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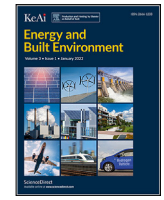

nZEB: bridging the gap between design forecast and actual performance data

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ABSTRACT

The nZEB objectives have raised the standard of building performance and changed the way in which buildings are designed and used. Although energy dynamic simulation tools are potentially the most suitable way for accurately evaluating and forecasting the thermal performance, they need several data inputs and user's knowledge that can affect the reliability of the results. It is precisely these two aspects that proved to be particularly critical, since the reliability of the ICT calculation tools has been widely proven in recent time.

However, in order to foster credibility in sustainable architecture, bridging the gap between predicted and measured performance is pivotal to boost the building market towards energy efficiency and provide reliable data to inhabitant, investors and policy maker.

The present research aims to identify and quantify the main factors that affect the energy performance gap through a detailed energy analysis carried out on a case study, which can be considered one of the first nearly zero energy residential complex built in Italy. Based on the analysis, the study identifies the main causes of the deviation between the calculated and measured data and demonstrates how it is possible to achieve very reliable models and, therefore, real buildings.

Although the procedure traces a classic model calibration scheme, actually it consists of a verification of possible downstream errors mainly due to human factors, such as the provision of incorrect technical data or inappropriate operation.

Some observations on the technical, management and regulatory gaps that may generate these errors are reported at the end of the study, together with practical suggestions that can provide effective solutions.

1. Introduction

As well known, efficient buildings are an essential component of sustainability and energy transition strategies and represent a techno-economic and socio-economic challenge. The decarbonisation of building stock is one of the most important goals of policies, considering the energy impact of buildings at the global scale [1].

During the coming years, building sector will be galvanized by mandatory codes and standards that aim to reach nearly zero energy buildings (nZEBs)[1] [2–5]. The European Performance of Buildings Directive (EPBD) requires all new buildings to be nearly zero energy buildings by 2020, including existing buildings through major renovations [6]. Despite the recent global health emergency, caused by the spread of COVID-19 [7] and the related socio-economic issues are likely to slow down this process, the road ahead is already marked.

A recent study [8] shows that so far, the penetration of nZEB in new and renovated buildings varies a lot across EU countries. This study also demonstrates that nearly-zero energy standards are preferably applied to newly constructed buildings, i.e. on EU28 level 27% times more new buildings are constructed in nearly-zero energy buildings standard than renovated buildings. However, it is not still possible to properly compare the ambition level of national nZEB definitions due to different indicators, calculation methodologies, applied primary energy factors, system boundaries, etc. [9,10].

Although building dynamic simulation tools are commonly recognized as a suitable way for accurately assessing the performance of buildings and thus to develop the nZEB policies, in general, more or less large discrepancy between simulated and real features can still be observed both for new or existing buildings [11–15]. Moreover, the actual gap observed in many cases seems too wide to be acceptable; in fact, measured energy use can be as much as 2.5 times the predicted energy use [12,13].

Consequently, the design phase methodologies can negatively impact the reliability of building expected performance, considering the

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[1] nZEB definition varies across different EU countries based on different indicators; one of the most common indicator is related to Primary Energy Requirement [8]

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Nomenclature

nZEB	nearly Zero Energy Building
GIGO	Garbage In - Garbage Out
EPBD	Energy Performance of Buildings Directive
BEMS	Building Energy Management System
HVAC	Heating, Ventilation, Air-Conditioning
PV	Photovoltaics
DC/AC	Direct Current/Alternating Current
DHW	Domestic Hot Water
COP	Coefficient of Performance
AHU	Air Handling Unit
H/C	Heating/Cooling
MBE	Mean Bias Error
cv(RMSE)	Coefficient of Variation of the Root Mean Square Error
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
Aux	Auxiliaries
Heating Demand	Annual energy demand for space heating derived from energy balance of building envelope (kWh/m^2)
Cooling Demand	Annual energy demand for space cooling derived from energy balance of building envelope (kWh/m^2)
Primary Energy Consumption	Final energy Consumption of the building, considering the contribution of technical systems, derived from primary energy content of different energy carriers (kWh/m^2)

essential problem of matching simulated and measured performance [16,17].

In the light of the above facts, it can be certainly said that bridging the gap between predicted and measured performance is crucial to achieve the nZEB goals.

This paper aims to identify and quantify the main factors that affect this mismatch, with particular reference to those that do not concern the correctness of the calculation model. Thus, through a detailed analysis carried out on a highly representative case study (one of the first residential nZEB built in Italy) and its design and running phases, attention has been focused on these misleading factors.

Finally, this work is intended to bring a further added value to current research, given that, generally, residential buildings have been almost entirely overlooked in previous studies because of the complexity of the ways in which they are used and the difficulty of tracing them accurately [12,13].

In detail, Section 2 contains a brief overview of the main uncertainty factors in the energy simulation models, which must be considered as the background of the present research. After that, in Section 3 the case study is described, and the results of a "standard" simulation carried out during the design stage are presented. The methodology applied to identify the performance gap and the obtained results are described respectively in Section 4 and 5. Finally, before the conclusions, the main lesson learnt, and the outcomes of the specific research are highlighted in Section 6.

It is worth pointing out that the main purpose of this study is not the ex post fine tuning of simulation models (which has already been widely investigated), but rather the definition of how they can be used more effectively in the early decision-making and project phases, based on more reliable information and assumptions. Authors would like to remind, in fact, that one must not confuse the scientific interest of increasingly refined and precise simulation procedures with the practical need to rely on tools and information that preventively allow to analyse and design in detail real high-performance buildings.

2. Uncertainty in energy simulation model: a brief literature review

Literature on the energy performance gap suggests various causes for the mismatch between prediction and measurements. These causes can be grouped in three main categories related to design, construction and operational phases.

The first cause of a performance gap within the design stage is related to the energy modelling and simulation of the building [18]. In fact, although building dynamic simulation tools are potentially most suitable way for accurately assessing the thermal performance of buildings, they are much time-intensive and require considerable experience and skill. Moreover, the correct use of tools alone is not sufficient; the user/analyst/modeller of tools also needs to have the proper knowledge and sensibility to apply them in the right manner [19].

Furthermore, the simulation tools are generally affected by several limitations [20,21]. Examples include the use of standard thermophysical data measured on a dry sample to model a wet surface (e.g. the brickwork of an exterior facade of a building exposed to frequent dry/wet cycles due to rain) or the use of constant air leakages value, even if they vary with air pressure gradient [22]. Moreover, some other works point out that generally simulations do not take into account performance deterioration of materials [23] and technical component [24,25], which again will lead to a mismatch between prediction and measurement.

However, even with a correct model applied by a well-trained analyst, all predictions remain subject to fundamental uncertainties, related to the actual weather conditions, occupancy profile, inhabitants' solar control effectiveness and internal heat gain distribution [13,26,27]. A further key problem, in fact, is that designers often cannot fully predict the precise future use (functions) of the buildings [13,28–31].

A different group of causes for the gap arises from the actual construction process undertaken and the handover to the client. Even if the design itself is energy efficient, lack of attention to buildability, simplicity, sequencing of the construction process, or of appropriate detail might be a built-in source for later underperformance [32].

Many authors point out that the quality of building is often not in accordance with the specification, with insufficient attention to both insulation and airtightness features [13,28,31]. Often, details are left unspecified by designers or the contractor are not able to build and solve them properly, for instance with potential risks for the creation of thermal bridges [33]. Problems where actual construction does not meet with specification might be hard to spot; some problems will be evident from measurement but in many cases also visual inspections are needed to establish the actual issues [24]. Further discrepancy between design and actual building is introduced by the building services [26,33]. Nowadays, buildings are often equipped with advanced HVAC system even beyond the state of art [34] which generally require several complex control logic and hardware able to properly manage their operations. Such systems, however introduce further uncertainties, due to their complexity and limited capability to keep pace with changes of the boundary conditions [35].

Once a building is commissioned and in use, the operational side can also contribute significantly to the performance gap. Occupant behaviour is often different from the assumptions made in the design stage; this is repeatedly mentioned as the main reason for the deviation [13,28,29,36,37]. In the last decade, many researchers have dedicated their efforts to better understand occupant behaviour and appliance use models [36,38,39]. More specifically, assumptions regarding occupant behaviour often lead to a mismatch between input for any calculations/simulations and actual values for internal gain [36,40] and plug loads [26]. Technological developments can also cause a mismatch; for instance, parasitic or IT-related loads are often neglected or underestimated [30]. Furthermore, the actual operation of the building is typically different from the idealized assumptions made in the design stage, both in terms of actual control settings (such as thermostat settings, operation hours, BEMS settings) as well as facility management [13,26,28,31,41,42].

The state of art about the performance gap also suggests underlying factors. These includes the overall industry culture of construction sector, where traditional processes are hard to change in favour of innovative techniques and where there are often issues with quality, integrity, and responsibility [12]. Poor client knowledge and labour skills are also contributing to this situation [32]; regulatory pressure to make buildings more energy efficient might in fact contribute to over-optimistic predictions, as a consequence of a "wishful design", and hence contribute to the performance gap [43].

In conclusion, many causes, which generally occur simultaneously, contribute to the performance gap of buildings. In this sense, the magnitude of the performance gap is also dependent on time, contextual factors such as climate and building use, as well as on the temporal resolution at which the performance gap is assessed, as demonstrated by several research studies [12,44]. According to a recent literature review, the ratio between the calculated and the measured performance vary, on average, between 0.25 and 2.5 [44]. Very recently, a research paper summarized several studies to understand or proposed methods to overcome the performance gap [45]. Thus, in order to summarize the main causes that affect the performance gap have been outlined as follows:

- wrong use of the simulation tools by the user;
- application of statistical weather data rather than actual one;
- uncertainties related to the user behaviour, heat gain distribution and airtightness;
- neglection of the deterioration of materials and appliances;
- HVAC systems and construction materials in real operating conditions might not perform as specified by the manufacturers in nominal conditions.

3. TerraCielo case-study

In order to identify and quantify the main performance gap factors, a detailed energy analysis of a nZEB case study, designed, built and monitored in recent years with the support of Politecnico di Milano, is presented. It should be noted that it is a housing estate, so this study can have a twofold value: on the one hand, to deepen the issues related to the performance gap, and on the other to strengthen the related studies on residential buildings, which, as has been introduced, are currently scarce.

The building process of the complex began in 2010, hence one of the main design references was represented by the Directive 2010/31/EU (EPBD recast), according to which: "*nearly zero-energy building means a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby*" [46].

3.1. Building description

The residential estate TerraCielo is located in the eastern metropolitan area of Milan (latitude 45°28′N, longitude 9°21′E and altitude 112 meters a.s.l.) [47]. It consists in 59 living units divided in three buildings of approximately 14,800 m^2 (7,500 m^2 above ground and 7,300 m^2 underground) arranged around a courtyard, as shown in Fig. 1.

The complex has been designed in order to reduce as much as possible the final energy consumption by addressing proper sustainable strategies, according to the following main priorities [48]:

- maximize the envelope energy efficiency, through passive and climate-interactive solutions;
- adopt high-efficiency technical systems and advanced control/management strategies;
- maximize on-site renewable energy production and self-consumption.

More in detail, the building envelope has been carefully designed in order to achieve low transmittance values (thermal transmittances of vertical walls, as well as the basement floor are on average between 0.17 and 0.19 W/m^2K, while the roof transmittance is around 0.2 W/m^2K) and a high global thermal capacity able to assure a good thermal inertia value [49,50], with time-lag higher than 14 hours. In addition, the morphological configuration of the entire complex has been conceived to maximize energy gain in winter and to reduce summer overheating, thanks to appropriate orientation, shape and shading devices [51].

Regarding the HVAC system, the emission sub-system consists in radiant floor used both in heating and cooling mode.

In summer, relative humidity and condensation risk are controlled by means of temperature/RH sensors installed in every housing unit and different Air Handling Units (AHUs); each AHU serves dwellings connected to each staircase of the building.

Heating and cooling are provided to all dwellings by a centralized water-to-water heat pump connected to a horizontal geothermal heat exchanger, integrated into the foundation slab.

An insulated water distribution loop, placed in the basement floor of the complex, connects the central heat pump and all dwelling. This water loop is constituted by steel pipes with an average diameter of 100 mm and a design insulation characterized by a thickness of 40 mm and a thermal conductivity of 0.04 W/mK.

A photovoltaic system (86 kW_p) placed on the buildings' roofs, supplies electricity to the centralized heat pump and subordinately to the complex common loads (e.g. garden lighting, intercoms, etc.). The PV generator is composed of multi-crystalline modules installed with 3 different tilt angles (10°, 20° and 25°), depending on the features of the different surfaces in which they are integrated, and the same azimuth angle (0°C = towards South). The DC/AC power conversion is done through inverters with a nominal efficiency of 98%.

Given its innovative and experimental character, since its design phase it was decided to equip the complex with a series of sensors and specific meters, in order to monitor its performance during the operational phase. For this, regarding the heat pump water temperatures on load and geothermal sides are monitored with 4 PT100 probes. Moreover, individual heat meters are installed in each dwelling to monitor the actual thermal energy used for heating/cooling purposes. Finally, 2 electric meters, in addition to the grid meter, measure the heat pump consumption and the PV production, respectively (Fig. 2).

3.2. Performance data

As already mentioned, TerraCielo represents an advanced project, which has been carefully developed both in the design and operational phases, in order to reach high performance levels and draw also technical and scientific learning. For this reason, its energy features and performance have been studied in detail, before construction by means of detailed computer simulations, after commissioning by means of monitoring, in-situ surveys and cross-referenced data analysis.

As stated above, the main focus of this study is on the deviation between forecasts and on-field collected data, the identification of the main mismatch causes and the correction of possible errors that may affect the design of high-performance buildings such as the one in the present study.

Fig. 1. Overview of TerraCielo complex.

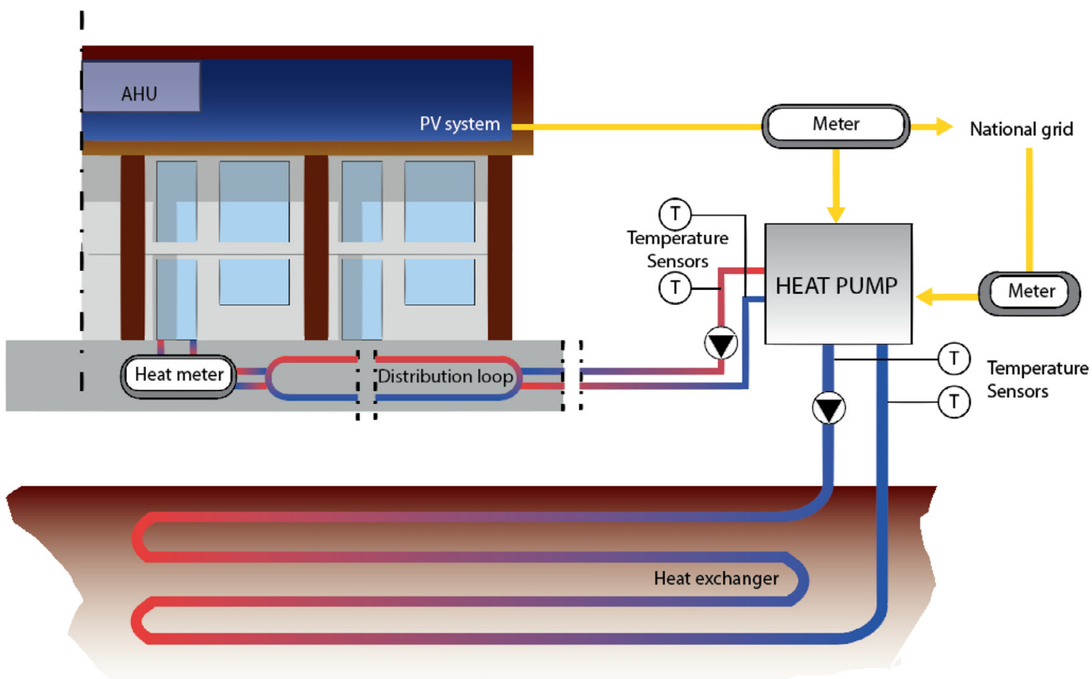

Fig. 2. General scheme of the HVAC system and main monitoring equipment.

As a starting point for the entire study carried out, this section presents the assumptions made during the preliminary project evaluation, along with the main deviations that emerged from the first phase of post-occupancy analysis.

3.2.1. Standard design simulation

Within the design phase of the buildings, an energy performance simulation has been run, in order to ensure the compliance with regulatory requirements and to guide the development of the project, to achieve better performance compare to the imposed baseline. The simulations were carried out with the support of the EnergyPlus software, which represents the main reference for the international building energy analysis community [52–54]. Being based on standard tools, regulatory parameters and references, this is referred to as the *standard simulation*.

In detail, the input parameters of such simulation were set according to national and regional building energy regulation [55–57] and manufacturers specifications concerning building and technical systems. The *Conduction Transfer Function,* able to take into account the thermal inertia of the materials in EnergyPlus has been adopted as algorithm. Technologies and related data have been selected in order to reach values that comply with or improve regulatory limits in force at the time of construction (Tables 1–4 and Fig. 3).

Regarding the climate context, the typical meteorological year suggested by the national building code for the reference location (Milan) [58] was adopted.

For the simulation, each apartment has been divided into 2 thermal zones able to reflect the distribution of the flats in living and sleeping area. Further zones, such as staircase blocks, garage areas, underground cellars and small hollow spaces in the attic floor have been also modelled as no heated/cooled spaces. It should be noted that, since the interior partition of the walls are mainly built with plasterboard, the thermal inertia of such surfaces has not been considered in the simulations.

In Fig. 4 the virtual model of the residential complex is shown, where also the neighbouring buildings and overhangs are represented (in purple). Such surfaces have been considered as shadings areas with no thermal proprieties, since just the projection of their shading on the target buildings have been considered in the dynamic simulation.

According to the above boundary conditions, a simplified external routine was applied to the model, in order to calculate with hourly steps

Table 1
Design characteristics of the building envelope.

	Unit	Building regulation	Adopted value
Exterior wall transmittance	[W/m^{2}K]	0.34	0.19
Roof transmittance	[W/m^{2}K]	0.30	0.17
Ground transmittance	[W/m^{2}K]	0.33	0.20
Transparent surfaces transmittance	[W/m^{2}K]	2.20	1.35
Solar gain coefficients of transparent surfaces with perpendicular radiation	[-]	-	0.30
Opaque surfaces absorbance external walls	[-]	-	0.30
Opaque surfaces absorbance external roof	[-]	-	0.60

Table 2
HVAC design conditions.

Efficiency of the generation subsystem	Based of manufacturer's specifications (Fig. 4)
Efficiency distribution subsystem	84 % (average value based on design specification)
Efficiency emission subsystem	98 %
Efficiency control subsystem	97 %
Auxiliaries working hours	13 hr/day
DHW flow rate	60 l/day/person
DHW Water supply	50°C
Main water temperature	15°C
Air flow rate of AHUs	6 m^3/m^2 of heated/cooled surface

Table 3
Design PV features.

PV peak power	86 kW$_p$
PV technology	Multi-crystalline
Temperature coefficient	−0.43 %/°C
Inverter efficiency	98%

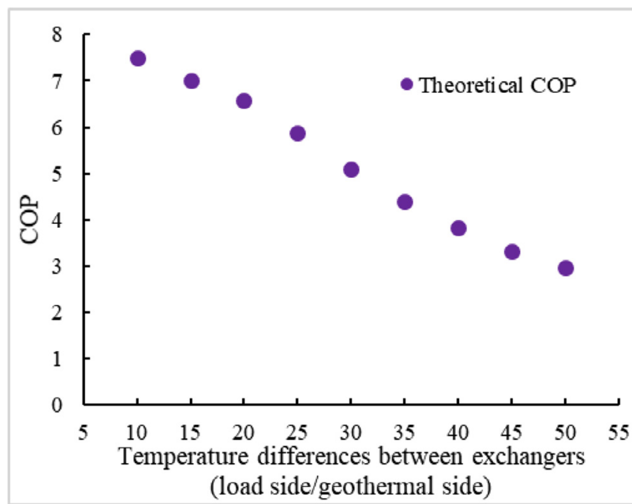

Fig. 3. Theoretical COP (Coefficient of Performance) of the heat pump. The data is based on technical data sheet provided by the manufacturer.

the primary energy consumption starting from thermal energy demand, taking into account the dynamic performance of mechanical systems, such as variable performance curves depending on the specific applied loads. At this stage, in fact, it would be unnecessarily onerous and redundant to develop a complex E+ model's section, which would require the development of an HVAC final design even before having identified the final choices.

It must be noted that the final consumption includes also the amount related to air handling and auxiliaries (water circulation pumps of the distribution loop and geothermal heat exchanger).

Similarly, the PV production has been assessed based on a detailed simulation carried out with PVsyst [59], one of the most reliable software adopted in such field [60].

It should be noticed that electricity is the only energy carrier present in the complex, covering all loads for space heating, cooling and DHW.

In this analysis, however, household electricity consumption (e.g. TV, oven, etc.) has not been taken into account, in agreement with the current national regulation on building energy rating and performance calculations. In fact, for residential buildings, the evaluation of energy demand for energy rating purposes considers space heating, cooling and DHW, excluding household appliances, which are not related to the quality of the design and of the construction of the building, but rather to the personal habits of the inhabitants.

Table 4
Buildings user profile.

		Apartment	Garage and staircase	Hollow space
Internal gain	W/m^2	4	2	0
	h/day	24	24	24
	Day/year	365	365	365
Infiltration	V/h	0.3	0.5	0.1
	h/day	24	24	24
	Day/year	365	365	365
Heating System	°C	20	-	-
	h/day	10	-	-
	Day/year	183	-	-
Cooling system	°C	26	-	-
	h/day	10	-	-
	Day/year	182	-	-

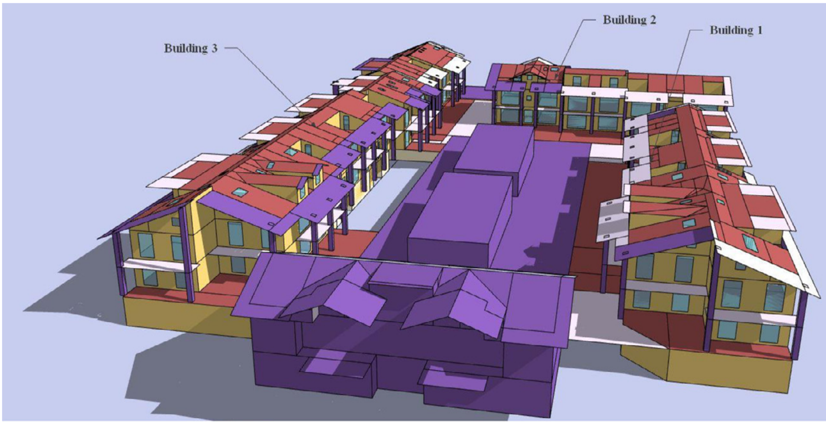

Fig. 4. View of the energy model.

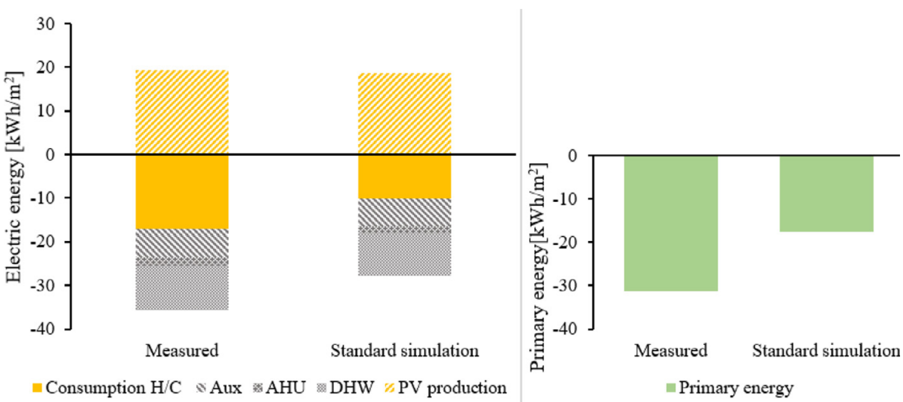

Fig. 5. Comparison between measurements and results of the standard simulation.

Table 5
Results of the standard energy simulation.

Electric consumption	27.7 kWh_{el}/m^2 y
PV production	18.7 $kWh_{el}/$ m^2 y
Net non-renewable primary energy consumption	17.7 kWh/m^2 y

Finally, the balance in terms of net non-renewable primary energy consumption was calculated, considering a conversion factor equal to 1.95 [61].

As confirmed by the results summarized in Table 5, TerraCielo complex was designed in order to reach a very low overall energy consumption with a share of 67% by photovoltaic energy.

3.2.2. Post-occupancy preliminary evaluation

After one year of operation (October 2014 - September 2015), the actual energy consumption and PV production of the complex have been assessed through measurements carried out by means of the equipment described in Section 3.1. Consequently, also the reliability of the simulation model has been checked. As reported in Fig. 5, the actual building energy consumption resulted about 1.7 times higher than the prediction. It should be outlined that such gap is mainly due to the electric consumption for heating and cooling since the relative deviation related to the PV production and other uses (DHW, AHU and auxiliaries) are respectively equal to 4% and 6%.

The various energy items were expressed with positive values if gains (photovoltaic self-production) and negative if loads (needs and consumption).

As can be noted, albeit in line with what stated in Section 2, the deviation recorded seems not to be acceptable and certainly requires a closer look at the methodologies adopted and the causes, or even errors that have affected them.

Based on these observations and collected data, in next section a step-by-step methodology for the analysis and calibration of design and simulations procedures is presented.

4. Methodology

Starting from the deviation detected, the entire design, analysis, performance simulation and implementation phase were carefully reexamined. First of all, some important features have been verified and established:

- the software tool used is commonly recognized as reliable;
- simulation procedure was correctly followed;
- all standard requirements were satisfied.

Finally, as a precautionary measure, the simulation model developed in the design stage of the building and its results were carefully checked to ensure the absence of errors.

Excluding calculation errors, the possible causes of deviation and errors were then analysed, based mainly on the review carried out previously. Reasonably, these are the factors pertaining to the design assumptions, rooted in the construction stage and related to the operational phase, as summarized below:

- weather data parameters;
- thermal features and performance of envelope;
- building operations in terms of ventilation, occupancy, set point;
- technical system's features and performance;

In detail, the proposed methodology aims to identify and rectify uncertainties and misleading effects related to the above possible causes. To this end, a step-by-step check and validation process has been developed according to a two-phase approach, as described below.

Table 6
ASHRAE Guidelines 14 threshold limits of metrics for model calibration.

Metric	Monthly	Hourly
MBE %	± 5	± 10
cv(RMSE) %	15	30

Phase A aims to reduce the uncertainty focusing only on factors that influence the thermal energy demand. It includes the adoption of a weather file based on actual monitored data (step 1); after that, geometrical/thermal properties of the building envelope (i.e. thermal transmittance, time lag, etc.) have been checked and updated according to on-site measurements (step 2); then, the occupancy/load profiles have been set according to a post-occupancy survey (step 3) and the real set-point adopted from the user has been replaced (step 4).

In order to ease the comparison among results during the whole calibration process, besides thermal demand, electric/primary energy data were also calculated in each step. It should be noted that in this first phase, no changes in HVAC standard parameters were made.

Phase B is based on the validated energy demand obtained in Phase A, by adding calibration performances of the HVAC plant. More in detail, starting from the energy demand evaluated in step 4, the actual values based on experimental measurements of the COP of the heat pump and the insulation level of the distribution loop were updated in the model (step 5). Subsequently, the actual weather file used in the step 1 was also adopted as an input for the simulation of the PV production, and the updated output was used for the calculation of the final calibrated primary net energy demand (step 6).

It must be noted that for the electricity consumption for air handling, DHW preparation and auxiliary equipment of HVAC system, a simplified assessment was used along the fine-tuning process, because the needed electric energy is not strictly related to the specific design features of the building for the following reasons:

- the power consumption of circulation pumps is fixed, since they are switched on/off in specific time intervals of each day, independently from the energy demand of building. Thus, in the standard simulation the design operation interval was selected, while in step 6 the actual operation interval set by the facility manager is used.
- the shares for DHW preparation and air handling are mainly related to users' behaviour (hot water use profile of each dwelling and air flow rate manually adjusted in each room, respectively), the precise measure of which would be too complex and expensive in a post-occupancy assessment. In this case, in the standard simulation the design hypotheses were assumed (see Table 2) while in step 6 the actual electricity consumption for such items was determined as the difference between the whole electricity consumption and the sum of the amount used for heating/cooling and that of circulation pumps. The associated gap was consequently assessed separately from the one that is related to dynamic energy simulation.

Fig. 6 shows a graphical scheme of the procedure.

The main advantage of the proposed methodology is that mismatches related to the building envelope and user behaviour are first assessed separately from those related to technical systems, thus reducing reciprocal interferences of the process.

Regarding the validation process, in order to evaluate and compare properly the simulation results and measured data in operation phase, ASHRAE Guideline 14–2002 [62] was followed in the statistical validation of the model, assuming the MeanBias Error (MBE) and the Coefficient of Variation of the Root MeanSquare Error cv(RMSE), as error indicators.

The threshold metrics considered in ASHRAE Guideline 14, are reported in Table 6.

The above-mentioned errors related to monthly calculation have been adopted since the resolution of the main energy meters installed in the building are set on monthly basis. The reported metrics are evaluated in Phase A on the thermal demand of the building, while in Phase B on the corresponding heating and cooling electricity consumption. Finally, the overall deviation related to the net primary energy is also reported in each step.

5. Detailed update and calibration of the energy model

As explained above, the update/calibration procedure was carried out by comparing the calculated values with those measured in the field, about the various items of energy consumption and self-production, gradually correcting errors and updating the model.

Characteristics and reliability of the measuring instruments used are shown in the following table.

5.1. Phase A: thermal energy demand update

This part of the study was carried out through comparisons between thermal demand for heating and cooling resulting respectively from standard simulation and real data acquired by heat meters installed in each dwelling, thus excluding the influence of HVAC systems.

5.1.1. Step 1: set-up of proper weather data

As already said, the first evaluation was carried out according to the weather file based on national standard [58], which, however, refers to a record period between 1951-1970. Of course, the historical data cannot be considered longer reliable due to the climate change. In such respect a tailored weather file was set up based on the real measurements provided by ARPA Lombardia for Rodano, the site of the complex, corresponding to the years 2014 and 2015, coinciding with on-site measurement period of actual energy demand.

By comparing the two set of data (Fig. 7), it is possible to observe that both the outdoor temperature and the global solar radiation data acquired on-site are higher than the values from national standard. As well known, in fact, due to global warming effect the average outside temperature is constantly increasing from the 1990s. So, warmer summers and milder winters generally result both in higher demand for cooling consumption and in lower use or misuse of heating system.

Based on these considerations, the simulation was run again adopting the tailored weather data file. Obtained results in terms of thermal, electric and primary energy are shown in Fig. 8.

As a first remark, considering the results in terms of net primary energy, it can be noted that the deviation between measured and simulated data grows, since it moves from 43.8% (standard simulation) to 49.7% (step 1).

More in detail, as to be expected from the assessment of the weather data, the heating demand has been reduced in comparison to the previous simulation, while the cooling increased a bit.

As shown in Fig. 8, in this case the actual energy needs (measured data) for heating is 49%, higher than the simulated values, while the demand for cooling is lower of about 34%.

Finally, the MBE and cv(RMSE) were calculated (on thermal demand only) and compared to the calibration thresholds. The obtained results equal to 22.1% and 44.7% respectively, should be considered quite far from considering the simulation results reliable.

5.1.2. Step 2: set-up U-values

Once the correctness of the weather file used was ascertained, the second logical step is to verify the actual thermal characteristics of the envelope, through on-site instrumental measurements.

In this respect it must be noted that the U-value experimental verification only for external walls was considered feasible for the reasons described below.

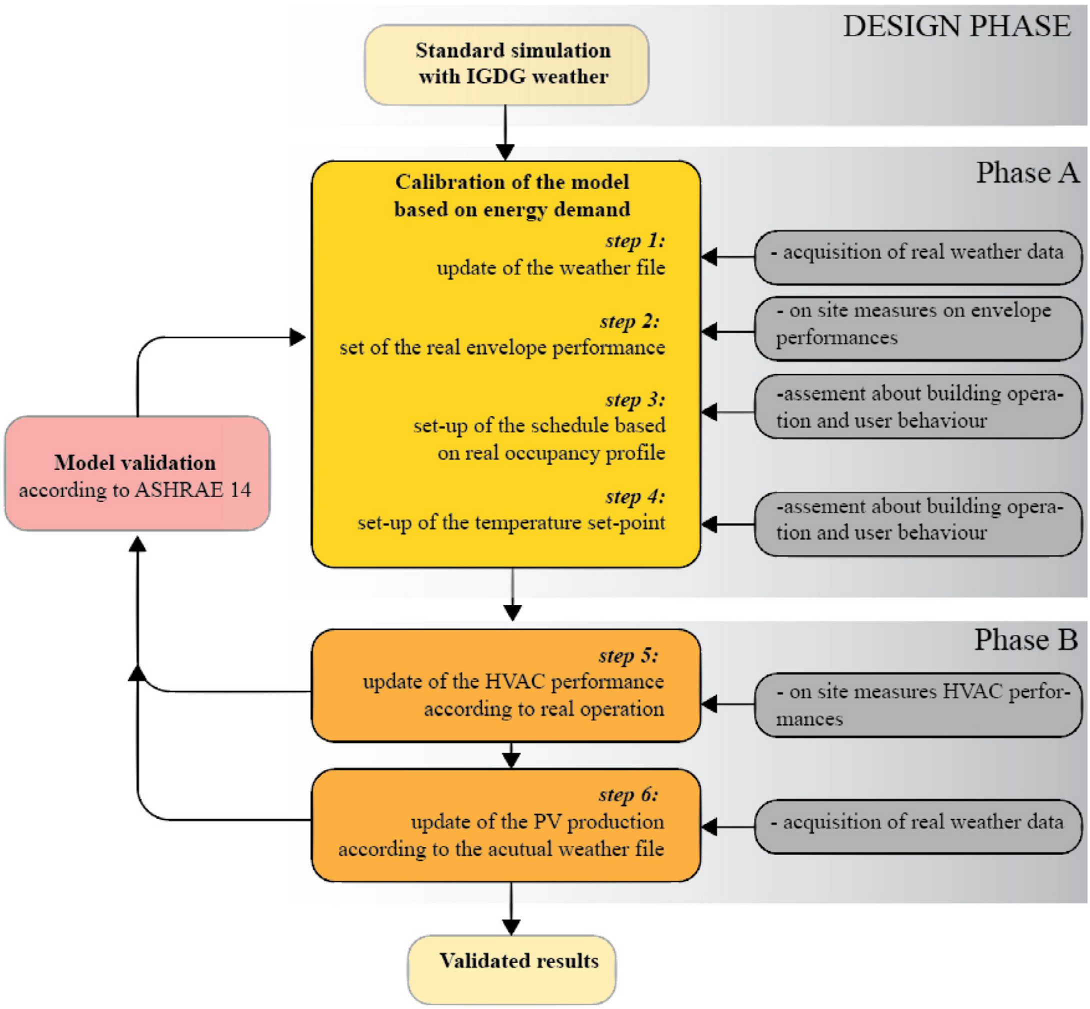

Fig. 6. Overview of the proposed update/validation methodology.

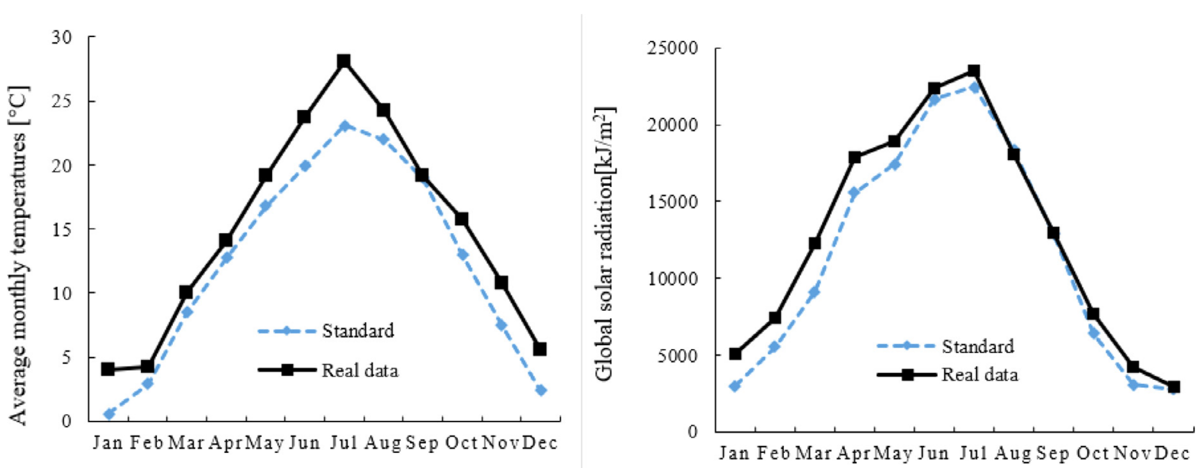

Fig. 7. Comparison between real and standard weather data in terms of temperature (left) and global solar irradiation (right).

- Regarding glazed surfaces, the features of each window are certified by the manufacturer according to a specific national standard [63] and considered reliable. A more detailed verification would require piece-by-piece disassembly and laboratory tests, which would not be compatible with a post-occupancy survey.
- Similarly, rooftop experimental verification would have been very critical. Given the complex type and stratification (wooden structure and substructure, insulation and back-ventilated roof tiles, replaced in many parts by PV modules), it would have been very difficult to make exhaustive on-site measurements. Furthermore, in order to obtain reliable data, invasive analyses would have been necessary, with the risk of compromising the water tightness and closing performance of the roof. Therefore, even since the roof consists in a dry construction system, par-

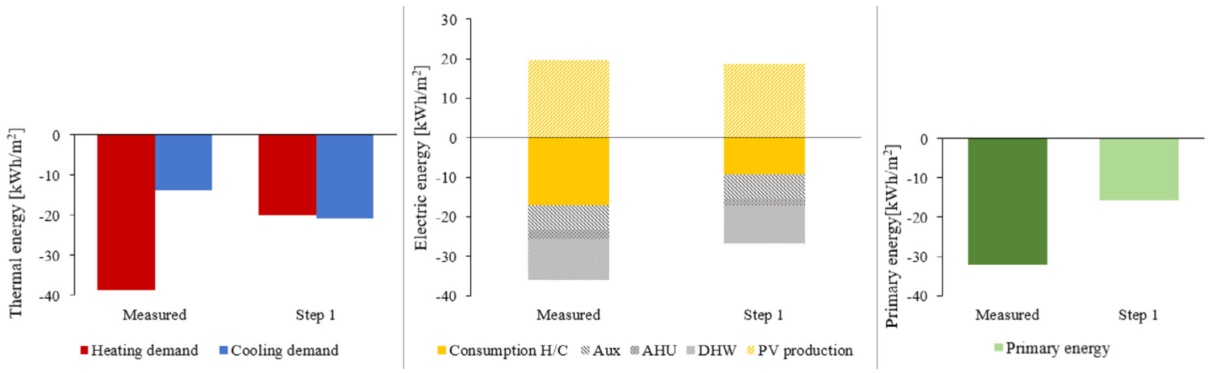

Fig. 8. Comparison between simulated and measured energy demand (Step 1).

Table 7
Measurement instruments and related accuracy.

Instrument	Measured parameters	Accuracy	Position
Heat flow meter	[W/m^2K]	+/- 5%	External walls
PT100	[°C]	+/-0.21°C	Heat pump's water inlet/outlet
Ultrasonic water flow meter	[l/s]	+/- 1%	Heat pump's water outlet
Electric meter	[kWh_{el}]	+/- 1%	Grid connection
Electric meter	[kWh_{el}]	+/- 1%	Heat pump
Electric meter	[kWh_{el}]	+/- 1%	Photovoltaic system
Radiant floor heat meter	[kWh_{th}]	+/- 1%	Hydronic connection to each dwelling

tially pre-assembled off-site, its design U-value was assumed reliable.

- Finally, a precise experimental evaluation of the basement slab's U-value was considered impracticable, since the slab contains the radiant floor and other technical systems (water pipes, cables, etc.) that would strongly invalidate the measure. It should also be noted that ground losses generally account for a minority share of the building's energy balance [64]. Again, therefore, it was considered reasonable to assume the design value.

Of course, ideally a complete evaluation would have required the experimental verification of all the envelope components. However, being external walls custom-made elements, assembled and built on site and particularly subject to possible deterioration over time due to rain wetting and condensation, it seems reasonable to assert that the associated performance uncertainty is higher than that of the other components and deserves more in-depth examinations.

Thus, the transmittance of the walls has been analysed with a heat flow meter (see Table 7 for technical details). The measurements were carried out on site in two different wall portions, both facing north, in order to prevent the effect due to solar radiation. The obtained results outlined that the external wall transmittance is much higher than expected; in fact, while the value derived from the data sheets of the various layers (bricks, insulation, plaster) and standard calculation [65], was around 0.19 W/m^2K, the heat flow meter measured an average value of 0.35 W/m^2K.

The simulation model was consequently further updated, and results are reported in Fig. 9. As shown, this correction highly affects the simulation outcomes: the net primary energy deviation decreases in fact from 49.7% (step 1) to 32.5% (step 2).

However, considering the deviation in term of heating and cooling respectively equal to 13% and 27%, and the related statistical indicators (based on monthly data), the simulation results cannot yet be considered within the acceptable threshold. The MBE and the cv(RMSE) are, in fact equal to -5.4% and 30.8% respectively.

5.1.3. Step 3: set-up of building operation mode

As described in the methodology, a further step to calibrate the model consists in the definition of the occupancy profile as well as the people behaviour to be added in the model, based on post-occupancy audit and interviews. In such respect, different profiles have been assumed concerning infiltration, ventilation flow rate and internal gains, as shown in Table 8.

The corresponding results (Fig. 10), therefore, show a further reduction of the mismatch. The deviation becomes equal to 29.5% for net primary energy and to 2.7% and 12% for heating and cooling. Similarly, the errors in terms of MBE and cv(RMSE) were reduced significantly and respectively achieved the following values: -3.6%, 16.3%. In this case, even if the MBE comply with the validation threshold defined by the ASHARAE, the cv(RMSE) still doesn't fall within such range.

5.1.4. Step 4: Temperature set-point correction

With respect to user profiles, an additional calibration has been performed, checking the actual heating and cooling set point defined by each tenant. It turned out that the real winter set points (and thus actual temperatures) in almost all the apartments were equal to 22°C, rather than 20°C as defined by building and energy regulation [56]. Regarding the cooling set-point, it must be noted that a minimum temperature of 26°C was programmed in the thermostats, thus lower values are not allowed. It has to be mentioned that this is the regulatory threshold [56], which corresponds to the comfort value, but is generally considered slightly higher by the user. In fact, a specific survey confirmed that in all dwellings the actual air temperatures were held on average around such value during the whole summer period.

Results shown in Fig. 11 highlights again a further reduction of the mismatch. The deviation between measured and simulated data for heating and cooling resulted equal to 2.7% and 12% respectively. Similarly, the errors in terms of MBE and cv(RMSE) were reduced significantly and reached the values of -2.1% and 13.8%, finally complying with the validation threshold of the ASHARAE. It should be noted, however, that even if the results for heating and cooling energy demand fit quite well with measured data, the deviation in terms of net primary energy is still significant and equal to 29.1%. It confirms that a specific analysis on technical systems performance must be carried out, as described in the following section.

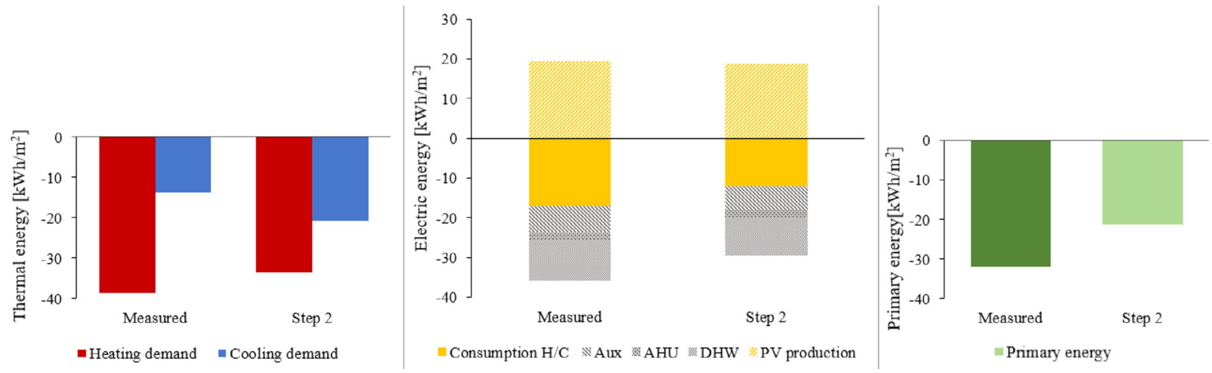

Fig. 9. Comparison between simulated and measured energy demand (Step 2).

Table 8
Detailed user profile.

Hours	1-6	7	8	9	10-12	13	14	15	16-17	18-19	20	21	22	23-24
Internal gain [W/m²]	1	6	8	8	1	8	10	1	8	1	8	10	8	1
Air infiltration [V/h]	0.01	0.01	0.01	2.3	0.01	0.01	2.3	0.01	0.01	0.01	0.01	2.3	0.01	0.01

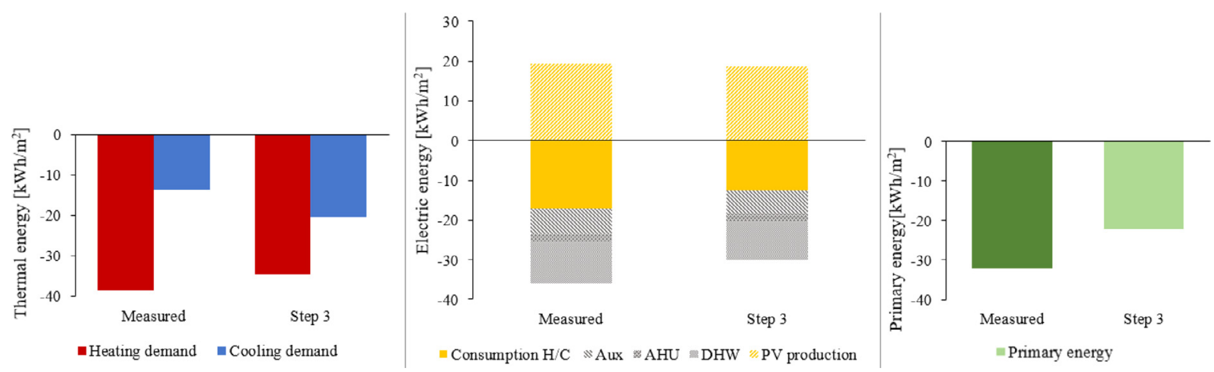

Fig. 10. Comparison between simulated and measured energy demand (Step 3).

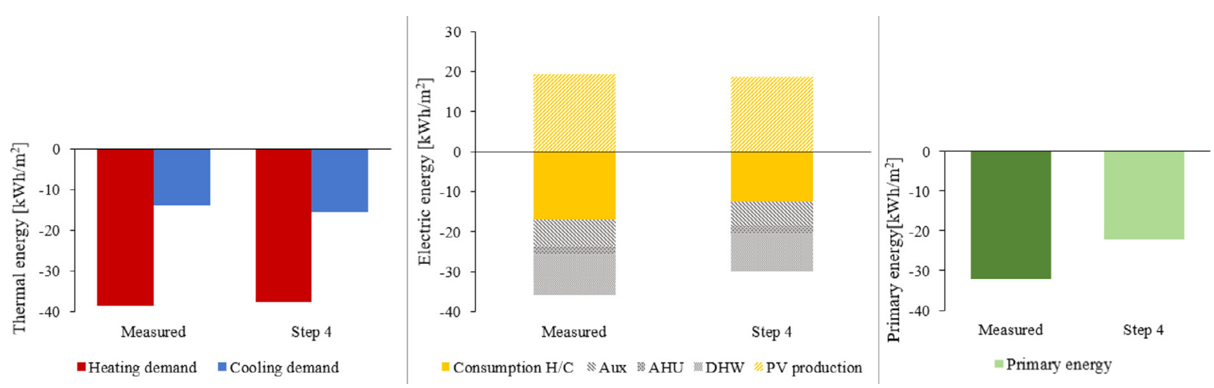

Fig. 11. Comparison between simulated and measured energy demand (Step 4).

5.2. Phase B: Update based on electric energy consumption

In the second phase, a fine tuning based on the net final primary energy use, and therefore on the electricity consumption of HVAC and production of PV system, has been performed. The results of the simulations were thus compared with the actual measured electricity final consumption.

5.2.1. Step 5 and 6: set-up of real HVAC and PV performance

The last discrepancy observed (Fig. 11), underlines that probably some calculation parameters related to the HVAC system do not fit well with the actual performances. In such respect the real COP and EER, which are the main features that affect the efficiency of the heat pump, have been measured on site. In such regard, a specific testing campaign was performed using an additional monitoring equipment, by measuring the thermal energy output of the heat pump, the electricity consumption and the supply/return water temperatures in different operating conditions, manually forcing the machine's control logic to simulate different load profiles. By elaborating such data, a new performance map of the heat pump was calculated. As can be noted by the results reported in Fig. 12, there is a noticeable difference with theoretical data provided by the manufacturer. The deviation is more evident with low temperature differences between load and geothermal sides, thus at part-load conditions, when the frequent on-off switching of the compressor (which is

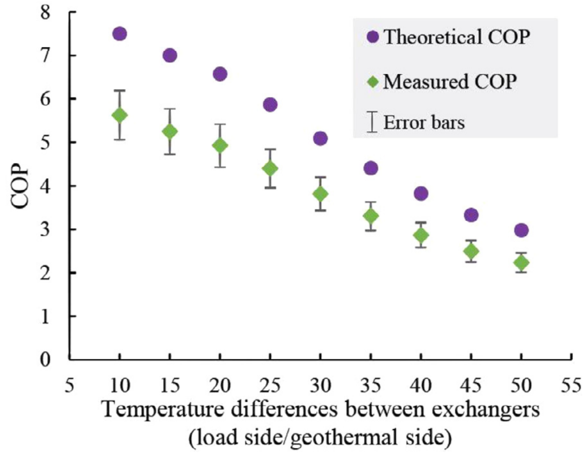

Fig. 12. Theoretical and measured COP of the heat pump.

not a modulating type) strongly penalizes the performances. In general, an average performance difference of the same magnitude (20-25%) was measured also in other heat pump systems [66–69] and thus can be considered in agreement with actual on-field performances of such technology.

For the sake of completeness, a further on-site measurement was carried out on the insulation type and thickness of the distribution pipes and it was found that a thickness of 20 mm is present instead of 40 mm, as indicated in the design of technical system.

According to the measurements, the new data were added in the simulation model and the net primary energy was calculated again. In addition, as outlined in the proposed methodology, in this step the consumption for auxiliaries, DHW and air handling was updated according to the actual operating hours. In detail, for circulation pumps it was found that, during the heating seasons, the pumps are operated for 14 h/day instead of 13 h/day, with an increase of 4.5% in the related electricity requirements. The share for DHW and air handling was instead calculated as the difference between the overall measured electricity consumption and the sum of the amount used for heating/cooling and that of circulation pumps; in this case an increase of 26% was found. Of course, the latter amount is mainly due to the difference in the COP of the heat pump.

As reported in Fig. 13 the final overall deviation results equal to 7.4% with related monthly error indices (based on electric consumption for heating and cooling) equal to -4.9% and 12.6% for MBE and cv(RMSE) respectively.

Such values, of course, falls within the ASHRAE threshold, thus the model should be considered validated and reliable.

Finally, the update of the PV production according to the actual weather data (step 6) doesn't affect significantly the overall results. As shown in Fig. 14, in fact, the deviation related to the PV production decreases from 4% (step 1-5) to 3.3% (step 6) and the overall deviation in terms of primary energy changes just from 7.4% (step 5) to 7.3% (step 6).

Of course, a more detailed calibration on the PV performance could be carried out by means of complex experimental analyses such as the verification of actual power of each module (flesh test analysis); however, considering the limited impact on the overall deviation, within the current research work it has been considered reasonable to skip further such detailed analysis.

6. Results discussion

In order to better understand the main factors that affected standard and further simulations, the net primary energy results obtained in each step and the related deviation are outlined in Fig. 15.

As can be observed from the graph, the deviation of the standard simulation from the real data is equal to 43.8%, with a remarkable difference [70]. However, through the verification and the gradual update of the model inputs, the final deviation reaches 7.3%, which is a commonly acceptable value [70].

Therefore, it can be affirmed that the data inaccuracy, mainly due to incorrect technical information, leads to an underestimation of about 1/3 of the real energy consumption. This is definitely a critical aspect, especially in the framework of a design process aimed at minimizing building energy consumption.

More in detail, it should be mentioned that the fine tuning of the results is based on progressive corrections, according to which each step represents an improvement of the previous one. According to a systemic approach, however, instead of evaluating the contribution of each step (in absolute value), it is interesting to evaluate the variation with respect to the preceding one.

In this respect, it has been observed that step 1 (weather file), even if increasing the precision of the model, also slightly raises the deviation between the simulation and the measured data (13.5%), while the successive steps in turns reduce it. In particular, step 2 (vertical opaque envelope's transmittance) decreases the deviation approximately by 35%, while step 3 (use-profile) and 4 (set-point) bring a successive incremental reduction respectively of 3% and 1.3%. Step 5 (HVAC), on the other hand, provides a further substantial reduction of the deviation by 74.5% compared to the previous step. The last step (weather file on PV productivity) brings a final reduction of the gap by 1.3%

The main influencing factors in the described procedure are therefore associated with steps 1, 2, 5, being represented by the climate context and energy data related to building envelope and technical systems (i.e. the main elements for the energy-efficient design). It should be noted, however, that the quantities involved depend on the specific case study which, although representative, does not allow to generalize the obtained results.

7. Conclusions and lesson learnt

In order to achieve sustainable architecture and specifically ZEB targets, preliminary analysis and design phases, if carried out correctly, can guarantee the quality of the final product and its compliance with energy-environmental requirements. To this aim, together with appropriate professional skills, modern IT tools offer excellent support. For example, energy simulation software can test and validate performance under conditions very similar to the real ones. These programs even allow to put the building into a sort of virtual reality, where all boundary factors and features can be correctly taken into account and managed. These very precise instruments must, however, be based on correspondingly precise input data. According to the GIGO (Garbage In, Garbage Out) principle, if the simulations are based on incomplete or wrong information, the whole process can only be negatively affected. For these reasons, in order to foster the building sector and design practices evolution, it is necessary to identify the main causes of errors and deviations and to reduce or remove them.

In this paper, after a review of the most recent literature dedicated to the topic, a focus on residential buildings is presented, through the analysis of a real case study. The impact of the most influencing factors has been confirmed and precisely quantified, with particular reference to those, which are independent of the calculation quality of the model. In particular, weather data, actual performance of building components and technical systems, operating profiles and user behaviour were considered and possible countermeasures and remedies for calculation errors and deviations between predicted and final results were suggested.

The analysis carried out allows to learn many lessons, ascribable to the design, building and operation phases of the case-study. These findings can undoubtedly be extended to similar cases, to improve the quality of the whole process, from design to operation phase.

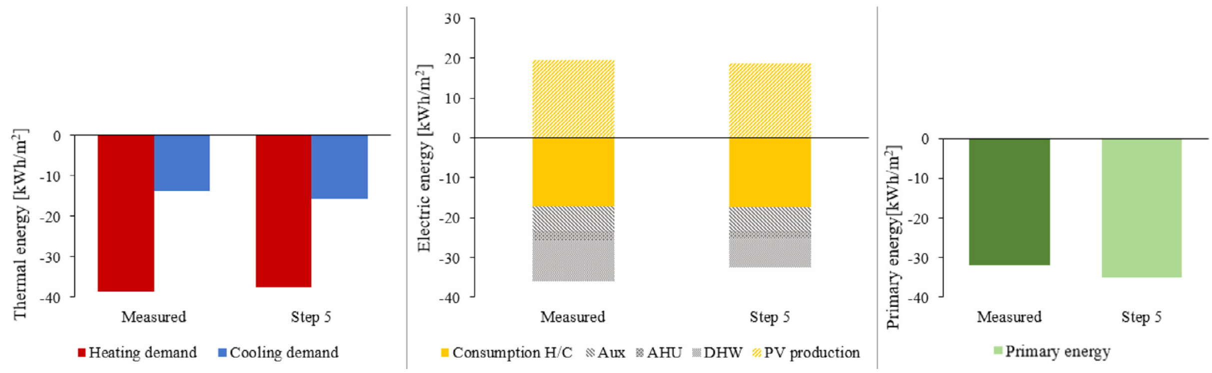

Fig. 13. Comparison between simulated and measured net primary energy consumption (Step 5).

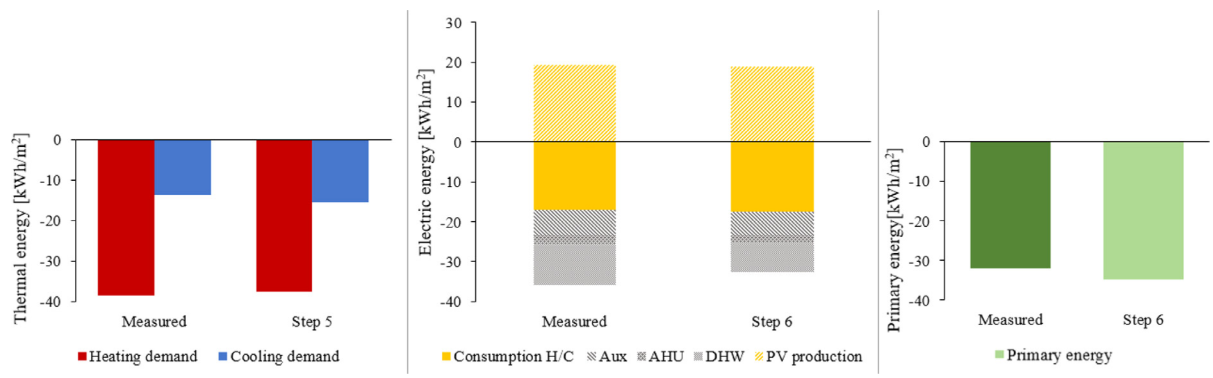

Fig. 14. Comparison between simulated and measured net primary energy consumption (Step 6).

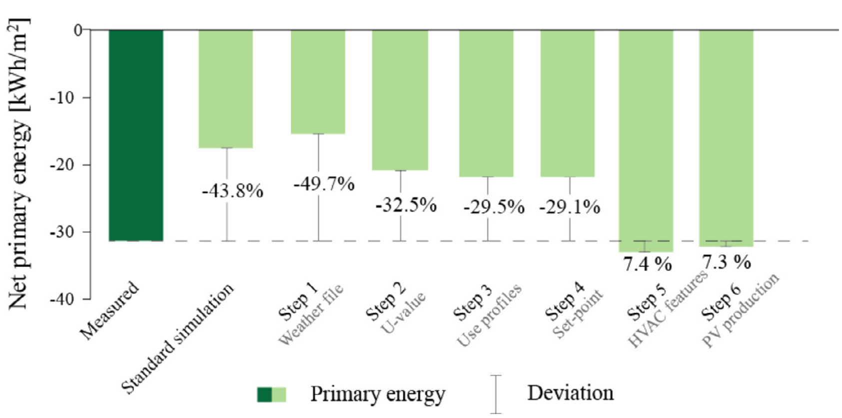

Fig. 15. Overall net primary energy results and related deviations.

First, the adoption of generic weather data, based on historical acquisition, can lead to significant errors and different energy distribution between heating and cooling. As well known, in fact, outdoor temperature is constantly increasing over years, therefore, the real consumption of buildings is progressively shifting from heating to cooling. Furthermore, the weather data are generally acquired from rural or decentralised areas, far from urban centres where building are mainly located. Thus, also specific microclimates can significantly affect estimates and expectations. In such respect, a more up-to-date and specific set of weather data should be developed and taken as standard at national and local level, so that it can be used more consistently with respect to real cases.

Second, the actual properties of the building material and components even can be quite different from the one shown in technical data sheet or derived by standard calculations. In this respect, operational performance should be clearly guaranteed by legal certifications, behaviour in real conditions (e.g. under the action of weathering effects); and standardized guidelines for proper installation, use and maintenance should be provided.

In addition, it is confirmed that the role of users is becoming increasingly important as the overall energy performance improves. Provided that individual variability and needs are respected, building operating conditions, if possible, should be more clearly defined since the design stage and checked for regulatory compliance. Energy-waste or inappropriate user behaviour should also be discouraged or sanctioned (e.g. with specific repercussions on bills).

Furthermore, the importance of the actual performance of technical systems under real conditions is stressed, since the related calculation and forecasting errors can severely distort the expected results. Products should be placed on the market with data sheets containing not only standard reference values, but also contextualised ones with respect to possible actual applications.

Last but not least, the study of non-technical measures to bridge the performance gap of buildings should not be neglected. Encouraging communication and collaboration among building professionals and a better management of the whole building process can go a long way in reducing execution errors and related underperformance.

It can be concluded that, besides ensuring the correctness of design, construction and operating procedures, the various stakeholders (decision makers, manufacturers, designers, builders, end users etc.) should contribute to the creation of a reliable and detailed reference and regulatory framework, able to reduce the gap between expectations and actual results related to buildings' energy efficiency.

Since the urgent need to transform, as soon as possible, the building sector from an energy-intensive to a highly efficient and sustainable system, it does not seem audacious to push for the implementation of concrete legislative actions that guarantee the above.

Declaration of Competing Interest

None.

CRediT authorship contribution statement

N. Aste: Conceptualization, Methodology, Writing - review & editing. **R.S. Adhikari:** Writing - review & editing. **M. Buzzetti:** Data curation. **C. Del Pero:** Investigation, Writing - review & editing. **H.E. Huerto-Cardenas:** Software. **F. Leonforte:** Investigation, Writing - original draft, Validation, Software. **A. Miglioli:** Visualization, Validation.

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