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Energy Procedia 140 (2017) 141–150

Energy Procedia

www.elsevier.com/locate/procedia

AiCARR 50th International Congress; Beyond NZEB Buildings, 10-11 May 2017, Matera, Italy

From high-energy demands to nZEB: the retrofit of a school in Catalonia, Spain

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Abstract

Since existing buildings are responsible for almost 40% of the energy consumption, a major focus in the construction sector is represented by building energy-saving retrofits. Considering the limited current economic possibilities in the construction market, the retrofit of existing buildings has become a target for both private actors and public administrations in most of European countries. In this context, the province of Catalonia in Spain is defining strategic plans and guidelines to help energy retrofits according to nZEB criteria. In this framework, the present paper evaluates the effectiveness of a series of strategies considered in the energy refurbishment of a school located in the Metropolitan Area of Barcelona. Firstly, the study reports the results of an extensive (level three) energy audit. This data is then used to create a reliable energy simulation model. A set of possible interventions is hence investigated considering technical feasibility, cost, and potential energy saving and indoor comfort benefits. Results show the actual possibility of reaching the nZEB standard at the end of the refurbishment of this high-energy consuming building. Finally, the case study is discussed as a valuable example for promoting energy retrofits in Catalonia and beyond.

Peer-review under responsibility of the scientific committee of the AiCARR 50th International Congress; Beyond NZEB Buildings.

Keywords: nZEB, energy retrofit, Mediterranean climate, energy simulations, Phase Change Materials.

1. Introduction

This paper presents a real case retrofit project of a school in Catalonia, Spain. The aim of the study is to develop a reference case for other ongoing projects of the same typology in the metropolitan area of Barcelona. The comparison among different retrofit strategies offered several scenarios, which were evaluated in terms of energy efficiency, technical feasibility and costs, considering the influence of each factor over the goal of reaching the nZEB target [1]. Since, the 2010 European Energy Performance of Buildings Directive (EPBD) recast defined the need to promote nZEB, to reduce the energy use in European buildings [2], a significant attention towards advanced best practices and

1876-6102
Peer-review under responsibility of the scientific committee of the AiCARR 50th International Congress; Beyond NZEB Buildings
10.1016/j.egypro.2017.11.130

case studies in the field of energy efficiency among the EU Member States has been recorded. The EPBD recast demanded to each member state to translate the nZEB target into national legislation and practical guidelines, establishing minimum energy performance requirements for new buildings and for the major renovation of buildings and building elements. In this ongoing process, Spain has suffered a general delay, since a lack of national framework for ZEB exists. The nZEB scenario for the project described in this paper was defined in order to comply with the most stringent requests identified in the Spanish National Code (CTE) [3]. For commercial buildings, these parameters are:

- 35% saving in the energy demand compared to the reference National Code case;
- 70% of energy savings in the production of hot water;
- 70% of electricity produced with Renewable Energy Technologies;
- Maximum thermal transmittance for opaque elements of 0.2 W/(m^{2}K);
- Maximum thermal transmittance for transparent elements of 1.6 W/(m^{2}K).

In Table 1, the framework that identifies the nZEB scenario for Spain is compared with the current energy code.

Table 1. Spanish National Code standard and comparison with the related nZEB standard proposal.

	Current National Regulation – Residential Buildings (kWh/m^2 y)	Current National Regulation – Commercial Buildings (kWh/m^2 y)	nZEB proposal – Residential Buildings (kWh/m^2 y)	nZEB proposal – Commercial Buildings (kWh/m^2 y)
Limits of energy demand of heating and cooling	20 + 1000/ Building Area	25% savings in energy demand	<15	35% savings in energy demand
Limits of energy consumption	50 + 1500/ Building Area	Class B	Class A	Class A
% renewable energy production for hot water	⩾ 40%	⩾ 40%	⩾ 70%	⩾ 70%

The measures adopted in the retrofit project presented in this paper aimed to achieve the nZEB standards with a minimal increase in the overall cost compared to a standard refurbishment project. Moreover, the considered actions aimed to improve the poor indoor comfort conditions in the building in terms of lighting, thermal, and acoustic comfort.

The project started with an energy audit and a collection of data of the construction elements, HVAC system, and energy consumptions through bills. The core part of the project was the definition of the retrofit strategy and the evaluation of each action in terms of potential energy savings.

The climate context and the activity profile made then suitable the analysis of the value of interventions based on the inclusion of Phase Change Materials (PCM) materials for limiting temperature fluctuations. In particular, a significant part of the research was dedicated to the possibility to apply panels PCM on the inner surfaces of the walls.

The research on PCMs has become one of the major topics in the building material field for energy retrofits. PCMs have the capability to store and release energy in the form of latent heat thanks to a solid-liquid/liquid-solid phase change at their melting point temperature and they may hence be used as thermal storage systems in order to store excessive heat from inside the building [4-6]. The analysis focused on the most significant aspects of PCMs such as the frequency of activation, the surface temperature, the effective operative temperature, and the energy saving effects.

2. Case studybuilding

2.1. Definition of the current state

The project started with an extensive (level three) energy audit of the existing building. Data was gathered from the available information provided by the administration and through on site analysis and energy audit measurements (thermal transmittance measurements, IR survey, thermal bridge analysis, and so on). All the data were used to realize an energy model in Energy Plus. Once the energy model was calibrated with the actual energy consumptions, it was possible to analyze the energy performance of different proposed retrofit interventions.

The scholastic building considered as case study is located in a rural area at the edge of Barcelona. The building is oriented north-west/south-east along its longitudinal axes; this orientation does not help getting high solar heat gains, which are also limited by the presence of large trees around the building.

The building has a jagged perimeter with an unfavorable surface area to volume ratio. The envelope consists of an exterior façade made of local brickwork without insulation. The structural elements consisting of concrete pillars and beams are visible, representing clear thermal bridges. The north part is cantilevered with the external floor exposed without insulation (Fig. 1). The roof is a semi-exterior unconditioned that leans on the structure; the exterior façades with a prominent concrete curb constitutes another significant thermal bridge. The main construction assemblies are summarized in Table 2.

Fig 1. Photos of the outside façades of the school investigated in this paper.

Table 2. Construction assemblies of the case study.

Element	Description	U-value W/(m^2 K)
Exterior wall	Double layer brick wall with 7cm air gap and inside plastering	1.76
Pitched roof	Traditional ceramic tiles roof above unventilated semi-exterior space	2.18
Internal floor	Unidirectional concrete floor structure with ceramic elements	2.05
Internal wall	Single layer brick wall with plastering	1.69
Bottom floor	Unidirectional floor structure with ceramic elements	2.34
Window	Single glazing with aluminum frame with no thermal break	5.70

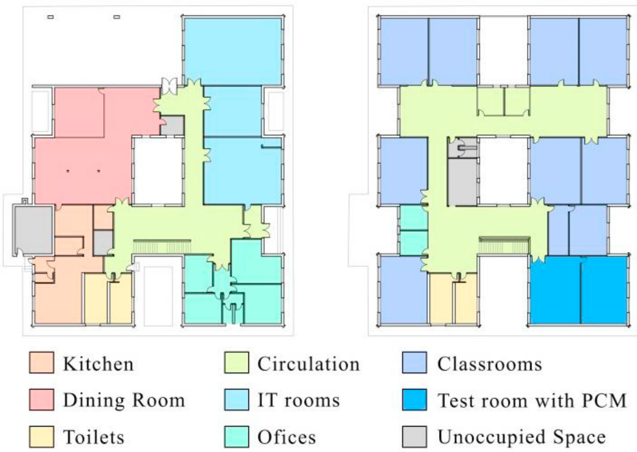

Fig 2. Floor plans and internal distribution of the case study investigated in this paper.

The schools is a two storey building with 1641 m^2 of occupied area and 5586 m^3 of occupied volume. The access to the building, the administrative area (secretary and the teachers' offices), the cooking area with its warehouse, the dining hall and common activity rooms are all located in the ground floor. In the first floor, the classrooms and other common activities are located (Fig.2).

The heating system is an old gasoil boiler with a single loop water distribution and high temperature radiant heaters with an overall heating capacity of 116 kW and a COP of 0.65. There is no cooling system. The lighting is provided with T8 tubes fluorescent lights. The hot water is produced with a dedicated electric boiler. Every classroom is equipped with a PC and a projector.

The occupancy and activity profiles were captured according to the real use of the building: so in the late evening and night, and on weekends and during summer time the school is unoccupied.

2.2. Energy Model

The energy model was designed according to the current state and spatial distribution of the building. The model accurately reproduces the geometry and the building features. In fig.2, the zones are displayed according to their activity. IT rooms have an occupation of 0.22 people/m^2 corresponding to 22 people per room, active from 8:30 to 13:30 and from 15:00 to 16:30. The kitchen is occupied from 8:00 to 16:00 with internal gains of 363 W/m^2 generated by the equipment for cooking and food storage. The dining area is occupied only from 13:30 to 15:00 with an occupancy density of 1 person/m^2. The circulation area and toilets have a negligible rate of occupation and are conditioned from 8:30 to 16:30. The heating and cooling demands were calculated according to a set point temperature of 22 ºC for winter and 25 ºC for summer. According to these data, the energy demand of the current building has the distribution shown in Fig.3.

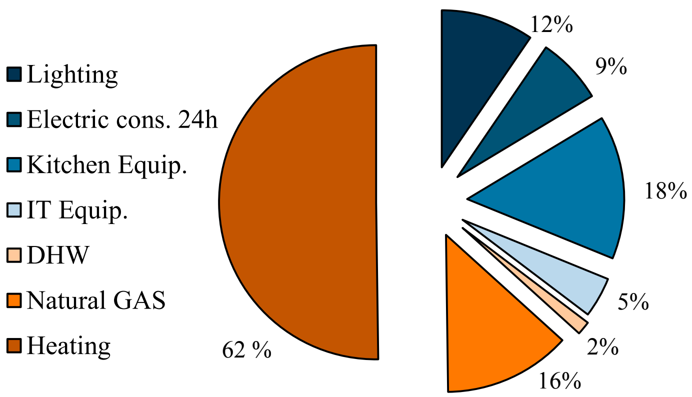

Fig 3. Consumption breakdown in the school according to the simulations in the present situation.

2.3. Proposal of the several interventions

The analysis of the existing energy demand scenario (shown in Fig.4) was the starting point of the evaluation of each proposal in terms of energy consumption, users comfort and payback time. Each solution was first considered individually and then the final results of a retrofitting project obtained realizing different measures were assessed [7,8]. This method was requested by the Public Administration responsible to fund the present project in order to conduct a multi-years execution plan where the several measures could be eventually applied gradually depending on the annual financial availabilities.

A list of all the possible retrofitting measures was first evaluated and discussed as reported in Tables 3 and 4. Then, a scenario with the combination of the most viable and effective passive retrofitting solutions was made. Finally, a second scenario with the addition of renewable energy system was considered (Table 5).

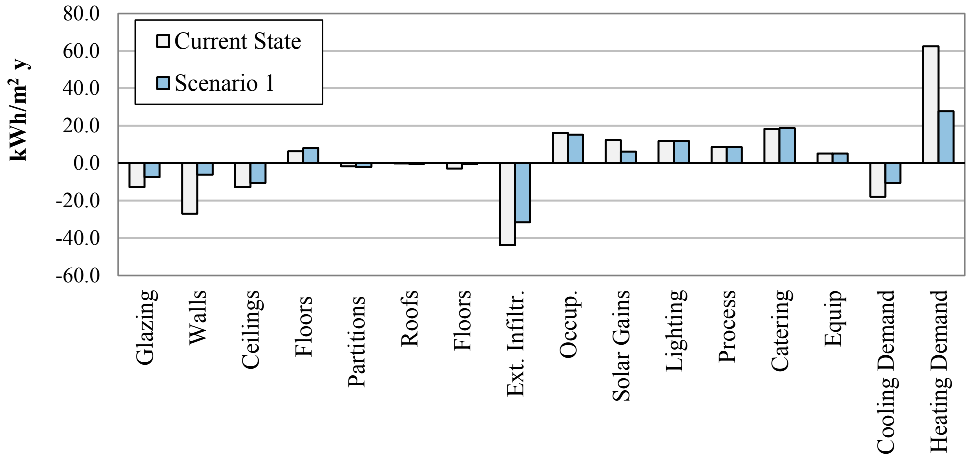

Fig 4. Consumption breakdown in the school according to the simulations in the present situation

Table 3. Passive retrofitting measures evaluated for the retrofit project.

Measure	Pros	Cons	
XPS wall external insulation (15cm)	it does not create thermal bridge on the façade	it does not solve the roof-façade thermal bridge	M1
Internal insulation	cheap and good to also fix the acoustic problems	room surface reduction and creates thermal bridges	-
Wall cavity insulation	cheap	not sufficient to meet nZEB standards	-
Application of PCM on internal ceiling surfaces	improves climate comfort during occupied hours	not efficient in energy/cost payback	-
Application of PCM on internal walls and partitions	improves climate comfort during occupied hours	not efficient in energy/cost payback	-
Windows replacement with double glazing low-e	improve thermal, light and acoustic quality	generally expensive	M2
Increase window-wall ratio in south and east façade	improve light and architectural quality	not completely effective due to the surrounding obstruction	M3
Solar protection	improve light and architecture quality	-	M4
Enclose patios to create light shafts	improve architectural quality and thermal comfort	expensive	M5
Ceiling insulation (15 cm)	improve acoustic quality and thermal comfort	it does not fix the roof-façade thermal bridge	M6
Roof insulation - inside cavity	improve thermal comfort	it does not solve the roof-façade thermal bridge	-
Retrofitting of the roof with the implementation of light chimneys	improve passive solar radiation and light quality	only effective for the last floor	-
Ground floor insulation	improve thermal comfort	-	-
Insulation under cantilevered floors	improve thermal comfort	it creates thermal bridges	M7

Table 4. Passive retrofitting measures evaluated for the retrofit project.

	M1	M2	M3	M4	M5	M6	M7
Heating	19%	22%	4%	1%	8%	15%	*19%
Cooling	-6%	-6%	-4%	2%	-	0	*-39%

Table 5. Active retrofitting measures evaluated for the retrofit project.

Measure	Pros	Cons	
Biomass HVAC system with COP 0.925	It improves energy efficiency		M8
LED lighting	It improves electricity consumption	-	M9

3. Energy Retrofit Results

The first stage of the project consisted of the evaluation of each retrofitting measure individually (Tables 3 and 4). The most effective solutions resulted to be the M1 (15cm XPS wall external insulation) and the M2 (windows replacement) with 19% and 22% of energy saving respectively; an energy saving of 15% could be obtained by doing the intervention M6 (insulation of the inner surface of the roof). Smaller improvements came from the increase of window to wall ratio and the use of solar shading systems. The intervention M5 (enclosure of patios to create light shafts) showed 8% energy saving when compared to the current state. Besides the building is not equipped with cooling system, the cooling demand was calculated in order to monitor the global effect of each proposal. The first scenario consisted of a combination of all the aforementioned passive measures. The energy saving that this intervention would guarantee is 56% of the current heating demand.

In the second scenario, the intervention on the HVAC system and the implementation with renewable energy systems was assessed. The gasoil boiler was changed with a biomass boiler and the delivery system was changed with one with low temperature radiant heaters and local ventilation. The overall efficiency of the system passed from 65% to 92.5%. In this case 300 m^2 of photovoltaic panels were considered for an installed peak power of 38 kWp.

The second scenario for the retrofit project shows an improvement of 75% in heating consumption of which 56% comes from the intervention on the envelope and the remaining 21% comes from the improvement of the HVAC system. For what it concerns the electricity demand, the change of fluorescent lights with LEDs resulted in an energy demand reduction of 11%. The PV contribution was estimated to be around 70% of the electricity consumption. No intervention was considered for the consumption of natural gas related to the cooking activity.

The construction was planned to be carried out during two consecutives summers, when the school was unoccupied. In Table 6, the cost of each retrofitting measure applied is reported. The payback time (Table 7) was calculated from the "Report on cost optimal calculations and comparison with the current and future energy performance requirements of buildings in Spain" redacted by the European Commission in the EPBD.

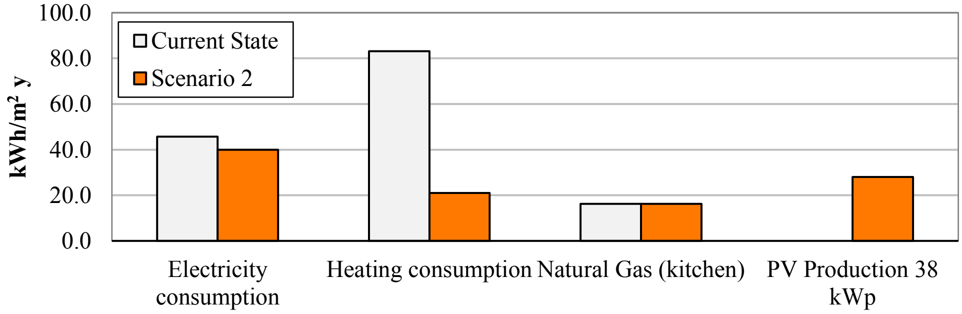

Fig 5. Consumption breakdown in the school according to the simulations in the present situation.

Table 6. Cost of each retrofitting measure.

	Measure	Surface (m^2)	Cost (€)
M1	XPS wall external insulation (15 cm)	1677	192,963.10
M2	Windows replacement with double glazing low-e	192	111,108.94
M3	Increase window-wall ratio in south and east façade	55	67,785.20
M4	Solar protection	198	57,480.90
M5	Enclose patios to create light shafts	208	179,314.67
M6	Ceiling insulation (15 cm)	1236	119,935.05
M7	Insulation under cantilevered floors	103	7,787.80
M8	Biomass HVAC system with COP 0.925	-	262,799.19
M9	LED lighting	-	120,672.55
M10	PV system	305	108,050.00

Table 7. Cost and payback time.

Intervention Cost	Heating Savings	Electricity Savings	Payback Time
€ 1,369 276.40	€ 830,573.00	€ 567,657.00	41 years

3.1. Proposal of latent thermal energy storage with PCM

The PCM evaluated for possible introduction in the present retrofit case study is Phase Change Energy Solution by BioPCM™. This material is made from a rapidly renewable plant extract which is harvested and then manufactured into blankets with small cells. The different types of considered BioPCM were M51Q21, M51Q23, and M51Q25 (the M-value refers to the heat storage capacity of the material in BTU per square foot and the Q-value refers to the melting point temperature).

A first set of simulations was ran on the actual state with the application of a layer of PCM on the inner surface of the ceiling of the classrooms. In each case the PCM did not show any significant improvement that could justify the extra cost of this intervention. However, the PCM did work as it could be seen on the reduced global amount of heat losses through floors and ceiling assemblies.

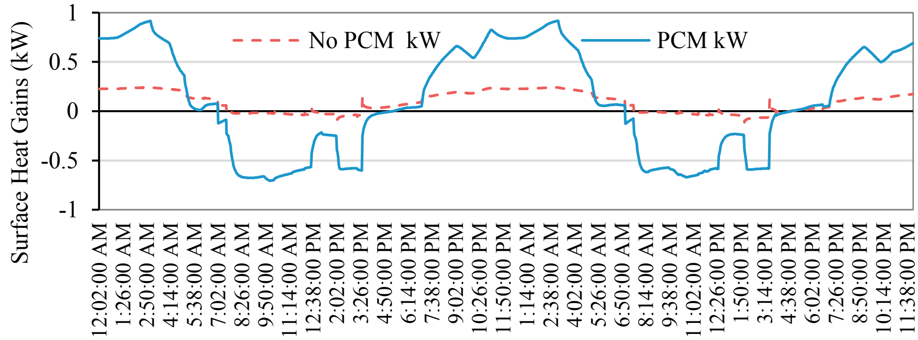

Fig 6. Interior surface temperature comparison.

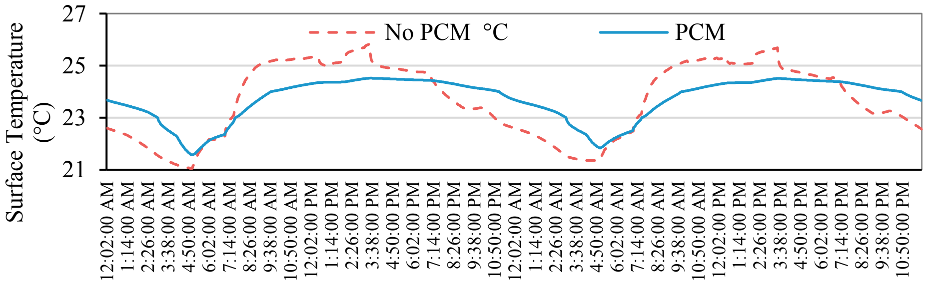

Fig 7. Surface Heat Gains.

A second set of simulations was ran on the model of the retrofit proposal. Even in this case no significant improvement was detected. Another set of simulation was ran over the retrofit proposal, with the PCM layer on the inside surfaces of walls and partitions. In this case, a reduction of the cooling demand resulted. Any PCM was active for most of the time, being the internal surface temperature of the assemblies, close to the melting point temperature of the PCM. It was also possible to detect a positive contribution of it in the zone losses through the walls and partitions. The behavior of the PCM was further studied over a South-East oriented classroom, at the beginning of June. The PCM was tested on the ceiling surface of the retrofitted scenario where 10 cm of insulation was also considered. In fact the external gains when not controlled would be of a higher influence on the material and the PCM would not help controlling the internal comfort conditions. In comparison, the global transmittance of the assembly was kept constant in order to focus only on the phase change effect.

Night ventilation was allowed to improve the solidification process. The case with PCM showed a reduction of the 58% in sensible cooling demand compared to the case without PCM. In Figs. 6 and 7, the comparison between the surface temperatures and the surface heat gains of the two cases, during two consecutive days, is shown.

The surface temperatures of the ceiling with PCM show a more regular trend during the period analysed with lower peaks. On the other hand, comparing the surface heat gains, it is possible to see a more constant behaviour in the case without PCM and a higher fluctuation in the case with PCM. At night the PCM releases energy in form of heat to the zone, since the phase change from liquid to solid occurred. During the day, the inverse process is detected; the PCM absorbs internal gains from the zone during occupied hours, thus reducing the cooling energy demand.

To evaluate the effectiveness of the PCM, a series of simulations were conducted in free floating mode over the same week. The case study with PCM showed an operative temperature distribution 1 °C lower than the case without PCM during occupied hours (Fig.8). In this case, the ceiling surface temperature with PCM is found 2°C lower at a value around 25°C, indicating that the material is undergoing phase change (Fig.9).

The Frequency of Activation (FA) as defined by [9] was hence used as indicator to quantify the percentage of time during a given period when the inside surface temperature of the ceiling falls inside the PCM melting point range. Although this indicator is not sufficient to fully estimate the PCM behaviour [10,11], it gives useful information on the physical state. When the surface temperature falls in the range between 24°C and 26°C, the material is under phase changing, while lower temperatures indicate a solid state and higher temperatures indicate a melted state (Fig.10).

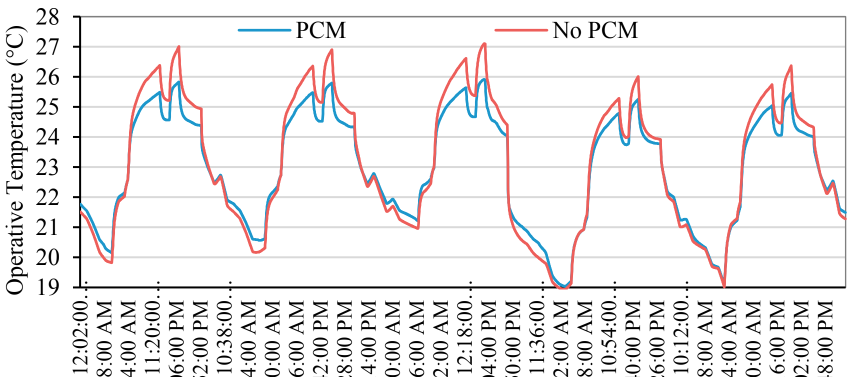

Figure 8 – Operative Temperature comparison

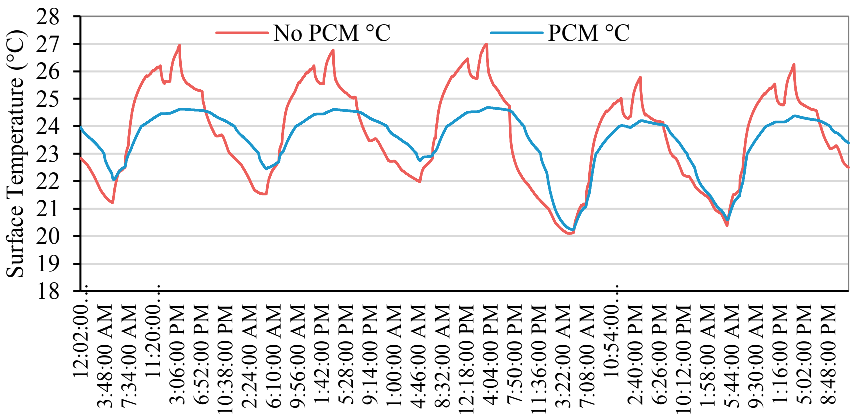

Figure 9 – Surface Temperature comparison

In the case study, the material is found in the phase change range for the 48% of the period analyzed (Fig.9). For the 52% of time, it is in a solid state and it is never found in a fully melted state, suggesting that the cooling potential of the material is not fully exhausted.

4. Discussion and Conclusions

The project described in this paper intended to be a pilot for further projects of the same type in the metropolitan area of Barcelona. The possibilities of the design team was conditioned by economic constrains, therefore each retrofitting measure was designed in order to be at the same time energy efficient and cost effective. Many proposals that might have been beneficial under the energy efficiency aspect had to be discarded due to their elevated cost.

The particular location and the surrounding conditions did not offer a favorable context for the full exploitation of every passive strategies typically adopted in this macroclimatic area. In fact the location, orientation and surrounding obstructions impeded the contribution of passive solar heating, highly beneficial in the Mediterranean area. This condition and the occupancy profile (unoccupied in summer) shifted the retrofitting process towards the contention of energy losses in winter. This aspect was supported by the energy simulation of the current state which displayed that 62% of the energy consumption comes from heating.

A way to benefit from solar gains was with light shaft. However, windows exposed to significant solar gains were mainly concentrated in the adjacent rooms and corridor, without reaching directly the classrooms all placed in the perimeter of the school distant from the shafts. Nevertheless, this strategy gave good contribution to the overall energy balance creating a buffer zone between the classrooms and the external patios.

It is important to underline the important impact of passive solutions in reducing the building energy demand. It was indeed possible to decrease by 56% the heating consumption, consisting in the biggest energy consumption of the building. The most effective strategy was the intervention on the envelope with 15 cm of insulation and a relative low value of thermal transmittance U-value of 0.2 W/m^{2}k. The replacement of all the windows with double glazing low emitting ones had a consistent impact on heat losses through glazing and external infiltration.

The replacement of the existing boiler with a biomass one made possible to reuse part of the water distribution circuit and so containing the cost of installation. Moreover the biomass has a nearly zero CO_2 emission factor. The vast roof area of the school gave the opportunity to install PV panels enough to meet the 70% of the total electricity consumption. This is mainly caused by the kitchen and the IT equipment, for this reason it was impossible to significantly reduce this electricity consumption with passive solutions.

The test of PCM materials showed interesting results, however in the overall building, its global contribution was not fully appraisable. From literature, it well known that the behavior of PCMs is very variable and dependent on the surrounding circumstances. The absence of sufficient solar gains did not play in favor of its potential in winter, moreover being the rooms occupied mainly in the morning, the delay of heat release was not useful and caused higher heating loads in the system. In practice, the potential benefits of PCM during the cooling season could not fully exploited since the school remains unoccupied during this part of the year. The application of the PCM in the non-retrofitted scenario showed an interesting aspect: when the PCM state was outside the phase change, it prevented the thermal mass effect of the ceiling (without insulation) due to the lower conductivity of the PCM.

The behavior of the material was further analyzed in a sample classroom where the PCM was applied on the ceiling surface. The cooling demand in the case with PCM was more than halved. From the analysis of the surface temperatures it was possible to verify the correct functioning of the material and its contribution in increasing the thermal inertia of the room, and thus reducing cooling demand. The ceiling surface was able to subtract a consistent amount of heat from the room during occupied hours, with a peak rate of almost 800 W. During unoccupied hours the heat absorbed was released and exhausted during night time when natural ventilation contributed to the solidification of the PCM, proving the importance of the discharge cycle. The difference of temperature along 24 hours guaranteed a correct operation of the PCM which could be fully discharged during the night and thus exploited again during the day. The analysis in free floating mode where coherent with the other results showing a reduction of 1°C in operative temperatures, consistently with other studies of the same kind [12-14].

The surface temperature was lowered by 2°C, from 27°C to 25°C. This fact proved once again the effect of the phase change that kept the surface temperature at the melting point temperature of 25°C. The FA showed that most of the time the PCM was undergoing phase change during occupied time and it was never found in melted state, indicating that its heat capacity was never exceeded and the potential of the material was not completely exploited.

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