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Occupant behaviour lifestyles and effects on building energy use: Investigation on high and low performing building features

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Abstract

Occupant behaviour is known to be one of the key sources of uncertainty in the prediction of building energy use. Extended literature reviews linked the large performance gaps between residential buildings with same properties and similar climate conditions to the way occupants interact with the building envelope and systems. Furthermore, in the last decades, more stringent energy codes have led to energy efficient design strategies with the aim of reaching the nearly-zero energy target. The success of these strategies is now heavily dependent on how the occupants interact with the building, or rather, on the energy-related lifestyles they assume. In line with this, the present study employs building simulations to demonstrate the potential impact of different occupant behaviour lifestyles on the energy use of a Mediterranean (i) residential nearly-zero energy building (nZEB) under-construction and a (ii) Reference Building (RB) whose envelope-driven loads dominate the consumption profile.

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Keywords: Occupant behaviour; behavioural lifestyles; dynamic energy simulation; building energy use; nearly-zero energy building

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1. Introduction

Energy-related occupant behaviour in buildings is a key aspect for building design optimization, energy diagnosis, performance evaluation, and building energy simulation due to its significant impact on real energy use and indoor environmental quality in buildings [1]. Human actions affect the real building energy use directly and indirectly by

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regulating the heating and cooling set-point, the ventilation rate, the window blind position, turning on/off or dimming lights, turning on/off equipment, and setting indoor thermal, acoustic, and visual comfort criteria. A variety of internal and external factors drives the human to interact in a certain way with the building and its systems [2]. Various field studies measured the impact of occupant-driven parameters on energy consumptions in residential buildings means to data gathering setups and monitoring campaigns [3,4]. The outcomes showed large discrepancies in the effect of occupant behaviour among houses in a community and across communities, with corresponding large impacts on energy use. In detail, some studies have shown that the behaviour of the household members may lead to differences in energy consumptions of over 300% [5,6]. Therefore, the consideration of occupant behaviour becomes a crucial aspect and should be addressed accurately as standard practice in low-energy design and post-occupancy behavioural change programs.

Promoting and achieving energy-conscious behaviour among households is indeed a key issue for reducing energy consumptions in the residential sector [7]. Outcomes from domestic behavioural change programs at national level [8] and worldwide [9] showed an energy saving potential around 15 to 18% by raising the awareness of the building occupants in homes.

Furthermore, in the past 20 years, more stringent energy codes and environmental standards have led to energy efficient design strategies in the building sector in order to reach the nearly zero energy target. Indeed, the technological solutions for the building envelope and the efficiency of the building systems were optimized and now the success of these high performing buildings are heavily depend on how the occupants interact with them [10]. In this context, the unpredictable loads generated by the users gain greater influence than in buildings whose envelope-driven loads dominate the consumption profile [11] and stakeholders of energy behavioural change programs might have to focus on different key aspects depending on the energy performance levels of the building.

In line with this, this paper aims to stress the urgent need of more solid occupant behaviour reference models and to show how the impact of human-related factors on the building energy use might change by assuming different levels of building energy performance. In particular, three occupant behaviour lifestyles were assumed: low consumer (LC), standard consumer (SC), and high consumer (HC). These lifestyles were established by considering six different types of occupants' interaction with the building system regarding the (a) regulation of heating and cooling set-points, (b) energy use for equipment, lighting and domestic hot water (DHW), (c) ventilation rates, and (d) regulation of window blinds. This study wants to highlight the behavioural patterns that mostly influence the energy use with regard to the energy performance levels of the building and consequently to identify key variables that should be mainly addressed by decision-makers of behavioural change programs in low and high performing buildings.

2. Methodology

This study deploys EnergyPlus (version 8.4) simulations [12] for describing the effect of the occupant-driven variables on the building energy performance of a (i) residential nearly-zero energy building (nZEB) under-construction and a (ii) "traditional" Reference Building (RB) whose envelope-driven loads dominate the consumption profile. In detail, the characteristics of the RB are established by using the same geometrical model of the nZEB, but considering different performance levels of the building envelope and the HVAC systems.

The weather conditions of Turin are considered, based on the Italian Climatic data collection Gianni De Giorgio (IGDG) Weather for Energy Calculation database of climatic data [13].

2.1. Case study

The case study (Figure 1) represents an Italian significant design experience of a residential 147-m^2 nZEB [14], the so-called CorTau House, in which the architectural quality in the refurbishment of a traditional rural building is combined with high-performing energy solutions [15]. The design is based on bioclimatic principles and the strategies adopted consist of a strongly insulated building envelope characterized by an exterior layer made of high density rock-wool panels (λ =0.037 W/mK; ρ = 150 kg/m^3). Windows are composed by aluminium frame with thermal break with low-e triple-pane glass with argon. With regard to the building primary system, a controlled mechanical ventilation (CMV) system with heat recovery and dehumidifier is combined with radiant floors for space heating and cooling in all rooms. Space heating and cooling is provided by a water-to-water heat pump, which also supplies DHW production.

The CorTau House represents a model of an all-electric building; according to nZEB definitions, a distinctive element of the building is, thus, the possibility to increase the energy independence from fossil energy sources. Electricity needs of the building for space heating and cooling, ventilation, lighting, equipment, and DHW production are covered by a grid-connected photovoltaic (PV) system installed on the roof. Table 1 summarises the main building feature characteristics of the case study as an nZEB (i) and the assumed RB (ii), whose energy performance requirements for the building envelope refer to the Italian directive for Climatic Zone E [16]. The building system of the RB was assumed to be composed by a traditional condensing boiler connected to radiant floors for space heating and a multi-split system for space cooling.

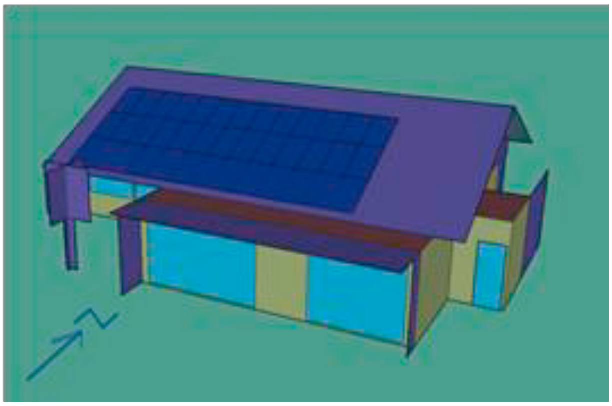

Fig. 1. CorTau House: EnergyPlus model.

Table 1. Description of the building features assumed for the (i) nZEB and (ii) RB scenario.

Building characteristics	Description	(i) nZEB	(ii) RB
Envelope U values (W/m2K)	External wall	0.15	0.27
	Ceiling	0.15	0.24
	Slab	0.19	0.26
	Window	0.96	1.8
HVAC system	Heating	Water heat pump (coefficient of performance = 4.4) + radiant floors	Condensing boiler (nominal efficiency = 0.95) + radiant floors
	Cooling	Water heat pump (energy efficiency ratio = 4.2) + radiant floors	Multi split system
	Ventilation	Controlled mechanical ventilation (CMV) with heat recovery	Natural ventilation
	PV system	7 kW_{peak}	2.62 kW_{peak}

2.2. Occupant Behaviour Lifestyles

Three categories of energy-related occupant behaviour lifestyles were defined and analysed in order to comprehend their effect on the energy performances of two case studies (low and high performing) characterised by different energy performance levels of the building features:

- Low consumer (LC)
- Standard consumer (SC)
- High consumer (HC)

These occupant behaviour lifestyles were assumed to influence the building energy performance through several key variables outlined in Table 2 [17].

In particular, the heating/cooling set-points and the ventilation rates refer to comfort categories described in EN15251 [18]; the high consumer variables refer to comfort category I, while the standard and low consumer variables refer to categories II and III, respectively. The temperature setting is constant for the high consumer level, while in the standard and low consumer profiles a setback of 2°C in the evening and night hours was taken into account (Table 2). In all configurations, the heating system was assumed to be active from October 15th to April 15th, according to Italian regulations for Climatic Zone E (Turin). The cooling system was set to operate from April 30th to September 30th.

Table 2. Key variables for the assumed occupant behaviour lifestyles.

Occupant Behaviour	Low consumer (LC)		Standard consumer (SC)		High consumer (HC)	
Heating operation and set-point (°C)	5am-11pm	18°C	7am-8pm	20°C	0am-12pm	21°C
	11pm-5am	16°C	8pm-7am	18°C		
Cooling operation and set-point (°C)	5am-11pm	27°C	7am-8pm	26°C	0am-12pm	25.5°C
	11pm-5am	28°C	8pm-7am	27°C		
Ventilation rate (ACH)	0.5		0.6		0.7	
Equipment (schedule)	-10% referred to average operational level for equipment		Average operational level for equipment		+10% referred to average operational level for lighting	
Lighting (schedule)	-10% referred to average operational level for lighting + optimization through daylight control (continuous/off dimming)		Average operational level for lighting		+10% referred to average operational level for lighting	
Blinds	Optimization through daylight control (only if glare index is higher than 22)		Only if solar radiation major than 300W/m^2 engraves on fenestration surface, in summer		Always open	
DHW (l/pers.day)	40		60		80	

As regards the occupancy level, the number of people per zone floor area were fixed to 0.04 person/m^2, as defined by Italian Standard UNI 10339 [19], which leads to 5.88 occupants in the building. Lighting and electric equipment power densities were respectively defined equal to 3.88 and 5.89 W/m^2, according to ASHRAE Standard 90 [20]. The standard consumer schedules for lighting and equipment refer to those of residential reference buildings available on the Department of Energy (DOE) dataset [21]. In order to assess the high consumer and low consumer scenarios (Figure 2 and 3), the operational levels of these standard schedules were, respectively, increased (HC) or reduced (LC) by 10% [11]. Additionally, the low consumer lighting use was optimized through daylight control (continuous/off dimming) means to the definition of illuminance set points throughout the building; in this method, daylighting illuminance levels are calculated by the software and then used to determine how much the electric lighting can be reduced. In particular, an illuminance level of 500 lux was guaranteed for the reference point in the studio and 300 lux for the other reference points in all the other rooms of the building.

Window blinds were considered always open for the high consumer lifestyle. The standard user was assumed to close the blinds in summer only if a solar radiation major than 300 W/m^2 would engrave on the fenestration surface [22], while the low consumer blinds control was optimized through daylight control and activated if the glare index resulted higher than 22. The use of DHW was set to 60 l/pers day for the standard consumer and to 40 and 80 l/pers day respectively for the low and the high consumption profiles [23].

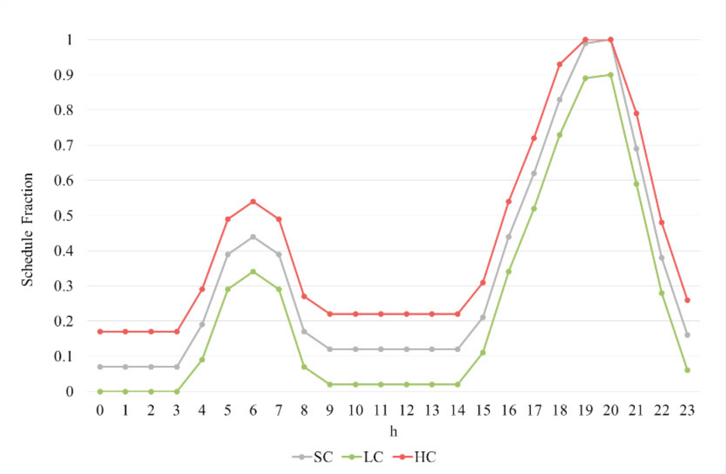

Fig. 2. Schedule variation for LC and HC scenarios: Lighting.

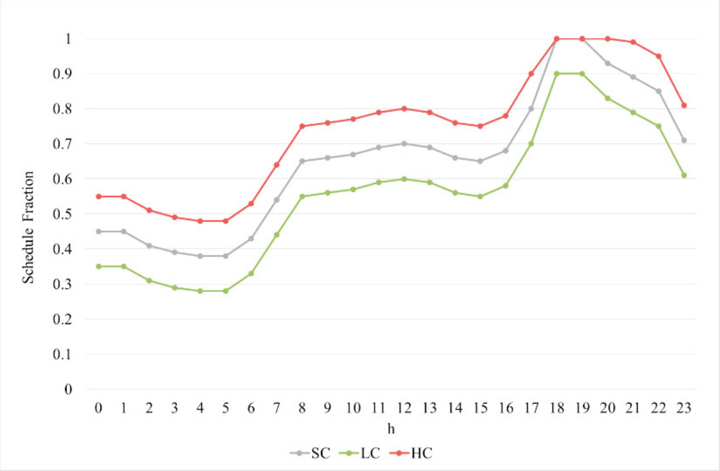

Fig. 3. Schedule variation for LC an HC scenarios: Equipment.

3. Results

The simulation results show the annual primary energy consumption (conversion factor from electricity to primary energy = 2.18) of the analysed scenarios divided by end uses (space heating and cooling, lighting, equipment, pumps and fans, DHW production). In both cases, (i) nZEB and (ii) RB, the outcomes highlight significant differences in terms of building energy performance related to the different occupant behaviour lifestyles (Figure 4). If the total energy consumptions are considered (without taking into account the energy production by the PV system), the LC scenario leads to a variation of -23% and -24% in the nZEB and RB scenario, respectively. On the other hand, the HC scenario, instead, leads to an increase in terms of building energy use of +20% and +26%. Moreover, the outcomes show that in all the nZEB scenarios the most relevant incidence on the total energy consumptions is related to equipment (50-58%) and lighting use (13-20%) rather than to the energy uses for space heating (6-8%), space cooling (4%), DHW production (8-10%), fans (9-10%) and pumps (0.3-0.5%). In the RB scenario, instead, the incidence of the energy use for space heating gains much more importance (23-39%). In detail, this aspect is further highlighted in Figure 5 showing a large gap between primary energy consumptions for space heating and cooling in the low and high performing scenarios and higher variations due to different occupant behaviour lifestyles in the RB scenario.

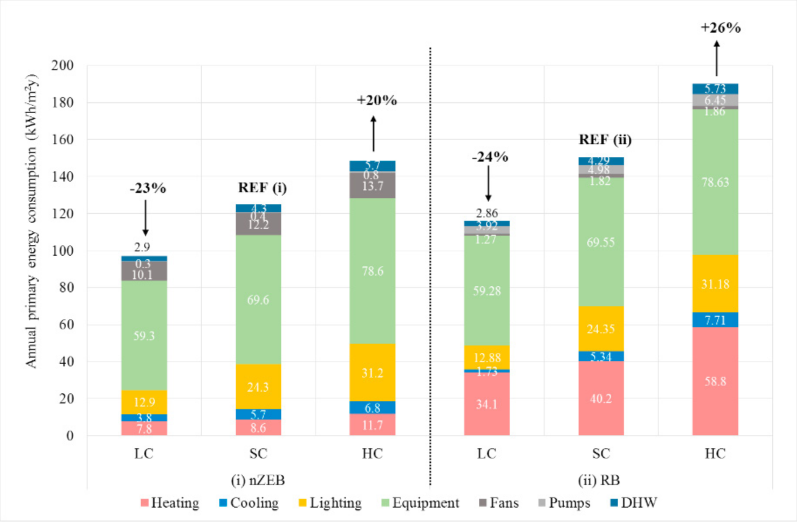

Fig. 4. Annual primary energy consumption of the analysed scenarios.

Furthermore, Figure 6 highlights the amount of energy consumptions covered by the energy production (in terms of primary energy) by the PV system (dotted blue line) for the nZEB and the RB scenario. This graph depicts that in the nZEB scenario a large amount of the total energy consumption is covered by energy production on-site by the 7kWp PV system (PV_{cov}= 65-100%). Nevertheless, these outcomes also reveal that the entire amount of energy consumptions are only covered in the LC scenario. Indeed, if the behaviour of the building occupants is energy wasting, it might not be possible to reach the nZE target, although if the building itself is considered high performing. In the RB scenario, instead, the PV system is able to cover only from 22 up to 36% of the total energy consumptions.

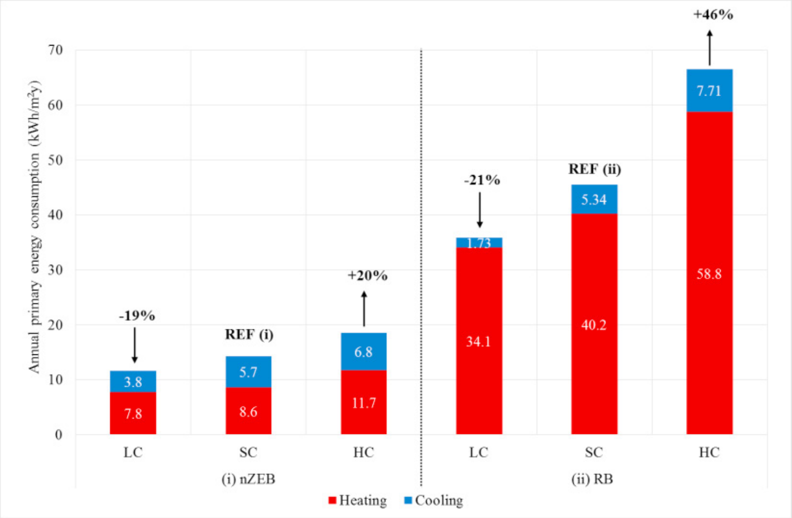

Fig. 5. Annual primary energy consumptions for space heating and cooling.

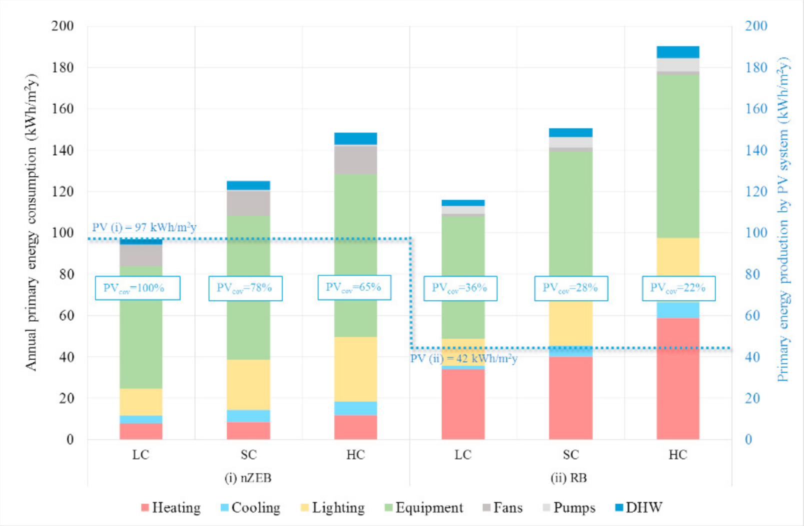

Fig. 6. Coverage of the annual primary energy consumptions by the PV systems.

The impact of the single variables on the total energy consumptions (Figure 7) are presented as percentage changes of the annual primary energy consumption of the low consumer and high consumer lifestyles compared to the standard profile for the single energy-related behaviour patterns indicated by a vertical black (dotted) line. This analysis takes into account the coverage of energy consumptions by the PV systems on-site defined for the nZEB and the RB scenario. The outcomes highlight that the most significant impact on the total energy use is given by different key variables in the two scenarios. As regards the nZEB scenario, the highest variation of the building energy use is due to the occupants' interaction and use of the equipment and lighting for both the low consumer and high consumer scenario. In particular, a low consumer might save up to 28 and 24% of the total energy use by operating more consciously the equipment and lighting systems installed in the home. On the other hand, a wasteful user might increase the energy consumptions 25 and 17%, respectively, for the use of equipment and lighting.

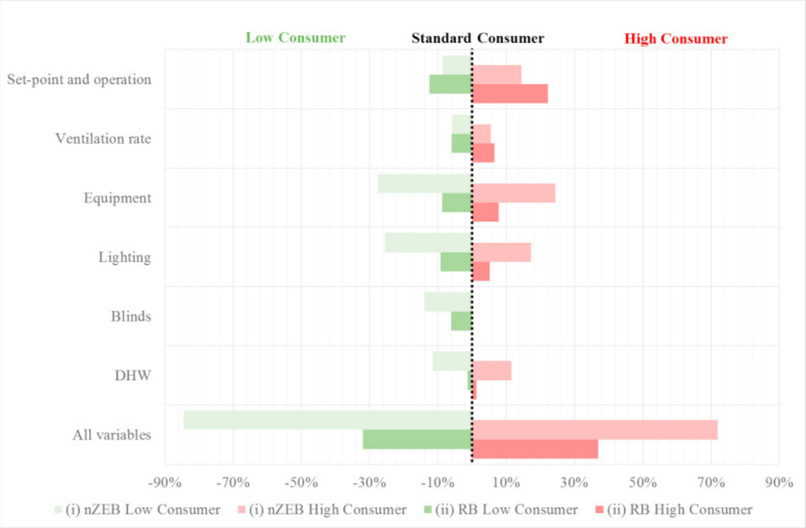

Fig. 7. Impact of the single lifestyle key variables on the building energy use.

The highest variation of the building energy consumptions in the RB scenario, instead, corresponds to the behavioural patterns related to the heating/cooling set point and operation profiles of the systems for the low and high consumer setting. In detail, the results show that the HC scenario related to this pattern might lead to an increase of the building energy use by 22%. The equipment and lighting settings instead have a lower incidence with respect to the nZEB scenario, -6 and -8.8 %, respectively, for the LC scenario and -9 and +5% for the HC profile. Furthermore, Figure 7 clearly highlights that the total energy performance gap due to the implementation of the complete low and high consumer profiles (combination of all the behavioural patterns) has a higher effect on the nZEB scenario (-84% for LC and +72% for HC) rather than on the RB scenario (-32% for LC and +37% for HC). These outcomes stress that once the building design and the technological solutions for the building envelope and system have been optimized, the effect of the occupants' attitude and interaction with the building gains even more importance.

In line with these outcomes, Table 3 provides a ranking of the behavioural patterns that mostly effect the building energy consumption in the (i) nZEB scenario and in the (ii) RB scenario and, therefore, highlights the key variables that should be particularly stressed in energy engagement programs. The authors emphasize that these results are based on one solely case study and on specific assumptions for the different occupant behaviour lifestyle settings.

Table 3. Ranking of the key variables (behavioural patterns) for scenario (i) and (ii).

Rank of key variables	(i) nZEB	(ii) RB
1	Equipment use	Temperature set-points and operation
2	Lighting use	Equipment use
3	Temperature set-points and operation	Lighting use
4	DHW use	Ventilation rate
5	Adjustment of window blinds	Adjustment of window blinds
6	Ventilation rate	DHW use

4. Conclusions

The main goal of this work was to exploit the effect of assumed occupant behaviour lifestyles on energy performances of an (i) nZEB and a (ii) RB scenario, which are characterized by different performance levels related to the building features (envelope and building systems). In this research, three different levels of occupant behaviour lifestyles (high, standard, and low consumer) were evaluated by considering six types of interactions between inhabitants and the building envelope/systems (regulation of the heating and cooling set-points; energy use for equipment, lighting and DHW, ventilation rates, adjustment of window blinds).

The outcomes show that the assumed occupant behaviour lifestyles significantly influence the building energy use of the reference scenarios (SC). Therefore, this study denounces the compelling necessity of more solid reference models related to human behavioural issues in different building typologies, especially in nZEBs. Indeed, this paper shows that, according to different performance levels of the building features, different behavioural patterns of the building occupants result as key variables in the variation of the building energy use. This means that decision-makers of energy engagement campaigns in low and high performing building might have to give priority to different key variables while raising user awareness, even though, certainly, all the mentioned variables should be carefully addressed in both low and high energy performing scenarios. In particular, as regards the (i) nZEB scenario, the most influencing occupant-driven variables on final energy consumptions are related to the equipment use in first place (from –28% up to +25%), and second, to the lighting use (from –26% up to +18%). Indeed, the unpredictable loads related to these variables gain greater influence than in buildings whose envelope-driven loads dominate the consumptions profile. Indeed, in the latter, or rather the scenario related to (ii) RB show that the most influencing key variable on energy consumption is given by the variation of the behavioural patterns related to the space heating/cooling set-points.

Furthermore, the results of this study confirm that the total energy performance gap due to the implementation of the complete low and high consumer profiles (combination of all the behavioural patterns) has a higher effect on the nZEB scenario rather than on the RB scenario. Indeed, since in the high performing version of the building (nZEB) the performance of envelope and systems are optimized, the unpredictable loads generated by the occupants gain greater influence with respect to low performance building scenario (RB). Understanding and evaluating the potential effect of both technology-based and occupant behaviour-based strategies on building energy performance becomes therefore a key aspect for reaching the nZE target and reduce spread in energy consumptions.

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