energies

MDPI

Article

Phase Change Materials for Reducing Cooling Energy Demand and Improving Indoor Comfort: A Step-by-Step Retrofit of a Mediterranean Educational Building

Fabrizio Ascione [1,*], Nicola Bianco [1], Rosa Francesca De Masi [2], Margherita Mastellone [1] and Giuseppe Peter Vanoli [3]

1 Department of Industrial Engineering, Università degli Studi di Napoli Federico II, Piazzale Tecchio 80, 80125 Napoli (NA), Italy; nicola.bianco@unina.it (N.B.); margherita.mastellone@unina.it (M.M.)
2 Department of Engineering, Università degli Studi del Sannio, Piazza Roma 21, 82100 Benevento (BN), Italy; rfdemasi@unisannio.it
3 Department of Medicine and Health Sciences "Vincenzo Tiberio", Università degli Studi del Molise, Via Francesco De Sanctis 1, 86100 Campobasso (CB), Italy; giuseppe.vanoli@unimol.it
* Correspondence: fabrizio.ascione@unina.it; Tel.: +39-081-7682292

Received: 25 July 2019; Accepted: 16 September 2019; Published: 25 September 2019

check for updates

Abstract: The present work concerns the energy retrofit of a public educational building at the University of Molise, located in Termoli, South Italy. The study provides a comparison of the results obtained by different dynamic simulations of passive strategies to improve thermal comfort and energy behavior of the building during the summer regime. Firstly, the building model was calibrated against historical consumption data. Then, a subsequent step involves the technical-economic analysis, by means of building performance simulations, of energy upgrading scenarios, specifically, cool roof and green roof technologies for the horizontal opaque envelope and thermal insulation, vented façade, and phase change materials' applications for the vertical opaque envelope. Improving the indoor thermal comfort and reducing the thermal energy demand during summertime through innovative solutions will be the primary objective of the present study. The energy efficiency measures are compared from the energy, emissions, costs, and indoor comfort points of view. Phase Change Materials applied to the inner side of the external walls are analyzed in depth and, by varying their melting temperature, optimization of design is performed too. This innovative material, with a melting temperature of 23 °C and a freezing temperature of 21 °C, determines the reduction of summer energy consumption of 11.7% and the increase of summer indoor comfort of 215 h. Even if consolidated, other solutions, like the cool roof, green roof, thermal insulation, and vented façade induce improvements in terms of summer energy saving, and the percentage difference compared to the basic building is less than 2%. For this case study, a Mediterranean building, with construction characteristics typical of the 1990s, traditional passive technologies are not very efficient in improving the energy performance, so the investigation focused on the adoption of innovative solutions such as PCMs, for reducing summer energy demand and improving indoor thermal comfort.

Keywords: energy retrofit; simulation; educational buildings; cost-optimal; cool roof; green roof; thermal insulation; phase change materials; vented façade

1. Introduction: The Role of the Building Sector in the Overall Issue of Environmental Protection

During the last years, CO_2 emissions have seen significant growth, and specifically, the building stock has been considered responsible for about the 38% of climate change-related emissions [1,2].

Indeed, in the last decades, protocols and guidelines have been enacted to address human climate changes, and milestones have been established for instance at the Copenhagen Conference in 2009 and at the United Nation Conference on climate changes (COP21), hosted during the 2015 in Paris. At the EU level, European Institutions in the climate and energy framework established, within 2030, the following well-known energetic and environmental targets:

(1) Reduction in greenhouse gas emissions of 40% (compared to 1990 levels),
(2) Improvement of at least 27% in energy efficiency,
(3) Increase of 27% the use of renewable energy sources.

In particular, concerning the building sector, the EPBD (Energy Performance of Building Directive) 2002/91/CE [1] introduced the first measures, at the EU level, in terms of energy building efficiency, regarding both existing and new buildings. This directive has been updated through the Directive EPBD Recast 2010/31/EU [3], Directive 2012/27/EU and Directive 2018/844 [4] to improve the energy performance of public buildings and buildings used for public services. The new objective for 2050 has been established for the high-energy efficiency of the future and present buildings. For new buildings, the approach has been the Cost Optimal and, since 1 January 2019, the required target is the fulfilling of the nZEB standard. Conversely, for existing buildings, a generic energy refurbishment by public administrations for an area equal to 3% yearly is needed.

The aforementioned EU Directives have been transferred into all national legislations, in Italy starting with the Legislative Decree 192/2005, aimed at defining energy performance parameters and calculation methods and to favor the use of energy from renewable sources. Even if a second upgrading of the EPBD was recently enacted [4], presently the national laws receiving the EPBD Recast are in force. Besides giving an illustrative role to public administration, the national law has established new energy efficiency targets in the building industry, aiming at the reduction of the emissions, the respect of nearly zero energy buildings standards and, in particular, the achievement of optimal levels of energy efficiency depending on costs.

The pressing objective of European and Italian laws are related to the global warming, urban heat island, the progressive growth of emissions and human necessity changes related to the growth of thermo-hygrometric comfort request. The development of new solutions and new interventions technologies in the building field are becoming necessary, particularly to fulfill the cooling demand. In fact, as Benestad [5] has investigated, there will be a general reduction of heating demand and a substantial increment of cooling demand. A very interesting report, published by the Tyndall Centre for Climate Change Research, shows potential impacts and effects, on natural ecosystems, of the temperature increase at regional levels, by taking into account an increment variable from 0 to 0.5 °C/decade. The study collects investigations of several authors and, surely, a great vulnerability of nature and life is evidenced.

Evaluating the national situation, Italy has one of the oldest and most degraded building stock from the energetic point of view. As common in the EU, a great part of Italian building stock has been built between the post-war period and the late seventies, and thus in decades characterized by a predominant architectural construction technology based on the use of reinforced concrete, completely ignoring thermal insulation needs. The necessity of interventions on present building stock, in order to improve energy efficiency and cut down energy consumption, becomes incumbent and indispensable. Until the beginning of the third millennium, because of the inefficiencies of the building envelope and the related high thermal dispersions, the most diffused way of intervention on existing buildings was simply an excessive and inappropriate use of facilities, in order to balance the heat losses, getting an excessive increase of energy consumption and climate changing emissions. Really, the very inefficient buildings of European cities, and thus the ones built quickly and without attention to thermal and energy performances (from the fifties to the seventies), already have been often interested by deep refurbishments promoted and funded starting by the EPBD. For the future, the new challenge, as it has been established also by the Directive 844/2018, will be focused on the improvements of thermal resilience and energy behaviors of recent buildings, the ones built around the 1990s and 2000s, often characterized by high energy demands for cooling. This phenomenon, by taking into account also the pressing climate change, the condensation heat of air conditioning systems, the urban heat islands, is more and more actual.

By taking into account the aforementioned issues, the attention must be paid on existing buildings and on the exemplary role required to the public hand. The proposed study refers to a demonstrative and quite innovative energy retrofit design, which aims to improve the thermal comfort during the summer regime and to reduce energy consumption through passive technologies. It concerns one of the main buildings of the University of Molise, located in Termoli (Province of Campobasso, Italy), that hosts the Engineering and Science of Tourism university departments. After a fact-finding study of the building, specifically, of its constructive technologies, equipment and facilities, heating and cooling systems, and thermal zones, a digital energy model was developed and calibrated. The calibration was performed by comparing the results of dynamic energy analysis with real energy consumption data, and once the model was validated, it has been employed to test energy efficiency measures and verify the reduction of energy consumption [6]. Specifically, the present study aimed to test and evaluate the application of passive technologies, employed at the University of Molise, from the points of view of energy consumptions, emissions, costs and thermal comfort. In particular, the following energy conservation measures were initially evaluated, with the aim to reduce mainly the cooling demands:

- Cool roof technology.
- Green roof technology.
- Thermal insulation and thus increment of envelope thermal resistance.
- Application of a wall phase change material.
- A vented façade.

The present technologies have been compared to evaluate the best compromise between energy consumption, costs, and thermal comfort. The results will show the positive effects of their application, according to previous scientific studies, and the best solution in terms of reduction of cooling energy demand will result in the adoption of plaster with phase change material (PCM). During the summer regime, this innovative material, with a melting temperature of 23 °C and a freezing temperature of 21 °C, provides an energy saving of 11.7% and an increase of thermal comfort hours of 215 h. The choice of the phase change temperature of the PCM, as described in Section 4.4, is performed through an optimization of the results of different PCM, with different melting temperatures and by considering the summer and winter energy savings. An accurate study on the advantages and the costs of the additional hours of comfort, resulting from the application of the PCM, is reported too.

On the other hand, even if consolidated, other energy efficiency measures provide an energy-saving, but not as remarkable as the PCM, for our case study. These results depend on the typology of the building and its constructive features. The building was renovated in 2005 and, even if it doesn't have prestigious passive technologies for the building envelope, the current thermal transmittance of the components is already quite low, so that the positive effects of proposed retrofit solutions are limited. For this reason, the traditional solutions can't give substantial effects on energy saving, with a consequent acceptable payback period. Conversely, passive technologies, which act on the decrement factor of the heat transfer and on time lag effect, by increasing inertia and thermal storage capability (sensible or latent), from the inner side, can be considered a valid solution. A phase change material is one of these.

In the next sub-section, the introduced technologies will be studied in depth, with the support of a broad literature review. Sequentially, the energy conservation measures will be compared, also with reference to the baseline building (i.e., the present one) and carefully examined according to the lower energy consumption based on costs.

2. State of Art: Energy Requalification of Present Buildings and Passive Technologies for the Energy Retrofit

Many studies concerned energy refurbishment projects for improving the energy behavior of existing buildings, also with the aim of improving the thermal conditions during the summer period. Talking about the improvement of the thermal conditions in the hot season, and thus reduction of cooling demand and primary energy request, different approaches and intervention technologies are possible, and thus:

(1) Passive cooling and improvement of the building;
(2) Improvement of HVAC (Heating, Ventilation and Air Conditioning) systems' efficiency;
(3) Integration of systems powered by renewable energy sources.

As inferred by [7], usually all "levers" (i.e., building envelopes, active energy systems, renewables) for energy efficiency must be pressed, consecutively, in order to reduce firstly the heat gains, then the cooling demands and finally by allowing clean energy by means of renewable sources. A suitably designed building envelope reduces heat gains and minimizes cooling loads. In the case of heat gains, cool colors, solar screens, new generation windows glass, and thermal mass are suitable solutions to decrease the building overheating. Heat gains can be mitigated through the thermal capacity storage or accumulation of latent heat and, moreover, useful heat dissipations can be obtained with the building envelope capacity to disperse heat to lower temperature environments, like the sky, ambient air, ground, and water [7]. Cooling strategies such as phase change materials, natural night ventilation, vented walls and roofs, green walls and roofs, water ponds, dynamic thermal insulation, earth-tubes, and solar chimney are technologies for the free or low-energy cooling of buildings. In detail, some of these exploit the conversion of solar and wind energy for reducing the building heat gains and cooling loads, by means of various physical phenomena and heat transfer mechanism, and thus convection, reflection, long-wave radiation, stack effect, evaporative cooling and evapotranspiration and so on.

Obviously, the building has to perform properly, and this is achieved by means of deep studies concerning the operating boundary conditions (that affect greatly the efficiency of passive cooling strategies) and by nullifying the penalizing effects of punctual and local inefficiencies, such as common criticalities caused by thermal bridges [8]. Ascione [9] has accurately studied themes like energy conservation and renewable technologies aiming a lowered use of cooling systems. He discussed traditional and emerging technologies in the bioclimatic field, oriented to summer cooling and microclimatic internal conditions enhancement, focusing also on active equipment and the active use of renewable energy sources.

In the following lines, even if briefly, some descriptions of common and emerging technologies for the passive and low-energy cooling of buildings—namely: (a) cool roof, (b) green roof, (c) thermal insulation, (d) PCM technologies, (e) ventilated façade—are described, in order to underline its working principle and for identifying limits and potentialities. Then, in the next lines, these will be considered for the application on a public building owned by the University of Molise (Italy).

Green roofs are bioclimatic solutions that improve thermal comfort and reduce summer and winter energy consumptions of the building, giving, therefore, a positive grant to urban heat island. This system exploits solar radiation to activate chlorophyll photosynthesis of vegetation, and through the evaporative cooling induce a lower heat transfer toward the indoor building.

Green roofs are consolidated technologies and have been studied by many researchers. Alcazar et al. [10] investigated the positive effects of green roofs in internal and external microclimatic conditions for the Mediterranean–continental climates and observed a temperature reduction of 1 °C of internal areas not directly irradiated by sun and a reduction of 2 °C at the street level. Yaghoobian et al. [11] studied the variations of roof surface temperature in combination with the variation of plant coverage and concluded that the higher is the plant coverage, the lower is the surface temperature. Obviously, this effect is due to the reduced solar absorbed by the soil and the incremented evapotranspiration by soil and vegetation. Finally, a higher leaf area index (LAI) is recommended in order to increase the green roof performance [12,13]. In the same way, Gagliano et al. [14], through a multi-criteria analysis, contrasted the performance of traditional, cool and green roofs in the Mediterranean climate, and confirmed the positive effects of cool and green roofs on summer energy consumption. In particular, green roofs with different insulation thickness were compared and, in its specific case, the extensive and moderately insulated green roof resulted more convenient in terms of energy needs and UHI (Urban Heat Islands) mitigation.

The cool roof is another quite innovative technology based on a well-known, for many centuries, heat transfer principle, namely the reflection of solar radiation by means of suitable coatings. In more detail, a cool coating is able to reflect solar radiation and to emit thermal energy in the infrared wavelengths. Pisello et al. [15] developed a new typology of roof by combining a cool and green roof, through the implementation of a particular type of plant reflecting the short-wave radiation. In this way, they obtained the reduction of summer space overheating, in terms of hours, around 98.2%. Santamouris et al. [16] analyzed inexpensive passive cooling techniques to improve the life conditions of low-income households. In particular, the aim was to show the efficiency of cool and reflective materials, by comparing them with traditional ones and to evaluate the potentiality of earth tubes and new ventilation systems for improving indoor thermo-hygrometric comfort conditions.

In the tradition of the building sector, a relevant role is occupied by the thermal insulation of the envelope. Several materials, from the traditional to the innovative ones, can be mentioned: organic and inorganic materials, metallic or metalized reflective membrane, aerogels, thermal insulators from waste materials and composite materials. The organic thermal insulator can be natural (flexible wood fiber) or synthetic (cork, polyurethane or polystyrene) [17]. Expanded polyurethane is formed by a chemical expansion reaction, where the pores are filled by an expansion gas. Some researchers are working on the improvement of this high-performance material. Cao et al. [18] studied a novel functionalized graphene (FGN) to improve fire resistance and smoke suppression. They obtained positive results with a reduction of the values of over 60%. More in general, Cabeza et al. [19] examined the performance of three insulation materials on a Mediterranean construction. They compared polyurethane, mineral wool (MW) and polystyrene (XPS) on a cubicle. The results showed a reduction in energy consumption for cooling and heating. Specifically, the cubicle with a polyurethane insulation material, during a typical summer week, had an energy consumption for cooling 18% and 26% smaller than the ones of the MW and the XPS cubicles.

Another strategy that gives positive effects on thermal indoor conditions and on the reduction of primary energy consumption is the vented façade. The ventilated slab of external walls, thanks to the stack effect in the vertical cavity, determines a heat exchange by convection and it cools the walls' surface. This solution has been widely studied by Stazi et al. [20], and in particular the variation of the height, the solar radiation and the effect of wind were considered as the main factors that influence the system working. Varying the system height from 6 m to 12 m, the results have shown that increasing the height, the temperature and the air velocity in the cavity are higher during sunny days. Marinosci et al. [21] investigated the performances of a vented façade, focusing on the variation of open joints, ventilation grills and the thickness of the cavity. The outcomes highlight that it is important to minimize the longwave radiation and reduce the pressure losses to limit the temperature values in the cavity.

A new frontier of energy efficiency in buildings, with particular regard to the improvement of the summer performances, is the use of phase change technologies. Their use in buildings is already diffused and more and more increasingly.

These materials are suitable for intervention on the opaque horizontal (i.e., roofs) and vertical envelope of buildings, particularly characterized by a diurnal use, like offices, educational and university edifices. Usually, different layers are separately added to the vertical envelope, specifically, a traditional or innovative thermal insulation material and a PCM coupled with night ventilation. PCMs ensure the same advantages of thermal mass; indeed, these are suitable for storing thermal energy at a constant temperature and thus allowing no indoor overheating of a building when interested by heat gains, due to high indoor temperature, solar radiation on the facades, indoor gains due to persons, lighting and equipment.

The use of PCMs is becoming more and more diffused in the building sector. Kasaeian et al. [22] proposed a large review about the possible applications of PCMs and nano-PCMs in buildings. The study started from passive applications for the space cooling and heating and arrived to the investigation of active use of PCMs in the building HVAC systems. In the same way, Baetens et al. [23] reviewed the possible use of PCMs for buildings, focusing deeply on the typologies of PCMs. The three macro-categories of PCMs are the organic phase change compounds (paraffin and non-paraffin), inorganic phase change compounds (hydrated salts) and eutectics (organic-organic, inorganic-inorganic, inorganic-organic eutectics). Furthermore, Feldman et al. [24] evaluated the application of an organic bio-PCM in the specific case of a gypsum wallboard. The developed PCM was made up of methyl palmitate (MeP), methyl stearate (MeS), with latent heat of phase transition of 180 kJ/kg and a melting-freezing temperature in the range 23–26.5 °C. Feldman et al. demonstrated the considerable increment of thermal storage (twelve times higher) of the PCM wallboard (23% impregnation) compared to the traditional coating. Theodoridou et al. [25] applied PCM-enhanced lime plasters in a vernacular and contemporary architecture in the southern Europe climate conditions, and analyzed the thermal, physical and mechanical performances of the innovative material. It was observed the improvement of thermal characteristic and no significant change of mechanical properties between the PCM plaster and the traditional one.

The main limit in the use of PCMs is in the fact that these are a relatively new technology so that their capabilities and achievable performances are not well-known, the costs are not always low and also the installation techniques are not usual for construction companies. In some cases, further barriers can be the difficulties in the macro or micro-encapsulation or risk of flammability. All these criticalities can be overcome. For instance, against flammability, there is the possibility of adding a fire retardant, and this is proposed, as a valid solution, in Sittisart et al. [26]. For what concerns problems related to the encapsulation, this constructive phase today is quite consolidated and consists of a process of coating or surrounding the material particles or droplets with a polymeric film (shell) to produce capsule in the order of micrometers or millimeters [27].

Many studies are focused on the improvement of building efficiency and passive solutions are gaining more and more priority. Gil-Baez et al. [28] enhanced the sustainability of a school in the Mediterranean climate, through the passive solution for the building envelope. They analyzed technologies like internal and external insulation, external vented façade, internal cavity insulation and external prefabricated façade for the opaque envelope and solar screens and low emissivity glazing for the transparent envelope. They combined a set of measures on the building: solar window protection, external canopy, a screen of trees, external Thermal Insulation Composition System, low-emissivity glazing, external roof insulation, and a removable textile canopy. The results of this combination showed a 15.9% reduction of energy consumption for cooling, without compromising the functionality and accessibility of the building.

De Santoli et al. [29] in the same way, focused on the building envelope to improve the energy performance of a school building in Rome. They compared the passive intervention on walls and windows frames with the improvement of the active systems. In general, they underlined the environmental benefits of passive strategies despite the higher investment costs.

Mao et al. [30] studied the thermal comfort condition in bedrooms, after the application of a task/ambient air conditioning system (TAC), depending on different envelope heat gain. It was found that the energy consumption of the TAC system increases as the heat gains increases and the PMV (Predicted Mean Vote) value decrease under higher airflow rate, reducing the effect of envelope heat gains on thermal comfort.

Starting from the aforementioned studies, aimed at describing, even if very synthetically, the technologies here adopted and some authoritative examples of their applications, the present work focuses on the analysis of energy efficiency measures applied to an existing building owned by public

Institutions that, according to the recent EU Directives in matter of energy efficiency in buildings, must have demonstrative and exemplary roles. Examples of typologies of study like this are not very widespread, and unlike the studies cited [28,29], the proposed work compares traditional solutions with innovative, which makes it rare if not unique in its field.

The outcomes will show the suitability in terms of energy consumption, thermal comfort, costs, and emissions, of new materials and technologies as part of the building envelope. The optimization of various technical solutions and the difference in the effectiveness of the roof and vertical envelope technologies, mainly during the summer period, will be the central issue of this manuscript. The results will demonstrate the relevance of the study dealt with. Traditional passive technologies will be not very suitable for reducing the consumption of energy for cooling, in a building of the 1990s-2000s, whose envelope does not have very poor performance. The study, therefore, aims to find and demonstrate the effectiveness of innovative solutions like PCMs, for buildings that largely characterize the existing building stock in Italy (1990–2000) with a view of reducing the cooling demand of energy, a pressing objective widely supported by current regulations.

3. Case Study and Methodology

The building has been refurbished in the last fifteen years and, starting from the 2006, it is used by the Italian University of Molise (UNIMOL). It is developed in the north-south direction, and features four floors, one of which is partially buried, as shown in Figure 1. The inter-floor height is 3.2 m and the overall height aboveground is around 13.2 m. The building surface area and the overall volume are 2626 m^2 and 9456 m^3 respectively. The net conditioned building area is 2113 m^2, the net conditioned volume is 7606 m^3.

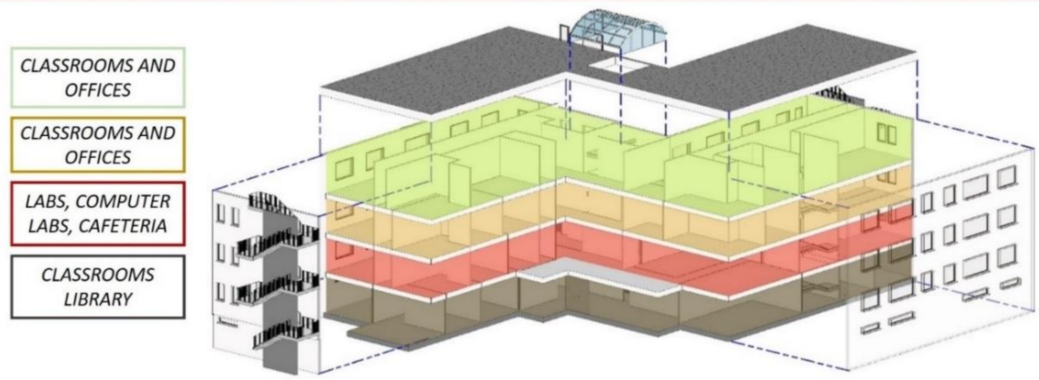


Figure 1. Axonometric exploded view with the uses for each floor.

The building shape is quite regular, constituted by two different rectangular blocks, connected by the stairwell. Each floor has a different use as illustrated in Figure 1. The analysis of the requalification interventions will focus on the achievable energy savings in the spaces that actually are air-conditioned. Finally, technical rooms, presently not provided with heating and cooling services, also in the refurbishment here proposed will remain in conditions of free-running indoor temperatures.

Through the technical reports, provided by the Technical office of the University of Molise, all the necessary information and data about materials, systems and equipment, fruition and occupancy, required for characterizing the building systems, were transposed.

These technical reports consist of:

- Planimetry of each floor.
- Monthly energy bills of 2014, 2015 and 2016.
- An energy performance certificates and label:

- Calculation report (constructive features of the building, materials, and dimensions, thermal transmittance of the opaque and transparent envelope, solar inputs, heat losses ...).
- Technical reports (climatic parameters of the thermic zone, technical and constructive. information of the building, plant and system data).
- Energy analysis, dispersion calculation and energy demand.
- Reports about systems and equipment, occupancy and fruition.

Space active heating and cooling are allowed, mainly, by a direct expansion system—a VRV (Variable Refrigerant Volume) air-to-air heat pump—with a nominal heat capacity of 133 kW, at rated conditions. Indoor units are installed in the ceiling and the thermoregulation, for each area, operates through the control of the internal temperature. The remote management system provides adjustments based on the outdoor climatic conditions and the hourly operations are allowed through a programmable daily thermostat that acts on the zone valves with a proportional action.

As said, the gross volume is of about 9500 m^3 but 1850 m^3 has been evaluated as not conditioned. The following primary energy demands have been calculated, by converting electricity into primary energy, by taking into consideration the ISPRA (higher institute for environmental protection of research) value on energy efficiency of thermo-electric plants, equal to 0.488 $Wh_{el}/Wh_{PRIMARY}$ [31]:

- space heating energy demand: 35,364 kWh_{el}/year, and thus 72,467 $kWh_{PRIMARY}/y \rightarrow 34.3\ kWh_p/m^2y$;
- space cooling energy demand: 29,640 kWh_{el}/year, and thus 60,738 $kWh_{PRIMARY}/y \rightarrow 28.7\ kWh_p/m^2y$;
- annual energy demand for the domestic hot water: 20,894 kWh_{el}/year and thus 42,815 $kWh_{PRIMARY}/y \rightarrow 20.26\ kWh_p/m^2y$.

The energy efficiency interventions on the building, analyzed in the next sections, will influence exclusively the consumption of the HVAC system, and so the energy demand for cooling and heating, (including the auxiliary energy), reported in Table 1.

Table 1. HVAC energy consumption of the calibrated building model.

Calibrated Building HVAC Consumption	HVAC Energy Consumption		
	kWh_{el}	$kWh_{PRIMARY}$	kWh_p/m^2
Energy demand for cooling	35,364	72,467	34.3
Energy demand for heating	29,640	60,738	28.7
Total/year	65,004	133,205	63.0

All told, the total end uses for the electric systems, including heating, cooling, interior equipment, interior lighting, fans and water systems is about 127,296 kWh_{el}/year (260,853 $kWh_{PRIMARY}/y$, 123.5 kWh_p/m^2y). Obviously, the energy demand of the building depends not only on the electric systems, but also on the thermo-physical features of the thermal envelope. Specifically, two different typologies of opaque envelope characterize the building. In detail, the partially buried floor has a thermo-concrete external wall with a thermal transmittance (U-value) of 0.51 W/m^2K, while the walls above the ground have two hollow brick layers with an intermediate air gap, and a calculated U-value of 0.66 W/m^2K. Moreover, the basement slab on the aerated crawl space and the building roof have respectively U-values of 0.40 W/m^2K and 0.37 W/m^2K. The transparent building envelope is characterized by double glazing windows with aluminum frames (equipped with a thermal break technology) and thus an overall U_W equal to = 3.67 W/m^2K. Some indoor spaces have solar shadings. The energy performance investigations of the present building, and the impact analysis of the applied energy efficiency measures (EEMs, in the following lines) were realized through dynamic simulation studies, by using the well-known software EnergyPlus [32], by defining the model geometry through DesignBuilder [33] (Figure 2).

The numerical model, for an accurate dynamic analysis of the building, has been built through the definition of the 3D geometry and other information about the location and the building orientation, the thermo-physics of the building envelope, the definition of the activity and operation parameters. More in detail, in the building model, the following boundary conditions were defined: materials, layers, and construction for the opaque and transparent envelope, occupancy, lighting, equipment with respective schedules, profiles of use of each thermal zone, temperature set-point, operational conditions, heating cooling, and ventilation systems and hot water production. Input information for the calibration are reported in Table 2.

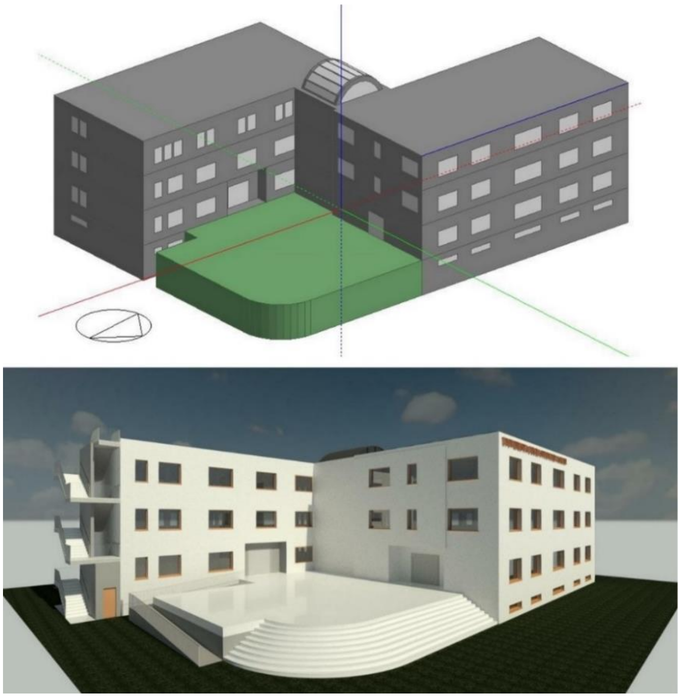


Figure 2. Geometrical 3D model (Design Builder) and realistic view (Revit Architecture).

Table 2. Information data for the building modelling.

BUILDING GEOMETRY – MAIN DATA			
Gross roof area	681 m^2	Gross wall area	2167 m^2
Total building area	2626 m^2	Window opening area	333 m^2
Net conditioned area	2113 m^2	Total building volume	9456 m^3
Gross height above ground	13.2 m	Conditioned total volume	7606 m^3
DIGITAL MODEL – MAIN BOUNDARY CONDITIONS			
Setpoint during the heating season	20 °C	Number of thermal zones	57
Setpoint during the cooling season	26 °C	Simulation Time steps per hour	6
BUILDING ENVELOPE THERMOPHYSICS			
U wall	0.67 W/m^2K	Shading System	Horizontal slats
U roof	0.37 W/m^2K	U windows	3.2 W/m^2K
U slab on the ground	0.41 W/m^2K	Infiltration and natural ventilation	4.0 ACH
INTERNAL GAINS			
People occupancy: classrooms and labs			0.7 people/m^2
People occupancy: circulation and other thermal zones			0.3 people/m^2
Lighting average, Watt per zone floor area			3.0 W/m^2
Electric equipment, Watt per zone floor area			5.0 W/m^2
HVAC SYSTEM			
Typology			VRV air-to-air heat pump, direct expansion system
In room cooling and heating terminals			Indoor Units installed in the ceiling
Supply fan total efficiency			0.7
Energy efficiency of thermo-electric plants (ISPRA)			0.488 $Wh_{el}/Wh_{PRIMARY}$
Emission factor for electric energy (ISPRA)			0.308 tons CO_2/MWh_{el}

In order to check the reliability of the numerical model, the results of the simulations have been compared with the energy bills relative to the electricity demands of the last three years. The comparison with historical consumption and the knowledge of the use profiles of the plants and the installed systems allowed the calibration of the numerical model using the indicators proposed by the ASHRAE (American Society of Heating, Refrigerating and Air-conditioning Engineers) Guideline 14 [34] and the M&V Guidelines [35]. These indicators, moreover, have highlighted some current management criticalities. A first calibration index, for investigations calibrated on the basis of monthly values, is the Mean Bias Error (MBE). In detail, the correspondence between energy demands required by the real building and the model are compared and thus the MBE indicator identifies the average percentage error by comparing energy consumption in individual months and throughout the year. This calculation, therefore, allows to understand how much the energy requirement of the numerical model differs from the monitored building on a monthly basis. The MBE value is obtained through the following Equation (1), where "M" means the consumption measured annually in kWh, and "S" is the same value but referred to the numerical model:

$$MBE[\%] = \frac{\sum_{period} (M - S)_{month}}{\sum_{period} M_{month}} \times 100 \tag{1}$$

As suggested by relevant standards [34,35], another important indicator, to evaluate the mean monthly error, is the $CV(RMSE)$ calculated by Equation (2):

$$CV(RMSE_{month})[\%] = \frac{RMSE_{month}}{A_{month}} \times 100 \tag{2}$$

For the calculation of the coefficient of variation, the $RMSE$ (namely, the root-mean-squared monthly-error) and the A_{month} should be evaluated, respectively by means of the following Equations (3) and (4):

$$RMSE = \sqrt{\frac{\sum_{month} (M - S)^2_{month}}{N_{month}}} \tag{3}$$

$$A_{month} = \frac{\sum_{year} M_{month}}{N_{month}} \tag{4}$$

According to the M&V Protocol 2015 [35], the values of MBE and $CV(RMSE)$, when monthly values are used for monitoring and simulations, are acceptable only within the following thresholds:

- MBE_{month} (%) ≤ ±5%
- $CV(RMSE)$ (%) ≤ 15%

The aforementioned indicators are useful to compare the different simulations and related monthly energy consumptions, with the real energy uses of the building. Different parameters have been modified, according to present regulations, to obtain the validated model. These are the hours of switching on and off of the HVAC system during the hot and cold periods, the infiltration, the power of equipment and lighting systems, the occupation schedule. For the system activation, it has been considered the Italian Presidential Decree (D.P.R.) n. 412/'93 [36], and in particular the table A, that specifies the maximum admitted number of hours per day and the heating periods, depending on the climatic zones [36]. The climatic zone C, in which Termoli is located, has operating limits of thermal plants, with reference to the cold season, from 15 November to 31 March, for a maximum of 10 h/day, with a maximum ambient temperature of 20 °C ±2 K. Conversely, the cooling period has no stringent limitations but, usually, the operation of chillers is not admitted before June and after September. Finally, with reference to the building here studied in Termoli, the values of MBE and $CV(RMSE)$ respect the thresholds of the M&V Protocol 2015, with the following values:

- MBE_{month} (%) = + 2.0%,
- *CV(RMSE)* (%) = 10.9%.

Moreover, the energy consumption derived by building simulations, compared to the one of the existing building, follows the same monthly evolution (Figure 3), and the corresponding values are reported in Table 3. Thus, the numerical model can be considered calibrated. Of course, these significant correspondences have been achieved after several corrections, mainly concerning the definition of building use and every choice and schedule has been supported by surveys. It should be noted that, in summer, the building is not used only for few days so that the energy demands of August is comparable to the one of other warm months.

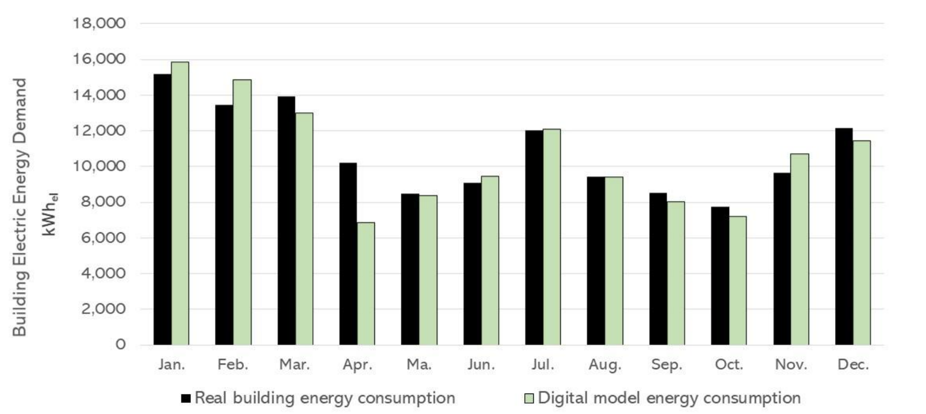


Figure 3. Monthly comparisons of energy demands between monitored and simulated data.

Table 3. Energy consumption (all energy uses) for the calibration of the numerical model.

Calibration Data	Main Building Energy Consumption		Digital Model Energy Consumption		*MBE*	*CV(RMSE)*
	kWh_{el}/year	$kWh_{PRIMARY}$/year	kWh_{el}/year	$kWh_{PRIMARY}$	%	%
summer energy consumption	57,724	118,287	54,206	111,079	-	-
winter energy consumption	72,177	147,903	73,090	149,774	-	-
tot/year	129,901	266,190	127,296	260,853	2.0	10.9

To achieve the aforementioned *MBE* and *CV(RMSE)* indicators, we have corrected, compared to standard and literature average data, the people occupancy, profiles, by taking into account the use of the single space. Of course, we have verified that each schedule is compatible and reasonable with the use of a single room. Besides endogenous gains, the occupant presence and behavior affect deeply also (a) the natural ventilation, (b) infiltration due to the opening of windows and doors, (c) local adjustment of set points. To avoid aleatory definitions, we didn't change these three input categories.

Once the model was calibrated, various solutions for the improvement of summer conditions were examined, by taking under deep consideration investment costs, profitability, reduction of polluting emissions, energy consumptions, indoor thermal comfort. The energy efficiency measures —EEMs—have the aim to confer a new and highest performance quality to the existing building, from the energetic point of view. Each EEM has been suitably simulated in order to evaluate the potential reduction of primary energy consumption. In detail, starting from a calibrated base scenario, it is expectable that also the simulation of a retrofit intervention gives reliable results and predictions.

Then, the costs of investment, the payback periods of the invested capital, the evaluation of economic indexes and global costs under a macro-economic analysis have been calculated, as explained below.

The reduction of primary energy demand for cooling and heating has been calculated as the absolute (or percentage) difference between the base building primary energy consumption (EP^B) and the one of the building as refurbished (EM^{EEM}) (Equation (5)). In the same way, but referring to operating costs and polluting emissions, the emission and cost reductions have been calculated (Equations (6) and (7)):

$$\Delta EP = EP^B - EP^{EEM} \tag{5}$$

$$\Delta C = C^B - C^{EEM} \tag{6}$$

$$\Delta EM = EM^B - EM^{EEM} \tag{7}$$

The investment costs have been calculated considering common costs from price lists for public construction projects. More in depth, regional price lists consist of specifications for finished works and/or supplies with installation, the cost of which includes all the necessary work phases for the definition of the complete work and realized to the perfect state of the art; the listed costs have been compared with metric calculations of similar construction works in the same Italian zone. When a material or a specific typology of work was not listed in the price list, its cost has been obtained by comparing the construction work with a similar one. Besides, the technical-economic feasibility has been evaluated through usual indicators, and thus the Discounted Pay Back (Equation (8)) and Net Present Value (Equation (9)). In addition, the investment Global Cost, for an overall cost assessment, has been estimated according to European Regulation 244/2012 [37]. The Global Cost is the sum of the initial investment costs, management costs and replacement costs (referring to the starting year), as well as disposal costs. The additional cost of greenhouse gas emissions has been added for the macroeconomic calculation (Equation (10)), according to instructions and methodologies of the EU Delegated Regulation 244/2012.

The energy efficiency measures have been finally investigated according to optimal levels of energy efficiency depending on costs:

$$DPB = N : \sum_{i=1}^{N} \frac{F_i}{(i + R_d)^i} = C_i \tag{8}$$

$$NPV = \sum_{i=1}^{LF} \frac{F_i}{(1 + R_d)^i} - C_i \tag{9}$$

$$C_g(\tau) = C_I + \sum_{i=1}^{\tau} [(C_{a,i}(j) R_d(i) + C_{c,i}(j)) - V_{f,\tau}(j)] \tag{10}$$

With reference to the above equations, the following terms are defined:

- F_i = based on *i*-th year, annual cash flow;
- R_d = discount rate;
- N = number of years;
- C_i = investment cost of the intervention;
- LF = life cycle of the technology installed;
- $C_g(\tau)$ = global cost;
- $C_{c,i}(j)$ = cost of carbon emissions for the measure or set of measures *j* during the year *i;*
- $C_{a,i}(j)$ = annual cost of *j* measure (management and maintenance) in the year *i;*
- $V_{f,\tau}(j)$ = residual value of the measure or set of measures at the end of the calculation period.

The technical-economic analysis has been worked out by considering the following prices and emissions factors:

- Electricity costs deduced from monthly energy bills, equal to 0.20 €/kWh_{el},

- Emission factor for electric energy equal to 0.308 tons CO_2/MWh_{el} [38].

For the global cost calculation, the European Regulation establishes, in the cost-optimal methodology framework in Section 4.2 point 8, that residential and public buildings shall use a period of calculation of 30 years [37]. Conversely, commercial and non-residential buildings should provide a calculation period of 20 years. It follows that, in the specific case of the University of Molise, the calculation period is 30 years. The calculation of CO_2 equivalent emissions requires a cost of 20 € per ton of CO_2 equivalent up to 2025, 35 € up to 2030 and 50 € after 2030 [37]. This is the approach of the EU Institutions in order to penalize buildings strongly impacting on the environment.

The base building has an energy demand for all energy uses, including heating, cooling, interior equipment, interior lighting, fans, and water systems, of about 260,853 $kWh_{PRIMARY}$/year, to which corresponds a cost of 25,459 €/year and 39.2 ton of CO_2 emissions/year. Specifically, the energy consumption for heating during the winter period is 72,467 $kWh_{PRIMARY}$/year, and the one for cooling during the summer period is 60,737 $kWh_{PRIMARY}$/year. In Figure 4 the monthly energy consumptions, during winter and summer seasons, respectively, are reported. These are the results of a thermo-energetic analysis, performed with a time-step of 6 (i.e., six time-steps per hour, and thus an energy balance every ten minutes), on the existing building, which corresponds to the real needs. The annual costs for heating are around 7073 €/year and for cooling 5928 €/year. The emissions during the winter period correspond to 10.9 tons of $CO_{2\text{-equiv}}$/year and, concerning the summer, the emissions are around 9.1 tons of $CO_{2\text{-equiv}}$. As said, to convert electricity into primary energy, a conversion factor of 0.488 Wh_{el}/$Wh_{PRIMARY}$ has been used.

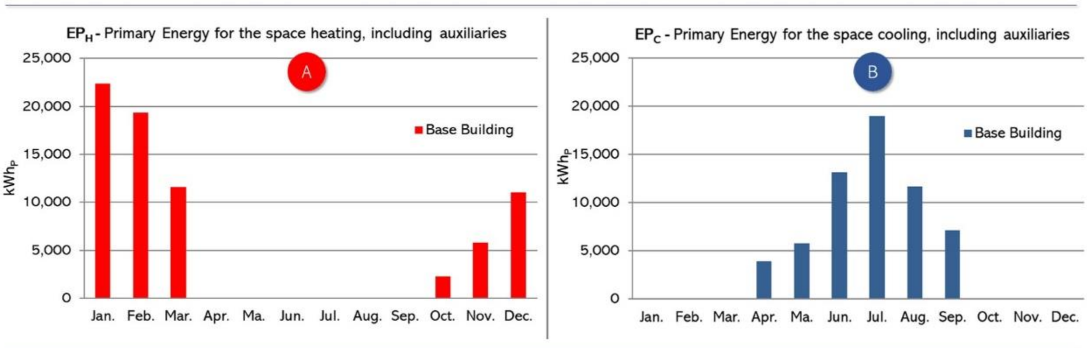


Figure 4. Heating and cooling primary energy demand.

Beyond emissions, costs and energy analysis, the different energetic measures have been compared in terms of thermal comfort. As it is well known, the indoor thermal comfort in buildings depends on environmental and psychophysical factors, so on objective and individual parameters. The first ones depend on dry bulb air temperature, average radiant temperature, the relative humidity of the air and relative average airspeed. The second ones are related to the thermal resistance of clothing and energy metabolism and thus are directly connected to the personal perception of the occupant. The comfort methods employed in the current study are both the traditional Fanger approach, suitable for fully-conditioned buildings, and the ASHRAE 55-2004 comfort analysis, adaptive approach useful for the summer period. Being the case study building heated and cooled, each energy efficiency measure has been analyzed by taking into account its impact on thermal comfort along all occupied hours, during the heating and cooling seasons. Finally, comfort has been evaluated for all the occupied hours. In the specific case of the PCM intervention, a deeper detailed Fanger analysis has been performed, evaluating and comparing the monthly PMV and PPD values with the ones of the base building. The scheme in Figure 5 summarizes the adopted methodology.

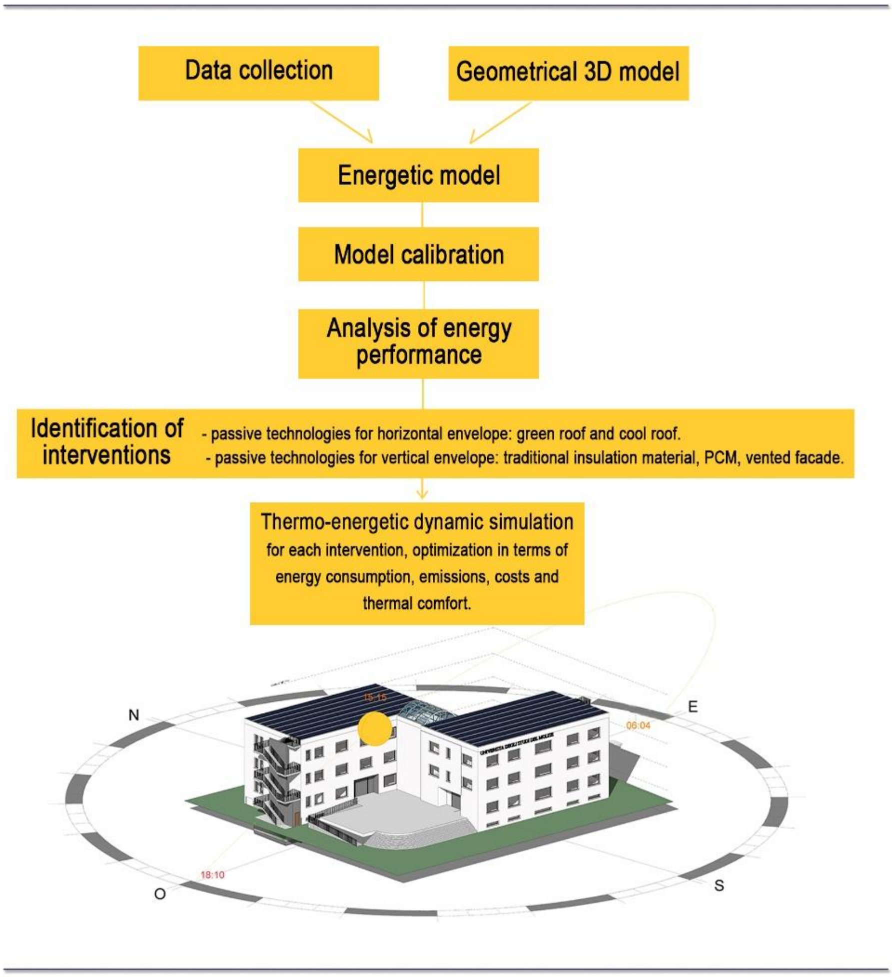


Figure 5. Outline of adopted methodology.

Moreover, the next sections describe the energy efficiency measures adopted and their positive impact on building energy performance.

4. Applications of Energy Efficiency Measures with the Respective Results

The evaluated energy efficiency measures for the building retrofitting concern the opaque building envelope and in particular the vertical and horizontal components. In depth, two possibilities of improvement of the horizontal envelope were examined: (4.1) cool roof and (4.2) extensive green roof.

Conversely, with reference to the vertical opaque thermal envelope, addition of (4.3) a traditional thermal insulation and (4.4) a PCM layer were evaluated. A further investigation will concern the adoption of a vented façade (4.5).

Further passive technologies for the improvement of the summer behavior of the buildings, specifically applicable on the vertical envelope, are green facades and infrared-reflective coatings. In this study, these two strategies are not taken into account, for the following reasons. A green façade is not the simple and spontaneous growth of vegetation on the building walls, but it requires several layers, among which vegetation, soil substrates, waterproofing layers, ventilation cavity, and anchorage equipment. Moreover, an automatic irrigation system should be designed, as well as a sufficient coverage of foliage is required for solar reflection, evapotranspiration, alteration of thermal convection in the canopy. These large and complex boundary conditions, also quite difficult to model without significant risks of errors, discouraged us to simulate this technology [39]. Finally, for this technology aimed at improving, in summer but also winter conditions, the thermal performance of the building envelope, experimental studies are needed, in which some of the authors of this paper are already involved [40].

In a matter of energy refurbishment of existing buildings, and also for new projects, a promising technology could be the adoption of infrared reflective coatings. In this regard, Becherini et al. [41] characterized experimentally two coatings, performed durability tests, and carried out a large study both in the laboratory, real buildings, and employing numerical simulations. Two climate conditions were taken into account. Results of the adoption of infrared coatings revealed positive performance in reducing the cooling need. In particular, the application of IR reflective coatings decreased the temperatures of building outer surfaces and thus the heat transfer into the building. Moreover, also the visual compatibility was assured, as well as the conservation of the cultural value of the architecture. Further study must test other behaviors, such as the anti-bacterial and anti-pollutant characteristics. Finally, even if very interesting, this is an emerging technology and thus we have not included it in our study.

4.1. Retrofit with a Cool Roof

A cool roof technology helps in reducing the outer temperature of the building roof and thus the summer heat gains and cooling loads and, moreover, it is capable of limiting the urban heat island effects and the ambient overheating because of the capacity to reflect solar radiation. Besides an extremely high solar reflectance, cool coatings have a high value of thermal emissivity in the infrared spectrum, which allows the roof to release heat to the surrounding environment, by thermal radiation. The Italian Ministerial Decree 26/06/2015 [42], Annex 1, establishes a mandatory verification of the effectiveness of cool coatings in terms of cost-benefits and assumes a solar reflectance value not lower than 0.65 for new or deeply refurbished flat roofs. The proposed cool coating has the following thermal characteristics:

- Infrared emissivity: 90%;
- Solar absorbance: 16%;
- Visible absorbance: 16%.

Figure 6 shows the constructive details of the roof slab, with the addition of the reflective layer. The transient energy analysis, by beans of BPS (building performance simulation) proves a summer energy primary energy reduction of 2.0% (1222 $kWh_{PRIMARY}$) and, conversely, a winter increment of primary energy demand for the space heating, of around 0.8% (588 $kWh_{PRIMARY}$).

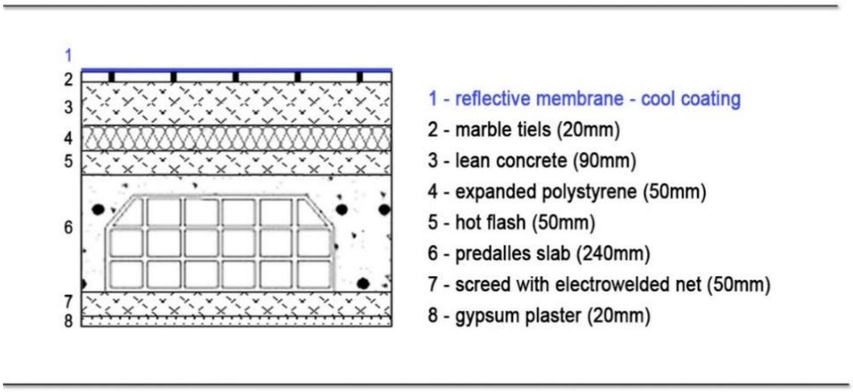


Figure 6. Roof covering with the addition of cool roof layer.

These outcomes can be seen in Figure 7. The results reveal a limited, but positive, effect during the hot season due to a lower surface temperature caused by the reflection of the solar radiation. Conversely, during the winter, the roof absorption of the solar radiation would be a favorable heat gain but, in case of cool roof, this effect is reduced too.

By assuming that the present coating has a satisfactory maintenance level, from the economic point of view, the investment cost is about 14,000 € (15 €/m^2 for the painting, 5 €/m^2 in addition, for taking into account a light preparation of the slab, including installation, transport of materials and labor costs). This type of intervention, during the occupied hours, when the cooling system is available and runs, does not imply a relevant increment of the indoor thermal comfort. Conversely, as it was seen, a reduction of heat gain and thus of the cooling load would be achieved.

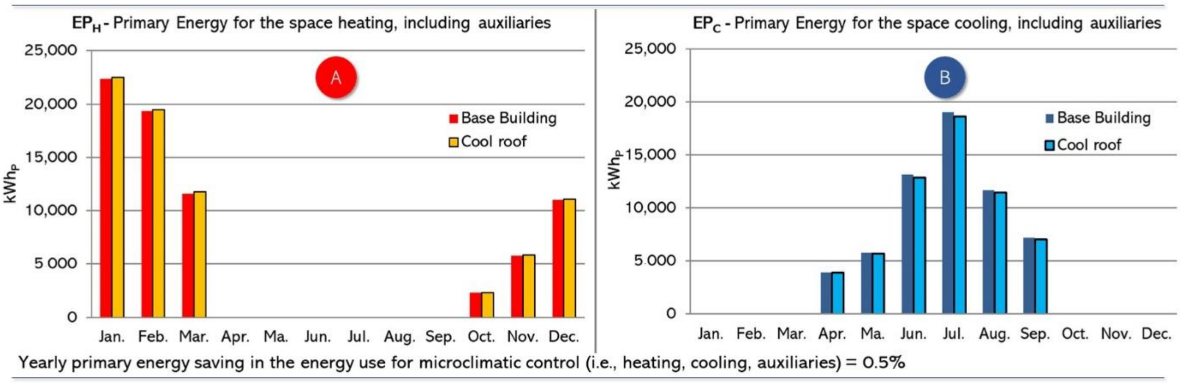


Figure 7. HVAC Heating and cooling primary energy demand, before and after the cool roof installment.

4.2. Evaluation of a Green Roof

This is a complex technological system, whereby the plant layer becomes an integral part of the roof slab. Green vegetation provides numerous advantages, including the improvement of the internal microclimate and energy savings in both heating and cooling seasons, as well as large-scale benefits such as, for instance, the reduction of urban heat islands, enhancement of air quality, reduction of urban pollution due to the filtration of particulate matters and, moreover, also attenuation of peak loads on the sewage systems during the peaks of raining. The aforementioned Italian Ministerial Decree 26/06/2015 [42] makes explicit reference to this technology; in detail, at the point 3 of the requirements in Annex 1, it establishes a mandatory evaluation in terms of cost-benefits of passive air conditioning technologies such as green roofing. These roofs are characterized by a cropped layer of different plant species, which require minimal maintenance, for the extensive roof, and medium-high maintenance for intensive roofs.

The proposed intervention involves the installation of an intensive type roof, characterized by a stomatal resistance (depending on the opening and closure of the stomata) equal to 120 s/m, a leaf area index (indicative of leaf density) of 3.5 m^2/m^2 and vegetation with a height of 40 cm. The current building has a horizontal envelope, a "predalles" slab, whose total thermal transmittance is equal to 0.37 W/m^{2}K. The suggested intervention reduces the thermal transmittance of the envelope, reaching the value of 0.32 W/m^{2}K, according to the minimum requirements proposed by the Ministerial Decree of 26/06/2015 [42]. This reduction of U_{factor} has been achieved because of the addition of some centimeters of soil and other layers that characterize a typical green roof, as represented in Figure 8. No increasing of thermal insulation has been applied. It should be noted that the installation of intensive green roofs often requires a structural verification.

From the energetic point of view, the addition of the "green roof" layer, produces a summer primary energy reduction of 1.6% (993 kWh$_{PRIMARY}$), and a winter primary energy reduction of 0.6% (443 kWh$_{PRIMARY}$) (Figure 9). In summer, the improvement is due to the evaporative cooling while, in winter, benefits are achieved because of the lower thermal transmittance and the lower convection, linked to the low speed of air in the canopy. Obviously, the reduction of solar absorptance is a winter contrasting effect.

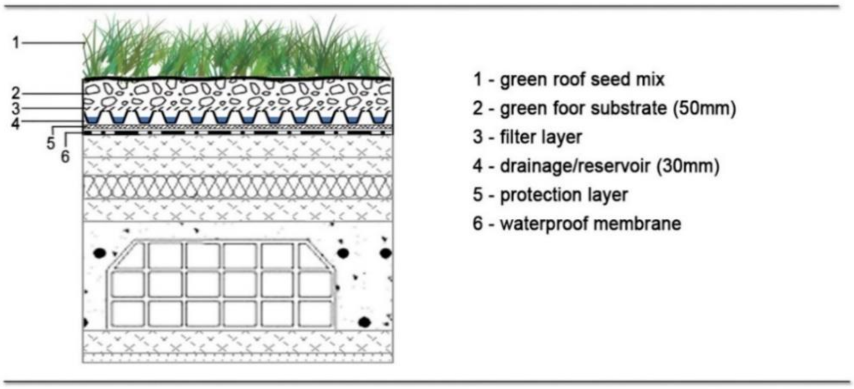


Figure 8. Roof covering with the addition of an intensive green roof.

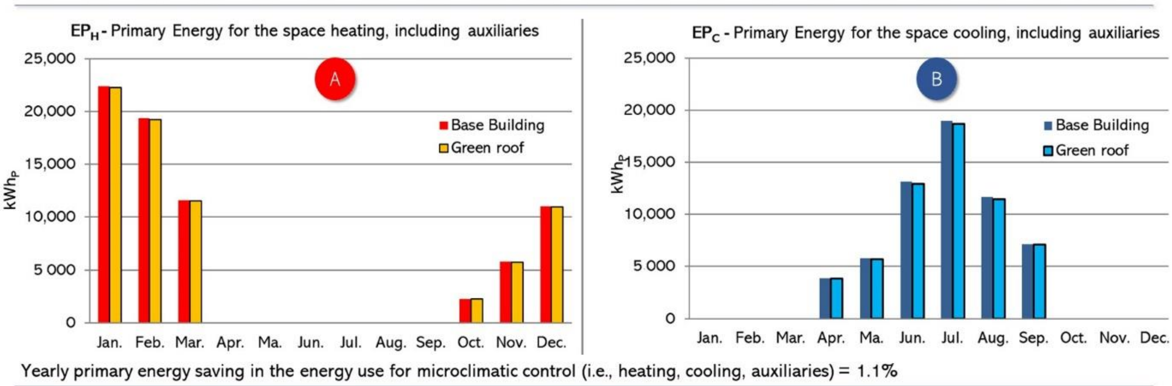


Figure 9. HVAC Heating and cooling primary energy demand, before and after the green roof addition.

The estimated investment cost associated with the proposed EEM was determined on the basis of European market trends, and by the metrics of similar works. All told, the calculated investment is equal to 120 €/m^2, including installation of an intensive green roof, transport of materials, labor and maintenance costs. The surface object of intervention is around 700 m^2, so, the total cost is about €84,000.

According to the present Italian legislation, public Institutions—but also private stakeholders—can benefit from incentives for energy efficiency measures that imply energy savings. In detail, the incentive is paid by the Italian manager of electric system, the GSE (energy services manager), and the so-called "Thermal Account" ("Conto Termico", in Italian)[43] establishes that for thermal insulation of the opaque building envelope, a refunding of 40% of the total intervention cost within the expenditure of €400,000 can be achieved. In this specific case, we tried to test the chance to achieve that incentive also for green roofs that, usually, are equipped with a significant layer of thermal insulation. In our case, the thermal insulation was not added, being the building roof already thermally-insulated, so that the U-value reduction until a value of 0.27 W/m^{2}K was not achieved and thus incentive cannot be obtained. Finally, the cost of investment is entire, without economic benefits or incentives from funding programs.

4.3. Thermal Insulation for the Vertical Opaque Envelope

The building is an example of educational edifice built in Italy in the second half of the 1900s. This means that, as typical, the structural frame is made of reinforce concrete, with walls made of a double layer of bricks, with a quite low thermal conductivity, with an interposed air gap. This provides a satisfactory level of thermal resistance, so that, during the 2005 refurbishment, the thermal vertical envelope was not improved by means of insulation. At this stage, by taking into account the aims of this study, however, a further addition of thermal insulation for walls has been considered, in order to reduce the thermal losses in winter and the thermal gains in summer, during the daytime and when the outdoor temperatures and solar radiation are high. It should be specified, however, that in summer, it is quite important the thermal capacity, besides the thermal insulation. Indeed, high masses or materials with high specific heat allow to accumulate heat without increasing the indoor temperatures. This is the common sensible storing of building components that provides attenuation and time lag of the heat transfer.

The case study building is in the climatic zone C, and the thermal transmittance of the vertical envelope is 0.67 W/m^{2}K. Still with reference to the energy performance of the building envelope, the Ministerial Decree 26/06/2015 [42] defines the limit values of thermal transmittance for buildings object of energy refurbishment. In particular, the reference thermal transmittances for refurbished buildings should be 0.36 W/m^{2}K. The reduction of thermal transmittance requires 8 cm of insulation material on the external side of the vertical envelope as represented in Figure 10 (expanded polyurethane, λ = 0.026 W/m^{2}K, density ρ = 35 kg/m^3, specific heat c = 1464 J/kgK), and the achieved U_{value} is 0.22 W/m^{2}K. This value is significantly lower than the aforementioned threshold (i.e., 2021 limit) thermal transmittance for refurbished buildings. The energetic analysis shows a yearly reduction of primary energy demand of 1.9% (from 260,853 kWh/m^{2}y to 255,794 kWh/m^{2}y) referred to the whole facility and all energy uses. Specifically, as Figure 11 shows, the positive effects on energy consumption of HVAC system, are evident during winter season (reduction of HVAC energy demands for the active heating of about 6.9%), while these are not relevant during summer, and similar to the percentage variation of a simulative error. The installation cost is 59.6 €/m^2, including materials, labor and scaffolding, and so the total investment is 128,140 €. For the economic analysis, in order to evaluate the convenience of the investment, the incentives paid by the aforementioned "Thermal Account" [43] were taken into account, because these incentives are possible for this kind of energy efficiency measure. To access the incentive, in the case of thermal insulation of opaque surfaces, the maximum allowable cost in relation to the perimeter walls is 80 €/m^2, and the incentivized percentage corresponds to 40% of the total investment, as long as it does not exceed €400,000. In the specific case of the proposed redevelopment, the total incentive is 51,256 €, paid in annual cashflow of €10,251/year, for five years. Of course, this incentive can be achieved, because the final U value is lower than the threshold established by the funding program, equal to 0.30 W/m^{2}K for the climatic zone C.

In our study, by considering that the building is heated and cooled during the occupied hours, there aren't significant changes in indoor thermal comfort due to the refurbishment by means of additional insulation. Conversely, as it was seen, there will be a significant reduction in energy demand for heating.

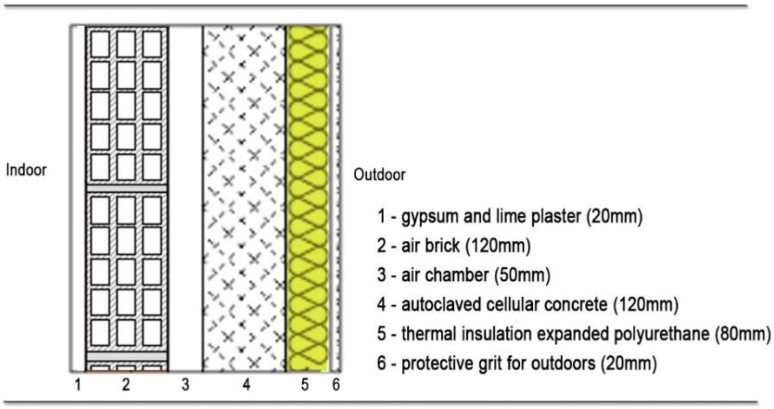


Figure 10. Wall stratigraphy with thermal insulation.

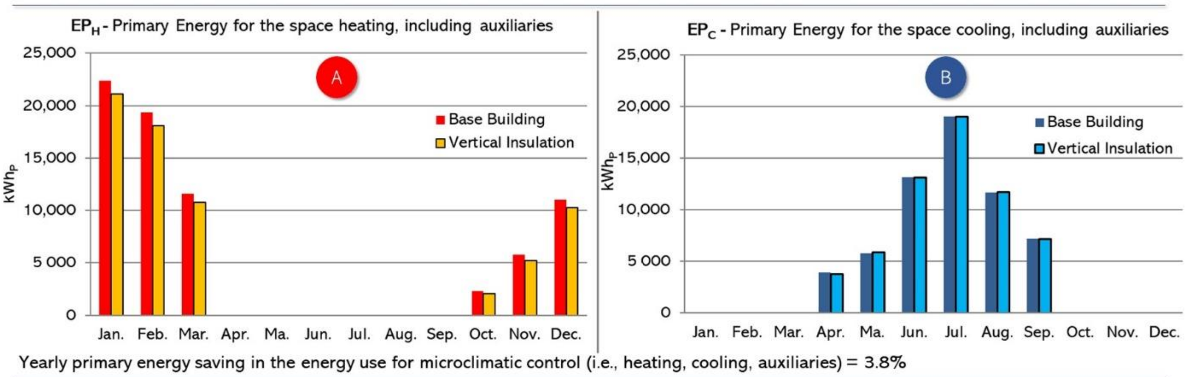


Figure 11. HVAC heating and cooling primary energy demand, before and after the thermal insulation addition.

4.4. Application of a Phase Change Material (PCM) Plaster

Phase change materials are a promising building technology, being able to absorb energy, as latent heat, during the melting process, and to release it during the solidification. In this study, we have tested the capability of PCMs, applied on the internal side of external building components, in containing the thermal excursion during the day, by attenuating the indoor thermal levels and so the use of air-conditioning. The simulated PCM exists and is a melting material encapsulated in a plastic film. Initially, in a first simulated configuration, it has a melting temperature of 23 °C and a freezing temperature of 21 °C. Starting from the values of specific heat of the material (985 J/kgK in the solid phase, 2251 J/kgK in the liquid phase), the different values of the enthalpy variation have been calculated, following Equation (11):

$$Q_{sens} + Q_{lat} = \int_{T_1}^{T_{phase\ change}} m \cdot c_{sol} \cdot dT + \left(m \cdot \Delta H_{sol-liq}\right) + \int_{T_{phase\ change}}^{T_2} m \cdot c_{liq} \cdot dT \quad (11)$$

where:

- Q_{sens} and Q_{lat} are the stored sensible and latent heat, respectively,
- m is the mass of the PCM material,
- c_{sol} and c_{liq} are the specific heat in the solid and liquid phase respectively,
- $\Delta H_{sol\text{-}liq}$ is the latent heat of fusion,
- T_1, T_2 and $T_{phase\text{-}change}$ are the temperatures at the beginning, at the end of transformation and during the phase change, respectively. Of course, in the reality, $T_{phase\text{-}change}$ is a small range and not a unique temperature.

The simulated PCM, starting from all characterizations derived from real datasheets, has a reliable thickness of 2 cm, a latent heat storage capacity of 165–200 J/g, a thermal conductivity of 0.7 W/mK, and it has been installed in the inner side of the building envelope, as Figure 12 shows.

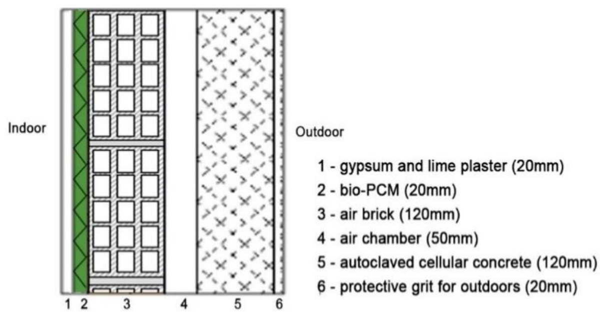


Figure 12. Wall stratigraphy with the PCM-layer.

The building performance simulation (i.e., BPS) of PCM in building components must be performed through the conduction finite difference algorithm (Con-FD), with a Crank Nicholson difference scheme. Thus, in this case, a different heat balance algorithm has been used, being necessary the Con-FD instead of the CTF (conduction transfer function) methods. On the other hand, the green roofs previously analyzed can be modeled only by means of CTF and this last algorithm works very properly for the characteristics of our case study. In the case of PCM, conversely, the conduction finite differences are necessary, being mandatory the knowledge of the nodal temperatures inside the walls.

Finally, being obliged to use two different solution algorithms, and thus CTF (for the base case, cool roof, green roof, addition of thermal insulation and so on) and Con-FD (for the PCM implementation into vertical walls), a further calibration of a second Con-FD base case was performed, with the achieved following indexes MBE_{month} (%) = 2.8, *CV(RMSE)* (%) = 10.9%. Again, these values are within the aforementioned M&V limits (i.e., $MBE_{month} \leq \pm 5\%$, *CV(RMSE)* ≤ 15%) and very close to those previously calculated for the building simulated by means of CTF. A summary between Conf-FD and CTF differences was proposed in Table 4.

Table 4. Base Building: Differences in electric energy due to the different simulation algorithm, Conduction Transfer Function (CTF) and Conduction Finite Difference (Cond-FD).

Base Building	Heating [kWh_{el}]	Cooling [kWh_{el}]	Fans [kWh_{el}]	Electricity HVAC [kWh_{el}]	Electricity FACILITY [kWh_{el}]
CTF building	26,432	26,349	12,223	65,003	127,296
Con-FD building	26,293	25,482	12,249	64,023	126,218
Δ Energy	0.53%	3.40%	−0.21%	1.53%	0.85%

As is clear from Table 1, the comparison of "numerical simulations" also gives favorable results in terms of values of calculated energy uses. Once achieved this positive feedback, in order to perceive the difference properly, the effectiveness of the PCMs was evaluated by comparing the building with phase change materials to the base case simulated with the Con-FD.

Figure 13 shows the indoor temperature variation of a typical classroom, during a typical summer week (from 03 to 09 July). The constant temperature value, around 26 °C from 8:00 to 18:00 for the first five days, is due to the activation of space cooling by means of the VRV. Instead, for the two last days, Saturday and Sunday (when there is not an active temperature control), the maximum peak without PCM is 29 °C and 28 °C with PCM application.

Definitively, two effects are clear, and thus:

- a significant attenuation of high-temperature peaks (more evident in the weekends, when the cooling system is turned off);
- a consistent decrease of temperatures at the nights, every day.

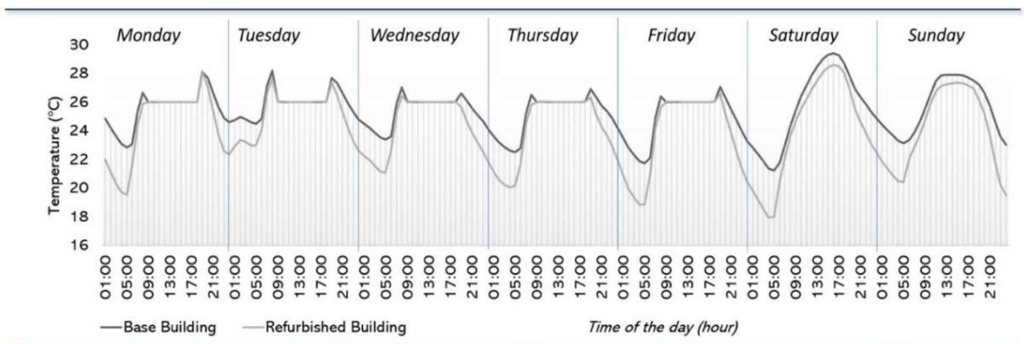


Figure 13. Curves of indoor temperature.

The first effect happens during the diurnal hours: the PCM melting allows storage of latent heat, until the melting point of 23 °C, stealing it to the ambient. Conversely, the second effect (i.e., a more accentuated temperature decrease at the night) is contrary to what it can be expected. Indeed, the addition of thermal storage, sensible or latent, produces time lag and attenuation of both hot peaks (and this is verified here) and of low peaks (in our case study, this is not verified). Really, the simulation with PCMs produces lower cold peaks, at the night, because we have incremented the amount of nocturnal ventilation, so that during the day, the building avoids overheating thanks to the latent storage while, at the night, the additional nocturnal ventilation, necessary for discharging the phase change material (i.e., the reducing of internal energy and consequent solidification), allows a convective cooling of the building. Finally, the PCM works as thermal mass and thus, during the nocturnal hours, when the building is not occupied, it requires a cool ventilation for the solidification and the discharging process, so that during the following diurnal periods is again ready for storing heat. In any case, it has been verified accurately that the beneficial cooling effects are due to the combined effect "PCM plus night cool ventilation" and not merely to this last.

The reduction of summer cooling of the PCM building compared to the base case is relevant and it is around 11.7% (i.e., 6888 $kWh_{PRIMARY}$ saved). During the winter season, a small energy-saving occurs too, around 1.6% (1141 $kWh_{PRIMARY}$ saved). This positive effect is due to the capability of PCM in storing also the surplus energy (due to internal gains, equipment, endogenous sources and lighting) that sometimes, in the heating season, overheats the indoor space beyond 23 °C (the melting temperature of the PCM). Of course, this happens only in the central hours of the day, with maximum occupancy and solar gains. Moreover, also a second reason for this saving can be found and thus the addition of a layer (the PCM) that contributed to a further reduction of the building U-value. In any case, the achieved saving in heating demand is not relevant (Figure 14).

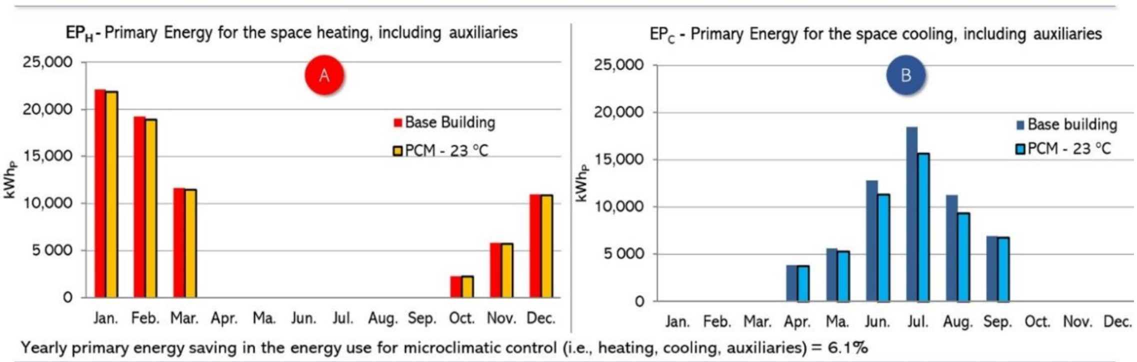


Figure 14. HVAC Heating and cooling primary energy demand, before and after the PCM plaster addition.

Similarly, in the same percentage, the reduction of greenhouse emissions is equal to 1.2 tons of $CO_{2\text{-equiv}}$. In terms of economic profitability and cost analysis, it has been considered an investment cost of 29.5 €/m^2 (i.e., 36,875 € in total), including the PCM cost and the plaster reconstruction, with an annual reduction of operating costs of about 784 €. By calculating the global cost according to equation 10, it results that C_g is higher, compared to the base building, of about 14,570 € in a calculation period of 30 years. Besides the reduction of energy demands in summer and also in winter, the advantages of this application are also related to the indoor thermal comfort; in fact, the uncomfortable hours from the thermic point of view are 1543 for the base building and 1469 for the refurbished building with the PCM plaster. The positive effects of this energy efficiency measure on thermal comfort are demonstrated by the ASHRAE 55-2004 comfort analysis. Annually, as the results prove, 74 h of "net" thermal comfort were gained (Table 3), because 215 h of additional thermal comfort were gained in summer, while, during the heating season, 141 h of comfort were lost. These outcomes depend on the PCM characteristic of storing latent heat, subtracting this from the ambient air.

By taking into account the aforementioned increment of global cost, it results that, along the lifetime, the cost of one hour of summer comfort regained (i.e., additional) is equal to of 2.25 €/h. This is a quite favorable result, given that, by means of active cooling, a single hour of comfort costs about 6.10 €/h. If both seasons of heating and cooling are considered, as it was said some lines above, the net annual increment of thermal comfort hours is 74, and the cost of one additional hour of comfort as a result of the PCM retrofit measure is 6.56 €/h, in the face of the 7.85 €/h necessary to obtain the same condition of thermal comfort through the use HVAC system. A summary is proposed in Table 5.

Table 5. Costs of additional hours of comfort during a year and during the summer.

All-Year Analysis		Summer Analysis	
Additional Hours of comfort with PCM adoption	74 h	Additional Hours of comfort with PCM adoption	215 h
PCM wallboard: average cost of one hour of additional comfort	6.56 €/h	PCM wallboard: average cost of one hour of additional comfort	2.25 €/h
Use of HVAC: average cost of one hour of comfort	7.85 €/h	Use of HVAC: average cost of one hour of comfort	6.10 €/h

In the specific case of the PCM wallboard, a Fanger thermal comfort analysis was performed too. Particularly, the PMV and PPD indexes were examined for three typical classrooms, one for each story of the building. The PMV is the Predicted Mean Vote, and it depends from the vote of a large number of people about the thermal comfort of an ambient. As it was well-known, it is based on a thermal scale of 7-points, from −3 (very cold) to 3 (very hot), and the values are acceptable when are between −1 and +1 (0 is the thermal neutrality). The PPD is the Predicted Percentage Dissatisfied index and is related to the people's perception of cool or warm. When PMV is ±1, PPD is 25%; when PMV is ±0.5, PPD is 10%; in case of PMV = 0, PPD is 5%.

The PMV and PPD values reported in the Figure 15 correspond to the three typical classrooms of the University of Molise. As shown, the PCM retrofit intervention reduces considerably the PMV value during the cooling period compared to the value of the base building. It is interesting to underline the results of the PCM application in June. In fact, in all the three considered rooms, the PMV passes from a positive value (perception of a warm indoor ambient) to a negative one (perception of a cool indoor space), always within the PMV limits of acceptability. This different perception of comfort depends from the PCM behavior. In June, this innovative material reaches the melting point of 23 °C, storing latent heat from the ambient air and avoiding a further heating of the room, so that the classrooms are also a bit cold for the specific season. In other words, the building spaces are even considered "cool". Consistently with the PMV results, the PPD values have the same trends. During the winter season, as Figure 15 shows, the PMV of the classrooms with PCM is the same as the reference building and the same happens for the PPD index, of course. That depends on the melting temperature of the PCM. In fact, the results of thermal analyses show that the PCM does not store latent heat and does not reach the fusion temperature during winter. Please note that the worse values of the PMV-PPD of January are related to the fact that, in many days at the beginning of the month, the University is closed and the HVAC systems are turned off.

In terms of cost analysis, with reference to the PCM, the NPV (net present value) is negative, even if slightly, and this outcome reveals that, merely under the point of view of the costs, the addition of phase change material, for this building, is not repaid along the lifetime. In any case, the difference between the global costs of the PCM refurbished building and the base case building is minimal. The base building has a global cost of 523,748 € and the building with PCM has a G_C of 538,318 €, in a calculation period of 30 years. A difference of 14,570 € probably, for a public Institution involved in having a demonstration role can be accepted, mainly if the better summer and yearly comfort are achieved after the PCM refurbishment. Furthermore, considering the future trends of the increasing earth temperature and the enhancement of the electric energy prices, the PCM retrofit may be a convenient energy conservation measure for the improvement of the building energy efficiency.

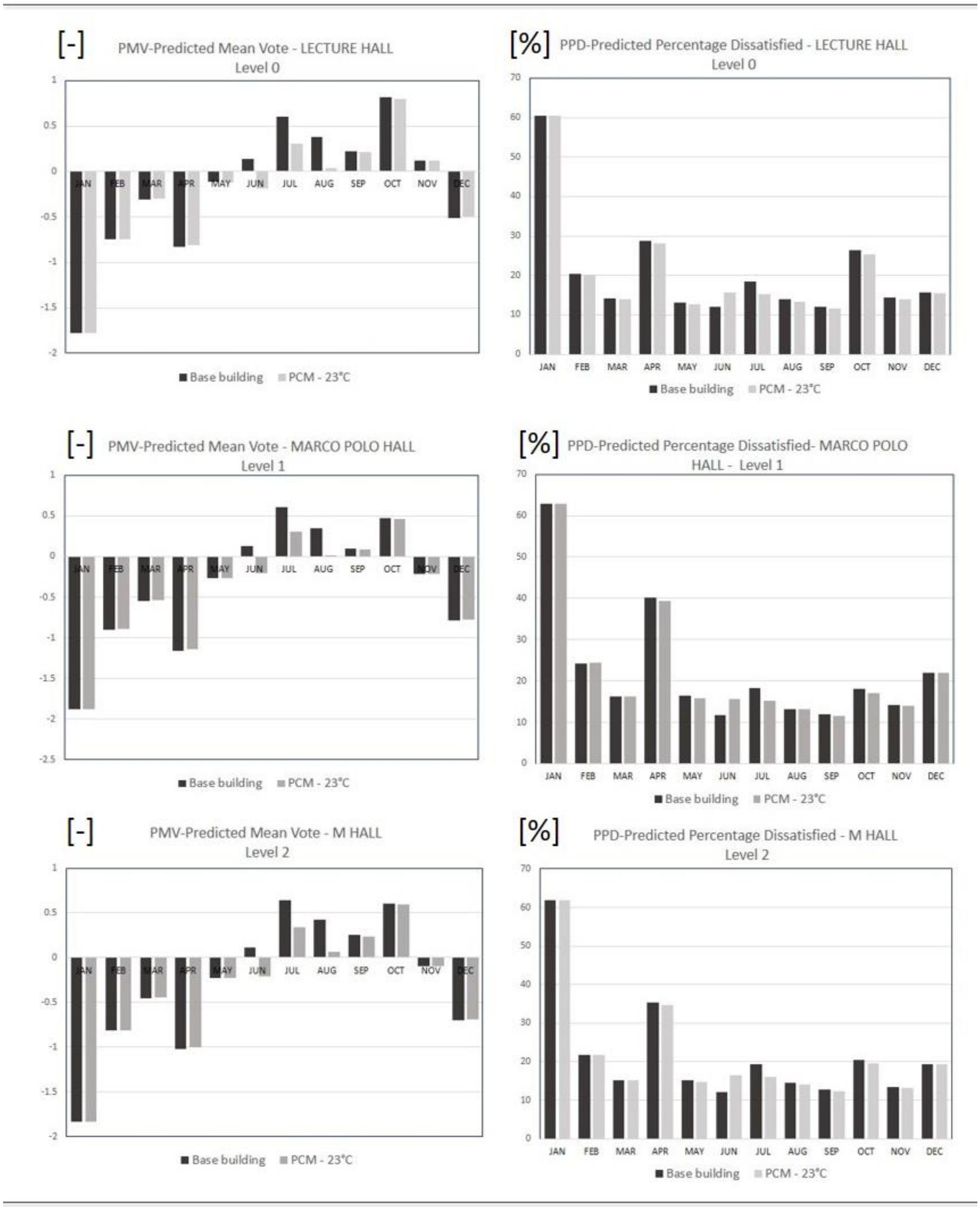


Figure 15. PMV and PPD average month values for three typical rooms during the year.

Optimization of the Phase Change Layer

The design of phase change materials for improving the thermal performance of the building envelope is, as known, a quite delicate issue, being necessary tailored evaluations concerning the melting temperature, enthalpy of fusion, quantity of materials (i.e., thickness, encapsulation, weight), and other physical and constructive characteristics. In this deepening, a wide study is proposed for optimizing the selection of the most proper phase change material in order to do as more convenient is possible its application in our case study, by considering the building technology, building thermo-physics, building location and its use. It should be noted, moreover, that a further optimization would involve also the PCM layer position inside the wall. Really, in our case, we have supposed the application of the PCM on the inner side of the external walls, in order to preserve it from too frequent cycles of charging and discharging (typical for application in the external side) and being this kind of application less invasive in the frame of the building retrofit.

To identify the best PCM configuration, and thus the best results in terms of energy consumption, costs, emissions and comfort, different phase change materials were evaluated. Specifically, ten PCMs were tested, according to their melting temperature: from 18 °C to 28 °C. Comparing the results, the energy consumption reduction is quite the same during the cold season. In fact, even if the melting point is 18 °C or 19 °C, and the corresponding freezing temperature is 16 °C and 17 °C respectively, the heat stored by the PCM would be released during the nocturnal hours when the building is uninhabited and the systems are turned off. At the same way, with the exception of some hours in few days of the heating periods (when indoor gains are quite high), the ambient air can't reach a higher temperature than 20 °C because the heating set-point is 20 °C, so, if the freezing temperature of the PCM exceeds the 20 °C, it would be always solid and couldn't release the heat stored (there is no phase changing). Finally, the energy consumption reduction of 1.6% during the winter is mainly related to the addition of a layer in the external building wall, which implies the reduction of thermal transmittance. The choice of the PCM was carried out evaluating the summer primary energy reduction of the different applications of PCMs (Figure 16).

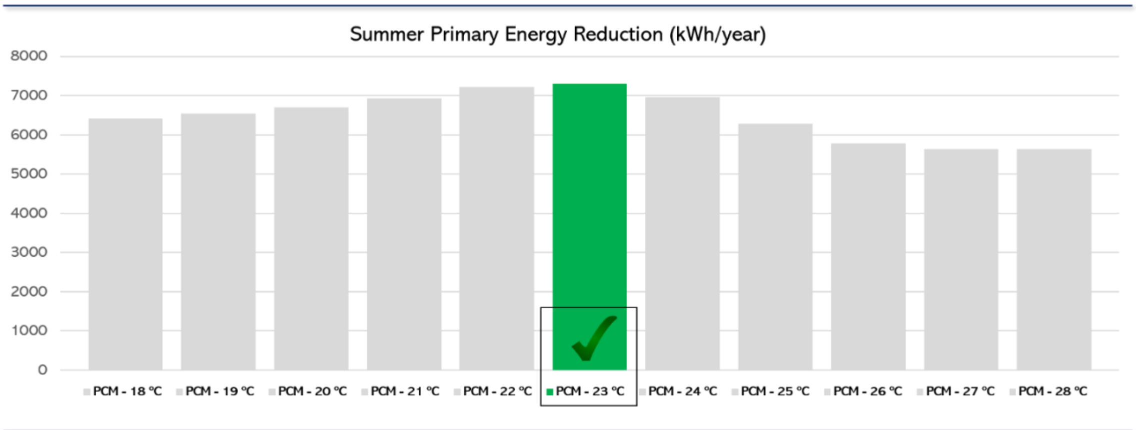


Figure 16. Comparing PCM additions in terms of summer primary energy reduction.

The results show a considerable reduction of energy consumption when the melting point of the PCM is 23 °C and growing energy demand when the PCM melting point increases or decreases. The advantages of the PCM building integration occur when the material changes its phase from solid to liquid and vice versa, in order to collect heat, subtracting it to the ambient and releasing it during the solidifying phase. When the PCM melting point is too low (18 °C–20 °C) the material will be melted all the time, instead, when it's too high the PCM will be predominately solid (25 °C–28 °C). For these reasons, the best PCM, in our case study, is the one with a melting temperature of 23 °C and a freezing temperature of 21 °C. Of course, these outcomes are the ones that maximize the cooling energy savings with reference to our peculiar case study, characterized by well-defined constructive technologies, building use, location and specific other boundary conditions.

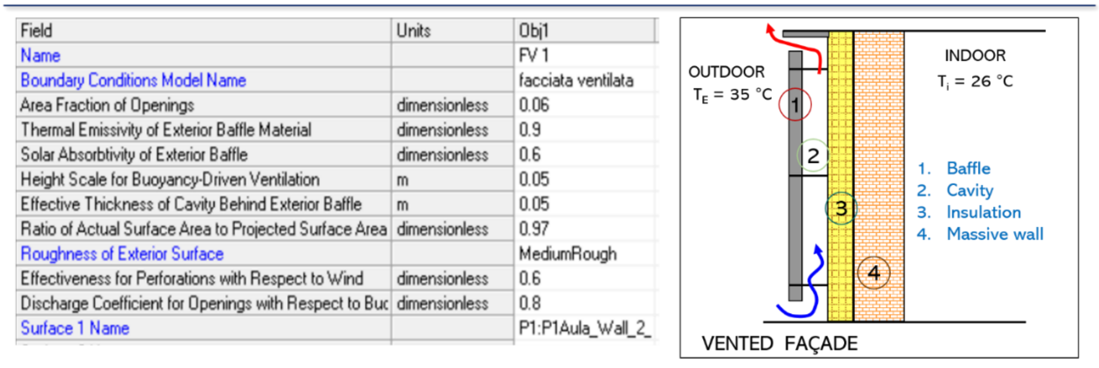
4.5. Addition of a Second Envelope Skin: Vented Façade

Natural ventilation can be used as a cooling passive strategy for buildings. In the specific case of a vented façade, the external air is used to reduce the temperature of a cavity between the thermal insulation material and the external coating. This strategy can dissipate the incident solar radiation and reduce the energy demand of the building, for both heating and cooling purposes. The vented façade proposed is made up of:

- Rockwool thermal insulation material (thickness 8 cm, thermal conductivity 0.035 W/mK, density 60 kg/m^3, specific heat 1030 J/kgK);

- Air cavity of 5 cm;
- Exterior baffle with 6% of openings (thermal emissivity 0.9, solar absorptivity 0.6).

Benefits can be achieved in both the seasons of heating and cooling, because, in winter, the thermal insulation is dry, not affected by rainfall, so that the thermal conductivity does not rise because of water and humidity. Besides the ventilation, the external cavity allows also a better preservation of the wall. In summer, conversely, the ventilation of the cavity, powered by the solar radiation on the baffle, allows the stack effect with a consequent heat dissipation and a lower cooling load of the building. With reference to the educational building of Termoli, the vented façade was added to the present wall. The vented coating was modeled in the software EnergyPlus, through the natural vented cavity and the gap convective radiation as other side conditions model, with input data are reported in Figure 17.



Field	Units	Obj1
Name		FV 1
Boundary Conditions Model Name		facciata ventilata
Area Fraction of Openings	dimensionless	0.06
Thermal Emissivity of Exterior Baffle Material	dimensionless	0.9
Solar Absorbtivity of Exterior Baffle	dimensionless	0.6
Height Scale for Buoyancy-Driven Ventilation	m	0.05
Effective Thickness of Cavity Behind Exterior Baffle	m	0.05
Ratio of Actual Surface Area to Projected Surface Area	dimensionless	0.97
Roughness of Exterior Surface		MediumRough
Effectiveness for Perforations with Respect to Wind	dimensionless	0.6
Discharge Coefficient for Openings with Respect to Buc	dimensionless	0.8
Surface 1 Name		P1:P1Aula_Wall_2_

Figure 17. Energy-Plus model of the vented façade.

The application of the vented façade implies a reduction of the primary energy required for the winter heating (4.8%) due to the addition of the thermal insulation layer. During the hot season, conversely, the natural vented cavity reduces the surface temperature of the external wall, but the addition of a thermal insulation material makes its effect negligible. Indeed, even if the daily temperature of the external environment (and thus the cavity temperature) goes down, the high thermal resistance of the cavity does not allow a significant heat dissipation from the inside to the outside. These phenomena can be understood better by analyzing the performances, by comparing the base building (e.g., the present building) with the building refurbished with a rockwool thermal insulation and the building refurbished with rockwool thermal insulation and the vented cavity. The results of the thermo-energetic simulations are shown in Table 6. Compared to a simple retrofit with thermal insulation and a new external plaster, the addition of a vented facade reduces the summer energy consumption only of about 0.3%, with no variation of yearly primary energy consumption. For this reason, in this design, that technology was not considered as profitable.

Table 6. Comparison, with respect to the base building, of the retrofit with thermal insulation and the retrofit with thermal insulation and vented façade.

Building with Vented Facade			**ΔENERGY**
Winter Primary Energy Reduction	3472	$kWh_{PRIMARY}$	4.8%
Summer Primary Energy Reduction	1953	$kWh_{PRIMARY}$	3.2%
Yearly Primary Energy Reduction	5425	$kWh_{PRIMARY}$	4.1%
Building with Rockwool Thermal Insulation			
Winter Primary Energy Reduction	3688	$kWh_{PRIMARY}$	5.1%
Summer Primary Energy Reduction	1791	$kWh_{PRIMARY}$	2.9%
Yearly Primary Energy Reduction	5480	$kWh_{PRIMARY}$	4.1%

5. Energetic and Economic Analysis Results and Discussion

Summarized energy performances of all retrofit measures, proposed and evaluated for the energy requalification of the building, are shown in Table 7. More in detail, the following parameters are synthetically reported and thus: energy demands (primary energy) and CO_2 equivalent emissions, as well as their reduction compared to the base building (ΔEP and ΔCO_2), the investment costs, return time of the invested capital (SPB and DPB), and the net present value (NPV) associated with each intervention. The evaluation of the different solutions follows the cost-optimal approach [3]. The cost-optimal level corresponds to an energy performance level with the lowest cost, during the economic lifecycle:

- the cost takes into account the investment costs, maintenance and operating costs and disposal costs, where applicable;
- the economic lifecycle is determined by each member state and is the estimated period where the building preserves entirely its energy performance.

In accordance with the EU legislative frame [37], the calculation time of the economic analysis is 30 years. All energy efficiency measures have a lifespan longer than 30 years, so that a second installation is not necessary during the time horizon of the investigation (i.e., no second installation, no residual value). The investment cost generally includes the cost of disposal of the technology; therefore, the cost of rebuilding has not been increased by the costs of removal and transport to the landfill.

Comparing the different interventions, it should be noted that:

- The green roof technology determines a reduction in HVAC energy consumption, produces a summer primary energy reduction of 1.6% (993 $kWh_{PRIMARY}$), and a winter primary energy reduction of 0.6% (443 $kWh_{PRIMARY}$). The thermal transmittance of the roof, with and without the green roof are: 0.32 W/m^{2}K and 0.37 W/m^{2}K. Niachou et al. [44] examined different scenarios, comparing the addition of a green roof on a well-insulated building and a non-insulated building, with a typical Mediterranean climate (Loutraki, Greece). For a well-insulated building, and particularly for a roof whose thermal transmittance switches from 0.39 W/m^{2}K to 0.33 W/m^{2}K, the energy-saving for heating corresponds to 8%, and the energy-saving for cooling to 0%, with a total energy saving of 2%. The performance of the green roof would be better if the thermal transmittance of the roof had been greater than 0.4 W/m^{2}K. To higher thermal transmittance corresponds a major thermal flux. In this case, the roof is well insulated and, even if the roof surface temperature is reduced by the green roof vegetation, the advantages in terms of energetic saving are not relevant. This reduction of energy demand is not enough if analyzed contextually to the investment cost, and therefore the NPV is negative at 30 years. The installation of this technology would allow energy savings not high enough to compensate an investment cost of €84,000.
- Analogously, the cool roof technology does not produce positive results in economic terms. The primary energy reduction of 0.6% is not enough to get back the investment cost (14,000 €), and the NPV is negative. About this, Synnefa et al. [45] focused on the effect of cool roofs in different climatic conditions on energy consumption, but also on the relation between thermal transmittance and cool roof energy saving. When the thermal transmittance of a roof is low, like the case study we have analyzed (0.37 W/m^{2}K), the heat transfer between the roof surface and the indoor ambient is small and the energy saving is not important.
- The thermal insulation layer reduces the energy consumption of 1.1% during a year, but the investment costs are too high. In fact, the vertical insulation with expanded polyurethane, having a thermal conductivity equal to 0.026 W/m^{2}K, implies an investment cost of €128,140, but also a return time of the capital higher than 30 years and thus a negative NPV has been calculated. These results are in line with those obtained by Ascione et al. [46]. The study focused on the application

of different measures for the retrofit of a Conference Hall in Naples. In the specific case of the thermal insulation (8 cm of polyurethane), they obtained an annual variation of primary energy of 0.7% and a SPB major than 30 years.

- The cooling strategy through the vented façade is not economically convenient, even if the primary energy demand for cooling and heating decreases of 4.1%, the investment cost of 344,000 € cannot be repaid before 30 years, and thus the NPV is negative. In terms of energy savings, the simulated solution has results coherent with those obtained by Balocco et al. [47]. A vented facade high 14 m, with an air cavity of 7 cm, was tested on the southern wall of a building in Florence. The results showed the reduction of energy for cooling of 7% compared to the building without a vented façade. The vented façade here examined, with a height of 13.2 m and an air cavity of 10 cm, could reduce the cooling demand of the University of Molise located in Termoli, of 3.2%. This result is lowest than the case study of Balocco et al. because the vented façade was tested on all the walls of the building, differently oriented, and not only on the southern surface. Besides, although comparable, there are certain differences related to the climatic conditions of Florence and Termoli.
- The phase change material offers advantages from the energetic point of view but not actually from the economic point of view. For an investment cost of 36,875 €, the NPV is negative, and the DPB is longer than 30 years. From the energetic point of view, the summer energy saving is 11.7%, instead, the winter energy saving is 1.6%. The results obtained are comparable, although qualitatively, with those provided by Saafi et al. [48]. The study focused on the application of a PCM on the internal surface of the building envelope, under the Tunisia Mediterranean climate. A PCM with a melting temperature of 23 °C, guarantee a cooling energy reduction rate of 12%, and a heating energy reduction of 7.8% for freezing temperature of 20 °C.

Really, it should be noted that:

- The present building already has a quite satisfactory level of energy efficiency: it means that the high potential of energy-saving already was exploited during the previous energy retrofit.
- These economic analyses have been performed with a particularly low electric energy price. In fact, the University of Molise pays only 0.20 €/kWh$_{el}$, but considering the certain increase of energy cost, and the future increment of energy demand for active cooling, the innovative PCM intervention can be considered a valuable energy efficiency measure.

Moreover, by taking into account a large number of stakeholders involved in energy efficiency projects, and thus the community besides the building owners and managers, a macroeconomic analysis has been provided too, which takes into account the investment cost but also the maintenance, management, and any additional costs. As established by the aforementioned "Commission Regulation (EU) No. 244/2012 of 16 January 2012" [37], the macroeconomic analysis also considers the costs of greenhouse gas emissions and the residual value of the investment for a calculation period of 30 years (for the redevelopment of residential and public buildings). More in detail, Table 8 infers the so-called global costs, and all economic and technical parameters provided by the aforementioned EU Delegated Regulation.

As can be seen from Table 8 and Figure 18, the intervention with the highest overall global cost is the vented façade and is equal to 645,042 €. Conversely, the global cost of PCM intervention is the lowest (538,318 €).

Table 7. Results of the energy and economic analyses of the retrofit measures applied to the case study.

Type of Intervention	Primary Energy Demand (HVAC)	Primary Energy Demand (Building)	Tot/m^2	Annual EP Saving (HVAC) *	CO_2	Annual CO_2 Reduction (HVAC) *	Investment Cost	SPB	DPB
Unit of measurement	[MWh]	[MWh]	[kWh/m^2]	[%]	[Ton/year]	[%]	[€]	[years]	[years]
Green roof	131.8	259.4	99.0	1.1%	39.0	1.1%	84,000	>30 years	>30 years
Cool roof	132.6	260.2	99.3	0.5%	39.1	0.5%	14,000	>30 years	>30 years
Vertical Insulation	128.1	255.8	97.7	3.8%	38.4	3.8%	128,100	>30 years	>30 years
PCM wallboard	123.2	250.6	95.7	6.1%	37.7	6.1%	36,900	>30 years	>30 years
Vented facade	127.8	255.4	97.5	4.7%	38.4	4.7%	344,000	>30 years	>30 years

* the percentage values take into account the HVAC systems, because only the results of the HVAC consumption have changed (electricity for cooling and heating, pumps and funs).

Table 8. Technical and economical analysis according to the indication EU delegated regulation n. 244/2012; fuel cost 0.20 €/kWh$_{el}$, discount rate 3.0%, economic lifecycle = 30 years.

Type of Intervention	Investment Costs	Lifetime Discounted Management Costs	Emission Costs	Residual Value	Global Costs
Unit of measurement	[€]	[€]	[€]	[€]	[€]
Green roof	84,000	498,226	29,049	13,843	597,432
Cool roof	14,000	497,800	29,138	2,307	538,631
Vertical insulation *	128,140	489,335	28,643	21,117	625,001
PCM plaster	36,875	479,455	28,065	6,077	538,318
Vented facade	344,000	329,129	28,602	56,689	645,042

* “Thermal Account” (“Conto Termico”, in Italian) incentives have been considered. The “Thermal Account” establishes a refunding of 40% of the total intervention cost for thermal insulation of the opaque building envelope.

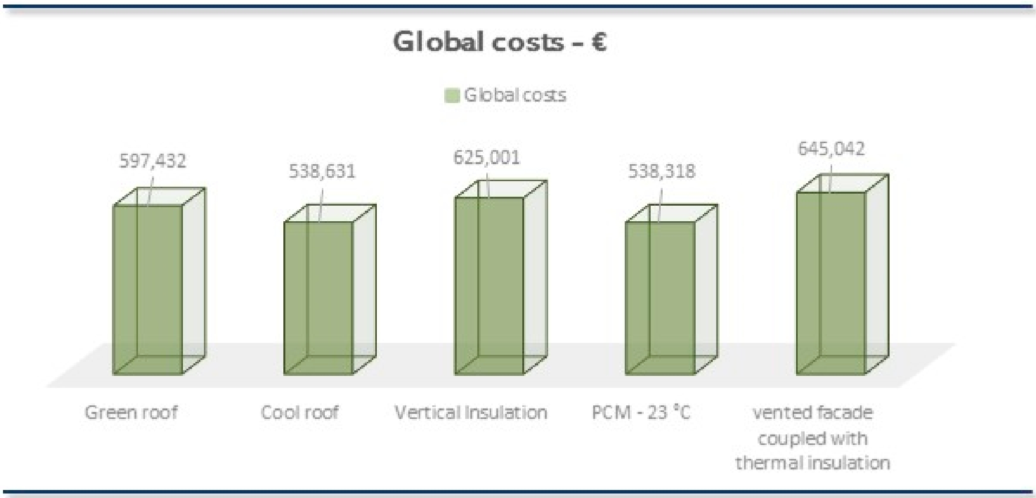


Figure 18. GC global costs of the considered energy efficiency measures—calculation period of 30 years.

Furthermore, in order to provide some suggestions, the following possible future events can be considered:

- an increase of energy price of 25%,
- funding measures also for energy efficiency strategies devoted to cooling (i.e., 40% of the investments, as already established by the thermal account),
- stagnancy of value of money and thus a discount rate equal to 1% (in this paper, the discount rate is imposed as 3%, but really, in the last years, the value of money remained quite constant. Finally, a discount rate of 1% is reliable today),
- reduction of costs of phase change materials because of their diffusion and thus positive economies of scale.

According to these new boundary conditions, that are surely reliable, the payback would be around 12 years.

6. Conclusions

Very inefficient buildings, and thus ones built after the Second World War (concrete structures, low thicknesses, absence of insulation, large windows), are already the subject of profound refurbishments, mainly to add thermal insulation and reduce the energy demands for heating. Today and for the next years, the challenge is and will be to limit the energy demands for cooling and improving the microclimatic comfort during the hot seasons. Thus, the targets are the buildings built around the 1990s and 2000s, conceived with a good thermal performance for what concerns the winter behavior but without care toward the summer energy comfort. This is the focus of this paper, also according to the aims of the new Directive 844/2018, aimed at a decarbonized building stock in the future decades, starting from the existing buildings. In this regard, guidelines for refurbishing quite recent buildings, mainly to improve the summer conditions and reducing the energy demands for cooling—also by taking into account the more and more pressing climate change and urban heat island phenomenon, that overheat our cities and communities—are needed and up to date.

The present study focused on the energy refurbishment of a public building, one of the main edifices of the University of Molise, located in Termoli (Province of Campobasso, Italy). The retrofit was aimed at reducing the increasing energy demands for the summer space cooling. The energy efficiency measures investigated and optimized in terms of energy, emissions, costs, and thermal comfort have positive effects on the reduction of summer energy demand. Considering the public role of the building, present regulations were taken into account and, in particular, the ones in a matter of energy efficiency of the public buildings were considered, aimed at a low-carbon future through energy savings. The proposed interventions are passive strategies for the building envelope: cool roof and green roof for the horizontal building envelope, thermal insulation, phase change materials and vented façade for the vertical envelope. Firstly, a transient energy model was calibrated, starting from the historical energy consumption; secondly, once having a reliable numerical model of the present scenario, the different solutions were simulated through the software EnergyPlus. Then, all results have been analyzed according to different points of view, and thus energy, costs, and emissions analyses. The economic analysis was not limited to the evaluation of operational energy and costs savings, but focuses on the investment assessment, by taking into account the global costs (European Regulation 244/2012 [37]). In the specific case of the PCMs application, different PCMs were compared, varying their melting temperature from 18 °C to 29 °C in order to verify the best solution in terms of microclimatic indoor comfort and reduction of energy consumption. The innovative solution of phase change wallboard with a melting temperature of 23 °C behaves as the best. In fact, it causes a reduction of primary energy demand during summertime (11.7%), and a consequent decrement of CO_2 emissions. This solution offers advantages in terms of indoor thermal comfort, by increasing the summer indoor comfort of 215 h. According to another comfort model, and thus the Fanger analysis for casual classrooms, a significant improvement of PMV and PPD was achieved during the cooling period and almost no variation during the heating seasons are registered. In terms of costs, the PCM intervention is not actually convenient but considering the future climate evolution and increasing of energy prices, the PCM intervention may be a convenient measure for the improvement of the building energy efficiency. As clear from the results, only an innovative solution as a PCM could improve effectively the thermal comfort and the energy saving of the building. A building like the one analyzed renovated in 2005 and with an envelope with low thermal transmittance, can't be redeveloped energetically through traditional passive strategies, but only with an innovative solution that influences the apparent thermal capacity (employing the latent heat-storing) of the opaque envelope acting from the inner side. A phase change material is a valid solution.

Author Contributions: M.M. proposed and prepared the initial investigation (Conceptualization), according to materials and methodologies supervised by F.A. and R.F.D.M. (Methodology). The manuscript was completed thanks to suggestions and revisions of N.B. and G.P.V. (Supervision).

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. EU Commission and Parliament Directive 2002/91/EU of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings. *Off. J. Eur. Union* **2003**. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32002L0091&from=EN (accessed on 20 July 2019).
2. Legislative Decree 19 August 2005, n. 192. Available online: http://www.bosettiegatti.eu/info/norme/statali/2005_0192.htm (accessed on 20 July 2019).
3. EU Commission and Parliament, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (EPBD Recast). *Off. J. Eur. Union* **2010**. Available online: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:153:0013:0035:EN:PDF (accessed on 20 July 2019).
4. Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L0844&from=IT (accessed on 20 July 2019).
5. Benestad, R.E. *Heating Degree Days, Cooling Degree Days, and Precipitation in Europe: Analysis for the CELECT-Project*; Report for the Norwegian Metereorological Institute; Norwegian Meteorological Institute: Oslo, Norway, 2008.
6. Ascione, F.; Bianco, N.; Böttcher, O.; Kaltenbrunner, R.; Vanoli, G.P. Net zero-energy buildings in Germany: Design, model calibration and lessons learned from a case-study in Berlin. *Energy Build.* **2016**, *133*, 688–710. [CrossRef]

7. Santamouris, M.; Kolokotsa, D. Passive cooling dissipation techniques for buildings and other structures: The state of the art. *Energy Build.* **2013**, *57*, 74–94. [CrossRef]
8. Ascione, F.; Bianco, N.; De Masi, R.F.; De Rossi, F.; Vanoli, G.P. Simplified state space representation for evaluating thermal bridges in building: Modelling, application and validation of a methodology. *Appl. Therm. Eng.* **2013**, *61*, 344–354. [CrossRef]
9. Ascione, F. Energy conservation and renewable technologies for buildings to face the impact of the climate change and minimize the use of cooling. *Sol. Energy* **2017**, *154*, 34–100. [CrossRef]
10. Alcazar, S.; Olivieri, F.; Neila, J. Green roofs: Experimental and analytical study of its potential for urban microclimate regulation in Mediterranean–continental climates. *Urban Clim.* **2016**, *17*, 304–317. [CrossRef]
11. Yaghoobian, N.; Srebric, J. Influence of plant coverage on the total green roof energy balance and building energy consumption. *Energy Build.* **2015**, *103*, 1–13. [CrossRef]
12. Ascione, F.; Bianco, N.; de Rossi, F.; Turni, G.; Vanoli, G.P. Green roofs in European climates. Are effective solutions for the energy savings in air-conditioning? *Appl. Energy* **2013**, *104*, 845–859. [CrossRef]
13. Ascione, F.; Bianco, N.; De Masi, R.F.; De Rossi, F.; Vanoli, G.P. Technical and economic analysis of green roofs to reduce building cooling needs. In *Eco-efficient Materials for Mitigating Building Cooling Needs—Design, Properties and Application*; Pacheco-Torgal, F., Labrincha, J., Cabeza, L., Granqvist, C., Eds.; Woodhead Publishing: Sawston, UK, 2015; pp. 349–378.
14. Gagliano, A.; Detommaso, M.; Nocera, F.; Evola, G. A multi-criteria methodology for comparing the energy and environmental behavior of cool, green and traditional roofs. *Build. Environ.* **2015**, *90*, 71–81. [CrossRef]
15. Pisello, A.L.; Piselli, C.; Cotana, F. Thermal-physics and energy performance of an innovative green roof system: The Cool-Green Roof. *Sol. Energy* **2015**, *116*, 337–356. [CrossRef]
16. Santamouris, M.; Pavlou, K.; Synnefa, A.; Niachou, K.; Kolokotsa, D. Recent progress on passive cooling techniques: Advanced technological developments to improve survivability levels in low-income households. *Energy Build.* **2007**, *39*, 859–866. [CrossRef]
17. Lucchi, E.; Tabak, M.; Troi, A. The "cost optimality" approach for the internal insulation of historic buildings. *Energy Procedia* **2017**, *133*, 412–423. [CrossRef]
18. Cao, Z.J.; Liao, W.; Wang, S.X.; Zhao, H.B.; Wang, Y.Z. Polyurethane foams with functionalized graphene towards high fire-resistance, low smoke release, superior thermal insulation. *Chem. Eng. J.* **2019**, *361*, 1245–1254. [CrossRef]
19. Cabeza, L.F.; Castell, A.; Medrano, M.; Martorell, I.; Pérez, G.; Fernández, I. Experimental study on the performance of insulation materials in Mediterranean construction. *Energy Build.* **2010**, *42*, 630–636. [CrossRef]
20. Stazi, F.; Tomassoni, F.; Vegliò, A.; Di Perna, C. Experimental evaluation of ventilated walls with an external clay cladding. *Renew. Energy* **2011**, *36*, 3373–3385. [CrossRef]
21. Marinosci, C.; Semprini, G.; Morini, G.L. Experimental analysis of the summer thermal performances of a naturally ventilated rainscreen façade building. *Energy Build.* **2014**, *72*, 280–287. [CrossRef]
22. Kasaeian, A.; Pourfayaz, F.; Khodabandeh, E.; Yan, W.M. Experimental studies on the applications of PCMs and nano-PCMs in buildings: A critical review. *Energy Build.* **2017**, *154*, 96–112. [CrossRef]
23. Baetens, R.; Jelle, B.P.; Gustavsen, A. Phase change materials for building applications: A state-of-the-art review. *Energy Build.* **2010**, *42*, 1361–1368. [CrossRef]
24. Feldman, D.; Banu, D.; Hawes, D.W. Development and application of organic phase change mixtures in thermal storage gypsum wallboard. *Sol. Energy Mater. Sol. Cell.* **1995**, *36*, 147–157. [CrossRef]
25. Theodoridou, M.; Kyriakou, L.; Ioannou, I. PCM-enhanced lime plasters for vernacular and contemporary architecture. *Energy Procedia* **2016**, *97*, 539–545. [CrossRef]
26. Sittisart, P.; Farid, M.M. Fire retardants for phase change materials. *Appl. Energy* **2011**, *88*, 3140–3145. [CrossRef]
27. Tyagi, V.V.; Kaushik, S.C.; Tyagi, S.K.; Akiyama, T. Development of phase change materials based microencapsulated technology for buildings: A review. *Renew. Sustain. Energy Rev.* **2011**, *15*, 1373–1391. [CrossRef]
28. Gil-Baez, M.; Padura, Á.B.; Huelva, M.M. Passive actions in the building envelope to enhance sustainability of schools in a Mediterranean climate. *Energy* **2019**, *167*, 144–158. [CrossRef]
29. De Santoli, L.; Fraticelli, F.; Fornari, F.; Calice, C. Energy performance assessment and a retrofit strategies in public school buildings in Rome. *Energy Build.* **2014**, *68*, 196–202. [CrossRef]

30. Mao, N.; Pan, D.; Li, Z.; Xu, Y.; Song, M.; Deng, S. A numerical study on influences of building envelope heat gain on operating performances of a bed-based task/ambient air conditioning (TAC) system in energy saving and thermal comfort. *Appl. Energy* **2017**, *192*, 213–221. [CrossRef]
31. ISPRA Report. Available online: http://www.isprambiente.gov.it/files2018/pubblicazioni/rapporti/R_280_18_Emissioni_Settore_Elettrico.pdf/view (accessed on 20 July 2019).
32. *EnergyPlus Simulation Software*; Version 7.2.0; U.S. Department of Energy: Washington, DC, USA, 2012.
33. *Design Builder*; Version 3.4; Design Builder Software Ltd.: Gloucestershire, UK, 2013.
34. ASHRAE—American Society of Heating. *Refrigerating and Air-ConditioningEngineers, Guideline 14 2002, Measurement of Energy and Demand and Savings*; ASHARE: Atlanta, GA, USA, 2002.
35. U.S. Department of Energy, Federal Energy Management Program (FEMP). *M&V Guidelines: Measurement and Verification for Performance-Based Contracts*; FEMP: Washington, DC, USA, 2015.
36. Italian Presidential Decree n 412/1993. D.P.R. 26 august 1993, n. 412. Available online: http://efficienzaenergetica.acs.enea.it/doc/dpr412-93.pdf (accessed on 20 July 2019).
37. Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32012R0244&from=GA (accessed on 20 July 2019).
38. ISPRA Report, Atmospheric Emission Factors of Greenhouse Gases in the National Electricity Sector and in the Main European Countries. Available online: http://www.isprambiente.gov.it/files2019/pubblicazioni/rapporti/R_303_19_gas_serra_settore_elettrico.pdf/view (accessed on 20 July 2019).
39. De Masi, R.F.; de Rossi, F.; Ruggiero, S.; Vanoli, G.P. Numerical optimization for the design of living walls in the Mediterranean climate. *Energy Convers. Manag.* **2019**, *195*, 573–586. [CrossRef]
40. Project Horizon 2020, Green INSTRUCT (Green Integrated Structural Elements for Retrofitting and New Construction of Buildings). Available online: https://www.greeninstruct.eu/ (accessed on 20 July 2019).
41. Becherini, F.; Lucchi, E.; Gandini, A.; Barrasa, M.C.; Troi, A.; Roberti, F.; Bernardi, A. Characterization and thermal performance evaluation of infrared reflective coatings compatible with historic buildings. *Build. Environ.* **2018**, *134*, 35–46. [CrossRef]
42. Ministerial Decree 26/06/2015. Available online: https://www.mise.gov.it/images/stories/normativa/DM_requisiti_minimi.pdf (accessed on 20 July 2019).
43. GSE—Energy Services Manager. Available online: https://www.gse.it/servizi-per-te/efficienza-energetica/conto-termico (accessed on 20 July 2019).
44. Niachou, A.; Papakonstantinou, K.; Santamouris, M.; Tsangrassoulis, A.; Mihalakakou, G. Analysis of the green roof thermal properties and investigation of its energy performance. *Energy Build.* **2001**, *33*, 719–729. [CrossRef]
45. Synnefa, A.; Santamouris, M.; Akbari, H. Estimating the effect of using cool coatings on energy loads and thermal comfort in residential buildings in various climatic conditions. *Energy Build.* **2007**, *39*, 1167–1174. [CrossRef]
46. Ascione, F.; Bianco, N.; De Stasio, C.; Mauro, G.M.; Vanoli, G.P. Building envelope, HVAC systems and RESs for the energy retrofit of a Conference Hall on Naples promenade. *Energy Procedia* **2015**, *75*, 1261–1268. [CrossRef]
47. Balocco, C. A simple model to study ventilated facades energy performance. *Energy Build.* **2002**, *34*, 469–475. [CrossRef]
48. Saafi, K.; Daouas, N. Energy and cost efficiency of phase change materials integrated in building envelopes under Tunisia Mediterranean climate. *Energy* **2019**. [CrossRef]