Analysis of Energy Consumption Scenarios of the Italian Residential Building Stock

Enrico Prataviera – University of Padova, Italy – enrico.prataviera@unipd.it
Jacopo Vivian – University of Padova, Italy – jacopo.vivian@unipd.it
Francesca Gaudino – University of Padova, Italy – francesca.gaudino@studenti.unipd.it
Angelo Zarrella – University of Padova, Italy – angelo.zarrella@unipd.it

Abstract

Building stock energy models have been receiving increasing attention in the last years as powerful tools to forecast energy policies at national levels. This work contributes to the existing discussion on this topic by presenting a bottom-up physic-based model of the Italian residential stock that can calculate national energy consumption using data collected by ISTAT from a 2013 survey. Such a model exploits electric appliance data and dynamic building energy simulations to analyse the current state of Italian houses' energy consumption, and by presenting possible scenarios for 2050. The analysis of the current state focuses on the energy vectors employed, primary energy, and validation with respect to external sources. Results show good accuracy with respect to national energy balance and with respect to regional data for heating and domestic hot water. The presented future scenarios are based on expected changes in climatic condition, technology replacement, and retrofits of buildings. Considering current renovation rates, envelope insulation and heat pump installation could produce a reduction of 12% of the final energy.

1. Introduction

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). In this perspective, Italy has outlined the first phase of the plan's implementation for the period 2021-2030 in the "Piano Nazionale Integrato per l'Energia e il Clima" (PNIEC), which is now extended with new REPowerEU investments. 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, emphasizing the importance of focusing on its decarbonization.

National building stock energy modeling represents a great opportunity for stakeholders and policy makers in the process of fostering energy efficiency and European carbon emission targets. 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 energy efficiency directives, as the EPBD ("Energy Performance of Buildings Directive, (2018/844/EU)", 2018). In this context, developing new tools to analyze the national energy consumption of buildings, disaggregate it, and predict future trends is a crucial step. The most used methodology in analyzing country-wide building stock typically uses top-down approaches. In this case, demographic and economic reports at the national level are combined with purely statistical methods to calculate specific indicators for the building stock energy consumption, (Summerfield et al., 2009). 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 physic simulation of representative buildings whose results are then scaled up to the stock level, allows more detailed analysis and permits the evaluation of future scenarios.

This paper presents a nationwide bottom-up model of the Italian residential building stock, built on top of the data provided by the Italian Statistical Institute survey on households' energy consump-

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tion, dated 2013 (ISTAT, 2016). The model exploits the survey responses to build dynamic Building Energy Simulations for each entry, providing great granularity and detail on the energy consumption of the whole stock. First, the paper includes a brief description of the data in the survey, then the model and methodology are detailed. Finally, the results section shows the calculation reliability with respect to well-known benchmarks and the model's potential in analyzing future scenarios.

2. Material and Methods

After the description of the data included in the survey, this section provides the details of the performed calculation.

2.1 ISTAT Survey Outline

The model's core strongly depends on the dataset describing the building stock. For this purpose, the 2013 Italian survey of household energy consumption was chosen (ISTAT, 2016), as it provides the answers of 20 000 different house owners to more than 350 queries on their building and energy consumption spread around the country. In particular, the questions are subdivided in the following categories:

- *Occupancy*: information about the occupants, including gender, number, and age.
- *Dwelling characteristics*: typology (single family house, apartment, …), floor plan, construction period, footprint area, windows, materials, orientation. The location of the dwelling is provided only as a region.
- *Space heating*: type, number, layout, energy vector, and emission system.
- *Domestic Hot Water* (DHW): similar to heating.
- *Space cooling*: type, number of rooms cooled, average usage during summer.
- *Biomass consumption*: system type, yearly consumption, rough costs.
- *Lighting*: number of light bulbs, divided by type, traditional bulbs or energy-saving bulbs, typical usage.
- *Appliances*: presence, number, size, frequency of use, for every type of appliance, including refrigerators and freezers, washing machines, dryers, dishwashers, cooking tops and ovens, screens and computers, and others.
- *Energy expenses*: generic yearly costs for each energy vector.

In addition to these data, each survey entry is assigned to a national refactor coefficient, i.e., the number of houses at the nation level represented by that specific entry. This number is calculated by ISTAT using literature methods, and it produces a statistically relevant representation of the whole national building stock, starting from the 20 000 entries of the dataset. Fig. 1 shows, as an example, the percentage of type of dwelling split by region.

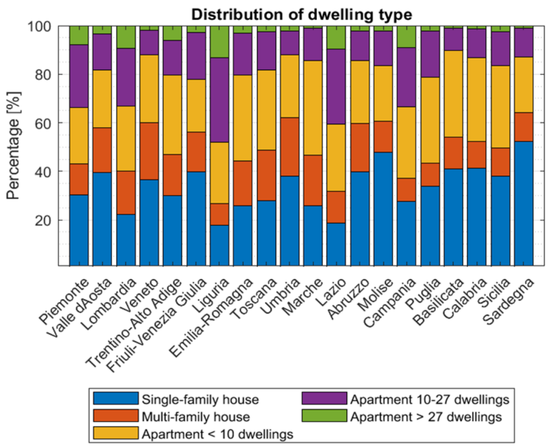

Fig. 1 – Distribution of dwelling types across Italian regions

2.2 Model Description

The model presented in this work, i.e., MODENA (MODello Energetico Abitazioni, housing energy model), was developed as part of a collaboration between the University of Padova and the Italian Research on Energy System company (RSE, Ricerca sul Sistema Energetico). The input of this model consists of the microdata matrix collected in the previously described survey. The application, written in Python, uses the survey to build a dynamic building energy simulation of all households, calculating the consumption of appliances, heating, and cooling. The model structure is divided into four phases, i.e. input loading, appliances and domestic hot water consumption calculation, space heating and cooling consumption, output processing, and national scaling of results. Apart from the first section, which only loads the dataset, each phase is outlined in the following sections.

2.2.1 Lights, electric appliances and DHW consumption

Results from previous work have been applied to electric appliances (Besagni et al., 2020). Once the necessary data for individual devices are obtained, each respondent's electrical and gas consumption (for cooking uses) is calculated by combining the ISTAT survey responses with the unit consumption of the devices. For example, the annual consumption for lighting is calculated by multiplying the number of light bulbs, the average power consumption of each bulb, the number of daily hours of use, and the annual number of days in use. The assumed power consumption is 15.36 W for energy-saving bulbs and 40.19 W for traditional bulbs, and three daily usage patterns are also assumed: 3 hours, 7 hours, and 14 hours. For the sake of brevity, the calculation for other appliances is not detailed. However, the method is similar and always consists of multiplying the typical consumption of a type of appliance (from external sources, Growth for Knowledge, 2021) by the estimated yearly usage. The reader can find the detailed calculation in Besagni et al., 2020, and the report from Ricerca Sistema Energetico 2022.

The domestic hot water energy need, D_{dhw}, is calculated using UNI/TS 11300-2 Standard (Ente Italiano di Normazione, 2014), which calculates the DHW consumed daily volume, V, with respect to the floor area of the dwelling, A_{floor}.

$$V = a \cdot A_{floor} + b \quad (1)$$

$$D_{dhw} = \varrho \cdot c_p \cdot V \cdot 365 \cdot \Delta T_{av} \quad (2)$$

Where coefficients a and b are provided in the standard depending on the size of the building.

2.2.2 Heating and cooling consumption

Concerning heating and cooling consumption, the EUReCA building energy model was used for the simulation (Prataviera et al., 2021). The latter is a Python package that implements physic-based simplified lumped parameter models to run the hourly dynamic simulation of the building. In particular, the BES model is developed considering the following assumptions.

Climatic data are taken for each region from the dataset of Comitato Termotecnico Italiano, n.d., considering the most representative city. The geometry of each dwelling is created by considering its type (single-family house, multi-family house, or apartment), footprint area, prevailing orientation of external walls, and the number of windows reported in the ISTAT survey responses. A square footprint is assumed for each case, while the number of floors and boundary conditions are assumed depending on the other data. An archetypical envelope representation is selected based on the age class (Carnieletto et al., 2021) and subsequently corrected by the possible presence of an insulation retrofit. These assumptions allow the construction of the RC equivalent network to calculate the heating/cooling demand (Prataviera et al., 2021).

Concerning the usage, systems operation is assumed based on the responses from the survey, which allows a first estimation of the number of hours the heating and cooling systems are operated. Instead, heating/cooling system efficiency is calculated using the well-known method of subsystem efficiencies and following the UNI-EN 15316 Standard (CEN, 2017). In particular, the emission, distribution, control, and generation efficiency are assumed for each dwelling considering the type of emitters, the system layout, the age declared in the responses. The only exception to this method is represented by heat pumps, whose efficiency is calculated dynamically using the correlation proposed by Staffell et al., 2012.

$$COP_{ashp} = 6.81 - 0.121 \cdot \Delta T + 0.000630 \cdot \Delta T^2 \quad (3)$$

$$COP_{gshp} = 8.77 - 0.150 \cdot \Delta T + 0.000734 \cdot \Delta T^2 \quad (4)$$

Where ΔT represents the temperature difference between the outdoor air (or ground) and the heating loop water (considered 35 °C for radiant panels, 45 °C for fan coils, and 60 °C for radiators). With geometry, envelope, and systems assumptions, EUReCA simulation is set, and consumption is calculated accordingly.

2.2.3 Post processing

After the calculation from the previous steps, energy consumption for each final use is combined to obtain the yearly consumption for each energy vector, including electricity, gas, biomass, LPG, and others. Such a calculation allows for granular analysis of the different end-uses and the regional distribution of consumptions. Ultimately, it is possible to multiply each dwelling's consumption by the national refactor coefficient, moving to regional and national consumption.

2.3 Methodology

The analyses proposed in this work are mainly two. First, the model is validated using national energy consumption from TERNA 2013 and International Energy Agency, n.d. Space heating and DHW final energy is also compared GSE data at the regional level (Gestore Sistema Energetico, 2021).
After the validation process, the model is exploited to run future scenario analyses. Three cases are considered:

1. Future scenario with 2050 climate without any retrofit of the building stock;
2. 2050 future scenario with envelope insulation and condensing boilers;
3. 2050 future scenario with envelope insulation and heat pump substitution.

Concerning weather conditions, 2050 climatic data were obtained using CCWorldWeatherGen (Jentsch et al., 2008), developed by the University of Southampton. This tool converts standard *epw* weather files into climate-changed *epw* files. The second-to-last most critical scenario for 2050 was chosen for this simulation, i.e., scenario A2. Moreover, it is worth mentioning that 2050 weather conditions are calculated starting from the historical Test Reference Year datasets (available at the EnergyPlus website, "Weather Data | EnergyPlus," n.d.), whereas the starting simulation has been carried out considering the real weather condition from 2013, allowing validation. Simulations 2 and 3 account for the advancements expected in energy efficiency in building envelopes by 2050. On these, the former considers the retrofit of building envelopes (opaque and glazed considering current criteria) of a portion of the residential building stock and the replacement of traditional boilers with natural gas condensing boilers, while the latter considers both these measures and the replacement of boilers with heat pumps. The estimated fraction of renovated buildings has been assumed to be 21.8% by 2050 (Ministero dello Sviluppo Economico, 2020), and renovated buildings were chosen randomly within the dataset.

3. Results

3.1 Standard Simulation

First, the results from the standard simulation, referring to the 2012 building stock, are presented. To start, Fig. 2 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, central, and southern regions, 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/m²; 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 vector. Their specific consumption ranges from approximately 135 kWh/m² in the central area to 250 kWh/m² in the North-East. Natural gas consumption on the islands is quite limited as Sardinia is not connected to the natural gas network, resulting in a higher share of LPG and electric energy.

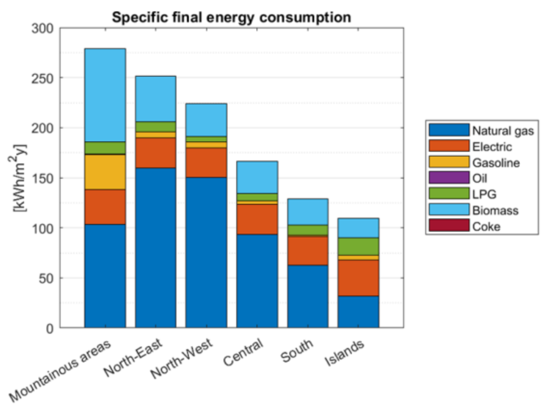

Fig. 2 – Specific final energy consumption divided by energy vector

Concerning primary energy, the estimated national total primary energy consumption is equal to 39.4

Mtoe. 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 vectors, is reported in Table 1. 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%), and the use of oil and coke is negligible (less than 1%).

Table 1 – Primary energy consumption by energy vectors

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 2 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 and electricity consumption have an error of about 0.6% and -4%, respectively. Such an error increases when other fuel types, such as wood and pellets, are considered. This larger error is mainly due to a larger uncertainty in the modeling process (stove/biomass boiler efficiency is not precisely modeled) and due to the wood self-production and consumption, which is not easily predictable with the available information. However, such fuels are less spread nationwide, keeping the overall model error below 9%.

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

Energy vector	Model results	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%

To move further with the validation, a deeper comparison is presented concerning data obtained from a top-down method by GSE (Gestore Sistema Energetico, 2021). GSE data refer to 2018, while the model's values refer to weather conditions of 2013. For this reason, a correction of the results using Heating Degree Days (HDD) of each weather file for 2013 and 2018 has been applied before comparing them. It can be observed that the model can simulate with good accuracy the energy consumption for most of the regions, in particular Piemonte, Lombardy, Friuli-Venezia Giulia, Valle d'Aosta, and Abruzzo. However, the values reported in the graph below are underestimated for other regions such as Lazio, the islands, and the southern regions. Such errors occur in areas where the difference in HDD between 2013 and 2018 is higher. The error in this case can therefore be associated with the uncertainty linked to weather conditions of the two different sources, as data from the same source was not available.

Fig. 4 compares the regional final consumption for DHW with the values provided by GSE. It can be observed that the model accurately estimates these consumption values, providing a total of 4293 ktoe/y. In comparison, GSE's estimation is 3943 ktoe/y, resulting in an error of 9%.

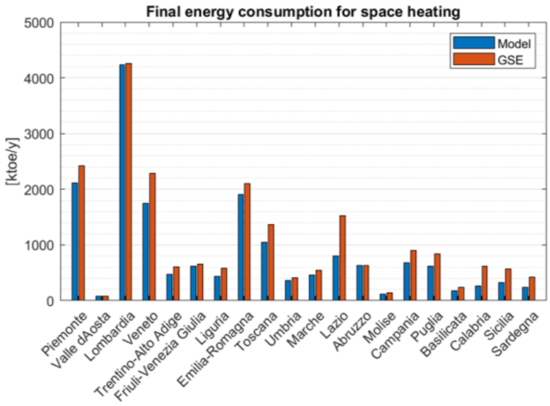

Fig. 3 – Validation of the final energy consumption for space heating with GSE data

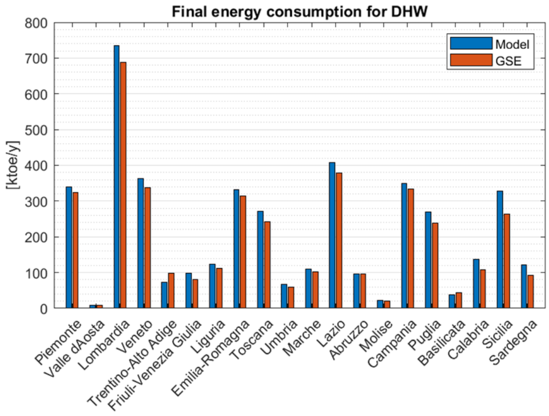

Fig. 4 – Validation of the final energy consumption for domestic hot water with GSE data

3.2 Future Scenarios

Moving to the future scenarios results, the average difference between 2050 average temperatures and 2013 average temperatures is 1.39 °C, leading to an increase of cooling consumption. Fig. 5 provides an overview of the final energy consumption for space cooling in each region, allowing for a comparison between the values from 2050 and those from 2013. Notably, all regions either experience an increase or show no significant variation in space cooling consumption. Among them, Veneto, Emilia-Romagna, and, to a lesser extent, Sicily demonstrate the most prominent increases. Veneto exhibits a substantial 71% increase in space cooling consumption compared to 2013, rising from 189 ktoe to 323 ktoe. Similarly, Emilia-Romagna experiences an even higher increase of 125%, with consumption rising from 141 ktoe to 319 ktoe. Sicily also sees a significant increase of 24%, going from 241 ktoe to 310 ktoe. Even though such increases might look overestimated, it is worth noting that the final energy for space cooling is still a minor fraction of the total electric consumption of the residential sector.

Besides some increases, a few regions, such as Lombardy and Calabria, present a reduction in cooling consumption. This behavior is due to an average temperature for 2013 (CTI data) higher than the projected 2050 average temperature. These inconsistencies and uncertainties lead to lower cooling consumption, which is particularly problematic for the Lombardy case, as it represents 20% of the national energy consumption in the residential sector.

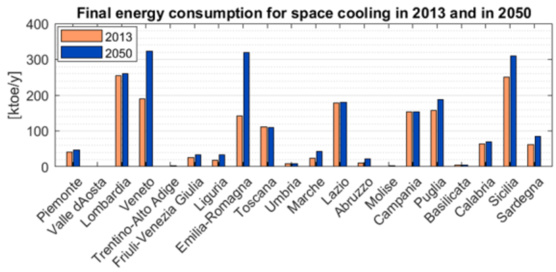

Fig. 5 – Comparison of space cooling final energy consumption between 2013 and 2050

Moving to the building stock retrofit, national results from all future scenarios are reported in Table 3. 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. 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 installing heat pump 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 replacing traditional boilers with condensing gas boilers and heat pumps. Additionally, there is a 20% increase in final electric energy consumption, equivalent to 11765 GWh. The final energy consumption shows a decrease of 12%, equivalent to 3605 ktoe, providing a better solution compared to the previous case (no PV selfconsumption is considered, resulting in a conservative analysis).

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

	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%)
Total [ktoe/y]	31297	31197 (0%)	28667 (-8%)	27592 (-12%)

4. Conclusion

Using a bottom-up model based on simplified dynamic energy simulation, this work has explored consumption patterns within the Italian residential sector, specifically focusing on heating, as it is the major contributor to households' consumption. The utilized model has demonstrated good accuracy in calculating natural gas and electric consumption with respect to national benchmark data, with deviations of +0.6% and -4%, respectively. The total consumption error stands at -9% due to the difficulty in tracking the annually consumed quantity of biomass and other fuels, which are marginally used. Besides the current state, possible future scenarios involving envelope insulation and heating system subtitution are analyzed based on current national renovation rates. Considering that 21.8% of the building stock will be renovated by 2050, natural gas consumption reduction is forecasted to be around 18%. These scenarios show that despite a relatively high rate of renovation, driven by recent incentivization measures, achieving complete decarbonization by that date, and therefore accomplishing the goal set by the European Union, will require significant efforts.

Nomenclature

Acronyms

DHW	Domestic Hot Water
BES	Building Energy Simulation

Symbols

A	Area (m^2)
COP	Coefficient Of Performance (-)
c_p	Specific heat (kJ kg^{-1} K^{-1})
D	Demand (kWh)
ΔT	Temperature difference (K)
ϱ	Density (kg m^{-3})
V	Volume (m^3)

Subscripts/Superscripts

ashp	Air Source Heat Pump
av	Average
floor	Net floor area
gshp	Ground Source Heat Pump

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