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Energy retrofit of a day care center for current and future weather scenarios

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Abstract

Many scientific evidences have shown that Earth's climate is rapidly changing. By 2050, European Union is aiming to significantly reduce greenhouse gas emissions (GHG) in the building sector. Achieving this target might help the mitigation of global warming, but the climate change seems inevitable. This means that both new and refurbished buildings should be able to face those conditions that they are going to experience during their lifetime. Therefore, any building design should be checked both for current and future climate scenarios. This study describes the use of a downscaling method named *morphing* to generate future weather scenarios and intends to support the design process of a deep energy retrofit of a day care center in order to improve the energy and thermal comfort performance of the building under the current and future weather scenarios. The retrofit concept of the building also includes hybrid ventilation, automated solar shading, lighting controls and renewable energy generation systems.

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Keywords: Climate change, climate change adaptation, climate resilience, future weather scenario, net-zero energy buildings.

1. Introduction

The 195 countries were participating in the 2015 United Nations Climate Change Conference (COP 21) in Paris recently agreed on a set of global actions to limit the global warming below 1.5 °C with respect to the pre-industrial period [1]. The recent assessment report by the Intergovernmental Panel on Climate Change (IPCC) highlights the

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considerable technological, economics and institutional challenges that are required to achieve this goal [2]. Moreover, designers and managers of the built environment have to take into account the forthcoming changes since the global warming can cause extreme conditions such as summer overheating and a substantial shift from space heating to space cooling both for existing and new buildings in temperate, winter-dominated climates [3]. IPCC developed future climate scenarios based on possible future GHG emissions. These scenarios are considered as most likely future global conditions. In order to make these scenarios suitable for the building sector, local scenarios are required. Belcher et al. [4], developed a methodology called 'morphing' that generates future weather scenarios with an hourly resolution from general circulation models of the atmosphere, which have a monthly resolution. In this work, three different future weather scenarios for the city of Milan in Italy were developed using IPCC scenarios and the morphing method. Such three scenarios, namely 2020, 2050, and 2080, are used to assess the deep energy retrofit design of a day care center [5], against future climate change. To date, in the design process of high-performance buildings, typical meteorological year are mostly used, and little attention has been reserved to future weather projections. Robert and Kummert [6] have shown that a net-zero energy building, designed under typical weather conditions, can miss the net-zero energy target in future projected years. The focus of this paper is to evaluate the behavior of a net-zero energy day care center under future weather scenarios, in terms of energy and thermal comfort. To this aim, the long-term thermal discomfort indices proposed in the European standard EN 15251 [7] are used to assess indoor thermal comfort conditions and suitable climate severity indices have been applied to characterize the severity of the future weather scenarios.

Nomenclature

ASHRAE	American society of heating, refrigerating, and air-conditioning engineers
BPS	Building performance simulation
CDD	Cooling degree-day
COP	Conference of the Parties
CV(RMSE)	Coefficient of variation of the Root mean square error
HadCM3	UK Met Office Hadley Centre coupled model version 3
HDD	Heating degree-day
HVAC	Heating ventilation and air conditioning
IPCC	Intergovernmental panel on climate change
MBE	Mean bias error
PV	Photovoltaic
SRES	Special report on emission scenarios
TMY	Typical meteorological year

2. Materials and methods

A deep energy retrofit of a day care center was supported by building performance simulation (BPS) to improve the energy and thermal comfort performance of the building and to achieve the net zero energy balance under the current, typical and future weather scenarios.

First, an environmental monitoring of the building allowed to identify the most important deficiencies of the existing building and address the retrofitting concept. Then, BPS was used to support the retrofit design of a day care center and the consequent decision-making process. A model of the existing building was created and calibrated against both monthly measured delivered energy and hourly indoor air temperature [3]. Then, several refurbishment options were implemented in the model and compared in order to identify the best options to apply into the final retrofitting concept of the building, which includes hybrid ventilation, automated solar shading, lighting controls and a photovoltaic (PV) generation systems. The model of the existing building (also referred as the pre-retrofit model) was after that used as the reference to evaluate the energy saving and the thermal enhancement of the post-retrofit building under typical, current and future weather scenarios.

2.1. The case study: the day care center of Via Feltrinelli 11

The day care center is a one-story rectangular building located in Via Feltrinelli 11 in Milan, Italy. It has two 44-meter-long façades on southwest and northeast and two 23-meter-long façades on southeast and northwest. The building has a total gross area of 944 m^2 and a net floor area of 855 m^2. Around 58% of the net floor area is dedicated to the children activities and the remaining are staff and service areas. The total heated volume of the building is 3422 m^3, and the building is characterized by surface to volume ratio (S/V) equal to 0.77 m^2/m^3. Table 1 reports the designed values of the opaque and glazing components of the building envelope implemented in the numerical models representing the existing building and the retrofitting concept.

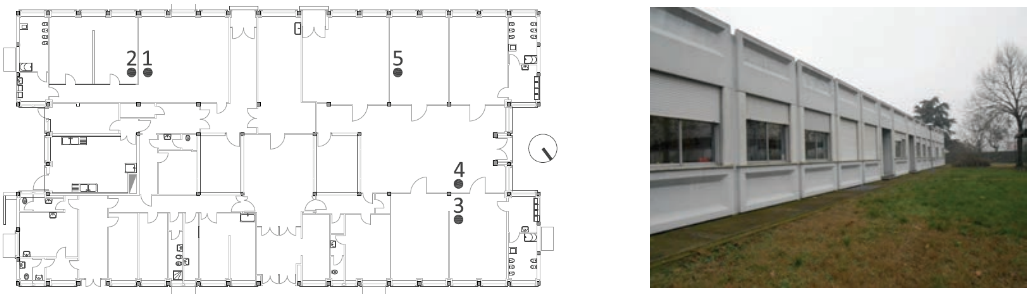

Fig. 1. (a) Kindergarten plan view including the five monitored rooms; (b) picture of the southwest facade.

Table 1. Descriptions of the building envelope opaque and glazing components of the pre- and post- retrofit models.

Building envelope component	Description of the existing components	Pre-retrofit estimated U-value, $W/(m^2K)$	Post-retrofit calculated U-value, $W/(m^2K)$
Roof	Pre-cast concrete slab	1.3	0.10
Vertical opaque wall	Pre-cast concrete panel	1.2	0.10
Floor (facing an unheated basement)	Pre-cast concrete slab	1.3	0.30
Windows	Clear double glazing + Aluminum frame without thermal break	5.8	0.73

2.2. Environment monitoring of the building

Currently, a natural gas boiler with metal radiators for heating are installed in the day care center, and no active cooling system is available. The occupants manually operate the windows to refresh indoor air all year round and cool down the building during summer days. In order to evaluate the thermal quality of the building envelope of the existing building, an inspection with an infrared thermal camera was performed during winter 2014. The analysis clearly showed a poor thermal resistance of the envelope due to a very low thermal insulation and the existence of noteworthy thermal bridges. The indoor environmental conditions of the building are under monitoring since July 2014; it was therefore possible to note a very high drop of indoor air temperature (Figure 2b) during the Christmas holidays of 2014, because the heating system was switched off and the building envelope performance are poor. Carbon dioxide concentration was monitored in Room 4 (Figure 2a) to assess indirectly indoor air quality in the building. The result shows noticeable peaks after September with values considerably higher than the reference value of 700 ppm above the 400 ppm background level recommended by the standard ASHRAE 62 [8]. The recorded data shows that the buildings clearly needs a better ventilation strategy [9].

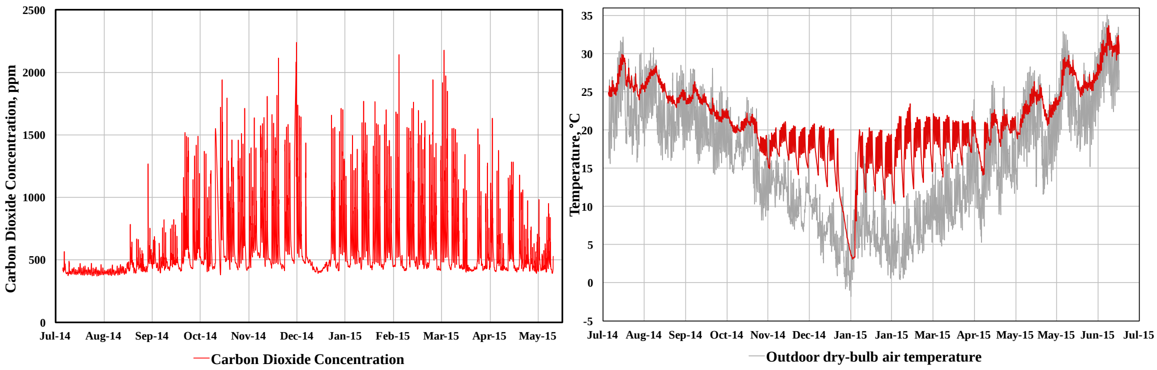

Fig. 2. (a) Carbon dioxide concentration in Room 4; (b) Air temperature in Room 4 versus outdoor air temperature.

2.3. Modeling and simulation of the pre- and post-retrofit numerical models of the building

Modeling and simulation of the building were performed in the whole-building dynamic software EnergyPlus [10], version 8.3.0.1. Within the capability of EnergyPlus, the building model was created to reproduce in detail the geometry of the existing building, and the algorithms were selected in order to reproduce accurately physical phenomena. Two rounds of simulations were carried out, one for the pre-retrofit building model and the second for the post-retrofit building model to assess both the building models under typical, current, and future weather scenarios.

Regarding the existing building, it was modeled without mechanical ventilation and cooling systems, and, hence, the whole building was modeled to be passively operated during summertime. According to the Italian law DPR 412 [11], in Milan, heating systems can be turned on during the period ranging from 15th October to the 15th April. This period was adopted to schedule the operation of the heating system, and, during the rest of the year, the model was simulated in free-running mode. The heating set-point temperature was set according to the design values recommended by EN 15251 and based on the Fanger comfort model. The internal gains are heat produced by occupants, electrical equipment, and artificial lighting. Then, the pre-retrofit model was calibrated to provide consistent and reliable simulation outcomes. Two calibration processes were carried out, following the ASHRAE Guideline 14 [12]. In the beginning, the pre-retrofit model was calibrated based on the monthly measured delivered energy. The model was then refined with a second calibration using hourly measured indoor air temperature as the benchmark.

The post-retrofit building was simulated in two configurations: the first configuration assumes that no mechanical cooling system is installed, and the building is in free-running during summertime while the second one assumes that an ideal reversible air-to-air heat pump is installed. Hence, the building is mechanically conditioned throughout the year. The cooling set-point temperature is set according to the design values recommended by EN 15251 and based on the Fanger comfort model. In the two post-retrofit building models, a PV system is included. The generation system is assumed to be adequate to meet the net-zero energy target expressed in primary energy and calculated on a yearly basis.

2.4. Generation of the future weather scenarios

In this paper, the approach proposed by Jentsch et al. [13] is adopted. They developed a tool called CCWorldWeatherGen that provides future weather projections with an hourly resolution. Such future weather data are suitable for being used in BPS. The calculation method implemented in this tool uses three factors: first, the A2 emission scenario that is developed by the Special report on emission scenarios (SRES) of IPCC working group 3 [2]. Second, the *UK Met Office Hadley Centre Coupled Model version 3* (HadCM3) [14], and third, a downscaling method called *morphing*, which was introduced by [4]. This calculation method is applied in the Typical Meteorological Year (TMY) file to obtain hourly weather data for the three future scenarios in 2020, 2050 and 2080.

In summary, five different scenarios are created: the typical weather file (TMY), the monitored weather file for the year 2014, and three weather projections for the years 2020, 2050, and 2080. For each scenario, heating degree-day (HDD) and cooling degree-day (CDD) are calculated and used to evaluate their climate severity (Table 2).

Table 2. Comparison of climate severity of the typical, current and future weather scenarios.

Parameter (unit of measure)	TMY	2014	2020	2050	2080
HDD (°C h)	3002	2274	2718	2384	1988
CDD (°C h)	3	45	26	116	289

2.5. Assessment of the energy and thermal performance of the building models

Since the existing building is operated in free-running mode during summer, to assess the enhancement of the post-retrofit concept a long-term thermal discomfort index is used for the thermal comfort assessment [15]. The *Percentage out of range* method, proposed by the European standard EN 15251, was used to assess the building thermal performance, although it is characterized by some limitations [16,17]. It calculates the percentage of occupied hours when the indoor operative temperature falls outside of a given thermal comfort category. This index is symmetrical, i.e. it measures both overheating and undercooling occurrences [17]. Moreover, EN 15251 suggests the use of Category I for spaces occupied by very sensitive and fragile people, such as day care centers.

For the second configuration of the post-retrofit model, since the building is assumed fully conditioned, the energy needs for space heating and cooling, before and after the retrofit, are compared in the typical, current and the three future weather scenarios.

3. Results and discussion

The calibrated model of the existing building reproduces the general thermal behavior of the actual building with a good agreement (Figure 3). The calibration process comprised two subsequent calibrations. The first calibration was based on monthly energy use over a 1-year period (2014) and showed a Mean bias error (MBE) and a Coefficient of variation of the Root mean square error (CV(RMSE)) equal respectively to MBE = 3.7 % and CV(RMSE) = 11.6 %. According to ASHRAE Guideline 14, a numerical model can be considered calibrated if MBE and CV(RMSE) are lower than 5% and 15% correspondingly, for monthly data. In order to further refine the model and to reduce the uncertainty, a second calibration run was carried out for the hourly indoor air temperature measured in Room 4. In the second run, the best building variant showed MBE = 0.8 % and CV(RMSE) = 4.2 %. ASHRAE Guideline 14 recommends that MBE has to be lower than 10% and CV(RMSE) has to be lower than 30% for hourly data. Therefore, the model is also calibrated in terms of hourly temperatures. For further details on the calibration procedure of the model, please refer to [3].

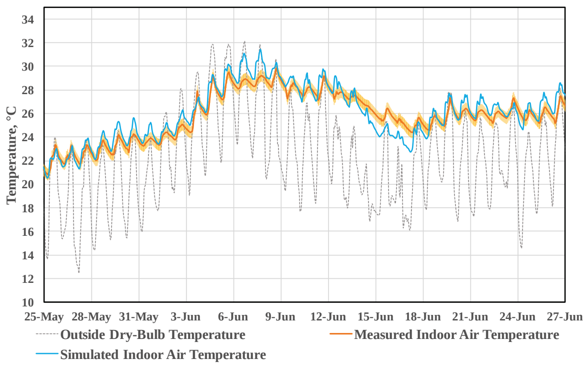

Fig. 3. Comparison of simulated and monitored indoor air temperatures in Room 4. The shaded area is the measurement uncertainty of ±0.5 ºC.

3.1. Post-retrofit model simulated in free-running mode during summer under typical and future weather scenarios

In this first simulation round, the building has been simulated in free-running during the period 15th May to 15th September. The obtained results provide information on the period in which the building might experience thermal discomfort due to overheating. Figure 4 shows the indoor operative temperature contrasted with the exponentially-weighted running mean outdoor temperature only for the occupied hours. Although the Category I is suitable for a day care center according to EN 15251, all three categories proposed by such standard are depicted in Figure 4, to show the effect that the selection of the comfort category can have on the building assessment [18]. According to the simulations, the energy retrofit design concept for the existing day care center performs quite well concerning the overheating issue during the summer period under the current year (2014), TMY and 2020 scenarios. In 2050 and 2080 scenarios the temperature falls outside the upper thresholds of the comfort categories.

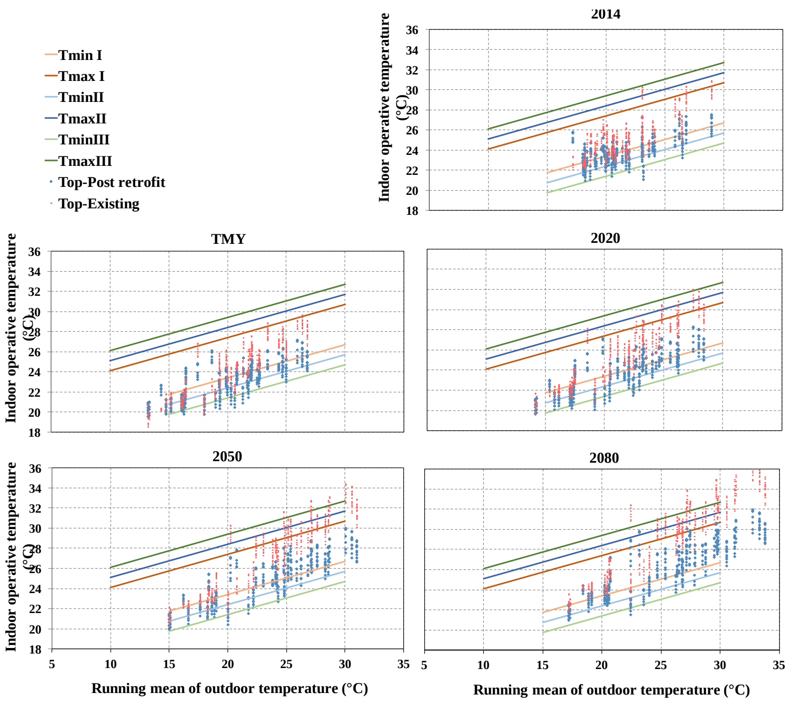

Fig. 4. Comparison of the running mean of the outdoor temperature and the indoor operative temperature in the five weather scenarios. In red the conditions referring to the existing building model and in blue the conditions referring to the retrofitted building model.

According to the 2050 and 2080 projections, it is expected that the running mean of outdoor temperature will fall outside the applicability domain of the adaptive thermal comfort model as proposed by EN 15251. Furthermore, considering both upper and lower overshoots, the total amount of hours out of Category-I range increases drastically in the 2080 scenario, but the percentage of undercooling tends to decrease for future weathers accordingly to the global warming predictions.

Figure 5 presents the difference between the pre- and post-retrofit situation of respectively primary energy usage (ΔPE) and absolute difference of long-term thermal discomfort index (ΔLDI). It can be seen that the gain of energy performance between the post-retrofit and pre-retrofit conditions reduces in the future warmer conditions, whereas the thermal discomfort difference value increases considerably. It means that the post-retrofit building shows not only a much better energy performance but also a much lower occurrence of overheating conditions compared to the existing building, particularly under future climate scenarios.

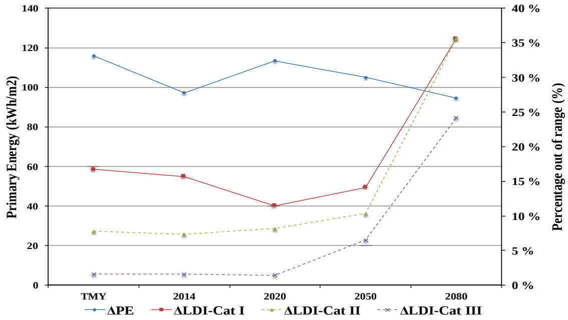

Fig. 5. Difference of primary energy usages (ΔPE) and absolute difference of long-term discomfort index (ΔLDI) of pre- and post-retrofit models

3.2. Post-retrofit model simulated in conditioning mode under typical and future weather scenarios

The second round of simulations considers the post-retrofit building model fully conditioned throughout the year by assuming the installation of an ideal system that guarantees the achievement of the heating and cooling set-point temperatures. Figure 6 shows primary energy disaggregated by energy service for the whole building in the five weather scenarios under study. The primary energy conversion factors are assumed to be symmetric for the electricity delivered from the grid to the building and for the electricity generated by the photovoltaic (PV) system i.e. 2.18 kWh_{PE}/kWh_{el} [19]. Considering the TMY scenario, a PV system with a total capitation area of 120 m^2 and a nominal efficiency of 13% was required to balance (over one year) the whole building primary energy.

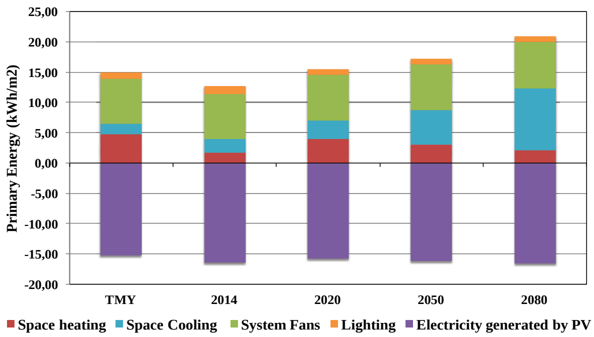

Fig. 6. Primary energy breakdown of the post-retrofit building including electricity generated by the PV system.

Energy simulation indicates that global warming could determine, in Milan, a shift from heating dominance to cooling dominance. Furthermore, although the energy need for heating will decrease, the overall energy usage of the building will increase. Furthermore, in 2050 and 2080, the post-retrofit building concept might not be anymore compliant with the net-zero energy target if the capitation area of the PV system is not increased. Moreover, it is worth to be reminded that the performance decay of the PV system has not been modeled.

4. Conclusions

The energy retrofit project for a day care center targeting the net zero primary energy balance and high indoor environment quality has been developed on the base of a TMY weather file. Such weather scenario synthesizes climate in the recent past, 1951-1970. Energy simulation of the pre- and post- retrofit building models were carried out under five weather scenarios: TMY, current (2014), and three future weather scenarios (2020, 2050 and 2080) projected according to the methodology proposed by [13]. The objective of the analysis was to investigate whether the chosen energy concepts that were selected on the base of typical/past climate conditions would be resilient to future expected climate change. The study showed that the retrofitting concept of the building including hybrid ventilation, automated solar shading, lighting controls, renewable energy generation systems and improvement of the building envelope thermal resistance may result quite robust in the mid-term also in free-running during summertime. However, in the long-term, to face climate change effects, the installation of an active cooling system might be necessary. Regarding the assessment of the long-term thermal discomfort condition in a building, our analysis suggests that care should be taken in using symmetric indexes, since a design strategy targeting to reducing overcooling occurrences in the present weather might make the building less resilient to overheating in future climate conditions.

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