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Energy performance gap of the Italian residential building stock: Parametric energy simulations for theoretical deviation assessment from standard conditions

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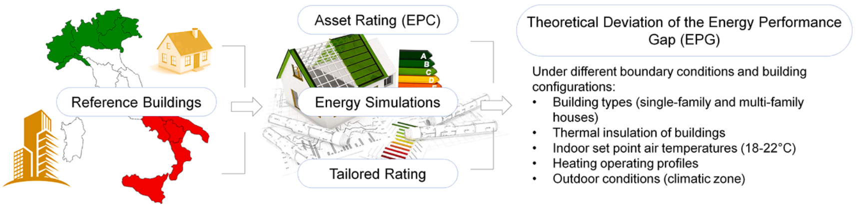
HIGHLIGHTS

- First attempt to quantify the Energy Performance Gap of the Italian building stock.
- Theoretical Energy Performance Gap assessment with parametric energy simulations.
- Energy Performance Gap as a function of the climatic zone and building type.
- Rebound and Prebound effects range of values under different user profiles.
- Energy Performance Gap assessment for standard calculation method correction.

GRAPHICAL ABSTRACT



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ABSTRACT

Energy Performance Gap (EPG) is a crucial issue in the building sector that can lead to an overestimation of the national energy policies. It is the difference between the calculated energy consumption and actual energy use, and it is relevant mainly for space heating. As EPG quantification or correction methods could lead to more realistic energy policies, EPG has become a focus of many studies and research. In this framework, this study aims to quantify the theoretical deviation of EPG, i.e., concerning to the standard conditions, for the Italian residential building stock by performing parametric energy simulations of thousands of representative reference buildings. After a comprehensive thermophysical characterization of the national building stock, parametric simulations were carried out by varying the main standard conditions set in the Energy Performance Certificate (EPC) calculation. This approach allowed the quantification of EPG according to the climatic zone, building type, usage profile, and thermal insulation level of buildings, while also analysing the influence of these parameters on the EPG and checking for prebound or rebound effects (i.e. when standard consumption is greater or smaller than actual one). The study identified a range of EPG variability for both prebound (0% to +80%) and rebound (−30% to 0%) effects and quantified an average EPG between −3 and +16 kWh per heating degree day of the selected location as a function of the usage profile. This work represents the first attempt to calculate the EPG of the Italian residential building stock and it could lead to the correction of the national energy policies implemented in the building sector.

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1. Introduction

The new international and European agreements, such as Clean Energy Package and Green Deal [1], have raised the standard objective to achieve carbon neutrality (net-zero emissions) by 2050. Energy refurbishment and efficiency of buildings are identified as important targets to significantly reduce energy consumption and greenhouse gas emissions since they account for about 36% of total energy consumption [2]. In this framework, European countries have adopted a variety of energy policies to achieve energy efficiency and savings with an increase in overall investments of about 11% in 2020 [2].

Italy, whose buildings sector accounted for about 30 Mtep of total energy consumption in 2020 [3], has implemented different energy strategies for building refurbishment. According to the national report, a typical Italian family (made up of four users) consumes about 1400 m^3 of natural gas and 2700 kWh of electric energy on average (values referred to the main representative climatic zone - E) [3]. Thanks to the implemented national energy efficiency strategies, an energy savings of 0.392 Mtep in 2020 and a cumulative energy savings of 1.345 Mtep (2014–2020 period) for the buildings sector were achieved [3]. However, the expected energy savings derived by adopting these energy measures should have been greater, but the target was overestimated also due to the adopted calculation method which is based on the monthly calculation step.

The monthly calculation method used for building energy performance assessments and Energy Performance Certificates (EPCs) is provided at national and European levels and it is considered a valuable tool for spreading energy knowledge and culture, especially in the residential sector [4]. However, the reliability of EPC outcomes can be questioned [5] as standard user occupancy profiles, standard heating period based on the climatic zone, conventional space heating switch-on, operating conditions, average climatic conditions, and limited energy services (such as in Serbia [6] where only space heating is taken into account) can lead to significant discrepancy from actual energy consumption.

In Italy, the mean monthly energy calculation method is mandatory by D.M. 2015 [7] and it is detailed by technical standards UNI TS 11300 [8-12]. It is used for energy performance assessment of buildings as well as for EPCs by taking into account space heating, hot water production, cooling, and ventilation as energy services for the residential sector. Additionally, all European Countries have established EPC databases, such as the Informative System on Energy Performance Certificates (SIAPE) in Italy, representing a valuable data source for national energy policy. SIAPE and any other EPC databases can have wider applications beyond their original intent as long as higher standards on data quality and content are put in place [13,14]. For instance, the first national application of EPC database was attempted by Buratti et al. [15] where the EPCs data of the Umbria Region was used for implementing an Artificial Neural Network able to check the reliability of EPCs, i.e. capable of checking the standard energy performance of certified buildings. This work demonstrated the potential of the EPC database at the national level.

Energy Performance Certificate was introduced in 2008, amended in 2012, and its data is currently one of the most extensive data sources of information on the energy performance of building stock, offering valuable support for researchers and policymakers to regulate and forecast energy use, as well as to promote energy efficiency in buildings [16].

In this context, von Platten et al. [17] developed a three-step method to attain comparability between old and renewed EPCs. This work not only exposed the overestimation of energy performance improvement associated with EPCs, but also highlighted that both old and renewed EPCs can be effectively used to evaluate the impact of energy policies and measures on the building sector's energy performance. The literature has also underscored the potential of integrating EPC databases with other national sources, as evidenced by a study utilizing data from various national databases to train an Artificial Neural Network, which evaluated the impact of medium-to-long energy national strategies at different levels of context [18]. Results proved that this kind of algorithm can be a useful tool in supporting local energy strategies.

Despite the usefulness of EPCs as a resource for the national building stock and in guiding energy policies, as noted in [14], their accuracy, reliability, consistency, and quality can be inadequate [19]. Furthermore, the standard calculation method adopted in EPC, namely asset rating, can lead to significant divergences from actual energy consumption resulting in a relevant divergence gap between the simulated or predicted energy consumption of buildings (outcomes of EPC) and the actual energy consumption (billings) [20,21].

Cozza et al. [22] tried to assess this gap between EPC and actual energy consumption for about 1170 residential buildings; results have shown a negative performance gap (of about –23%) for pre-retrofit buildings, i.e. the actual consumptions were smaller than calculated ones (also namely *prebound effect*), while a positive gap (close to 2%) was found after retrofitting (also namely *rebound effect*, i.e. the actual energy use is higher than the calculated one). Prebound and rebound effects were also pointed out in other works such as [23,24]; prebound (i.e. actual energy consumption is smaller than simulated one) was mainly highlighted in the existing buildings, i.e. the ones with poor energy performance, while rebound (i.e. actual energy consumption is greater than simulated one) was more notable in buildings with very good energy performance, i.e. mainly in new construction.

Burman et al. [25] revealed further evidence of the rebound effect in residential space heating, with discrepancies ranging from 20% to 30% in Austria and up to 68% in Europe and North America. At the same time, in the UK, buildings with good energy performance ratings tend to consume more energy than less efficient households, as demonstrated by a large-scale study [26] involving around 200,000 dwellings. This study corroborates previous findings [22,25], indicating that dwellings with low energy labels consume much less energy than theoretical predictions, while energy-efficient dwellings consume more than expected.

This gap, commonly known as Energy Performance Gap (EPG), is a significant issue, leading to an overestimation of the goals set by national energy policies; to overcome this challenge, policymakers must gain greater insight into this issue and explore new ways to reduce this gap [27,28]. From the analysis of 90,000 dwellings built in the Netherlands before and after renovation comparing the actual energy consumptions with calculated ones related to space heating and domestic hot water (DHW) production, van den Brom [29] highlighted that energy-saving measures often involve lower-than-expected energy savings, making EPG a critical concern. However, policymakers prefer to use precautionary estimates of energy savings in the development of energy policies, despite the discrepancy between intended goals and actual outcomes [29,30].

EPG has been observed not only in existing buildings, i.e. the ones which need to be refurbished [31], but also in the new constructions, so it seems to be a systemic problem released by the energy calculation method, including the mean monthly energy calculation method provided by European Union and the standard boundary conditions adopted in the asset rating.

Organisation for Economic Cooperation and Development [27], has recognized EPG as an important issue in European energy policy, reflecting the substantial gap between calculated and actual energy use, particularly for space heating. This discrepancy can be also attributed to factors such as simulation tools [32-34] and occupants' behaviour [35,36].

A comprehensive review of EPG was carried out by Cozza et al. in [37], introducing the concept of optimal consumption defined as "*the energy consumption when the building is performing in an ideal way with respect to its intended design and construction quality, while satisfying the reasonable needs of its occupants*". Therefore, "*optimal consumption*" is completely different from "*theoretical*", i.e. the one calculated with standard method (such as EPC), and "*actual*", i.e. the measured energy consumption (billings). Particularly, *optimal* differs from *theoretical* in the limitations of using the standard models to describe the real conditions of building use. Standard calculation limitations are primarily associated with conventional boundary conditions, such as occupancy profiles, heating operating hours, indoor thermal conditions, and outdoor climatic conditions. By this new definition, EPG can be made up of two contributions: theoretical deviation resulting from limitations inherent in theoretical models, and actual deviation concerning malfunctioning and unrecommended use of the buildings.

In this framework, the objective of this study was to assess the theoretical deviation of the Energy Performance Gap (EPG) of the Italian residential building stock, by scrutinizing the standard boundary conditions adopted in the Energy Performance Certificates (EPCs). Currently, an absence of data or information regarding the EPG of the Italian building stock, in both theoretical and actual aspects, for each energy service, prevails. Consequently, the present research endeavours to hit this gap by trying to identify the EPG associated with standard user profiles, with the purpose of quantifying the theoretical deviation caused by the standard models.

In pursuit of this objective, the present study adopts the tailored rating method, which is complementary to the asset rating mandated by national regulations [8-12], to investigate the impact of key parameters, including indoor set point air temperatures and heating operating hours, on the energy performance gap of the Italian residential building stock. The tailored rating approach is commonly employed at the national level to carry out energy audits, which offer more accurate results by leveraging the same monthly calculation methodology as the EPC. However, it entails additional data acquisition requirements, such as billing information, and imposes higher costs on users. The key distinction between these two methods lies in the tailored rating's ability to use a more dependable user occupancy profile, heating operating hours, operational conditions, and climatic conditions to evaluate energy performance.

The goal of the paper was reached by performing energy simulations using both methods prescribed by national regulations (asset and tailored ratings) on representative reference buildings. In particular, the tailored assessment approach was used because capable of simulating the most common and typical user behaviour patterns which were defined based on data from national databases and reports as well as representative reference buildings that were previously studied by ENEA [38].

Unlike previous studies, which will be extensively discussed in the following section, this paper is the first to quantify the theoretical deviation of energy performance gap (EPG) for space heating, the energy service with the greatest discrepancy, for the Italian building stock under specific standard boundary conditions.

The present study includes several novelties and strengths, such as:

1. a comprehensive national characterization of the residential building stock, which takes into account all climatic zones, in contrast to the current limitation to E climatic zone buildings only;
2. an analysis of the theoretical deviation of EPG for different building types (single and multi-family houses) that considers multiple heating operating profiles (based on climatic zone) and building thermal insulation levels;
3. a quantification of the theoretical deviation of EPG as a function of the indoor set point air temperature in dwellings, the thermal insulation level of buildings, and the heating operating profiles;
4. a probabilistic investigation of negative or positive gaps compared to EPC outcomes under different conditions.

These features make the present work a valuable contribution to the field of energy performance evaluation in the residential building sector.

The present work has been structured as follows: section 2 provides a thorough review of the literature on EPG assessment and correction, while section 3 outlines the methodology employed, including the overview of the national building stock, the development of representative reference models, the definition of unconventional usage profiles, and the use of parametric energy simulations to quantify the EPG. Section 4 is thus dedicated to a comprehensive discussion of the EPG outcomes under different boundary conditions, and the conclusions highlight the most significant and impactful findings of this study.

2. State of the art on energy performance gap

Manifold studies were carried out to identify the Energy Performance Gap (EPG) or to develop methods to reduce it. As aforementioned, Cozza [22] attempted to evaluate the discrepancy between asset rating calculation, i.e., the method used for Energy Performance Certification (EPC), and actual energy consumption by investigating approximately 1170 residential buildings. In this as in other works, both positive and negative gaps were found by indicating them as follows:

- Prebound effect: when the actual energy consumption is smaller than the calculated one;
- Rebound effect: when the actual energy consumption is greater than the calculated one.

According to this work, the negative performance gap (calculated as the difference between actual and simulated one) is found for pre-retrofit buildings, whilst a positive gap is observed post-retrofitting.

Other works [23-31] have highlighted these two effects confirming that prebound can be a possible outcome for buildings with poor energy performance, whilst rebound for new construction or buildings with good energy performance. Nevertheless, the percentage discrepancy of the two effects may be significantly different, proving relevant a quantification of it as the building under investigation varies. This issue could be also relevant since policymakers can use standard outcomes for energy policy elaboration, although a more precautionary outcome is generally preferred.

The Organisation for Economic Cooperation and Development have identified EPG as a relevant issue of European energy policy, causing many researchers to focus their attention on methods to reduce or correct this gap. One of the latest works carried out by Cozza distinguished EPG in two main contributions: *theoretical deviation* and *actual deviation* [37]. This review, not only focused on the identification of causes of EPG, but also on solutions found in Literature to reduce EPG.

Manifold efforts have been made to address the issue of EPG reduction. Some practical approaches were developed to reduce this gap by using multiple indicators, but they can be extendable and effective only if data about energy consumption from a representative sample are available [39]. On the other hand, more complex and less widespread solutions, such as the implementation a Fuzzy Analytic Network integrated with scenario modelling, allowing the calculation of relative weights through complex interactions among often conflicting criteria [40], can be also adopted to reduce EPG.

Furthermore, a system for systematically monitoring and diagnosing the energy performance in the operation and maintenance phases of existing buildings, known as the Dynamic Operational Rating (DOR), was developed by Koo et al. [41] to address the limitations of the conventional rating system, including building category, region, and net area. DOR was developed as a solution to reduce EPC divergence, and it can be used as a tool for building energy performance diagnostics, allowing policymakers to establish a reasonable rating in EPC. However, this approach developed for South Korea, required specific data such as building characteristics, user information, and energy consumption which could be only available if national databases for each sector have been implemented.

Balaras [5] and Anđelković [6] have carefully investigated the relevance of EPC in meeting the national energy efficiency and carbon target and they have proposed correction methodologies to account for actual energy use in representative building types. Balaras [5] elaborated an empirical methodology that adapts the deviations between actual and calculated primary energy use for different types of buildings (single or multi-family houses), construction periods, and climate zones in Greece. The methodology is based on a small sample data of 8500 EPC and adopts average empirical factors to relate EPC energy consumption with actual energy use. Results have shown that the EPC overestimates energy consumption by 44% on average, with a ratio of actual and EPC energy consumption of 0.56. Although this correction method raises some issues, such as its limited applicability to different case studies and climatic conditions, it remains effective for specific types of Hellenic dwellings.

Anđelković [6] emphasized the potential value of EPC as a valuable tool for policymakers, but warns that they do not account the entire process of thermal energy delivery, including user behaviour, real regulation, automation control equipment, and building management systems. As a result, policymakers may have to relay on unrealistic data and rough assumptions when developing energy plans. To address this issue, Anđelković investigated buildings in Novi Sad, Serbia, connected to district heating systems (DHS) or with individual gas boilers (IGB) by comparing EPC outcomes with actual energy consumption. The findings revealed significant differences in specific energy consumption for heating between IGBs and DHSs, highlighting greater divergence for buildings with individual plant systems (around 11.19 kWh/m^2 to 101 kWh/m^2) and smaller differences for DHS (between 3.16 kWh/m^2 to 18.58 kWh/m^2) from EPC. These results underscored the need to achieve energy savings and reduce actual energy consumption in specific cases, such as buildings with IGBs, while also highlighting the reliability of EPC outcomes in DHSs.

The literature revealed important limitations of EPC calculation, underscoring its less reliability in energy consumption. Nonetheless, it is widely recognized that EPC is a crucial tool for the energy performance assessment of the building stock, given its ease of application and utility in energy assessment, although, EPC energy consumption figures may systematically deviate from actual energy consumption.

Nevertheless, as introduced by Cozza, it could be crucial to break down EPG into theoretical and actual deviations since it could be the first important step in correcting the EPC gap. Specifically, quantifying the gap due to theoretical deviation (related to optimal consumption) under various standard conditions could allow for a reduction in the EPG and therefore a first important step towards systematic correction of EPC.

3. Materials and methods

Based on the findings in the state of the art on the EPG, this study aims at quantifying the theoretical component of EPG for space heating (as it is the energy service for which a greater difference was found in Literature) for the Italian residential building stock. A detailed parametric research procedure was thus developed, starting with a description of the main differences between the standard (EPC) and tailored calculations focused on indicating the parameters that: i) are set at conventional values, ii) can be varied in the parametric analysis, and iii) most influence the monthly energy calculation.

Therefore, section 3.1 is focused on the description of the main differences between the standard and tailored calculation methods, whilst the research procedure developed and adopted in this work is thoroughly described in section 3.2. highlighting all the first two steps followed to achieve the objectives of the work:

1. Step 1: this represents the first crucial step where representative models of the national residential buildings stock were defined in terms of geometry, thermal properties of the building envelope, heating system, and outdoor and indoor conditions. This step was based on data provided by the national database or reports of which an extensive description of the main findings is reported. Particularly, the geometric and thermal overview of the national building stock is thoroughly described in section 3.3 to provide useful insights to define reference buildings (reported in section 3.4) to be used for the parametric energy analysis
2. Step 2: parametric analysis was performed by adopting both the standard and tailored approaches by varying specific usage parameters, such as heating operating hours and indoor set point temperature, according to section 3.1. From the combination of the multiple variables taken into account in this work (reported in section 3.4), billions of energy simulations were thus performed and analysed to quantify the theoretical deviation of the energy performance gap.

3.1. Energy performance certificate vs tailored rating assessment

Asset rating (used to perform EPC) and tailored rating (TR) are based on the same monthly calculation method detailed in [8-12] which allow assessing the energy need for space heating of buildings ($Q_{H,nd}$) starting from the thermal properties of the buildings envelope and climate conditions according to the following equation provided by [8]:

$$Q_{H,nd} = (Q_{H,tr} + Q_{H,ve}) - \eta_{H,gn} \bullet (Q_{int} + Q_{sol,W})[kWh] \tag{1}$$

This equation consists of the monthly energy balance of the heat losses through the building envelope for transmission ($Q_{H,tr}$) and for ventilation ($Q_{H,ve}$) and the total heat gains including solar contribution through windows ($Q_{sol,W}$) and internal heat gains (Q_{int}). In the heating energy balance, the total heat gains are corrected by a utilization factor ($\eta_{H,gn}$), provided by national regulation [8], which represents the gains that reduce the heating energy need. The energy losses and the inbound energy through each subsystem heating system are thus assessed according to [9-11], depending on heating system types and energy services until the energy efficiency of the heating system is assessed. Once calculated the inbound energy need of the heating system, the primary energy need is therefore assessed on the basis of adopted energy carriers.

The described energy balance for space heating is the same for the asset rating (EPC) and tailored one; nevertheless, they can differ in setting and definition of some input parameters, such as:

1. Heating Degree Day (HDD): EPC requires the use of conventional climatic conditions provided by UNI 10349-1 [42], on which conventional HDD for each city is assessed as the sum of the positive differences between indoor set point air temperature (set at 20 °C) and outdoor temperature. On the other hand, TR needs the use of both conventional and real climatic conditions. Real climatic conditions are required for validating model simulations and checking the actual state of buildings with billing, while standard data is used for carrying out technical-economic assessments of improvement solutions over time [43,44]. Nevertheless, real climatic conditions may not always be available in many cities across the country, forcing the use of standard climatic conditions in all the TR processes;
2. Indoor thermal conditions: EPC sets standard values in all the environments such as the set point air temperature ($T_{set\text{-}point}$) equal to 20 °C in residential buildings. On the other hand, TR requires the measurement of the effective thermal conditions in each environment and their incorporation in the model simulations;
3. Heating operating hours ($h_{heating}$): in EPC assessment the heating system works until the energy need of buildings is satisfied, whilst in TR the actual operating hours per day of the heating system have to be set;
4. Ventilation and internal gain: unconventional values for ventilation and internal heat gains, such as the one due to the people, should be taken into account in TR. However, no data on user habits and ventilation are available at the national level, and long-term data is often unavailable due to their significant variability throughout the year. In addition, the influence of the internal loads on energy needs calculated with the monthly calculation method is typically

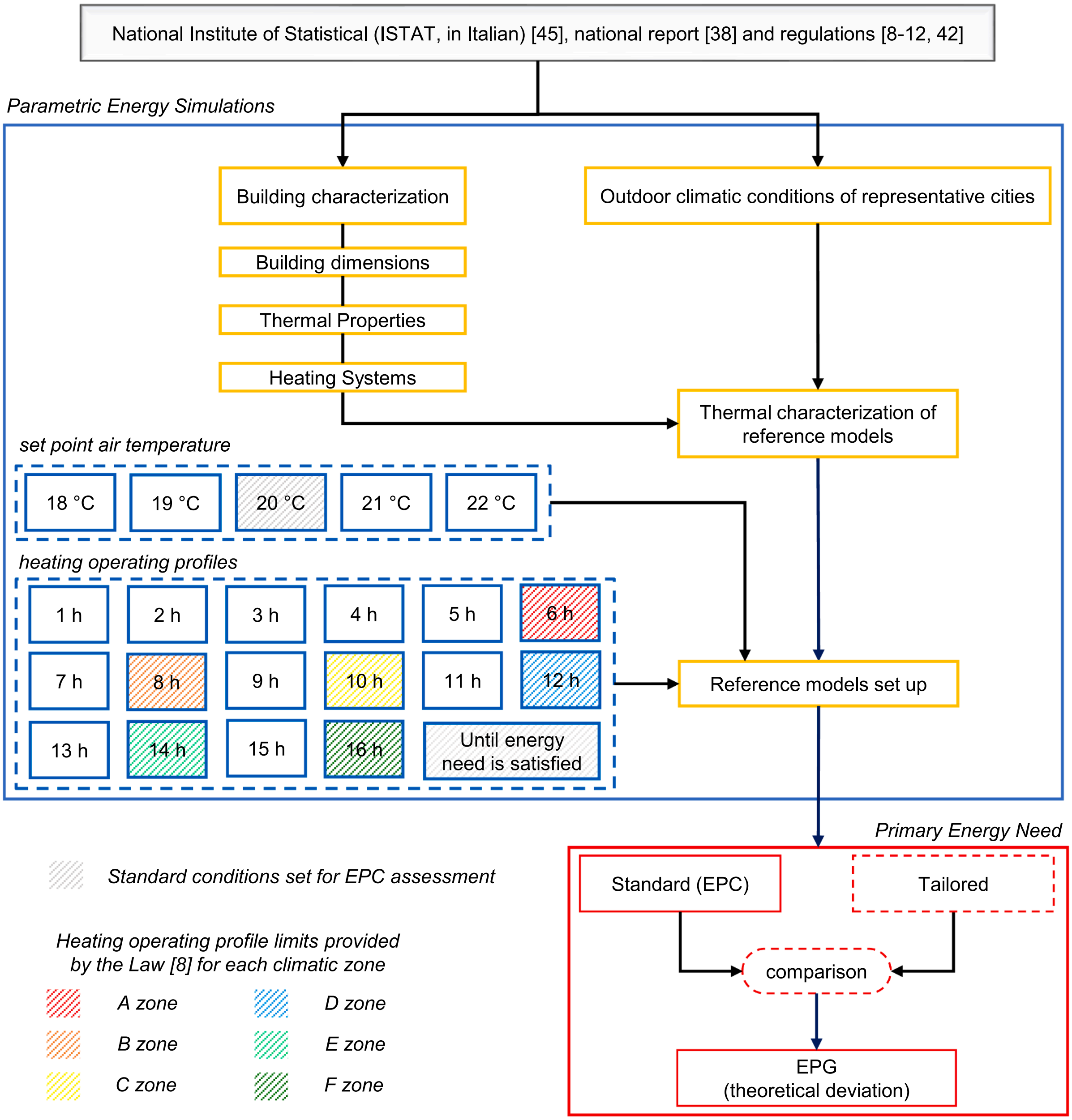


Fig. 1. Research procedure adopted in this work for the EPG assessment (EPC = Energy performance Certificates, EPG = Energy Performance Gap).

negligible due to their small order of magnitude. Consequently, conventional values adopted in EPC are generally used in TR assessments.

In evaluating medium-to-long energy strategies, policymakers have typically relied on conventional input parameters such as outdoor climatic conditions and indoor set point air temperature. Similarly, in technical-economic assessments of improvement solutions over time, the same assumptions are often made in TR evaluation. These factors have been carefully considered in the parametric analysis setup detailed in the following section 3.2.

3.2. *Research procedure development*

A detailed research procedure (Fig. 1), consisting of three main steps (highlighting with yellow, blue, and red squares in Fig. 1), was finally defined as follows:

1. Definition of the reference building stock models (yellow blocks): based on the national database [45] and report [38], around 1,000 reference models were defined both for single-family houses (SFH) and multi-family houses (MFH), adopting around 100 million possible configurations varying the building form, thermal properties of the building envelope, and heating system (all the configurations were accurately described in section 3.3). Furthermore, data from national regulation [42] was used to characterize the outdoor climate conditions of the cities chosen as representatives at the national level (see section 3.4);
2. Parametric Energy Simulations (blue square including yellow blocks): energy simulations were thus performed for each reference model in manifold and representative national cities by adopting both the standard profile (EPC) and unconventional ones properly defined for TR assessment. Specifically, the following parameters were taken into account:
   a. Heating operating profile ($h_{heating}$): as described in 3.1, one of the main differences between EPC and TR lies in the definition of the

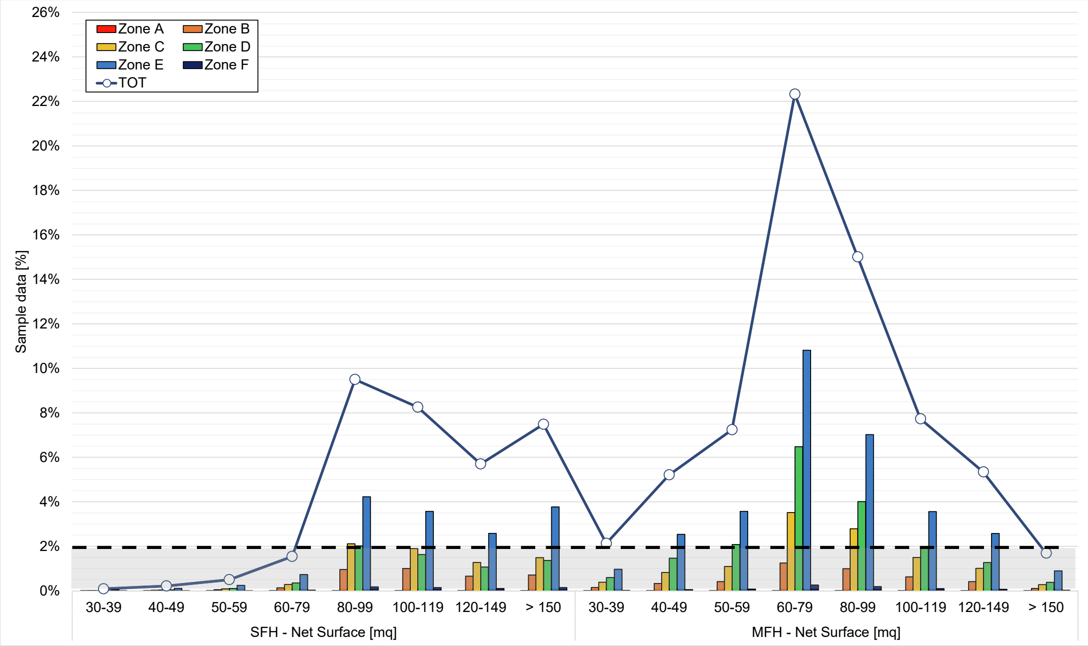


Fig. 2. Percentage of the sample of buildings as function of the net surface of the building units: elaboration from national report data [42] and National Institute of Statistics sample data [43].

Table 1
Thermal properties range for the different building envelope components: thickness (s), superficial mass (Ms), thermal transmittance (U), and periodic thermal transmittance (ψ) [38].

Components	Materials	s [m]		Ms [kg/m^2]		U [W/m^{2}K]		ψ [W/m^{2}K]	
		min	max	min	max	min	max	min	max
Masonry	stone	20	94	460	2070	0.27	3.40	0.00	1.64
	brick	20	74	348	1150	0.24	2.31	0.00	1.29
	concreate	24	74	540	1510	0.27	2.90	0.00	1.09
	“a sacco”	41	74	761	1390	0.25	1.52	0.00	0.22
	cavity	41	94	636	2065	0.23	1.85	0.00	0.23
Wall	concreate	49	84	1020	1510	0.26	1.56	0.00	0.11
	brick	19	58	174	377	0.17	1.48	0.01	1.11
	cavity	39	78	288	452	0.16	0.76	0.00	0.26
	facing brick	29	67	360	633	0.17	1.40	0.01	0.56
	thermal block	44	48	229	288	0.13	0.45	0.00	0.02
	new construction - highly insulated	30	38	105	155	0.15	0.38	0.01	0.04
Roof	wood	6	22	45	45	0.20	1.50	0.17	1.42
	brick pot	24	50	381	381	0.19	1.63	0.01	0.61
	eps pot	33	60	292	292	0.16	0.48	0.00	0.06
Floor	wood	14	32	27	27	0.40	1.09	0.07	0.96
	concreate	36	51	515	733	0.23	2.41	0.01	0.56
	with brick pot	34	60	617	617	0.19	1.57	0.01	0.32
	with eps pot	43	70	528	528	0.16	0.47	0.00	0.02
ceiling	wood	12	22	174	174	0.63	2.18	0.18	1.89
	brick tiles	20	25	379	379	0.52	2.72	0.18	1.72
	with brick pot	24	40	420	420	0.51	2.56	0.10	1.39
	with eps pot	24	38	399	399	0.16	0.41	0.00	0.04

operating hours for space heating. To account human habits and standard limits, manifold operating profiles for heating systems were defined, ranging from a minimum of 1 h (as deemed appropriate by [38]) to the maximum heating operating hours provided by the law [8] for each climatic zone (6 h for A, 8 for B, 10 for C, 12 for D, 14 for E) with increments of 1 h. For the F zone, since there were no set limits, a maximum of 16 h was assumed based on the findings of [38];

b. Indoor set point air temperature ($T_{set\text{-}point}$): to quantify the theoretical deviation of EPG resulting from the model simplification, unconventional indoor set point air temperatures were assumed based on the national report [38] and Author experience. Five indoor set point air temperatures ranging from 18 °C to 22 °C

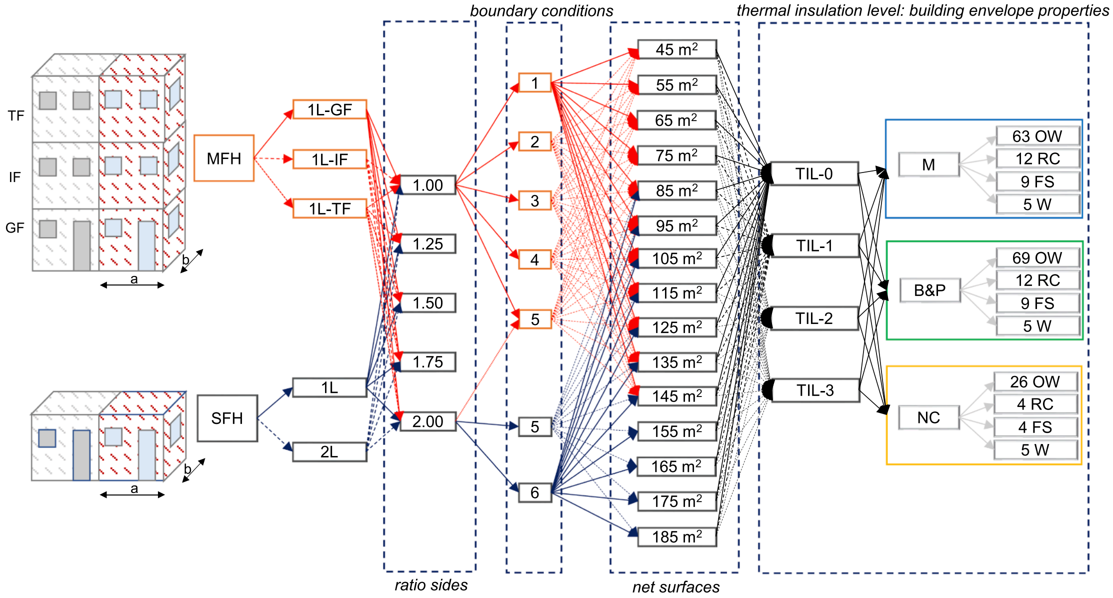


Fig. 3. Reference model definition (a = length, b = depth, SFH = single-family house, MFH = multi-family house, GF = unit at ground floor, IF = unit at intermediate floor, TF = unit at top floor, 1L = unit on one level, 2L = unit on two levels, 1L-GF = unit on one level at ground floor, 1L-IF = unit on one level at intermediate floor, 1L-TF = unit on one level at top floor, TIL = thermal insulation level, M = masonry, B&P = beams and pillars, NC = new construction technology, W = external wall, RC = roof ceiling, FS = floor slab, W = windows).

were investigated, and they were assumed as a fixed value across all the building units since they generally have only one temperature control for all the environments;

3. Analysis and comparison (red block): around 28 billion of EPCs were performed as well as for each TR, i.e. for each $T_{\text{set-point}}$ and h_{heating}. The obtained outcomes were thus compared to EPC ones allowing to quantify the theoretical deviation of EPG, i.e. the EPG due to the use of standard conditions, for the national building stock under different usage profiles and different thermal insulation configurations.

3.3. National overview and background

The national background represents the first crucial point from which the present work started. This first analysis has allowed learning about the state of the art of the building stock in geometric and thermal terms, allowing to define multiple reference models useful for the parametric analysis performed in this work. This study was based on the National Institute of Statistics [45] and national reports [38,46] which contain much different information useful for describing the state of the art of the building stock.

According to [45], in Italy, the number of buildings amounts to more than 14.4 million of which more than 84% are exclusive residential buildings (corresponding to more than 30 million building units). 86.1% of residential buildings were built before 1990, i.e. before the second more important national energy regulation on energy efficiency and performance of buildings, whilst more than 67% were built before the issue of the first national regulation of 1976 on energy containment of buildings. Less than 5% of buildings were built with higher energy efficiency standards, instead: around 3–4% were in agreement with the national regulations of 2005–2006, and only 1% with the current energy requirements provided by D.M 26 June 2015 [38,46].

Italy is divided into six climatic zones, indicated from A (the warmest) to F (the coldest), classified by Heating Degree Days (HDD) values introduced by D.P.R. 412/93 [47]. According to [45], it can be observed that approximately 47% of building units are built in the E zone, resulting the most representative climatic zone (Fig. 2 – blue bars), around 25% in D, less than 19% in C, about 8% in B, and the rest in F (about 2%) and in A (less than 1%). The majority of these units are predominantly in multi-family houses (MFH), making up around 67% of the total sample (Fig. 2), whilst single-family houses (SFH) comprise about 33%, mainly on one level.

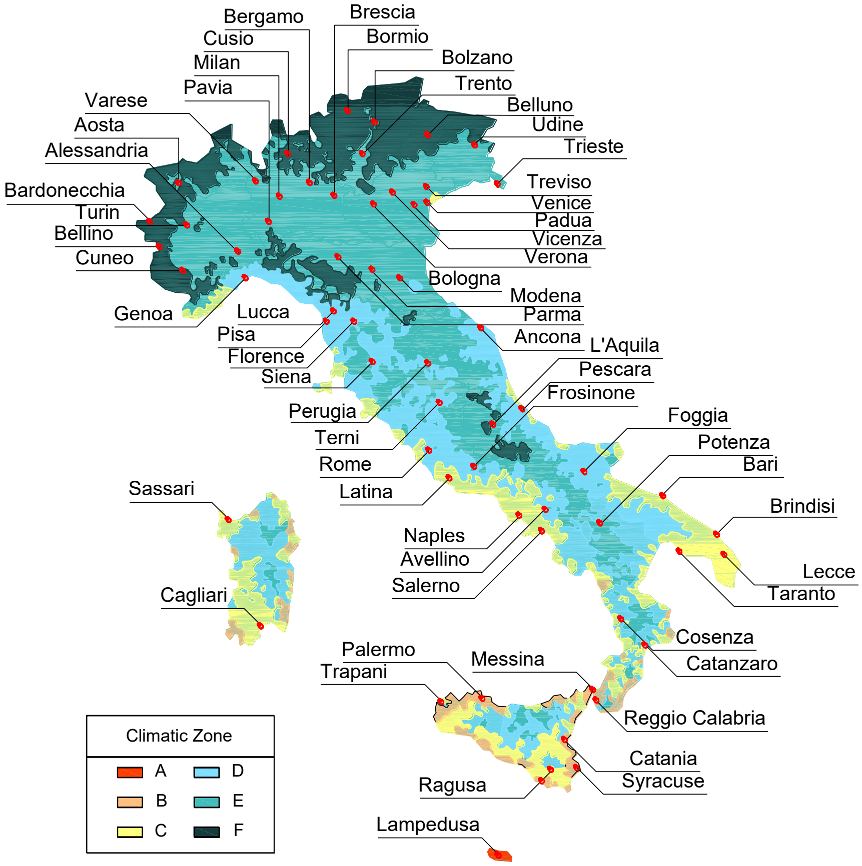
The mean and most representative net surface of building units (Fig. 2) is around 95 m^2, with a higher incidence in ranges: 60–79 m^2 (less than 24%), 80–99 m^2 (around 25%), 100–119 m^2 (16%), and 120–149 m^2 (11.0%). Particularly, it was observed that the most representative SFH have a net surface greater than 80 m^2 (97% of the sample), whilst the MFH has a higher incidence in 40–150 m^2 range (94% of the sample). According to Fig. 2, high values of net surface are generally more common for SFH whilst smaller values are representative of MFH.

A comprehensive analysis of construction materials used in the building industry was also carried out in the recent national study [38]. The study revealed that some materials, such as tuff or clay, are widespread only in some parts of the countries, causing a different thermal behaviour of the building envelope without thermal insulation. Conversely, the massive use of thermal insulation has led to a standardization of construction materials, resulting in a uniform thermal performance of the building envelope across the country, depending on the climatic zones. The study categorized building types into masonry, beams and pillar, and new construction, each with varying thermal properties of opaque and transparent surfaces, based on the prevalent construction materials and thickness of thermal insulation.

The thermal properties of the different opaque building envelope components were found to vary within the range shown in Table 1, whilst thermal transmittance of windows mainly varied between 1.0–4.0 W/m^2K. For a more detailed examination of this topic, readers are referred to the aforementioned report [38].

Furthermore, the same study [38] has provided useful information on the heating system: the most widespread heating system is a standard boiler (around 58%), followed by a condensing boiler (less than 30%), DHS (around 5%), and heat pump (less than 5%), but the last one mainly used in new construction or as integration to other heating systems. In addition, the main energy carriers are natural gas (more than 70% of the sample), biomass (around 14.5%), G.P.L. (about 5.8%), and electric energy (5.1%).

Based on data from the National Institute of Statistics [45] and the national reports [38,46], it is evident that the majority of the Italian



Climatic Zone	Cities	HDD	Altitude [m]	City BU	City P	Local representativeness BU	Local representativeness P
A (HDD≤600)	Lampedusa	568	16	5,190	6,337	5,563	6,395
B (600<HDD≤900)	Palermo	751	14	285,701	637,885	700,304	1,199,626
	Catania	833	7	144,577	300,356	575,343	1,068,835
	Messina	707	3	116,468	222,329	479,992	599,990
	Reggio Calabria	772	15	95,924	173,026	433,848	518,978
	Syracuse	799	17	59,993	117,053	305,445	383,743
	Trapani	810	3	37,069	65,378	414,846	415,233
C (900<HDD≤1400)	Lecce	1153	49	54,880	95,037	795,198	772,276
	Naples	1034	17	361,966	922,094	736,461	2,967,117
	Salerno	994	4	55,729	129,206	519,050	1,060,188
	Cosenza	1317	238	34,825	64,070	525,833	671,171
	Bari	1185	5	140,982	317,205	451,993	1,224,756
	Brindisi	1083	15	38,803	83,690	331,291	379,851
	Cagliari	990	4	71,161	149,572	330,836	419,770
	Sassari	1185	225	59,847	122,506	224,521	474,142
	Taranto	1071	15	90,960	190,717	353,625	558,130
	Ragusa	1324	502	46,296	72,579	306,263	315,082
	Latina	1220	21	53,507	127,560	304,284	565,840
	Catanzaro	1328	342	40,222	86,183	273,804	341,991
D (1400<HDD≤2100)	Rome	1415	20	1,258,241	2,770,226	989,752	4,222,631
	Florence	1821	50	171,441	368,419	328,848	994,717
	Foggia	1530	76	59,225	147,467	305,893	597,902
	Genoa	1435	19	309,566	566,410	248,697	816,250
	Ancona	1688	16	48,494	99,273	209,516	461,745
	Pescara	1718	4	59,883	118,766	152,939	313,346
	Lucca	1715	19	44,525	89,378	325,730	381,890
	Avellino	1742	348	22,870	52,819	316,646	399,623
	Pisa	1694	4	49,898	89,969	204,158	417,245
	Terni	1650	130	53,994	107,982	126,648	218,254
	Siena	1943	322	29,766	54,123	130,391	262,046
A+B+C+D	total	-	-	3,902,003	8,347,615	11,407,718	23,028,763
	%	-	-	16.2%	14.2%	47.3%	39.0%

Climatic Zone	Cities	HDD	Altitude [m]	City BU	City P	Local representativeness BU	Local representativeness P
E (2100<HDD≤3000)	Turin	2617	239	448,512	858,205	814,157	2,205,104
	Milan	2404	122	642,588	1,374,582	557,879	3,237,101
	Treviso	2378	15	40,823	84,837	497,264	876,755
	Verona	2468	59	121,823	258,031	429,109	927,108
	Venice	2345	1	133,283	256,083	401,383	839,396
	Perugia	2289	493	73,905	164,721	376,039	641,318
	Udine	2323	113	54,236	98,156	392,203	517,848
	L'Aquila	2514	714	29,505	69,349	281,845	288,439
	Bologna	2259	54	206,687	391,686	311,635	1,015,701
	Modena	2258	34	93,773	186,414	299,180	702,787
	Potenza	2472	819	30,722	65,420	289,588	348,336
	Bolzano	2791	262	48,495	107,467	215,326	535,774
	Trieste	2102	2	111,577	200,609	78,377	230,623
	Frosinone	2196	291	26,824	44,491	368,104	468,438
	Varese	2652	382	39,059	79,350	414,125	878,059
	Brescia	2410	149	98,503	197,304	580,309	1,254,322
	Vicenza	2371	39	58,058	111,113	484,512	852,861
	Trento	2567	194	58,186	118,879	315,009	542,158
	Pavia	2623	77	36,984	71,122	345,047	534,691
	Alessandria	2559	95	46,648	91,089	323,289	407,049
	Parma	2502	55	94,486	195,998	226,266	450,044
	Bergamo	2533	249	60,383	119,993	455,365	1,102,670
	Aosta	2850	583	18,469	33,523	108,664	34,361
	Padua	2383	12	100,434	209,730	481,825	930,898
F (HDD>3000)	Cuneo	3012	534	27,683	55,822	452,685	580,789
	Bellino	4264	1572	384	97	2,426	97
	Bormio	3838	1225	5,398	4,074	34,122	4,165
	Belluno	3043	389	20,347	35,522	128,619	198,518
	Bardonecchia	3043	1312	10,167	3,078	25,561	3,173
	Cusio	3546	1050	524	216	3,311	240
E+F	total	-	-	2,738,466	5,486,961	9,693,224	20,608,823
	%	-	-	11.3%	9.3%	40.2%	34.9%

Fig. 4. Distribution over the country of the 60 cities chosen for the parametric energy simulation.

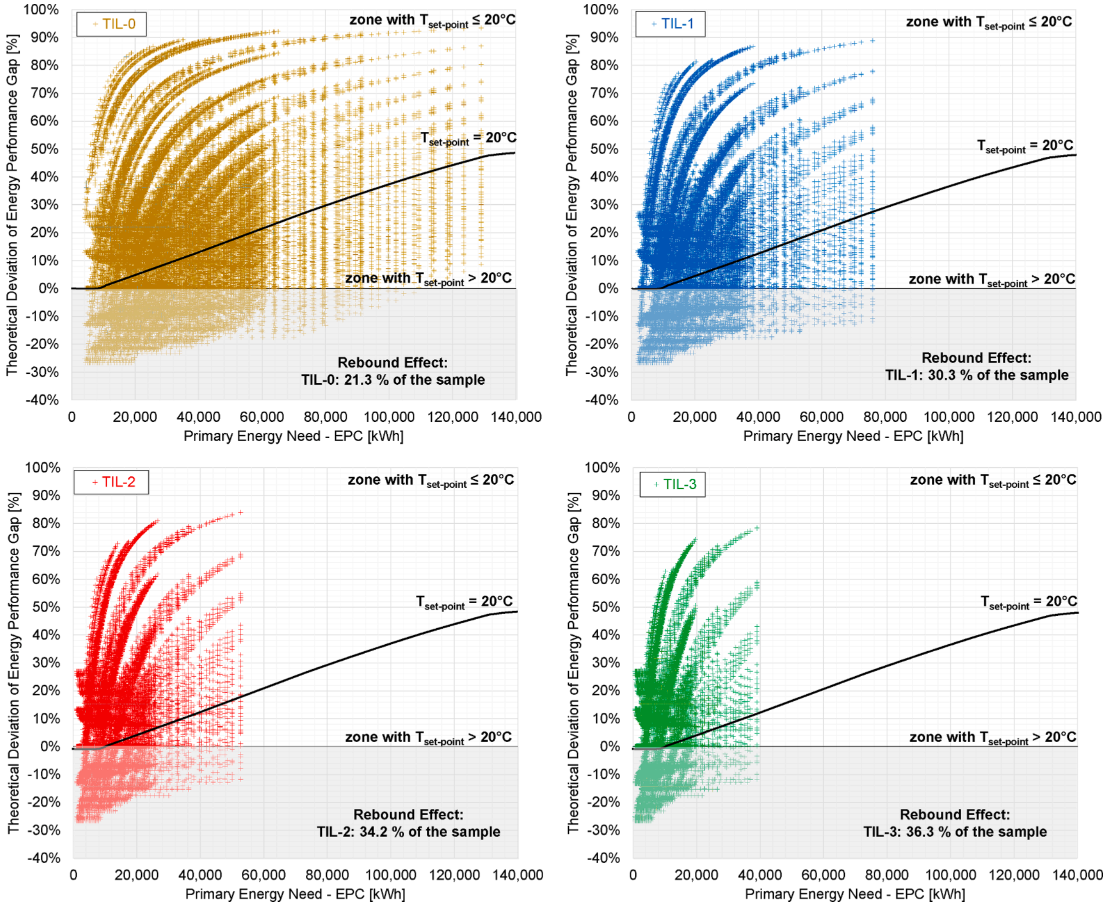


Fig. 5. Theoretical deviation of Energy Performance Gap ($EPG_{Th\text{-}De}$) for the four thermal insulation levels of buildings as a function of energy needs assessed with EPC.

building stock is located in colder climatic zones (more than 66% of buildings are in D, E, or F climatic zones), it has poor energy performance as they were built before 1990, and rely on natural gas boilers (standard or condensing) for space heating. This critical information was duly considered for defining the reference buildings and performing the parametric energy simulations.

3.4. Reference building definition

The characterization of the reference buildings was based on the national overview and background (section 3.3), i.e. on the ISTAT database [45] and on the national report carried out in 2019 [38], which allows defining the main geometric and thermal characteristics of the simulation models. Manifold reference buildings with rectangular planimetry were defined (following the pattern shown in Fig. 3) both for SFH and MFH by adopting the following approach:

1. SFH: they are generally detached buildings mainly on one (1L) and minimally on two (2L) levels. The ratio of the building sides (the ratio between *a* and *b* of the rectangular planimetry indicated in Fig. 3) was varied between 1 and 2 with 0.25 step, five or six surfaces were considered as the surfaces bordering on the outside (indicated with dashed red area in Fig. 3) or on other heated or unheated environments (grey volume in Fig. 3), and the net surfaces were varied in 85–185 m^2 range with 10 m^2 step according to the previous section (section 3.3). 220 reference models that differ in size and boundary conditions were thus defined, representative of more than 90% of SFH over the country;
2. MFH: multi-family houses group the semi-detached, terraced houses, and condominiums, i.e. building units generally on 1 level (1L) located at different floors (ground - GF, intermediate - IF, or top floor - TF) and with one to five sides adjacent to the outside or another building unit or unheated environment (indicated with dashed red area or grey volume as neighbouring building in Fig. 3). The same ratio of the building sides was also adopted (the ratio between *a* and *b* indicated in Fig. 3). Finally, according to the previous section (section 3.3), the net surfaces were varied in 45–145 m^2 range with 10 m^2 step, obtaining 715 reference models overall that differ in size and boundary conditions.

Based on the previous study of building envelope properties [38], three construction types were assumed: masonry (M), beams and pillars (B&P), and new construction (NC). Their thermal properties (specifically, their thermal transmittance) were selected from the ones shown in Table 1 considering the construction type:

1) Masonry: 63 walls, 12 roofs/ceilings, and 9 floors were selected from Table 1 [38], corresponding to thermal transmittance values falling into 0.22–3.40 W/m^2K range for opaque walls and into the 0.16–2.72 W/m^2K range for roofs/ceilings or floors;
2) Beams and pillars; 69 walls, 12 roofs/ceiling, and 9 floors were selected from Table 1 [38], corresponding to thermal transmittance values falling into 0.13–1.56 W/m^2K range for opaque walls and into 0.16–2.56 W/m^2K range for roofs/ceilings or floors;
3) New Construction: 26 types of walls, 6 roofs/ceilings, and 4 floors were selected from Table 1 [38]. All the adopted thermal

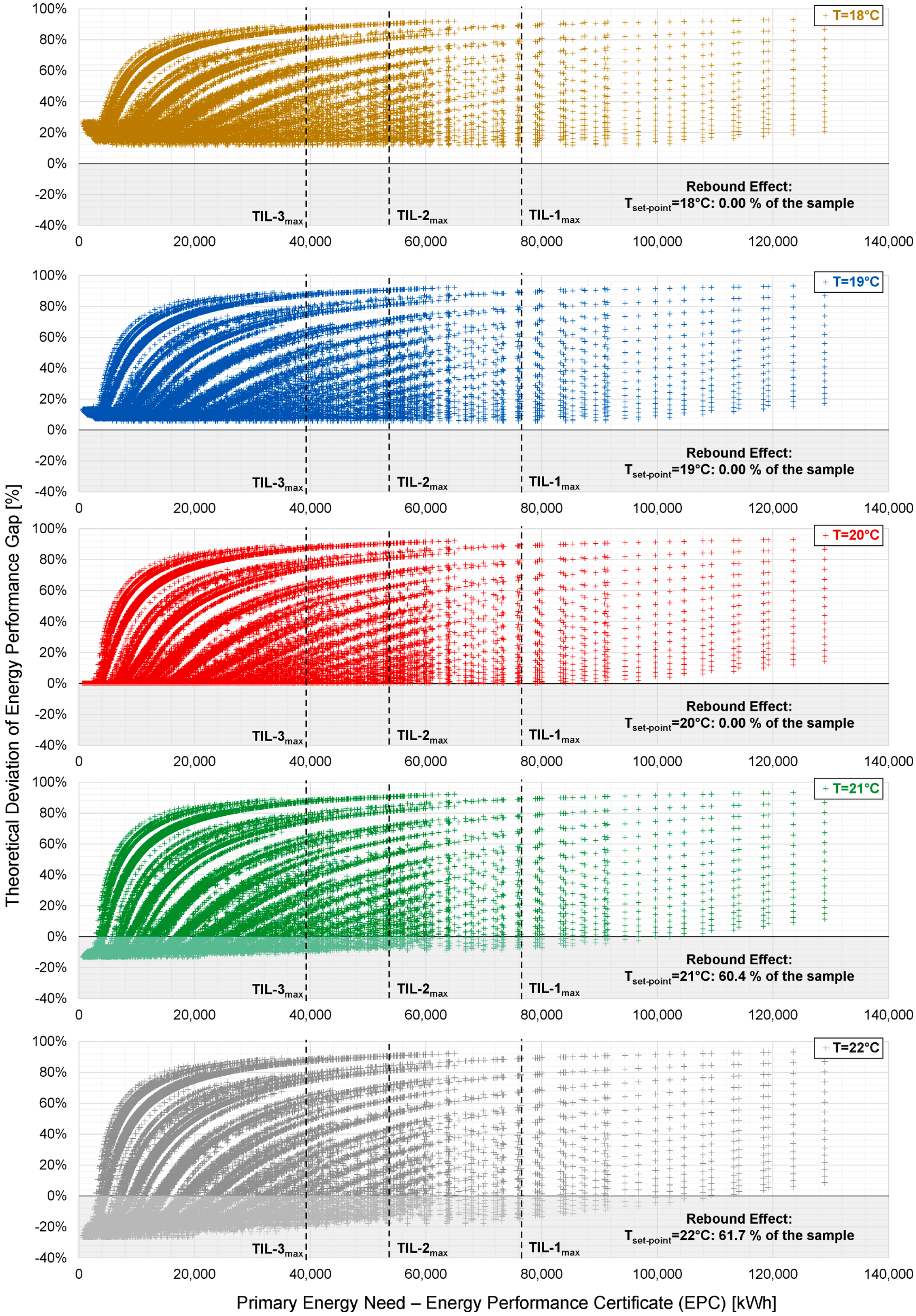


Fig. 6. Theoretical deviation of Energy Performance Gap ($EPG_{Th\text{-}De}$) for the five indoor set point air temperatures within the buildings as a function of energy needs assessed with EPC.

transmittance are lower than the limits depending on the climatic zone provided by national regulations [7].

The same study provides information on transparent surfaces allowing to characterize windows for all construction types. Unlike opaque surfaces, lower variability was found for transparent surfaces that can be well represented by adopting five types of windows having mean thermal transmittances equal to 3.5 W/m^{2}K, 2.7 W/m^{2}K, 2.0 W/m^{2}K, 1.3 W/m^{2}K, and 1.0 W/m^{2}K. All the chosen thermal properties were thus combined obtaining around 73,000 different configurations

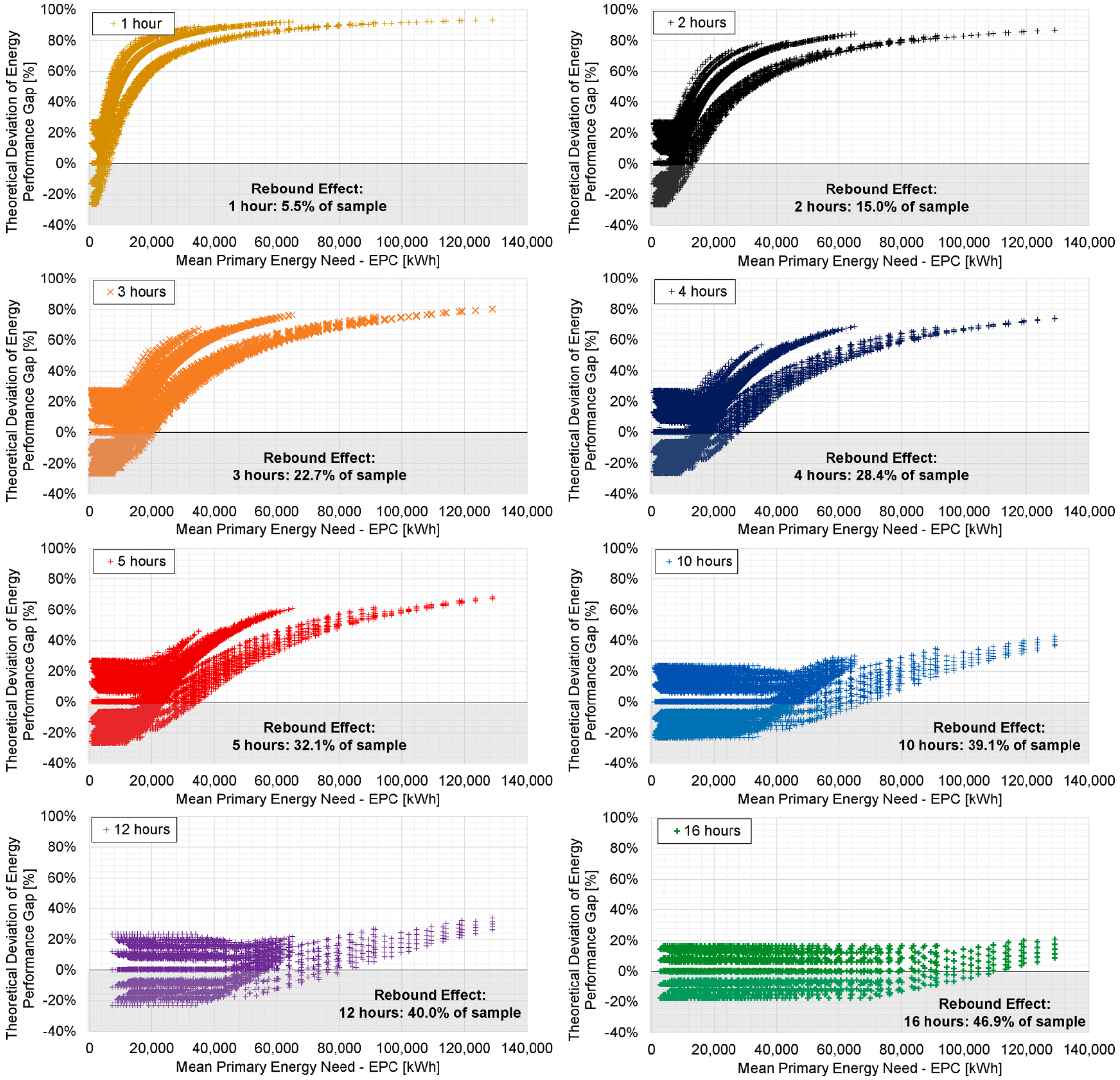


Fig. 7. Theoretical deviation of Energy Performance Gap ($EPG_{Th\text{-}De}$) for some heating operating profiles as a function of energy needs assessed with EPC.

which are adopted for the present parametric energy analysis.

Nevertheless, based on the thermal transmittance and surfaces of building components, national regulation [7] has defined the mean thermal transmission coefficient (H'$_T$) calculated as follow:

$$H_T^{'} = \frac{H_{tr}}{\sum_k A_k}\left(\frac{W}{m^2K}\right) \tag{2}$$

Where H_{tr} is the overall transmission heat transfer coefficient of the envelope (W/K) calculated using UNI/TS 11300-1 [8], and A_k is the surface area of the k-th component (opaque or transparent) constituting the building envelope (m^2). According to national regulation, H_{tr} has to be calculated considering the thermal transmittance and the exchange surface area of each building envelope component and adopting a correction value related to the wall exposition or indoor temperature of the thermal zone [8].

Based on this parameter, four insulation levels were also defined and used to group the reference models:

1. TIL-0: it corresponds to a building envelope without thermal insulation materials, i.e. with great values of mean thermal transmission coefficient (higher than 1.3 W/m^{2}K), a typical value for buildings built before 1990;
2. TIL-1: it corresponds to a building envelope with a small thickness of thermal insulation, i.e. to a mean thermal transmission coefficient around 1 W/m^{2}K (assumed in this work between 0.7 to 1.3 W/m^{2}K). It generally corresponds to buildings built between 1991 and 2000;
3. TIL-2: it corresponds to a building envelope with a good thermal insulation level, i.e. to a mean thermal transmission coefficient around 0.5 W/m^{2}K (assumed in this work between 0.3 to 0.7 W/m^{2}K). It is the typical value of buildings built around 2005 (between 2000 and 2015);
4. TIL-3: it corresponds to a building built with a high level of thermal insulation, i.e. buildings built after 2015 in compliance with the current national requirements for new construction, corresponding to a mean thermal transmission coefficient lower than 0.3 W/m^{2}K.

Reference model characterization was completed by taking into account the most widespread heating systems according to the national overview and background. Particularly, two systems were considered:

1. Configurations 1: it corresponds to a standard boiler (SB with nominal power equal to 26.3 kW, efficiency 0.93) with radiators as emission system, representing the most widespread space heating configuration in the country. It commonly works at high temperatures (around 80 °C) and it is generally used in old or poorly thermal insulated buildings (TIL-0 or TIL-1). Furthermore, manifold energy

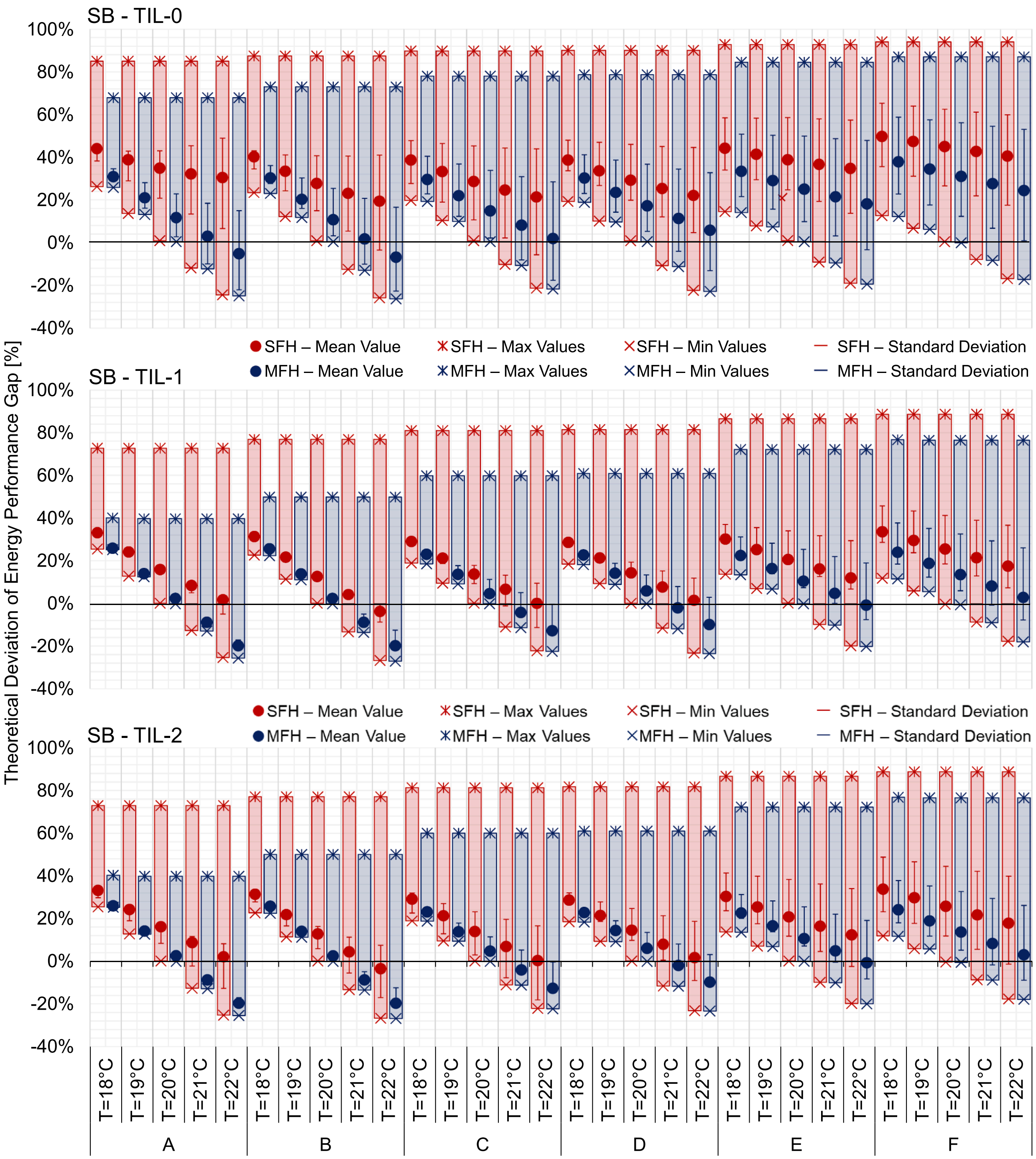


Fig. 8. Energy Performance Gap (EPG) for reference models with SB heating system and for TIL-0 (above), TIL-1 (middle), and TIL-2 (below) configurations: comparison between SFH (red) and MFH (blue) varying the indoor thermal conditions (from 18 °C to 22 °C) and climatic zones. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

policies were also implemented since 2014 to refurbish the building stock and to improve their thermal properties. For that reason, this configuration with good thermal insulated buildings (TIL-2) can be also possible;

2. Configurations 2: it corresponds to a condensing boiler (CB with nominal power equal to 26.7 kW, efficiency 0.97) with radiators as emission system, representing the current heating solution adopted over the country. It generally works at high temperatures (around 80 °C) and it is generally used in all kinds of buildings, for old or poorly thermal insulated buildings (TIL-0 or TIL-1), for renovated or good thermal insulated buildings (TIL-2), or new construction (TIL-3).

Other types of emission and generation systems (such as radiant panels and heat pumps) are less widespread over the country, as described in the previous section, and they are mainly adopted in new construction (about 1%). Hence, they have not been taken into account in the present work.

Considering the definition of reference models thoroughly shown in Fig. 3, as well as the technical characteristics of the heating systems, around 17 million possible configurations for SFH and more than 53

Fig. 9. Energy Performance Gap (EPG) for reference models with CB heating system and for TIL-0 (above), TIL-1 (middle-above), TIL-2 (middle-below), and TIL-3 (below) configurations: comparison between SFH (red) and MFH (blue) varying the indoor thermal conditions (from 18 °C to 22 °C) and climatic zones. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

million for MFH (about 30–32 million for units located on the ground floor or the top floor, and about 18–20 million for the one located on the intermediate floor) were thus defined for each thermal insulation level and heating configuration.

Finally, reference models should be representative of the national building stock by taking into account also the climatic outdoor conditions in terms of outdoor air temperature, solar radiation, and air speed. Based on [45], for each climatic zone, cities with the higher number of building units (BU), more populated (P), and with different outdoor climatic conditions were chosen with the aim of selecting the most representative cities over the country. 60 cities were selected overall, which individually represent about 22% of the national building

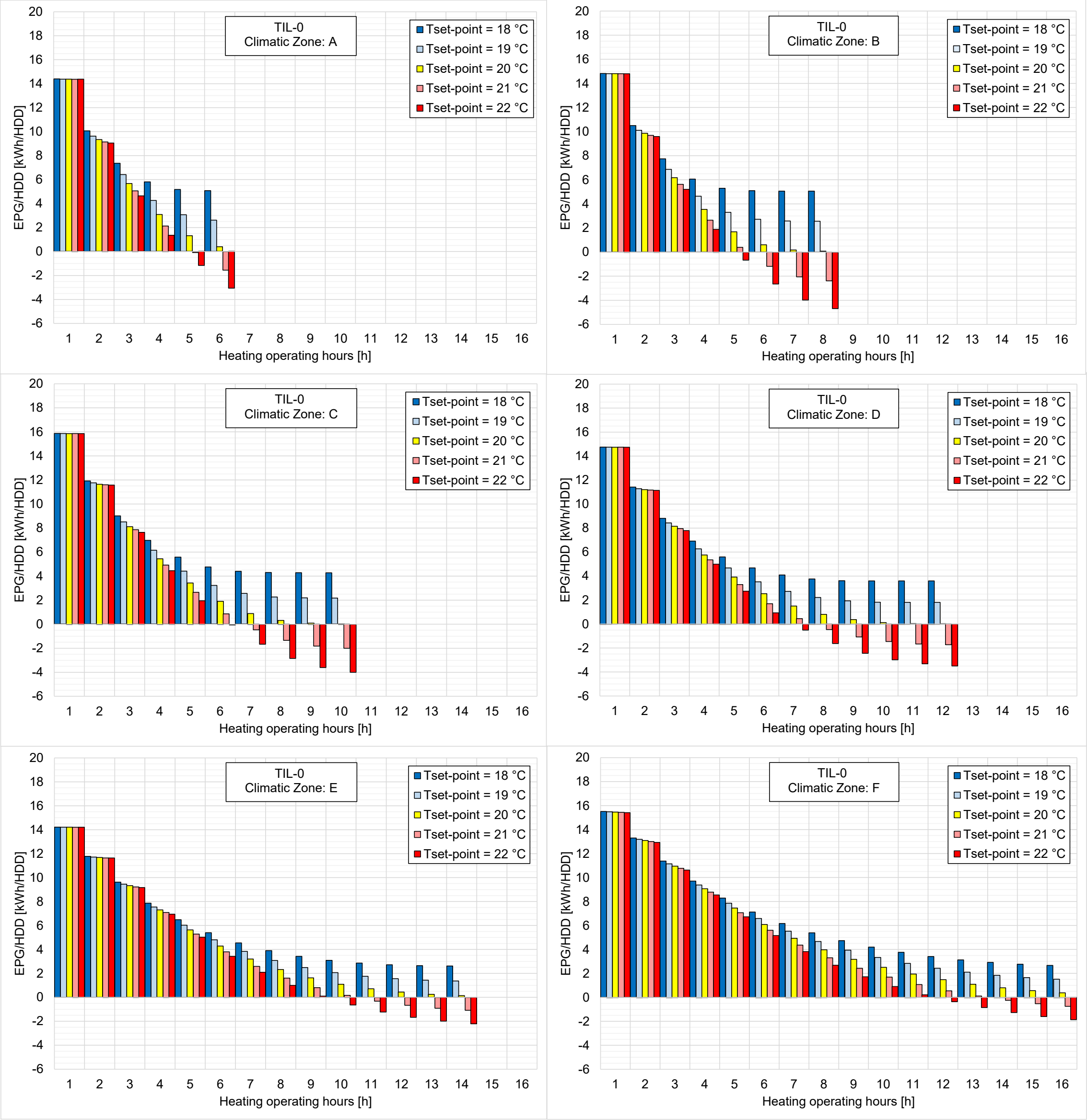


Fig. 10. Energy Performance Gap (EPG) normalized for the mean Heating Degree Day assessed for each climatic zone: reference models falling in TIL-0 configuration under different usage profiles and climatic zones.

stock and 23% of the national population (total population close to but lower than 60 million [45]). Nevertheless, the selected cities have climatic conditions that well represent the smaller neighbouring towns. If this local representativeness is also taken into account, the chosen cities would cover more than 73% of the population and more than 68% of the building units. Hence, for the present work, these cities were considered representative of the national country.

The distribution over the country of the selected cities is highlighted in Fig. 4, whilst the number of BU and the population covered by them are detailed in the table below. Besides, although cities falling in F climatic zone as Bellino, Bardonecchia, and Cusio have a small number of both BU and population, they have been selected for their severe climatic conditions which differ from the other ones of the same climatic zone.

Considering the good distribution over the country, the selected cities were considered as well representative of the national overview and suitable for the parametric energy simulations.

4. Results and discussion

Theoretical deviation of EPG ($EPG_{Th\text{-}Dev}$) was firstly analysed as a function of the most significant parameters considered in this work; it was assessed as the relative difference of the energy needs (EN) returned by EPC and TR assessment for all the heating operating profiles:

$$EPG_{Th-Dev} = \frac{EN_{EPC} - EN_{TR_{h_{heating}}}}{EN_{EPC}} \tag{3}$$

According to this assumption, negative values indicate rebound effect (i.e. the simulated energy consumption is greater than the EPC one), whilst positive values indicate prebound effect (i.e. the simulated energy consumption is smaller than the EPC one).

In Appendix A, the mean energy needs of EPC and the mean theoretical deviation of EPG were reported under different climatic zones, heating operating profiles, and thermal insulation levels, whilst, in this section, the main relative results and considerations were shown.

Firstly, the influences of the thermal insulation level (TIL) of buildings, the indoor set-point air temperature ($T_{set\text{-}point}$), and the heating operating profiles ($h_{heating}$) on the theoretical deviation of EPG were

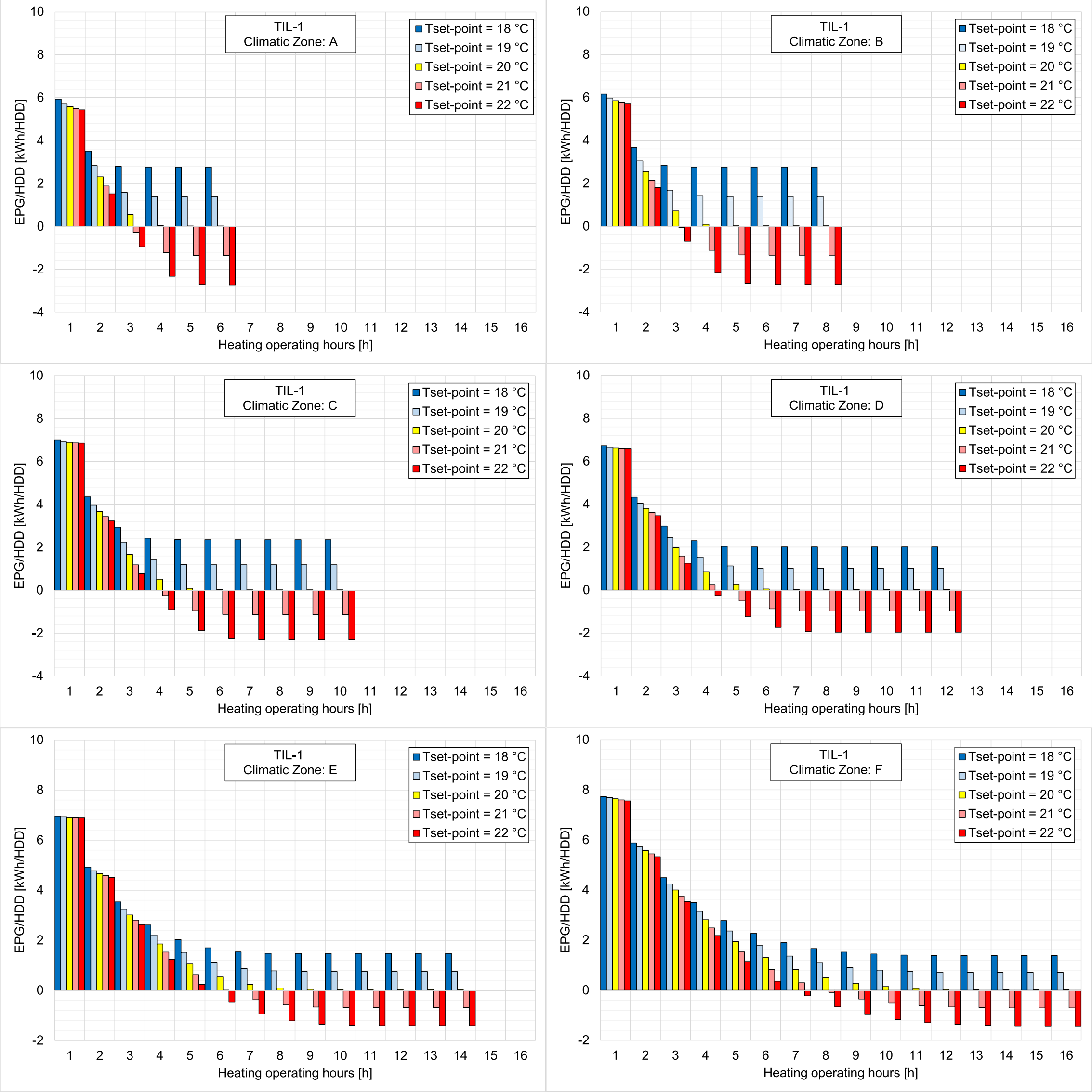


Fig. 11. Energy Performance Gap (EPG) normalized for the mean Heating Degree Day assessed for each climatic zone: reference models falling in TIL-1 configuration under different usage profiles and climatic zones.

analysed as a function of primary energy need of EPC. Results allow highlighting the following:

- Influence of thermal insulation level (TIL) of buildings (Fig. 5): data related to different thermal insulation levels (TIL) was distinguished by different colours, ranging from gold for TIL-0 to green for TIL-3. The indoor set-point air temperature ($T_{set\text{-}point}$) above or below 20 °C is indicated by a dividing line marked in black. To highlight the prebound (positive values) and rebound (negative values) effects, a grey zone is depicted: cases falling in this grey area exhibit rebound effects. As expected, models with poor thermal properties (TIL-0 in gold) show higher energy needs in EPC evaluation, resulting mainly in $EPG_{Th\text{-}Dev}$ greater than 0% (i.e., with the prebound effect). Nevertheless, interestingly, 21.7% of TIL-0 models shown the rebound effect (when $EPG_{Th\text{-}Dev}$ is lower than 0%), while 51.9% and 54.8% of models with $T_{set\text{-}point}$ set at 21 °C and 22 °C, respectively, shown the rebound effect. With the improvement of the thermal properties, a clear reduction of energy needs in EPC is observed, as well as an increase in the number of cases falling in the rebound effects, up to 36.3% of the sample models in the TIL-3 configuration (green symbol). Notably, for TIL-1, TIL-2, and TIL-3, more than 70%, 80%, or 90% of models with indoor set-point air temperatures set at 21 °C or 22 °C exhibit the rebound effect, highlighting the significant influence of these two parameters on the theoretical deviation of EPG. Moreover, it is worth underlining that this trend is more pronounced for $T_{set\text{-}point}$ set at 21 °C or 22 °C, mainly due to the assumptions made in this study;
- Influence of indoor set-point air temperature (Fig. 6): each series of indoor set-point air temperatures was denoted with different colours (ranging from gold for Tset-point = 18 °C to grey for Tset-point = 22 °C). In addition, the EPC limit was marked for each thermal insulation level configuration by a black dashed line. A noticeable finding of this study is the impact of indoor set-point temperatures greater than 20 °C on the energy performance gap. As the energy need of models decreases (i.e., as the thermal insulation level of buildings improves), the number of cases exhibiting the rebound effect significantly increases when the indoor set-point air temperature is greater than 20 °C. Particularly, more than 50% of models with $T_{set\text{-}point}$ equal to 21 °C or 22 °C exhibit the rebound effect when the energy need is less than 30 MWh, while this percentage reduces for higher energy needs (around 10–20% for primary energy need higher than 100 MWh). The results indicate that overall, more than

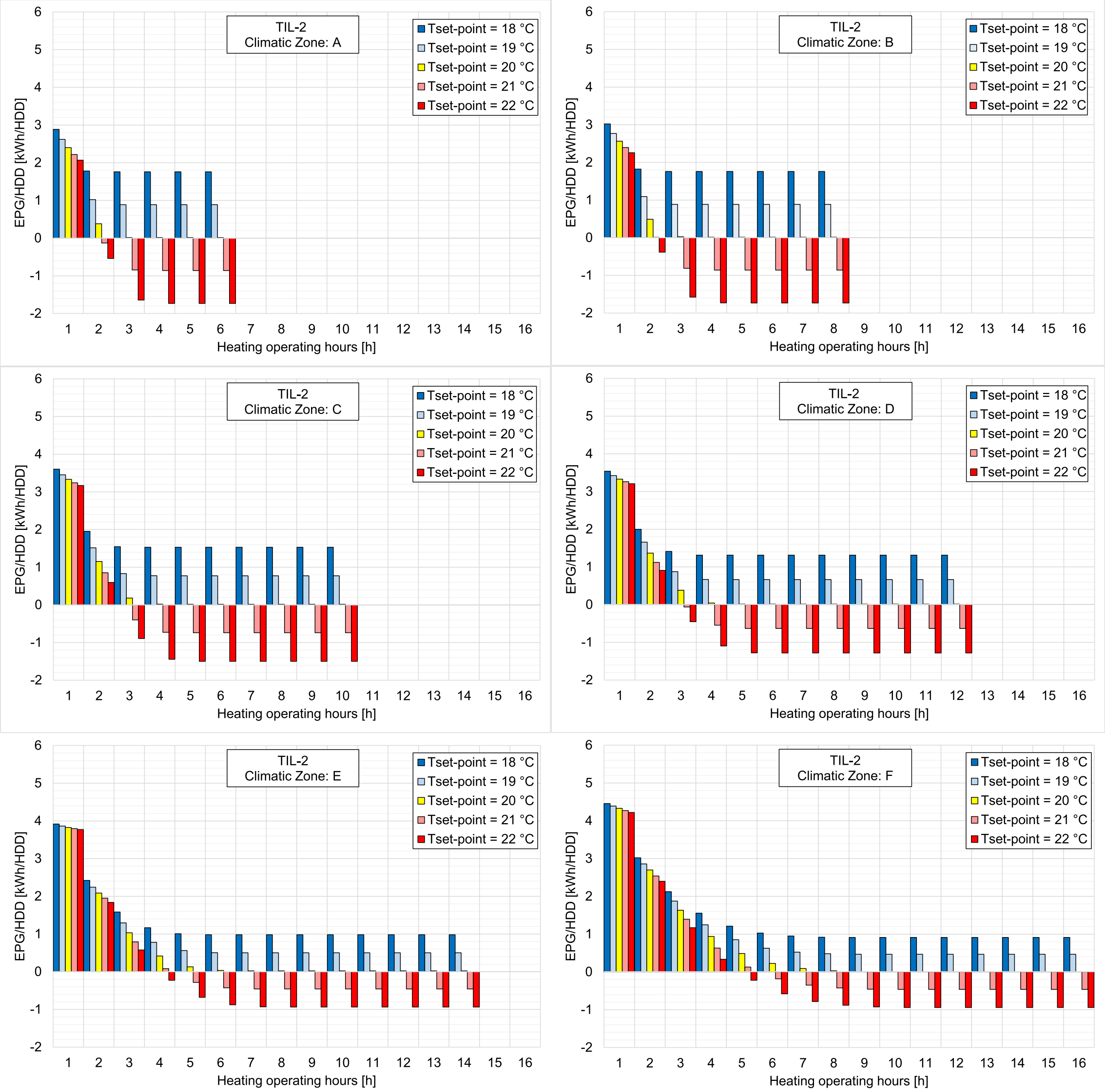


Fig. 12. Energy Performance Gap (EPG) normalized for the mean Heating Degree Day assessed for each climatic zone: reference models falling in TIL-2 configuration under different usage profiles and climatic zones.

60% of models with $T_{\text{set-point}}$ equal to 21 °C or 22 °C exhibit the rebound effect;

- Influence of heating operating profiles (Fig. 7): the results revealed a remarkable disparity among profiles, with a logarithmic trend observed for lower operating profiles (from 1 to 5 h), indicating a failure to meet the actual energy needs for most cases (the greater distance from the x-axis, the greater $EPG_{\text{Th-Dev}}$ values). On the other hand, the trend for greater operating profiles (10–16 h) exhibited a flattening trend, indicating their ability to meet the energy needs of the majority of the models. Notably, the rebound effect increased almost linearly, albeit with a gradually declining trend, with the heating operating profile. Up to the profile "5 h" the increase of rebound effect can be considered almost linear, getting around 32.1% of the sample exhibited rebound effect, whilst for the heating profiles with more hours, from "10 h", the increase of rebound effect is slower up to reach the maximum values for profile "16 h", up to 46.9% of the sample. Furthermore, a clear separation between prebound and rebound case studies was observed for the 10–16 h operating profiles, indicating that these profiles were able to meet the energy needs of the reference models. The intersection point with the x-axis was also observed for small values of energy needs, ranging from 2100 kWh (1 h) to 6000 kWh (4 h), corresponding to more insulated or smaller net surfaces of the models.

According to these results, prebound effect seems to be the most likely outcome if the same climatic conditions of EPC are set; on the other hand, as also highlighted in previous works [22-25], the rebound effects could be also possible but only if indoor air set-point temperature is higher than 20 °C. However, this does not imply that rebound effects are not possible in other configurations or for lower indoor set-point air temperatures, but it has been confirmed that rebound effects could be possible only if the outdoor climatic conditions are milder than the standard ones, which means that the climate is warmer.

The EPG outcomes were thus grouped for thermal insulation level of models, heating systems, and building types; they were shown in Fig. 8 and in Fig. 9 for each heating configuration. Particularly, the red series represent the $EPG_{\text{Th-Dev}}$ obtained for SFH building types, whilst the blue is the one related to MFH. The mean $EPG_{\text{Th-Dev}}$ values are highlighted with dots, the minimum (corresponding to the maximum heating profile provided by the law for each climatic zone) and the maximum values (corresponding to the heating profile equal to 1 h assumed as the minimum heating profile in this work) are marked with X ($EPG_{\text{Th-Dev-min}}$) and *($EPG_{\text{Th-Dev-max}}$) symbols respectively, whilst the continuous lines

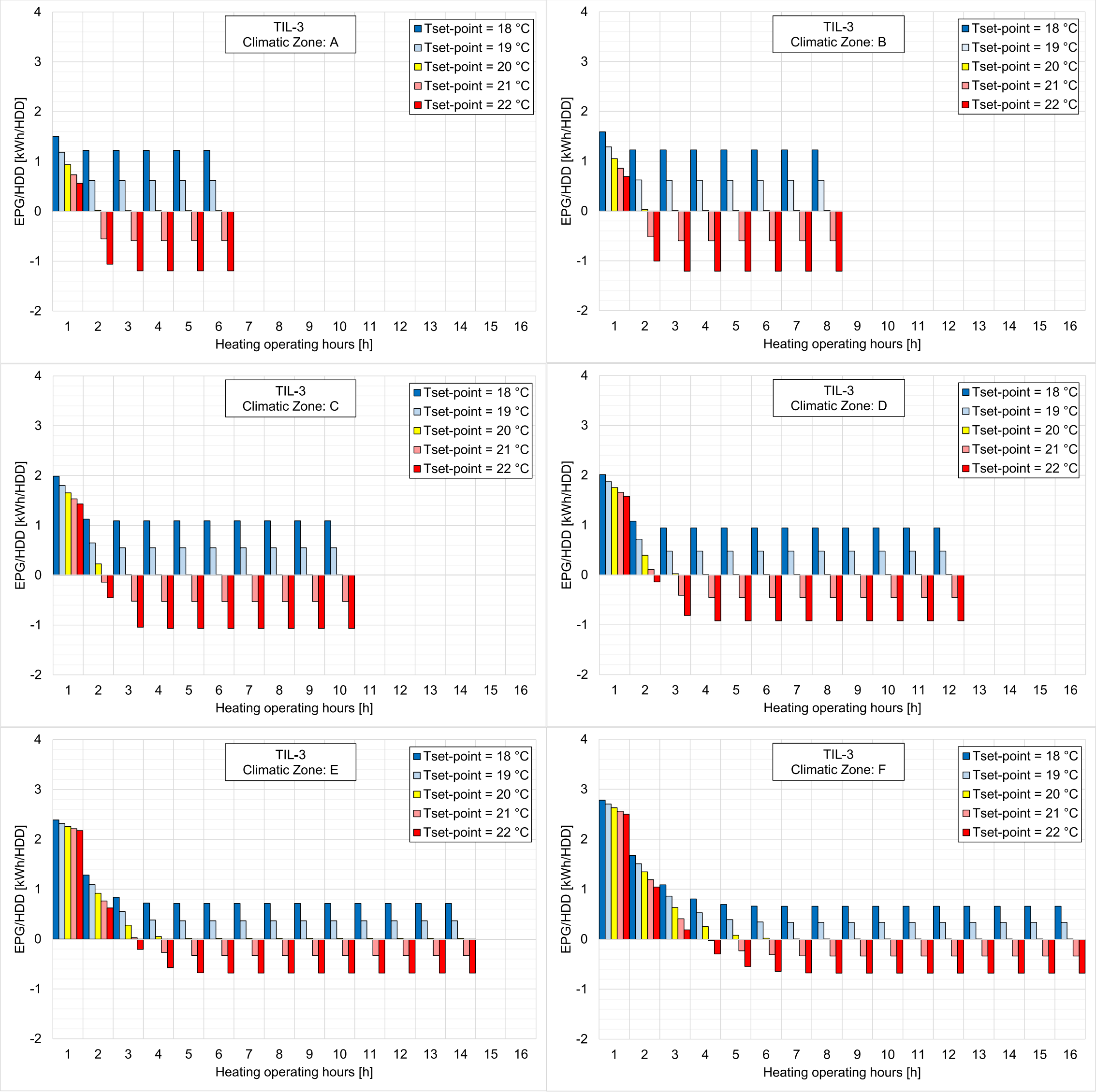


Fig. 13. Energy Performance Gap (EPG) normalized for the mean Heating Degree Day assessed for each climatic zone: reference models falling in TIL-3 configuration under different usage profiles and climatic zones.

represent the standard deviation from the mean values. Finally, the red or blue transparent areas represent the $EPG_{Th\text{-}Dev}$ range found for each investigated configuration (for different reference models and heating operating profiles).

Interesting trends were found highlighting prebound and rebound effects in both the heating systems with varying degree of incidence.

Because of the assumption of this work, findings suggest that prebound effects were prevalent in indoor set-point air temperatures lower or equal to 20 °C, assuming the same outdoor climatic condition. It's worth noting that the absence of rebound effects does not rule out the possibility of their occurrence in such a configuration, but rather confirms that they're more likely to manifest under warmer weather conditions. At the same time, the range of $EPG_{Th\text{-}Dev}$ variations for indoor air temperatures around 18 °C was smaller, indicating that rebound effects are unlikely to occur, even under warmer climatic conditions.

According to these figures, a similar trend can be also highlighted for both heating systems, such as:

1. $EPG_{Th\text{-}Dev}$ range (depicted as the red or blue areas) widens for both SFH and MFH as the indoor set-point air temperature and severity of the climatic zone increase. This means that EPG increases with the increase in energy needs. Interestingly, SFH (the red areas) exhibits a broader $EPG_{Th\text{-}Dev}$ range than the MFH, implying that the energy needs for MFH are generally lower in both EPC and TR assessments;
2. The $EPG_{Th\text{-}Dev\text{-}max}$ (*symbol) remains constant with the indoor set-point air temperature, except for the highly efficient MFH buildings (falling in TIL-2 and TIL-3 configurations) located in the warmest climatic zone (A), where it decreases with the indoor set-point air temperature up to −21% ($T_{set\text{-}point}$ = 22 °C). For SFH, the $EPG_{Th\text{-}Dev\text{-}max}$ falls within the range of +44% to +93% depending on the climatic zone (with colder zones having higher $EPG_{Th\text{-}Dev\text{-}max}$ values), whilst for MFH it falls within the range of −21% to +87%. This trend suggests that rebound effects are more likely to occur for the highest operating heating profile;
3. The $EPG_{Th\text{-}Dev\text{-}min}$ (X symbol) remains the same for both SFH and MFH, but it decreases with the harshness of the climatic zone. It undergoes significant changes with the indoor set-point air temperature, leading to the emergence of both prebound and rebound effects. Its values fall within the range of −26% to +25%, indicating the possibility of prebound or rebound effects. The likelihood of observing these effects increases with the greater operating heating profiles;

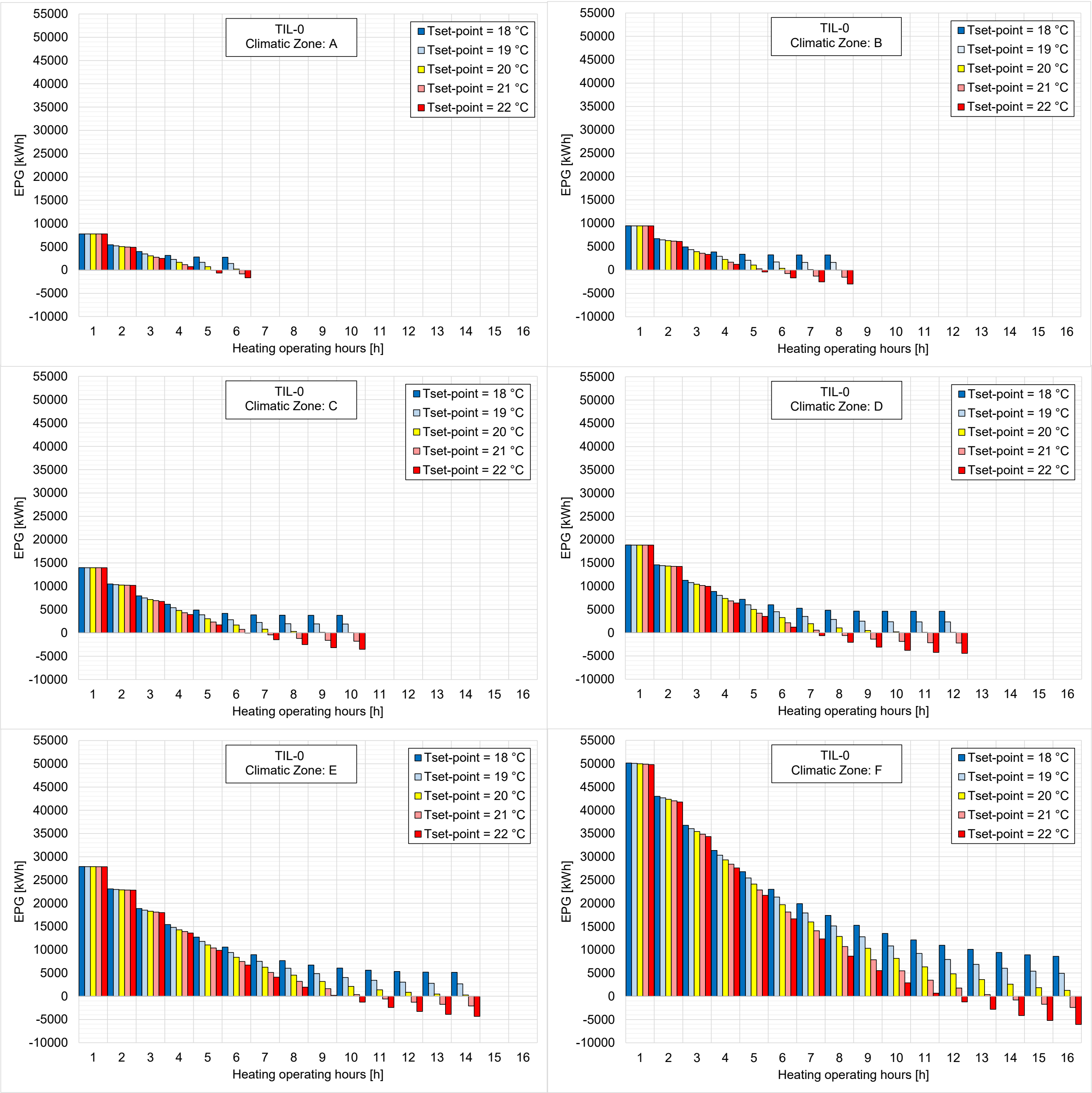


Fig. A1. Mean Theoretical Deviation of EPG (expressed in kWh) as a function of operating heating profiles, climatic zone, and indoor set-point temperature: building falling in TIL-0 configuration.

4. The $EPG_{Th\text{-}Dev\text{-}mean}$ (depicted as red or blue dots) reveals intriguing trends. While it decreases with increasing indoor set-point air temperature, it tends to rise with climatic severity of the city (at the same indoor set-point air temperature). These findings suggest that greater the energy needs translate to a larger theoretical deviation of EPG. Additionally, $EPG_{Th\text{-}Dev\text{-}mean}$ in MFH are consistently lower than those in SFH (7.4% vs 17.2% on average, meaning a greater likelihood of higher EPG in the latter. This trend is particularly pronounced for TIL-3 configuration, indoor set-point air temperature lower than 20 °C, and in the warmest climatic zone. Moreover, in MFH, $EPG_{Th\text{-}Dev\text{-}mean}$ is skewed towards the minimum value, meaning that rebound effects are more likely to occur with a greater number of operating heating profiles. Notably, the decreasing trend of the mean $EPG_{Th\text{-}Dev}$ values is primarily influenced by the buildings' thermal insulation level, with higher insulation leading to a more significant decline. This trend is consistent across all the building configurations, with MFH showing a greater decrease even for TIL-0 configurations compared to SFH;
5. Standard deviation (lines in red or in blue) related to the mean value assumes considerable values only for SFH, especially for TIL-0 and TIL-1 configurations. On the other hand, for the more efficient MFH (i.e., those in TIL-2 and TIL-3 configurations), the standard deviation assumes values around ±0–5%, depending on the climatic zone. This trend suggests that the rebound effect is obtained only for a small percentage of the sample, even at the indoor air temperature higher than 20 °C, confirming that the prebound effect is the more likely outcome;
6. This trend corroborates previous findings, suggesting that the rebound effect is more likely to occur in new constructions with lower energy needs, particularly in multi-family buildings (MFH)

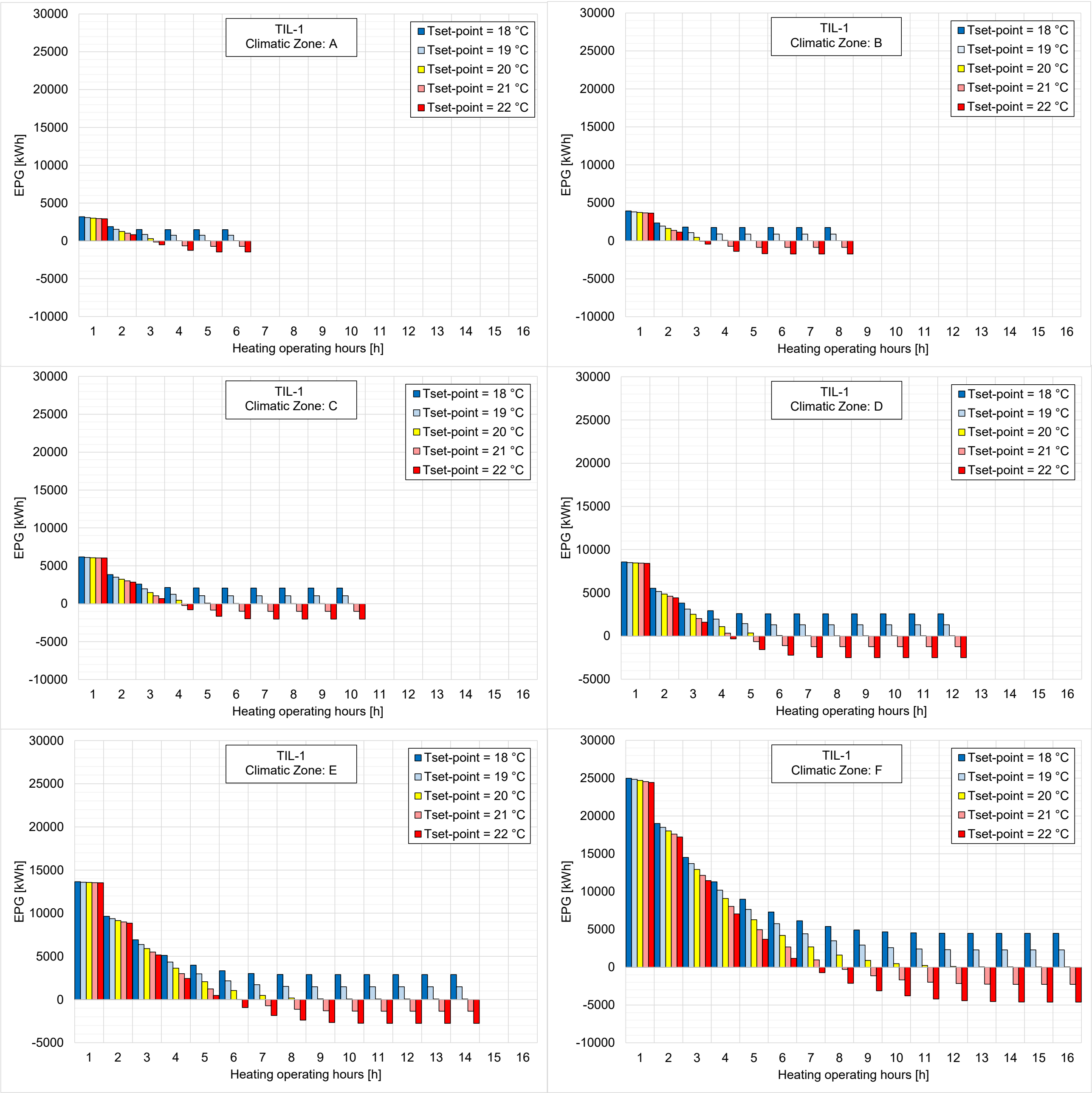


Fig. A2. Mean Theoretical Deviation of EPG (expressed in kWh) as a function of operating heating profiles, climatic zone, and indoor set-point temperature: building falling in TIL-1 configuration.

where the $EPG_{Th\text{-}Dev\text{-}mean}$ assumes negative values in both TIL-2 and TIL-3 configurations;

7. Changing heating systems (SB or CB) produces negligible variations, indicating a limited influence of the heating systems on the theoretical deviation of EPG.

Fig. 8 and Fig. 9 suggest that the prebound effect is the most likely outcome in all the examined reference models; nevertheless, it is worth noting that rebound effects could still occur under certain circumstances, namely when:

1. the indoor set-point air temperature is greater than 20 °C;
2. the energy need of reference models is low, typically corresponding to smaller net surface areas of buildings or better thermal properties of the building envelope;
3. the operating profile for space heating is high or tending to the maximum profile provided by the law.

Finally, to quantify the theoretical gap, the mean EPG found under different boundary conditions, such as indoor set-point air temperature, thermal insulation of building, climatic zone, and operating heating profile, was normalized for the mean HDD value assessed for each climatic zone. Results were shown from Fig. 10 (TIL-0 configuration) to Fig.13 (TIL-3 configuration)), highlighting the histograms blue for $T_{set\text{-}point}$ lower than 20 °C and in red for $T_{set\text{-}point}$ greater than 20 °C, as a function of the climatic zone and heating operating hours (on the abscissa).

Interesting outcomes can be highlighted; firstly, the order of magnitude of EPG is primarily dependent on the usage profiles (heating operating hours and indoor set-point air temperatures) and thermal

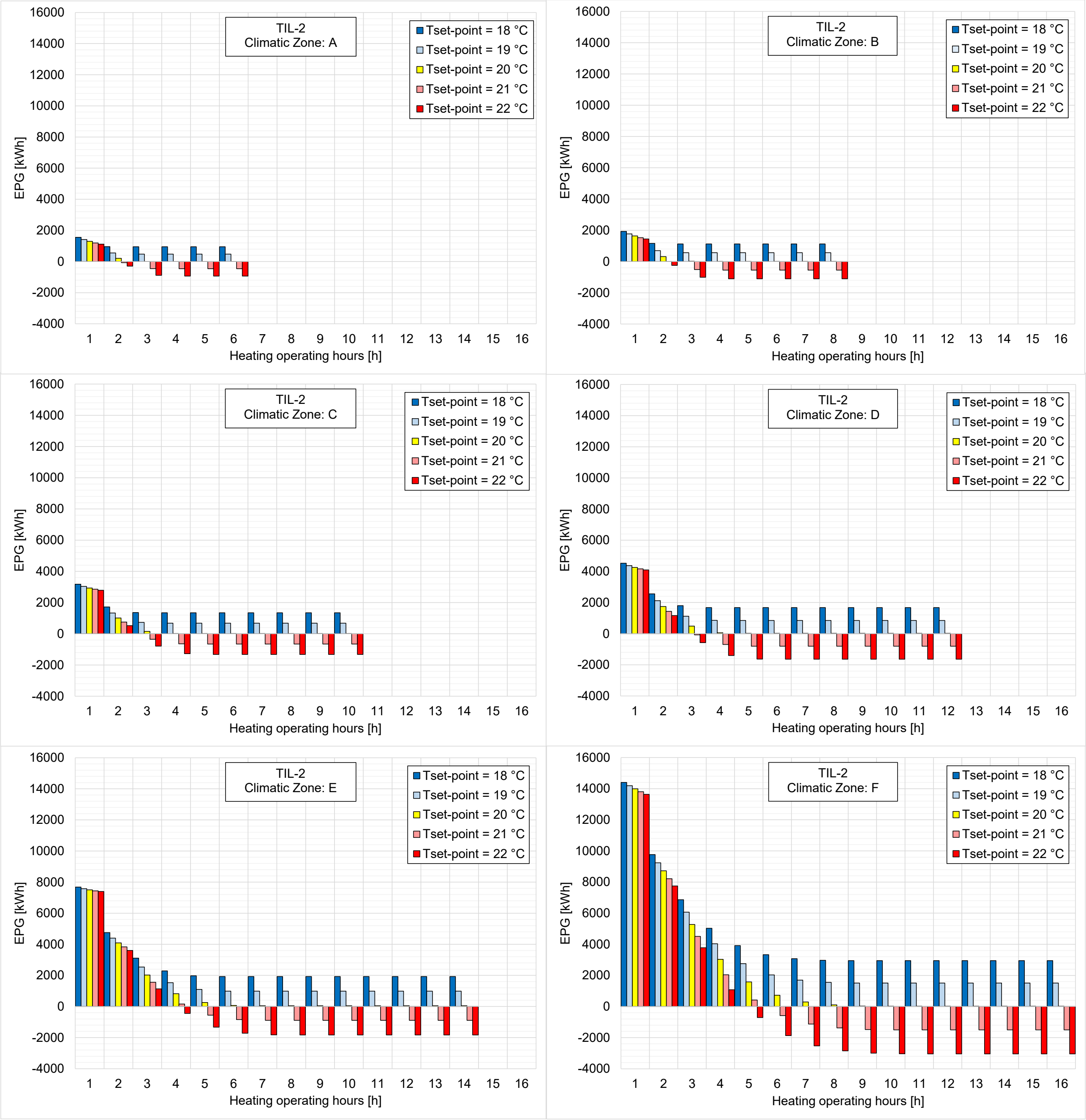


Fig. A3. Mean Theoretical Deviation of EPG (expressed in kWh) as a function of operating heating profiles, climatic zone, and indoor set-point temperature: building falling in TIL-2 configuration.

insulation of building envelope (TIL) rather than the climatic zone. The highest EPG values were found for TIL-0 configuration (around 14–16 kWh/HDD) when "1 h" profile is adopted for space heating. However, this value decreased with the increase of thermal insulation level of buildings, reaching values of 6–7 kWh/HDD for TIL-1, 3–4 kWh/HDD for TIL-2, and 2–3 kWh/HDD for TIL-3.

Furthermore, the figures provided evidence that rebound effect already occurs with a smaller heating operating profile than the one provided by the regulations. Specifically, the heating operating hours for which the rebound effect is observed tend to decrease with increasing severity of the climatic zone and increasing thermal insulation of buildings. As the energy need of buildings decreases with higher thermal insulation, the number of operating hours for which the rebound effect occurs also decreases.

The quantification of the theoretical deviation of EPG as a function of the thermal insulation level of buildings and the more actual usage profiles, provides an opportunity to correct the results of the EPC. Indeed, if the building's usage profiles were known, it would be possible to adjust the EPC results by utilizing the average EPG values obtained in this study, as illustrated in Fig. 10 through Fig. 13.

To better explain this concept, a practical example is provided. Consider a building located in Perugia, Italy, which falls in the E climatic zone, without thermal insulation on building envelope (TIL-0), and an indoor set point temperature of 19 °C with a heating operating profile averaging 2 h per day. Based on Fig. 10, the mean theoretical deviation is estimated to be around 12 kWh/HDD, i.e., around 27,400 kWh (as the Heating Degree Day (HDD) of Perugia is equal to 2283). This indicates that if the energy consumption calculated using the standard method

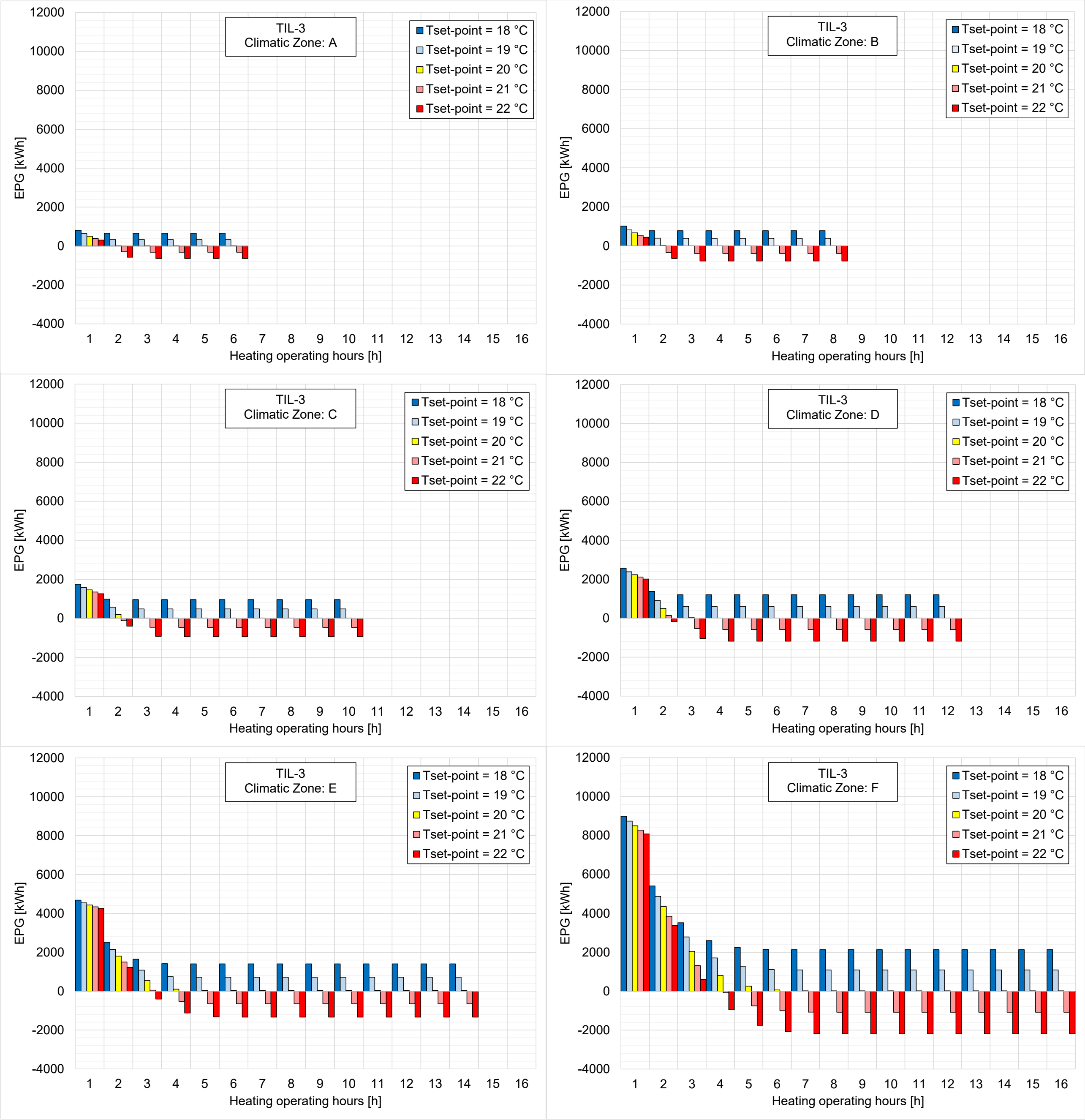


Fig. A4. Mean Theoretical Deviation of EPG (expressed in kWh) as a function of operating heating profiles, climatic zone, and indoor set-point temperature: building falling in TIL-3 configuration.

(EPC) was approximately 50,000 kWh, the more realistic energy consumption for the building under those conditions could be around 22,600 kWh. On the contrary, if the same building has a heating operating profile of 10 h per day, the difference could be around 2.5 kWh/HDD (Fig. 13), i.e., approximately 5,700 kWh, indicating that the most realistic energy consumption of the same building (assuming the same energy consumption of previous example) under those new conditions could be around 44,300 kWh.

Obviously, this represents only a first attempt at correction that needs further studies as well as validation with real case studies in order to be reliable, but at the same time, it already provides a rough indication of the effect of standard conditions on a building's energy consumption.

5. Conclusion

Energy-efficient buildings are crucial for reducing energy consumption and achieving sustainability goals. However, there is a gap (namely Energy Performance Gap) between the energy performance assessed with standard calculations (the one adopted in Energy Performance Certificates) and the actual energy consumption of buildings, resulting in a crucial issue as it can affect national policies and the effectiveness of energy refurbishment actions.

To address this problem, the present work focused on quantifying the theoretical deviation of the Energy Performance Gap (EPG) in the Italian building stock, i.e., the one resulting from the standard assumptions adopted in EPC assessment, such as the heating operating hours and the indoor set point air temperature within the environments.

Table A1
Mean Primary Energy Need derived from EPC calculation as a function of thermal insulation of buildings (TIL), net surfaces, building type (SFH and MFH), and climatic zone.

SFH		EPC				MFH		EPC			
Zone	Su [m^2]	TIL-0	TIL-1	TIL-2	TIL-3	Zone	Su [m^2]	TIL-0	TIL-1	TIL-2	TIL-3
A	[85–105]	11,413	6204	4004	2736	A	[85–105]	4597	2209	1169	726
	[105–125]	13,580	7533	4943	3420		[105–125]	5829	2872	1565	1000
	[125–145]	15,255	8557	5688	3987		[125–145]	6567	3304	1848	1215
	[145–165]	16,871	9578	6419	4547		[145–165]	7822	4083	2393	1650
	[165–185]	18,444	10,598	7148	5109		[165–185]	8804	4712	2849	2024
B	[85–105]	13,712	7439	4806	3276	B	[85–105]	5500	2665	1434	908
	[105–125]	16,327	9032	5930	4125		[105–125]	6986	3471	1920	1252
	[125–145]	18,349	10,260	6820	4805		[125–145]	7875	3993	2266	1516
	[145–165]	20,302	11,484	7694	5475		[145–165]	9384	4930	2925	2047
	[165–185]	22,204	12,707	8566	6148		[165–185]	10,565	5686	3475	2501
C	[85–105]	18,970	10,418	6840	4771	C	[85–105]	7690	3850	2173	1449
	[105–125]	22,553	12,600	8384	5945		[105–125]	9778	5014	2906	1989
	[125–145]	25,316	14,274	9596	6874		[125–145]	11,010	5749	3405	2383
	[145–165]	27,986	15,941	10,787	7790		[145–165]	13,082	7046	4331	3141
	[165–185]	30,587	17,607	11,973	8707		[165–185]	14,694	8080	5088	3773
D	[85–105]	25,043	13,821	9126	6411	D	[85–105]	10,202	5161	2957	2002
	[105–125]	29,752	16,692	11,160	7960		[105–125]	12,972	6718	3949	2743
	[125–145]	33,378	18,889	12,752	9181		[125–145]	14,599	7694	4616	3272
	[145–165]	36,882	21,078	14,316	10,384		[145–165]	17,325	9404	5841	4278
	[165–185]	40,295	23,265	15,873	11,589		[165–185]	19,441	10,763	6837	5111
E	[85–105]	35,115	19,711	13,235	9460	E	[85–105]	14,568	7569	4496	3152
	[105–125]	41,597	23,695	16,073	11,627		[105–125]	18,499	9831	5977	4286
	[125–145]	46,569	26,725	18,276	13,317		[125–145]	20,779	11,217	6938	5058
	[145–165]	51,370	29,744	20,438	14,979		[145–165]	24,555	13,598	8653	6474
	[165–185]	56,044	32,759	22,591	16,644		[165–185]	27,468	15,474	10,028	7623
F	[85–105]	62,074	34,681	23,140	16,386	F	[85–105]	25,656	13,149	7659	5262
	[105–125]	73,571	41,756	28,175	20,222		[105–125]	32,559	17,078	10,191	7172
	[125–145]	82,398	47,147	32,096	23,225		[125–145]	36,584	19,509	11,862	8500
	[145–165]	90,920	52,520	35,946	26,182		[145–165]	43,282	23,722	14,882	10,980
	[165–185]	99,216	57,884	39,780	29,142		[165–185]	48,461	27,054	17,319	13,013

In pursuit of this objective, the present study began by defining thousands of reference models representative of the entire national building stock for the first time (i.e., for all the six climatic zones) considering the main thermal properties and geometrical characterization that most represent the existing buildings. Through parametric energy simulations carried out adopting both the standard calculation (EPC) and tailored approach, the theoretical deviation of EPG was assessed as a function of the following parameters: indoor set-point air temperatures, thermal insulation level of buildings, climatic zone, building types (single or multi-family dwellings) and heating operating profiles.

The results corroborated findings of previous international works, highlighting that the prebound effects (i.e. when standard consumption is greater than actual one) occurred for existing and poorly insulated buildings, whilst rebound effects (i.e. when standard consumption is smaller than actual one) for new constructions but only under specific boundary conditions. Existing buildings without thermal insulation have a greater likelihood of having the prebound effect due to higher energy needs, although a few cases of the rebound effects were found only for smaller dwelling units with a set-point temperature greater than 20 °C, and with a heating operating hour profile tending to the maximum value provided by the national regulation. On the other hand, the most energy-efficient buildings had a higher probability of rebounding even for smaller heating operating hours due to their lower energy needs.

The likelihood of rebound effects in existing and poorly insulated buildings under the same outdoor climatic conditions as those used in Energy Performance Certificates (EPC), is very low (only 14% of the sample examined), except when the indoor air temperature is set at 22 °C and the heating operating hour is equal to the maximum allowed by national regulation. The probability of rebound effects significantly increases with higher levels of thermal insulation of buildings, ranging from 14% to 38% at the same boundary conditions. The study also suggested that thermal insulation has the greatest impact on the energy performance gap, while heating systems (standard or condensing boiler) have less influence.

The present work represented the first attempt to quantify the energy performance gap associated with the standard simplifications adopted in Energy Performance Certification, allowing to provide a valuable contribution to the knowledge of the energy performance of the Italian building stock. Furthermore, the normalization concerning the Heating Degree Day of each climatic zone allows observing and quantifying the mean theoretical deviation gap due to indoor set-point temperature, heating operating profile, and climatic conditions, although the latter has shown a modest influence on normalized value. The highest EPG, ranging from 14 to 16 kWh/HDD, was observed for buildings with no insulation and a heating profile of “1 h per day”, but this gap tends to decrease with increased thermal insulation levels of buildings and greater heating operating profiles. The greater EPG values were found when the prebound effect occurred (up to +16 kWh/HDD), whilst a small variation was found (up to −3 kWh/HDD) for the rebound effect.

This study allowed quantifying and parameterizing EPG according to specific parameters that are generally set at conventional values in EPC calculation, opening up the possibility of using these findings for a first attempt at the correction of EPG. Further studies as well as validation with real case studies should be carried out to make accurate and reliable this correction method (such as quantifying the influence of external climatic parameters although currently, climatic data for all the selected locations are not available), but at the same time, it already provides a rough indication of the effect of standard conditions on a building's energy consumption.

Founding

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CRediT authorship contribution statement

Domenico Palladino: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A

See Fig. A1, Fig. A2, Fig. A3, Fig. A4 and Table A1.

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