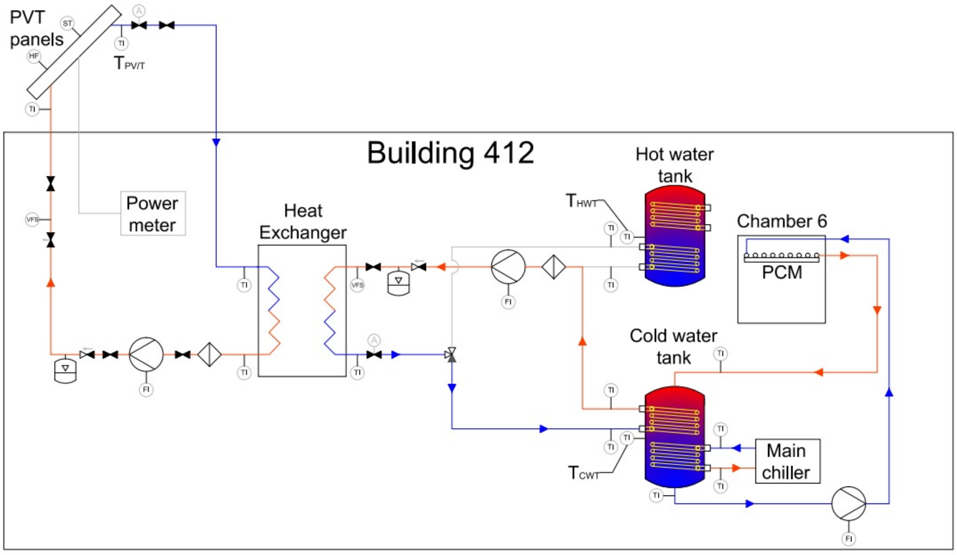


Figure 45. Schematic view of the hydraulic systems in the upgraded version.

The second series of experiments took place between July and September 2015. Five different cases of one week each were then investigated. The flow rates were kept constant, but different combination of nighttime ventilation, improved air mixing (presence of fans in the chamber) and activation of the PCM water circuit were tested. The cases investigated and the results obtained are summarized in Table 15, and more detailed analysis can be found in (Bourdakis et al., 2016b).

Table 15. Summary of second experiment with PCM.

Case number	**1**	**2**	**3**	**4**	**5**
Nighttime ventilation	No	No	30 l/s at 18°C – 20°C	30 l/s at 18°C – 20°C	30 l/s at 18°C – 20°C
Improved air mixing	No	Yes	Yes	No	No
Activation of embedded water system	Yes	Yes	Yes	Yes	No
Category I, %	45	59	57	37	19
Category II, %	63	84	81	58	29
Category III, %	92	95	99	95	50
Average electrical power, W/m^2	51	51.9	63.2	31.9	28
Average hot water production power, W/m^2	35	27	72.1	39.7	72.2
Average cold water production power, W/m^2	70.8	56.3	76.5	67.1	82.1

Those results show that coupling PCM and radiative cooling with PV/Ts can be an efficient combination for conditioning an office space in the summer season. In fact, the heat energy removed from the climate chamber by the PCM was 38 to 59% lower than the cooling energy produced by the PV/Ts and stored in the cold water tank. At the same time, the indoor thermal environment stayed within the limits of Category III for minimum 92% of the time (when the PCM panels were in use).

The PV/T panels proved to be an efficient system for producing electricity, heated and chilled water. No tapping occurred in the hot water tank, but its temperature was kept between 45 and 55°C thanks to the daytime operation of the panels. The electricity produced covered from 56 to 122% of the usage of the chamber, which highlights the potentials of this system.

6. Parametric analysis on environmental parameters

To understand better the influence of the weather on the output of nocturnal radiative cooling, a parametric study was carried out using the software TRNSYS. Both types of solar panels (unglazed collectors and PV/Ts) have been modelled using existing types of the TRNSYS software. Because of some uncertainty in several input parameters necessary for the simulations, a validation of the model has previously been carried out. For this validation, the experimental data recorded during the experiment of summer 2014 (see results in IV.4) have been used to adjust the TRNSYS model. The weather data and water supply temperature were provided as input to the TRNSYS model, and the output from the software was compared to the experimental data. The average error between experiment and simulation resulted to be 28 and 14% respectively for the PV/Ts and the unglazed collector. Since part of this error is due to the presence of rain during the experiment (not accounted for in TRNSYS) and to some inaccurate weather data (cloudiness was missing), the model has been considered reliable enough to carry on with the parametric analysis.

In the parametric analysis, a reference case was chosen: the nights from 01/08 to 04/08 from the reference weather file of Copenhagen from the International Weather for Energy Calculations (IWEC). Those nights presented favourable case for the production of nocturnal radiative cooling, with mainly clear sky, and were used to perform a first simulation in TRNSYS. Starting from this reference case, one weather parameter at a time was varied, within the ranges reported in Table 16.

Table 16. Parameters studied for the analysis.

Parameter	**Range observed for the parametric study**
Relative Humidity	20% to 100% by steps of 20%
Air temperature	The reference temperature curve is shifted by -9°C, -6°C, -3°C, +3°C, +6°C and +9°C
Cloud cover	0 to 100% by steps of 20%
Cloud base height	0.5 km, 1 km, 5 km, 10 km, 20 km
Wind speed	0 to 15 m/s by steps of 5 m/s

The graphs summarizing the results of the parametric study are presented in the following figures.

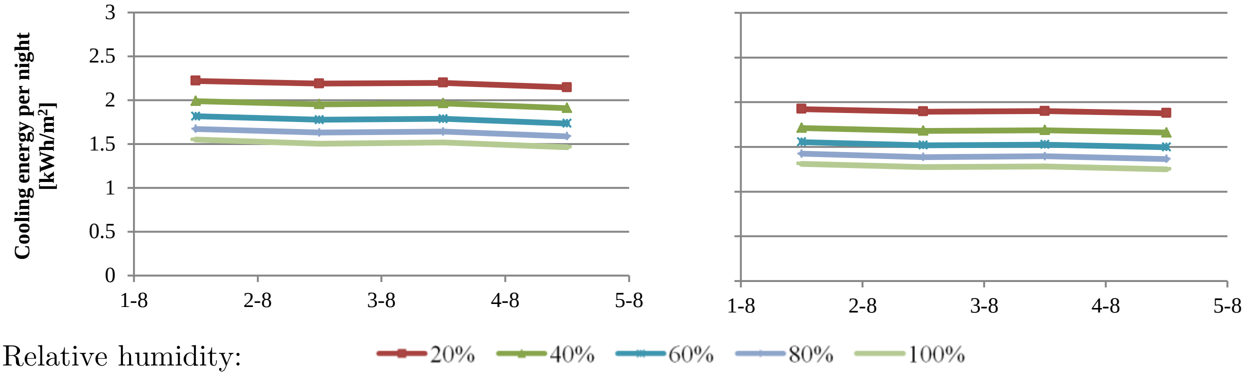


Figure 46. Parametric analysis of the relative humidity for unglazed collector (left), and PV/T (right).

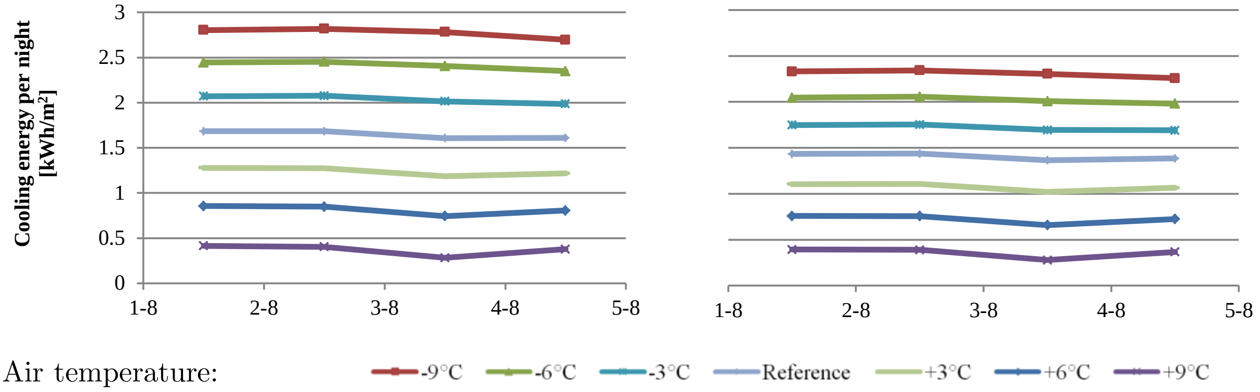


Figure 47. Parametric analysis of the ambient air temperature for unglazed collector (left), and PV/T (right).

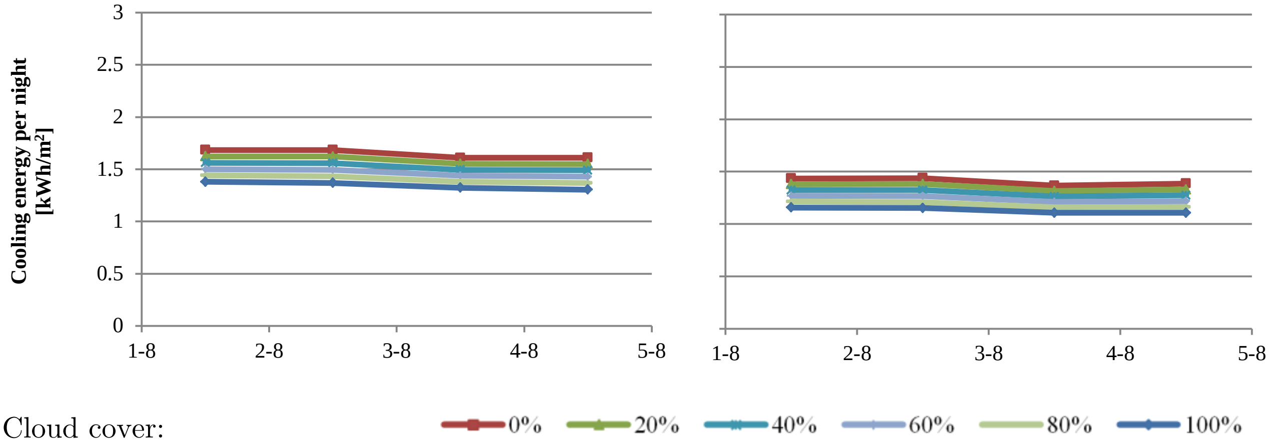


Figure 48. Parametric analysis of the cloud cover for unglazed collector (left), and PV/T (right).

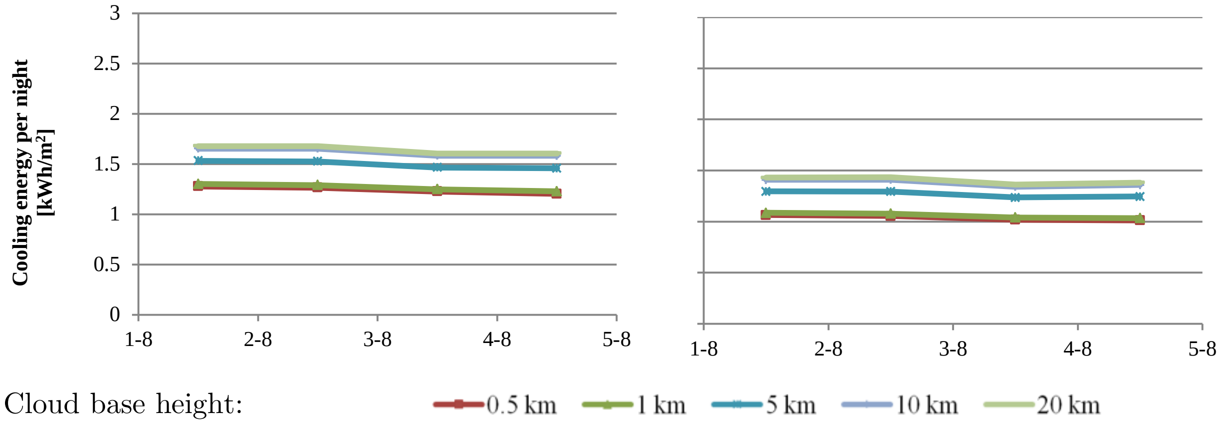


Figure 49. Parametric analysis of the cloud base height for unglazed collector (left), and PV/T (right).

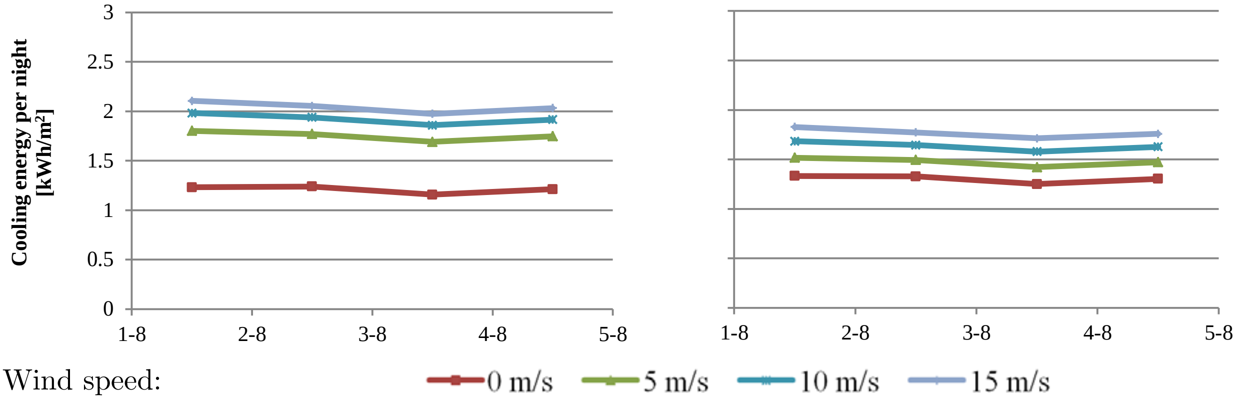


Figure 50. Parametric analysis of the wind speed for unglazed collector (left), and PV/T (right).

From these graphs, it can be seen that nocturnal radiative cooling depends highly on the weather conditions. As for other types of renewable energies such as solar or wind power, the cooling output can fluctuate significantly, and it mostly depends on the sky temperature, which depends itself on several parameters. The air temperature is the environmental parameter that has the largest influence on the cooling output of the panels since it impacts both the convective part of the heat exchange and the radiative part (through the sky temperature). For example, compared to the reference case for the unglazed collector, the variation in cooling energy is +69% when the temperature is lowered by 9°C, and -78% when the temperature is increased by 9°C. These values are comparable for the PV/T case, with +64% and -75% respectively.

The study also shows that unglazed collectors are slightly more efficient for cooling operation than PV/Ts, which does not concur with the findings of the experimental studies. The main reason for the difference is the composition of the panels: PV/Ts are covered by a glazing pane that reduces the heat losses (which is optimized for heating purpose), while the unglazed collectors inherently lose more heat (which is not optimal for heating purpose but becomes an advantage for cooling applications). The difference is particularly more pronounced when the cooling power reaches higher values (mostly above 100 W/m^2). These levels were almost never reached during the experiment, which explains why no difference was then observed.

7. Radiative and convective heat exchange

Further than the parametric analysis which gave results in terms of total cooling power, it is interesting to detail the respective contributions of radiative and convective cooling.
For the unglazed collector, some experimental results are presented on Figure 51 for one night arbitrarily chosen as example (20/08/2014). The theoretical model (see IV.3.2) enabled to compute separately the convective and radiative parts of the heat exchange. The dashed curves show the two other experimental methods, and the good matching proves the validity of the theoretical model, which is thus analyzed further. It can then be seen on the solid line curves that radiation accounts for 83% of the cooling energy produced that night, which concurs with the designation of "radiative cooling". To put this information into perspective, it should be noted that the average outdoor air temperature was 12.3°C during that night, and the average wind speed 2.1 m/s.

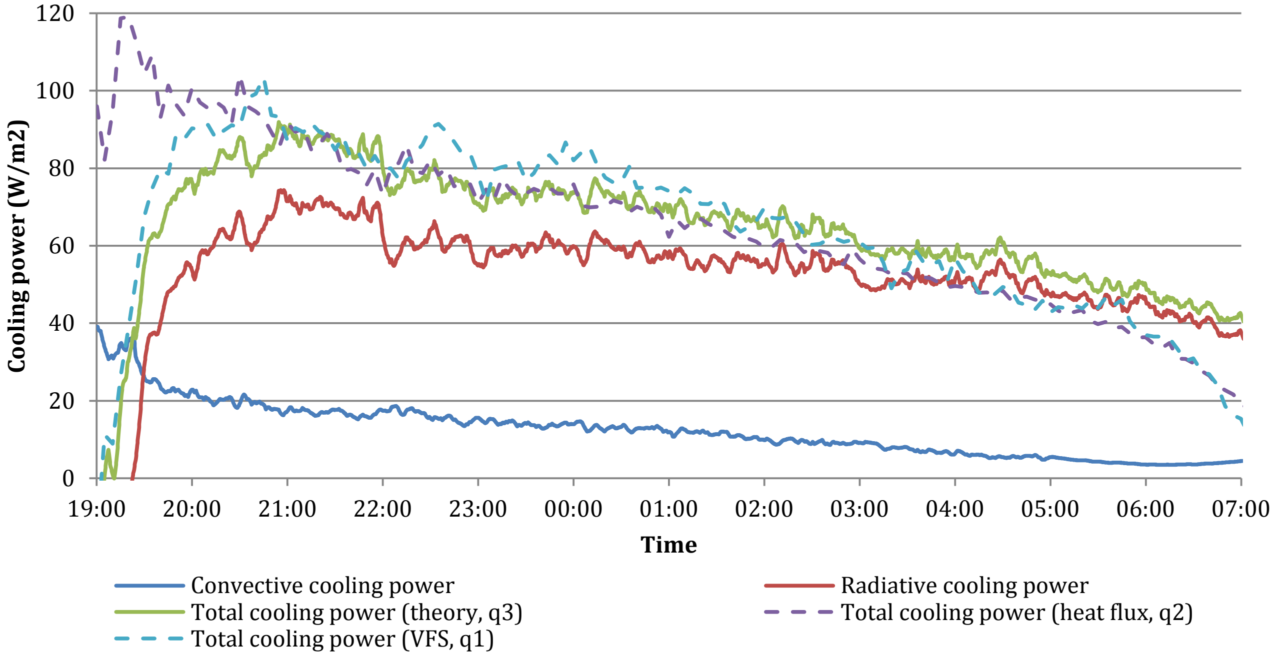


Figure 51. Convective and radiative components of the cooling power for the unglazed collector, during the night pf the 20/08/2014. The green line (theoretical cooling power q_3) is the sum of the blue (convective cooling) and the red (radiative cooling) curves.

For the PV/T panels, the results of the reference case of the parametric analysis are considered. During the four nights between 01/08 and 04/08 of that case, the radiative heat exchange accounted from between 86 and 89% of the total cooling, hence close to what was described previously for the unglazed collector. These results are derived from the simulations carried out in TRNSYS. The climate was rather stable during these four nights, with average external temperature ranging from 17.9 to 18.4°C and the average wind speed ranging from 2.5 to 3.4 m/s.
The percentages of radiation and convection can vary significantly with the weather conditions. The parametric analysis on the outdoor air temperature provides relevant study cases to support this statement. For instance, in the case where the temperature curve was shifted by -9°C, the radiation heat exchange accounted for 78 to 82% of the total cooling, the remaining 22 to 18% being attributed to convection. In contrast, when the temperature curve was increased by +9°C, the air became too warm to cool the panels by convection, and instead it warmed them up, reducing the effective cooling power. Consequently, the radiation

heat exchange then accounted for 125 to 141% of the total cooling. Convection reduced the cooling energy by 20 to 30% because of the high temperatures. The heat gain by convection was around 9 W/m^2 in this case. This phenomenon was already observed by Eicker and Dalibard (2011) under the climate of Madrid, with convective heat gains of around 13.5 W/m^2.

Eventually, these results show that radiation is always prominent over convection, which justifies *a posteriori* the designation of radiative cooling for this kind of applications. At lower temperatures and higher wind speed, the convection supplies a more important share of the cooling, but never overrides the radiative part. At higher outdoor temperatures, the convection can reduce the cooling efficiency by actually warming up the panels.

V. Discussions

1. EMBRACE

The full-scale measurements have been carried out in the EMBRACE house with all the necessary precautions and attention to details. However, some uncertainties are inherent to any experiment setup of this type. First of all, EMBRACE is only a prototype, and as such, it has never been truly occupied by a real family. In summer, visitors would enter the house during the opening hours of the park, and in winter the occupancy was simulated by thermal dummies. The behaviour of a building's inhabitants greatly influences the energy balance and the indoor environment, therefore this might represent an issue, especially during the summer period. In winter, the occupancy was better controlled with the thermal dummies, but these only represented the thermal contribution of the occupants, not their movements, indoor activities, opening of doors and windows, CO_2 and bioeffluents pollution etc.

One objective of the project was to draw an annual balance of the house's performance. The Universe park was delayed in finishing the house in time during Spring 2015, and some technical problems occurred (rats eating cables to only cite one) which caused data loss during several periods. Two periods of approximately four months each have been studied thoroughly (summer and winter), which represent the most extreme cases, both for energy balance and indoor thermal comfort. It is safe to assume that the remaining four months of the year, which represent mid-season, would not drastically affect the energy balance or the indoor environment.

Lastly, the evaluation was carried out using different settings, mainly with variations of the indoor temperature set-point. However, the weather was different in every period, therefore it is difficult to compare the different cases. An evaluation using degree-days would provide more accurate comparison data, and it could be the subject of further research.

2. Discussion on EMBRACE from the point of view of external consultants

External solar shading

The location of the house/EMBRACE modules is intended for rooftop of old houses being renovated and where the roof is utilized by adding prefabricated roof dwellings. This is typically at 5^{th}-6^{th} floor and the wind speed in this height can be significant. The external solar shading on the southern façade of the house will be very exposed to the outdoor climate and must be very robust. Alternatively windows with a very low g-value in the southern façade can be used – products with a relative high light transmittance and RA-index are available.

Utilization of exhaust air

With the location of the houses on the roof top surrounding the exhaust ventilation shafts, which typically are located on the roof, the heat from the exhaust air can be utilized by installing either heat recovery or a heat pump for preheating of domestic hot water or heating of ventilation air.

Weather shield (roof)

One should not underestimate the impact on humans of direct sky light which is reduced in the semi-outdoor space. Roof top terraces are very much appreciated and highly valued on the real estate market and such a terrace in the southern oriented roof would be a great asset for the house and its residents.

Neighbours

When the house is assembled on a roof top side by side with equal houses, the wonderful light flowing through the window façade will be reduced. If the houses are placed with the common semi-outdoor spaces adjacent the privacy will be reduced.

Connection between indoor and semi-outdoor space

Experience from low energy houses shows that residents often leaves windows and doors open in order to get fresh air either because they can't regulate the ventilation system or because they think "the house regulates itself – it's low energy". There will be an increased risk that the residents will leave the door from the bedroom and living room to the semi-outdoor space open in longer periods than just the summer. In the summer time it will increase the quality of life to have the doors open to utilize the extra space and this will become a habit. When the heating season begins it will lead to increased heat losses due to the system trying to heat up the semi-outdoor space.

Architectural element of PV on semi-outdoor space

The architectural benefit of the PV-cells placed in a pattern on the weather shield can be discussed. The view from the inside to the sky seems to be disrupted by the dark cells even though the majority of the light is passing through and moreover it is an expensive way to install PV. However, it is demonstrated how PV can be integrated in buildings in different interesting ways.

3. *Nocturnal radiative cooling*

The studies performed on the topic of radiative cooling are also subject to discussion on their accuracy. During the full-scale experiments, the calculation of the sky temperature was made through measurements from a handcrafted sensor. A detailed theoretical model has been applied to this sensor, in order to obtain the most accurate measurement of the sky temperature. As the sky temperature has the largest influence on the cooling output, some error could stem from these measurements, but validations have been made to ensure the reliability of the results.

During the computer simulations, numerous input parameters were needed to model the solar panels. Some of them were not available in the products' datasheets, therefore several assumptions had to be made, with the most realistic values. Furthermore, radiative cooling is a relatively new utilization for solar panels; the existing models of unglazed collectors or PV/Ts are thus optimized for daytime heating (heat gains), not for nighttime cooling (heat losses). To reduce the consequent bias, some adjustments were realized in the model, which was then validated by comparison with the experiment data.

Another possible source of errors comes from the independent variations of the weather parameters for the parametric analysis. Climate consists of a whole set of interdependent parameters. Extracting one of them to realize separate variations is not a realistic approach. However, this part of the study focused on the relative impact of each parameter, and therefore the realism of the absolute values was not the prime interest.

Finally, it is unfortunate that the studies on the water flow rate in the panels did not result conclusive. The weather during the series of experiments with changes in the flow rate changed significantly from one study case to the other, therefore conclusions could not be drawn safely about the influence of the flow rate on the cooling output. However, it is certain that the flow rate does impact the cooling power. More studies should be made in this regard to determine an optimal flow rate for the functioning of the panels in radiative cooling. To avoid the inevitable weather variations, this work could be carried out in TRNSYS.

VI. Conclusions

1. EMBRACE

The full-scale measurements in EMBRACE, whether they were performed during SDE2014 or afterwards in Denmark, showed the capacity of the house and its mechanical systems to provide a comfortable indoor environment. Several indoor temperature set-points have been tested: 20 to 22°C in winter, and up to 24°C in summer. EMBRACE never experienced real trouble to reach those set-points, even though the indoor climate was less stable during the periods where the house was operated in cooling mode. In fact, the house was capable of providing excellent thermal comfort: with a heating set-point of 22°C, up to 92 and 98% of the time was observed within the range of Category I of EN15251, which is a remarkable performance. This leads to the conclusion that a plus-energy house such as EMBRACE can be as comfortable to live in as a standard dwelling, and this performance can be achieved without excessive energy use.

During the annual measurement campaign performed in Denmark, the energy balance has been studied. In the summer period, the house produced 1563 kWh while using 333 kWh of electricity; in the winter period it produced 432 kWh while using 1521 kWh. In total for those considered 8 months, the house produced 1995 kWh while using 1854 kWh, which results in a positive balance (excess of energy) of 141 kWh. The remaining months in spring and autumn would not affect significantly the energy balance, since the mid-season is considered close to equilibrium between energy supply and demand (as can be seen from the neighbouring months, e.g. February 2016 where already 73% of the demand was covered by the PV production). Furthermore, if a dysfunction did not occur in the PV system in summer 2015, the production during this period could have been doubled, which would have improved the energy balance significantly. For these reasons, it is very safe to state that EMBRACE achieved its plus-energy target during the annual evaluation.

Large differences have been observed between the expected and the actual performance of the house. For example, it was estimated that the PV system could produce 5357 kWh per year in Copenhagen (with the whole 6.8 kWp functioning, Gennari and Péan, 2014). Over the course of 10 months, a production of only 2497 kWh was observed (from 27/05/2015 till 29/03/2016). The difference is explained by the fact that only part of the PV tiles were connected, and because of the dysfunction of one semi-transparent panel. Such issues could also occur in any dwelling, therefore it poses the question of the maintenance of the PV systems: would the owner of a plus-energy house spend money or time on repairing defective PV panels? This would of course influence greatly the actual outcome of a plus-energy house.

Another difference between prevision and realization concerned the energy used for heating and cooling the indoor space. It was estimated during the design phase that the house would consume 1090 kWh/year for heating, cooling and ventilation. During 8 months, the house already consumed 1854 kWh, therefore the annual value would be considerably higher than what was predicted. This can also be seen in the recorded peak powers: 1.6 kW was expected for heating (with -12°C outside), while 1.7 kW was recorded (with -5°C outside). In summer, the peak cooling load was recorded at 0.7 kW while 1.3 kW was expected. Those differences are partly accounted for by a different use of the house than expected.

Another explanation can be found in the air tightness of the house: the specific air leakage rate was measured at 5.9 $l/s.m^2$, while the Danish Building regulation recommends a maximum of 1.0 $l/s.m^2$ for low-energy houses. The consequent air infiltration partly caused the observed increased heating consumption and lowered cooling consumption. The poor air tightness stems from a hurried finishing of the house, and also from the repeated assemblies of the house, where the air barriers might not have been reconnected tightly. These observations concur with the statements raised in the introduction: the actual realization and the quality of the building works have a great impact on the energy consumption. Such conclusions can lead to justified doubts about the claimed energy performance of some buildings.

Globally, the original design of the house has been validated through this evaluation. The sheltered garden was able to provide a more comfortable environment than outdoors, with up to 3°C increased temperature during sunny days, protection from the rain and large reduction of the wind velocity. The occupancy of this semi-outdoor space is therefore possible during a large part of the year, and it extends the living space of the house.

As a general conclusion, the project has confirmed the feasibility of realizing a plus-energy house that is at the same time comfortable, aesthetically and architecturally pleasing, and energy-efficient. As a study case, EMBRACE has proven its achievements in all these domains.

2. Nocturnal radiative cooling

Through the present project, nocturnal radiative cooling has proven to be a promising technology. The observed cooling power in the experiments ranged from 28 to 82 W/m^2, which corresponds to what was previously observed in the existing literature. This range of cooling power is relatively low, which means a large surface of panels is necessary to achieve a usable cooling power for a building. A quick calculation enables to link the building demand to the area of panels needed. This estimation must be done on a 24 hours cycle, given that the supply and demand are not simultaneous. Considering indoor heat gains of 40 W/m^2 and a concrete slab system operated during 16 hours per day, it is estimated that 350 Wh/m^2 of heat are rejected per day (Babiak et al., 2009). On the other hand, considering a cooling production of 100 W/m^2 of panel, during an operation of 8 hours per night, the radiative cooling amounts to 800 Wh/night (level of production also observed experimentally in Figure 44 for instance). This means that around 350/800 = 43% of the building's conditioned area should be installed as solar panels on the roof of that building, i.e. that 0.4 m^2 of solar panels is needed for every 1 m^2 of building. This is of course only a very rough estimation, but it enables to give an approximation of the possibilities for implementation. For instance, it would be difficult to use radiative cooling in a building that comprises more than two storeys, if the radiative cooling is meant as the only source for cooling. With three or more storeys, radiative cooling could supply part of the demand, but another active system would be needed.

The COP (defined as the ratio between the cooling energy produced and the energy consumed by the circulation pump) reached very high values, which highlights the potentials of energy savings through radiative cooling. The same observations have been seen in the literature, and notably by an exhaustive report published by the U.S. DOE. This report also mentioned several barriers to the implementation of radiative cooling, such as the necessity of storage for the chilled water between its nighttime production and its daytime use.

In the lower range of cooling powers (less than 100 W/m^2), no significant difference was observed between the PV/Ts and the unglazed collector. In a higher range of cooling powers (above 100 W/m^2), the PV/Ts are slightly less efficient for cooling than the unglazed collector, because their glass cover hinders the heat exchange.

Radiative cooling highly depends on the weather conditions, as can be seen by the large span observed in the cooling energy during the different simulations. Among the studied parameters, the air temperature has the largest impact on the cooling output, since it influences both the sky temperature (which in turn affects the radiative part), and the convective part of the heat transfer. An increase of +9°C in temperature causes the cooling output to drop by approximately 75%, and a -9°C decrease in temperature causes the cooling output to increase by 65%. Clouds, relative humidity and wind speed also affect the cooling performance considerably. According to the parametric study analysis, the most favorable climates for nocturnal radiative cooling should present the following criteria during a large part of the year: lower temperatures at night, clear skies, relatively dry weather and possibly windy.

The longwave radiation effect always prevails over the convection effect in the cooling process. At lower temperatures, it was observed that the radiation accounted for around 80% of the total cooling power, the remaining 20% being attributed to convection. On the other hand, at higher temperatures, the convection produces the unwanted effect of warming up the panels, thus reducing the effective cooling power by 20 to 30%.

The combination of PV/Ts for radiative cooling and PCM ceiling panels has proven to be an efficient method to provide cooling to an office building. For instance, the heat removed by the PCM from the test climate chamber was 38 to 59% lower than the cooling energy produced by the solar panels, during the second series of experiments. This highlights again an unexploited potential of radiative cooling. PV/Ts alone are considered as a promising system, since they can produce three forms of energy: electricity, hot water, and cold water at night through radiative cooling. The combined productions can cover significant percentages of a building's demand.

3. Learnings, recommendations and further research

With already two participations in the Solar Decathlon and two houses which have been the subject of extended evaluations, Team DTU can formulate some learnings and recommendations based on its experience.

- From FOLD to EMBRACE, the design has been improved. Large glazing areas which caused overheating issues in FOLD have been avoided in EMBRACE. As a consequence, overheating was never a problem in that second house, and the cooling system could probably have been avoided (it was implemented for the summer competition in France), running the house only passively in summer.
- On the other hand, the reduction of the glazed areas has caused a reduction in the quality of the daylight in the house. EMBRACE scored poorly in this category, although some efforts have been made like the implementation of a skylight.
- The air tightness has been an issue in both houses, because of the successive assemblies. If DTU is to participate again in Solar Decathlon, a special attention should be paid in reconnecting each time the air barriers, since it will influence greatly the energy consumption. Maybe during the design phase, this precise element should be kept in mind, anticipating the places where the membranes have to be connected between modules, and providing easy access to realize this operation.
- The modular concept, implemented in both cases, has facilitated the fast mounting of the houses. It probably constitutes the best option, but the air tightness problems should maybe leave place to discussion on this topic.

- The high consumption of the control systems was identified as an issue in the FOLD house, reaching up to 39% of the total consumption. In EMBRACE, part of the control system has been relocated to a cloud, reducing the consumption of the control systems in the house itself.
- In both houses, attempts have been made at designing complicated control systems, aggregating several systems with different protocols in a single app, used to operate the entire house. This proved difficult to realize in practice, and no support was provided after the competition to restart this complicated and customized system. The authors advise future teams to choose a unique integrated control system already available in the market. This would result less innovative, but the safe operation of the systems and the datalogging would be ensured.
- PV/Ts had been integrated in the roof of FOLD to produce heating and electricity in a single system. Because of their high cost, the production of hot water and electricity has been separated in EMBRACE, with solar collectors on one hand and PV cells on the other hand. The present study has proven that PV/Ts could provide hot water, cold water at night through radiative cooling, and electricity. This combined production can reduce significantly the initial investment cost, therefore the choice of PV/Ts should be considered again.

Further points of research have also been identified, both on the EMBRACE house and on the radiative cooling technology:

- An evaluation using degree days would give a more accurate idea of the performance of the systems, independently of the weather conditions. It would also enable to compare the EMBRACE and FOLD houses more thoroughly for example.
- Similarly than what has been done in FOLD, some improvements in the design or in the systems could be investigated by means of dynamic simulations. For instance, the option of removing the storage tank (whose presence is not totally justified in the Danish context), could be studied. Else the storage tank could be studied as a means of providing energy-flexibility to the building, operating the heat pump and charging the tank only at times where electricity from renewable sources is available.
- Regarding nocturnal radiative cooling, the coupling of this technology with a heat pump could be investigated. Possible operation of such systems would include the precooling of water by radiative cooling, enabling the heat pump to function afterwards at a higher efficiency.
- Following the parametric analysis on the weather conditions, simulations should be carried out in different climates. Arid climates have for example been identified as favourable for the production of radiative cooling. Using real weather files to estimate the potential of radiative cooling in different locations would enable to get a better picture of this technology.
- More detailed analysis on the flow rate and the supply water temperature should also be carried out, most probably in TRNSYS to eliminate the bias introduced by variating weather conditions. Preliminary research had been carried out by Gennari and Péan (2014), and attempts at experimental measurements by Bourdakis et al., (2016a) but these works should be continued.

VII. Dissemination

The project has been running from 2013 and the design phase of the house, until 2016 and the completion of the annual evaluation of EMBRACE. During this period, at least 14 students have written their thesis on a topic related to Solar Decathlon or nocturnal radiative cooling. A list is enclosed with the references of all these theses; most of them were written in the frame of the ICIEE, and some in other departments, therefore on topics less relevant with the present report.

In addition to the theses, several articles have been published in conference proceedings or peer-reviewed journals. They have constituted the basis for the composition of the present report, and they are presented in section 2. Finally, a list of other dissemination activities and presentations is enclosed in section 3. The quantity, quality and variety of all the publications and works carried out in the frame of this project show how profitable it has been for the students, the partners involved and the general audience.

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Wohlenberg B. (2015). Test and Measurement of the Performance of Plus-Energy House EMBRACE. Bachelor thesis project, Department of Civil Engineering, Technical University of Denmark.

2. Articles in conferences and journals

Bourdakis E., Péan T.Q., Gennari L. and Olesen B.W. (2016a). Experimental study of discharging PCM ceiling panels through nocturnal radiative cooling. In: *Proceedings of the 9th International Conference on Indoor Air Quality, Ventilation & Energy Conservation in Buildings – IAQVEC,* Seoul, Korea.

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3. Presentations, events and dissemination activities

30 April 2014: A presentation was given for Korean Professor Kwang-Woo Kim, in visit in Denmark, about the design of EMBRACE. DTU, Kgs. Lyngby, Denmark.

22 May 2014: EMBRACE was officially opened by the Danish minister of Climate, Energy and Buildings, in presence of the French ambassador in Denmark, partners of the project and the heads of DTU.

June-July 2014: Numerous presentations and visits of the house occurred during the competition period. The European ministers of Energy and Buildings were introduced to all the projects. The Danish minister of Climate, Energy and Buildings was interviewed in the EMBRACE house by the Solar Decathlon organization.

June 2015: A presentation was given at the 2015 ASHRAE Annual Conference in Atlanta, GA, USA.

1 September 2015: A presentation was given at the Universe park about the current state of the project, for a Center Komité meeting of the ICIEE. Nordborg, Denmark.

10 September 2015: A presentation was given at the CLIMAMED 2015 Conference, based on the article submitted by Péan et al. (2015) about nocturnal radiative cooling. Antibes, France.

14 December 2015: A presentation was given to Klimaklubben, an organization gathering people interested in solutions to fight climate change. Copenhagen, Denmark.

17 December 2015: Two presentations were given at the DTU Sustain conference, based on the two abstracts submitted by Kazanci et al., 2015 (about Solar Decathlon) and Péan et al., 2015 (about radiative cooling and PCM). DTU, Kgs. Lyngby, Denmark.

January 2016: A presentation was given at the 2016 ASHRAE Winter Conference in Orlando, FL, USA.

May 2016: Four presentations will be given at the CLIMA 2016 conference based on the papers submitted by Péan et al. (2016a and 2016b), Foteinaki et al. (2016) and Papachristou et al. (2016). Aalborg, Denmark.

October 2016: A presentation will be given at the IAQVEC 2016 conference based on the paper submitted by Péan et al. (2016c) on the winter performance of EMBRACE. Seoul, South Korea.

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