A New Approach to Assess the Building Energy Performance Gap: Achieving Accuracy Through Field Measurements and Input Data Analysis

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A new approach to assess the building energy performance gap: Achieving accuracy through field measurements and input data analysis

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ABSTRACT

The performance gap is defined as the difference between a calculated and measured quantity, and in buildings, it may refer to the energy performance or the indoor thermal conditions. According to the literature analysis, most studies start from simulation results and define methods and approaches to minimise the discrepancy against the measured values. This paper presents an alternative and innovative approach to the problem, starting with measurements in a fully instrumented and monitored living lab consisting of seven office rooms used to build and validate an accurate calculation model. The model is applied to observe how different input modes of the most relevant parameters affect the performance gap. The model exhibits high accuracy: the coefficient of variation of the root mean square error scores is 2.3 % for thermal free-floating and 10 % and 14 % for final cooling and heating energies, respectively. Depending on the single input variations, overestimation above 50 % and underestimation below 40 % are calculated for a given energy service. Results show that the weather data, occupancy profiles, related internal gains, and ventilation rates can significantly affect the performance gap. The outcomes of this field study call for new analyses aimed at generalising the achieved results and developing appropriate modes to input the relevant parameters to minimise the performance gap with limited calculation efforts.

Abbreviations

AC	Air Conditioning	IEQ	Indoor Environmental Quality
COP	Coefficient of Performance	KPI	Key Performance Indicator
CV(RMSE)	Coefficient of Variation of the Root Mean Square Error	MBE	Mean Bias Error
EER	Energy Efficiency Ratio	PG	Performance Gap
EPBD	Energy Performance of Building Directive	PREDYCE	Python Realtime Energy DYnamics and Climate Evaluation tool
EPC	Energy Performance Certification	RMSE	Root Mean Square Error
H	global Horizontal solar irradiation [W/m^2]	SC	Static shading coefficient
IAQ	Indoor Air Quality		

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1. Introduction

The performance gap (PG) is generically defined as the difference between the current performance and the desired or expected performance in a given process. The topic has gained high interest in the construction sector since simulation tools started being used to predict buildings' thermal and energy performance [1]. Two main patterns can be identified:

1. Energy performance gap (EPG), which refers to the difference between predicted and measured energy performance in buildings with mechanical systems for one or more energy services (space heating, cooling, ventilation, etc.).
2. Indoor environmental quality (IEQ) PG, which refers to the difference of predicted and measured environmental parameters and/or indicators in buildings in thermal free floating.

The former is particularly relevant because of the decarbonisation objectives in the construction sector. Several studies have aimed to set the framework for the definition, the analysis, the causes, and the mitigation of the EPG [2–4]. Minimising the EPG is crucial to increase the credibility and implementation of energy policy actions and provide reliable tools to professionals for design and operational choices [5]. Conversely, energy and IEQ PGs negatively affect sustainability, economy, health, and well-being in buildings [6]. The topic is widely discussed in the European Union (EU) because of the Energy Performance Certification (EPC) schemes implemented in the Member States as a consequence of the enforcement of the Energy Performance of Buildings Directive (EPBD) framework [7]. The calculation of energy performance in standardised operating conditions, as pushed by EPBD for comparison purposes, conflicts with the risk that "energy-related procurement issues go unnoticed", justifying PG with the sole variations in building operational inputs, which may compromise the potential for energy efficiency in the EU context [8]. The PG issue is, in fact, more pronounced for buildings with presumed high energy performance [9,10].

1.1. State of the art

As underlined by Refs. [11–13], the performance gap is not only justified by the differences between the standard inputting definition and the actual operative ones but is correlated to several potential causes. Remaining on this point, the study of [11,14,15] focused on PG among compliance modelling and actual (measured) energy needs. In particular [15], identifies three PG families in the adoption of compliance modelling: i. 'regulatory PG', i.e. differences between compliance modelling outputs and actual (measured) values; ii. 'static PG', i.e. differences between adapted operational model outputs ('performance modelling') and actual values, and iii. 'dynamic PG', i.e. differences between calibrated model outputs and actual values. Additional works also enlarge the applicability of the PG concept to extended topics, such as energy flexibility, defining the "flexibility gap" for electrified services [16].

According to a recent extensive review of PG causes in the EU residential building stock [17], the PG can be identified as a double difference between the optimal consumption and two deviated consumptions: the theoretical one referring to standard conditions and the actual one measured during operation. This new 'optimal consumption' defines the energy needs of a building under ideal conditions, including the conceptualised design and construction values and assuring satisfying conditions to end-users. Among aligned studies, it is possible to mention the work of [18], which underlined how the PG is correlated on the one side with divergencies among optimal and realistic usage inputs concerning standard ones and, on the other side, with the divergencies among current and optimal usage inputs. The authors reach this result thanks to a building retrofit simulation analysis considering three prominent families of PG causes: i. unprecise definition of the standard values, e.g. indoor temperatures and/or airflow rates; ii. input data quality during building simulations, e.g. weather/climate, shading factors, and/or conditioned volumes; and iii. additional issues include divergencies between the actual constructed building and as-built technical designs. Considering standard and actual variations, the adapted condition approach that supports the definition of optimal adapted levels, e.g., set points, COPs or other variables, is incorporated in Ref. [19]. The main aspects impacting energy use are climate, building envelope, building equipment, building operation and maintenance conditions, occupant behaviours, and IEQ conditions [9,20,21]. These aspects can be organised into two main macro-categories: physical variables and human variables [22,23]. The review study in Ref. [24] classified the EPG causes by considering their recurrence in literature as follows, suggesting the need for new studies, especially on the last voices: occupant behaviours, building envelope, system performance, and weather data. Nevertheless, the other causes also require additional studies: the review in Ref. [25], for example, underlines that identifying occupancy impacts on EPG is still challenging, considering the lack of data on actual occupant profiles. Continuing in the analysis of the potential PG causes, the review of [17] identifies the following divergence families of causes due to theoretical aspects: i. modelling input imprecisions and assumptions; ii. climate imprecisions [26–29]; and iii. imprecisions in occupancy profiles and actions [30,31]. In particular, it is possible to expand the modelling input family considering the aspects correlated to: a. modelling operator errors, like typos or mistakes during data acquisition [18,32,33]; and b. simplifications, assumptions and adoption of standardised data [34,35], including set points [19,36,37], ventilation airflow and airtight [18,38], envelope thermal transmission [39,40], and other factors such as thermal mass [41], geometrical dimensions, and dimensions of heated/cooled spaces. According to Ref. [14], three prominent families of causes primarily impact PG: uncertainty in building modelling, with a potential magnitude in the range of 20–60 %; occupants' behaviours, 10–80 %; and poor operational practices, 15–80 %. A survey-based study on EPG mechanisms [42] added to the previous PG causes the lack of supervision, knowledge education, and the psychology of occupants, suggesting 9 strategies to drive PG-reducing mechanisms. The latter included the need for accurate meteorological data, the need for precise information correlated to building simulation parameters, and the organisation of knowledge education for designers. Also, the systematic study [43] underlined organisation- and knowledge-related causes, mentioning, among the other knowledge gaps, that the dynamic nature is inadequately considered and that the studies on the influence of the different factors on the EPG are limited, suggesting new investigations. Similarly [44], recommends developing new investigations on factors influencing EPG reduction.

Most studies on PG investigated simulated input variation impacts concerning base model results [45–48]. In particular [48], explored, via a parametric variation analysis in jE+, the impact that simulation input modelling variations on uncalibrated models may have on PG results concerning base simulation output data. Nevertheless, the authors can correlate input with relative result variations; the work cannot correlate PG with actual measured performances, requiring additional studies on this specific point. Similarly, the [47] work on energy PG adopts parametric energy simulations based on thousands of simulated reference buildings for the Italian context. Results give a domain of variation of the energy PG for standard buildings. Still, they are not validated with actual building-measured behaviours and focus on a simulation-based steady-state vision.

Ref. [17] highlighted that studies focusing on the correlation between potential PG causes and impacts are still needed, especially considering both single causes and their combination being PG causes often interdependent [49].

1.2. Objectives of the study and elements of innovation

The literature underlines the need for studies investigating the effects of several input categories in an integrated and combined vision, in which numerical and simulation analyses are coupled to measured data for a deeper analysis of the PG. A major limit in existing studies is the scarcity of measured data or their availability in aggregated form, which limits the understanding of the origin and causes of the PG.

The novelty of this study is related to the detailed measurements carried out in an office space operated as a living lab, which regards not only the energy and environmental performances but also detailed information about the users' occupation profiles and their interaction with the built environment. In addition, all the data are acquired with a sub-hourly resolution step, which ensures that the real dynamic of the building is captured. While most of the studies try to understand PG originated by comparing aggregated measured quantities and numerical analyses, our data allows the implementation of a detailed and fully calibrated building model with minimised PG [50–52]. By changing specific data in the model, the paper's objective is to assess the PG's origin and magnitude as a function of several input categories, thus providing insight into the most sensitive parameters that shape the discrepancies between expected and measured performance. Such elements of knowledge are relevant for the stakeholders involved in the building construction chain:

- policy makers, in charge of the implementation of technical standards and of building energy efficiency schemes,
- designers, in charge of the definition of awaited building performances,
- professionals, in charge of keeping the building performance aligned with the expected ones during operation.

2. Materials and method

Most literature studies on the energy performance gap start from simulated data. They assess its potential reduction by calculating fine-tuning against measured data, usually aggregated, or comparing reference simulated buildings with simulation input variations. This paper approaches the problem according to an inverse perspective; in fact, the thermal and energy performances of a fully monitored living lab are used to calibrate the building model, and, in the next phase, the deviation due to assumptions and simplifications is calculated.

The approach finds the ground in living lab equipment, whose energy, environmental and functional parameters are controlled and operated via the building's smart energy systems; this feature allows the collection of a vast amount of spatial and temporal data, which can be accurately inputted in the building energy modelling.

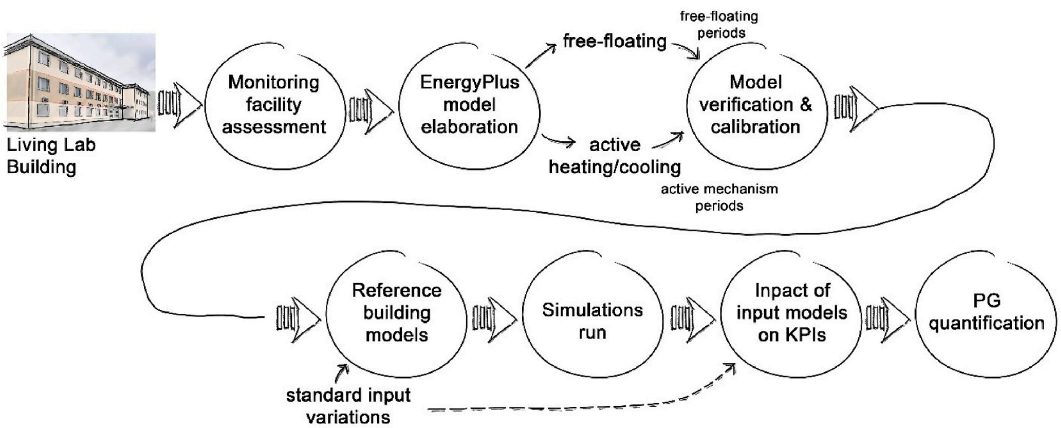

Fig. 1. Conceptual scheme of the methodology.

The study is structured in the following phases:

- Definition of the living lab monitoring architecture and procedure to provide a detailed data set of measured quantities.
- Implementation of the calculation model and run of the calculation in thermal free-floating conditions and with active heating and cooling energy systems
- Model verification and calibration against measured data through the comparison of the identified KPIs
- Construction of the reference building model starts from the calibrated model and introduces some standardised assumptions to run seasonal simulations.
- Impact of different input modes on the final performance of the living lab and quantifications of the performance gap.

For clarity and to visually synthesise the approach to the problem, a graphical scheme of the methodology is presented in Fig. 1.

2.1. Description of the living lab

The living lab consists of seven office rooms on the second floor of the F40 Building of the ENEA Casaccia Research Centre. This was built about forty years ago and hosts offices, laboratories and a technological hall for advanced energy system experiments. The layout of the living lab is presented in Fig. 2; the seven rooms have a single external façade, west/northwest oriented (110° azimuth angle, setting 0° for the south and moving clockwise); the only exception is R1 (room 1 in Fig. 2) that has a second external wall, north/northeast oriented. The living lab rooms border with a corridor on the second floor and rooms of the same geometry and use on the first and third floors.

All the rooms have the same geometric characteristics, and they are reported in Table 1. The external walls are made of a double layer of bricks with 6 cm thermal insulation panels placed in the 10 cm air gap (0.50W/m^{2}K); the internal masonry horizontal floors at the second and third floors have no thermal insulation (1.67W/m^{2}K). Each room is equipped with a reversible air conditioning unit, whose power is 2.5 and 3.4 kW in cooling and heating mode, respectively. The efficiencies, declared according to the relevant technical standards, are 4.03 EER and 3.74 COP for cooling and heating; the seasonal values rise to 6.5 and 4.2, respectively. The window opening provides ventilation according to users' preference and additional time during the room cleaning early in the morning.

2.1.1. The window system

The building's original windows were double float glass units (9 mm air gap) mounted on the aluminium frame without thermal break. The windows were equipped with hinged sashes, large 120 and 60 cm, respectively; the windows also have an external manually operated blind. These windows (W1) are still installed in rooms 5, 6 and 7, referring to Fig. 2. Instead, two new windows were installed in the other four rooms – see Fig. 3. These windows, designed according to the original elements, have a thermal-break aluminium frame and a small sash motorised with a chain system, which allows the 30° maximum opening angle. Concerning the glazing systems, they are as follows:

- Double glazing unit (W2) in rooms 3 & 4 - Low-emissivity spectrally selective double-glazing unit with argon-filled gap and a moveable white Venetian blind in the gap
- Triple glazing unit (W3) in rooms 1 & 2 - Low-emissivity spectrally selective double-glazing unit with argon-filled gaps and a moveable aluminium-alike Venetian blind in the gap

Fig. 2. Layout of the living lab on the second floor of the F40 Building in the Casaccia Research Centre of ENEA.

Table 1
Main geometrical parameters of the rooms.

Parameter	Length [cm]
Room width	390
Room depth	434
Room height	320
Window width	200
Window height	160
Window intrados	30

Fig. 3. Inside view of a W2 window with the solar shading device partially activated (left) and outside close-up of the facade, where the intrados of the windows are clearly visible.

These new windows have dynamic features that can improve the rooms' energy and thermal performance by regulating the solar gains and the natural ventilation by rules implemented via the smart management systems they are connected to. The main thermo-physical properties of the windows and their elements are reported in Table 2; W1 data are taken from literature, except for the blind, whose optical properties were measured with a spectrophotometer.

Fig. 3 shows the appearance of new windows when the solar shading devices are partially activated on the left photo. On the right, the retreat of the windows with respect to the facade is clearly visible; the so-determined 30 cm intrados provide additional shading in some irradiation conditions.

2.1.2. *The occupancy profiles*

Formally, rooms 1, 3, 6 and 7 host one worker, and rooms 2, 4 and 5 host two workers. In practice, the situation is much more dynamic: i) post-COVID-19 rules introduced smart working up to 6 days per week; ii) workers in the same rooms used to set schedules aimed at minimising the contemporary presence; iii) rooms 3 and 7 may host an additional worker in some periods (typically graduate/PhD students). The effective occupancy was monitored through field sensors; see the following sections. For the calculation analysis, however, it was necessary to rebuild an occupancy profile similar to that of the living lab occupants on a weekly basis. For this purpose, a tailored standard occupation profile was developed for each room, and the occupants were interviewed about their usual schedule, including the days they worked at home. The schedules are reported in Table 3; offices are off on Saturdays and Sundays.

Table 2
Thermo-physical properties of the three windows typologies.

Parameter	Symbol	Component	Unit	W1	W2	W3
Thermal transmittance	U_w	Window	W/m^2K	5.0	1.4	1.1
Thermal transmittance	U_f	Frame	W/m^2K	5.7	1.4	1.4
Thermal transmittance	U_g	Glazing	W/m^2K	2.9	1.1	0.7
Solar factor[a]	g	Glazing	–	0.79	0.35	0.31
Light transmittance	τ_v	Glazing	–	0.82	0.69	0.61
Solar transmittance	τ_e	Shading element	–	0.10	–	–
Solar reflectance	ρ_e	Shading element	–	0.15	0.71	0.68

[a] of the glazing system without shading.

Table 3
The occupancy profile in living lab rooms. The smart working refers to weekdays from 1 to 5; the user is absent on the indicated days.

	Worker 1			Worker 2		
Room	In	Out	Smart working	In	Out	Smart working
1	08:30	17:30	1			
2	08:30	16:30	1	09:30	15:30	2, 4
3	09:30	17:30	2			
4	08:30	17:00	3	08:30	17:00	1
5	09:30	18:30	5	08:30	16:30	2, 4
6	08:30	17:00	4			
7	09:30	18:30	5			

2.2. The energy management and monitoring system

The building has a smart energy management system able to control, among other building services, the air-conditioning (AC) units and the windows operating conditions as a function of selected rules; alternatively, the system monitors such conditions according to settings defined by the building occupants [53]. For each room, the monitored parameters are:

- Electric data of the AC unit (voltage, current, power)
- Final energy of the AC unit
- Status of the machine AC unit
- Fan speed and air direction of the AC unit
- Status of the shading devices (from retracted to fully pulled down, including intermediate state)
- Tilt angle of the lamellae of the shading devices
- Opening of the motorised sash of the window

Each AC unit was equipped with the SDM630MCT meter by Eastron Europe series to measure the relevant electrical parameters. The meter has 1 % accuracy for power factor, voltage and current and holds Class 1 for active energy accuracy. The meters are connected via Modbus to the local heating/cooling management system that communicates data via API to the smart building management system.

Each room was equipped with the multisensor ERS2 (Elsys Room Sensor) by ELSYS.se, which can acquire indoor air temperature and relative humidity, presence, illuminance, and CO_2 concentration. These sensors are connected to the smart building management system in wi-fi mode using the LoRaWAN wireless network. The specifications of the ERS2 sensor are reported in Table 4.

The relevant climatic data (air relative humidity and temperature, wind speed and direction, and global horizontal solar irradiation) were also measured on the roof of the building. The resolution step for data acquisition was set following the requirements of the specific equipment and instruments; the recording of each quantity was next averaged to a 1-h resolution to implement time-homogeneous data sets.

It is noted that the room temperature was continuously measured in the boundary corridor and in the offices on the floors above and below the living lab when possible.

3. The monitoring

The living lab was monitored over several periods across two years to understand the building's real thermal and energy response and, consequently, to compare field data with calculation results. The monitoring periods are summarised in Table 5.

The setup in the living lab rooms during the above-specified periods is described in the following subsections. It should be noted that in the rooms with the advanced system, it was possible to record the state of the windows, even for those cases in room 4, where the occupants were free to choose their preferred configuration. The window and shading configuration in rooms 5, 6, and 7 was agreed upon with the occupants before the monitoring periods to have the correct information for the calculation phase.

3.1. Summer monitoring in thermal free-floating conditions

This monitoring task was carried out during the summer closing. Thus, the building was primarily unoccupied, except in room 5,

Table 4
Specifications of the portable multi-sensor.

Quantity	Range	Resolution	Accuracy (±)
Air temperature (°C)	0–40	0.1	0.5
Air relative humidity (%)	0–100	1	2
Illuminance (lux)	0–2000	1	10
CO_2 concentration (PPM)	0–2000	1	50 (3 %)

Table 5
The monitoring phases analysed in the study.

Operative conditions	Period	Days	Occupancy
Thermal free-floating/summer	12-22/08/2021	11	no
Active space cooling	02-12/06/2022	11	yes
Thermal free-floating/fall	15/10-01/11/2022	17	yes
Active space heating	23/12/2022-02/01/2023	11	no

whose cooling system was always turned on because of the presence of the person in charge of an experimental energy plant surveillance. This room was excluded from the analysis, but its monitored air temperature was used as a boundary condition for rooms 4 and 6. Table 6 reports the rule implemented to operate the shading activation (with lamellae oriented on the closure position, exactly 75° tilted against the sun) and the automated sash opening. It can be observed that the control rule was based on a schedule or physical parameters' thresholds, namely the global horizontal solar irradiation H (W/m2) for the shading activation and the temperature difference between the indoor (Ti) and external (Te) conditions ΔT (°C) for the motorised window opening activation. The latter aimed to test the rooms' thermal responses with night ventilation. In two cases, a single strategy was implemented to calibrate the model according to different set-ups and compare the impact of various strategies, which will be reported in future publications. Boundary condition measurements included two not-cooled and two cooled rooms on the first and third floors.

3.2. *Intermediate monitoring in thermal free-floating conditions*

The office rooms were occupied according to the workers' schedules; thus, the conditions were more challenging for the model calibration. In rooms 1, 2, and 3, the shading system was pulled down for the superior half of the glazing. The lamellae were horizontal under diffuse irradiation conditions to ensure daylighting and the external view. In contrast, lamellae were tilted 60° against the sun from 14:00 until 20:00 to prevent glare and overheating during the afternoon working hours. The automatic window-opening rule was implemented for rooms 2 and 3 for model calibration purposes only. In room 4, no rules were implemented to let the users set their preferred conditions, which were directly collected by the management system for the model calibration.

3.3. *Summer active cooling*

The workers were present in the living lab according to the schedules, and the air conditioning system was running from 08:00 until 19:00, whether the office room was occupied or not. The set-point was 26 °C, and the fan velocity of the split unit was 3 on the 1 to 5 scale of the AC unit. Here, a single strategy was set for all the rooms with the advanced window but differed in room 4. The blind was pulled down with the lamellae tilted 40° in the early afternoon hours (providing daylighting and blocking the direct radiation from the sun); the tilt increases to 60° from 16:00 until 20:00, and this time with no direct sun, the blind got retracted. Users in room 4 were allowed to set their preferences for the shading system. The night ventilation was ruled in rooms 2 and 3 as in the summer free-floating monitoring.

3.4. *Winter active heating*

The mild climatic season and the heating from blundering rooms cause extremely low energy use. To increase them to a minimum significant level, it was decided to carry on the monitoring during the winter closing, setting the heating point at 22 °C, a high set-point that does not comply with the national requirements (20 °C, diminished to 19 °C during the high energy price periods) and not

Table 6
Rules implemented by schedule or physical parameters to activate the shading system and the motorised window opening.

Room	Summer thermal free-floating		Autumn thermal free-floating		Summer active cooling	
	Window Op/clos	Shading Op/clos	Window Op/clos	Lamellae tilt	Window Op/clos	Lamellae tilt
1	No	$H > 150W/m^2$ $H < 100W/m^2$	no	0°/20:00–14:00 60°/14:00–20:00	no	40°/14:00–16:00 60°/16:00–20:00
2	21:00 08:00[a]	14:00 20:00	17:00 23:00	0°/20:00–14:00 60°/14:00–20:00	21:00 08:00[a]	40°/14:00–16:00 60°/16:00–20:00
3	$\Delta T > 3$ °C $\Delta T < 2$ °C	$H > 150W/m^2$ $H < 100W/m^2$	17:00 23:00	0°/20:00–14:00 60°/14:00–20:00	21:00 08:00[a]	40°/14:00–16:00 60°/16:00–20:00
4	$\Delta T > 3$ °C $\Delta T < 2$ °C	No	no	Users preferences[b]	no	Users preferences[b]
5	No	No	no	no	no	no
6	No	No	no	no	no	no
7	No	No	no	no	no	no

[a] 08:00 refers to the following day.
[b] The users can operate the shading system to maximise their comfort, differently when the rule is "no" means that the control is inhibited (Op = opening time or condition; clos = closing time or condition).

acceptable for most users. The AC unit switching schedule was from 08:00 until 19:00, and the fan speed was 3, as for the summer season. The air temperature on the first floor was measured in the rooms below 1, 2, 4, 5, and 6 and all the rooms on the third floor but not above room 6. Due to climatic conditions, the shading system was never activated, and the motorised windows did not activate the ventilation; thus, all the windows were static during the period.

4. Calculation

4.1. Thermal model of the living lab

Data related to the building geometry, envelope characteristics, and performance of energy systems were taken from original design sheets and manufacturer's data sheets. Data on air infiltration were calculated according to the procedure defined in the standard [54], considering the air permeability class, as declared by the manufacturer and the average wind speed during the winter monitoring period. Data related to the occupancy and the associated internal gains of the appliances were taken from the users' presence in each room, assuming, in line with the in-situ check, 250W per person, including the work electric devices. Data from windows opening and blind activation were set according to the identified rules. Data related to the electric lighting use were inputted, considering the monitored illuminance levels in each room, after preliminary measurements on the contribution of the lighting on the overall illuminance level during the operating hours.

4.2. The model validation and calibration

The validation of the model was verified against two main performance indicators:

- The air temperature in thermal free-floating conditions. Although standards on adaptive thermal comfort set the operative temperature as the base calculation parameter, i. the operative temperature is a calculated indicator, not a measured parameter; ii. it requires expansive and bulky set-ups, as it is necessary to measure air and globe temperature and air velocity; iii. preliminary measurements carried out in an exemplary room of the living lab facility proved that the air and operative temperature difference was more significant than the sensor accuracy in only 1 h across more than 40 days of continuous monitoring. For such reasons, and considering the nature of the problem, it was decided to select the air temperature as the relevant indicator.
- The final (electric) energy in active cooling/heating conditions. A crucial indicator for energy performance assessment is net cooling/heat energy use, which is the ideal thermal energy needed to keep the built environment in the desired comfort condition. Nevertheless, this measurement cannot be made directly, as the measurable energy is the one used by the air conditioning unit (final energy) and embeds its own efficiency. For this reason, we selected the final energy as the relevant indicator.

The following parameters are inputted from field measurements into the building model: envelope dynamic characteristics, local weather data, and effective occupancy (and associated internal gains). A preliminary calibration has been carried out during unoccupied periods to characterise the building without internal gains.

The model validation is based on the method defined by the ASHRAE standard for building energy measurements (ASHRAE, 2022). The accuracy is evaluated through three relevant statistical indicators: MBE (Mean Bias Error), RMSE (Root Mean Square Error) and CV (RMSE) (Coefficient of Variation of the Root Mean Square Error).

4.3. Definition of the reference building and variants

Once the model was validated, it was necessary to downscale its complexity (e.g. different windows with different rules in each room) and define a realistic base case, considering the parameters most affecting the energy performance. The following assumptions were made:

- The climatic conditions are those measured in the building proximity.
- The seven rooms of the living lab are equipped with a sole window type (W2); the shading system is activated in summer from 14.00 until 18:00, and lamellae are tilted 60° against the sun and retracted during the rest of the day.
- The occupancy profile is the one defined in Table 2. The internal gains of electrical appliances are switched on only when the users are present.
- Independently from the above assumption, the heating/cooling system is switched on from 08:00 until 18:00 of the working days. The air temperature set-points are 20 °C in winter and 25 °C with 55 % relative humidity in summer.
- The infiltration was set at 0.1 air exchange per hour.
- The winter ventilation is calculated assuming a 1-h window opening from 07:00 to 08:00, before the occupants' arrival, and 1 h at lunchtime (12.30), according to the usual management of the building by the cleaning staff and the users. The ventilation takes place at night in summer, according to the rule of rooms 3 and 4 in thermal free-floating (see Table 3).

The calculation periods were the three coldest (December, January, and February) and the three hottest months (June, July, and August) for space heating and cooling, respectively.

The variants of the reference building are implemented for several important input modes of the calculation process. The variants are selected considering the standard approach used for the energy certification scheme in Italy and other configurations taken from the relevant technical literature. They are following listed in Table 7, together with relevant references.

5. Results

5.1. The model validation

Several fine-tuning actions were put in place for the correct calibration of the model [13], and the final relevant results are summarised in Table 8 for the thermal free-floating conditions in both the summer and the autumn periods.

The results are satisfactory when looking at the average conditions in the seven rooms of the living lab; in fact, the average temperature deviation is 0.20 and 0.44 °C in summer and autumn, respectively, and the related RMSEs are 0.67 and 0.74. The MBE is 0.1 and 2.00 % in the same periods, and the CV(RMSE) is 2.3 and 3.1 %, respectively. These values testify to the excellent accuracy of the implemented calibrated model, as the accuracy for the two indicators is ±10 and ± 30 %, respectively, according to the mentioned technical standard. The results are satisfactory. Also, looking at the room level results are performative, as reported in the table, although a partial exception to the trend is the room 7 behaviour, whose average temperature difference is more significant than 1 °C in both periods (close to 2 °C in autumn) and with 3 °C as peak difference. This is explained by the fact that this room has the entrance hall of the building on the floor. Thus, the thermal boundary conditions are very variable, while measuring the below zone temperature during the monitoring period was impossible. It should be noted that CV(RMSE) would drop to 1.7 % during the autumn period if room 7 were excluded from the analysis.

Figs. 4 and 5 compare, respectively, the final energy uses for heating and cooling during their monitoring periods in the seven rooms and the Living Lab as a whole. The latter's aggregate CV(RMSE) is 10 % for cooling and 8 % for heating; the results are fully compliant with the ASHRAE standard requirements, which set the CV(RMSE) accuracy range to ±15 % for monthly data. The result is particularly valuable as it was achieved on a period (11/12 days) shorter than the monthly time spam considered by the standard. Even if outside of the calibration purposes, a high scattering of results found for the single rooms can be observed; this aspect is affected by the small energy quantity involved: on average, 1–1.5 kWh per day per room. In such conditions, high percentage discrepancies can be found for slight absolute variations, which may depend on the sensitivity of the measuring equipment.

Table 7
Reference input variations to the input model.

Variants category	Variants	Description	Ref.
1. Weather data	1.1 Meteonorm database	Worldwide used tools generating typical meteorological years for given coordinates (EPW format) for energy performance assessment of buildings	[55]
	1.2 Italian technical standard database	UNI Italian technical standard containing the weather data sets for building thermal and energy applications	[56]
	1.3 IWEC database	IWEC typical weather database file (EPW) from a nearer site (Fiumicino meteorological station) (WMO id: 162420)	[57]
2. Occupancy and internal gains	2.1 Italian standard profiles	UNI standard occupancy and other internal thermal gains according to the Italian standard, hourly distribution dividing weekdays and weekends assuming occupied and not-occupied periods – see the prospectus 15 of the reference	[58]
	2.2 CEN standard profiles	Hourly defined standard occupancy and other gains according to CEN standards suggested schedules considering the office landscaped profiles	[59]
	2.3 Italian fixed value	UNI fixed global average total internal gains according to the prospectus 15 data of [58] but without temporalisation, i.e. a unique averaged fixed value	[58]
3. Summer night ventilation	3.1 Wind and Stack	Daily schedule 21:00–08:00 (next day) adopting the WINDANDSTACKOPENAREA zone ventilation mode of EnergyPlus supporting wind-driven and stack-driven ventilation (opening area 0.12, discharge coefficient 0.61)	[60]
	3.2 Constant ACH	Constant 5 air exchange per hour (ACH) with daily schedule 21:00–08:00 (next day)	[61]
	3.3 ASHRAE 62.1	ASHRAE 62.1 IAQ ventilation strategy, supporting 2.5L/s per person during the occupancy and 0.3 L/s per square meter 24h/7d, extending the area-correlated ventilation to the whole period	[62, 63]
4. Winter ventilation	4.1 Italian standard airflow rate (occupancy)	UNI Standard air exchange per hour for office buildings (39.6 m^3/h per person) activated during occupancy hours	[64]
	4.2 Italian standard airflow rate (fixed coefficient)	UNI/TS Standard air exchange per hour for office buildings (39.6 m^3/h per person) continuously activated and corrected with the 0.59 fixed coefficient	[58]
	4.3 ASHRAE IAQ	IAQ ventilation strategy, supporting 2.5 L/s per person and 0.3 L/s per square meter during the sole occupancy – this supports average ventilation during occupancy of 8.5 L/s considering average office dimensions	[62,63, 65]
5. Shading system	5.1 Static SC0.1	Static shading coefficient (SC) 0.1 for the selected glazing system, calculated for the current window with the procedure defined in the given reference	[66]
	5.2 Static SC0.2	Static SC set to 0.2 for the selected glazing system, calculated for the current window with the procedure defined in Ref. [66], considering the sun at 45° altitude	[66]
	5.3 Italian Standard SC	UNI activation of the monthly shading coefficient as described in the Italian relevant standard	[58]

Table 8
Statistical indicators for the living lab rooms during the thermal free-floating monitoring (

Room	Summer free floating monitoring			Autumn free floating monitoring		
	ΔT_av [°C]	RMSE [°C]	CV(RMSE) [%]	ΔT_av [°C]	RMSE [°C]	CV(RMSE) [%]
1	0.22	0.38	1.3	−0.12	0.44	1.9
2	−0.01	0.36	1.3	0.16	0.61	2.6
3	0.00	0.43	1.5	0.28	0.50	2.0
4	0.15	0.43	1.5	0.71	0.93	3.7
5	–	–	–	0.15	0.48	1.9
6	−0.27	0.38	1.3	−0.13	0.42	1.7
7	1.13	1.18	3.8	1.99	2.02	8.5
All	0.20	0.29	1.0	0.44	0.56	2.3

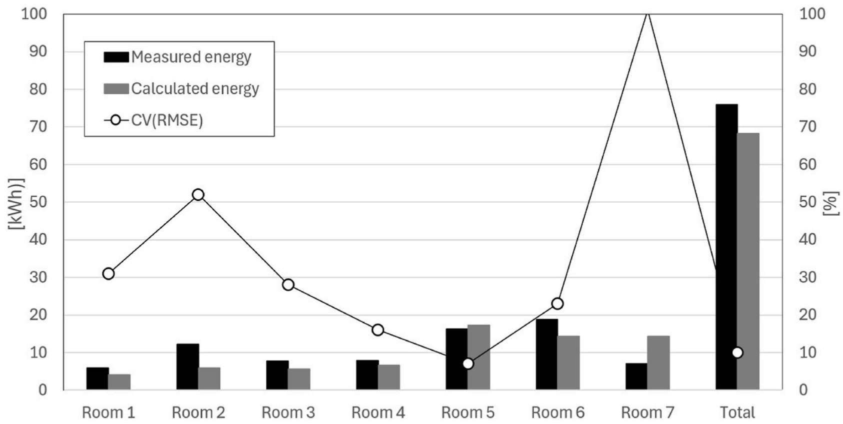

Fig. 4. Final energy use in the living lab rooms during the active cooling monitoring. The coefficient of variation in the last column refers to the total measured and calculated values.

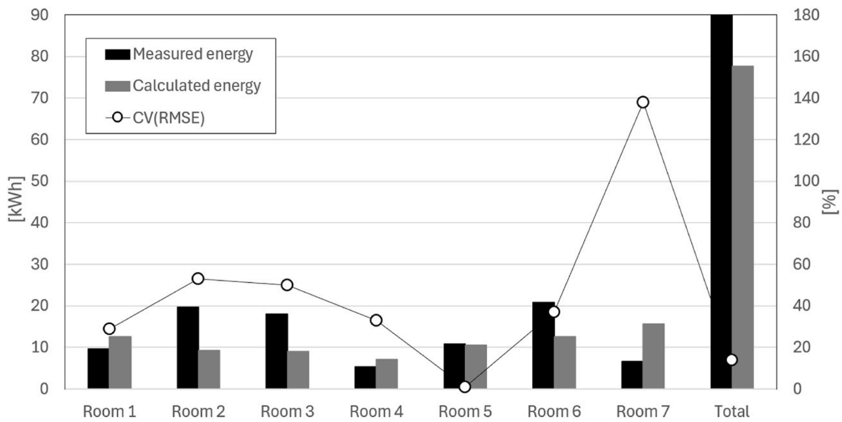

Fig. 5. Final energy use in the living lab rooms during the active heating monitoring. The coefficient of variation in the last column refers to the total measured and calculated values.

5.2. Energy performance of the reference calibrated building and its variants

Figs. 6 and 7 report the results of the simulation set of the reference case and the variants defined in the previous sub-sections. The results report the absolute net and final energy for space heating and cooling, as well as the variation with respect to the reference case. It is noted that the variation does not change for the two energy indicators, as the final is obtained as the ratio of the net energy of the efficiency of the air conditioning unit in the related season.

Some variants are season-dependent. Thus, no results are reported for the not related energy indicator. The results are expressed in kilowatt-hours; normalising the energy to the net floor area, the space cooling and heating intensity are 3.9kWhm^2 and 6.4kWm^2 for the reference case, respectively. The quantities are very low, but they must be reported due to the mildness of the climate, the thermal

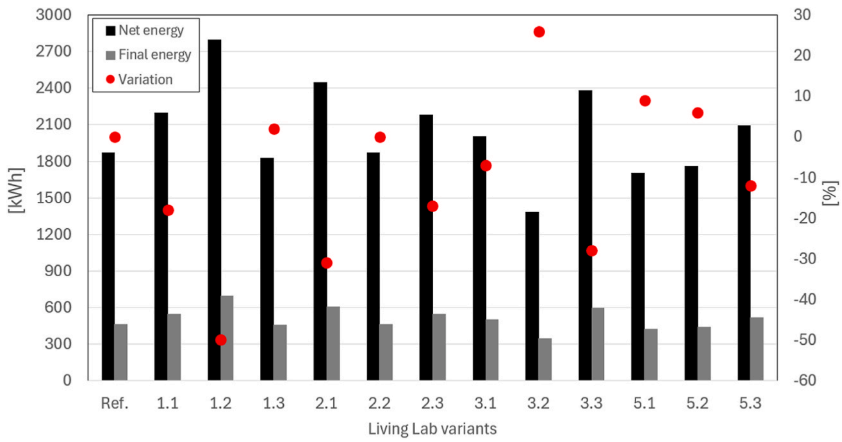

Fig. 6. Calculated Annual net and final energy for space cooling and variation with respect to the reference case.

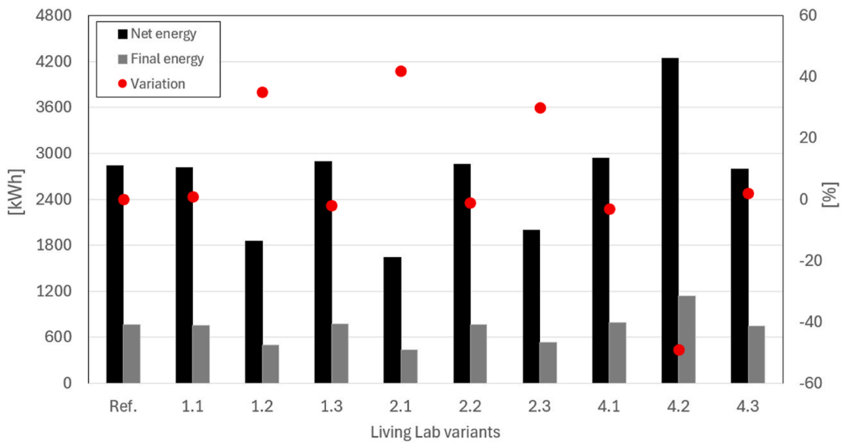

Fig. 7. Calculated Annual net and final energy for space heating and variation with respect to the reference case.

quality of the building envelope, the high efficiency of the air conditioning units, and, most importantly, the form factor. The latter, defined as the ratio of external surfaces on the cooled/heat volume, is 23 %, meaning that the interaction between the living lab volume and the outdoor environment is limited to a relatively small surface.

The results exhibit high variability in relative terms; penalties (negative percentage values in Figs. 6 and 7) up to 50 % and savings above 40 % are calculated for both energy services. In some cases, negligible variations are observed. The different input modes lead to different results for every variant identified for each input class, and they are discussed in the next section.

6. Discussion

The results presented in the previous section show relevant variations in terms of energy needs and uses. It is essential to observe that the measured average daily final cooling energy intensity was about 0.053 kWh/m2, which projected across the whole cooling season led to 4.8 kWh/m^2. In this perspective, the study first demonstrates the high level of accuracy that can be reached by energy modelling once it is based on robust and detailed input data; as an example, the measure of 10 % of the cooling needs variation corresponds, in this case, to less than 0.5 kWh/m^2 on a yearly basis.

The results stimulate the discussion about the impact of different input modes on the calculated energy performance and, consequently, on the magnitude of the energy performance gap.

The first relevant issue is about the use of weather data. It is interesting to observe that data coming from national standards overestimate the cooling performance by 50 % and underestimate the heating performance by 35 % when applied to a building located in the far outskirts (thus not affected by an urban heat island). This result raises the importance of local climate data to properly assess the energy performance of buildings; this aspect becomes crucial in cities suffering from high urban heat island intensities, which may lead to relevant differences depending on the building position (historical centre, residential district, outskirts, etc.). Conversely, it surprises the very good alignment achieved using the IWEC database, as substantial geographic differences are observed between the living lab sited (20 km from the seashore and 150 m above the sea level) and a coastal weather station; this result appears more a case rather a compelling similarity of conditions. It is to be noted finally that the Meteonorm database is very well aligned for space heating use, while it overestimates the cooling use by 18 %. The results related to the weather data are affected by a relevant methodological difference, consisting of the fact that databases refer to multi-year time series. In contrast, the adopted reference case refers to local data measured in a specific year. This is a crucial issue to be faced when approaching performance methods based on operational ratings rather than asset ones.

Using standardised occupancy and internal gain patterns strongly overestimates the cooling use (31 %) and underestimates the heating use (42 %); the slightly better agreement is achieved using those patterns that spread occupancy over the 24 h, suggesting that people's presence is over-concentrated during standardised occupancy periods. The national standard with rigid schedules cannot report the dynamicity of occupancy in a working environment. Conversely, the European standard EN16798-1 [59], which uses hourly occupancy pattern variations (office, landscaped), provides very accurate results compared to the reference case. The results express the need to put in a more precise relation the occupancy with the internal gains, strictly correlated to the former; also, new working modes (e.g. smart working from home) call for a reconstruction of schedule and intensities based on old paradigms.

The impact of ventilation during the cooling season exhibits a relevant variability as a function of the input mode. Using a simple night schedule provides minor discrepancies (17 % more cooling energy) compared to the strategy based on physical parameters as in the reference case; this is a positive aspect as it may simplify the calculation and modelling effort. Using design night ventilation data (variant 3.2) reduces the cooling use by more than 25 %, and it is not realistic as it is based on theoretical ACH values that cannot be reached in single-side night ventilation. Such an approach should be accurately evaluated by comparing the literature study assumptions with the characteristics of the building to be analysed. Variant 3.3 proves that ventilation strategies aimed at ensuring indoor air quality are ineffective in replacing those aimed at night ventilative cooling; a 28 % cooling increase is calculated for this variant.

Concerning the ventilation during the heating season, the results are in good agreement (3 % and −2%) when the ventilation is activated during the occupancy hours; when standardised fixed values are applied (variant 4.2), the space heating use may increase by 50 %. This is a well-known fact for buildings in which natural ventilation is achieved through windows opening by the users; in fact, such opening takes place for a limited amount of time and the air exchanges considered by the standards are never reached in practice.

The variations induced by the different input modes for solar shading during cooling are in the acceptable range (−12/9 %), and this might be highly beneficial in simplifying the calculation task for angular selective materials such as lamellae systems. Using the solar factor for fixed solar conditions underestimates the cooling use within 10 %, but solar gains are pretty small for the orientation of the windows (north/west); more tests should be done to explore the response of such a simplified approach in the case of more relevant solar gains for both, geometry and characteristics of the façade, as well as the orientation of the building. The same actions require the standardised monthly shading factor defined by the Italian standard.

The results show that high relative discrepancies can be achieved depending on the input modes, and the variation may strongly propagate depending on when the effect of multiple inputs is taken into account. As an exemplary case, two combinations are tested and implemented, one per winter and one per summer season. The combination case for the cooling season includes variants 1.2, 2.1, 3.3, and 5.3; in this case, the energy use scores are 135 % higher than the reference case. The combination case for heating season includes variations 1.2, 2.1, and 4.3, resulting in an 84 % reduction in energy use compared to the reference case.

At the same time, it has to be noted that high variations correspond to limited variation in absolute values, as the space and cooling final energy uses are low in the present study. Another remark is about modelling the building energy system, whose efficiency is known to be a function of several boundary conditions [67]; however, both standards and models require a number of input data seldom provided by the technical sheets of the supplier. The impact of the different input modes and modelling approach could not apply to this exercise, and only the declared efficiency values were used. Due to the low energy uses, the performance variations are likely limited for different input modes in this study; however, this is a crucial issue in addressing the performance gap in buildings with standard energy uses.

7. Conclusions

The performance gap is a significant issue for the reliability and acceptance of building energy rating schemes worldwide. Many studies have demonstrated the relevance and magnitude of the problem, which is particularly critical in some contexts, like Europe, where energy analyses are often based on standardised input mode. In this paper, we implemented a different approach, starting from the operational assessment and analysing the impact of single inputs on the calculated energy performance. Starting from detailed measurements carried out in a fully monitored living lab, we built a very accurate model validated against cooling and heating energy uses, as well as thermal-free floating conditions. The coefficient of variation of the root mean square error was 2.3 % for thermal free-floating and 10 % and 14 % for final cooling and heating energy, respectively. From the validated model, we observed how specific input modes, based on standards and literature, may affect the quality of the calculation and increase the performance gap. The main findings of the study are:

- The detailed monitoring allows the implementation of accurate building energy models with a very low performance gap; in this case, it accounts for less than 0.5kWm2 for both space heating and cooling energy services on an annual basis.
- The local climate plays a crucial role, especially in cities profoundly affected by urban heat islands; in fact, using standard urban datasets causes a significant performance gap, especially during the cooling reason that resulted underestimated by 50 % in this study.

- Input data related to occupancy is critical in energy-efficient buildings, particularly in the post-Covid19 era, which led to new standards for remote working. The study demonstrated that the energy performance gap may reach 50 % when using standard simplified profiles for services linked to occupancy (e.g. ventilation in winter). Still, hourly occupancy profiles can effectively reduce it.
- Discrepancies were found for other inputs as well; however, the combination of input modes that are different from the accurate ones can significantly increase the performance gap. In fact, in this study, an overestimation of 135 % and an underestimation of more than 80 % in the final energy uses were calculated for assigned inputs' combinations.

The outcome of the research calls for more field studies to generalise the findings and build robust data sets varying in building typologies, climatic conditions, and energy performance levels to understand better the acceptable simplification in required inputs to reduce the performance gap without too high modelling efforts. On the other hand, the study also proves the importance of smart technologies, which are able to collect relevant data about the way the building is actually "used" and make them available as reliable input data to be applied in tailored calculation analyses.

The latter issue might be a starting point for future developments. In fact, the advanced approach proposed here could effectively be used to detect and minimise the performance gap, identifying and eliminating the limitations intrinsic in the current calculation standards, strongly oriented versus standardised formulations, and upgrade them towards mixed, more reliable operational and calculation tools.

CRediT authorship contribution statement

Giacomo Chiesa: Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Data curation, Conceptualization. **Stefano Pizzuti:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Michele Zinzi:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Giacomo Chiesa reports financial support was provided by European Union. Michele Zinzi reports financial support was provided by European Union. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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