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Energy modelling of the Italian residential building stock

Electric and thermal energy consumption of non-residential buildings: real data analysis and modeling

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Executive summary

This policy brief highlights two interconnected research initiatives focused on estimating energy consumption in buildings: the first examines the energy modeling of Italy's residential building stock, while the second focuses on analyzing and modeling real energy data for non-residential buildings.

The first contribution advances energy modeling for Italy's residential sector to support decarbonization goals under the European Green Deal. It addresses the sector's significant energy consumption and carbon footprint through a refined modeling approach. The study builds on data from the 2013 ISTAT household energy survey, covering 20,000 households across Italy. The model integrates building archetypes, regional climate variability, energy simulation tools for heating and cooling demand. It also accounts for incomplete data and user behavior via probabilistic methods. The model results accurately replicate national energy consumption patterns: there is less than a 9% error compared to data from TERNA and IEA. A scenario analysis is also implemented. The key findings reveal that retrofit measures and the adoption of renewable energy technologies, such as heat pumps, offer substantial energy savings and emissions reductions. For this reason, they should be considered for future policy development related to the Italian energy transition.

The second research investigates energy consumption patterns across a sample of University buildings, including schools, offices, laboratories, and recreational facilities. The analysis focuses on the building stock of the Alma Mater Studiorum University of Bologna, and it evaluates various energy vectors, such as electricity, natural gas, and district heating, identifying diverse end uses and their impact. This work addresses two challenges: on the one hand, the multi-purpose nature of university buildings; on the other hand, the diversification of energy consumption end uses. The proposed method to estimate annual electrical and thermal consumption profiles on an hourly basis is based on categorizing days into typical types (e.g., summer and winter working days, weekends, holidays). By identifying consumption drivers for each end use, normalized trends were derived using Fourier transforms and other analytical techniques. Key findings include the value of analyzing electricity consumption in different time slots to determine predominant building use and the potential to estimate consumption for different services in the absence of divisional meters. This work contributes to improving energy efficiency and sustainability in public buildings.

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1. Presentation and description of the research activity undertaken

The building sector accounts for 40% of final energy consumption and 36% of CO2 emissions. In this respect, Directive 2018/844/EU promotes long-term renovation strategies to achieve the 2050 EU-wide energy and climate targets (Bragolusi and D'Alpaos, 2022). Consequently, buildings energy retrofitting and a proper evaluation of buildings energy consumption play a fundamental role in the successful implementation of the energy transition. The Italian building stock is one of the oldest and least energy efficient in Europe: about 70% of the assets were built before the entry into force of first regulation on buildings energy performance, namely Act n. 373/1976 (D'Alpaos and Bragolusi, 2021). Changes in end-user behavior, energy saving, and buildings efficiency are consequently a crucial issue in Italy, due to the potential of the existing stock in energy savings and reduction of greenhouse gas (GHG) emissions (Bragolusi and D'Alpaos, 2022). To inform the design of cost-effective policy that contributes to accelerating the energy transition in the building sector, data on the energy consumption of the existing building stock are essential. Unfortunately, this data are scarcely available and collected systematically. The research activities described in what follows are indeed meant to cover this information gap for residential and office and school/university buildings.

1.1 Energy modelling of the Italian residential building stock

In 2019, the European Commission presented the Green Deal, a package of proposals to reduce net greenhouse gas emissions by 55% by 2030 compared to 1990 levels (European Commission 2020). This plan and EU energy policies are crucial to speed up the decarbonization process, trying to reach carbon neutrality by 2050.
Several international sources report the great inefficiencies connected to the European building stock (Economidou et al. 2011), which is mainly due to a great percentage of buildings built before the first laws on the energy performance of buildings, which differ from country to country. In 2018, the first directive was issued to harmonize the laws at

European level ("Energy Performance of Buildings Directive, (2018/844/EU)" 2018).

Italy has outlined the first phase of the Green Deal implementation for the period 2021-2030 in the "Piano Nazionale Integrato per l'Energia e il Clima" (PNIEC).

According to PNIEC, the residential sector accounts for approximately 30% of the final energy consumption in Italy, and a significant share of it is covered by natural gas, thus emphasizing the importance of the decarbonization of buildings' energy supply.

National building stock energy modeling is therefore an important tool for stakeholders and policy makers to assess the status quo and to evaluate the effectiveness of energy policies in reducing primary energy consumption and CO2 emission of buildings, as well as other relevant indicators such as the demand for different fuels.

To this purpose, a suitable model to simulate the energy consumption of the Italian residential building stock has been developed. The core of the model depends on a dataset describing the building stock itself. In particular, the 2013 Italian survey of household energy consumption was chosen (ISTAT 2016), as it provides the answers of 20000 people distributed among all 20 Italian regions to more than 350 queries about their building and their energy consumption. The questions are subdivided into nine categories according to the type of information they aim to obtain: occupants (number, gender, age, etc.), dwelling (type, floor plan, construction period, size, materials, orientation, etc.), space heating, space cooling and Domestic Hot Water (DHW) production systems, biomass consumption, lighting devices, appliances and energy expenses.

In addition to these data, each entry of the survey is assigned to a refactor coefficient, i.e., the number of houses, which are represented by that specific entry. Such coefficients allow us to upscale the simulation results to the whole sample, making it possible to represent the whole national building stock. **Error! Reference source not found.** shows, as an example, the regional distribution of dwelling types.

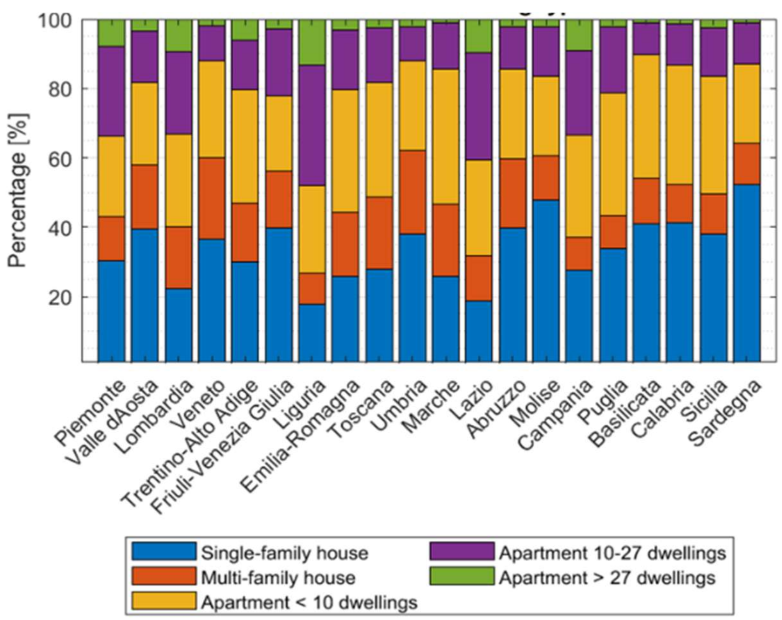

Figure 1 - Distribution of dwelling types across Italian regions

Model structure

The model is divided into five modules, that are graphically represented in Figure 2.

In the first module, the input data are read and imported. Beyond the dataset coming from the ISTAT survey, we employ dataset including the average energy consumption of domestic appliances available in the market (Growth for Knowledge 2021), and a dataset containing weather data (air temperature, relative humidity, global irradiance on the horizontal plane and wind velocity) from all Italian prvinces with hourly resolution (Comitato Termotecnico Italiano, 2016).

In the second module, the first two datasets are used to simulate the energy consumption of the appliances in the households of the selected sample (participants to the ISTAT survey). The appliances include lights, fridge, computer, TV, washing machine, etc. and heat generators for DHW production. The calculation consists in multiplying the typical consumption of a type of appliance (by the estimated yearly usage (Besagni et al., 2020).

In the third module, the calculated consumption of appliances is processed together with the ISTAT dataset to calculate all the relevant data about the buildings. The latter are then used in the fourth module to simulate the energy demand for space heating and cooling. The simulation relies on EUReCA's models (Prataviera et al., 2021), which a software for urban scale building simulations that has been developed and is currently maintained by researchers of the BETA_Lab research group of the Department of Industrial Engineering, University of Padova.

In the fifth module, the simulation results of modules 2 and 4 are combined and upscaled to obtain the consumption of all energy carriers at national level with the refactor coefficients. From those consumptions, all other indicators (primary energy consumption, CO_2 emissions, etc.) can be obtained and visualized either at national or regional level.

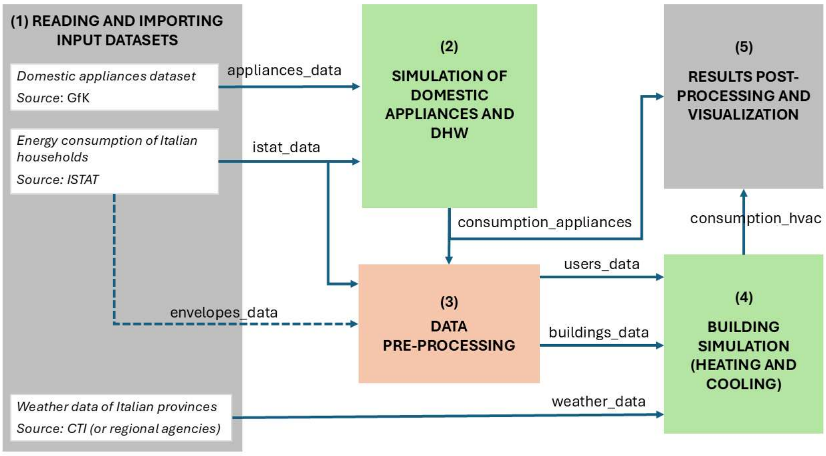

Figure 2 – Model structure

Improvements compared to the previous model

The model is based on a previous simulation tool developed at BETA_Lab research group. The model has been completely rewritten for the purposes of GRINS project, with the following main improvements:

- The model structure has been simplified, and all intermediate results can be easily accessed, thus making the model easier to be maintained compared to the previous version.
- Una-tantum calculations that depend on the input data have been performed and results have been stored so that running the model is approximately 10x faster compared to the previous version.
- The building simulation part for the calculation of heating and cooling demands now relies on EUReCA, which is a well-known and maintained package developed by BETALab research group, thus making this part more reliable compared to the previous version.
- The location of each entry is specified only as a region. However, the diversity of weather conditions inside each region makes this level of detail rather inaccurate.

To compensate for this lack of information, each entry is assigned to a province according to a probability distribution based on the ISTAT census (2011).

Moreover, as the building simulation is based on building archetypes, open-source databases (e.g., ISTAT and energy performance certificates), previous studies, regulations, and sector literature have been analyzed to characterize the national building stock according to climate zones. In addition, an analysis of user behavior about environmental parameters will be carried out by researchers of University of Venice. A crucial parameter influencing both indoor environmental conditions and building energy performance is the user behavior. While reference values for these variables are often prescribed by national and international Standards, the subjective actions of residents can strongly differ and are at the base of the performance gap between energy consumption forecast and real. Therefore, residential units that align with the defined archetypes have been selected for the monitoring of indoor environmental conditions. Monitoring equipment will be installed to continuously gather data on indoor temperature, globe temperature, relative humidity, and CO2 levels. Additionally, residents will complete an anonymous questionnaire to detail their habits and to identify any correlations with the collected data. They will also provide critical information about their summer and winter conditioning systems and report their annual gas and electricity consumption to offer a comprehensive characterization of their energy-behavior.

1.2 Electric and thermal energy consumption of non-residential buildings: real data analysis and modeling

Public administration buildings, such as schools, offices, and recreational facilities, represent a significant portion of national energy consumption. The primary goal of this study is to develop a tool capable of reconstructing annual energy consumption profiles on an hourly basis and deriving associated key performance indicators (KPIs) using minimal data about the building-plant system. This was achieved by analyzing the energy consumption data of the Alma Mater Studiorum University of Bologna's building stock.

The study focuses on a detailed examination of energy consumption across a selection of University buildings, including schools, offices, laboratories, and recreational facilities.

It evaluates various energy vectors, such as electricity, gas, and hot water provided by district heating, and investigates their diverse end uses. The research not only aims to characterize these energy consumption patterns but also proposes strategies for energy optimization to address sustainability and efficiency needs in university buildings.

2. Relationship with the existing literature on the topic

2.1 Energy modelling of the Italian residential building stock

Building stock energy models (BSEMs) can be broadly divided into two types according to the methodology they follow. The first type is top-down BSEMs, which derive relationships between the aggregated total energy consumption of the sector and various economic and technological factors.

The second type is bottom-up BSEMs, which start from estimating energy consumption at the individual building level and extrapolate that to represent a portion of the sector (e.g., residential buildings) or the entire sector (Kavgic et al., 2010).

Most analyses of country-wide energy consumption rely on top-down approaches. In this case, demographic and economic reports at the national level are combined with purely statistical methodologies to calculate specific indicators for the building stock energy consumption (Summerfield et al., 2010). Despite this methodology being fast and easy to implement, it often does not give a wide and disaggregated representation.

On the contrary, the bottom-up approach, based on the physical simulation of representative buildings whose results are then scaled up to the stock level, allows a more detailed analysis and the evaluation of future scenarios.

It is difficult to obtain high quality input data for bottom-up building stock models. For instance, it was shown that urban-scale simulations lead to high errors both in heating demand and peak load estimation due to uncertainties about geometric, physical and operational parameters (Prataviera et al., 2022).

Another problem concerns the incompleteness of data. A recent paper (Penaka et al., 2024) applied probabilistic record linkage to integrate records from energy performance certificates (EPC) and from a nationwide survey on the technical status of the buildings across Sweden, called BETSI. The survey employed on-site measurements on a sample of 1800 buildings to determine their thermal performance. This technique uses common variables between the two datasets (EPC and BETSI) to build a comprehensive dataset, thus addressing the challenge of incomplete data. The method was tested on the city of Umeå.

EPC are often used as input data for building stock simulations due to their availability and standard structure, which can provide valuable information on the characteristics of the building stock. For instance, EPC were used to develop nation-wide models for Switzerland (Streicher et al., 2019) and Spain (Beltrán-Velamazán et al., 2024).

Grouping and clustering techniques are commonly used to simulate space heating and cooling demands for a large number of buildings at a regional or national scale. These techniques enable simulations on a subset of representative buildings, also commonly referred to as building archetypes, which can then be used for upscaling.

Archetypes for building stock simulations can be based on building characteristics such building type, size, end use and age (Carnieletto et al., 2021) as well as the spatial characteristics of the neighborhood the building belongs to (e.g., rural versus urban) (Streicher et al., 2019).

The advantage of relying on a simplified building stock representation is not only the reduced computational cost for the analysis but also the reduced need for detailed input data of individual buildings which are often protected and difficult to obtain (Eggimann et al., 2022). In a recent analysis performed on three Swiss regions, it was found that clustering buildings into representative archetypes leads to low errors at regional scale (2% for heating and 7% for cooling demand) but that the errors increase significantly when the looking at the aggregated energy demand at neighborhood scale (Eggimann et al., 2022).

Summarizing, building simulations can help estimate the effect of energy efficiency policies at a large scale (Vulic et al., 2023). The reliability of such simulations does not only depend on the accuracy of the underlying models, but also on the quality of input data including weather conditions, technological diffusion within households, and user behavior. Incorporating these aspects into building stock simulations at a national scale is a challenging task due to the diversity of users and households and to the computational burden required to simulate millions of buildings.

In this project, the researchers try to address these challenges by presenting a new version of a previously developed bottom-up model of the Italian residential building stock. The model will be released as an open-source Github repository and application results will be reported in the AMELIA platform.

2.2 Electric and thermal energy consumption of non-residential buildings: real data analysis and modeling

Attention to energy efficiency in public buildings is well-documented in existing literature. For instance, past research conducted at the University of Perugia (Barelli and Bidini, 2003) introduced a methodology for energy diagnostics in university buildings, emphasizing the evaluation of electrical and thermal consumptions in relation to factors like outdoor temperature and space use. This analysis highlighted how inefficiencies in heating and cooling systems significantly increase energy consumption, underscoring the importance of planning interventions such as improved thermal insulation and retrofitting thermal systems.

Further studies, such as in Quevedo et al. (2023), explored the challenges and opportunities of energy management on university campuses. The complexity of these campuses, with their diverse buildings and services, necessitates specific performance indicators to accurately represent energy consumption intensity relative to space usage and occupant behavior. This research highlighted the value of integrating advanced technologies, such as IoT and geographic information systems (GIS), to enhance data accuracy and improve comprehension for non-expert users.

Building on these findings, the current study extends the focus to the University of Bologna's building stock, integrating detailed consumption data and proposing optimization strategies. It leverages insights from previous methodologies and aligns with the literature's emphasis on monitoring, advanced analytics, and sustainable practices to enhance energy efficiency in public buildings.

3. Research Output

3.1 Energy modelling of the Italian residential building stock

The results presented here refer to a preliminary release of the model. They are divided into model validation and example scenarios.

After the validation process, the model is exploited to run future scenario analyses. In fact, the main scope of the model is the generation of scenarios at national level. As an example of the possible analyses, three scenarios have been considered: (S1) Future scenario with 2050 climate without any retrofit of the building stock; (S2) scenario S1 with thermal insulation of building envelopes and condensing boilers; (S3) scenario S1 with thermal insulation of building envelopes and replacement of gas boilers with air source heat pumps.

Concerning the weather condition, 2050 climatic data are obtained using *CCWorldWeatherGen* (Jentsch et al., 2008).

Model validation

Error! Reference source not found. shows the specific final energy of the households, split by fuel type and area. The energy mix is mostly consistent for the North-East, North-West, the central area, and southern areas, while it is very different for mountainous areas and islands. The latter, including Valle D'Aosta and Trentino Alto Adige, exhibit high specific consumption values that exceed 275 kWh/m^2, they rely heavily on biomass, and partly on gasoline, due to difficulties in extending the gas network to the more elevated zones and the greater availability of biomass from nearby woods. North-East, North-West and central regions present similar energy mixes, with natural gas being the main energy carrier. Their specific consumption ranges from approximately 170 kWh/m^2 in central area to 250 kWh/m^2 in the North-East. Natural gas consumption on islands is quite limited as Sardegna is not connected to the natural gas network, therefore the shares of LPG and electric energy are greater than in other zones.

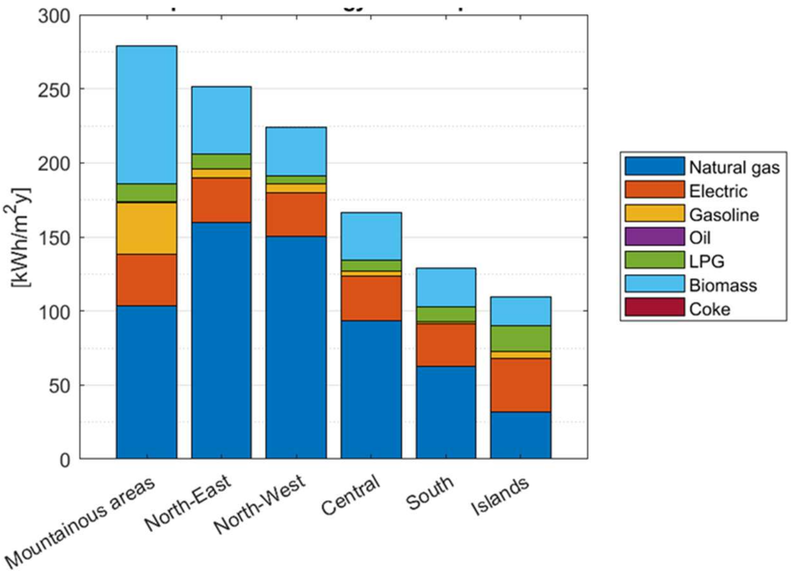

Figure 3 - Specific final energy consumption divided by energy vector

Concerning primary energy, the estimated national total primary energy consumption is equal to 39.4 Mtoe. Out of this total value, 35.9 Mtoe is non-renewable primary energy (91%) and 3.5 Mtoe is renewable primary energy (9%). The primary energy consumption, related to the different energy carriers, is reported in **Error! Reference source not found.**. Natural gas covers almost half (48%) of the primary energy consumption, followed by electric energy (31%) and biomass (14%). The use of LPG and gasoline is limited (4% and 2%), the use of oil and coke is negligible (less than 1%).

Energy vector	*Primary energy [ktoe]*
Electric energy	12266 (31%)
Natural gas	19100 (48%)
Biomass	5552 (14%)
LPG	1591 (4%)
Gasoline	884 (2%)
Oil	16 (<1%)
Coke	0 (<1%)
Total	39428

Table 1 - Primary energy consumption by energy vectors

Error! Reference source not found. presents the energy consumption by energy vector obtained by simulating the model, compared with the data provided by TERNA and IEA for 2013 (TERNA 2013; International Energy Agency, n.d). From these values, it is possible to observe how the model can estimate the consumption of natural gas and electricity with good accuracy. Concerning national references, natural gas consumption and electricity consumption stand around and error of about 0.6% and -4%, respectively. Such error increases when other fuel types are considered like wood and pellets, as self-consumption and modeling issues emerge; however, such fuels are less spread all over the country, keeping the overall model error less than -9%.

Energy vector	*Model*	*Reference*	*Error*
Natural gas [ktoe/y]	18190	18073	+0.6%
Electric energy [GWh/y]	58948	61379	-4.0%
Biomass [ktoe/y]	5552	6633	-16.3%
LPG [ktoe/y]	1515	1193	+27.0%
Gasoline [ktoe/y]	826	1511	-45.3%
Total [ktoe/y]	31166	34230	-9.0%

Table 2 - Italian final energy consumption compared with data from TERNA and IEA

Example of scenarios

The simulation results of the scenarios considered are reported in **Error! Reference source not found.**. From the simulation results considering only the retrofit of building envelopes, S2, a reduction in natural gas consumption of 7% is observed compared to the simulation with 2050 climatic data, equivalent to 1407 ktoe. Additionally, there is a decrease of 965 ktoe in biomass consumption, a reduction of 148 ktoe in LPG consumption, and a decrease of 177 ktoe in diesel consumption, all due to the replacement of traditional boilers, and envelope insulation. Electric consumption remains relatively unchanged, due to its marginal use for space heating. Overall, there is an 8% reduction in total final consumption. Compared to the simulation that considers only 2050 climatic conditions, the simulation that considers both retrofitting of building envelopes and installation of heat pumps systems, with a renovation rate of 21.8%, exhibits a reduction in natural gas consumption by 18%, equivalent to 3340 ktoe. This reduction is primarily attributed to the replacement of traditional boilers with condensing gas boilers and with heat pumps. Additionally, there is a 20% increase in final electric energy consumption, equivalent to 11765 GWh. The overall final energy consumption shows a decrease of 12%, equivalent to 3605 ktoe, providing a better solution with respect to the previous case (no PV self-consumption is considered, resulting in a conservative analysis).

	2013	**S1**	**S2**	**S3**
Natural gas [ktoe/y]	18190	18309 (0%)	16983 (-7%)	14969 (-18%)
Electric energy [GWh/y]	58948	59314 (0%)	59202 (0%)	71079 (+20%)
Biomass [ktoe/y]	5552	5461	4496	4474
LPG [ktoe/y]	1515	1490	1342	1283
Gasoline [ktoe/y]	826	822	645	650
Total [ktoe/y]	31297	31197 (0%)	28667 (-8%)	27592 (-12%)

Table 3 - Final energy consumption provided by the four model simulations, for the different energy vectors

As it can be observed, the model can provide estimates on the effect of energy efficiency measures in future scenarios, thus being a useful tool to inform policy makers.

Future work will update this analysis using ISTAT surveys conducted in 2021 and 2024, when the latter will be publicly available.

3.2 Electric and thermal energy consumption of non-residential buildings: real data analysis and modeling

Regarding non-residential buildings, both public administration and private, the objective of the research is to determine annual consumption profiles on an hourly basis and energy consumption KPIs for buildings of which only some general data are available, such as location, size, energy services present, and facility use. To achieve this goal, the idea is to create a tool that will return, starting from some minimal input, the desired results.

The starting point was the energy consumption data associated with the building stock of the Alma Mater Studiorum University of Bologna. The historical evolution of energy consumptions was examined in the period 2018-2024 for various energy vectors such as electricity, natural gas, and district heating. The analysis considered a sample of about a hundred buildings characterized by different uses. The predominant percentage is represented by the category of buildings associated with school activities and light laboratories (43%), and another important subset is linked to offices (29%).

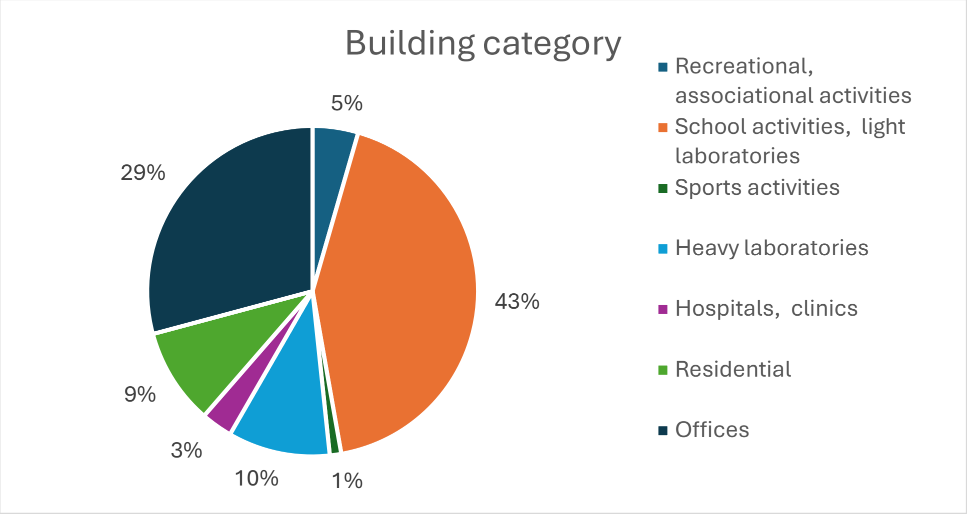

Figure 4 - Uses of the sample of buildings analyzed

To obtain a complete overview of the buildings examined in the sample, two studies were conducted: one on electrical consumption and one on thermal consumption. Specifically, the items shown in Table 4 below were defined.

Electrical analysis	Thermal analysis
Prevalent use	Average transmittance of the envelope
Percentage of consumption by band (F1, F2 and F3)	S/V ratio
Facility use	Weekly profile of heating service
HVAC equipment	HVAC equipment
Other high-absorption equipment	

Table 4 - Electrical and thermal analysis of the building sample

This characterization was made possible through an exhaustive understanding of consumption data, also carried out through the construction of graphs relating energy consumption as a function of time and temperatures inside and outside air-conditioned buildings (consumption bands, energy signature, etc.).

During the research, the need to address two common and well-documented issues in the literature for large nonresidential buildings, such as university buildings, emerged: multi-purpose use of buildings and diversification of energy consumption end uses.

To address these challenges, a focused study was conducted in the Bertalia University District. A series of divisional meters have been installed within this university district with the aim of measuring electricity consumption for different end uses (i.e. lightning, cooling, room ventilation and so on). The data collected are recorded and analyzed using a building management system (BMS), which allows accurate monitoring and a detailed analysis of all energy consumptions. This study allows to conclude:

1. For the definition of the predominant use of a building, in addition to the analysis of the different types of rooms present, it can be useful to observe the distribution of electricity consumption in the different time slots (F1, F2, and F3) during the day, week and seasons.
2. Electricity consumption for different services, in buildings without divisional meters, can be estimated by difference, considering the plant equipment present and its use within the structure. Figure 5 shows the existence of a base consumption associated with lighting, mechanical ventilation, and internal apparatus, and a variable consumption related to air conditioning during the summer, influenced by outdoor temperature, solar radiation, and internal loads.

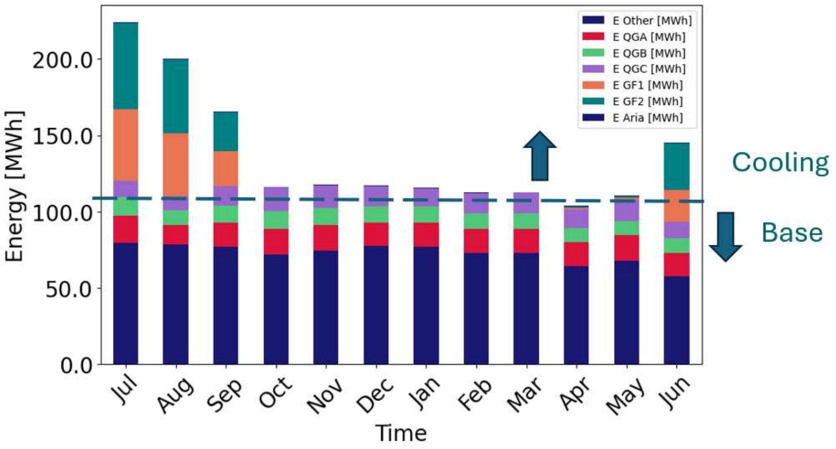

Figure 5 - Electricity consumption broken down for various end uses: base consumption and variable consumption

The work of characterizing the buildings and their associated consumption was necessary for proper and thoughtful clustering of the buildings.

To estimate annual electrical and thermal consumption profiles on an hourly basis for a building, it is necessary to divide the year into typical days:

- Summer and winter working days (i.e. Mon-Fri)
- Summer and winter weekends (i.e. Sat-Sun)
- Summer and winter holidays

For each of these categories, the hourly consumption profile was observed, breaking it down into the different components associated with energy end uses. To do this, it is essential to identify the drivers that influence consumption for each end-use. The following is a description of the procedure used to determine trends in electricity consumption related to the use of the facility for lighting, mechanical ventilation, and internal apparatus.

The work began by analyzing electricity consumption profiles (quarter-hourly cadence) related to buildings assimilated to a specific cluster, which, in the case in example, are offices. The analysis focused on consumption in the second half of April and throughout May to obtain a 'clean' trend of the influence of consumption related to cooling and heating (auxiliary) services. The trends reported in Figure 6 were smoothed, eliminating instantaneous peaks, by applying Fourier transforms.

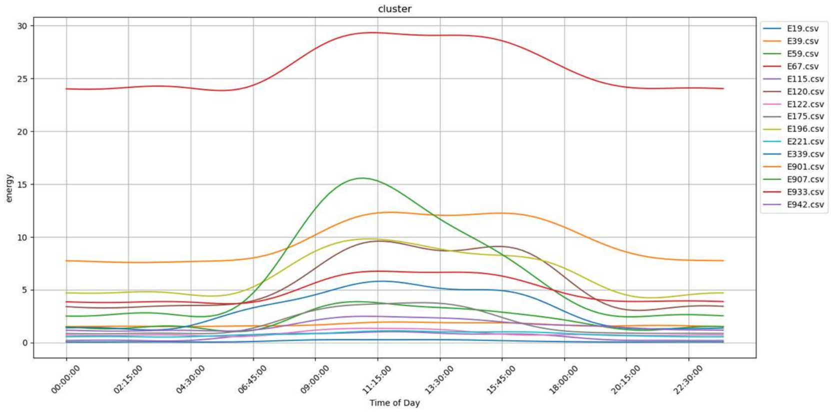

Figure 6 - Office cluster electricity consumption profiles

To compare the various consumption trends (Figure 7) just described with each other, it was necessary to carry out some steps:

1. Subtraction of constant base consumption related to always-on systems.
2. Normalize consumption using peak energy for each building.

3. Normalize the time axes using the following relationship: $\tau = \frac{t-t_0}{\Delta t}$

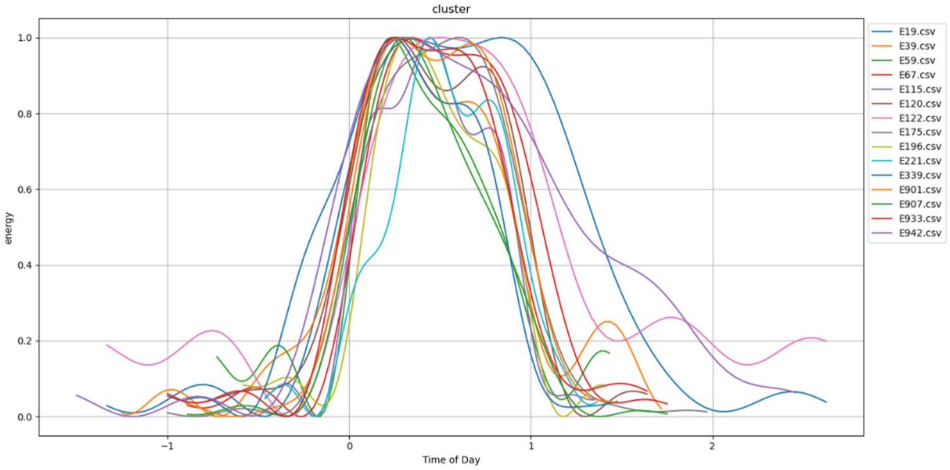

Figure 7 - Comparison of electricity consumption profiles cluster offices post normalizations

After these steps, it becomes possible to obtain an average trend for the office cluster (Figure 8) that describes the normalized trend in electricity consumption related to lighting, mechanical ventilation, and apparatus services.

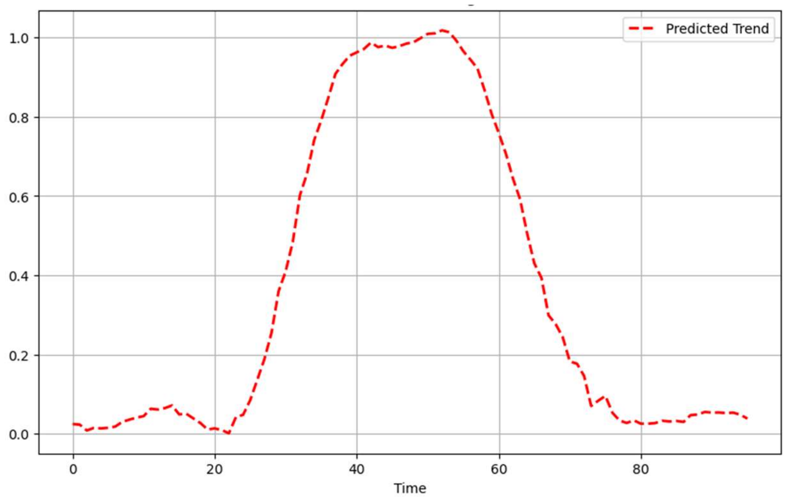

Figure 8 - Activity-related electricity consumption trends for the office cluster

With similar logic, it is possible to reconstruct consumption curves related to cooling and heating services. This allows the development of a tool able to estimate energy consumption profiles on an hourly basis for the main energy vectors (electricity, natural gas, and district heating) and energy KPIs (consumption by size, person employed, service, etc.) for each building based on a limited number of input data.

4. Policy Implications

The policy implications of the above-described research activities and related findings are various. First, they can contribute to supporting the Italian Government in the design of cost-effective incentive schemes. Second, they can provide public administration and local authorities with valuable insights on: i) the energy efficiency of the status-quo building stock and ii) the potential of buildings energy retrofitting in reducing energy consumption and CO2 emissions and mitigating energy poverty. Energy poverty is indeed a plague that affects a significant share of the Italian population in Italy, i.e. about 2.2 million households at the end of 2021, according to OIPE estimates (OIPE, 2023).

The research activities here presented provide a robust framework for addressing key energy and climate objectives in Italy, aligning with the European Green Deal's targets for greenhouse gas emissions reduction and buildings' energy efficiency. The open-source nature of the models and tools proposed and their integration with the AMELIA platform facilitate ongoing monitoring and evaluation of policy measures (Long-Term Monitoring and Policy Evaluation). Policymakers can continuously refine strategies based on updated data, such as the upcoming ISTAT surveys. Furthermore, the proposed methodologies and results align closely with EU directives, such as the Energy Performance of Buildings Directive, ensuring compatibility with European funding mechanisms. This alignment increases the likelihood of securing financial support for large-scale retrofitting and renewable energy projects. Considering the above, the developed tools and models have several critical policy implications for public stakeholders and policymakers:

Data-Driven Policy Formulation and Strategic Planning for Decarbonization

National and regional energy modelling for residential and non-residential buildings provides granular insights into energy consumption patterns and emissions. By simulating scenarios such as retrofitting with thermal insulation or transitioning to renewable energy sources, policymakers can identify the most effective interventions to meet decarbonization targets. Furthermore, the research delineates an essential overview of the distribution of buildings and the characteristics of interventions required based on their typology. This enables policymakers to allocate incentives and implement supportive policies tailored to specific locations, types of buildings, and retrofit impacts. Such an approach ensures that resources are targeted efficiently, maximizing the environmental and economic benefits of retrofitting efforts and enabling more targeted and effective policy design.

Regional and Local Adaptation Strategies

The research's location-based nature emphasizes the importance of differentiating regional strategies to reflect the diverse socio-economic, climatic, and infrastructural characteristics of Italy's regions. By providing a detailed breakdown of energy consumption, emissions, and building typologies at a regional-local level, the tools enable policymakers to craft tailored strategies for each area. For example, mountainous regions may require specific policies promoting biomass utilization or renewable solutions suitable for remote areas, while urban centers might benefit from retrofitting incentives for densely packed building stock. This differentiation ensures equitable and effective policy impacts, addressing the unique challenges and opportunities of each region.

Cost-Benefit Analysis of Energy Efficiency Measures

The capability of the models to project economic and environmental outcomes of interventions allows stakeholders to prioritize policies with the highest return on investment. For example, comparing scenarios reveals the trade-offs between retrofitting costs and long-term energy savings, aiding in the allocation of public funds.

Enhancing Public Sector Energy Management

Analyzing non-residential buildings, particularly public administration structures, introduces tools to optimize energy efficiency in critical facilities like schools and offices. By integrating technologies like IoT and Building Management Systems (BMS), public stakeholders can monitor and manage energy use more effectively, setting a benchmark for energy savings in public infrastructure.

Support for Renewable Energy Tariff Design

The research's ability to reconstruct consumption curves for cooling, heating, and electricity in non-residential buildings such as schools, universities, labs, and offices offers a significant opportunity for policymakers to design incentive-based renewable energy tariffs. By understanding and modelling energy use across different time slots (e.g., peak and off-peak hours), stakeholders can calibrate dynamic tariff structures. These tariffs could encourage the adoption of renewable energy by aligning economic incentives with consumption patterns, ensuring energy availability aligns with peak demand.

Public Engagement and Behavioral Change

Recognizing the role of user behavior in energy consumption, the research incorporates survey data and environmental monitoring to understand and influence residential energy practices. Policymakers can design educational campaigns and incentives that align user habits with energy efficiency goals.

At a microscale, determining buildings' annual energy consumption on hourly basis and final users' behavior can support energy managers of real estate assets in improving the energy efficiency of the building stock they manage, by comparing actual energy profiles with baseline profiles estimated from a theoretical standpoint. This comparison can easily permit the identification of inefficient buildings and consequently reduce the timing requested to activate corrective interventions. The estimation of consumption profiles on an hourly basis is crucial for the simulation and implementation of diffuse self-consumption models, such as energy communities, and for accelerating the pathway towards optimization and intelligent use of the national power grid. The knowledge of energy peak loads and grid management can allow to minimize costs. At local scale, this knowledge addressed to a group of buildings located in a delimited area can also support policy makers in the decision to invest in the setting-up of positive energy districts in the subject area. In addition, models' findings can provide forecasting of the effect of energy efficiency measures in different scenarios and can be used to inform public policies.

To conclude, the findings and tools developed in this research can contribute to the definition and implementation of an actionable roadmap for achieving energy efficiency and carbon neutrality in the Italian building sector. By adopting these tools, policymakers can craft evidence-based, regionally specific, and economically viable strategies that address both immediate energy challenges and long-term sustainability goals. These implications are instrumental in fostering a systematic transition to a low-carbon economy and reinforcing Italy's leadership in implementing the European Green Deal. Moreover, the opportunity to integrate dynamic energy tariff structures calibrated to consumption profiles ensures that renewable energy is leveraged effectively, offering a win-win scenario for sustainability and economic efficiency, andsimultaneously informing energy poverty mitigation strategies.

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