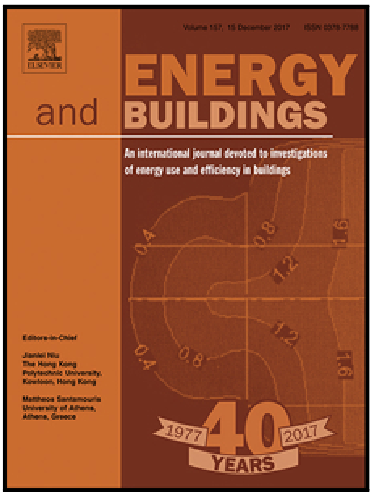

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PII: S0378-7788(17)33660-5
DOI: 10.1016/j.enbuild.2018.03.040
Reference: ENB 8426

To appear in: *Energy & Buildings*

Received date: 8 November 2017
Revised date: 24 January 2018
Accepted date: 13 March 2018

Please cite this article as: L. Canale , M. Dell'Isola , G. Ficco , B. Di Pietra , A. Frattolillo , Estimating the impact of heat accounting on Italian residential energy consumption in different scenarios, *Energy & Buildings* (2018), doi: 10.1016/j.enbuild.2018.03.040

Estimating the impact of heat accounting on Italian residential energy consumption in different scenarios

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Abstract

Directive 2012/27/EU has set the obligation for buildings supplied by central heating sources, or by district heating/cooling networks, to install individual heat metering and accounting systems. In Italy, almost 5 million dwellings are potentially subject to this obligation. To estimate the related potential benefit the knowledge of the energy saving achievable from the installation of such systems is needed. Unfortunately, in literature a wide range of variability of this benefit has been found and studies regarding Italian buildings are still lacking. The present study is aimed to estimate the impact of this EU policy in terms of potential energy saving in Italy. To this end, the authors first performed an experimental campaign on about 3000 dwellings located in major Italian cities, to assess the potential benefit obtainable. A model to estimate the energy consumption for space heating in the residential building stock has then been developed considering the building typologies and their main technical characteristics. An average benefit of about 11% has been found, leading to an estimated energy saving at national level ranging from 0.3% to 1.9% of whole energy consumption for space heating, depending on the effectiveness of applicable economic incentives and legal obligation scenarios.

Keywords: Individual metering; space heating; energy saving; residential building stock; building typologies.

Nomenclature

EP_H	Primary energy for space heating [kWh m^{-2} year $^{-1}$]
$EP_{H,min}$	Minimum value of primary energy for obliged buildings making efficient the installation of Heat Accounting and Thermoregulation systems [kWh m^{-2}year^{-1}]
HDD	Heating Degree Day [°C d]
h	Inter-storey height [m]
U	Thermal transmittance [W m^{-2} K^{-1}]
η	System efficiency [-]

Subscripts

d	distribution
f	floor
gen	generation
r	roof
wall	walls
win	windows

Abbreviations and acronyms

AEEGSI	Italian Regulatory Authority for Electricity Gas and Water
AiCARR	Italian Association for Air Conditioning, Heating and Cooling
AR	Asset Rating
BTM	Building Typology Matrix
CA	Construction Age
CHS	Centralized Heating Systems
EED	Energy Efficiency Directive
ENEA	Agency for New Technologies, Energy and Sustainable Economic Development
ESCO	Energy Service Company
EU	European Union
HAT	Heat Accounting and Thermoregulation
HCA	Heat Cost Allocators
ISTAT	Italian National Institute of Statistics
NEBs	National Energy Balances
OR	Operational Rating
PBT	Payback Time
REBs	Regional Energy Balances
TRV	Thermostatic Radiator Valve

1. Introduction

As well known, the Energy Efficiency Directive (EED) [1] established that energy consumers should be given easy and free access to consumption data through individual metering, allowing a better awareness about their energy use. To this aim, European Union (EU) has set the obligation for apartment and multi-apartment buildings supplied by a common central heating source or by a district heating/cooling network, to install sub-metering systems to allow a fair heat cost allocation, as long as the installation of such systems is technically feasible and cost-efficient.

With respect to the above-mentioned obligation, Member States adopted different approaches at the policy level [2]. In Germany and Austria, for example, individual metering for space heating is compulsory for almost the majority of the buildings supplied by a common central heating source. Sweden and Finland exempt nearly all the buildings potentially subject to the obligation, since the effectiveness of such measure at their actual climatic and operating conditions has not yet been demonstrated [3-5]. Despite it is explicitly required that installation of installation of sub-metering systems is mandatory only if technically feasible and cost-efficient, specific indications at the policy level are still lacking in actual regulation, especially from an economic point of view (e.g. neither a reference energy saving nor standard costs have been set). As a consequence, a wide discretion is left to technicians in exempting or obliging the installation of heat accounting systems in a given building. Furthermore, it is not specified if the economic feasibility analysis has to be performed considering the building primary energy calculated at standard rating conditions (i.e. Asset Rating, AR) rather than the actual primary energy consumed during the use of a building over a fixed time period (i.e. Operational Rating, OR).

Heat accounting systems mainly belong to two different categories [2, 6, 7]: direct (i.e. heat meters) and indirect (e.g. Heat Cost Allocators, HCA). EED has set the installation of direct heat meters as a priority. Unfortunately, due to the heating plant configuration (e.g. vertical mains in old buildings), technical (e.g. when flow and return pipes are not easily accessible) and architectural (e.g. in historical buildings) constraints, the installation of direct heat meters is often technically unfeasible in existing buildings [6]. On the other hand, indirect systems (e.g. HCA), are almost always technically feasible in older heating plants. Empirica GmbH [7] provides useful information about some of these issues in a guideline developed under a specific EU contract.

Italy transposed article 9 of EED without any substantial changes through Legislative Decree n. 102/2014 and subsequent modifications and integrations [8], setting the obligation to install individual heat metering systems by June 30th 2017. Due to the characteristic of the Italian building stock and to the fact that heating plants with vertical mains configuration are the most widespread in Italy, it is believed that in almost all existing buildings subject to the EED obligation indirect heat accounting systems will be installed. Moreover, in Italy when indirect system are used, the obligation to install heat accounting systems is combined also with the installation of thermostatic valves on each radiator [8]. Therefore, in the following the installation of indirect Heat Accounting and Thermoregulation systems (HAT) is analysed.

The “General Survey of Population and Housing” [9] performed by ISTAT highlighted that about 18.75% of Italian dwellings is supplied by a common central heating source. This means that almost 5 million dwellings are potentially obliged to install HAT systems [10, 11]. This would result in a potential capital flow of about 4-5 billion €, in the case that every dwelling supplied by a central heating system would fulfil the legislative obligation. Hence, the definition of the related installation costs represents a crucial issue in the analysis of the impact of this policy measure. The average cost of HAT systems ranges between 600 and 1200 €/dwelling, depending on several aspects, such as the type of HCA (i.e. single sensor, two-sensors) and TRV (mechanical, electronic), the number of dwellings in the building and on the type of heating plant available. These costs include also the design of the heat allocation system, the installation of data gathering devices, the adjustment of the heating plant itself and the related masonry works [2, 7, 12-14]. As regards payback time (PBT), Celenza et al. [2] show PBT for HAT systems variable between 3 and 16 years when the building energy need ranges from 300 to 100 kWh m^{-2} $year^{-1}$. In their analysis an expected benefit of 25% (i.e. the average benefit estimated for Central-European countries) and the absence of fiscal incentives have been assumed. At policy level, in Italy the installation of HAT systems is promoted to 50% of costs, if performed individually as a "building automation" system, and to 65% of costs if performed in combination with partial or integral substitution of the heating system [15]. Furthermore, when landlords are unable to access the fiscal benefit, this latter may be also transferred to an Energy Service Company (ESCO). In order to determine the effectiveness of this policy, it is thus necessary to carefully assess the actual energy saving achievable from the installation of indirect HAT systems. However, the amount of the energy saving is expected to be highly dependent on: *i)* the type and the set-up of the thermoregulation system [16], *ii)* the actual operating conditions of the heating system [17] , *iii)* the balancing of the heating system [16]; *iv)* the type of feedback and the users’ awareness [18, 19].

However, there is still a considerable resistance to the installation of HAT systems due to the significant issues in the transition between old and new heat cost charging criteria and to the uncertainty about the metrological reliability of HAT systems [20, 21]. Moreover, thanks also to the quite low investment costs related, the installation of HAT systems certainly represents an effective strategy to reduce the energy consumption of the existing buildings, being particularly suitable in historical or protected as cultural heritage ones [6, 22]. Nevertheless, many issues are delaying the spread of HAT systems in Italy. In fact, data from the heating systems register of the Lombardia Region [23] show that more than 50% of the obliged buildings has not yet installed heat accounting systems, despite it was mandatory since 2014 and subsequently postponed. On the other hand, in Central-European countries the installation rate of heat accounting systems is certainly higher, since they are historically more widespread [24]. As regards the heating system regulation in Italy, in Lombardia Region [23] about 60% of heating systems is regulated by individual dwelling thermostats with on/off or proportional control, while in about 18% regulation is absent. These figures may be reasonably applied to whole Italy.

Potential energy saving related to the spread of individual metering for space heating in the Italian building stock has not yet been determined, also because the scientific literature on the effects of the installation of HAT systems in Mediterranean climates is still lacking. In other EU Member States, mainly located in North-Central Europe, the potential energy saving has been estimated by Felsmann et al. [25] in a range of about 8-40% and, sometimes, opposing outcomes emerge [4]. In the scientific literature, only few studies are based on the actual measurement of the energy saving and have been carried out after the experimental observation of the buildings before and after the installation of HAT systems. Among these, Cholewa and Siuta-Olcha [26] analysed in a multifamily building located in Poland for over 17 heating seasons, the energy consumption of 40 dwellings all equipped with Thermostatic Radiator Valves (TRV) and only half of which equipped with Heat Cost Allocators (HCA). The experimental data highlighted higher energy savings in the dwellings equipped with both TRV and HCA compared to the ones with only TRV (18.8% one year after the installation and a further 7.8% two years after the installation). Paulsen and Gullev [27] also observed a reduction of heat consumption up to 30% due to the transition to individual metering, analysing the energy consumption of representative dwellings during the period 1991–2005. However, to the authors' best knowledge, no long-term experimental campaign for an empirical assessment of the benefit expected from the installation of HAT systems was performed in Italy. Thus, it is nearly unfeasible to estimate with a good confidence their actual effects on a national scale.

In order to estimate the impact of an energy policy, the complex issue to investigate energy consumption of large-scale building stocks should be considered. The scientific literature concerning the methodologies for assessing the energy performance of building stocks is quite rich, because of the related importance in identifying effective policy strategies for incentivising refurbishment actions. In this sense, two main approaches have been widely used to model the energy demand on an urban scale [28-30]: the top-down, mainly based on historical data analysis, and the bottom-up. The latter, relying on physical features of the buildings (such as geometry, thermal transmittance, equipment and appliances etc.), is able to determine the total energy demand of a residential building stock with higher accuracy showing also flexibility to model possible scenario's changes. However, when these methodologies are applied to the Italian residential building stock, the lack of data about the energy performance of buildings (such as thermal transmittance, systems efficiencies etc.) makes it difficult to determine its actual energy need. Anyway, efforts have been made mainly on regional level, [31, 32]. Ballarini et al. [33] applied the building typology method defined within the TABULA project for Piemonte region to the entire Italian residential building stock by means of a quasi-steady approach, in order to assess the effectiveness of different retrofitting actions.

Nevertheless, the development of a model to predict energy consumption in residential sector and the knowledge of a statistical benefit related to the installation of HAT systems should be useful at the policy level to assess the effectiveness of incentive measures and, on the practical hand, to help technicians in analysing the economic feasibility of such systems. With the necessary adjustments, the results of the present research should also be extended to other EU countries adequately considering the specific aspects which make the Italian building stock different from the European ones such as: *i)* the major influence of solar heat gains; *ii)* the lower consumption for space heating associated with Mediterranean climatic conditions; *iii)* the significant differences between the energy performance of existing buildings (especially those built in the post-war period and those in the last twenty years); *iv)* the current heat cost charging criteria normally based on floor area or installed power rather than on individual consumption.

In this scenario, this work is aimed to assess the potential of Italian policies about individual heat metering in the residential sector. To this end, an experimental campaign has been performed on a sample of about 3000 dwellings in 50 buildings located in the Italian regions mainly concerned by the obligation to install HAT systems. The mean energy saving resulting from the experimental campaign has been extended to the whole Italian residential building stock, through the development of a bottom-up model able to predict the mean energy consumption for residential space heating. The model has been validated and calibrated comparing the calculated energy need for space heating with energy data from the Regional Energy Balances (REBs) and National Energy Balances (NEBs). An economic feasibility constraint was applied under three different incentive scenarios in force in the Italian fiscal policy to achieve the estimation of the real reduction of energy consumption at national level. In fact, depending on incentives, the economic feasibility analysis applied to the Italian building stock will determine different spread of HAT installations and, consequently, different reduction rates of annual energy consumption.

2. Methods

In the following, an experimental approach on a limited sample of representative buildings aimed to estimate the energy saving after the installation of HAT systems is first presented. Subsequently, a methodology to estimate the energy consumption for space heating in the national building stock is proposed and the available scenarios related to incentive policies and to obligation approaches are discussed.

2.1 Experimental campaign to estimate the mean Italian energy saving

A sample of 3047 dwellings in 50 buildings has been investigated in the experimental campaign presented in this paper. The authors selected the sample with respect to size, construction age and climatic conditions representative of the Italian building stock potentially subject to the obligation to install HAT systems.

The investigated buildings are located in three representative regions (i.e. Piemonte, Lombardia and Lazio) summing about 55% of dwellings potentially subject to the obligation to install HAT systems in Italy (see figure 1 and table 1). Moreover, the buildings belong to the more widespread Italian climatic zones E (i.e. with a number of HDD - Heating Degree Days - between 1401 and 2100 °C d) and D (i.e. with a number of HDD between 2101 and 3000 °C d). In fact, about 50% and 20% of Italian cities belong to D and E climatic zones, respectively.

Table 1- Italian dwellings classified by heating plant (source: ISTAT).

Heating Plant	*Absolute values*	*Percentage values*
Centralized	4 871 072	18.75%
Individual	15 717 341	60.51%
Single devices supplying the whole dwelling	2 137 636	8.23%
Single devices supplying only part of the dwelling	3 246 891	12.50%
TOTAL	25 972 940	100.00 %

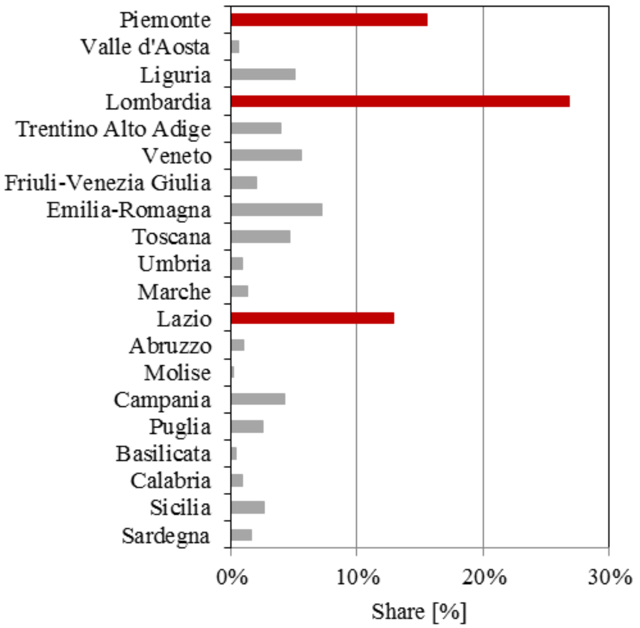


Figure 1 - Regional share of dwellings supplied by CHS (source: ISTAT).

In Table 2 the main characteristics of the investigated buildings are reported. The investigated buildings were all built between 1900 and 1990 and they are supplied by natural gas Centralized Heating Systems (CHS) whose energy consumption for space heating was measured through diaphragm gas meters [34]. Hot water production in each dwelling was provided through autonomous systems and, therefore, heat accounting for this purpose was not required. With regard to the heating plant, the heating fluid distribution is performed through vertical mains and heating bodies are represented by cast iron radiators. Low insulated pipes mainly run into the external walls. Before the installation of HAT systems, all dwellings were regulated by individual dwelling thermostats with on/off control system.

Table 2 - Characteristics of the investigated buildings sample.

Buildings	*Age*	*U-value [Wm^{-2}K^{-1}]*			
		Wall	*Roof*	*Floor*	*Windows*
4	ante 1930	1.10÷1.40 Solid bricks masonry (50/60 cm)	2.00÷2.50 Vault with bricks and steel beams	2.00÷2.50 Vault with bricks and steel beams	4.90 Single glass, wood frame
16	between 1950 and 1970	1.10÷1.20 Hollow wall brick masonry (30/40 cm)	1.40÷1.70 Reinforced brick concrete slab	1.40÷1.70 Reinforced brick-concrete slab	4.90 Single glass, wood frame
30	between 1971 and 1990	0.75÷0.90 Hollow wall brick masonry (30/40 cm), low insulation	1.00÷1.20 Reinforced brick-concrete slab, low insulation	1.00÷1.20 Reinforced brick-concrete slab, low insulation	3.70 Double glass air filled, metal frame, no thermal break

In all the investigated dwellings HCA, TRV and balancing valves have been installed and the whole building energy consumption was recorded for at least two heating seasons (the ones before and after the installation of HAT systems). In addition, for few buildings the energy consumption data available also for the heating season two years after the installation of HAT systems have been analysed in order to assess the benefit over time. For each heating season, the external temperature data were analysed in order to normalize energy consumption to the climatic conditions, through the division of energy consumption by the actual HDD calculated according to EN ISO 15927-6 [35]. Thirteen buildings of the sample have undertaken a major retrofit intervention, replacing the existing boiler with a high efficiency one together with the HAT systems installation. Although the present analysis regards the effects of the installation of HAT systems, also the reduction in energy consumption of these buildings has been analysed, in order to allow a further understanding about the possible benefits achievable by the combined effect of different retrofitting actions.

2.2 Estimating the Italian residential energy consumption for space heating and the related energy savings

To estimate the Italian energy consumption for space heating, a calculation method based on the classification of the building stock in building typologies [36-38] has been developed. The modelling scheme followed five subsequent phases, as shown in figure 2.

In *phase 1,* data from the latest "General Survey of Population and Housing" of ISTAT have been analysed and a first classification of the national building typologies has been performed. To this aim, the building category (single/two/multi-family buildings) and Construction Age (CA) have been considered. This required a preliminary analysis of the Italian building stock, in which peculiar national and regional features have been identified with regard to buildings' geometry (i.e. number of floors, net floor area, inter-storey height etc.) and to the available heating systems sources (i.e. centralized or autonomous).

Phase 2 concerned the characterization of the different building typologies by assigning a given shape, heating system efficiency and first attempt thermal transmittances retrievable from the existing scientific literature [33, 38]. To this aim, the authors developed a Building Typology Matrix (BTM) of the residential building stock for each Italian climatic zone. This has been tailored to each Italian region through the main geometrical peculiarities of each regional building stock, derived from both Italian and European statistical databases.

In *phase 3* the estimation of regional energy consumption for space heating has been performed in AR conditions, deriving then the corresponding one in OR conditions through suitable reduction coefficients available in the scientific literature [40, 41]. Data on actual energy consumption of each region have been obtained from the available European databases and from REBs (provided by ENEA).

In *phase 4* a check has been made in order to verify the deviation between the primary energy need estimated through the developed model and corresponding data from REBs. Subsequently, a tuning of the thermal transmittances has been performed to achieve a correspondence between the estimated and the actual primary energy within ±2%.

In *phase 5* the potential energy saving corresponding to applicable incentives and legal obligation constraints at national level and related to HAT systems installation have been estimated for suitable scenarios, also performing an economic feasibility assessment on the above defined national building typologies.

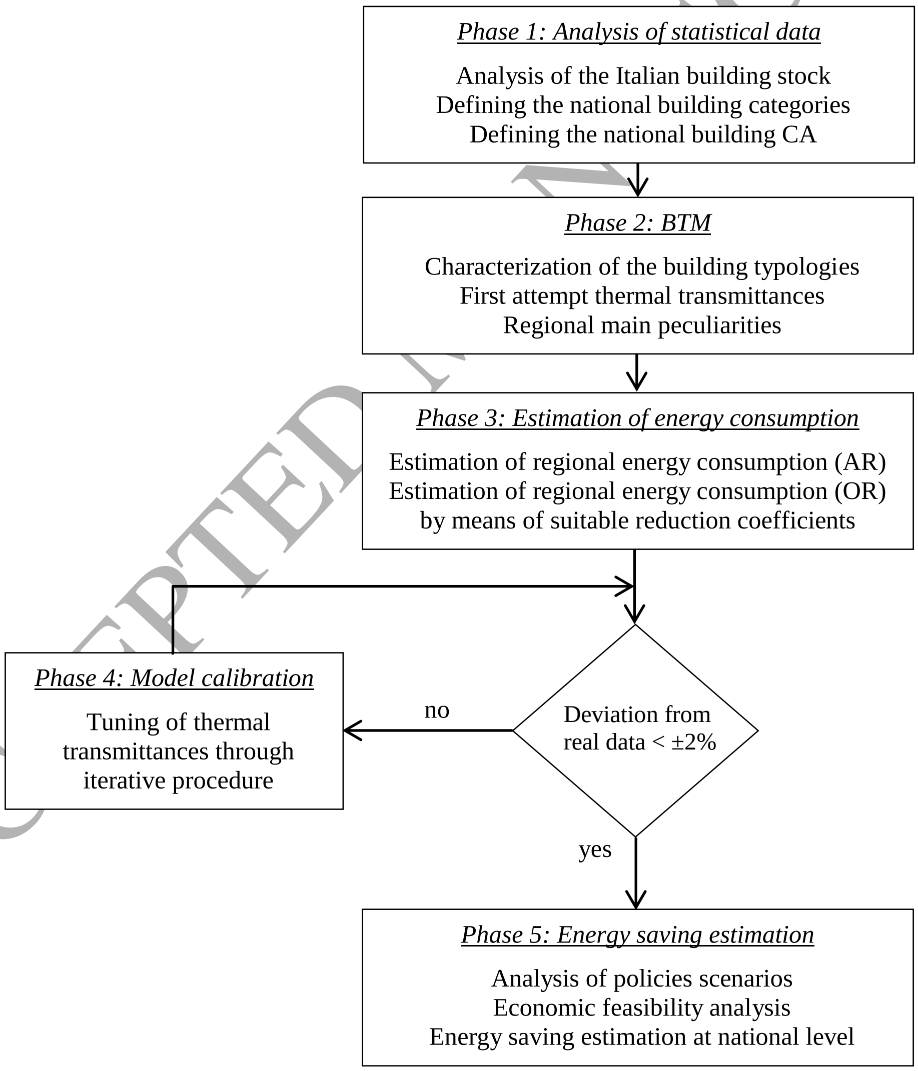


Figure 2 – Flow chart of the developed model.

In detail, the ISTAT clusters Italian dwellings in 6 categories and 9 CA (between 1918 and 2006). An overview of the data analysis performed is given in table 3 and figure 3. Data include also single-family buildings (clearly not obliged to install HAT systems) since they contribute to the national energy consumption for space heating. For the sake of simplicity, three CAs have been considered.

Table 3 - Italian dwellings occupied by residents classified by category and construction age.

Building category	*Number of dwellings in the building*	*Absolute values*	*Share*	*Before 1980*	*Between 1981 and 2000*	*After 2001*	*All ages*
Single-family	1	4 688 972	19%	14.27%	3.82%	1.39%	19.48%
Two-family	2	3 995 081	17%	12.32%	3.32%	0.96%	16.60%
Multi-family	3-4	3 518 114	15%	44.85%	13.28%	5.79%	63.92%
	5-8	3 443 130	14%				
	9-15	3 044 095	13%				
	>15	5 375 902	22%				
Total		24 065 294	100%	71.44%	20.43%	8.13%	100.00%

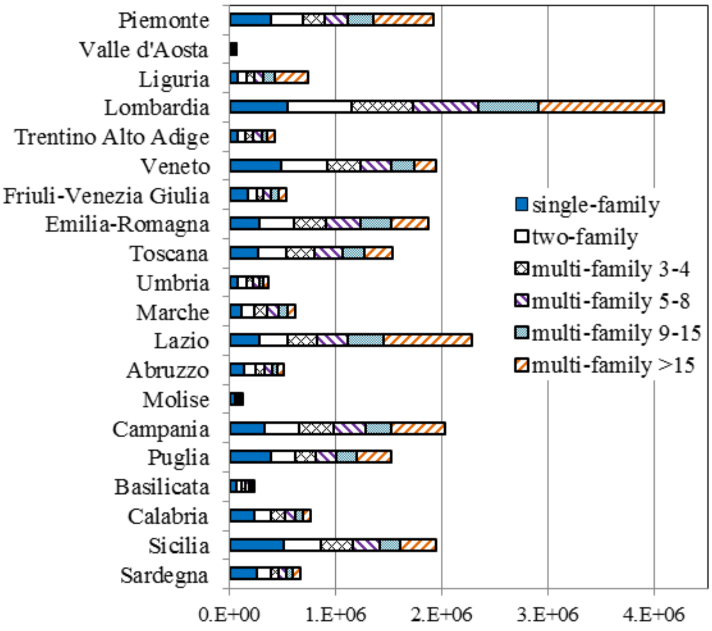


Figure 3 - Number of dwellings per region and per building type.

The same classification has been applied to the BTM, which consists of 54 rows (9 CA and 6 dimensional categories). Geometrical and thermo-physical properties have been assigned to each row as a function either of the CA or of the building dimensional category as follows:

i) inter-storey height (*h*), variable as a function of the CA; in absence of national statistical data of the residential buildings, values in [39] have been considered although they are related to offices since these are generally located in multi-purpose buildings;

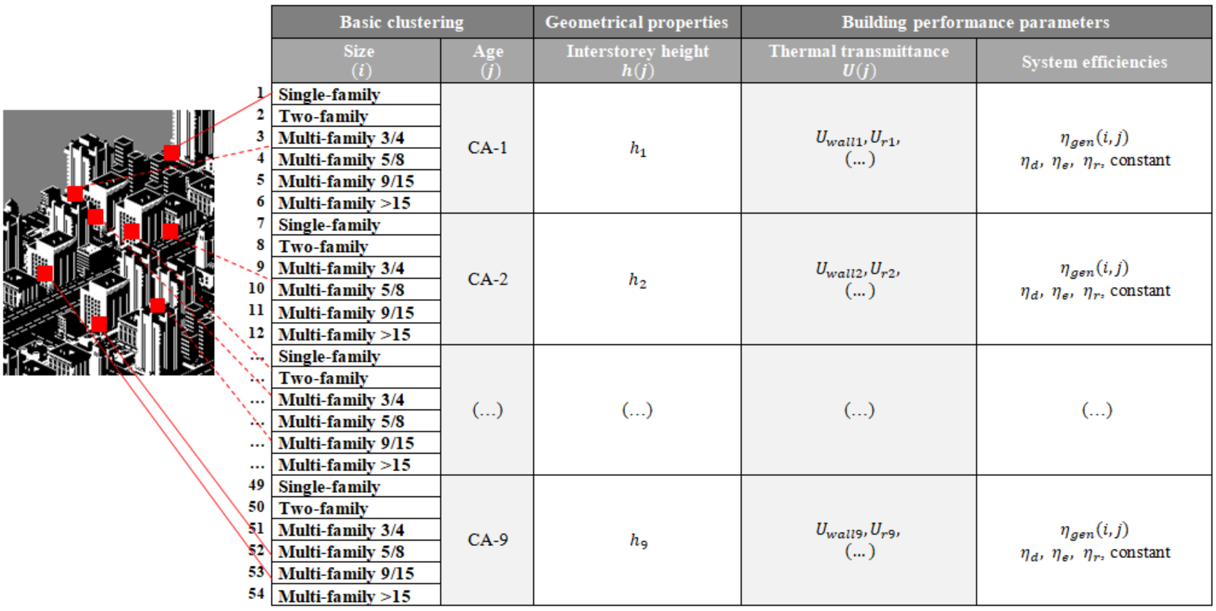
ii) wall, roof, floor, and window thermal transmittances (U_{wall}, U_r, U_f, U_{win}) variable as a function of the CA and climatic zone [33];

iii) generation system efficiency, η_{gen} , as a function of the building category and CA [42].

The distribution, emission and thermoregulation systems efficiencies, (η_d, η_e, η_r respectively) have been considered constant and equal to 0.95. Such figure is related to an average efficiency of the entire building stock and not of the investigated buildings sample and it is conceivably related to traditional plants with low thermal inertia and with simple temperature control. The authors assumed the average value of the corresponding efficiencies in UNI 11300-2 [43]. Furthermore, the following features have been considered: *i)* parallelepiped shape; *ii)* transparent/opaque surfaces ratio equal to 1/8 (i.e. the Italian legal limit in force).

For each building typology, the following further assumptions have been made: *i)* 15% increasing factor for thermal bridges (available literature data [44, 45] show that the total impact of thermal bridges on the heating energy need ranges between 7% and 28%); *ii)* no heat exchanges with unheated spaces. It is underlined that the arbitrariness of some of the aforementioned assumptions derives both from the lack of reliable empirical data of the constructive features of the Italian building stock and from the need to have a general model that could represent a heterogeneous building stock. Anyway, all the aforementioned assumptions are expressly declared, and authors will refine them when more detailed data will be available.

Due to the lack of data about the status of the existing Italian building stock, the first-attempt thermal transmittances have been obtained from data available in literature [33]. A graphic representation of BTM is given in figure 4. These data have been calibrated to the different climatic zones and regional areas.



	Basic clustering		Geometrical properties	Building performance parameters	
	Size (i)	Age (j)	Interstorey height $h(j)$	Thermal transmittance $U(j)$	System efficiencies
1	Single-family	CA-1	h_1	U_{wall1}, U_{r1}, (...)	$\eta_{gen}(i,j)$ η_d, η_e, η_r: constant
2	Two-family				
3	Multi-family 3/4				
4	Multi-family 5/8				
5	Multi-family 9/15				
6	Multi-family >15				
7	Single-family	CA-2	h_2	U_{wall2}, U_{r2}, (...)	$\eta_{gen}(i,j)$ η_d, η_e, η_r: constant
8	Two-family				
9	Multi-family 3/4				
10	Multi-family 5/8				
11	Multi-family 9/15				
12	Multi-family >15				
...	Single-family	(...)	(...)	(...)	(...)
...	Two-family				
...	Multi-family 3/4				
...	Multi-family 5/8				
...	Multi-family 9/15				
...	Multi-family >15				
49	Single-family	CA-9	h_9	U_{wall9}, U_{r9}, (...)	$\eta_{gen}(i,j)$ η_d, η_e, η_r: constant
50	Two-family				
51	Multi-family 3/4				
52	Multi-family 5/8				
53	Multi-family 9/15				
54	Multi-family >15				

Figure 4 – Graphical representation of the BTM for a given climatic zone.

The BTM has been tailored to each Italian region using the following parameters:

- the mean regional floor area [9];
- the mean number of building floors by building size, obtained through a dwellings-weighted average, variable as a function of the building size [9].

Finally, historical data of HDD for each region have been obtained from Eurostat database [46].

The estimation of the building energy need for space heating has been performed according to the standard EN ISO 13790 [47]. Then, the primary energy for space heating $EP_{H,AR}$ at standard rating conditions (i.e. AR) of each building typology has been estimated according to EN 15316 [48]. On the other hand, the estimation of the actual primary energy consumption at the real condition of use of the heating plant must be taken into account. Thus, the estimated primary energy consumption in AR conditions has been multiplied by suitable reduction coefficients to obtain the primary energy consumption of the Italian building stock in OR conditions, $EP_{H,OR}$. The aforementioned coefficients have been estimated by ENEA [40, 41] through a sample analysis of about 20 thousand dwellings performed in the Italian territory for each climatic zone and building typology.

With the aim to assess the error associated with the hypotheses introduced, data about actual national and regional energy consumption have been collected from REBs [49] and NEBs [50]. The energy consumption related to the sole space heating of residential buildings in single regions has been obtained from the whole residential consumption data (available from REBs and including air cooling, lighting and household electrical appliances, cooking and hot water production), through the Italian mean share for space heating. In particular, the latter ranges from about 65% to 70% of the whole Italian residential energy consumption, with a mean value of about 68% in the period from 1990 to 2015 [50]. In order to achieve a correspondence between the estimated and the actual primary energy consumption within ±2%, a calibration of the model has been performed by applying corrective coefficients to the first attempt thermal transmittances. This step has been necessary for both reducing the error due to the unavoidable uncertainty of the basic assumptions (e.g. thermo-physical properties, simplified geometry and shape etc.) and obtaining reasonable regional and national energy saving estimates.

Once obtained a reliable estimate of the residential energy consumption for space heating, different applicable fiscal incentive scenarios [15] have been analysed, since they could determine different spread rates of HAT systems by reducing the related investment costs. In particular these are:

- zero incentives (when landlords have insufficient income to meet the fiscal advantage);

- 50% of total costs incentive (applicable when the sole installation of HAT systems is performed and landlords have sufficient income to meet the fiscal benefit);
- 65% of total costs incentive (when the installation of HAT systems is performed together with the replacement of the boiler and landlords have sufficient income to meet the fiscal benefit).

Finally, an economic feasibility assessment according to the standard EN ISO 15459 [51] was performed on the above described building categories, with the aim to determine the minimum value of primary energy for space heating $EP_{H,min}$ above which buildings should be obliged at the policy level to install HAT systems. In particular, $EP_{H,min}$ has been calculated by iterating the cost-benefit method in Celenza et al. [2] to each building typology, until a net present value equal to zero occurs at the 10th year of the analysis. The energy benefit resulting from the experimental campaign (see par. 3.1) has been considered and the following assumptions have been made [7, 9, 12, 52]:

- dwelling floor area equal to 97 m^2;
- mean rooms number equal to 6;
- investment and operational costs for the Italian market;
- market interest rate of 4.50%;
- energy cost equal to 0.085 €/kWh, derived from the cost of natural gas monthly updated by AEEGSI [53].

The calculated $EP_{H,min}$ has then been applied as limit value of the estimated primary energy in AR and OR conditions of each building type, above which the installation of HAT systems is profitable. The respective scenarios have been simulated to estimate the related potential and the effective energy saving. In fact, while the first option is more easily applicable, since it is independent from how the heating system is used and from the unavoidable climatic variability (which are unlikely a priori predictable), the latter is more accurate in estimating the effective saving obtainable and, therefore, more effective in assessing energy efficiency retrofit interventions.

3. Results and discussions

3.1 Estimation of energy savings consequent to the installation of HAT systems

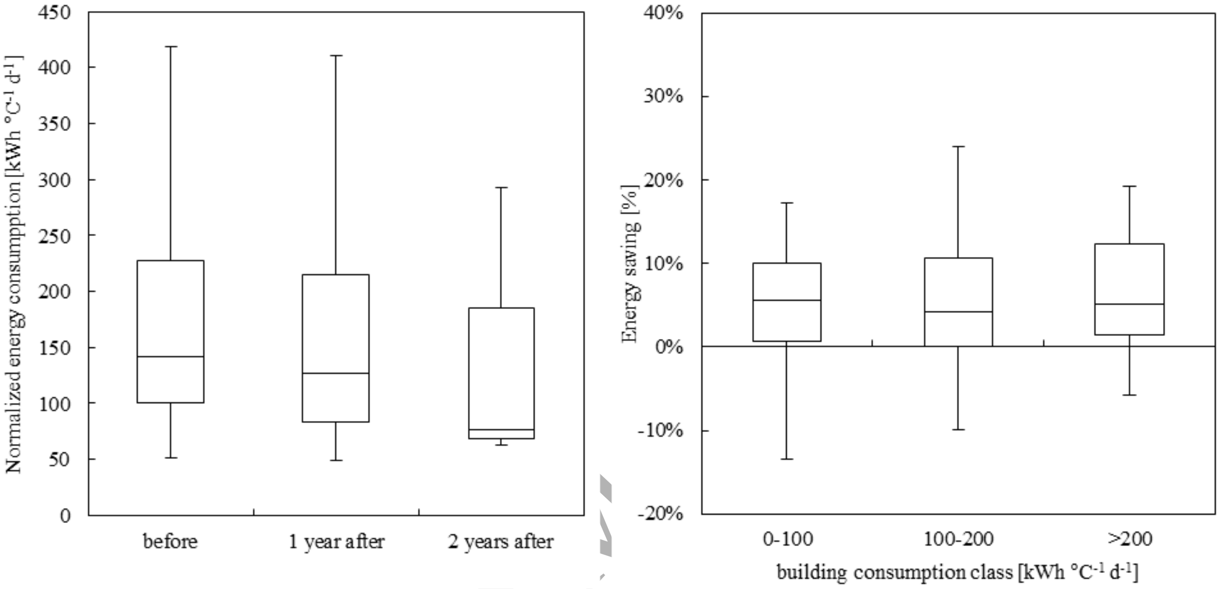
In table 4, for the buildings in which the sole installation of HAT systems has been performed, the energy consumption data recorded before and after the installation of HAT systems are reported together with the climatic data. In order to take into account the annual climatic variability, energy consumption data have been divided by the actual HDD, available for each heating season. The last two columns refer, respectively, to the percentage variation in energy consumption recorded one year after the installation of HAT systems and to the further variation observed two years after the installation, when available. Each row in the table represents a single investigated building.

Table 4 –Energy consumptions variation due the sole installation of HAT systems.

Region	*Number of dwellings*	*Previous normalized consumption [kWh°C^{-1}d^{-1}]*	*Actual HDD [°C d]*	*Normalized consumption after 1 year [kWh°C^{-1}d^{-1}]*	*Actual HDD [°C d]*	*Normalized consumption after 2 years [kWh°C^{-1}d^{-1}]*	*Actual HDD [°C d]*	*Var. after 1 year [%]*	*Var. after 2 years* [%]*	*Mean Variation*	
										After 1 year [%]	*After 2 years* [%]*
Piemonte	105	280.81	2501	293.01	2297	292.67	2281	4.4%	-0,1%	-5.5%	-2.3%
	48	144.96	2119	146.64	2199	n/a	n/a	1.2%	n/a		
	36	100.52	2119	76.42	2199	n/a	n/a	-24.0 %	n/a		
	21	62.88	2119	52.07	2199	n/a	n/a	-17.2%	n/a		
	30	86.42	2297	78.81	2356	77.01	2424	-8.8%	-2,1%		
	40	55.86	2501	64.67	2297	63.29	2424	15.8%	-2,5%		
	24	82.26	2297	70.79	2356	68.26	2424	-13.9%	-3,1%		
	68	221.45	2424	195.82	2501	185.11	2297	-11.6%	-4,3%		
Lazio	58	256.04	1408	217.90	1476	n/a	n/a	-14.9%	n/a	-17.1%	n/a
	36	104.29	1565	83.74	1579	n/a	n/a	-19.7%	n/a		
	21	141.32	1716	116.75	1579	n/a	n/a	-17.4%	n/a		
	54	248.00	1565	202.77	1579	n/a	n/a	-18.2%	n/a		
Lombardia	50	153.73	1899	153.68	1906	n/a	n/a	-0.0%	n/a	-3.4%	n/a
	650	1941.98	1899	1866.57	1906	n/a	n/a	-3.9%	n/a		
	110	331.95	1899	351.21	1906	n/a	n/a	5.8%	n/a		
	45	180.87	1899	143.05	1906	n/a	n/a	-20.9%	n/a		
	240	727.80	1899	740.43	1906	n/a	n/a	1.7%	n/a		
	20	79.78	1899	73.35	1906	n/a	n/a	-8.1%	n/a		
	25	73.77	1899	73.28	1906	n/a	n/a	-0.7%	n/a		
	25	100.22	1899	89.56	1906	n/a	n/a	-10.6%	n/a		
	70	222.30	1899	214.74	1906	n/a	n/a	-3.4%	n/a		
	30	101.48	1899	96.19	1906	n/a	n/a	-5.2%	n/a		
	20	61.10	1899	60.66	1906	n/a	n/a	-0.7%	n/a		
	40	132.43	1899	126.81	1906	n/a	n/a	-4.2%	n/a		
	50	155.53	1899	154.65	1906	n/a	n/a	-0.6%	n/a		
	70	227.79	1899	221.98	1906	n/a	n/a	-2.6%	n/a		
	60	194.67	1899	211.78	1906	n/a	n/a	8.8%	n/a		
	40	112.44	1899	123.57	1906	n/a	n/a	9.9%	n/a		
	40	121.92	1899	120.33	1906	n/a	n/a	-1.3%	n/a		
	60	189.82	1899	187.87	1906	n/a	n/a	-1.0%	n/a		
	40	108.18	1899	108.13	1906	n/a	n/a	-0.0%	n/a		
	90	320.08	1899	299.40	1906	n/a	n/a	-6.5%	n/a		
	90	345.43	1899	310.53	1906	n/a	n/a	-10.1%	n/a		
	40	118.72	1899	112.85	1906	n/a	n/a	-5.0 %	n/a		
	40	124.06	1899	117.55	1906	n/a	n/a	-5.3%	n/a		
	15	51.08	1899	49.46	1906	n/a	n/a	-3.2%	n/a		
	70	273.35	1899	220.72	1906	n/a	n/a	-19.3%	n/a		
Mean annual energy saving										*-8.7%*	*-2.3%*

* additional variation referred to the difference between energy consumptions 1 and 2 years after the HAT systems installation

The majority of the investigated buildings showed a reduction of energy consumption for space heating due to the installation of HAT systems. However, the variability of the estimated energy saving is high. In fact, only 17 buildings have undergone a high energy saving (between 5% and 24%), whereas in 13 buildings this was lower (from 0 to 5%). In 7 buildings an increase of energy consumption even occurred (up to about 15% in the worst case). The results are shown in figure 5. In particular, figure 5a clearly shows an energy consumption reduction over time, while figure 5b highlights energy savings of higher energy consuming buildings are more reliable than those of lower ones, since data dispersion is lower as buildings' energy consumption increases.



a) b)

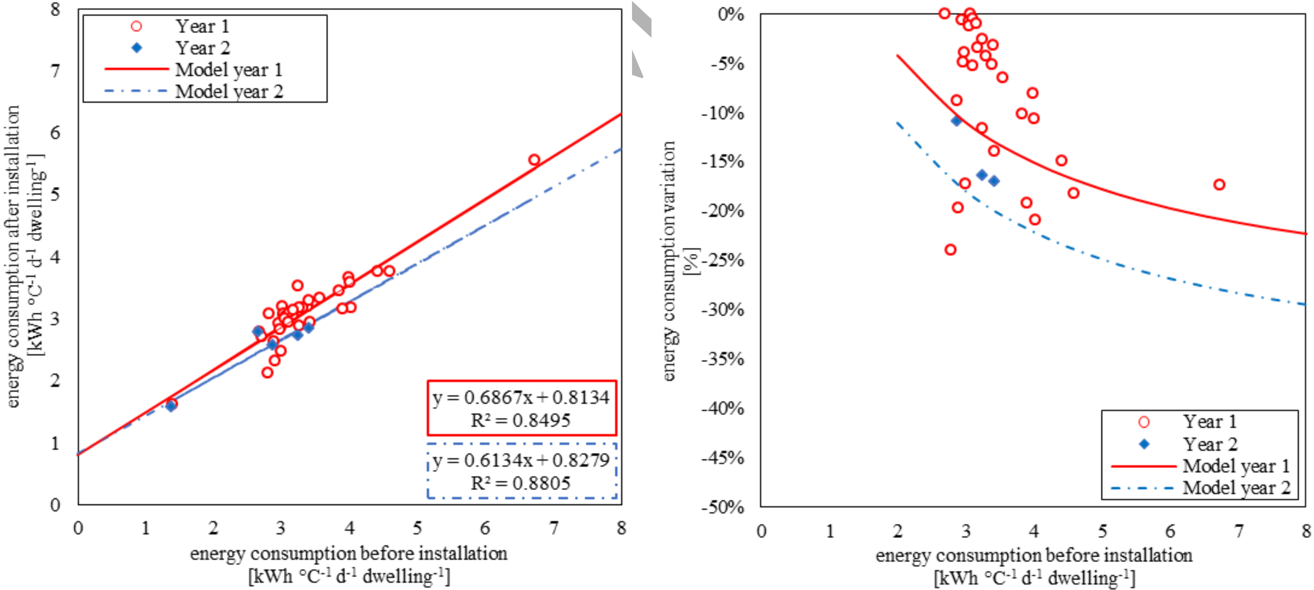
Figure 5: Analysis of energy consumptions of the investigated buildings before and after the installation of the sole HAT systems in terms of: a) Normalized energy consumption, b) Energy saving.

The results also highlight a huge difference between the two investigated climatic zones in terms of mean energy saving achieved after the installation of HAT systems. In fact, for buildings located in Lombardia and Piemonte (prevalent climatic zone E) a lower benefit (about 3.5% and 5.5% respectively) has been estimated. On the other hand, the mean energy saving in Lazio (prevalent climatic zone D) is about 17%. Such relevant figure is probably due to the fact that thermoregulation is more effective where solar heat gains are higher. In the few buildings in which energy consumption data two years after the installation of HAT systems were available, an additional benefit of about 2.3% has been observed. This effect is also described in the current scientific literature [26, 54], although in the present experimental campaign a lower value has been found. It is believed that the same may apply to the other investigated buildings.

Thus, the authors estimated the Italian mean expected energy saving of about 11%. This figure was obtained by simply averaging the benefit observed in the three investigated regions, equal to

8.7% one year after the installation of HAT systems, and then considering the additional benefit of 2.3% observed two years after (see table 4). This value has been used to estimate the overall potential of the current policy about individual heat metering for space heating in Italy.

The energy consumption data have been also normalized with respect to the number of dwellings per building, for a “specific dwelling consumption” analysis. Figure 6a shows a linear correlation between the specific energy consumption before and after the installation of HAT systems. In this figure, the bisector line represents the locus of points in which no variation of energy consumption occurs after the installation of HAT systems, while the lower and the upper areas represent, respectively, the decreased and increased energy consumption regions. The figure shows that high energy-consuming buildings gain a greater energy benefit from the installation of HAT systems. In figure 6b, the regression curve between the energy saving and the specific energy consumption per dwelling before the installation is presented. Such curve should then be used to estimate the expected energy benefit, as a function of the specific consumption of the building before the installation of HAT systems. It can be noticed that the expected benefit is negligible for low consumption buildings, whereas for higher ones it is higher and tends to a constant value. Both the curves of the expected benefit one and two years after the installation show the same trend, with a quite constant shift.



a)

b)

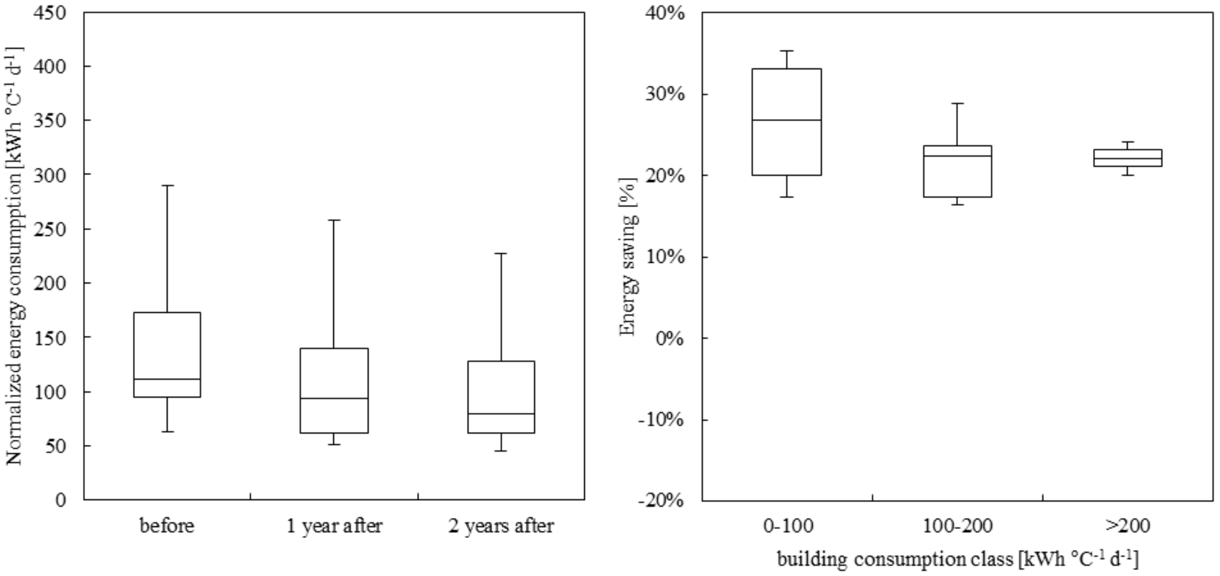
Figure 6 – Regression analysis of investigated buildings in terms of energy consumption before and after the installation of the sole HAT systems in terms of: a) Specific energy consumption, b) Energy saving.

The same analysis has been extended to the buildings in which the HAT systems were installed together with the replacement of the old boiler with a high efficiency one (all located in Piemonte, climatic zone E). In this case, a higher energy saving has always been observed, ranging from about 15 to 35% and none of the buildings increased energy consumption. Table 5 shows that the mean annual benefit was about 24.3% one year after the retrofit and that an additional benefit of about 5.7% was recorded two years after. Although there is a mutual influence of different energy retrofits carried out simultaneously, assuming negligible variation of the new boiler efficiency during the first two years, it is possible to attribute the increase of energy saving between the first and the second year to the sole effect of HAT systems. This result remarks the relevance of the end user awareness to obtain more significant energy savings.

Table 5 – Energy consumption in buildings where HAT systems were installed together with boiler replacement.

Number of dwellings	*Previous consumption [kWh°C^{-1}d^{-1}]*	*HDD [°C d]*	*Normalized consumption after 1 year [kWh°C^{-1}d^{-1}]*	*HDD [°C d]*	*Normalized consumption after 2 years [kWh°C^{-1}d^{-1}]*	*HDD [°C d]*	*Variation after 1 year [%]*	*Variation after 2 years* [%]*
30	111.80	2297	93.44	2356	81.15	2424	-16.4%	-11.0%
52	211.74	2501	160.59	2297	178.70	2281	-24.2%	8.6%
13	68.12	2297	55.56	2356	45.13	2424	-18.4%	-15.3%
13	62.40	2424	51.52	2101	57.18	2119	-17.4%	9.1%
21	99.70	2297	74.84	2356	66.86	2424	-24.9%	-8.0%
140	403.22	2297	322.36	2356	288.02	2424	-20.1%	-8.5%
20	125.26	2297	95.69	2356	79.15	2424	-23.6%	-13.2%
50	172.83	2356	122.84	2424	100.18	2424	-28.9%	-13.1%
40	170.76	2297	141.10	2356	127.65	2424	-17.4%	-7.9%
18	94.40	2424	61.09	2501	61.47	2297	-35.3%	0.4%
40	180.38	2297	139.91	2356	130.36	2424	-22.4%	-5.3%
18	95.76	2297	62.58	2356	54.05	2424	-34.7%	-8.9%
21	86.27	2297	61.49	2356	62.61	2424	-28.7%	1.3%
						Mean variation	*-24.3%*	*-5.6%*

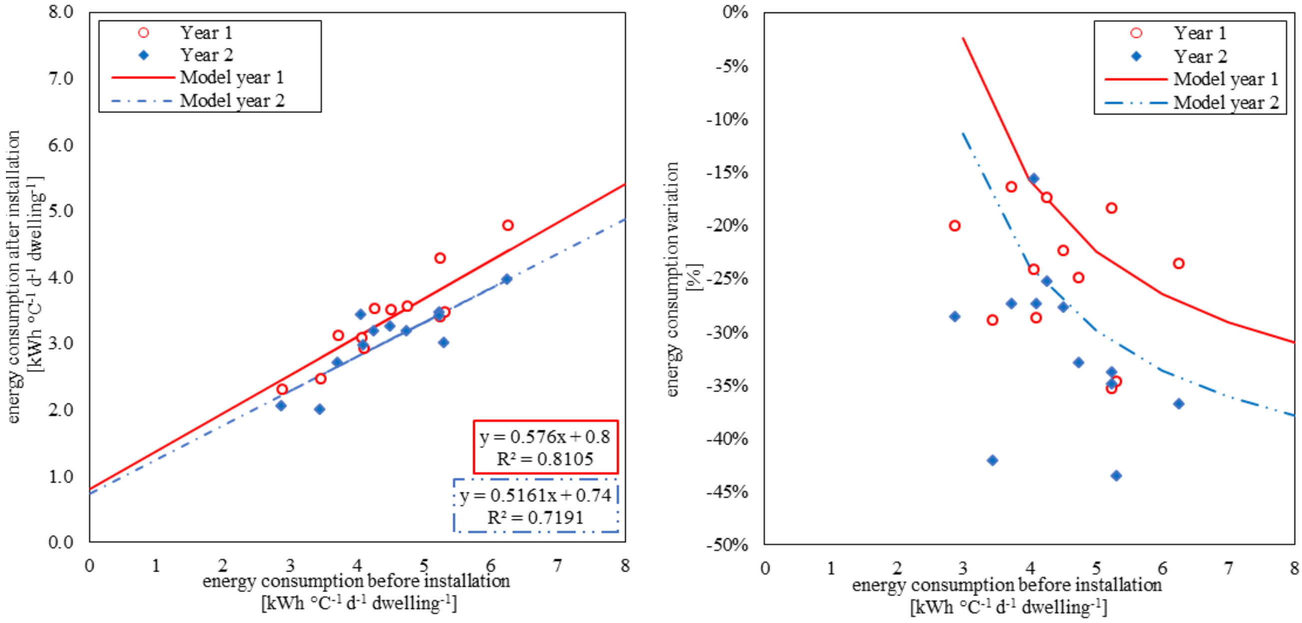
Figure 7a also highlights that energy consumption data two years after the retrofit intervention are more reliable than the ones before. Furthermore, referring to the box plot in figure 7b, it is confirmed that the data dispersion is lower for higher energy consuming buildings.



a) b)

Figure 7: Analysis of energy consumption of the investigated buildings before and after the installation of the HAT systems performed together with the replacement of the boiler in terms of: a) Normalized energy consumptions, b) Energy saving.

Figures 8a and 8b show similar trends to those found in buildings in which the installation of the sole HAT systems was performed, although with specific benefits and data dispersion significantly higher, as expected.



a) b)

Figure 8 – Regression analysis of investigated buildings in terms of specific energy consumption before the installation of HAT systems performed together with the replacement of the boiler: a) specific energy consumption after the installation, b) energy saving after the installation.

3.2 Energy consumption for space heating in Italy

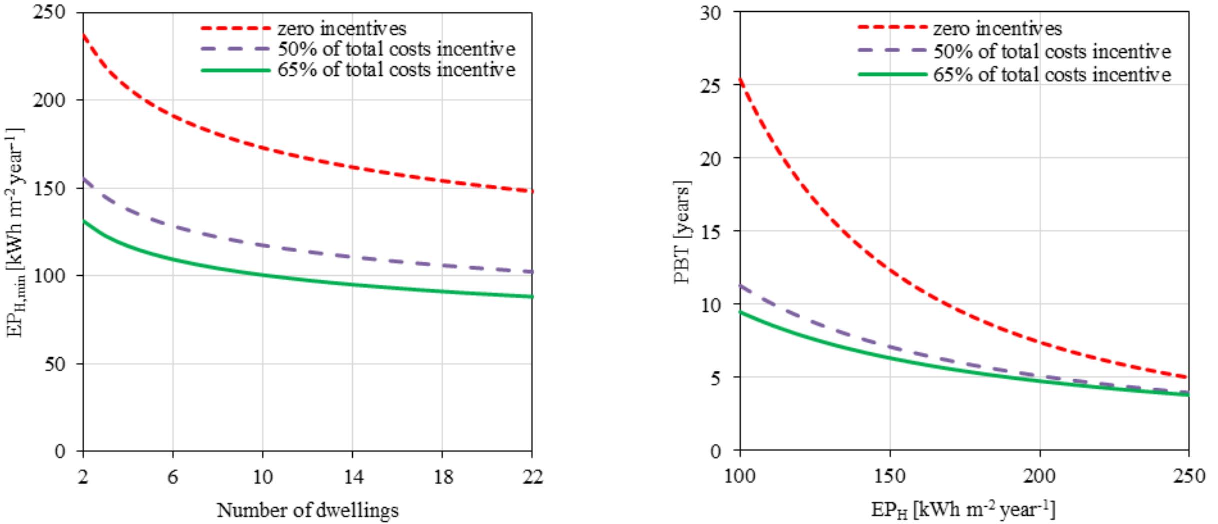
Table 6 presents the results of the validation and calibration of the model described in paragraph 2.2, showing the differences between the energy consumption data available from REBs and the ones estimated using the developed model. It can be pointed out that the mean deviation between the primary energy consumption for space heating in Italian regions calculated through the model and the corresponding data from REBs is initially within about ±22%. Subsequently, thanks to the calibration of U-values of building stocks of each single region, such deviation decreases to about ±2.0%, which is considered acceptable for the purpose of the present analysis.

Table 6 - Comparison between energy consumption for space heating estimated by the developed model and REBs/NEBs in 2015 [49, 50].

Region		*REBs [Mtoe]*	*Data from model validation*		*Data from model with U-values calibration*	
			[Mtoe]	*Deviation [%]*	*[Mtoe]*	*Deviation [%]*
North	Piemonte	2.076	2.046	-1.5%	2.081	0.2%
	Valle d'Aosta	0.093	0.074	-19.9%	0.092	-1.2%
	Liguria	0.552	0.571	3.4%	0.549	-0.6%
	Lombardia	4.960	3.842	-22.5%	5.037	1.5%
	Trentino Alto Adige	0.585	0.663	13.3%	0.589	0.7%
	Veneto	1.926	2.319	20.4%	1.926	0.0%
	Friuli-Venezia Giulia	0.461	0.533	15.7%	0.469	1.7%
	Emilia-Romagna	2.114	1.841	-12.9%	2.150	1.7%
Center	Toscana	1.419	1.415	-0.3%	1.415	-0.3%
	Umbria	0.410	0.389	-5.1%	0.412	0.5%
	Marche	0.554	0.572	3.3%	0.551	-0.5%
	Lazio	1.711	1.375	-19.7%	1.686	-1.5%
	Abruzzo	0.397	0.361	-9.3%	0.405	1.9%
South and Islands	Molise	0.118	0.135	14.2%	0.117	-1.3%
	Campania	1.234	1.201	-2.6%	1.234	0.0%
	Puglia	0.834	0.999	19.9%	0.837	0.4%
	Basilicata	0.158	0.174	9.9%	0.156	-1.5%
	Calabria	0.275	0.333	21.0%	0.275	-0.1%
	Sicilia	0.743	0.689	-7.4%	0.744	0.0%
	Sardegna	0.331	0.294	-11.1%	0.326	-1.3%
Italy		20.951	19.825	-5.4%	21.050	-0.5%

Figure 9a) shows the $EP_{H,min}$ for obliged buildings making efficient the installation of HAT systems resulting from the economic feasibility analysis, as a function of the number of dwellings in the building and of the three different incentive scenarios. Furthermore, in Figure 9b), the simple PBT is reported as a function of the primary energy EP_H (regardless of whether in AR or OR conditions) for a number of dwellings in the building equal to 10. It is important to

highlight that for buildings with a number of dwelling higher than 10 the simple PBT resulting from the economic feasibility analysis does not vary significantly.



a) b)

Figure 9 – Results of the economic feasibility analysis making efficient the installation of HAT in different incentive scenarios: a) $EP_{H,min}$ as a function of the number of dwellings; b) PBT as a function of EP_H.

Finally, in Table 7 the estimated energy saving obtainable through different incentive policies and obligation approaches is reported.

Table 7 –Energy savings achievable through different fiscal policies and obligation approach [Mtoe].

Region		*Fiscal policy 1 (0% incentives)*		*Fiscal policy 2 (50% incentives)*		*Fiscal policy 3 (65% incentives)*	
		OR	*AR*	*OR*	*AR*	*OR*	*AR*
North	Piemonte	0.000	0.019	0.034	0.056	0.041	0.065
	Valle d'Aosta	0.002	0.003	0.004	0.004	0.004	0.004
	Liguria	0.000	0.004	0.003	0.015	0.006	0.017
	Lombardia	0.042	0.089	0.107	0.141	0.128	0.143
	Trentino Alto Adige	0.011	0.016	0.019	0.023	0.022	0.024
	Veneto	0.000	0.000	0.003	0.014	0.008	0.017
	Friuli-Venezia Giulia	0.000	0.000	0.000	0.002	0.002	0.005
	Emilia-Romagna	0.000	0.030	0.021	0.036	0.027	0.037
Center	Toscana	0.000	0.007	0.005	0.017	0.010	0.018
	Umbria	0.000	0.003	0.002	0.004	0.003	0.004
	Marche	0.000	0.001	0.001	0.004	0.002	0.005
	Lazio	0.000	0.012	0.006	0.037	0.014	0.043
	Abruzzo	0.000	0.000	0.000	0.002	0.000	0.003
South and Islands	Molise	0.000	0.000	0.000	0.001	0.000	0.001
	Campania	0.000	0.000	0.000	0.007	0.000	0.008
	Puglia	0.000	0.000	0.000	0.001	0.000	0.003
	Basilicata	0.000	0.000	0.000	0.001	0.000	0.001
	Calabria	0.000	0.000	0.000	0.000	0.000	0.000
	Sicilia	0.000	0.000	0.000	0.001	0.000	0.001
	Sardegna	0.000	0.000	0.000	0.001	0.000	0.002
Italy (Mtoe)		0.056	0.186	0.204	0.366	0.268	0.399
Italy (share*)		0.3%	0.9%	1.0%	1.7%	1.3%	1.9%

* Share referred to the total energy consumption for space heating in residential sector of 21.1 Mtoe estimated in 2015

From data in table 7, it can be pointed out that if all the potentially obliged dwellings in Italy would install HAT systems, this can lead to an overall annual energy saving in residential sector ranging between 0.3% and 1.9%, corresponding to 0.056 and 0.399 Mtoe, respectively. Furthermore:

- nearly all the regions in Southern Italy would be exempted to install HAT systems, since negligible savings occur for both AR and OR approaches regardless of the incentive scenarios; this was expected as a result of the lower energy consumption associated with Mediterranean climate;
- significant energy savings are achievable only in the Central-Northern Italy regions; as for example, in Lombardia Region an energy saving of 75% of the whole national one (i.e. 0.042 out of 0.056 Mtoe) in OR approach without incentives has been estimated; this results from both the climatic conditions and the highest number of buildings potentially subject to the obligation;
- the AR obligation approach shows higher energy saving in respect to the OR one, especially in absence of incentives; in this case, a 0.9% energy saving of the national energy consumption in AR obligation occurs, which corresponds to about 0.3% in OR; as expected, this is due to the lower value of energy consumption estimated in OR which affects the calculated energy saving per year for each building typology;
- the 50% and 65% incentive scenarios present quite similar results at national level (especially for the AR obligation approach).

4. Conclusions

In this paper, the potential of the EU and Italian policy of mandatory installation of individual metering and thermoregulation systems for space heating has been analysed for the residential building stock in Italy. To this aim, the energy consumptions of 3047 dwellings in 50 buildings, located in the major Italian regions (i.e. Piemonte, Lombardia and Lazio) have been investigated before and after the installation of HAT systems. The experimental results show that:

- a mean benefit of about 8.7% has been found one year after the installation of HAT systems;
- an additional benefit of about 2.3% has been found two years after the installation of HAT systems, thus a total mean benefit of 11.0% is potentially achievable through the installation of HAT systems;

- the variation of energy consumption after the installation of HAT systems is very wide, due to the building characteristics and to the operative conditions of the heating plant; in any case, authors believe that the effectiveness of such systems is strongly dependent on user’s awareness;
- the combined effect of the installation of HAT systems together with the replacement of the boiler always resulted in higher energy savings and in a further decrease of energy consumption two years after the energy retrofit;
- the percentage energy saving increases as the specific consumption of the building increases and tends to stabilize to a constant value;
- although the energy saving of buildings located in warmer climate is in absolute lower in respect to the colder one, the percentage benefit is higher in presence of relevant solar gains contribution, thanks to the greater effectiveness of the thermoregulation systems.

The authors developed a model to predict the Italian residential energy consumption for space heating, also on a regional scale. The developed model allowed to estimate with a good accuracy the potential energy saving related to the installation of individual heat metering systems, taking into account the economic feasibility constraint fostered by the European Directive 2012/27/EU, under three incentive scenarios (i.e. 0 – 50 – 65 % of related costs) and two obligation approaches (i.e. OR and AR). The application of the model to the Italian residential building stock shows that:

- in Italy the installation of HAT systems in the residential building stock can lead to a potential energy saving ranging from 0.056 to 0.399 Mtoe/year (i.e. from 0.3 to 1.9% of the estimated energy consumption for space heating of Italy);
- from a policy perspective, the installation of HAT systems is ineffective in the South Italian regions regardless of existing incentives;
- fiscal incentives applied in Central/North Italy lead to significantly higher energy savings;
- the AR obligation approach leads to higher benefits in respect to the OR one, especially in the no-incentives scenario.

The authors believe the results presented in this paper should be useful for defining national policies to be adopted for the spread and the effective use of individual heat metering and charging systems. In fact, they allow both to better understand the expected effectiveness of the current regulation and to improve the effectiveness of monitoring and incentive actions, which may be addressed to the regions with a higher energy saving potential. In addition, the results obtained can also be used by designers for the assessment of the economic feasibility of the installation of HAT systems.

Acknowledgments

This work has been developed under the projects “Ricerca di Sistema Elettrico” funded by ENEA and “PRIN Riqualificazione del parco edilizio esistente in ottica NZEB” funded by MIUR. The authors wish to thank Eng. Norassi and Eng. Cappio for the data provided and for the useful discussion during the experimental campaign.

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