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Research paper

Assessing EPC-derived gas consumption estimates using metered data: A case study in Turin

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ABSTRACT

Buildings are major contributors to both energy consumption and carbon emissions, making them a key target for emission reduction. In the European Union, Energy Performance Certificates (EPCs) are widely used in urban building energy modelling; however, EPC-derived estimates may differ from actual consumption, while incomplete coverage limits their application. This study investigates the consistency between EPC-derived natural gas consumption estimates and metered data in Turin, Italy. The analysis covers 128,225 volumetric units, of which 22,551 (17.59%) are associated with at least one EPC. Results show overestimation by EPC-based estimates, with discrepancies exceeding 90% for the least efficient classes. For non-district-heating units, the median EPC estimate for Class G exceeds 230 kWh/m^2/y, compared with a metered median of approximately 9 kWh/m^2/y. To address these discrepancies, empirical Correction Factors (CFs) are derived for different energy performance classes and building characteristics. The results provide an empirical assessment of EPC-based natural gas consumption estimates at urban scale and demonstrate the potential of data-driven Correction Factors to improve their consistency with measured consumption.

1. Introduction

European cities are responsible for around 70% of energy-related greenhouse gas emissions while buildings represent around 40% of total energy consumption. For this reason, cities play a crucial role in the transition towards climate neutrality (Ali et al., 2022; International Energy Agency, 2023).

In response to this challenge, the European Union has introduced a series of legislative tools and action plans to support the decarbonisation of cities, with a particular focus on the building stock (Buildings Performance Institute Europe BPIE, 2022). A relevant example is the EU Mission "Climate-Neutral and Smart Cities" (European Commission, 2024a), funded through the Horizon programme. The 112 selected cities, including the City of Turin, have published their own Climate City Contract, a documented result of an iterative co-creation process with local, regional, and national stakeholders to reach climate neutrality by 2030. The European Green Deal, launched in 2019, is a key initiative to achieve climate neutrality by 2050 (European Commission, 2024b). A core element of this policy is the "Fit for 55" package (Council of the European Union, 2024), which includes the revision of several directives, such as the Energy Performance of Buildings Directive (EPBD). The first version of the EPBD (European Community, 2002) introduced a building energy classification system and required the Energy Performance Certificate (EPC) in case of sale, rental, or renovation. The 2024 recast (European Parliament and Council, 2024) introduced minimum energy performance targets and promoted electrification as part of a wider decarbonisation strategy.

In recent years, several studies have analysed the integration of EPC data into UBEMs. Indeed, for the purpose of modelling, Energy Performance Certificates (EPCs) offer a valid alternative to metered data thanks to the continuous updates of the related database. Therefore, they are often used as crucial input for bottom-up Urban Building Energy Modelling (UBEM). For instance, Beltrán-Velamazán et al. (2024) propose a UBEM based on EPCs and other open big data that is updated automatically in short intervals with standard computational resources. Johari et al. (2023) also describe a study in Sweden aimed at developing a UBEM at the city level, with the potential to be extended to the national level, calibrated and validated using EPC data. Conticelli et al. (2024) present a method based on the processing and aggregation of data collected through EPCs to identify distinct urban energy zones

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based on their energy performance index, applying this method to a municipality in Emilia-Romagna, Italy. Furthermore, Pasichnyi et al. (2019) adopted a statistical approach to process EPC data to define building archetypes and suggest strategic analyses for the energy retrofitting of buildings. Dall'O' et al. (2015) used the Italian EPC dataset to classify the building stock of the Lombardy region and propose a method for identifying representative buildings for each energy class. These studies underscore the potential of EPC data as a critical input for UBEMs, showcasing its ability to support urban energy planning and energy retrofitting strategies.

Although several studies have analysed the integration of EPC data into UBEMs thanks to the continuous updates in the related database (Streicher et al., 2019), the accuracy of EPC data remains often debated. These limitations primarily derive from the information gaps in data prior to 2015 and the uneven coverage of the building stock, which can affect the accuracy and representativeness of energy performance certificates. Moreover, the discrepancy between the estimated and the actual energy consumption is still evident and has been widely documented in literature. This phenomenon, universally known as the Energy Performance Gap (EPG), is generally defined as the difference between the expected energy consumption calculated through building performance assessments and the actual measured consumption (Cozza et al., 2021).

According to Yoshino et al. (2017), the EPG can be attributed to six main categories of interrelated factors: climate, building envelope, energy systems, operation and maintenance, occupant activities and behaviour, and indoor environmental quality. Among these, two of the most significant causes identified by the scientific community are the inaccuracy of physical building modelling and occupant behaviour (Hernandez-Cruz et al., 2023).

As highlighted by Cozza et al. (2021), the accurate representation of occupant behaviour remains one of the main causes of uncertainty in building energy modelling. Even in well-designed buildings, actual use often differs from that assumed during the design phase and varies over time. Moreover, factors such as occupancy density, daily presence patterns, user habits, and awareness of energy use strongly influence real energy consumption.

Recent studies have reported discrepancies in EPCs and have shown that the EPG can vary across building types and geographical contexts.

For example, Few et al. (2023) compared EPC-modelled and metered primary energy use intensity across 1374 gas-heated households in Great Britain, finding a significant overprediction that reaches up to 48% for the least efficient classes.

Similarly, Firth et al. (2025) evaluated the spatial variation of the energy performance gap across England and Wales, reporting an average national overprediction of 16.6–17.9% with substantial variation at the local authority level, ranging from −23.7% to + 56.4%.

To expand the geographical scope of these findings, Cozza et al. (2020) analysed 1172 Swiss dwellings, revealing a median pre-retrofit performance gap of −23%, where actual consumption was lower than estimated values.

Furthermore, Herrando et al. (2016) analysed the energy performance certificates of 21 university buildings in Spain and found an average deviation of around 30% between EPC-estimated and measured energy use.

Moving to the Italian context, several studies have already investigated the energy performance gap. For example, Palladino (2023) quantified a theoretical Energy Performance Gap through parametric energy simulation. Ferrari et al. (2021) monitored 227 social housing buildings in Northern Italy, concluding that relying solely on normative calculated EPC energy use leads to an overestimation of 44% compared to metered consumptions. At the urban scale, Mutani et al. (2021) did not analyse the EPG but demonstrated the potential of regional EPC databases to calibrate GIS-based urban-scale energy models in Turin.

These international and Italian studies have investigated the Energy Performance Gap; however, they differ substantially in terms of scale, data integration, and methodological purpose. Moreover, a comparison between estimated and measured consumption combined with the validation of empirical Correction Factors (CFs) specifically intended for UBEM applications, is limited to the neighbourhood level or to groups of buildings.

Following these considerations, this study aims to quantify the Energy Performance Gap between EPC-derived and metered natural gas consumption at the urban scale and to translate the observed discrepancies into empirical Correction Factors for UBEM applications.

The analysis addresses three main research questions: (1) what is the magnitude of the discrepancy between EPC-derived and measured natural gas consumption at the city scale; (2) to what extent does this discrepancy vary according to relevant building characteristics, including energy performance class, building use, and district heating connection; and (3) whether empirically derived Correction Factors (CFs) can improve EPC-based consumption estimates for Urban Building Energy Modelling (UBEM) applications at the urban scale.

In this way, the study moves beyond the assessment of the Energy Performance Gap at the individual-building level by investigating the phenomenon at the city scale, while providing an empirical approach for improving the reliability of EPC-based energy estimates in UBEM applications.

2. Methodology

2.1. Input data

This study focuses exclusively on natural gas consumption, as it is mainly associated with space heating and domestic hot water (DHW), two end uses assessed in the EPC methodology (Majcen et al., 2013; Pagliaro et al., 2021).

Electricity demand, in contrast, is strongly influenced by occupants' behaviour through plug loads and appliance use which are not directly represented in EPC estimates; consequently, discrepancies between estimated and measured electricity consumption reflect not only the thermal performance of buildings but also highly variable operational patterns (Johari et al., 2023; Sun et al., 2016).

This focus is further supported by the significant role of natural gas in the building sector: around 50% of the EU's gas consumption is attributed to buildings and within the total energy consumption of Turin (10,479.4 GWh/y), natural gas accounts for approximately 37.4% (Città di Torino, 2024).

A key methodological challenge in Urban Building Energy Modelling (UBEM) is the alignment of estimated and metered data, as they are originally collected at different spatial and administrative scales. To ensure a uniform spatial framework for the analysis, this research integrates three data sources: 3D building information from the Municipal Technical Map of the City of Turin, energy data from Energy Performance Certificates (EPCs) and measured consumption data from the SIATEL database.

The three databases are combined through a specific spatial aggregation process:

- Building unit: the fundamental unit represented by a single EPC. According to the Energy Performance of Buildings Directive (EPBD), a building unit is defined as "a section, floor or apartment within a building which is designed or altered to be used separately" (European Parliament and Council, 2024).
- Meter: the fundamental unit of the measured dataset (SIATEL), representing the physical delivery point of natural gas (serving either a single unit or a centralised heating system).
- Address: the intermediate spatial matching key, where both EPCs and meters are initially associated based on street name and street number.
- Volumetric Unit: the unit of analysis derived from the Municipal Technical Map (CTC) of Turin. It is used as the spatial reference for

linking SIATEL metered consumption data with building information, including heated useful floor area, energy performance class, and district heating connection. Each volumetric unit represents a three-dimensional geospatial entity defined by a uniform footprint and height (Ministero per la Pubblica Amministrazione e l'Innovazione, 2012).

2.1.1. Geospatial data

The dataset of volumetric units, extracted from the Municipal Technical Map of the City of Turin, initially comprised 128,225 volumetric units. The geospatial dataset provides fundamental geometric information for each volumetric unit, including the footprint area and the number of floors. Missing data regarding the number of floors were mathematically reconstructed by dividing the building's total volumetric height by the average inter-story height, calculated specifically for each building use category (residential, tertiary and industrial). These parameters enabled the subsequent estimation of the heated floor area for each volumetric unit.

2.1.2. Energy performance certificates (EPCs)

The Geoportal of the Piedmont Region (IGR Piemonte, 2026) provides access to EPC data, which were extracted from three regional CSV files:

- Energy Data: provided the main geometric information, particularly the heated floor area, used to calculate specific gas consumption, as well as the energy performance class.
- Heating Plants: provided detailed information on fuel types and on the specific energy services provided, such as space heating and domestic hot water (DHW).
- Energy Consumptions: provided categorical information required for data segmentation, including building use, construction year, EPC object (whole building or single unit), and the reason for EPC issuance. This dataset also reported the quantities of the different energy carriers used by each building in their original physical units (e.g., Sm^3, kWh, kg, or L), which were subsequently converted into kWh.

Firstly, the dataset was restricted to records located within the administrative boundaries of the City of Turin.

Then, a unique identifier was generated for each record by concatenating the certificate ID, submission date, standardised address, building typology, and reason for EPC issuance. Missing street numbers were handled programmatically during the address-standardisation procedure. Regional building-use codes (e.g., E1 for residential buildings and E2–E7 for tertiary uses) were mapped to standardised use categories, while technical energy-service tags were translated into standardised service categories, including Heating, Domestic Hot Water (DHW), and Cooling.

To ensure alignment with metered data, the analysis focused on computing the delivered natural gas. Since the regional database reports energy consumption values in various physical units (e.g., standard cubic meters, kilograms or kWh), a specific conversion algorithm was applied to standardise these values into kWh. Natural gas volumes expressed in standard or normal cubic meters (Sm^3/Nm^3) were converted into kWh by applying the Higher Heating Value (HHV) of 38.10 MJ/Sm^3 (Autorità di Regolazione per Energia Reti e Ambiente ARERA, 2026), multiplied by the standard conversion factor of 0.2778, resulting in approximately 10.6 kWh/Sm^3 . Specific gas consumption was subsequently calculated by dividing the delivered gas consumption by the heated floor area.

After the harmonisation process, an address-correction matrix was applied to geolocate the EPC records and link them to the corresponding spatial Volumetric Units. Despite this spatial assignment, EPC records were retained and analysed at their original disaggregated level. Aggregation at the Volumetric Unit level was performed only to associate the SIATEL consumption records with relevant building information derived from the EPC dataset, namely the energy performance class and the presence or absence of a district heating connection.

To support the evaluation of different input configurations, the EPC dataset was organised into three specific subsets. As reported by Anselmo et al., (2024)., EPCs issued prior to property rental or sale are generally characterised by a widespread use of default values. Conversely, EPCs issued for entire buildings provide information for the building as a whole, while certificates issued after renovation works can include information on the specific intervention, potentially reducing the use of default values. Based on these considerations, the following subsets were defined:

- Total Dataset: includes all valid and spatially matched records without exclusions.
- Whole Building Dataset: includes records corresponding strictly to certificates issued for entire buildings. Where multiple whole-building certificates were available for the same Volumetric Unit, records were ordered chronologically and only the most recent certificate was retained.
- Renovation Dataset: includes EPCs issued following energy retrofits, major renovations, or new construction.

As widely documented in literature, EPC databases frequently suffer from systematic human errors during the recording and reporting phases—particularly concerning expected delivered energy and heated floor areas (Johari et al., 2023). Therefore, to mitigate the impact of data-entry errors, records with specific gas consumption values below the 5th percentile or above the 95th percentile were excluded independently for each spatial subset.

2.1.3. SIATEL database

The SIATEL (*Sistema di Interscambio Anagrafe Tributaria degli Enti Locali*) database is a national fiscal registry that includes information about electricity and natural gas consumption records associated with active meters (Agenzia delle Entrate, 2025). A data extraction specifically referring to the urban area of Turin was made available by the Municipality within a collaboration framework aimed at the development of an Urban Digital Twin.[1]

SIATEL data were already provided in kilowatt-hours (kWh). To associate the measured consumption data with volumetric units, records were aggregated at the individual meter level to determine the total annual natural gas and then were aggregated by street address. The address therefore served as the common spatial matching key between the SIATEL and EPC datasets, allowing the aggregated metered consumption to be subsequently associated with the corresponding Volumetric Units extracted from the Municipal Technical Map of the City of Turin.

2.2. Analysis of gas consumption data

2.2.1. Energy performance certificates analysis

The EPC-based natural gas consumption (Q_{gas}) was normalised to the climatic conditions of the reference year 2023, corresponding to the year of the available metered data. The normalisation was performed using Heating Degree Days (HDD), by applying the ratio between the actual HDD recorded in Turin in 2023 and the standard HDD associated with the city's climate zone. The normalised consumption was subsequently divided by the heated floor area of each building unit to obtain the specific natural gas consumption, expressed in kWh/m^2/y, as shown in Eq. (1).

[1] Framework Agreement between the City of Turin and the Polytechnic of Turin, signed on 9th February 2023 and renewed on 6th March 2025, for the realization of pilot projects towards the implementation of a Digital Twin.

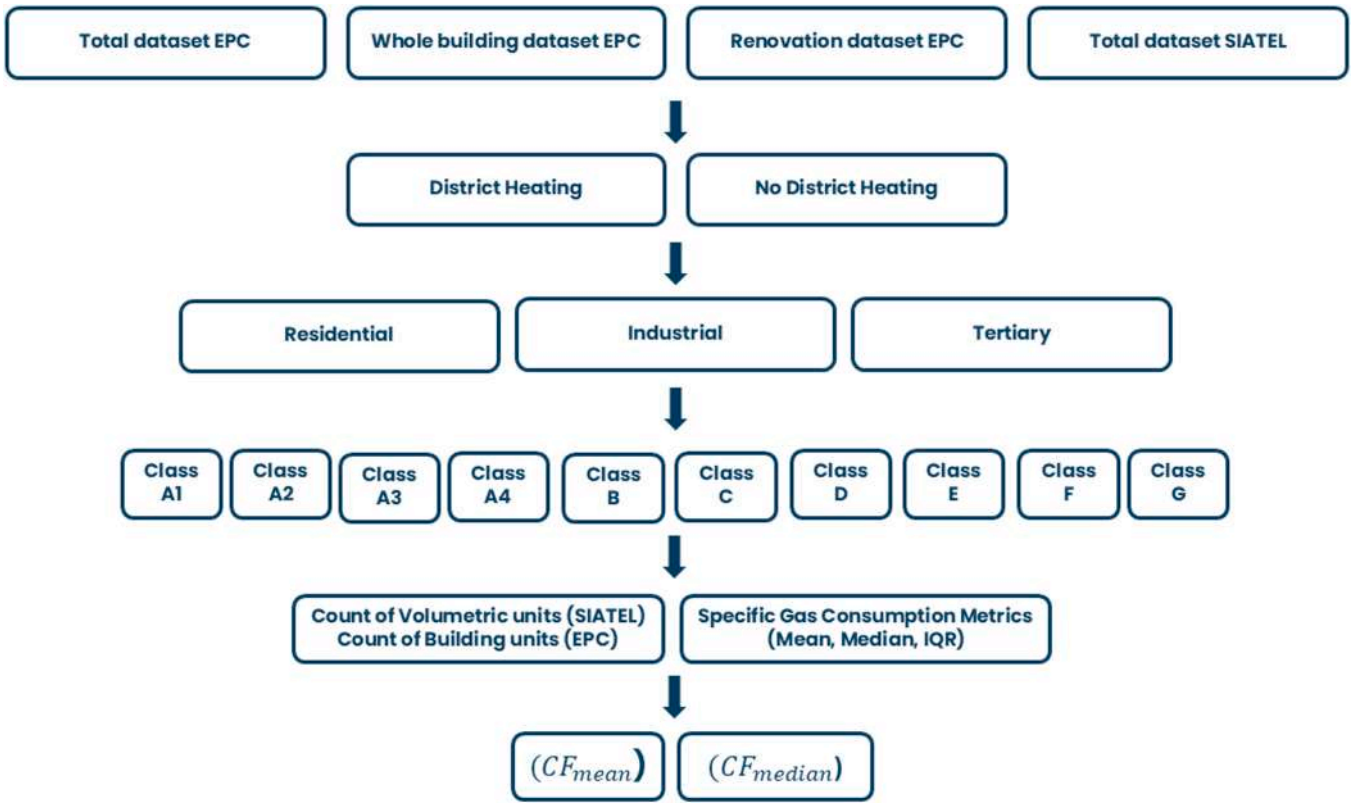


Fig. 1. Methodological framework.

$$SEC_{gas\ 2023} = \frac{Q_{gas} \times \left(\frac{HDD_{2023}}{HDD_{standard}}\right)}{A_{heated}} \quad (1)$$

Where:

- $SEC_{gas\ 2023}$ is the specific natural gas consumption normalised to 2023 climatic conditions [kWh/m^2/y];
- Q_{gas} is the annual natural gas consumption reported by the EPC [kWh/y];
- HDD_{2023} is the actual Heating Degree Days for the city of Turin in the reference year 2023 (equal to 2648) [°C·d];
- $HDD_{standard}$ is the standard Heating Degree Days for Turin's climate zone E (equal to 2617) [°C·d];
- A_{heated} is the heated floor area of the building, reported in EPCs [m^2].

Following this normalisation step, the three datasets were analysed to investigate the distribution of specific natural gas consumption across different building categories.

First, natural gas consumption was analysed according to the energy use, distinguishing between buildings using natural gas exclusively for space heating, for Domestic Hot Water (DHW), or for both space heating and DHW.

A subsequent segmentation stage considered three main dimensions: the presence or absence of District Heating (DH); building use, distinguishing among residential, tertiary, and industrial buildings; and EPC energy performance class, ranging from A4 to G.

Finally, for each segment, the statistical distribution of specific natural gas consumption and the number of EPCs were analysed.

2.2.2. Metered data

Metered data underwent a rigorous filtering and spatial allocation process since they did not provide the corresponding heated floor area.

From the Municipal Technical Map (CTC), for each volumetric unit, the Heated Floor Area (A_{heated}) was estimated by multiplying the building's footprint area ($A_{footprint}$) by the number of above-ground floors (n_{floors}) and subsequently applying a conservative reduction factor of 0.75, corresponding to the average ratio between heated useful floor area and gross floor area derived from the analysis of EPC data for buildings in the city of Turin. The calculation is expressed by the following Eq. (2):

$$A_{heated} = A_{footprint} \times n_{floors} \times 0.75 \quad (2)$$

where:

- A_{heated} is the estimated actively heated floor area of the volumetric unit (m^2);
- $A_{footprint}$ is the physical building footprint area derived from the volumetric unit of the Municipal Technical Map (m^2);
- n_{floors} is the total number of above-ground floors of the volumetric unit;
- 0.75 is the empirical reduction coefficient adopted to exclude non-climatised spaces (e.g., stairways, basements, and technical rooms).

Furthermore, since metered data did not include the energy performance class, a specific alignment with the EPC dataset was required. For each volumetric unit, the EPCs were aggregated to derive the relevant energy performance class. To adopt a conservative assumption the worst energy class among the available EPCs within each volumetric unit was systematically assigned to the corresponding SIATEL records. To assess the robustness of this assumption and quantify its influence on the results, a sensitivity analysis was then performed. In this analysis, the average energy class of the EPCs within each volumetric unit was assigned to the corresponding metered data instead of the worst-performing class.

Finally, the identification of volumetric units connected to the District Heating required a specific spatial and statistical approach, as this



Fig. 2. Building distribution by construction period.

information is not explicitly recorded in the SIATEL database. To address this limitation, the DH coverage was inferred using the georeferenced EPC dataset. A regular grid of 500 × 500 m was adopted: this resolution provides enough EPC records within each cell and preserves the spatial distribution of the district heating.

For each cell, the local DH penetration rate was calculated as the ratio between the area of EPCs connected to the network and the total EPC-certified area within that cell. Assuming the EPC dataset to be a statistically representative sample of the local building stock, this calculated percentage was subsequently applied to the SIATEL volumetric units falling within the same grid cell.

The assignment followed a strict logic based on the physical properties of building energy use: since DH provides the primary thermal load for space heating, buildings connected to the DH network utilise natural gas almost exclusively for residual loads, such as Domestic Hot Water (DHW) production and cooking appliances. Consequently, SIATEL volumetric units within each cell were sorted in ascending order of specific gas consumption (kWh/m^2/y). Based on the DH percentage derived from the EPCs, the corresponding share of volumetric units with the lowest gas consumption was systematically classified as DH-connected.

This assumption is supported by European data (Eurostat, 2026), which highlights that space heating accounts for over 60% of total residential energy consumption. Given the spatial resolution of the analysis, partially connected or mixed-use buildings are computationally approximated as either fully connected or fully disconnected, representing a methodological simplification.

2.2.3. Definition of a correction factor (CF)

After having analysed the three EPC datasets and the SIATEL dataset separately, a comparison was performed between EPC and SIATEL.

As a first step, a segmented value was identified for each energy class, based on the source dataset, the presence or absence of district heating, the building use and the energy class (Fig. 1).

The comparison was then performed by analysing specific gas consumption using the mean, the median, and the interquartile range (IQR) expressed in kWh/m^2/y.

The final step consisted of defining a Correction Factor (CF) for each segmented value to empirically adjust EPC-derived gas consumption estimates towards the corresponding metered consumption observed in the SIATEL dataset. At this stage, considering the low incidence of subclasses A1 to A4, EPC data were aggregated into a single class A. Moreover, under the revised Energy Performance of Buildings Directive (EPBD) (European Parliament and Council, 2024), energy performance certificates (EPCs) will adopt an A–G scale, with Class A representing the highest energy performance and Class G the lowest.

The Correction Factor (CF_m) is defined as the ratio between the specific gas consumption derived from the SIATEL dataset and that estimated from EPC data for a given statistical metric m (mean or median), as shown in Eq. (3):

$$CF_m = \frac{Q_{gas,\ SIATEL,m}}{Q_{gas,\ EPC,m}} \tag{3}$$

where:

- CF_m is the Correction Factor calculated for each segmented value;
- $Q_{gas,SIATEL,m}$ is the specific gas consumption derived from the metered SIATEL dataset for a given statistical metric m [kWh/m^2/y];
- $Q_{gas,EPC,m}$ is the specific gas consumption estimated from the EPC data for the same statistical metric m [kWh/m^2/y];
- m represents the chosen statistical metric, evaluated either as the arithmetic mean (CF_{mean}) or the median (CF_{median}) to account for the data distribution.

To further assess the robustness and predictive reliability of the proposed CFs, an independent holdout-sample validation was subsequently performed. The total dataset was randomly divided into an 80% training set and a 20% test set. The CFs were recalculated exclusively using the training set and then applied to the uncalibrated EPC-estimated gas consumption of the independent test set.

2.3. Case study

Turin, the capital of the Piedmont Region, in northwestern Italy, as of January 2024, has a population of 851,199 (ISTAT, 2025) and covers an area of approximately 130 km^2, divided into eight districts (*Circoscrizioni*).

After the World Wars, Turin underwent major urban changes, marked by rapid expansion driven by industrial growth. The urban development plan of 1906–1908 guided the city's expansion. Following the industrial crisis of the 1970s, the city began a deep reflection on its structure, leading to the definition of a new urban master plan in 1995.

Fig. 2 illustrates the distribution of the analysed building stock according to their construction periods. The data clearly highlights the impact of the post-war economic growth, with the largest share of buildings constructed between 1951 and 1970. Another substantial share consists of buildings constructed before 1900, reflecting the historical building heritage of the city. Conversely, from 1980 onwards, the

Table 1
Data attrition process for the EPC building units and SIATEL volumetric units, showing the number of retained records after spatial matching, specific gas consumption calculation, and statistical outlier filtering (5th–95th percentile).

Dataset/ Processing stage	Initial Spatially Matched Records	Records with valid Specific Gas Consumption (kWh/m²/y)	Records with valid Specific Gas Consumption (kWh/m²/y) and after Statistical Filter (5th–95th Percentile)
Total EPC Dataset (building units)	225,331	181,687	163,517
Renovation EPC Subset (building units)	20,203	14,768	13,290
Whole Building EPC Subset (building units)	2806	2329	2095
SIATEL (Metered Data) (volumetric Units)	73,465	32,668	29,400

distribution shows a marked decline in the number of buildings.

Despite their relevance within European policy and regulations, a significant limitation to the potential effective use of EPCs is their incomplete coverage. The analysed building stock comprises 128,225 volumetric units, of which 22,551 (17.59%) are associated with at least one Energy Performance Certificate (EPC).

The analysed EPC sample is strongly dominated by residential buildings, which account for 92.56% of the available certificates. In terms of energy performance, most certificates fall into the lowest efficiency ratings, specifically classes E (29%), F (25.35%), and G (13.75%). Together, these three worst-performing categories account for 68.10% of the total certified buildings.

For Turin, the official HDD value is 2617, according to the national standard, placing the city in climate zone E, as defined in Annex A of Presidential Decree No. 412/1993 (President of the Italian Republic, 1993). However, the Regional Environmental Agency (ARPA) reported an HDD of 2648 for 2023, the year to which SIATEL consumption values refer (ARPA Piemonte, 2025).

District heating was specifically investigated because Piedmont is among the Italian regions with the highest share. According to the statistical overview of the prevalence of district heating in Italy reported by the *Gestore Servizi Energetici* (Gestore dei Servizi Energetici GSE, 2022), approximately 42% of the total heated volume served by these systems nationwide (386 million m^3) is concentrated in Lombardy (162 million m^3), followed by Piedmont (106 million m^3, 27% of the national total). Furthermore, according to the same report, 95% of the energy source for district heating used in Piedmont is natural gas and the remaining part is solid biomass and renewable sources.

In Turin, the development of district heating began in the late 1970s, when the *Azienda Energetica Metropolitana Torino S.p.A.* (AEM), the energy company owned by the Municipality of Turin, expanded its activities in the field of cogeneration and heat distribution in response to the oil crises and the need to rationalise the use of energy sources. The district heating network serving the Southern part of the city became operative in 1994 (Ponta et al., 1999).

Currently, district heating is estimated to meet approximately 55% of the heat demand of buildings in Turin. Despite its widespread use, the district heating network is concentrated in specific areas of the city due to physical barriers (such as the River Po, the hills and the historical centre with its high building density) and technical and economic constraints (e.g. the presence of individual heating systems, inadequate pipe sizes and buildings with a volume of less than 2500 m^3) (Guelpa et al., 2017).

3. Results

3.1. Data attrition and sample definition

Table 1 summarises the different filtering stages for both data sources.

The initial spatially matched EPC records comprised 225,331 disaggregated certificates at the building-unit level, including 20,203 records in the Renovation subset and 2806 in the Whole Building subset. In contrast, the SIATEL dataset comprised 73,465 Volumetric Units with aggregated metered gas consumption. For the EPC datasets, each record represents an individual building unit, whereas for SIATEL, each record represents a Volumetric Unit to which one or more meters and their corresponding gas consumption records were spatially aggregated.

Subsequently, records lacking essential parameters required for the calculation of specific gas consumption—such as missing heated floor area or null gas consumption values—were excluded, resulting in 181,687 valid EPC records and 32,668 SIATEL Volumetric Units. Finally, a statistical filter was applied independently to each spatial subset, excluding records falling below the 5th percentile or above the 95th percentile of specific gas consumption. Following this filtering procedure, the final datasets used for the comparative analysis consisted of 163,517 building-unit records in the Total EPC Dataset, 13,290 in the Renovation subset, 2095 in the Whole Building subset, and 29,400 SIATEL Volumetric Units.

To quantify the impact of this filtering procedure, the exclusion of extreme outliers significantly modified the overall mean specific gas

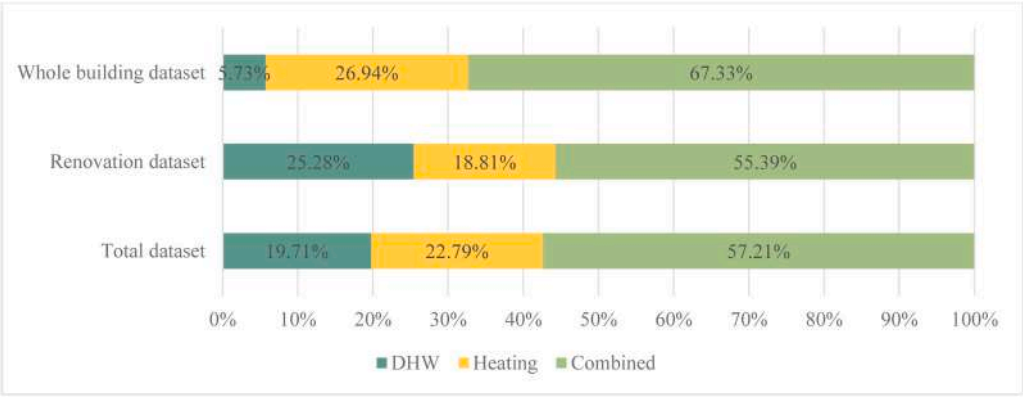


Fig. 3. Percentage distribution of building units by end-use across the three analysed datasets.

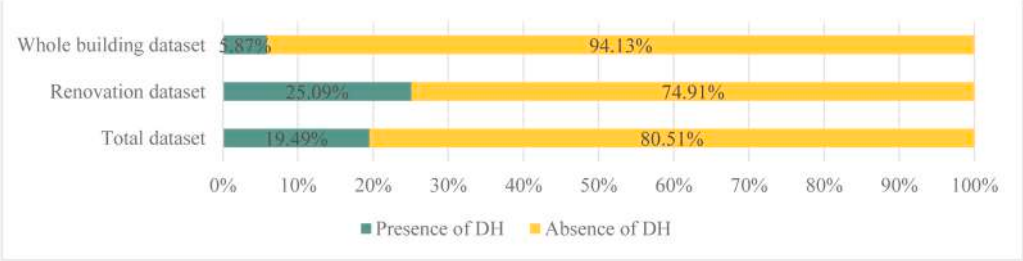


Fig. 4. Percentage of heated surface connected to district heating across the three analysed datasets.

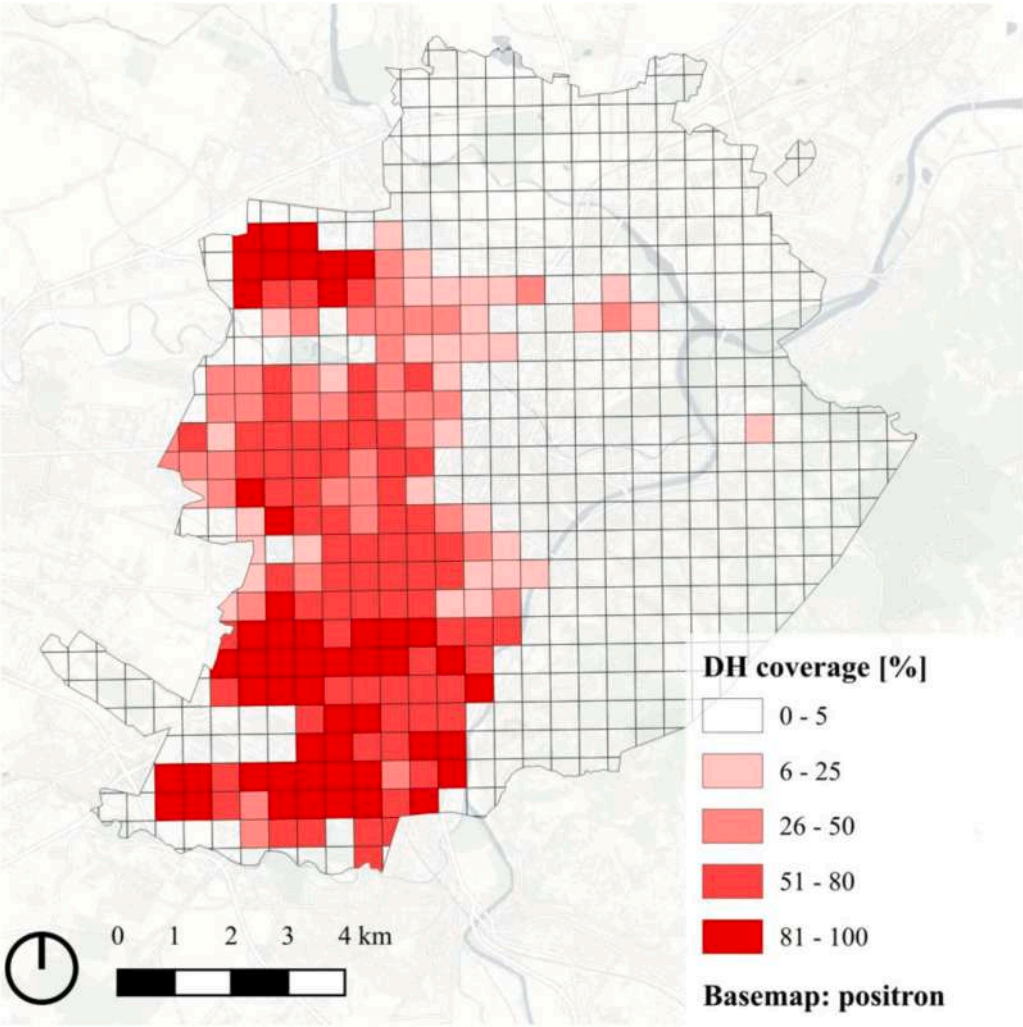


Fig. 5. Map of the district heating network in Turin.

consumption of the Total EPC dataset, above all for the lowest classes, which contain a larger number of records. Specifically, for buildings not connected to district heating, the overall mean dropped from 256.67 kWh/m^2/y (unfiltered) to 151.22 kWh/m^2/y (filtered), while for buildings connected to district heating, it shifted from 36.12 kWh/m^2/y to 35.06 kWh/m^2/y. The necessity of the application of this filter is most evident when examining the worst-performing buildings (Class G) not connected to the district heating network. Before filtering, the mean specific consumption for Class G reached a value of 846.43 kWh/m^2/y, clearly driven by severe data-entry errors. By applying the 5th–95th percentile filter, this mean reached a more realistic value of 226.54 kWh/m^2/y.

It should be noted that the EPC datasets were primarily analysed in their disaggregated form (single building unit) in order not to lose detailed categorical information. The spatial aggregation of EPC data at the building scale was utilised only in order to assign an energy performance class and a District Heating share to the corresponding Volumetric Units. Conversely, the SIATEL metered data was exclusively analysed in an aggregated form at the volumetric unit level, dividing the total metered consumption by the estimated heated floor area of the volumetric unit.

3.2. Energy performance analysis of EPC datasets

The first analysis, based on gas end-uses, shows that combined consumption (heating + DHW) represents the largest share in all three



Fig. 6. Percentage distribution of building units by building uses across the three analysed datasets.

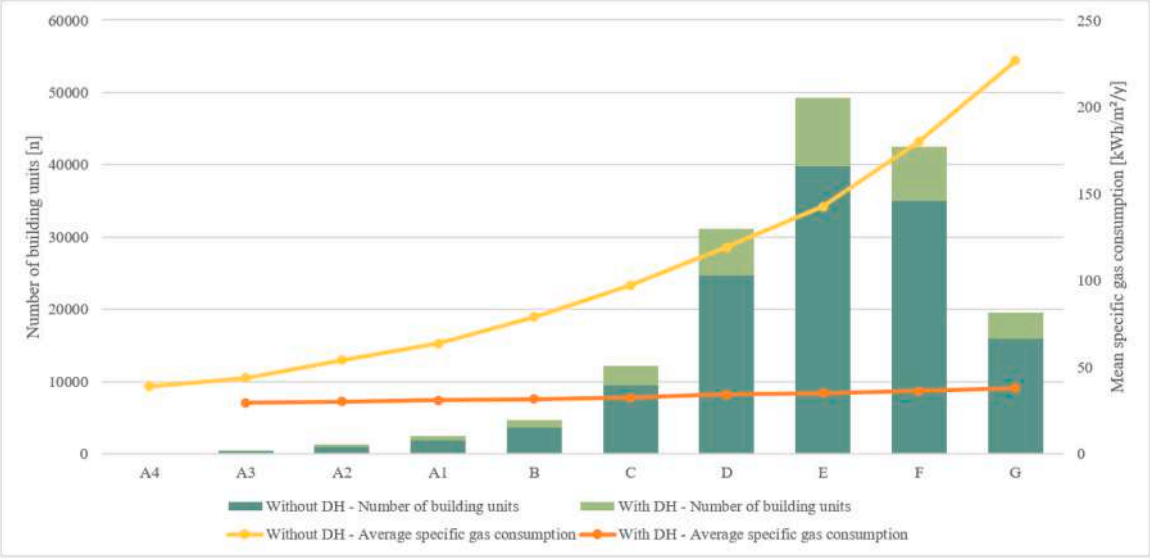


Fig. 7. Number of building units and mean specific gas consumption (kWh/m²/y) grouped by energy performance class (Total dataset).

datasets, with percentages ranging from 55.39% to 67.33% (Fig. 3).

Regarding the presence or absence of district heating, as shown in Fig. 4, in the total dataset 19.49% of heated surface is connected to district heating, in the Renovation dataset around the 25.09%, while in the whole building dataset only the 5.87%.

These results highlight that district heating coverage is still limited in the city of Turin, likely concentrated in the flat areas to the South and West, and more limited in the historic centre and hilly zones of the city, as confirmed by the map of Turin's district heating network (Fig. 5).

According to Fig. 6, all three datasets cover significantly high percentages of residential buildings, with the Renovation dataset predominantly composed of residential buildings (approximately 97%). In contrast, the whole building dataset shows a more heterogeneous composition: the tertiary and industrial sectors account for approximately 26.5% of the total.

This suggests that certifications of whole buildings tend to cover commercial and industrial sectors more extensively, whereas those for renovations primarily focus on residential buildings.

Table 2
Statistical metrics of specific gas consumption (kWh/m²/y) grouped by energy class for building units with and without District Heating (DH) (Total Dataset).

	Without DH				With DH			
Energy classes	**Building units**	**Mean**	**Median**	**IQR**	**Building units**	**Mean**	**Median**	**IQR**
A4	75	38.95	33.22	15.86	-	-	-	-
A3	403	43.75	38.90	16.82	67	29.51	27.92	2.98
A2	921	53.99	47.56	26.47	330	30.10	28.71	2.29
A1	1853	63.43	56.86	26.76	577	30.90	28.73	3.78
B	3585	78.87	70.34	33.72	1046	31.51	28.71	4.46
C	9479	97.30	85.61	44.70	2724	32.36	29.11	5.36
D	24,672	119.05	105.95	56.82	6416	34.33	29.61	6.07
E	39,801	142.60	131.27	70.90	9486	35.11	30.04	7.69
F	34,961	180.21	172.00	94.97	7535	36.26	30.56	15.23
G	15,902	226.54	230.72	107.95	3684	37.94	30.91	19.50
Total	131,652	151.22	136.25	102.16	31,865	35.06	29.90	7.92

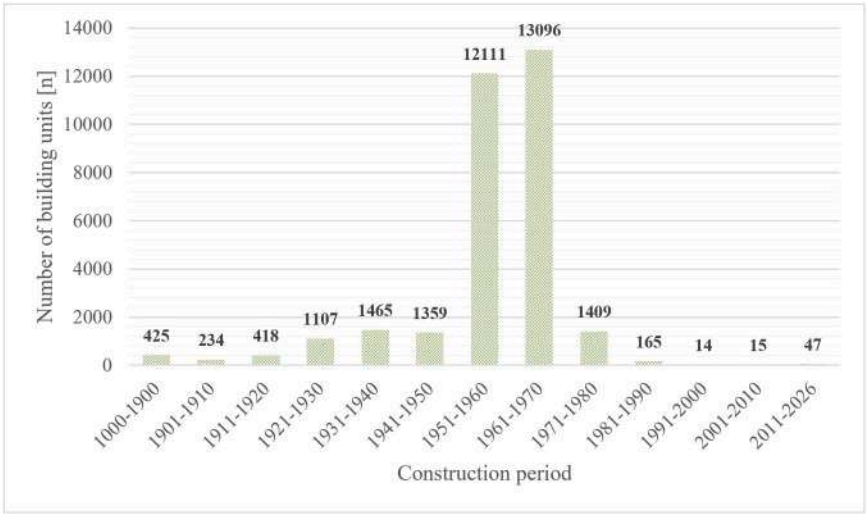


Fig. 8. Number of building units connected to the district heating network in the City of Turin by construction period.

Following this initial overview of the three datasets, a more detailed analysis is presented: For each class (from A4 to G), the number of EPCs and the mean, median, and interquartile range (IQR) of the specific gas consumption are examined, distinguishing separately between buildings with and without district heating (DH).

3.2.1. Dataset analysis –total dataset

As mentioned above, the Total dataset contains the highest number of records (with a total of 163,517 building units, combining 131,652 without district heating and 31,865 with district heating).

Fig. 7 shows the total number of building units and the mean specific gas consumption (kWh/m^2/y) by energy class (A4–G), distinguishing between units with and without district heating.

Overall, the number of EPCs increases progressively from the most efficient to the least efficient classes, with a light decrease in classes F and G. Most buildings with district heating are concentrated in the intermediate-to-low classes (D–F), while the most efficient classes (A4–B) show a lower presence of district heating.

Table 2 shows that, for building units without district heating the mean consumption increases from 38.95 kWh/m^2/y in class A4–226.54 kWh/m^2/y in class G, with an overall mean of 151.22 kWh/m^2/y across all classes. Similarly, the median follows the same trend, increasing from 33.22 kWh/m^2/y in class A4–230.72 kWh/m^2/y in class G, with an overall median of 136.25 kWh/m^2/y. Furthermore, the dispersion, measured by the Interquartile Range (IQR), grows from 15.86 kWh/m^2/y in class A4–107.95 kWh/m^2/y in class G. This indicates substantially greater variability in specific gas consumption among buildings belonging to the less efficient energy classes.

In contrast, for building units connected to district heating, both the mean and median specific gas consumption remain relatively stable across the energy classes and are consistently lower than those observed for buildings without district heating. The mean consumption ranges from 29.51 kWh/m^2/y in class A3, with no units recorded in class A4, to 37.94 kWh/m^2/y in class G, while the median exhibits a similar pattern, ranging from 27.92 kWh/m^2/y in class A3–30.91 kWh/m^2/y in class G. The IQR also remains relatively narrow, increasing from 2.98 kWh/m^2/y in class A3–19.50 kWh/m^2/y in class G, with an overall IQR of 7.92 kWh/m^2/y. This limited dispersion indicates more homogeneity in specific gas consumption among district-heated building units.

The concentration of building units connected to district heating in classes D–G suggests that district heating is more widespread among less energy-efficient buildings. This pattern is consistent with the age of the

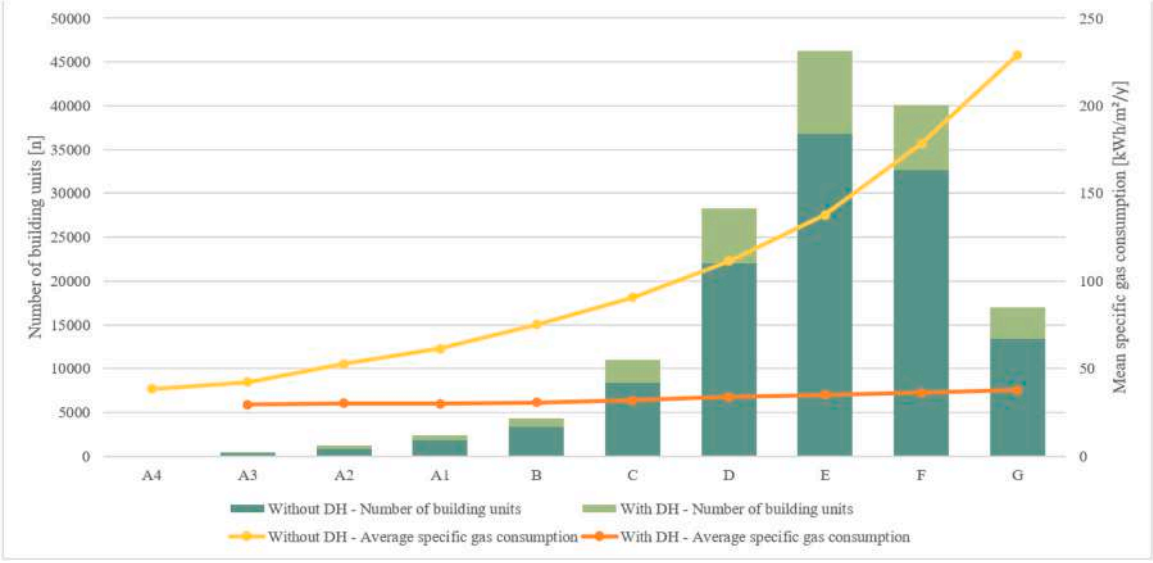


Fig. 9. Number of building units and mean specific gas consumption by energy performance class (Total dataset-residential sector).

Table 3
Statistical metrics of specific gas consumption (kWh/m²/y) grouped by energy class for building units with and without District Heating (DH) – (Total dataset - Residential sector).

	Without DH				With DH			
Energy classes	**Building units**	**Mean**	**Median**	**IQR**	**Building units**	**Mean**	**Median**	**IQR**
A4	72	38.46	33.14	13.96	-	-	-	-
A3	384	42.35	38.29	16.38	67	29.51	27.92	2.98
A2	887	52.65	47.49	25.60	330	30.10	28.71	2.29
A1	1772	61.26	56.57	25.58	573	30.05	28.73	3.70
B	3324	75.08	69.53	31.39	1038	30.73	28.68	4.43
C	8339	90.51	83.30	38.96	2699	31.98	29.06	5.29
D	21,971	111.34	102.74	48.65	6370	33.95	29.59	5.98
E	36,837	137.83	128.83	65.27	9448	34.95	30.02	7.52
F	32,620	178.34	170.19	92.26	7500	36.20	30.56	15.31
G	13,379	229.00	233.30	105.89	3653	37.78	30.88	19.38
Total	119,585	147.04	132.39	95.79	31,678	34.83	29.88	7.76

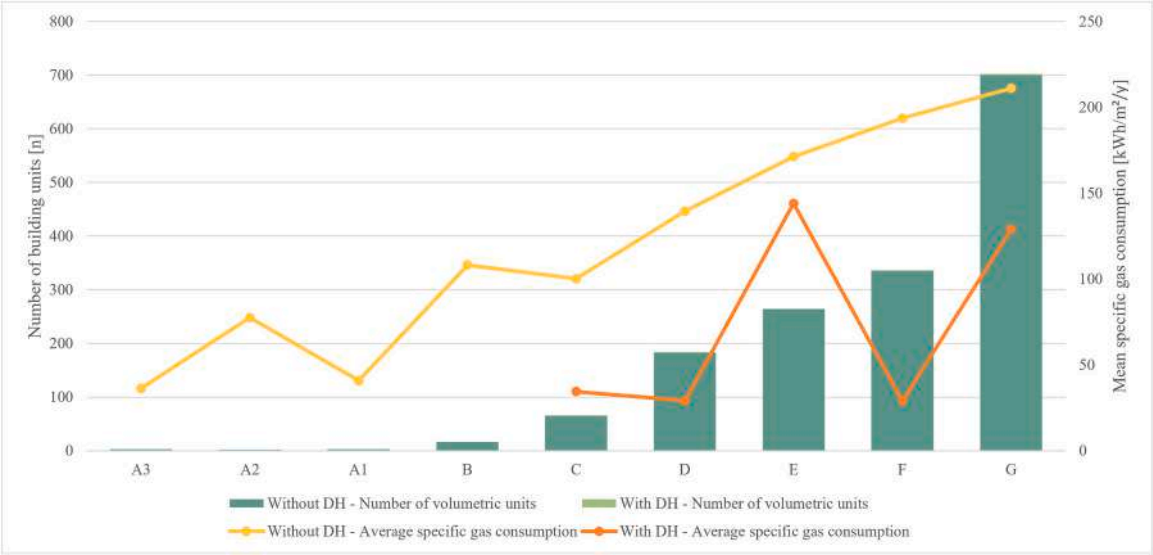


Fig. 10. Number of building units and mean specific gas consumption by energy performance class (Total dataset-Industrial sector).

Table 4
Statistical metrics of specific gas consumption (kWh/m²/y) grouped by energy class for building units with and without District Heating (DH) – (Total dataset - Industrial sector).

	Without DH				With DH			
Energy classes	**Building units**	**Mean**	**Median**	**IQR**	**Building units**	**Mean**	**Median**	**IQR**
A3	3	36.38	30.04	12.47	-	-	-	-
A2	2	77.51	77.51	31.89	-	-	-	-
A1	3	40.87	35.29	9.21	-	-	-	-
B	17	108.16	77.26	94.16	-	-	-	-
C	65	100.25	83.71	69.14	1	34.54	34.54	0.00
D	183	139.51	128.29	117.80	1	29.22	29.22	0.00
E	264	171.30	159.48	129.17	1	144.09	144.09	0.00
F	335	193.72	192.91	122.08	2	29.14	29.14	0.93
G	700	211.09	216.58	125.06	2	129.10	129.10	96.92
Total	1572	185.85	186.41	135.82	7	74.90	32.19	59.67

buildings connected to the district heating network: as shown in Fig. 8, most of these buildings were constructed between the 1950s and 1970s and therefore generally belong to older building stock with lower energy performance. In contrast, new constructed buildings, which typically fall within classes A4–B, are more likely to rely on high-efficiency electric systems, particularly heat pumps, often combined with photovoltaic systems.

Since 90% of the data represent the residential sector, any further analysis by sector shows that the residential profile is, as shown in Fig. 9 and Table 3, almost identical to that previously observed in the overall analysis (Fig. 7).

As shown in Fig. 10 and Table 4, in the industrial sector, among the 1572 building units not connected to district heating, 700 building units belong to the class, G. For this "Without DH" subset, the overall mean specific gas consumption is 185.85 kWh/m²/y (median: 186.41 kWh/m²/y; IQR: 135.82 kWh/m²/y). These values are generally higher than those observed for the residential sector and are consistent with the high proportion of building units classified as G. Finally, only 7 building units are connected to district heating with a lower mean gas consumption of 74.90 kWh/m²/y (median: 32.19 kWh/m²/y; IQR: 59.67 kWh/m²/y).

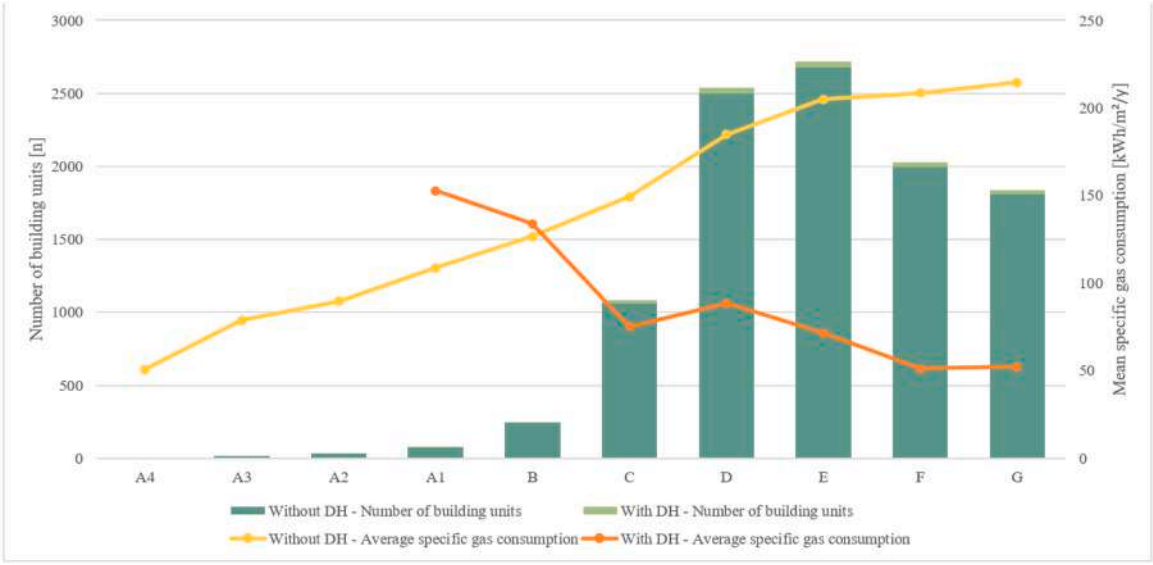


Fig. 11. Number of building units and mean specific gas consumption by energy performance class (Total dataset-tertiary sector).

Table 5
Statistical metrics of specific gas consumption (kWh/m²/y) grouped by energy class for building units with and without District Heating (DH) – (Total dataset - Tertiary sector).

	Without DH				With DH			
Energy classes	**Building units**	**Mean**	**Median**	**IQR**	**Building units**	**Mean**	**Median**	**IQR**
A4	3	50.67	44.93	21.50	-	-	-	-
A3	16	78.81	49.12	42.01	-	-	-	-
A2	32	89.62	61.98	77.16	-	-	-	-
A1	74	108.80	85.14	100.51	4	152.82	132.16	185.48
B	240	126.60	107.56	91.90	8	133.85	129.18	95.26
C	1057	149.25	136.75	111.61	24	75.13	47.78	58.36
D	2495	184.80	180.72	120.69	45	88.50	57.07	67.09
E	2679	204.95	207.13	132.28	37	71.64	47.13	49.80
F	1994	208.62	208.75	129.79	33	51.25	31.48	8.18
G	1809	214.47	219.29	111.85	28	52.29	40.18	29.52
Total	10,399	193.73	192.65	131.24	179	74.16	44.17	52.58

For the subset without district heating, the overall mean specific gas consumption is 193.73 kWh/m²/y (median: 192.65 kWh/m²/y; IQR: 131.24 kWh/m²/y). The data reveals a highly regular and consistent upward trend: gas consumption progressively increases as the energy performance worsens, starting from a mean of 50.67 kWh/m²/y in class A4 (median: 44.93 kWh/m²/y) and steadily peaking at 214.47 kWh/m²/y in class G (median: 219.29 kWh/m²/y).

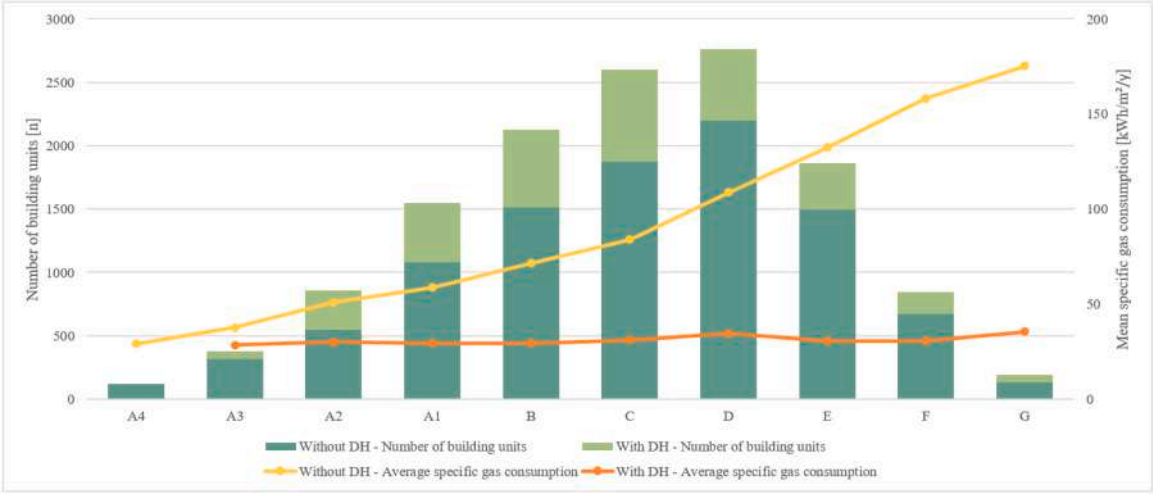


Fig. 12. Number of building units and mean specific gas consumption by energy performance class (Renovation dataset).

Moving to the tertiary sector, as shown in Fig. 11 and Table 5 most of building units are not connected to district heating and are widely distributed across the lower energy performance classes, with a prominent concentration from class D to G.

Table 6
Statistical metrics of specific gas consumption (kWh/m²/y) grouped by energy class for building units with and without District Heating (DH) – (Renovation dataset).

	Without DH				With DH			
Energy classes	**Building units**	**Mean**	**Median**	**IQR**	**Building units**	**Mean**	**Median**	**IQR**
A4	117	29.14	24.22	14.45	-	-	-	-
A3	319	37.65	35.71	17.00	61	28.58	27.80	2.93
A2	547	50.92	44.89	25.65	314	30.06	28.72	2.28
A1	1083	58.85	55.54	25.67	465	29.43	28.69	3.44
B	1514	71.52	68.49	32.53	611	29.50	28.35	3.93
C	1874	84.01	80.99	39.33	725	31.13	28.26	7.19
D	2200	108.81	106.91	69.49	561	34.50	29.19	11.86
E	1495	132.36	132.76	69.38	367	30.68	28.28	5.81
F	674	158.25	160.68	59.26	171	30.65	28.12	6.29
G	133	175.32	184.41	49.96	59	35.59	30.14	5.94
Total	9956	94.41	83.42	72.71	3334	31.02	28.61	5.27

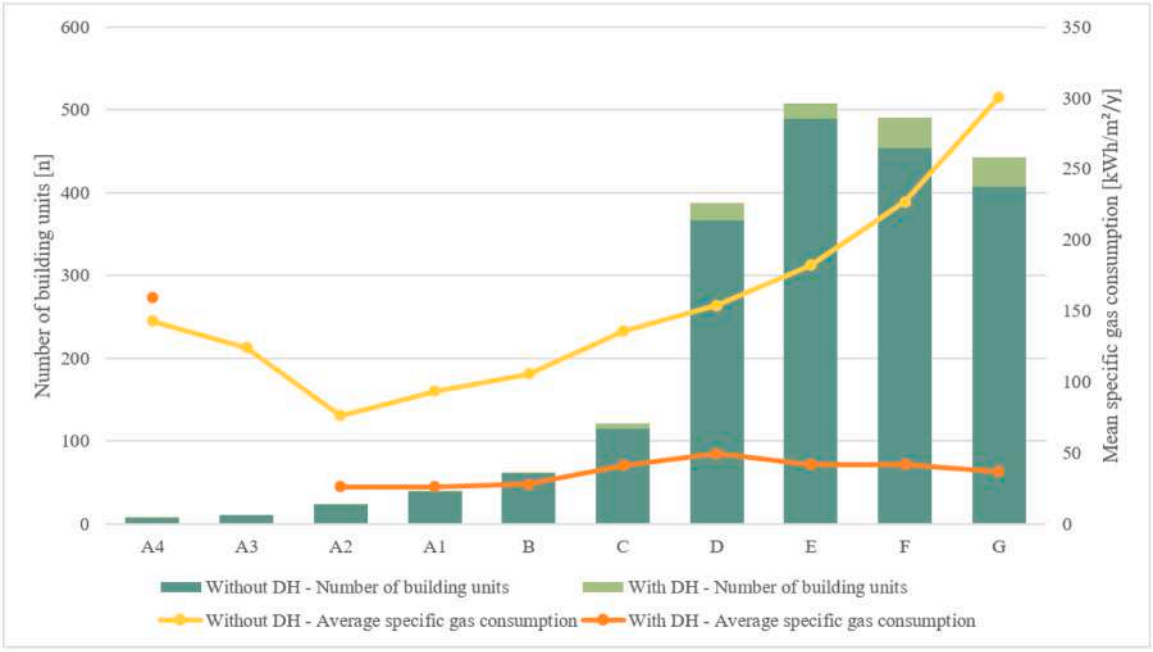


Fig. 13. Number of building units and mean specific gas consumption by energy performance class (Whole building dataset).

On the other hand, tertiary units connected to the District Heating (DH) network represent a much smaller sample (179 volumetric units). These buildings exhibit a drastically lower overall specific gas consumption, with a mean of 74.16 kWh/m²/y (median: 44.17 kWh/m²/y; IQR: 52.58 kWh/m²/y) and consumption irregularities in the highest efficiency classes given by limited number of records.

3.2.2. *Dataset analysis – renovation*

Out of the 163,517 records in the Total dataset, 13,290 (8.13%) belong to the Renovation dataset, related to EPC issued after renovation interventions.

As observed in Fig. 12 and Table 6, while in the total dataset the highest concentration of EPCs was observed in the least efficient classes (from D to G), in the renovation dataset most buildings fall into the intermediate classes (B, C, and D). This concentration can be justified by

Table 7
Statistical metrics of specific gas consumption (kWh/m²/y) grouped by energy class for building units with and without District Heating (DH) – (Whole building dataset).

	Without DH				With DH			
Energy classes	**Building units**	**Mean**	**Median**	**IQR**	**Building units**	**Mean**	**Median**	**IQR**
A4	7	142.86	128.17	200.00	1	159.17	159.17	0.00
A3	11	124.14	63.93	169.19	-	-	-	-
A2	23	76.25	61.60	45.98	1	26.42	26.42	0.00
A1	39	93.56	83.65	51.35	1	26.23	26.23	0.00
B	61	105.50	88.33	49.72	2	27.94	27.94	2.90
C	115	135.70	116.93	85.16	6	41.34	42.38	28.90
D	367	153.85	129.86	101.21	20	49.37	30.35	26.70
E	489	182.27	167.33	99.91	19	42.15	30.08	9.29
F	453	226.94	217.37	123.23	37	42.11	31.71	19.87
G	407	300.36	299.48	165.10	36	36.97	30.37	21.14
Total	1972	203.07	182.80	148.46	123	42.22	30.81	21.24

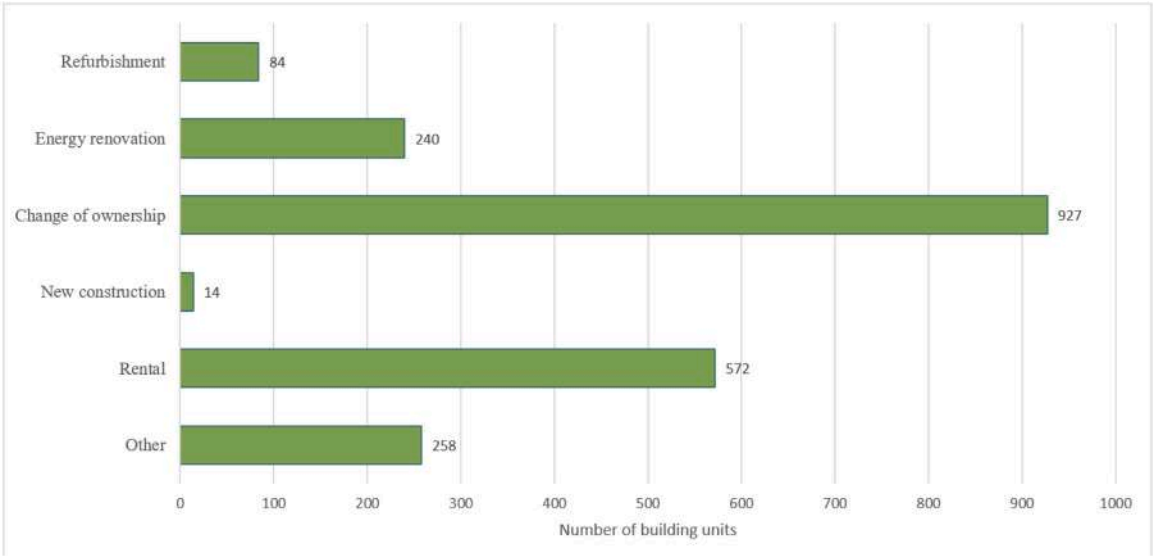


Fig. 14. Reason for issuing EPCs in the Whole Building dataset.

the fact that energy efficiency measures typically shift buildings from the worst to the intermediate ratings. Regarding specific gas consumption, for buildings not connected to district heating (9956 units), the overall mean is 94.41 kWh/m^2/y (median: 83.42 kWh/m^2/y; IQR: 72.71 kWh/m^2/y). As expected, this value increases progressively and consistently from the most efficient to the least efficient classes, starting from a mean of 29.14 kWh/m^2/y in class A4 (median: 24.22 kWh/m^2/y) and peaking at 175.32 kWh/m^2/y in class G (median: 184.41 kWh/m^2/y; IQR: 49.96 kWh/m^2/y). Conversely, in buildings connected to district heating, consumption remains stable and significantly lower across all energy classes. The overall mean for this subset is 31.02 kWh/m^2/y (median: 28.61 kWh/m^2/y; IQR: 5.27 kWh/m^2/y), with class-specific means ranging narrowly from 28.58 kWh/m^2/y (class A3) to 35.59 kWh/m^2/y (class G).

3.2.3. *Dataset analysis – whole building*

Finally, out of the 163,517 records in the Total dataset, 2095 (1.28%) belong to the Whole Building dataset.

As observed in Fig. 13 and Table 7, like the Total dataset, there is a strong concentration of EPCs in the lower energy performance classes (D–G).

Regarding the specific gas consumption, the same trend of the other datasets is observed. For buildings not connected to district heating, the average consumption increases from the most efficient classes to the least efficient ones, excluding classes A4 and A3, which exhibit irregular values probably due to low sample sizes.

In contrast, buildings connected to district heating exhibit a drastically lower overall mean consumption of 42.22 kWh/m^2/y (median: 30.81 kWh/m^2/y; IQR: 21.24 kWh/m^2/y) and the average consumption remains remarkably stable and flattened, ranging from 36.97 kWh/m^2/y to 49.37 kWh/m^2/y. The isolated anomaly observed in class A4 (mean of 159.17 kWh/m^2/y) is statistically insignificant because corresponds to a single volumetric unit.

As previously mentioned, the EPCs in the Whole Building dataset are mostly concentrated in the lower energy classes (D–G). This is further confirmed by the analysis of the reasons for issuing the EPCs shown in Fig. 14, where most building units were issued due to change of ownership or rental.

As for the other two previous datasets, the residential sector accounts for almost all the records (67%), thus making any analysis on either the industrial or tertiary sector statistically insignificant.

Unlike the Total dataset, separate analyses by building sector (residential, tertiary, and industrial) were not performed for the Renovation and Whole Building datasets due to the limited number of certificates.

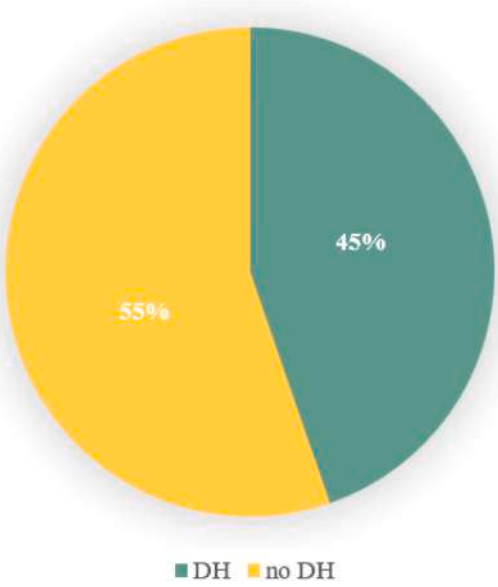


Fig. 15. Percentage of volumetric units connected to district heating (SIATEL Dataset).

3.3. *Energy performance analysis of SIATEL dataset*

Out of the initial 73,465 volumetric units with SIATEL data in Turin, the dataset was refined to 29,400 valid volumetric units after filtering for valuable specific gas consumption and applying the statistical filter (5th–95th percentile). Another analytical requirement for this study is the need to consider only those volumetric units with SIATEL data that can be spatially matched with at least one Energy Performance Certificate, which is essential to attribute an energy performance class and the district heating distribution. Following this specific spatial join, the subset of SIATEL volumetric units successfully associated with an energy class is 20,546.

As mentioned in the methodology, the raw SIATEL dataset exclusively provides energy billing data. To overcome this limitation, for each volumetric unit, the EPCs were aggregated to extract the worst energy

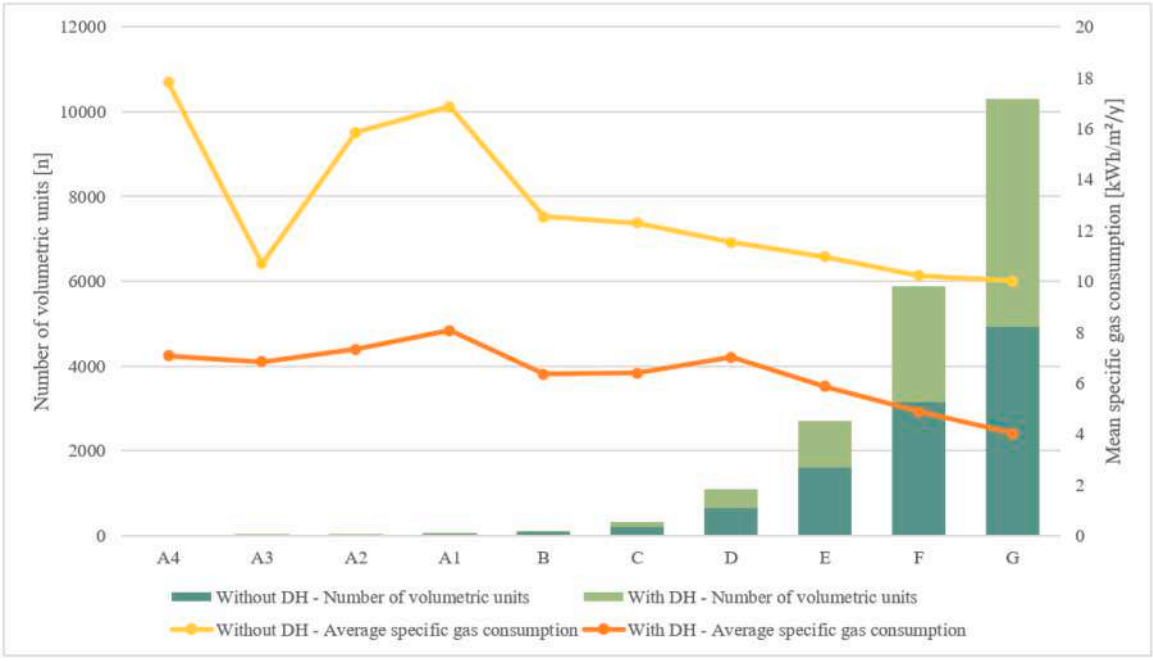


Fig. 16. Number of volumetric units and mean gas specific consumption by energy performance class (SIATEL dataset, worst-case class assignment).

Table 8
Statistical metrics of specific gas consumption (kWh/m²/y) grouped by energy class for volumetric units with and without District Heating (DH) – (SIATEL dataset, worst-case class assignment).

	Without DH				With DH			
Energy classes	**Volumetric units**	**Mean**	**Median**	**IQR**	**Volumetric units**	**Mean**	**Median**	**IQR**
A4	4	17.82	13.74	13.86	5	7.07	7.44	2.99
A3	13	10.70	8.15	9.64	7	6.83	5.00	1.78
A2	29	15.85	12.53	16.32	13	7.32	4.23	4.39
A1	36	16.87	14.65	19.76	20	8.06	4.28	6.84
B	84	12.53	10.09	10.31	35	6.35	3.97	5.73
C	202	12.30	9.75	10.81	121	6.38	5.15	6.70
D	658	11.52	10.07	8.15	434	7.00	6.15	6.74
E	1610	10.96	9.25	6.72	1091	5.86	4.15	6.37
F	3152	10.22	9.07	7.33	2726	4.87	2.96	5.29
G	4929	10.00	8.84	7.86	5377	4.01	2.47	3.08
Total	10,717	10.41	9.08	7.62	9829	4.64	2.74	4.65

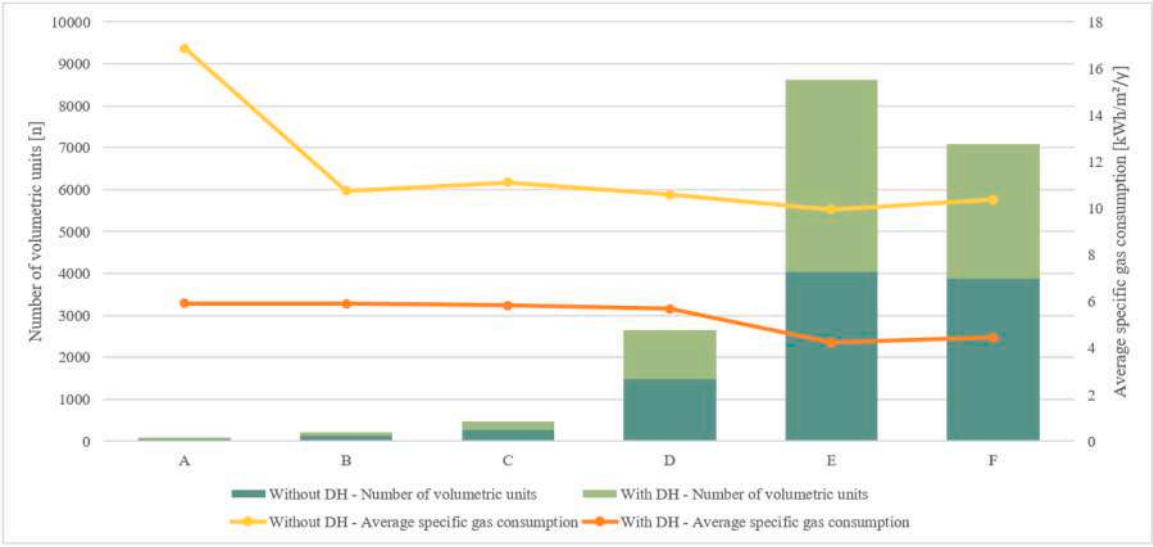


Fig. 17. Number of volumetric units and average gas specific consumption by energy performance class (SIATEL dataset, average-case class assignment).

Table 9
Statistical metrics of specific gas consumption (kWh/m²/y) grouped by energy class for volumetric units with and without District Heating (DH) – (SIATEL dataset, average-case class assignment).

	Without DH				With DH			
Energy classes	**Volumetric units**	**Mean**	**Median**	**IQR**	**Volumetric units**	**Mean**	**Median**	**IQR**
A	59	16.86	12.63	21.53	27	5.92	4.24	4.23
B	136	10.75	9.27	8.81	70	5.91	3.77	6.12
C	276	11.12	8.80	9.10	205	5.83	4.36	5.90
D	1472	10.59	9.10	6.51	1182	5.70	3.76	6.10
E	4050	9.96	8.83	7.80	4567	4.23	2.59	3.90
F	3881	10.37	9.17	7.67	3199	4.46	2.62	4.24
Total	9874	10.30	9.04	7.61	9250	4.55	2.71	4.55

performance class that was systematically assigned to the metered SIATEL records corresponding to that same unit.

Regarding the distribution of heating systems, Fig. 15 shows that out of the 29,400 filtered volumetric units, 13,144 (approximately 45%) are connected to District Heating (DH), while 16,256 (55%) are not connected. This indicates a much more balanced distribution compared to the EPC dataset.

Furthermore 92.58% of records belong to the residential sector.

Analysing the distribution of volumetric units and specific gas consumption in the SIATEL dataset, Fig. 16 and Table 8 show that the number of volumetric units increases progressively from the most efficient classes to the least efficient ones, with most of the sample in class G. This massive concentration in the lowest efficiency rating is a direct, expected consequence of the conservative "worst-case" class assignment methodology adopted for this dataset.

A prominent observation is that the actual metered energy consumption is drastically lower than the theoretical estimations reported in the EPCs. For instance, while in the Total EPC dataset the average gas consumption was 151.22 kWh/m²/y, the SIATEL volumetric units not connected to district heating exhibit an overall mean of just 10.41 kWh/m²/y (median: 9.08 kWh/m²/y; IQR: 7.62 kWh/m²/y). As expected, volumetric units connected to district heating present even lower values, with an overall mean of 4.64 kWh/m²/y (median: 2.74 kWh/m²/y; IQR: 4.65 kWh/m²/y).

Furthermore, in contrast to the trend of the EPCs, the metered consumption does not increase progressively as the energy class worsens. Instead, the specific gas consumption remains remarkably flat and unresponsive across all energy ratings.

To validate the robustness of the conservative "worst-case" class assignment a sensitivity analysis was performed. In this secondary evaluation, the average energy performance class of the available EPCs was attributed to the SIATEL volumetric units instead of the worst one. Fig. 17 and Table 9 illustrate the results of this alternative methodological configuration.

As expected, applying the average class metric significantly reshapes the categorical distribution of the building stock. The massive concentration previously observed in the lowest efficiency rating (class G) is entirely redistributed towards the intermediate categories. Under this configuration, most of the sample without District Heating peaks in class E and class F, while the class G completely disappears.

However, the specific metered gas consumption remains remarkably flat: for volumetric units without district heating the mean specific consumption remains between 9.96 and 11.12 kWh/m²/y. The district heating subset confirms an identical trend, with medians consistently ranging from 2.59 to 4.36 kWh/m²/y.

This sensitivity analysis conclusively demonstrates that the lack of correlation between the EPC efficiency ratings and the actual metered gas consumption is not generated by the worst-case assignment methodology.

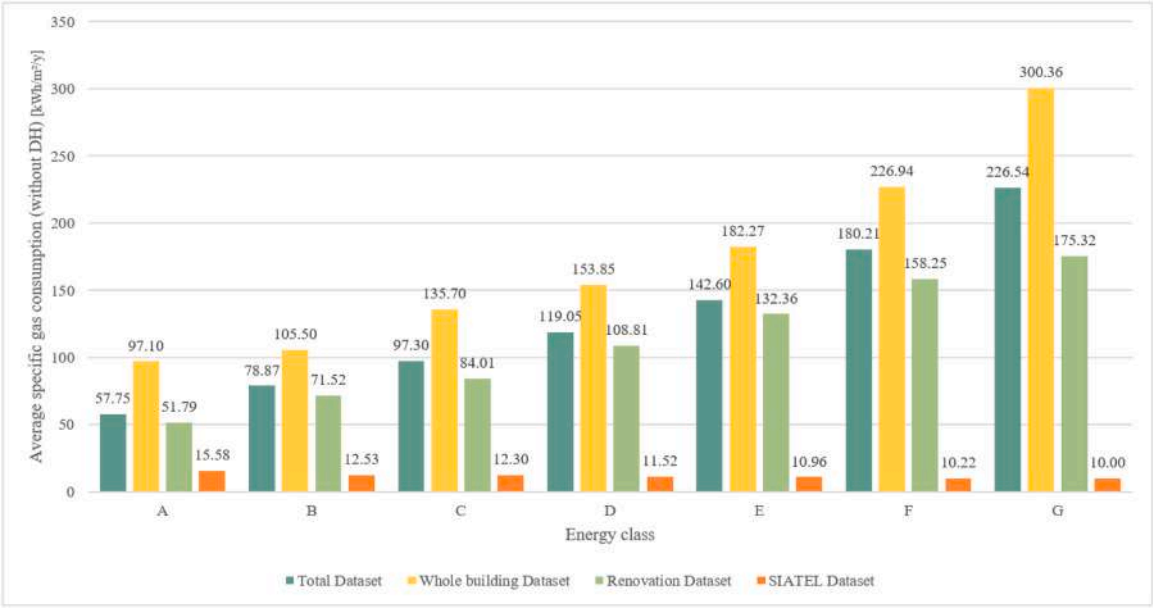


Fig. 18. Comparison of average specific gas consumption for building units (EPC) and volumetric units (SIATEL) not connected to DH across four datasets by energy class.

Table 10
Statistical summary of metrics of specific gas consumption (kWh/m^2/y) by energy class for building and volumetric units not connected to District Heating (DH).

	Total Dataset				Whole building Dataset				Renovation Dataset				SIATEL Dataset			
Energy class	N° of building units	Mean	Median	IQR	N° of building units	Mean	Median	IQR	N° of building units	Mean	Median	IQR	N° of volumetric units	Mean	Median	IQR
A	3252	57.75	51.34	26.94	80	97.10	73.89	63.28	2066	51.79	48.04	27.78	82	15.58	11.72	18.13
B	3585	78.87	70.34	33.72	61	105.50	88.33	49.72	1514	71.52	68.49	32.53	84	12.53	10.09	10.31
C	9479	97.30	85.61	44.70	115	135.70	116.93	85.16	1874	84.01	80.99	39.33	202	12.30	9.75	10.81
D	24,672	119.05	105.95	56.82	367	153.85	129.86	101.21	2200	108.81	106.91	69.49	658	11.52	10.07	8.15
E	39,801	142.60	131.27	70.90	489	182.27	167.33	99.91	1495	132.36	132.76	69.38	1610	10.96	9.25	6.72
F	34,961	180.21	172.00	94.97	453	226.94	217.37	123.23	674	158.25	160.68	59.26	3152	10.22	9.07	7.33
G	15,902	226.54	230.72	107.95	407	300.36	299.48	165.10	133	175.32	184.41	49.96	4929	10.00	8.84	7.86

4. Discussion

4.1. Comparison between the EPC and SIATEL dataset

To evaluate the reliability of EPC data, EPC-derived gas consumption was compared with metered data from the SIATEL database.

For buildings not connected to district heating (Fig. 18 and Table 10), the data clearly show that the metered gas consumption is significantly lower than the EPC values across all energy classes. While the EPC datasets exhibit a regular physical trend—with consumption progressively increasing as the energy class worsens—the metered data remains unexpectedly flat and drastically lower.

For instance, in class G, the specific gas consumption in the Total EPC dataset reaches a mean of 226.54 kWh/m^2/y and peaks at 300.36 kWh/m^2/y in the Whole-building dataset, while the actual metered consumption for the same class shows a mean of just 10.00 kWh/m^2/y.

For buildings connected to district heating (Fig. 19 and Table 11), all specific gas consumption values are drastically lower than those of buildings not connected to the network and discrepancies among the datasets are less pronounced.

However, the trend that EPC estimates systematically overestimate energy gas consumption remains.

4.2. Definition of correction factors (CFs)

Following the comparative analysis of the specific gas consumption, empirical Correction Factors (CF) for the City of Turin were calculated for each categorical subset. A CF strictly lower than 1.0 confirms that EPCs systematically overestimate the actual gas demand.

For volumetric units not connected to the District Heating (DH) network (Fig. 20), the Mean CF highlights a severe and progressive Energy Performance Gap. The calibration coefficient drops significantly as the energy class worsens. For instance, in the Total dataset, the Mean CF decreases from 0.27 in class A to a value 0.04 in class G. The Whole-building dataset exhibits the lowest calibration ratios across almost all classes (dropping to 0.03 in class G). Conversely, the Renovation dataset shows slightly higher CFs (ranging from 0.30 in class A to 0.06 in class G). This suggests that renovation interventions reduce slightly the energy performance gap. For volumetric units connected to the District Heating (DH) network (Fig. 21), the CF values are generally slightly higher than those observed for units not connected to DH. This result is consistent with the analysis of the EPC data presented above, which showed that buildings connected to the DH network generally exhibit lower estimated gas consumption.

Subsequently, a median-based Correction Factor (CF_{median}) was computed and compared against the mean approach (CF_{mean}). (Fig. 22 and Fig. 23)

A comparison between mean- and median-based correction factors highlights differences in the variability of the estimated coefficients. As shown in Figure 22, for buildings without DH, the median-based CFs are generally lower than the corresponding mean-based values, with a moderate reduction in the overall CF across classes. For DH-connected buildings (Figure 23), the differences between the two approaches are more pronounced, particularly in classes A and D. In these cases, the median-based CFs are considerably more homogeneous across the three datasets. For example, for class A, the mean-based CFs range from 0.107 to 0.255, whereas the corresponding median-based values range from 0.174 to 0.189. Similarly, for class D, the mean-based values range from 0.142 to 0.204, while the median-based values are clustered between 0.202 and 0.211. Overall, these results suggest that the median provides a more stable estimate of the typical correction factor, as it is less sensitive to high-consumption observations that can disproportionately affect the arithmetic mean.

To provide a comprehensive and easily accessible overview of the calibration metrics, the computed Correction Factors are summarised in Tables 12 and 13.

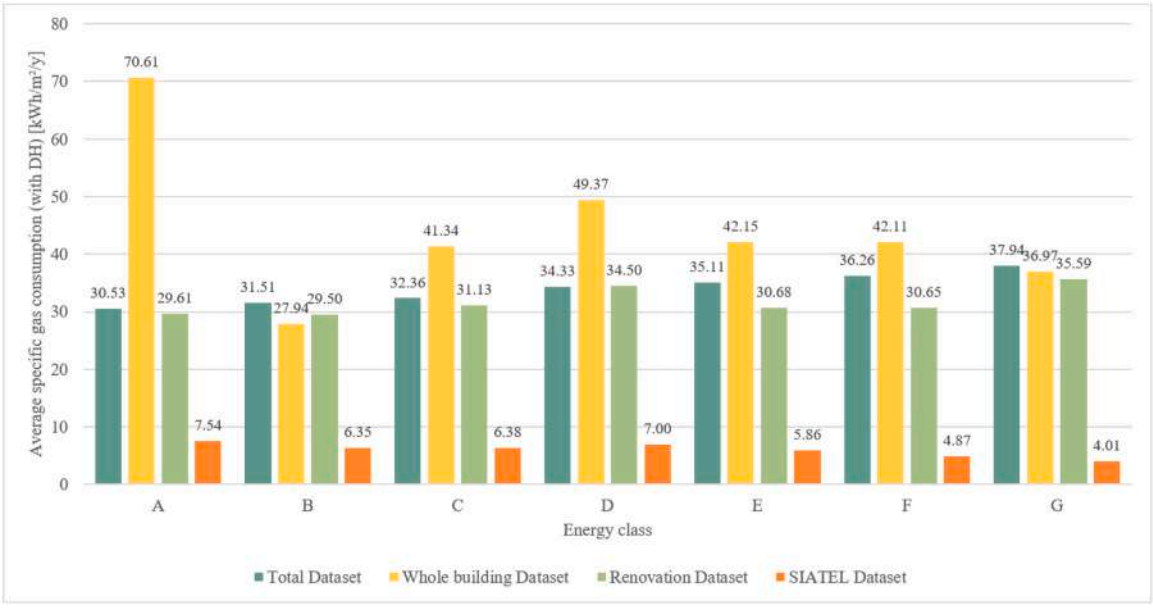


Fig. 19. Comparison of average specific gas consumption for building units (EPC) and volumetric units (SIATEL) connected to DH across four datasets by energy class.

4.3. Holdout sample validation for correction factors

To assess the predictive reliability of the proposed Correction Factors (CFs), an independent holdout validation was performed. The Total Dataset was randomly divided into two independent subsets, consisting of 80% of the observations used for calibration and 20% retained as an independent test set. The empirical Correction Factors were recalculated exclusively using the 80% training set and subsequently applied to the uncalibrated EPC-estimated gas consumptions of the 20% test set. The resulting predicted specific gas consumptions were then compared with the corresponding SIATEL-metered values in the holdout sample. The prediction error was calculated as the difference between predicted and actual consumption, such that negative values indicate an underestimation and positive values an overestimation.

The holdout results reported in Table 14 indicate a generally good predictive consistency of the calibrated estimates, particularly for the energy classes with a larger representation in the building stock. For buildings not connected to District Heating, the prediction error remains below 1 kWh/m^2/y in absolute terms for classes D–G.

The DH-connected subset also shows generally limited prediction errors for the lower-efficiency classes. The larger deviations observed for classes A and B in the DH-connected subset (+5.497 and +3.582 kWh/m^2/y) and for classes A and C in the non-DH subset (−10.886 and −2.690 kWh/m^2/y) should be interpreted with caution. These classes are characterised by a smaller number of records, so their holdout estimates are more sensitive to the composition of the randomly selected test sample.

Overall, the independent holdout test provides evidence that the proposed calibration framework can reproduce the measured consumption levels with relatively small prediction errors for the most represented energy classes, especially classes D–G.

4.4. Discussion of results

The comparative analysis between the Energy Performance Certificate (EPC) and SIATEL data reveals a systematic tendency of estimated consumption to overestimate metered data in the analysed building stock.

The initial descriptive results indicate a strong predominance of residential buildings across all data sources, accounting for between 92.58% of records in the SIATEL dataset and 96.26% in the Renovation dataset.

Furthermore, the limited presence of buildings connected to district heating—which serves 19.49% of the heated surface in the Total EPC dataset, 5.87% in the Whole Building subset, and 25.09% in the Renovation subset, compared with 47.71% in the SIATEL dataset—indicates the substantial role of natural gas as an energy carrier for the analysed building stock.

Moreover, when comparing the three EPC subsets, the Renovation dataset shows a smaller discrepancy with the metered data, suggesting that certificates issued for renovation interventions may provide information that more reflects current building conditions.

Overall, SIATEL metered consumption is substantially lower than the theoretical consumption reported in the EPCs and the magnitude of the energy performance gap varies across energy classes and becomes particularly pronounced for the least efficient classes.

Indeed, for volumetric units not connected to the district heating, metered gas consumption remains relatively flat across the classes, in contrast with the progressive increase of EPC values. As a result, the calculated Correction Factors (CFs) systematically decrease from high- to low-efficiency classes.

These discrepancies can be partially related to intrinsic limitations of EPC calculation procedure, which relies on standardised and default parameters which do not reflect the real physical, technological, and morphological characteristics of individual buildings.

In contrast, SIATEL data represent actual billed consumption and are therefore affected by real operating conditions and occupant behaviour.

To assess whether the flattened profile observed in the metered consumption could be caused by the data-processing procedure, a sensitivity analysis was performed by comparing a conservative worst-case class assignment with an average-case assignment for SIATEL volumetric units. The analysis showed that the lack of a clear correlation between estimated and metered consumption remains stable under both configurations.

Another significant aspect that emerged from the comparison concerns the presence of district heating: in these cases, the differences between EPC and SIATEL are less marked, since buildings connected to the district heating have lower average consumption. However, this result requires careful interpretation because natural gas may represent only a residual energy carrier in these buildings, mainly covering

Table 11
Statistical summary of metrics of specific gas consumption (kWh/m^2/y) by energy class for building and volumetric units connected to District Heating (DH).

	Total Dataset	Whole building Dataset					Renovation Dataset				SIATEL Dataset			
Energy class	N° of building units	Mean	Median	IQR	N° of building units	Mean	Median	IQR	N° of building units	Mean	Median	IQR	N° of volumetric units	Mean	Median	IQR
A	974	30.53	28.71	3.34	3	70.61	26.42	66.47	840	29.61	28.69	3.19	45	7.54	5.00	5.90
B	1046	31.51	28.71	4.46	2	27.94	27.94	2.90	611	29.50	28.35	3.93	35	6.35	3.97	5.73
C	2724	32.36	29.11	5.36	6	41.34	42.38	28.90	725	31.13	28.26	7.19	121	6.38	5.15	6.70
D	6416	34.33	29.61	6.07	20	49.37	30.35	26.70	561	34.50	29.19	11.86	434	7.00	6.15	6.74
E	9486	35.11	30.04	7.69	19	42.15	30.08	9.29	367	30.68	28.28	5.81	1091	5.86	4.15	6.37
F	7535	36.26	30.56	15.23	37	42.11	31.71	19.87	171	30.65	28.12	6.29	2726	4.87	2.96	5.29
G	3684	37.94	30.91	19.50	36	36.97	30.37	21.14	59	35.59	30.14	5.94	5377	4.01	2.47	3.08

domestic hot water, cooking, and other non-space-heating uses, while the main space-heating demand is supplied by the district heating network. Consequently, the smaller numerical gap observed for district-heated buildings cannot be interpreted as evidence that EPC estimates are intrinsically more accurate for these buildings.

Beyond methodological factors, the observed discrepancy may also be influenced by real building operation and occupant behaviour; indeed, building energy demand depends not only on the physical characteristics of buildings and their heating systems, but also on how occupants operate them.

Socio-economic conditions may constitute another potential factor: the literature consistently shows a positive correlation between income and energy consumption (Büchs et al., 2023).This phenomenon has been described in the literature as energy or heat rationing, whereby households facing financial constraints reduce energy consumption (Ugarte, 2016; Seguel-Vargas et al., 2024).

Such behaviour could potentially contribute to the relatively low measured gas consumption observed in some of the least efficient buildings, where theoretical EPC estimates predict substantially higher energy requirements.

However, this interpretation must be treated with caution in the context of the present study. The available dataset consists exclusively of energy-related and building-related information and does not include explicit variables describing household income, economic deprivation, energy poverty, or occupancy density.

5. Conclusion

This study analyses the consistency between natural gas consumption estimated from EPCs and metered data from the SIATEL database for the city of Turin.

The results show that EPCs tend to overestimate actual gas consumption and that the discrepancy varies across energy classes, becoming more pronounced for less efficient buildings. Among the three EPC datasets, the Renovation dataset reveals the highest level of consistency with metered consumption, confirming that certificates issued after energy efficiency interventions may better reflect current building consumptions.

A key outcome of the study is the identification of empirical Correction Factors (CFs) defined as the ratio between metered and estimated data. Moreover, these coefficients provide a data-driven approach to reduce the discrepancy between metered and estimated data at the urban scale. While previous studies have extensively investigated the energy performance gap and, in some cases, derived correction factors for specific building samples, typologies, or neighbourhoods, the present study extends this approach by deriving empirical CFs from a city-scale dataset. This allows the observed discrepancies between EPC estimates and metered consumption to be quantitatively translated into calibration coefficients that can be applied in urban-scale energy modelling.

However, the CFs derived in this study should be regarded as empirical, Turin-specific calibration coefficients rather than universally applicable correction parameters.

Several limitations should be considered when interpreting these results. First, the EPC and SIATEL datasets are not directly comparable at the individual building-unit level. SIATEL consumption is aggregated at the meter/address level, while the heated floor area used for normalisation is estimated from an independent spatial dataset. Consequently, the denominator used to calculate specific consumption may not always correspond exactly to the portion of heated space served by a given meter. In addition, energy performance class and district heating status are not directly observed in SIATEL but are inferred from the EPC dataset. In particular, the heuristic allocation of district heating connections to volumetric units introduces classification uncertainty and may not fully capture mixed-use buildings, partially heated buildings, or intra-building differences. These factors may affect subgroup

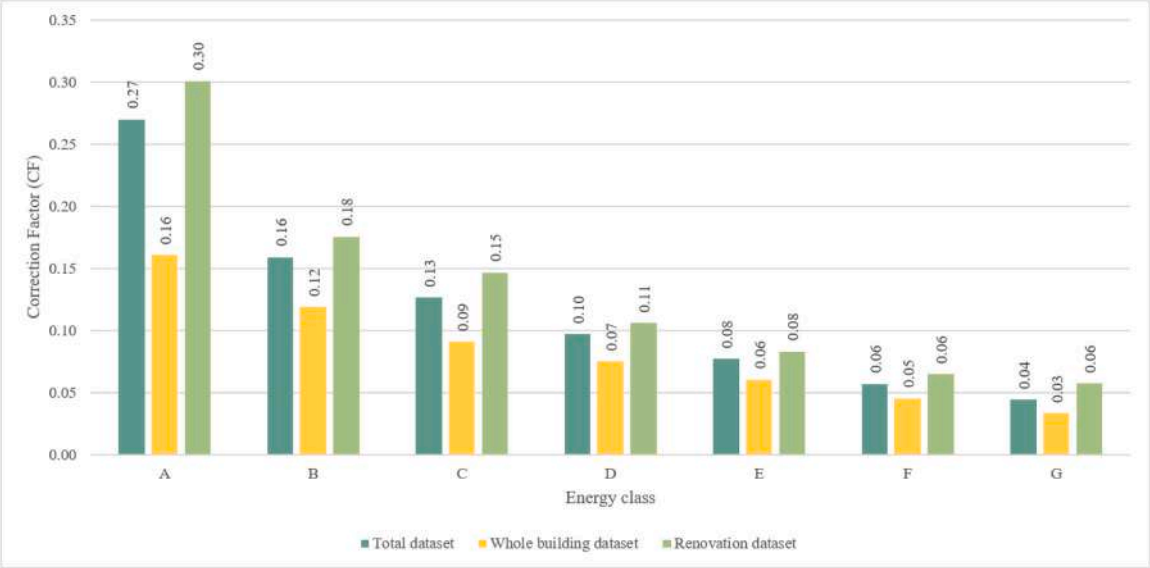


Fig. 20. Mean correction factor for volumetric units without DH.

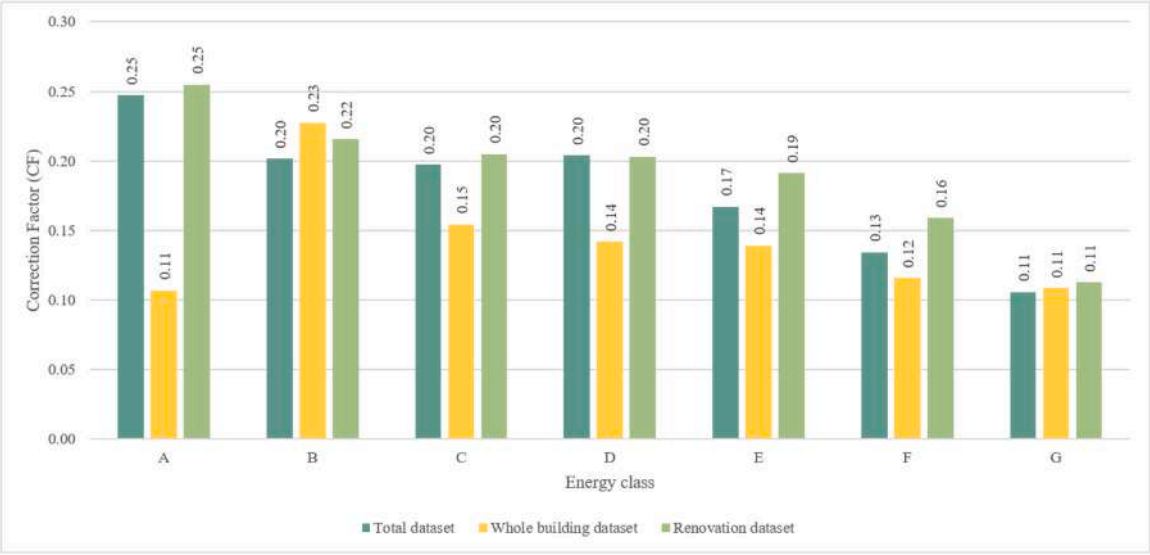


Fig. 21. Mean correction factor for volumetric units with DH.

comparisons and the resulting CFs.

Second, the SIATEL dataset covers only the reference year 2023, preventing temporal cross-validation against alternative years. The stability of the observed EPC–metered relationships over time therefore remains unassessed. Third, the EPC dataset covers only a subset of the Turin building stock: 22,551 of the 128,225 analysed volumetric units are associated with at least one EPC. The EPC sample cannot therefore be considered a statistically random or fully representative sample of the entire building stock, and selection effects related to certification requirements may influence its composition.

Overall, this study demonstrates the potential of using empirical, data-driven calibration coefficients to improve the consistency of EPC-derived energy estimates for urban-scale energy modelling. Their transferability and robustness should be assessed through external validation using meter-level building information, directly observed district heating connections, multi-year metered datasets, and broader EPC coverage.

Future developments should also address the increasing electrification of the building sector and the adoption of electric heat pumps by extending the methodology to electricity consumption and electric heating systems as building-scale monitoring data become more available. In parallel, more representative building archetypes could incorporate additional variables available from EPCs and other data sources, including year of construction, thermal-physical properties of the building envelope, HVAC systems, occupancy profiles, climatic conditions, and intended use. These extensions would support the application of the proposed methodology to increasingly heterogeneous building stocks and future decarbonisation pathways.

CRediT authorship contribution statement

M.V. Airoma: Conceptualization, Methodology, Software, Validation, Formal analysis, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization. **S. Anselmo:** Conceptualization, Methodology, Software. **M. Ferrara:** Conceptualization, Validation, Supervision.

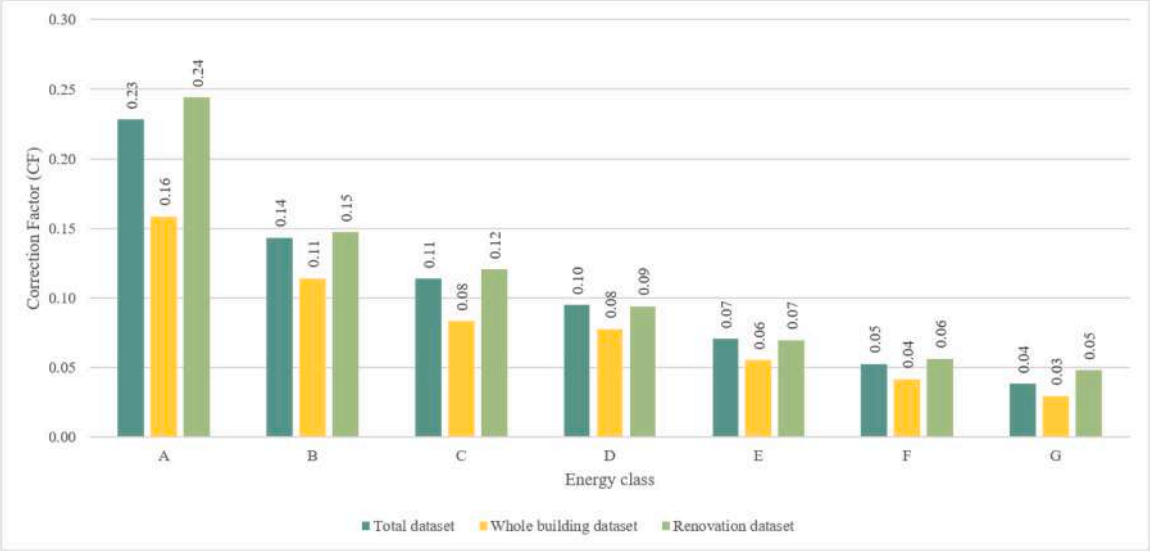


Fig. 22. Median correction factor (without DH).

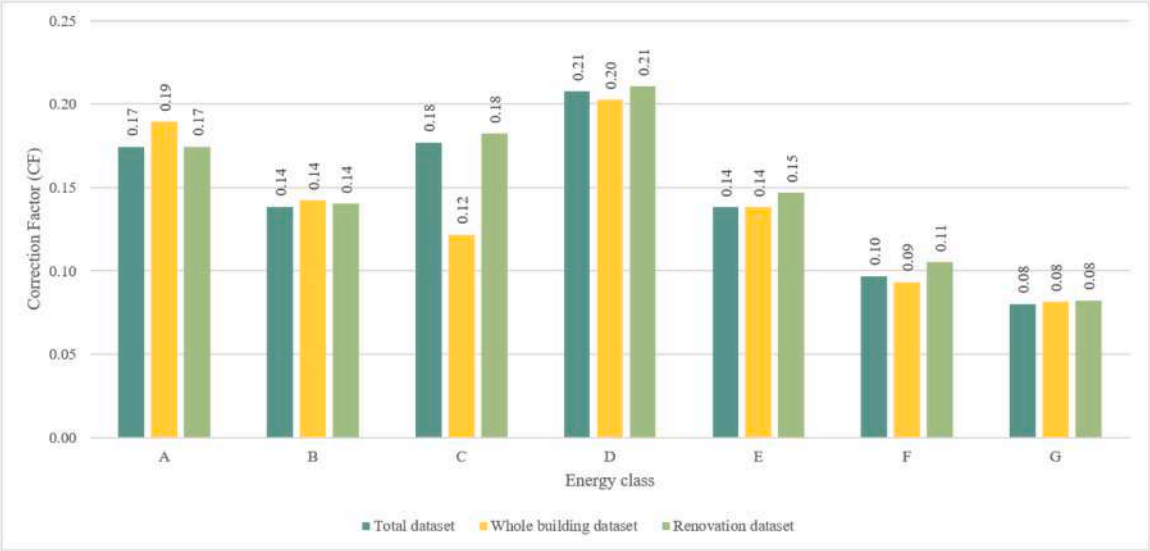


Fig. 23. Median correction factor (with DH).

Table 12
Mean Correction Factors (CF_{mean}) by energy class and overall dataset (CF across classes) with and without District Heating.

Mean correction factors (CFs)									
		A	B	C	D	E	F	G	CF across classes
CFs without DH	CFs (SIATEL/EPC Total dataset)	0.270	0.159	0.126	0.097	0.077	0.057	0.044	0.119
	CFs (SIATEL/EPC Whole building dataset)	0.160	0.119	0.091	0.075	0.060	0.045	0.033	0.083
	CFs (SIATEL/EPC Renovation dataset)	0.301	0.175	0.146	0.106	0.083	0.065	0.057	0.133
CFs with DH	CFs (SIATEL/EPC Total dataset)	0.247	0.202	0.197	0.204	0.167	0.134	0.106	0.180
	CFs (SIATEL/ EPC Whole building dataset)	0.107	0.227	0.154	0.142	0.139	0.116	0.109	0.142
	CFs (SIATEL/EPC Renovation dataset)	0.255	0.215	0.205	0.203	0.191	0.159	0.113	0.192

Nomenclature

CF	Correction Factor
CTC	Municipal Technical Map
DH	
DHW	District heatingDomestic Hot Water
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
EPG	Energy performance gap
EU	European Union
GHG	Greenhouse Gas
HDD	Heating Degree Days
SIATEL	*Sistema di Interscambio Anagrafe Tributaria Enti Locali*
UBEM	Urban Building Energy Model

Table 13
Median Correction Factors (CF_{median}) by energy class and overall dataset (CF across classes) with and without District Heating.

Median correction factors (CFs)									
		A	**B**	**C**	**D**	**E**	**F**	**G**	**CF across classes**
CFs without DH	CFs (SIATEL/EPC Total dataset)	0.228	0.143	0.114	0.095	0.070	0.053	0.038	0.106
	CFs (SIATEL/EPC Whole building dataset)	0.159	0.114	0.083	0.078	0.055	0.042	0.030	0.080
	CFs (SIATEL/EPC Renovation dataset)	0.244	0.147	0.120	0.094	0.070	0.056	0.048	0.111
CFs with DH	CFs (SIATEL/EPC Total dataset)	0.174	0.138	0.177	0.208	0.138	0.097	0.080	0.145
	CFs (SIATEL/ EPC Whole building dataset)	0.189	0.142	0.122	0.202	0.138	0.093	0.081	0.138
	CFs (SIATEL/EPC Renovation dataset)	0.174	0.140	0.182	0.211	0.147	0.105	0.082	0.149

Table 14
Holdout validation results: prediction error (predicted vs. actual SIATEL metered consumption) on the independent 20% test set.

Energy class	Prediction Error without DH (kWh/m²/y)	Prediction Error with DH (kWh/m²/y)
A	-10.886	5.497
B	0.240	3.582
C	-2.690	-0.890
D	-0.182	-0.252
E	0.585	-1.409
F	0.181	-0.094
G	-0.264	0.128

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.

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Data availability

Data will be made available on request.

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