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Ph.D. thesis

About the impact of individual metering on the energy efficiency of residential buildings

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A te,
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ABSTRACT

Since 2002, the European Union has promoted individual metering of energy consumption as an effective tool to improve energy efficiency in buildings.

In 2012, the Energy Efficiency Directive has set mandatory the individual heat accounting in buildings when centralized heating/cooling systems are installed, when technically feasible and cost efficient. As far, Member States of European Union adopted different approaches regarding this obligation, due to differences in their climatic conditions, building stocks characteristics and installed technologies but also to a lack of knowledge about the real impact of the use of such devices.

As a consequence, this measure has led to a series of technical, legal and consumer protection issues which still need to be solved.

This thesis aims to address, with a multi-thematic approach, the issue of measuring thermal energy consumption in residential buildings. A number of four research questions have been investigated in order to answer to the main question: "*What is the impact of the use of energy metering devices in residential buildings?*".

To this aim, a number of six case studies were investigated to: i) evaluate the expected metrological performances of individual metering devices on-field; ii) assess the potential energy saving gainable through the use of individual metering devices in Mediterranean climates and analyse possible feedback strategies to enhance end-user awareness; iii) evaluate the potential impact of different energy policies on the outcome of this energy measure; iv) evaluate the performances of current methodologies applied for end-users' profiling through individual metering.

Results of this thesis provide useful insights to researchers, designers and policy makers, filling some of the gaps highlighted in the existing scientific literature in all the analysed areas.

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Abbreviations and acronyms

AEEGSI	Italian Regulatory Authority for Electricity Gas and Water
AiCARR	Italian Association for Air Conditioning, Heating and Cooling
AR	Asset Rating
AU	Allocation Unit
BTM	Building Typology Matrix
CA	Construction Age
CFs	Compensation Factors
CF	Correction factor
CHS	Centralized Heating Systems
CV	Customer Value
DHMs	Direct Heat Meters
DM	Daily-Metered
EED	Energy Efficiency Directive
ENEA	Italian Agency for New Technologies, Energy and Sustainable Economic Development
ESCO	Energy Service Company
EU	European Union
HAT	Heat Accounting and Thermoregulation
HCA	Heat Cost Allocator
HDD	Heating Degree Days
IGC	Industrial Natural Gas Consumption
HE	Heating Element
IHASs	Indirect Heat Accounting Systems
ISTAT	Italian National Institute of Statistics
ITC-DDC	Insertion Time Counters Compensated with heating Degree Days
ITC-TC	Insertion Time Counters Compensated with average Temperature of heat transfer fluid
MID	Measuring Instruments Directive
MSs	Member States
MULTI_FAM	Multi-family
NG	Natural Gas
NGN	Natural Ga Network
NDM	Non-Daily Metered
OR	Operational Rating
REBs	Regional Energy Balances
RGC	Real natural Gas Consumption of Residential customers
SIN_FAM	Single-family
SLP	Standard Load Profile
TGC	Total natural Gas Consumption of the network
TRVs	Thermostatic Radiator Valves
TWO_FAM	Two-family

Symbols

$\bar{c}_p$	average specific heat capacity of the heating thermal fluid
e	error
$\dot{Q}_{HE}$	nominal heat power of the heating element
$T_{a,c}$	reference values for the ambient temperature
$T_{a,i}$	ambient temperature
$T_{e,c}$	reference value for the heating fluid temperature
$T_{m,c}$	reference value for the heating fluid temperature
$T_{m,i,c}$	average temperature of the heating fluid during ϑ_{CV}
$T_{m,i}$	average temperature of the heating fluid during ϑ_{OV}
ϑ_{CV}	closing time of the valve
ϑ_{OV}	opening time of the valve
E	Primary energy need [kWh m^{-2} year $^{-1}$]
h	Inter-storey height [m]
K	coefficient of proportionality between the allocation unit and the actual heat used
K_C	rating factor for thermal contact between heat cost allocator and the heating element
K_Q	rating factor for thermal output of the heating element
K_T	rating factor for indoor temperature
n	characteristic exponent of the heating element
q	volumetric flow rate
ΔT	temperature difference
η	System efficiency [-]
ρ	flow density
τ	time constant
U	Thermal transmittance [W m^{-2} K^{-1}]

Other subscripts

AC	Annual Consumption
DC	Daily Consumption
d	distribution
f	floor
gen	generation
H	heating
min	minimum
P	primary
r	roof
r	regulation
wall	walls
win	windows

INTRODUCTION

Achieving energy efficiency in both existing and new buildings has become increasingly important within the last decades, as buildings are responsible for 36% of global final energy consumption and nearly 40% of total direct and indirect CO_2 emissions [1]. Greenhouse Gas (GHG) emissions related to growing building energy use has been the cause of a severe environmental impact, leading governments to approve a number of protocols to reduce energy consumption from fossil fuels and promote energy efficient technologies and renewable energy use [2], especially in the buildings sector. In 2016, 75% and 60% of the countries had specific policies for, respectively, the implementation of energy efficiency strategies and for boosting the spread of renewable energy sources [3, 4]. Indeed, targeted policy actions on multiple fronts are therefore not only necessary, but indispensable for the mitigation of our energy and environmental impact. On the other hand, the vast majority of countries have not yet begun to face the energy transition process.

EU itself issued a series of directives, together with technical regulations, which are aimed at giving rules to reduce energy consumption of buildings in the direction of: i) increasing the energy performances of both buildings' envelopes and installed technologies; ii) raising users' concern about energy consumption and engage in correct energy management and, iii) making buildings' energy consumption measurable and tangible to people through smart technologies.

Within this framework, the measure of energy consumed in individual dwellings certainly has represented a very debated topic in the last recent years, given its potential to become a relatively low-cost tool to reduce energy consumption in buildings.

In Europe, the very first attempt to regulate the installation of heat accounting and temperature control systems in individual dwellings is indirectly contained in Directive 93/76/CEE (SAVE) [5] to limit carbon dioxide emissions by improving energy efficiency (through implementation of billing of heating, air-conditioning and hot water costs on the basis of actual consumption) and subsequently by Directives 2002/91/EU [6] and 2010/31/UE [7]. Indeed, these directives stated that the billing of heating, air conditioning and domestic hot water production based on individual consumption contributes to energy savings in the residential sector.

In this regard, in 2012 the Energy Efficiency Directive (EED) [8] imposed Member States (MSs) the obligation to install individual heat metering systems in buildings supplied by a centralized source of heating/cooling/hot water production provided its economic and technical feasibility and encouraged MSs to adopt transparent rules on consumption-based and informative billing. In fact, the installation of metering and sub-metering systems of energy consumption in the building sector is expected to increase end-user awareness, thus obtaining behavioural changes towards a greater energy efficiency. This is also emphasized in the newly amendment of the EED, in which it is explicitly stated that *“Member States should take into account the fact that the successful implementation of new technologies for measuring energy consumption requires enhanced investment in education and skills for both users and energy suppliers”* [9].

Results from several scientific papers and research projects stand behind such policy: it is nowadays clear that the only interventions to improve the efficiency of energy plants and structures of the buildings are not enough to guarantee a reduced energy consumption. These must be combined with actions aimed at increasing the awareness and participation of the final customer, also through more frequent and detailed information on energy consumption [10].

It has been demonstrated that, in absence of periodic information, houses with identical energy performance and thermo-physical characteristics, even those designed for N-ZEB energy standards, can consume up to twice as much as each other, depending on the behaviour of the inhabitants [11]. Thus, inducing energy-efficient behaviour among tenants should represent a complement to other actions directly aimed at improving energy efficiency at building level, such as lowering the thermal transmittance of the building envelope or updating the central heating system with more energy-efficient devices [12].

However, this obligation has led to several technical, legislative and consumer protection implications, which to date are still open topics. In fact, the potential savings achievable through this measure are strongly related to the thermophysical characteristics of the building stock and of installed heating systems, to the climatic conditions, to the diffusion of these devices in certain markets and to cultural and economic aspects, playing a crucial role on the real success of energy retrofit interventions. Thus, the potential for energy saving of heat accounting is related to both the technical characteristics of the system and to the behavioural component whose weight on overall savings are not easily predictable. This results in a total energy saving still unquantifiable due also to the wide variability of installation and operating costs of metering and sub-metering devices in different EU countries.

Overall, quantifying the potential for energy savings is a difficult task, because energy is largely an "invisible" good [13-15]. This can make it difficult for users to have a clear idea of how its use varies over time and how this relates to significant benchmarks. Hence, it is also crucial to correctly design the way in which the information gatherable from individual metering and sub-metering devices arrives to final user.

Different transpositions have been adopted within EU MSs, with some MSs setting mandatory individual metering for space heating for almost all buildings and others exempting all the building stock [16-18]. Regardless of EED requirement about individual metering is subject to technical feasibility and cost-effectiveness [19, 20], current legislation within MSs lacks official indications about reference energy saving and standard costs. Nevertheless, some efforts have been made (or are in the testing/drafting phase), as for example in Italy, United Kingdom and Spain [21-23] to give tools and/or guidance about how to perform the economic feasibility analysis of individual heat metering and accounting systems. Furthermore, it is not specified if the cost-benefit analysis has to be performed at standard rating condition of the building rather than at operational ones. This leads professionals to manage very wide margins of exemption or obligation for the installation of heat accounting systems in buildings.

Several studies conducted in central EU countries demonstrated potential benefits variable between 8% and 40% [24-26]. Besides, standard figures of cost related to the installation of individual metering systems are available only for few markets [16, 17, 27, 28]. As a matter of fact, it has been demonstrated that payback times vary between 3 and 16 years when the building energy need ranges from 300 to 100 kWh m^{-2} $year^{-1}$ with an expected benefit of 25% [27].

From a policy and regulatory point of view, the introduction of transparent allocation rules for heating/cooling/hot water costs ensuring at the same time the transparency and accuracy of the individual energy metering is a difficult subject. Heat costs in multi-apartment buildings supplied by centralized energy sources can be divided into variable (i.e. the consumption of the user according to his need) and fixed (i.e. the consumption to run the system including heating of common areas and costs for ancillary devices).

As a matter of principle, variable costs should correspond only to “voluntary” consumption of single apartments, while fixed ones to all other costs that occur also when all users close their radiators. In this way, unoccupied dwelling would not permanently undergone a forced charge for unsolicited energy costs. On the other hand, two issues such as the so-called "heat thefts" [29] and "split incentives" in the energy retrofit of buildings, make the above-mentioned principle critical. In residential buildings, split incentives signify a misalignment between the landlord who pays the energy retrofit intervention and tenants who pay for energy consumption, thus resulting the direct beneficiary of the intervention itself [30]. Therefore, setting a high share of voluntary energy consumption could lead to the situation in which only tenants with the more unfavourable location within the building would benefit from a retrofit intervention, while all tenants would pay for it. For this reason, in many EU MSs specific compensation factors have been introduced, or methods to partially compensate for the greater heat losses occurring in some apartments, setting the use of compensation factors as mandatory, whereas in others compensation is forbidden by law. On the other hand, a low share of voluntary energy consumption may cause energy-inefficient behaviours even if this could lower the problem of energy poverty in particularly disadvantaged buildings, meaning that best-practices in heat cost allocation are subordinated to the in-depth knowledge of both the characteristics of the buildings and the cultural and economic conditions of tenants.

On the technical hand, two different categories of heat accounting systems are available on the market: Direct Heat Meters (DHMs) and Indirect Heat Accounting Systems (IHASs). EED sets as a priority of the installation of DHMs when economically and technically feasible; alternatively, the installation of IAHSs (e.g. Heat Cost Allocators, HCA, or Insertion Time Counters, ITC) is permitted. Unfortunately, due to heating plant configuration and to technical and architectural constraints, DHMs installation is often not feasible, while IHASs installation is almost always technically feasible in existing buildings with conventional radiators [31, 32]. However, the use of IHASs implies some issues in terms of consumer protection. In fact, accuracy of IHASs could range from 3.0% to 12.4% [33] and up to 30% [34] while in different operating conditions it ranges from about 2.7 % to about 11.7 % [35]. Moreover, only DHMs are currently regulated by legal metrology [36], therefore they can be used both for measuring thermal energy at the point of supply and also for sub-metering of energy consumption within the building. Finally, IHASs are lacking from a regulatory point of view and in most MSs, DHMs are also subject to on-field verifications, while IHASs have no legal verification constraints of the on-field performances.

Metering and sub-metering devices are fundamental also in management of energy networks, such as district heating or cooling, or natural gas networks, where they play a key role in the consumption billing and in the allocation of energy consumption between the different actors of the network. Forecasting energy consumption through periodical meter-readings can guarantee that the energy network operates in balanced conditions, which not only has important economic implications, but above all determines whether the network operates safely and ensures the continuity of supply.

In the above described context, it is clear how individual metering of energy consumption is a subject of multi-disciplinary nature which involves metrology, policy, energy management together with social and behavioural aspects which will be all analysed within the framework of the present research.

Aim of the work and research questions

The present research aims to address some of the gaps in the current scientific literature concerning the subject of energy metering which have been described in the above introductory section. The different topics have been approached from different perspectives. For this reason, the chapters of the thesis have been compiled in a thematic way and consistently with the candidate's research experiences. Specifically, this research will try to answer with an integrated approach to the following main research question:

What is the impact of the use of energy metering devices in residential buildings?

The initial idea of the research was to evaluate the impact of individual energy metering and sub-metering systems with two different viewpoints. The first, purely technical, aimed at evaluating the main metrological issues related to the installation of individual metering devices in single buildings. The second, more focused on energy efficiency, aimed at assessing the potential impact of the installation of such devices in residential buildings in terms of energy consumption reduction at large-scale.

However, further research questions have arisen from the first analysis: after performing an experimental campaign aimed at assessing the mean statistical energy saving achievable through the installation of these devices, it has been clear that a simple figure could not explain the complexity behind the high variability of the benefit potentially obtainable through these devices. This also meant that, to have an in-depth understanding about the energy saving induced by using metering devices, it would have been necessary analysing the way in which these are perceived and actually used inside single dwellings and how their potential could have been increased by acting on end-user understanding and behaviour.

Nevertheless, there are several ways in which one could act to achieve the goal to enhance the potential for energy saving of these devices: from this point of view, the level of user education and involvement with such devices is not the sole weighting component, but the definition of appropriate energy policies on both micro- (i.e. single building level) and macro- (i.e. building stocks level) scales is also of fundamental importance.

Lastly, an investigation of the methodologies employed to profile end-user's energy consumption within energy networks has been performed aimed at evaluating the impact of correct individual metering and sub-metering at a building and district levels in the management and regulation of energy networks.

The research questions arising from the main question and sub-questions are described in the following:

A. *What are the expected on-field metrological performances of distributed individual metering and sub-metering systems with respect to consumer protection?*

B. *What is the potentially achievable energy saving through the installation of individual metering devices?*

  ***b1** – What is the statistical impact of individual metering devices in Mediterranean climate?*

  ***b2** – In which way it is possible to act on final users in order to enhance their engagement and to raise their awareness about energy consumption?*

C. *Is it possible to guide the success of the action about individual metering in residential buildings at a political/regulatory level?*

  ***c1** – What are the best practices in allocation of energy costs at a building level?*

  ***c2** – What is the impact of individual heat metering and accounting in different policy scenarios at a Country-scale level?*

D. *What is the impact of metering devices in management and regulation of energy networks?*

In the following, an overview about the research outline together with the thesis structure will be given in order to allow a clear understanding during the reading of the present work.

Research outline and thesis structure

The thesis is organized in four main thematic chapters, each containing an introductory section in which the scientific relevance of the research topic and the gaps in current scientific literature are highlighted.

Every chapter aims to address one of the main research questions by analysing one or more case studies each, in turn, answering one of the sub-research questions.

Chapter 1 addresses the problem of thermal energy measurement in terms of on-field reliability of indirect heat accounting systems in residential buildings. An overview about the technical and regulatory state of the art about thermal energy metering and accounting is provided and the analysis of a case study (case study #1) is provided in which a novel model for the estimation of heat accounting systems reliability is described and proposed.

Chapter 2 is dedicated at estimating the potential energy saving achievable through the installation of individual thermal energy metering and accounting and temperature control devices in residential buildings. The issue is addressed on two different scales. In *case study #2*, the author intends to determine the average statistical benefit obtained by installing the aforementioned devices in a sample of 3000 apartments in Italy, addressing the problem with a macro-scale approach. By analysing the *case study #3*, on the other hand, the author focuses on the main factors influencing end-user awareness, investigating possible strategies for optimizing user communication through the use of modern technologies made available by the Internet of Things, with a micro-scale approach (i.e. at a single building level).

In *Chapter 3* the topic is addressed with a policy-making perspective. A discussion is provided about the main issues related to: *i)* the current heat cost allocation rules within Europe, *ii)* the technical-economic feasibility constraints of the installation of individual metering devices and *iii)* the modelling of the energy consumption of building stocks for the projection of different policy scenarios. Viable energy policies are evaluated on both the micro- and macro-scales with particular focus on optimizing the heat cost allocation rules at a building-scale level (*case study #4*) and evaluating the impact of different policies to the whole potentially achievable energy saving at a Country-scale (*case study #5*).

Finally, *Chapter 4*, is aimed at evaluating the impact of correct individual metering and sub-metering at a building and district level in the management and regulation of energy networks, with particular focus on natural gas networks, which are more widespread on the Italian territory than the district heating/cooling ones (making it easier to find large-scale data for modelling purposes). In particular, in *case study #6*, the methodologies employed to profile end-user's energy consumption within energy networks have been evaluated in terms of performances in predicting final energy consumption of residential users.

In Table 0.1, an overview on the thesis structure is provided together with some additional useful information.

Table 0.1 – Thesis structure and outline

RQ		***Topic***	***Case study***	***Analysis***		***Chapter***
main	***sub***			***scale***	***type***	
A		Metrology	#1	single building	modelling/experimental	1
B	b1	Energy Efficiency	#2	building stock	experimental	2
B	b2		#3	single building	experimental	
C	c1	Energy Policy	#4	single building	modelling	3
C	c2		#5	building stock	modelling	
D		Forecasting	#6	building stock	modelling	4

CHAPTER 1. INDIVIDUAL HEAT METERING DEVICES

In this Chapter, after the analysis about technical and legal metrology features of direct and indirect heat accounting devices, a statistical model for the estimation of the uncertainty of heat accounting through indirect methods is proposed as case-study. The developed model has been applied to three different typical buildings: i) a two-family house, ii) a small building, iii) a large multiple building. The developed model has been proposed by Italian Association for Air Conditioning Heating and Refrigeration (AICARR) as reference method for heat accounting uncertainty estimation in the new version of the national standard UNI 10200 [37].

1.1 Measuring systems for heat accounting

As stated above, heat metering and sub-metering systems are normally classified as "direct" and "indirect". Thermal energy meters provide a “direct” accurate measurement of thermal energy supplied in a heat circuit and they are regulated by legal metrology [36] and detailed harmonized technical standards [38-46]. On the other hand, IHASs are based on the estimation of thermal energy emitted by single radiators/convectors or in certain thermoregulated zones of the heating/cooling plant.
Nowadays, in the European market, electronic HCAs are the most common indirect accounting systems. HCAs allow an “indirect” measurement of thermal energy, since they measure some parameters correlated to it, as described in corresponding EN 834 [47] and EN 835 [48] technical standards. For the sake of completeness, besides HCAs, in the Italian market other indirect accounting devices are quite common. Such

systems are based on the registration of the opening periods of a single thermal zone (i.e. a portion or the entire building unit) or of the valve of a single radiator. The opening periods of each valve are then compensated with the average temperature of the heat transfer fluid or with the actual degree days (i.e. the difference between the conventional ambient temperature and external one), according to [49] or [50] national standards, respectively. Besides, Compact direct Heat Meters (CHMs) applicable to single radiator/convector have been recently developed [51] and they are currently under type approval tests according to the Measuring Instruments Directive (MID) [36] and EN 1434 [38-43]. CHMs are made up of a miniaturized static flow meter mounted on the radiator holder together with a temperature sensor and the other temperature sensor embedded in the thermostatic valve and remotely read. Such devices, although interesting from a technical point of view, are still quite costly compared to traditional indirect systems.

As well known, indirect accounting systems do not perform a true measurement of the heat consumed by a heating element, but only an indirect estimation through the measurement of some strongly correlated parameters. Such estimation allows the share of space heating costs among single apartments as a fraction of the entire heat consumed in the building, typically measured through large HMs in District Heating or a Gas Meter when the central source is supplied with natural gas [52, 53].

Indirect heat accounting is not aimed at getting an accurate measurement of the thermal energy emitted by the single heating element, but at sharing space heating costs within the apartments of a building, through the estimation of the heat consumed by a single apartment/radiator/thermal zone in respect to the total amount consumed by the building itself. Therefore, this is carried out by defining suitable dimensionless allocation units (AU_{rad}) which are proportional to the energy emitted by the single radiator and are a function of: i) the temperature difference between the radiator and the environment; ii) the radiator thermal output; iii) the usage time. Indirect methods perform the estimation of the temperature difference as a function of the characteristics of the accounting device and of the control surface to which the heat balance is applied. To get the allocation unit of the j-th apartment of the building ($AU_{ap,j}$), the allocation unit of each i-th radiator in the apartment ($AU_{rad,i,j}$) is obtained by summation, according to equation (1.1).

$$AU_{ap,j} = \sum_{i=1}^{n_{rad,j}} AU_{rad,i,j} \qquad (1.1)$$

Therefore, the share S_j of each j-th apartment (i.e. the so-called "voluntary" heat consumptions) is given by equation (1.2).

$$S_j = \frac{AU_{ap,j}}{AU_b} = \frac{\sum_{i=1}^{n_{rad,j}} AU_{rad,i,j}}{\sum_{j=1}^{n_{ap}} \sum_{i=1}^{n_{rad,j}} AU_{rad,i,j}} \qquad (1.2)$$

where: i) $AU_{ap,j}$ and AU_b are, respectively, the allocation units of the j-th apartment and of the entire building; ii) $n_{rad,j}$ e n_{ap} are the number of radiators in the j-th apartment and of apartments in the entire building.

Although intrinsically more accurate than IHASs, the installation of DHMs is always technically and economically feasible only in new buildings in which apartments are supplied through flow and return pipes easily accessible.

Conversely, existing and historical buildings normally present heating plants with rising mains [27] and in such configuration the installation of IHASs is strongly recommended. In Table 1.1, a summary of technical and economic feasibility of direct and indirect heat accounting devices is presented.

Table 1.1 - Heat accounting systems feasibility in space heating and cooling plants.

	Direct Systems		***Indirect Systems***	
	DHM	***Hybrid DHM***	***HCA***	***ITC***
Legal metrology requirement				
Applicable Technical Standard	EN 1434 [38-43]		EN 834 [47]	UNI 11388 [49] UNI 9019 [50]
Expected accuracy	high	medium-high	medium	medium-low
Unit	kWh	kWh	dimensionless	kWh/dimensionless
Type approval	MID	*	not mandatory	not mandatory
Marking	CE+M	*	CE	CE
Initial verification	mandatory	not specified	not mandatory	not mandatory
Subsequent verifications	depending on MS	not specified	not mandatory	not mandatory
*Purchase and installation costs****	high	medium-high	low	medium
Feasibility in vertical pipe central heating plant configuration with heating element type:				
Radiator	uneconomical	optimal	optimal	optimal
Convection heater	uneconomical	optimal	good	optimal
Fan coil	uneconomical	optimal	not feasible	not optimal**
Underfloor heating panel	uneconomical	not feasible	not feasible	feasible
Wall/Ceiling heating panel	uneconomical	not feasible	not feasible	feasible
Hot air booster	optimal	not feasible	not feasible	not feasible
Feasibility in horizontal pipe central heating plant configuration with heating element type:				
Radiator	optimal	good	good	good
Convection heater	optimal	good	good	good
Fan coil	optimal	good	not feasible	not optimal**
Underfloor heating panel	optimal	not feasible	not feasible	feasible
Wall/Ceiling heating panel	optimal	not feasible	not feasible	feasible
Hot air booster	optimal	not feasible	not feasible	not feasible

* HMs for single radiators are not explicitly regulated by Legal Metrology
** feasible only for fan coils at fixed velocity
***costs considered for single device; the final cost depends on the number of HEs within the apartment

1.1.1 Direct Heat Meters

DHMs measure the thermal energy delivered to a given Heating Element (HE) through the flow and return pipes of the heating/cooling circuit. DHMs perform a simple thermal energy balance on the HE under the following assumptions: i) stationary and one-dimensional flow in the measurement sections; ii) a single inlet and a single outlet (i.e. the absence of leaks and fluid withdrawals); iii) negligible variation of kinetic and potential energy within the HE’s flow/return pipes. In the typical operating conditions, the measurement of thermal energy (E) in a given time interval can be carried out as per equation (1.3).

$$E = \int \rho \, \bar{c}_p \, q \, \Delta T \, d\vartheta \tag{1.3}$$

Where $\boldsymbol{\rho}$ is the flow density, $\boldsymbol{\bar{c}_p}$ is the average specific heat capacity of the fluid, $\boldsymbol{q}$ is the volumetric flow rate, $\Delta\boldsymbol{T}$ is the temperature difference between the flow and return pipes. The measuring system can be made up of a single indivisible unit or of differen sub-assemblies separately homologated (i.e. a flow sensor, a pair of temperature sensors, a calculator, as per Figure 1.1). DHMs are regulated by legal metrology [36] and detailed harmonized technical standards [38-46].

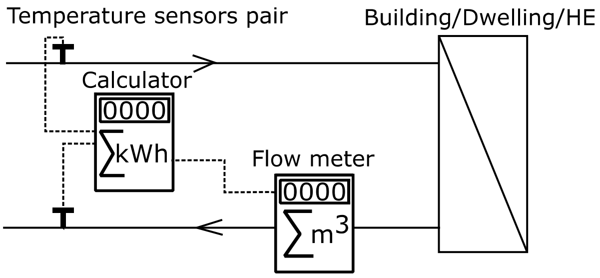


Figure 1.1 – DHMs constructive scheme

For major details about applicable technical regulations for DHMs, the reader should refer to Table 1.2.

Table 1.2 – Reference standard for DHMs

Reference	Title
EN 1434-1:2016	Heat meters – Part 1: General requirements
EN 1434-2:2016	Heat meters – Part 2: Constructional requirements
EN 1434-3:2016	Heat meters – Part 3: Data exchange and interfaces
EN 1434-4:2016	Heat meters – Part 4: Pattern approval tests
EN 1434-5:2016	Heat meters – Part 5: Initial verification tests
EN 1434-6:2016	Heat meters – Part 6: Installation, commissioning, operational monitoring, maintenance
OIML R75-1:2002	Heat meters – Part 1: General requirements
OIML R75-2:2002	Heat meters – Part 2: Type approval tests and initial verification tests
OIML R75-3:2006	Heat meters – Part 3: Test Report Format

Thus, according to the MID, it is possible to classify DHMs into three main categories:

- DHMs installed within residential buildings; generally not remotely read, with mechanical single-jet flow meters and with short-stem temperature sensors (mounted directly on the pipeline) with an accuracy class 3;

- DHMs installed on the supply points of bigger utilities; generally with static flow meters and long-stemmed temperature sensors (mounted directly on the thermowell) with an accuracy class 2;

- DHMs installed on the supply points of larger users (i.e. super-condominiums, hospitals, industrial users); generally remotely read, of the combined type, with static flow meters and long stem temperature sensors mounted on the well, with an accuracy class 1 or 2.

Depending also on the flow rate, the scope and the type of application of DHMs (i.e. residential, commercial, industrial etc.), another classification can be applied depending on the flow meter type. As highlighted by Choi, et al. [54] by summing sales data from Germany, Denmark, UK, Finland and Sweden the main types of flowmeter used in heat energy metering are: turbine, electromagnetic, ultrasonic, with average market shares between 2002 and 2006 of respectively 37.6%, 38.4% and 24.0%.

Depending on technical characteristics of the building heating plant and/or on architectural constraints, the installation of DHMs in not always technically and or economically feasible as for example in historical buildings, centralized heating systems with vertical mains etc. where it would be required to install a heat meter for each heating element [32].

1.1.2 Metrological issues of DHMs

The Measuring Instruments Directive (MID "recast") (2014/32/EU) fixes rules for the approval and initial verification of heat meters in terms of essential requirements and maximum permissible errors in its Annex VI "Thermal Energy Meters MI-004". Technical specification about the metrological performance, pertain to the corresponding national standards implementing the European harmonized standard (or OIML recommendations). For heat meters, these standards are EN 1434 and OIML R75 series. The Maximum Permitted Error, as per relevant applicable standards, are given in Table 1.3.

Table 1.3 – Maximum Permitted Errors for DHMs

Class	MPE Flow sensor	MPE Temperature sensor	MPE calculator	MPE DHM System
1	$\left(1+0.01\frac{q_p}{q}\right)^*$	$0.5+3\,\frac{\Delta T_{min}}{\Delta T}$	$0.5+\frac{\Delta T_{min}}{\Delta T}$	$\left(1+0.01\frac{q_p}{q}\right)^*+1+4\frac{\Delta T_{min}}{\Delta T}$
2	$\left(2+0.02\frac{q_p}{q}\right)^*$			$\left(2+0.02\frac{q_p}{q}\right)^*+1+4\frac{\Delta T_{min}}{\Delta T}$
3	$\left(3+0.05\frac{q_p}{q}\right)^*$			$\left(3+0.05\frac{q_p}{q}\right)^*+1+4\frac{\Delta T_{min}}{\Delta T}$

*in any case no more than 5%

q_p with stationary flows, ΔT_{min} lower limit of the temperature difference for the correct functioning of the DHM

For each sub-unit of the heat meter (flow sensor, temperature sensors and calculation module). There are specific installation and management issues affecting its on-field metrological performance, as following [55-61]:

1. installation effects, which are fluid-dynamic (i.e. occurring due to disturbances upstream and downstream of the heat meter) or thermal (i.e. thermal disturbances affecting the temperature sensors pair, such as inadequate immersion depth of the sensor causing conductive heat transfer with the pipe);
2. the presence of gas or impurities in the heat transfer fluid which can interact significantly with the heat meters by causing chemical reactions with alteration

of the characteristics of the fluid, corrosion phenomena, biological phenomena, fouling etc.;

3. the influence of the metrological characteristics from the thermodynamic operating conditions of the heat transfer fluid; these are calculated by the calculator module basing only on the measured temperature; however, the fluid may be a mixture of water and additives, with variable thermophysical properties (depending on the composition and the type of additive), and its characteristics in centralized heating systems can change greatly over time;
4. the potential use of measuring instruments outside its optimal measuring range; as for example the over-sizing of the maximum thermal heating power may result in the non-optimal functioning of the measurement system: in critical conditions the meter could work with too low flow rates or with a too low temperature difference.

Unfortunately, the installation effects are not fully regulated by legal metrology, thus a number of scientific papers have been produced with respect to on-field metrological characterization of DHMs, which are summarized in Table 1.4.

Table 1.4 – Scientific literature about DHMs on-field characterization

Subject	***Main outcomes***	***Reference***
DHMs installation effects, recalibration periods, accuracy over time	Meters correctly installed are accurate within MPE of MID. Flow meter is relatively resilient to incorrect installation Installation of temperature sensor pair is critical	Butler, et al. [61]
DHMs on field test accuracy, accuracy over time	Significant reductions in the heat meters performance	AGFW [62]
DHMs on field test accuracy, installation effects (position, rotation, vibration), durability test, accuracy over time	Electromagnetic and ultrasonic types have better performances than turbine one. Tested meters showed adequate durability. Deviations of the turbine and ultrasonic flowmeters during on-field tests were within ±2.5%. Electromagnetic flow-meter’s accuracy within 6.9% of mean flow rate.	Choi, et al. [54]
Accuracy of DHMs over time	Need of correction factors specifically designed for local plant installation characteristics.	Celenza, et al. [63]
Increasing metrological performances of DHMs	A new method to increase the measuring range of the flow sensor is proposed, consisting of mixing heat fluxes in a heat exchange circuit at the point in which the heat carrier is supplied to the exchanger.	Michnikowski and Deska [64]

Electronic heat cost allocators

Electronic HCAs are currently the most popular among indirect heat accounting devices. Such devices may only be used on radiators/convectors for which the emitting surface is accessible and they are applied to the radiating surface of the radiator in a suitable position to detect its average temperature. First HCAs available on the European market were based on the evaporation principle and, although still regulated by EN 835 [48], are now virtually obsolete because lacking of remote reading and needing annual maintenance to refill the evaporated fluid. Modern HCAs are completely electronic and they are regulated by EN 834 [47]. Electronic HCAs normally consist of a compact case composed by the following components: i) a calculation and data transmission module; ii) one or more temperature sensors (of which the one for the ambient temperature in some configurations is external to the case); iii) a display; iv) a power supply system; v) a metal plate for the installation and thermal coupling (Figure 1.2).

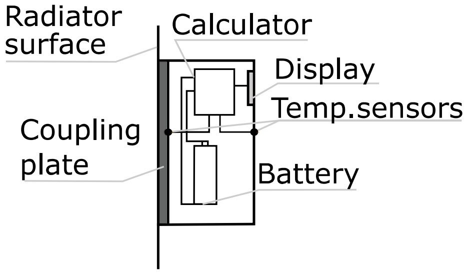


Figure 1.2 – Electronic HCA constructive scheme

Thus, heat accounting is based on the integration over time of the temperature difference between the radiator surface and the room ambient in which the HCA is installed. EN 834 [14] describes the following three types of HCAs:

- single sensor HCA, which measures the room heating surface or heating medium and use the conventional ambient temperature (20 °C);
- two-sensors HCA, made-up by one sensor that measures the room heating surface or heating medium and a second one measuring the ambient or a related temperature;

- multiple-sensor employing at least two sensors for the room heating surface or heating medium and one sensor for the ambient temperature.

The EN 834 [14] standard does not provide explicitly any algorithm for the calculation of the Allocation Units (AUs) of each radiator but, to this aim, describes two methods: i) non-rated displayed reading; ii) rated displayed reading. In the first, the AUs of each radiator are estimated on the basis of the time integral of the measured temperature difference between the radiator heating surface and the room. In the second, allocation units for the i-th radiator in the j-th apartment of the building are obtained from the non-rated displayed reading values by multiplication by rating factor K_C, K_Q and K_T for each radiator, through the following equation:

$$AU_{rad} = K_C K_Q K_T \int_{\theta} \left(\frac{\Delta T}{60}\right)^n d\theta \qquad (3)$$

where K_C and K_Q represent respectively rating factors at reference laboratory conditions of: i) the temperature sensors coupling; ii) the rated heat output of the radiator. Factor K_T is used only for single sensor HCAs when indoor temperature is less than the ambient reference one.

In particular, rating factor K_C takes into account that HCAs do not measure the actual temperature difference between the heat transfer fluid and room ambient, but actually a value proportional to it. This is mainly due to the following issues: i) the surface temperature measured in a specific point is different from the average surface temperature of the radiator; ii) the contact resistance between the plate and the radiator influences the measurement of the surface temperature; iii) in two-sensors HCAs the measurement of room ambient temperature is influenced by convective and radiative fluxes into the case.

Therefore, rating factor K_C is a function of the HCA characteristics, of the radiator type (but not of its rated heat output) and of the installation conditions. In particular, installation conditions are generally different from those at laboratory. Therefore, K_C at actual conditions of use can greatly differ from the one estimated by the manufacturer at rated conditions, especially when the installation is not carried out in accordance with specific technical instructions (e.g. wrong positioning, not adequate coupling plate-radiator). Rating factor K_Q, however, concerns the rated thermal output of the radiator. At rated installation and operative conditions, K_Q is a function solely of the radiator characteristics (i.e. type and size). Unfortunately, rarely installation and operative conditions are equal to the rated ones, thus the actual heat emitted by the radiator is affected also by installation conditions, hydraulic connections and surface painting. As a matter of fact, actual value of K_Q may differ from that estimated by the designer of the heat allocation system, both for the impossibility to accurately estimate rating factors at real actual conditions of installation and use and for the lack of fair and traceable certification of existing radiators. Table 1.5 summarizes main technical characteristics of HCAs in the market.

Table 1.5 - Technical characteristics of HCAs

Description	***Type***	***Comment***
Temperature sensors	1 or 2 sensors with external sensor	HCAs are equipped with sensors embedded into the case or with an external remote sensor for radiators not easily accessible. HCAs normally use one or two temperature sensors. In the first case the sensor (positioned in the back side and directly fixed on the plate) only measures a surface temperature proportional to the radiator one (assuming that the ambient temperature is set equal to 20°C). In the second case, in addition to the first sensor, a second one (on the front side of the HCA) measures a temperature proportional to the ambient one. Thus, allocation units are calculated through the difference between the two measured temperatures.
Software	Programmable Not programmable	Rating factor K is calculated as a function of the characteristics of the radiator. Such factor depends on the radiator heat output and size (height, width and depth), on the material (cast iron, steel, aluminum), on the type (shape and finning of the elements). Also, the type and size of valve and holder and the thermal contact HCA-radiator are to be adequately evaluated. EN 834 requires K to be directly programmed in the HCA's memory (in such case, the units of each HCA are proportional to heat consumptions) or not-programmed (in such case, the units of each HCA are subsequently multiplied by the specific K). Only in the first case the reading will be the allocation unit itself. In such case, allocation units will be visible and the user should aware of his own consumptions.
Reading	Local Remote (walk-by)	Readings can be performed from inside or outside single apartments. There are mainly two remote reading methods available: i) data are remotely

Description	***Type***	***Comment***
	Automatic Remote reading	downloaded by an operator without entering the apartment; ii) HCA is equipped with a radio module permanently connected via web or GPRS to a concentration unit at fixed frequencies.
Power	Normal/long life batteries. Permanent/changeable	One of the most important issues is the battery life (normally ranging 5 to10 years) and/or battery replacement to avoid complete HCA substitution.
Tampering	Seal (mechanical/ electronic) - Alarm	To prevent tampering, electronic HCAs are equipped both with seals and alarms detecting abnormal operative situations (fraudulent use).
Sensitivity to external heat sources		HCAs should be insensitive to external heat sources or recognize contributions from free heat sources (e.g. solar radiation, heaters) and from the heating plant itself.

1.1.3 Insertion time counters

In Italy, the first indirect heat accounting systems in multi-apartment buildings supplied by a central heating recorded the opening times of the zone valves. The technological evolution has subsequently allowed the development of more complex and effective solutions which are not related solely to the opening times of the zone valve. Nowadays, such systems together with an effective balancing of the heating plant, allow the compensation of opening times on the basis of: i) the temperature difference between the heating thermal fluid and the environment (Insertion Time Counter – Temperature Compensated, ITC-TC); ii) the actual Degree-Days (Insertion Time Counter Compensated with Degree Days, ITC-DD). These systems are used in central heating plants controlled by zone valves or by on-off valves installed on each heating terminal unit. In particular, ITC-TCs are made up of: i) a calculation and data transmission device; ii) a thermostatic valve combined with an actuator (for each zone or heating element); iv) an on-off sensor on the valve for the control of opening times; v) two sensors for flow and return temperature (installed in the boiler room) of the heating thermal fluid; vi) an ambient temperature sensor (optional). On the other hand, ITC-DDs, instead of the temperature sensor for each controlled environment, rely on a unique external temperature sensor for measuring the actual degree-day. Such systems are regulated only at technical level by national standards UNI 11388 [49] and UNI 9019 [50] for ITC-TC and ITC-DD respectively.

For ITC-TC, according to the standard UNI 11388 [49], the $AU_{op,k}$ of each i-th single zone/radiator is given by equation (1.4)

$$\left(AU_{op,k}\right)_i = K\,\dot{Q}_i \int_{\theta_{op,k}} \left(\frac{T_{f,op} - T_{air,in}}{T_{f,c} - T_{air,in,c}}\right)^n d\theta \tag{1.4}$$

where: i) $\dot{Q}_i$ is the nominal heat output of the zone/radiator, ii) $T_{f,op}$ is the temperature of the heating thermal fluid averaged on flow and return pipes and measured during the actual opening time of the valve $\theta_{op,k}$, iii) $T_{air,in}$ is the indoor air temperature (measured or set equal to 20°C), iv) $T_{f,op,c}$ and $T_{air,in,c}$ the corresponding conventional temperatures; v) K is a corrective factor between $\left(AU_{op,k}\right)_i$ and the effective heat consumed, whose estimation is described in par. 9.3 of UNI 11388 [49].

The standard also takes into account the heat exchanged during the k-th transient of valve closure. This scheme runs out normally in a time equal to 5 times the time constant of the heating body and the heat exchanged during this time is calculated through equation (1.5)

$$\begin{aligned}\left(AU_{cl,k}\right)_i &= K\,\dot{Q}_i \left(\frac{T_{f,cl} - T_{air}}{T_{f,c} - T_{air,c}}\right)^n \int_{\theta_{cl,k}} e^{-n\frac{\theta}{\tau}}\, d\theta \\ &= K\,\dot{Q}_i \left(\frac{T_{f,cl} - T_{air,in}}{T_{f,c} - T_{air,in,c}}\right)^n \frac{\tau}{n}\left(1 - e^{-n\frac{\theta_{CV,k}}{\tau}}\right)\end{aligned} \tag{1.5}$$

where: i) $T_{f,cl}$ is the the temperature of the heating thermal fluid averaged on flow and return pipes and measured at the closure of the valve, ii) τ is the time constant of the heating body, iii) $\theta_{cl,k}$ is the time of closure of the valve. When the valve is opened before the end of transient, ITC-TC automatically switches on equation (5). Time constant τ of heating bodies normally ranges 0.15 (convection heater) to 10 hours (not insulated underfloor heating panel) [16]. It can be estimated on the basis of the ratio between heat capacity and thermal transmittance of the heating body at reference conditions. The total $(AU)_i$ is simply given by the sum of the $AU_{op,k}$ and $AU_{cl,k}$ measured during the opening and closure times of the valve, as per equation ((1.6).

$$(AU)_i = \left(AU_{op,k}\right)_i + \left(AU_{cl,k}\right)_i \tag{1.6}$$

Technical standard UNI 11388 [49] sets maximum permissible errors for temperature and time measurements equal to ±1°C and ±0.5% respectively.

For ITC-DD, according to the standard UNI 9019 [50], the $AU_{op,k}$ of each i-th single zone/radiator is given by equation (1.7)

$$(AU)_i = K\sum_{k=1}^{n} \dot{Q}_i \left(\frac{DD_i}{T_{air,in,c} - T_{air,out,c}}\right)\left[\theta_{op,k} + \tau\left(1 - e^{-\frac{\theta_{cl,k}}{\tau}}\right)\right] \tag{1.7}$$

where: i) DD_i is the actual degree-days measured during the opening time of the valve and equal to the difference between indoor $\left(T_{air,in}\right)$ and outdoor $\left(T_{air,out}\right)$ air temperature, ii) $T_{air,in}$ and $T_{air,out}$ are the conventional indoor and outdoor air temperatures, respectively, iii) $\theta_{op,k}$ and $\theta_{cl,k}$ are the opening and closure times of the valve in the k-th period, iv) τ is the time constant of the heating body. K is the corrective factor between $(AU)_i$ and the effective heat consumed, whose estimation is not described in [50].

1.2 Metrological issues for distributed IHASs

Figure 1.3 shows the typical operative scheme of a distributed heat accounting system with several HCAs in a building served by a central heating plant with vertical mains.

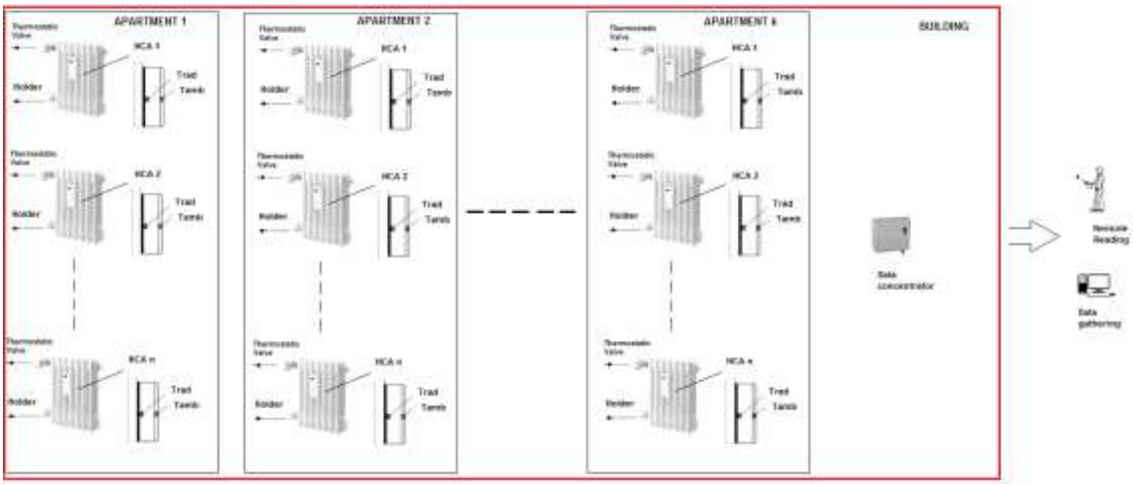


Figure 1.3 - HCA operative scheme

Several installation and operative effects may occur that substantially affect indirect heat accounting reliability and accuracy on field. Such effects are mainly due to:

- the differences between the rated heat outputs of radiators and the actual ones;
- the systematic errors on the measurement of the temperature difference (due to the installation of the sensors);
- the drift of the temperature sensors.

The estimation of the nominal heat output of radiators and convectors is encoded by EN 442-1 [65] and EN 442-2 [66]. Rated heat output estimation is based on the average temperature difference between the radiator and the room ambient fixed at 50 °C. Specifically, the standard defines the following nominal test conditions: i) average surface temperature of the radiator, T_{rad} = 70 °C (i.e. a flow water temperature of 75 °C and return one of 65 °C); ii) ambient air temperature, $T_{air,ref}$ = 20 °C. EN 442-2 also describes test methods and the related accuracy for the radiators whose heat transfer medium is water or steam at temperatures below 120 °C. The calculation of the thermal output of radiators $\dot{Q}$ according to EN 442, is based on equation (1.8):

$$\dot{Q} = K_m \Delta T^n = K_m \left[\frac{1}{2}(T_{in} + T_{out}) - T_{air,ref}\right]^n \tag{1.8}$$

where: i) K_m is the constant of thermal exchange of the radiator; ii) ΔT is the temperature difference between the radiator surface and the ambient; iii) T_{in} and T_{out}

are the flow and return temperature of the water, respectively, iv) $T_{air,ref}$ is the reference air temperature. Exponent *n* normally ranges 1.2 to 1.4 depending on the ratio between the radiated heat power and the one emitted by convection (typical for radiator type). For temperature differences other than nominal (e.g. ΔT = 60°C with flow temperature of 90 °C, return temperature of 70 °C and room temperature of 20 °C) the heat output of the radiator can be calculated through the equation (1.9).

$$\dot{Q} = \dot{Q}_{50} \left(\frac{\Delta T}{50}\right)^{n} \tag{1.9}$$

For radiators installed before EN 442 was in force, in absence of manufacturer's data, the dimensional method [11] may be adopted. As above-mentioned, only rarely the actual thermal output of installed radiators is equal to the nominal one, which is measured in the laboratory at rated temperature and at "standard" installation conditions. In fact, the thermal output emitted by the radiator is influenced not only by the operative temperatures, but also by installation, hydraulic connections and painting. Such issues can be adequately considered introducing specific corrective factors, as in the equation (1.10) [32, 33].

$$\dot{Q}_{nom,corr} = F\,\dot{Q}_{nom} = F_{in}\,F_{hyd}\,F_{pa}\,\dot{Q}_{nom} \tag{1.10}$$

where: i) $\dot{Q}_{nom}$ e $\dot{Q}_{nom,corr}$ are the nominal heat output and the corrected one at effective installation conditions; ii) F_{in}, is the corrective factor due to installation (ranging 0.75 to 1); iii) F_{hyd}, is the corrective factor due to hydraulic connections (ranging 0.95 to 1); iv) F_{pa}, is the corrective factor due to radiator surface painting (ranging 0.85 to 1). Therefore, in addition to the uncertainty due to the certification of the radiator heat output at rated conditions, estimated ranging 1% (i.e. radiators certified according to EN 442) to 10% (i.e. radiators manufactured in the '60s), actual installation conditions are to be carefully assessed [67, 68]. In this respect, heat output uncertainty range 2% to 20% at typical installation conditions has been estimated.

Radiators represent the most common heating body (installed since the end of '800) and in the last decades different radiators typologies have been proposed on the market, each characterized by different materials, sizes, shapes, etc. Arpino, et al. [67] carried out an experimental measurement campaign aimed to assess thermal output of different radiator typologies by varying installation and operative conditions. They demonstrated reductions of radiators thermal output up to 15% due to hydraulic connections and between 10% and 20% due to flow-rate variations. Finally, different installation conditions showed deviations between operating and standard thermal output between 5% and 15%. The main increasing and decreasing installation factors affecting radiators' thermal output are summarized in Table 1.6.

Table 1.6 - Installation influence factors affecting heat output of installed radiators

Increasing factors	*Decreasing factors*
– decrease of the gap between the radiator and the floor; – increase of the gap between the radiator and the wall; – presence of fins; – hydraulic connections (flow pipe on the top of the radiator); – reflector on the rear wall of the radiator.	– decrease of heat transfer fluid flows; – obstructions and reductions inside of the radiator; – air bubbles; – shielding panels close to the radiator (up to 70%); – installation (shelves, built-in boxes, vertical walls); – metallic paintings (up to 10%); – barometric pressure variation

Installation issues for HCAs are partly unavoidable due to intrinsic model errors and architectural constraints and partly avoidable due to installation procedures. The first should be greatly reduced through an appropriate characterization of the HCA through its rating factor K_C which takes into account the systematic deviation between the temperature difference measured by the HCA and the effective average logarithmic temperature difference between the heat transfer fluid and the room ambient. Systematic errors on the temperature difference due to the installation of the sensors are considerably different, depending on the sensor's type and methods used, and such error is more impactful on the uncertainty of heat allocation the smaller the temperature difference measured. An experimental study [68] assessed the installation of HCAs and showed the optimum (installation) point at a radiator height of about 60%, instead of 75% generally indicated by HCAs manufacturers measurement (although for a small number of HCAs). In any case, while optimizing the HCA position, given the complexity of the schemes and the thermo fluid-dynamic fields typical of each radiator, the value of K_C (and thus the model error on the estimation of the temperature difference) depends both on the installation (e.g. position of valves, type of radiator) and operative conditions of the radiator (e.g. actual flow rate, flow temperatures). On the other hand, rating factor K_C depends on the effectiveness of the coupling sensor-radiator, which can be very critical for radiators with tubular elements or for design radiators with non-conventional shapes. Taking into account the maximum allowable errors of EN 834, an uncertainty of K_C range from about 3% (corresponding to a temperature difference of 40 °C) to 12% (corresponding to a temperature difference of 5 °C) has been estimated conservatively.

By applying the ISO Guide for measurement uncertainties estimation [69], the expanded uncertainty of the single direct and indirect heat accounting devices has been estimated in Table 1.7.

Table 1.7 – Expanded uncertainties of single heat metering and accounting devices

	Type A, U_A			***Type B, U_B***			***Total***		
	min	***max***	***typical***	***min***	***max***	***typical***	***min***	***max***	***typical***
direct HM class 3 MID	0.8%	4.0%	1.8%	3.2%	7.3%	5.2%	3.3%	8.3%	5.5%
direct CHM, class 3 EN 1434	0.8%	4.0%	3.4%	5.2%	10.2%	8.1%	5.3%	11.0%	8.8%
electronic HCA EN 834	2.9%	20.6%	5.7%	4.0%	31.6%	5.8%	4.9%	37.7%	8.1%
ITC UNI 11388 and UNI 9019	2.7%	20.6%	5.7%	5.0%	30.8%	8.7%	5.7%	37.1%	10.3%

The uncertainty estimation of a single heat accounting device is not expected to be significant in sharing thermal energy consumptions among end users, since the allocation units for a single apartment and for each building are evaluated. In fact, compensation of systematic errors may occur and such compensation will be more relevant as radiators are similar for type, material, shape, dimensions, installation, operative conditions and so on. As a result, heat accounting uncertainty through indirect systems often results much lower for single apartments compared to the one estimated at each radiator.

Unfortunately, nor the technical regulations neither the scientific literature faced the issue related to the indirect heat accounting system reliability for heat cost sharing, taking into account the huge number of the devices installed in the building. In particular, applicable technical regulations normally require compliance with maximum errors of the individual device and this is absolutely inadequate to evaluate the uncertainty (i.e. the reliability) of the entire share of thermal energy consumption as shown in the scientific literature [32, 65, 70-72]. Looking at the scientific literature, it is also repeatedly stressed that the uncertainty of on-field measurements is significantly influenced by operating conditions and installation of heat accounting devices and systems [69, 72, 73]. To this regard, Brady, et al. [73] investigated the on-field effects of decorated covers on radiators finding heat output reductions up to 40% in the case of wooden cover.

To overcome such issue, a novel model for estimating the uncertainty affecting heat sharing in residential buildings through indirect heat accounting systems is proposed as case study in the following, starting from the uncertainty of single metering devices both in nominal and on-field operating conditions.

1.3 *Case study #1: An uncertainty model for IHASs reliability*

1.3.1 Methodology

The proposed model takes into account compensation effects when multiple metering devices are present and it could represent a useful tool to evaluate and improve the metrological performance of indirect heat accounting systems. In fact, advantages are expected in the following stages: i) design (e.g., through a more accurate knowledge of radiators' characteristics); ii) choosing (e.g. adopting the more reliable system such as electronic HCAs with double sensor or with external ambient sensor temperature), iii) installation (e.g. improving the thermal contact between radiator surface and device and the installation position of the device on the radiator itself), and iv) operation (e.g. avoiding direct solar radiation or presence of curtains/covers/obstructions on the radiators or introducing specific installation corrective factors).
For the application of the model an accurate preliminary inspection of the apartments in the building is needed, aimed at getting detailed information about the number and size of apartments, the number of radiators and the related thermal output, the installation and operating conditions of heating system. In Figure 1.4 a schematic flow chart of the developed model is reported.

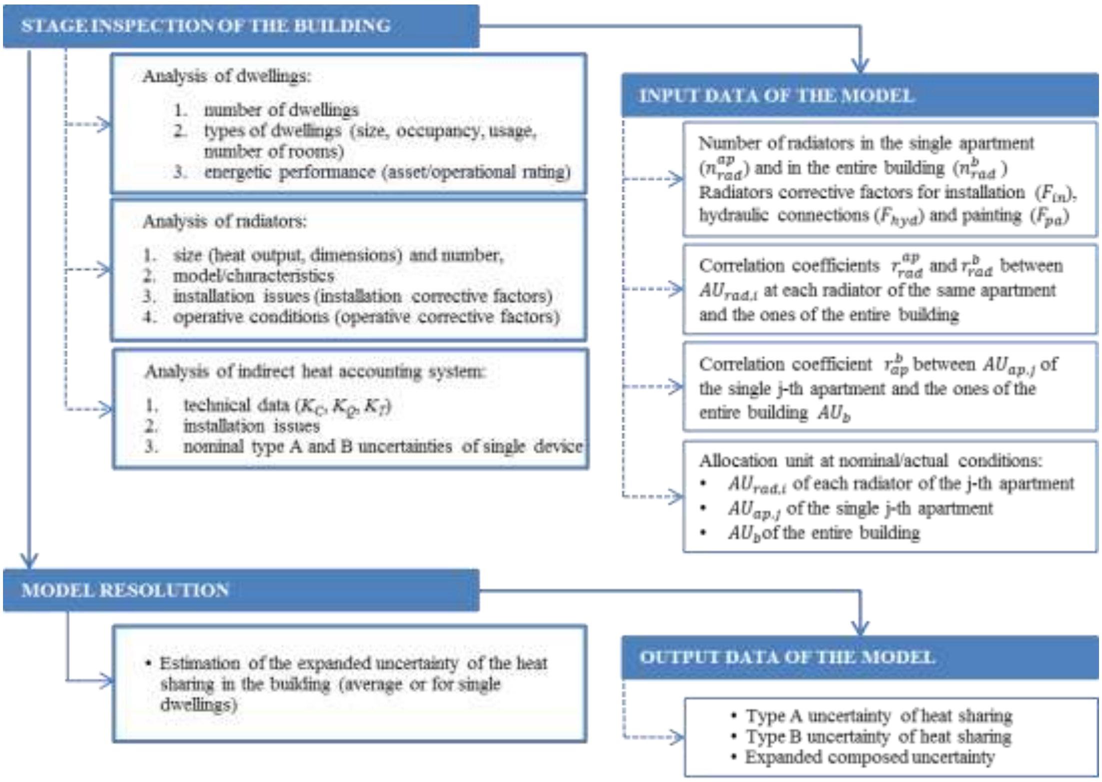


Figure 1.4 – Flow chart of the developed model

The model is based on the application of the uncertainty propagation law [69] to equation (1.2) for indirect heat accounting systems, under the following hypothesis: i) similar apartments, so that it is possible to assume the number of radiator per apartment constant and equal to the average value in the building; ii) similar thermal output of radiator at rated conditions and roughly equal thermal energy consumption among different apartments; iii) identical accounting devices in apartments; iv) installation effects assumed equal to the average value and correlation coefficients kept constant for each single device/apartment.

Under the aforementioned hypothesis, correlation effects on type B uncertainties can be punctually evaluated and the relative standard uncertainty of the heat share for a single apartment can be written as per equation (1.11).

$$\begin{aligned} u^2(S_j) = &\sum_{i=1}^{n_{rad}^{ap}} \frac{u_A^2(AU_{rad,i}) + u_B^2(AU_{rad,i})}{\left(n_{rad}^{ap}\right)^2} \\ &+ \sum_{i=1}^{n_{rad}^{b}} \frac{u_A^2(AU_{rad,i}) + u_B^2(AU_{rad,i})}{\left(n_{rad}^{b}\right)^2} \\ &+ 2r_{rad}^{ap} \sum_{i_1=1}^{n_{rad}^{ap}-1} \sum_{i_2=i_1+1}^{n_{rad}^{ap}} \frac{u_B(AU_{rad,i_1})}{n_{rad}^{ap}} \frac{u_B(AU_{rad,i_2})}{n_{rad}^{ap}} \\ &+ 2r_{rad}^{b} \sum_{j_1=1}^{n_{rad}^{b}-1} \sum_{j_2=j_1+1}^{n_{rad}^{b}} \frac{u_B(AU_{rad,j_1})}{n_{rad}^{b}} \frac{u_B(AU_{rad,j_2})}{n_{rad}^{b}} \\ &- 2r_{ap}^{b} \sum_{i=1}^{n_{rad}^{ap}} \sum_{J=1}^{n_{rad}^{b}} \frac{u_B(AU_{rad,i})}{n_{rad}^{ap}} \frac{u_B(AU_{rad,j})}{n_{rad}^{ap}} \end{aligned} \tag{1.11}$$

where:

- n_{rad}^{ap} and n_{rad}^{b} are the number of radiators in the single apartment and in the entire building, respectively;
- r_{rad}^{ap} and r_{rad}^{b} are the correlation coefficients between $AU_{rad,i}$ measured at each radiator of the same apartment and the ones of the entire building, respectively;
- r_{ap}^{b} is the correlation coefficient between $AU_{ap,j}$ of the single j-th apartment and the ones of the entire building AU_b;
- u_A and u_B are the relative type A and type B standard uncertainties of allocation units of single radiator, respectively.

Equation (1.11), under the hypothesis of constant u_A and u_B for each single device and of n_{rad}^{ap} and AU_{ap} roughtly equal for single apartments, simplifies as follows:

$$\begin{aligned} u^2(S_j) = {} & \frac{u_A^2(AU_{rad}) + u_B^2(AU_{rad})}{n_{rad}^{ap}} + \frac{u_A^2(AU_{rad}) + u_B^2(AU_{rad})}{n_{rad}^{b}} + \\ & r_{rad}^{ap} \frac{\left(n_{rad}^{ap} - 1\right)}{n_{rad}^{ap}} u_B^2(AU_{rad}) + r_{rad}^{b} \frac{\left(n_{rad}^{b} - 1\right)}{n_{rad}^{b}} u_B^2(AU_{rad}) + \\ & - r_{ap}^{b} \left(\frac{1}{n_{rad}^{ap}} + \frac{1}{n_{rad}^{b}} + \frac{n_{rad}^{ap} - 1}{n_{rad}^{ap}} r_{rad}^{ap} + \frac{n_{rad}^{b} - 1}{n_{rad}^{b}} r_{rad}^{b} \right) u_B^2(AU_{rad}) \end{aligned} \qquad (1.12)$$

The above hypothesis may certainly be assumed to estimate the typical uncertainty of heat share in large buildings with standardized apartments' types and sizes and with limited variability of thermal energy consumptions.

From equation (1.12) it is possible to point out that: i) the uncorrelated uncertainty contribution of $AU_{ap,j}$ (first term) decreases as the number of installed radiators in each apartment increases; ii) the uncorrelated uncertainty contribution of AU_b (second term) decreases as the number of installed radiators in the building increases and it can be considered negligible in large buildings; iii) the correlation effect between measurements at each radiator in the single apartment $AU_{rad,i}$ and in the building $AU_{rad,j}$ (third and fourth term respectively) increases the uncertainty contribution due to systematic effects of single devices; iv) the correlation effect between $AU_{ap,j}$ of the single apartment with the other ones in the building AU_b (fifth term) decreases the uncertainty contribution due to systematic uncertainties of single devices.

Typically, the above described effects lead to an overall uncertainty lower than that of single devices installed on single radiators. In order to roughly estimate the correlation coefficients, it is possible to evaluate the number of similar radiators (for model, material, shape, installation and operative conditions), r_{rad}^{ap}, with respect to the other radiators in the apartment and in the entire building, r_{rad}^{b}, as depicted in Table 1.8.

Table 1.8 - Weighting factors for the estimation of correlation factors

Radiator characteristics	*Model (40%)*	*Installation (30%)*	*Operative conditions (20%)*	*Size (10%)*
Fully different	▨	▨	▨	▨
Similar in size	▨	▨	▨	0.10
Similar in size and operative conditions	▨	▨	0.20	0.10
Similar in size, operative and installation conditions	▨	0.30	0.20	0.10
Fully similar	0.40	0.30	0.20	0.10

In order to calculate the correlation coefficient r_{rad}^{ap}, r_{rad}^{b} and r_{ap}^{b}, by considering the number of similar radiators in the apartment and in the building for each characteristic, equations (1.13) (1.14) and (1.15) can be employed.

$$r_{rad}^{ap} = 0.4\left(\frac{n_{rad,s}^{ap}}{n_{rad}^{ap}}\right)_{model} + 0.3\left(\frac{n_{rad,s}^{ap}}{n_{rad}^{ap}}\right)_{inst} + 0.2\left(\frac{n_{rad,s}^{ap}}{n_{rad}^{ap}}\right)_{op} + 0.1\left(\frac{n_{rad,s}^{ap}}{n_{rad}^{ap}}\right)_{size} \tag{1.13}$$

$$r_{rad}^{b} = 0.4\left(\frac{n_{rad,s}^{b}}{n_{rad}^{b}}\right)_{model} + 0.3\left(\frac{n_{rad,s}^{b}}{n_{rad}^{b}}\right)_{inst} + 0.2\left(\frac{n_{rad,s}^{b}}{n_{rad}^{b}}\right)_{op} + 0.1\left(\frac{n_{rad,s}^{b}}{n_{rad}^{b}}\right)_{size} \tag{1.14}$$

$$r_{ap}^{b} = r_b + \frac{(1 - r_b)}{n_{ap}} \tag{1.15}$$

where r_{ap}^{b} is the correlation coefficient between $AU_{ap,j}$ of the single j-th apartment and the remaining apartments of the entire building.

This coefficient has been introduced because the correlation between the single apartment and the entire building is a function of the number of apartments, by means of the self-correlation between $AU_{ap,j}$ and AU_b, as described in equation (11). Finally, as regards the estimation of correlation coefficient r_b, similarly to equations (1.13) and (1.14), it can be retrieved from the knowledge of the number of apartments with similar radiator model, installation, operative conditions and size in the building ($n_{ap,s}$), through equation (1.16).

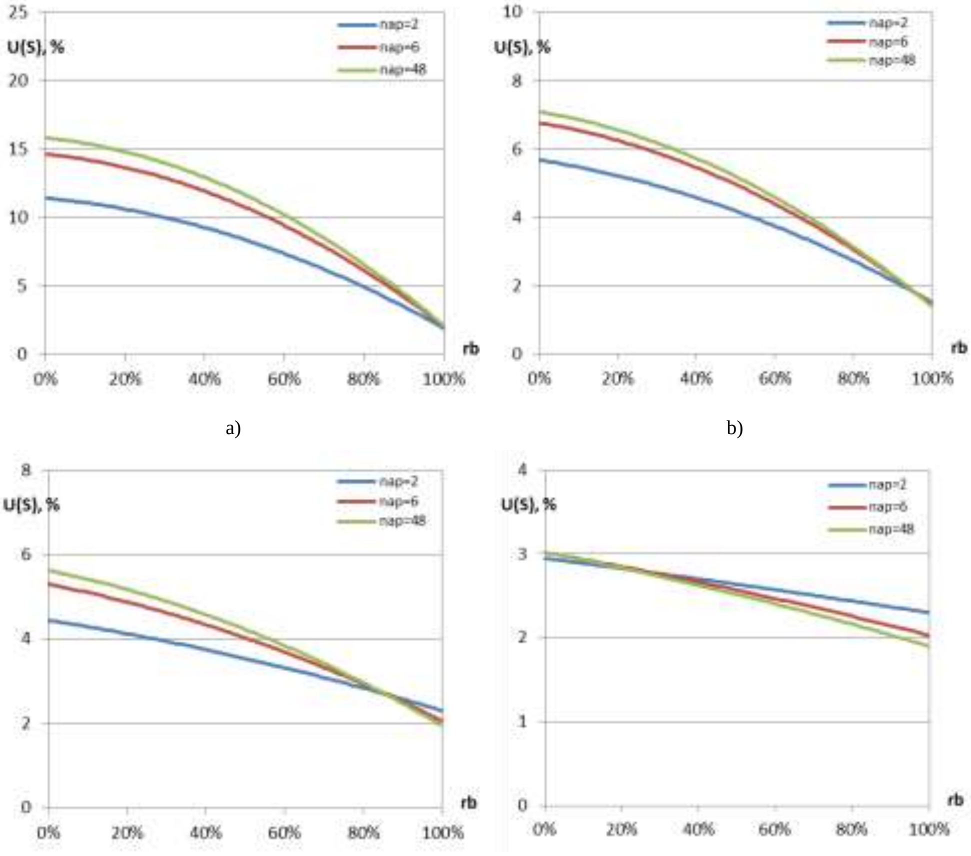
$$r_b = 0.4\left(\frac{n_{ap,s}}{n_{ap}}\right)_{model} + 0.3\left(\frac{n_{ap,s}}{n_{ap}}\right)_{inst} + 0.2\left(\frac{n_{ap,s}}{n_{ap}}\right)_{op} + 0.1\left(\frac{n_{ap,s}}{n_{ap}}\right)_{size} \tag{1.16}$$

Table 1.9 and Figure 1.5 show the expanded uncertainty of distributed indirect heat accounting systems with HCAs, as a function of the number of apartments in a building (e.g. small, medium, large building), of the installation conditions (e.g. critical with u_A=1.4% and u_B=6.0% or optimal with u_A = 2.3% and u_B = 2.0%) and of the correlation coefficients r_{rad}^{ap} and r_{rad}^{b}, assuming that apartment are of the same size (n_{rad}^{ap}=6).

Table 1.9 - Expanded uncertainty of IHASs as a function of r^{ap}_{rad}, r^{b}_{rad} and r_b

	r^{ap}_{rad}= r^{b}_{rad}=10% (different radiators in the apartment and in the building)						**r^{ap}_{rad}= r^{b}_{rad}=90% (similar radiators in the apartment and in the building)**					
Installation conditions	**Critical (u_A=1.4%, u_B=6.0%)**			**Optimal (u_A=2.3%, u_B=2.0)**			**Critical (u_A=1.4%, u_B=6.0%)**			**Optimal (u_A=2.3%, u_B=2.0)**		
n_{ap}	**2**	**6**	**48**	**2**	**6**	**48**	**2**	**6**	**48**	**2**	**6**	**48**
r_b=0%▲	5.7	6.8	7.2	3.0	3.0	3.0	11.6	14.8	16.1	4.5	5.3	5.7
r_b=5%	5.6	6.7	7.0	2.9	3.0	3.0	11.3	14.5	15.6	4.4	5.2	5.5
r_b=10%	5.4	6.5	6.8	2.9	2.9	2.9	11.0	14.1	15.2	4.3	5.1	5.4
r_b=50%	4.2	4.9	5.1	2.6	2.6	2.5	8.2	10.5	11.4	3.6	4.0	4.2
r_b=90%	2.2	2.5	2.5	2.4	2.2	2.0	3.9	4.8	5.2	2.6	2.6	2.5
r_b=95%	1.9	1.9	2.0	2.3	2.1	2.0	2.9	3.5	3.8	2.5	2.3	2.2
r_b=100%▼	1.4	1.2	1.2	2.3	2.0	1.9	1.4	1.2	1.2	2.3	2.0	1.9

▲ fully different apartments in the building; ▼ fully similar apartments in the building



a) b)

c) d)

Figure 1.5 - Heat share uncertainties trend as a function of the correlation coefficient r_b and of the number of apartments, assuming n^{ap}_{rad} = 6: a) Similar radiators and installations (r^{b}_{rad}= 0.90), critical condition; b) Different radiators and installations (r^{b}_{rad}= 0.10), critical condition; c) Similar radiators and installations (r^{b}_{rad}= 0.90), optimal condition; d) Different radiators and installations (r^{b}_{rad}= 0.10), optimal condition.

From the analysis of data in Table 1.9 and Figure 1.5 it can be pointed out that expanded uncertainty of indirect heat accounting systems is greatly reduced as the correlation between single indirect devices (due to the correlation between the radiators on which they are installed) in the apartment and when radiators in the building are almost similar. Moreover, such compensation is more relevant in small buildings, where the share of single apartments is higher. On the other hand, when radiators are different (due for example to a partial renovation of the apartment and/or of the building), compensation effects are negligible.

1.3.2 Validation of the uncertainty model and case studies

The application of the proposed uncertainty model for heat accounting at different heating plant types and installation conditions, demonstrates a wide variability of indirect heat accounting systems on-field. To this aim, the author applied the developed model in some typical applications: i) a two-family house, ii) a small building; iii) a large multi-apartment building.

Building #1 – Two-family house (critical condition)

In Figure 1.6 the heating plant installation scheme of the investigated two-family house is reported, whereas the related single indirect device uncertainty estimation for HCAs and ITCs is reported in Table 1.10 and Table 1.11.

Figure 1.6 – Heating plant scheme of the two-family house

Table 1.10 – Building #1: Uncertainty budget for a single device (HCA)

Uncertainty Contribution	***type***	u_i	c_i	$u_i c_i$	***Note***
Measured Temperature difference, $\Delta T_{s,i}$	A	0.5 °C	1/ΔT	1.0%	ΔT=50K
Heat output temperature correction $(\Delta T_{s,i}/50)^n$	A	1.0%	1	1.0%	-
Accounting interval, t	A	0.3%	1	0.3%	analogy with UNI 11388 par 7.4
Model (K_C)	B	1.5%	1	1.5%	ref. EN 834 par. 8.2
Model (K_Q), Nominal power of the radiator	B	0.5%	1	0.5%	ref. EN 442 par. 5.2.3.2
Model (F_{in}), Installation of the radiator	B	5.0%	1	5.0%	ranging 0.75 to 1
Model (F_{hyd}), Radiator hydraulic connections	B	2.6%	1	2.6%	ranging 0.95 to 1
Model (F_{pa}), Painting of the radiator's surface	B	1.5%	1	1.5%	ranging 0.85 to 1
u_A, type A standard uncertainty				1.4%	-
u_B, type B standard uncertainty				6.0%	-
u_C, combined standard uncertainty of the HCA				6.2%	-
k, coverage factor				2	i.e. approx 95%
U, expanded uncertainty of the single HCA				12.4%	-

Table 1.11 – Building #1: Uncertainty budget for a single device (ITC)

Uncertainty contribution	***type***	u_i	c_i	$u_i c_i$	***Note***
Average temperature of the radiator, *T*	A	0.75 °C	1.3/ΔT	3.9%	fe=1.3, ΔT=50K
Average room temperature, T_{air}	A	0.5°C	1-3/ΔT	2.6%	fe=1.3, ΔT=50K
Accounting interval	A	0.25%	1	0.3%	UNI 11388 par 7.4
Model ($\dot{Q}$), Nominal power of the radiator	B	0.5%	1	0.5%	ref. EN 442 par. 5.2.3.2
Model (F_{in}), Installation of the radiator	B	5.0%	1	5.0%	ranging 0.75 to 1
Model (F_{hyd}), Radiator hydraulic connections	B	2.5%	1	2.5%	ranging 0.95 to 1
Model (F_{pa}), Painting of the radiator's surface	B	1.5%	1	1.5%	ranging 0.85 to 1
Model, time constant of the radiator	B	2.5%	1	2.5%	UNI 11388 and UNI 9019
u_A, type A standard uncertainty				4.7%	-
u_B, type B standard uncertainty				6.3%	-
u_C, combined standard uncertainty of the single ITC				7.9%	-
k, coverage factor				2	i.e. approx 95%
U, expanded uncertainty of the single ITC				15.8%	-

The two apartments are located on different floors and their heating systems operate in a different way, since apartment #1 is continuously heated and regulated, whereas apartment #2 is heated only for few hours per day (i.e. heat share lower than 14% on average). In such condition, author estimated r_{ap}^{b} =0.50 and r_b=0.00. Radiators are almost similar inside the single apartment (r_{rad}^{ap}= 0.95) but different between the two apartments (r_{rad}^{b}=0.37), in terms of model, installation, operative conditions and size. The thermal output of radiators has been certified by manufacturers according to EN 442. Under the above-mentioned hypothesis, the developed model estimated $U\left(S_j\right)$=10.1% for HCAs and $U\left(S_j\right)$=11.7% for ITCs, respectively.

Building # 2 Small Building with 6 apartments

Figure 1.7 shows the heating plant installation scheme of each floor of a small building composed by six residential apartments, (two for each floor) in which an average of nine radiators per apartment were installed. The related single device uncertainty estimation for HCAs and for ITCs is reported in Table 1.12 and .

Figure 1.7– Building #2: Heating plant installation scheme

Table 1.12 – Building # 2: Uncertainty budget for a single device (HCA)

Uncertainty Contribution	***type***	u_i	c_i	$u_i c_i$	***Note***
Measured Temperature difference, ΔT	A	0.5 °C	1/ΔT	2.0%	T=50K
Heat output temperature correction $(\Delta T/50)^n$	A	1.0%	1	1.0%	
Accounting interval, *t*	A	0.3%	1	0.3%	analogy with UNI 11388 par 7.4
Model (K_C)	B	1.5%	1	1.5%	ref. EN 834 par. 8.2
Model (K_Q), Nominal power of the radiator	B	5.0%	1	5.0%	ref. EN 442 par. 5.2.3.2
Model (F_{in}), Installation of the radiator	B	5.0%	1	5.0%	ranging 0.75 to 1
Model (F_{hyd}), Radiator hydraulic connections	B	2.5%	1	2.5%	ranging 0.95 to 1
Model (F_{pa}), Painting of the radiator's surface	B	1.5%	1	1.5%	ranging 0.85 to 1
u_A, type A standard uncertainty				2.3%	
u_B, type B standard uncertainty				7.8%	
u_C, combined standard uncertainty of the single HCA				8.1%	
k, coverage factor				2	i.e. approx 95% coverage
U, expanded uncertainty of the single HCA				16.2%	

Table 1.13 – Building # 2: Uncertainty budget for a single device (ITC)

Uncertainty Contribution	***type***	u_i	c_i	$u_i c_i$	***Note***
Average temperature of the radiator, T	A	0.75 °C	1.3/ΔT	3.9%	fe=1.3, ΔT=50K
Average room temperature, T_{air}	A	0.50° C	1.3/ΔT	2.6%	fe=1.3, ΔT=50K
Accounting interval	A	0.25%	1	0.3%	UNI 11388 par 7.4
Model ($\dot{Q}$), Nominal power of the radiator	B	5.0%	1	5.0%	ref. EN 442 par. 5.2.3.2
Model (F_{in}), Installation of the radiator	B	5.0%	1	5.0%	ranging 0.75 to 1
Model (F_{hyd}), Radiator hydraulic connections	B	2.5%	1	2.5%	ranging 0.95 to 1
Model (F_{pa}), Painting of the radiator's surface	B	1.5%	1	1.5%	ranging 0.85 to 1
Model, time constant of the radiator	B	2.5%	1	2.5%	UNI 11388 and UNI 9019
u_A, type A standard uncertainty				4.7%	
u_B, type B standard uncertainty				8.0%	
u_C, combined standard uncertainty of the ITC				9.3%	
k, coverage factor				2	i.e. approx 95%
U, expanded uncertainty of the single ITC				18.6%	

Installed radiators are almost similar in type (3 columns) and material (cast iron), whereas major heating plant renovations have been carried out in 3 apartments, involving substantial modification of spaces and of the size of some radiators, especially in bathrooms where design radiators have been installed. Since the investigated building was built in 1950's before the EN 442 was in force, thermal output of old radiators has been estimated using the dimensional method, whose uncertainty has been estimated to be approximately 10%. Hydraulic connection and painting of radiators are almost similar, while the typical installation adopted is with shelf. One of the investigated apartments showed very low consumptions (i.e. lower than 10%). In such context, on the basis of Table 1.8, the following correlation coefficients have been estimated: i) r_{rad}^{ap}=0.89; ii) r_{rad}^{b}=0.89; iii) r_{ap}0.88; iv) r_b=0.86. Under the above-mentioned hypothesis, the developed model estimated $U(S_j)$=7.3% for HCAs and $U(S_j)$=8.1% for ITCs, respectively.

Building #3 Multiple Building with 48 apartments (optimal condition)

Finally, the developed model was applied to a new multi-apartments complex of two buildings. Each building is composed by six floors and one staircase (Figure 1.8), served by the same centralized heating plant. Each floor includes four apartments of the same typology.

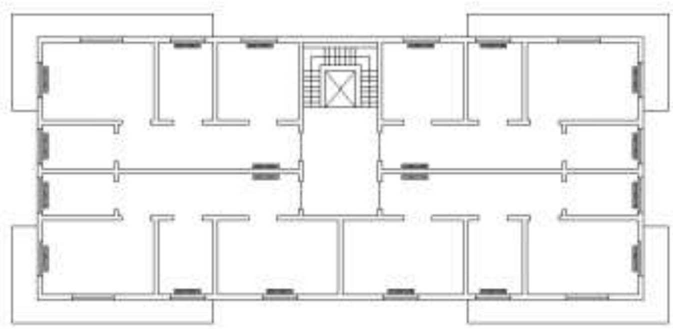


Figure 1.8 - Case study #3: Heating plant installation scheme

The number of radiators installed per apartment is equal to five. Radiators in the investigated apartments are very similar in terms of model, material, painting, installation conditions and hydraulic connections, whereas different operative conditions have been considered due to different uses. In such condition, the following correlation coefficients have been estimated: i) r_{rad}^{ap}=0.85; ii) r_{rad}^{b}=0.85; iii) r_{ap}0.88; iv) r_b=0.88. The related single device uncertainty estimation (for HCAs) is reported in Table 1.14 and Table 1.15. Under the above hypothesis, the developed model estimated $U(S_j)$=2.7% for HCA and 4.9% for ITCs, respectively.

Table 1.14 – Building #3: Uncertainty budget for single device (HCA)

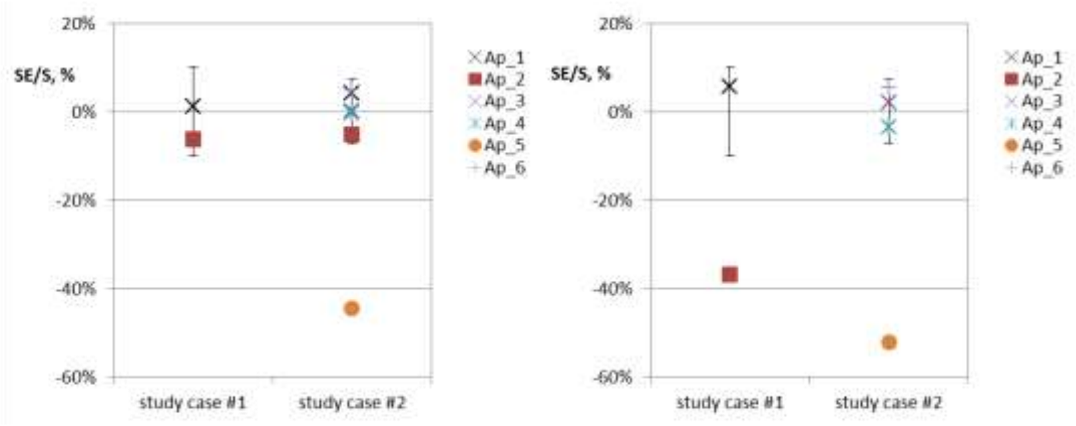
Uncertainty Contribution	***type***	u_i	c_i	$u_i c_i$	***Note***
Measured Temperature difference, ΔT	A	0.5 °C	$1/\Delta T$	2.0%	T=50K
Heat output temperature correction $(\Delta T/50)^n$	A	1.0%	1	1.0%	
Accounting interval, *t*	A	0.3%	1	0.3%	analogy UNI 11388 par 7.4
Model (K_C)	B	1.5%	1	1.5%	ref. EN 834 par. 8.2
Model (K_Q), Nominal power of the radiator	B	0.5%	1	0.5%	ref. EN 442 par. 5.2.3.2
Model (F_{in}), Installation of the radiator	B	1.0%	1	1.0%	ranging 0.75 to 1
Model (F_{hyd}), Radiator hydraulic connections	B	0.5%	1	0.5%	ranging 0.95 to 1
Model (F_{pa}), Painting of the radiator’s surface	B	0.5%	1	0.5%	ranging 0.85 to 1
u_A, type A standard uncertainty				2.3%	
u_B, type B standard uncertainty				2.0%	
u_C, combined standard uncertainty of the single HCA				3.0%	
k, coverage factor				2	i.e. approx 95% coverage
U, expanded uncertainty of the single HCA				6.0%	

Table 1.15 – Building #3: Uncertainty budget for single device (ITC)

Uncertainty Contribution	***type***	u_i	c_i	$u_i c_i$	***Note***
Average temperature of the radiator, *T*	A	0.75 °C	$1.3/\Delta T$	3.9%	fe=1.3, ΔT=50K
Average room temperature, T_{air}	A	0.25	$1.3/\Delta T$	2.6%	fe=1.3, ΔT=50K
Accounting interval	A	0.25%	1	0.3%	UNI 11388 par 7.4
Model ($\dot{Q}$), Nominal power of the radiator	B	0.5%	1	0.5%	ref. EN 442 par. 5.2.3.2
Model (F_{in}), Installation of the radiator	B	1.0%	1	1.0%	ranging 0.75 to 1
Model (F_{hyd}), Radiator hydraulic connections	B	0.5%	1	0.5%	ranging 0.95 to 1
Model (F_{pa}), Painting of the radiator’s surface	B	0.5%	1	0.5%	ranging 0.85 to 1
Model, time constant of the radiator	B	2.5%	1	2.5%	UNI 11388 and UNI 9019
u_A, type A standard uncertainty				4.7%	
u_B, type B standard uncertainty				2.8%	
u_C, combined standard uncertainty of the single ITC				5.5%	
k, coverage factor				2	i.e. approx 95% coverage
U, expanded uncertainty of the single ITC				11.0%	

Validation of the proposed model against experimental data

In the two-family house of *building #1*, Ficco, et al. [33] carried out an experimental comparison between DHMs (reference method) and indirect heat accounting systems (i.e. HCA and ITC). Indirect methods showed deviations ranging from 3.0% (for HCAs) to 8.2% (for ITCs). A data correction was also proposed, that allowed a deviation reduction within the range from 1.0% (for HCAs) to 5.0% (for ITC). In *building #2* an experimental campaign with direct and indirect heat accounting systems was carried out. The experimental data collected in a heating period of two months presented deviations ranging from 0.1% to 4.4% for HCAs and from 1.3% to 4.9% for ITCs, with respect to the direct HMs assumed as reference method [74]. The resulting $U(S_j)$ from the proposed model are available in Figure 1.9 together with the relative experimental share errors SE/E, available for study cases #1 and #2, both for HCA and ITC indirect systems.



a) b)

Figure 1.9 – Experimental relative share error and expanded uncertainty of the investigated buildings: a) HCAs, b) ITCs.

It can be pointed out that the data obtained by the developed model are tendentially consistent with the available experimental ones, except for Apartment #5 of *building #2* (both for HCAs and ITCs) and for Apartment_#2 of *building #1* (only for ITCs). In this aspect, it has to be considered that Apartment #5 of *building* #2 has been heated only for few days in the investigated period. Moreover, *building #1* is really critical, since it is a two-family house in which one of the apartments is heated only for few hours per day.

CHAPTER 2. ENERGY SAVING FROM INDIVIDUAL METERING

In this Chapter, a review of the state-of-the-art about energy saving deriving from installation of individual metering devices is provided in paragraph #2.1, while the analysis of available feedback strategies to increase energy efficiency in residential buildings is given in paragraph #0. Then, two case studies are discussed: *case study #2,* in which the author analyses the results of an experimental campaign aimed to assess the energy saving of individual metering in about 3000 Italian dwellings and *case study #3,* in which a novel feedback strategy designed for IoT applications is developed and tested on a sample of end-users to increase their energy awareness.

2.1 Energy saving from heat metering and accounting

Energy saving from individual heat metering and accounting systems represents a combined effect of a greater user's awareness and of the induced changes in behaviours of the end users. However, the amount of the related energy saving is expected to be highly dependent on: i) the type and the set-up of the thermoregulation system, ii) the actual operating conditions of the heating system, iii) the balancing of the heating system; iv) the type of feedback and the users' awareness [75]. While different types of individual metering and sub-metering devices are available on the market (Direct Heat Meters, DHMs, Heat Cost Allocators, HCAs, Insertion Time Counters, ITCs), Celenza, et al. [32] highlighted that the installation of DHMs is almost technically unfeasible and not cost effective in old buildings due to the heating plant configuration (e.g. vertical mains in old buildings), and to technical (e.g. when flow and return pipes are not easily accessible) and architectural (e.g. in historical buildings) constraints. Conversely, HCAs are almost always technically feasible and cost effective, thus resulting the most spread individual heat accounting system in EU Member States (MSs). As per EED, in fact, "*Use of individual meters or heat cost allocators for measuring individual consumption of heating in multi- apartment buildings supplied by district heating or common central heating is beneficial when final customers have a means to control their own individual consumption. Therefore, their use makes sense only in buildings where radiators are equipped with thermostatic radiator valves*".

For this reason, the installation of HCAs is often performed together with Thermostatic Radiator Valves (TRVs) and in some countries (such as Croatia, Italy, England, France [76-80]) this is reversely mandatory when installing indirect heat accounting systems. In other countries, if TRVs are not installed, the allocation rules are modified accordingly (as for example, in Poland if TRVs are not installed, a share of 90% fixed by law of the heat expenses is still divided on a proportional basis e.g. floor area, heating need, installed heat output and so on). Most part of the benefit of individual metering in residential buildings is, thus, attributable to the use of TRVs (about 60% according to [81]). Other studies demonstrated TRVs accounting alone for about 10-20% energy consumption reduction depending on installation conditions and balancing of the heating plant [82, 83]. For this reason, the vast majority of the studies related to individual heat metering refers to the combined installation of HCAs and TRVs. To the author's best knowledge, no experimental study about the benefits induced by the sole installation of DHMs was performed and no long-term experimental campaign for an empirical assessment of the benefit expected from the installation of individual metering systems was performed in Italy.

As a matter of fact, non-physical factors [26] affecting energy consumptions and savings are the ones whose global impact is less predictable, but they may significantly affect the energy consumption of a building [84]. In this respect, in fact, it has been demonstrated that the energy consumption of two building with nearly identical thermo-physical characteristics may differ up to 90/100% depending on occupants' behaviour and external climatic conditions [11, 85]. For this reason, extensive experimental campaigns in different climatic conditions on a high number of dwellings and final user typologies would be useful to predict the possible energy saving from individual metering and accounting systems. On the contrary, few research papers are available of this kind. The majority of the studies, in fact, is performed on a sample of few case-study buildings investigated during one or maximum two heating seasons and are mainly referred to continental climatic conditions [24, 25]. Felsmann, et al. [24] reviewed the results of 24 research studies conducted between 1956 and 2015 in Germany and in other Central European countries regarding the expected benefits from the installation of individual heat metering systems. The authors quantified the potential energy saving in a range of approximately 8-40%, with an average estimated energy saving of about 20% after IHASs and TRVs installation. However, only few of the analysed researches were experimentally conducted, and methodologies used to conduct the studies are not completely clear. On the other hand, the more recent literature seems to be more sceptical about the potential benefit of individual heat metering, leading to much lower estimates (about 1-4%), depending on the type of user's feedback adopted [86, 87]. Long-term experimentations are almost lacking in scientific literature. Cholewa and Siuta-Olcha [71] investigated the energy consumption of 40 apartments in a multifamily building located in Poland for over 17 heating seasons. They found an average benefit of about 26.6% at the second year from installation of HCAs and TRVs. Only one study experimentally evaluated the potential for energy saving of heat accounting and temperature control devices in temperate climates: Teres-Zubiaga, et al. [88] conducted in Spain, found a 15–20% reduction of normalized energy consumption during the first two years after HCAs and TRVs installation. Figure 2.1 gives an overview of the existing literature about the effects of individual metering in EU, highlighting the variability of the results together with the average or minimum-maximum benefit obtained. In the figure, it is evident the high variability of the results coming from the scientific literature, whose minimum/maximum range varies between 0 and 40%. When it comes to estimating an average benefit, the addition of the more recent studies [71, 86-88] to the ones already reviewed by Felsmann, et al. [24] and Oschatz [25] leads to an estimated mean energy saving ranging from about 16% to about 22%.

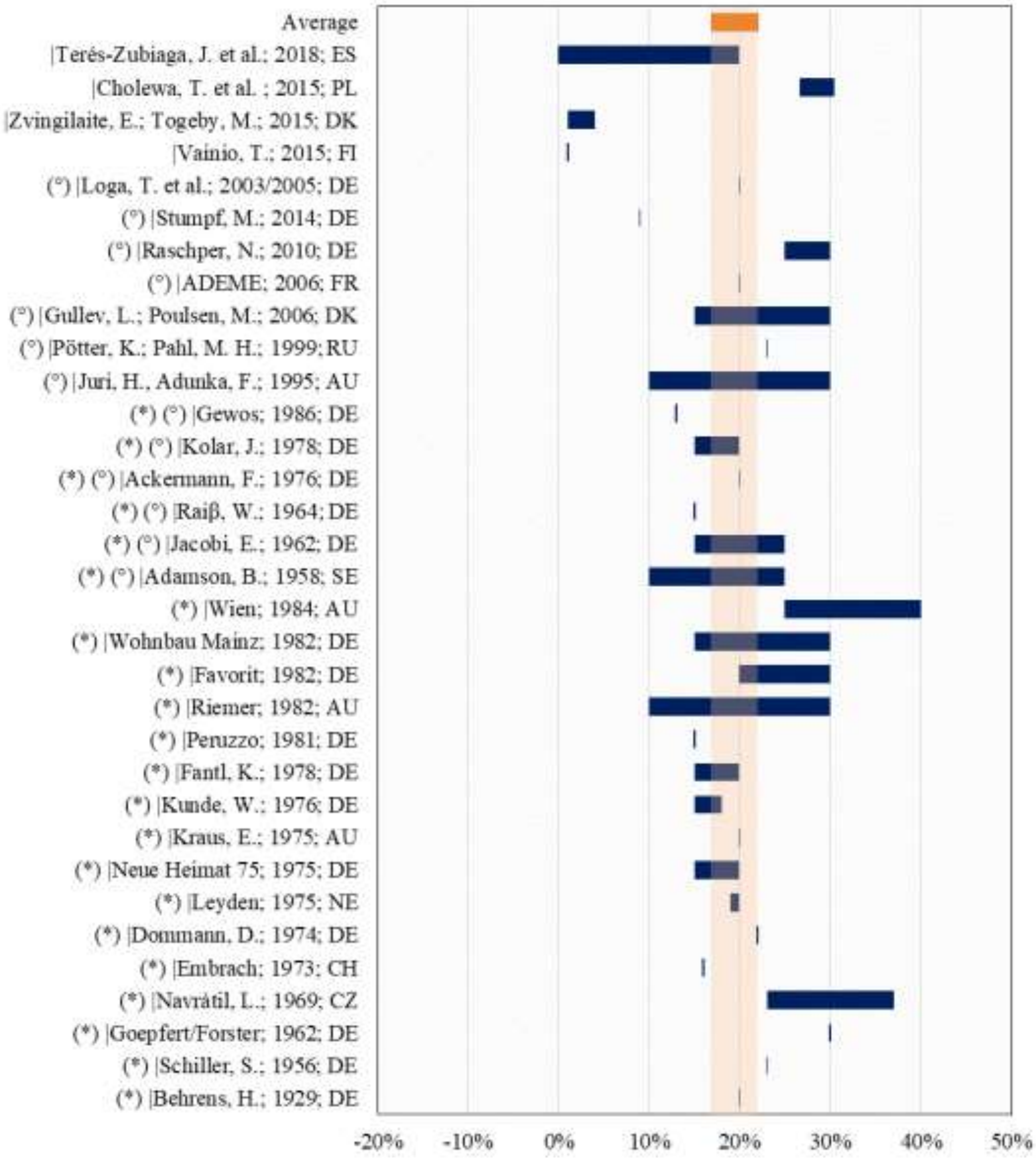


Figure 2.1 – Existing scientific literature regarding individual metering systems' energy saving, (°) papers reviewed in [25]; (*) papers reviewed in [24]

2.2 End-user feedback to increase energy-awareness in smart-homes

In recent years, ICT technologies allowed the possibility to set-up integrated systems to support decisions at the building, district and city stages. The potential of IoT and artificial intelligence technologies are opening up new scenarios in the communication of energy consumption data and are enabling new ways of interacting with end-users. However, these technologies are still not widespread due to the complexity of the problem, the reduced interoperability among the different systems and devices and high costs [89].

Generally speaking, the effectiveness of user's feedback actions addressed at the energy savings is a still debated topic in the scientific literature. Based upon the results of 38 different studies addressed to the effectiveness of interventions aimed at encouraging families to reduce their energy consumption [90] two macro-categories are identified, depending on the kind of information provided to families: i) antecedent strategies; ii) consequent strategies. Antecedent strategies include media campaigns, workshops, educational conferences and energy audits for targeted and personalized information [91, 92]. It is proven that antecedent strategies raise the user awareness, but do not necessarily lead to behavioural changes or sure energy savings. This category includes any type of user feedback e.g. real-time feedback, information presented on in-home displays, mobile apps or online services [93-95]. Feedback actions can be "direct", when learned directly from the instrument display (counter, sub counter etc.), or "indirect", when information on data consumption are preliminary processed before reaching the user. The inconsistencies in behaviours related to the use of energy in families are due to: i) temporal coherence of decisions, ii) difficulty in processing consumption data and in assuming simple decisions; iii) effects of presentation [96].

Available literature identifies three key problems related to the feedback: the poor evidence of effectiveness, the need for involving users and the potential occurrence of unwanted consequences. The main finding is that actual in-home displays could not be effective in orientating users' behaviours. Thus, it is necessary to develop and test novel feedback devices accounting the degree of user involvement [97]. In a recent experimental campaign [98], many interviewed users reported difficulties in the interpretation of the units (kW, kWh) and a poor feedback (e.g. lack in the corresponding economic value). This research also highlighted the usefulness of presenting disaggregated data for each device (sub-metering), at least for the most energy-consuming devices (stove, oven, dishwasher, washing machine, dryer, etc.) and of benchmarks with historical consumption.

In this scenario, low-income families, as those living in public housing, are a particular category of users to be approached in a specific way. A recent experimental study in 7 EU countries highlighted several problems both in the implementation of smart-metering solutions and in the use of personalized feedback for low-income families in the Mediterranean region [99]. Experimental results proved that the use of smart-meters associated with in-home displays is not so effective. On the other hand, the monitoring of individual electrical devices, the distribution of consumption inside the dwelling and the suggestions for energy retrofits are appreciated. The joint implementation of these measures and the personalization of user feedback resulted in electricity consumption savings varying in the range from 22 and 27% [100]. Unfortunately, the adoption of energy saving strategies in social housing could lead to a potential worsening of comfort conditions [101]. For example, the reduction of the average winter indoor air temperature could result in condensation phenomena and mould. In the same research paper, the authors also point out that information to users is more effective when people lives in relatively energy-efficient dwellings but is less useful for users living in public housing. In this framework, it is clear that achieving the goal of energy saving through a more frequent and detailed information to the user and, thus, the use of individual metering devices and smart technologies for user feedback, need a strategic design.

2.3 *Case study #2: Experimental campaign to assess energy saving from IHASs*

In the following, an experimental campaign on a sample of buildings located in Italy aimed at estimating the potential energy saving achievable through the use of Heat Accounting and Thermoregulation (HAT) systems in Mediterranean climate is described and discussed.

2.3.1 Methodology

A sample of 3047 dwellings in 50 buildings has been investigated in the experimental campaign presented as *case study #2*. The sample of buildings in which the experimental campaign has been carried out has been chosen with respect to size, construction age and climatic conditions representative of the Italian building stock potentially subject to the obligation to install HAT systems (i.e. HCAs and TRVs).

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 Table 2.1 and Figure 2.2). 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 2.1 - Italian dwellings classified by heating plant (source: ISTAT).

Heating Plant	***Absolute***	***Percentage***
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 %

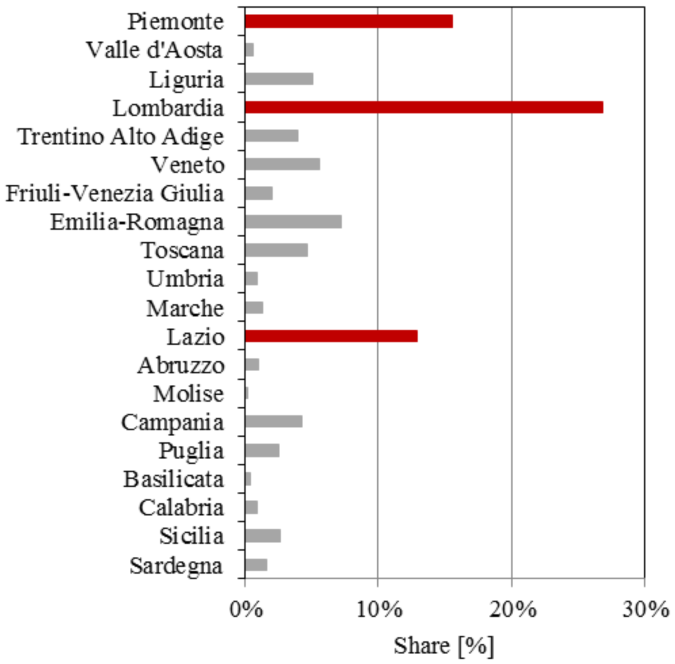


Figure 2.2 - Regional share of dwellings supplied by CHS (source: ISTAT).

In Table 2.2 the main characteristics of the investigated buildings are reported.

Table 2.2 - Characteristics of the investigated buildings sample.

Build. Num.	***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

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 [52]. 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.

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 [102]. 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.

2.3.2 Results and discussions

In Table 2.3 and Table 2.4, 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 account for the annual climatic variability, energy consumption data have been divided by the actual HDD, available for each heating season. The last columns in the tables 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.

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).

Table 2.3 – Energy consumption variation due the sole installation of HAT systems, 1-year post installation

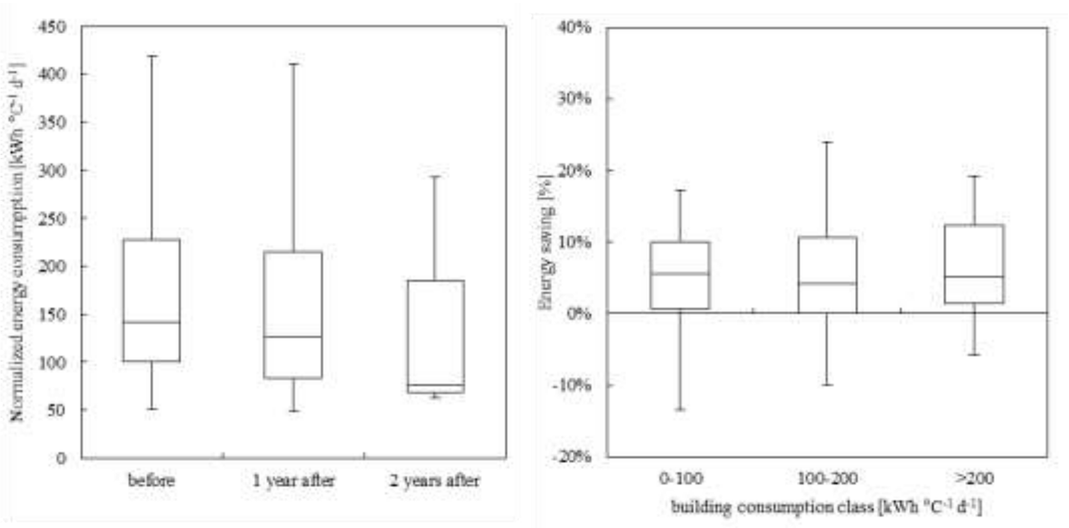
Region	*Number of dwellings*	*Previous normalized consumption [kWh°C^{-1}d^{-1}]*	*Actual HDD [°C d]*	*Normalized consumption after 1 year [kWh°C^{-1}d^{-1}]*	*Actual HDD [°C d]*	*Var. after 1 year [%]*	*Mean Variation After 1 year* [%]*
Piemonte	105	280.81	2501	293.01	2297	4.4%	-5.5%
	48	144.96	2119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

Table 2.4 – Energy consumption variation due the sole installation of HAT systems, 2-years post installation (data available only for Piemonte region)

Region	*Number of dwellings*	*Previous normalized consumption [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 2 years* [%]*	*Mean Variation After 2 years* [%]*
Piemonte	105	280.81	2501	292.67	2281	-0,1%	-2.3%
	48	144.96	2119	n/a	n/a	n/a	
	36	100.52	2119	n/a	n/a	n/a	
	21	62.88	2119	n/a	n/a	n/a	
	30	86.42	2297	77.01	2424	-2.1%	
	40	55.86	2501	63.29	2424	-2.5%	
	24	82.26	2297	68.26	2424	-3.1%	
	68	221.45	2424	185.11	2297	-4.3%	

* additional variation referred to the difference between energy consumption 1 and 2 years after the installation

The results are shown in Figure 2.3. In particular, Figure 2.3a clearly shows an energy consumption reduction over time, while Figure 2.3b 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.

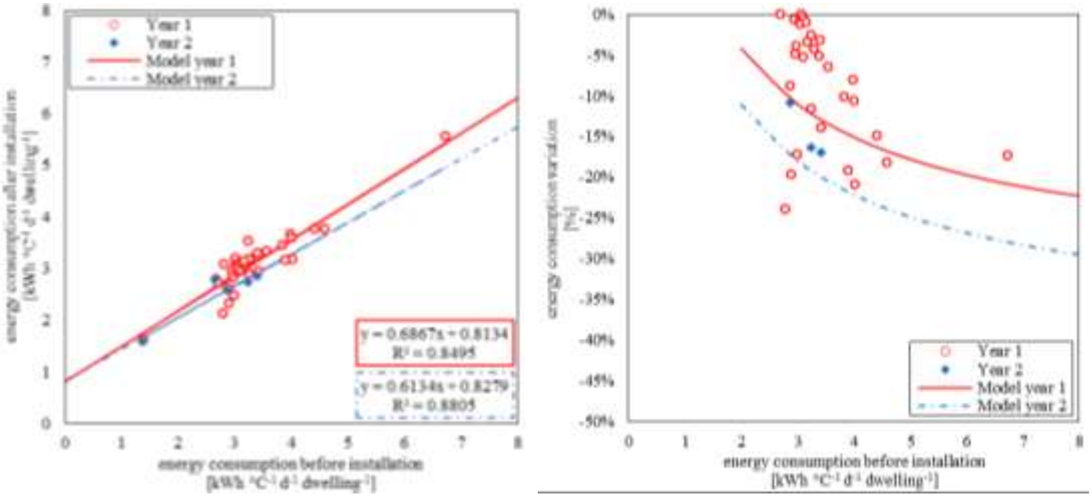


a) b)

Figure 2.3 - Energy consumptions of the investigated buildings before and after the installation of the sole HAT systems: 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 [71, 103], 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, a mean Italian expected energy saving of about 11% has been estimated 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 2.3 and Table 2.4). 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 2.4a 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 2.4 – Regression analysis of investigated buildings in terms of energy consumption before and after the installation of the sole HAT systems: 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 2.5 and

Table **2.6** show 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.

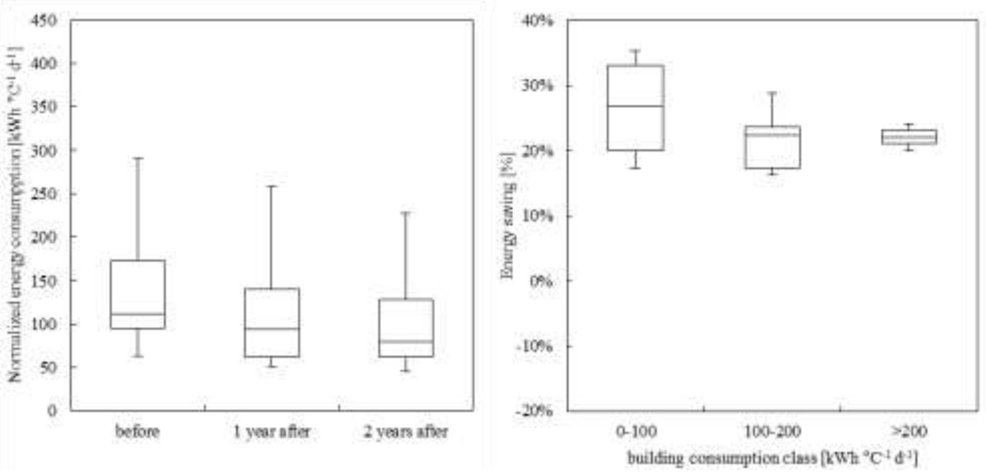
Table 2.5 – Energy consumption in buildings where HAT systems were installed together with boiler replacement, variation after 1 year

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]*	*Variation after 1 year [%]*
30	111.80	2297	93.44	2356	-16.4%
52	211.74	2501	160.59	2297	-24.2%
13	68.12	2297	55.56	2356	-18.4%
13	62.40	2424	51.52	2101	-17.4%
21	99.70	2297	74.84	2356	-24.9%
140	403.22	2297	322.36	2356	-20.1%
20	125.26	2297	95.69	2356	-23.6%
50	172.83	2356	122.84	2424	-28.9%
40	170.76	2297	141.10	2356	-17.4%
18	94.40	2424	61.09	2501	-35.3%
40	180.38	2297	139.91	2356	-22.4%
18	95.76	2297	62.58	2356	-34.7%
21	86.27	2297	61.49	2356	-28.7%
				Mean variation	**-24.3%**

Table 2.6 – Energy consumption in buildings where HAT systems were installed together with boiler replacement, variation after 2 years

Number of dwellings	*Previous consumption [kWh°C^{-1}d^{-1}]*	*HDD [°C d]*	*Normalized consumption after 2 years [kWh°C^{-1}d^{-1}]*	*HDD [°C d]*	*Variation after 2 years* [%]*
30	111.80	2297	81.15	2424	-11.0%
52	211.74	2501	178.70	2281	8.6%
13	68.12	2297	45.13	2424	-15.3%
13	62.40	2424	57.18	2119	9.1%
21	99.70	2297	66.86	2424	-8.0%
140	403.22	2297	288.02	2424	-8.5%
20	125.26	2297	79.15	2424	-13.2%
50	172.83	2356	100.18	2424	-13.1%
40	170.76	2297	127.65	2424	-7.9%
18	94.40	2424	61.47	2297	0.4%
40	180.38	2297	130.36	2424	-5.3%
18	95.76	2297	54.05	2424	-8.9%
21	86.27	2297	62.61	2424	1.3%
				Mean variation	**-5.6%**

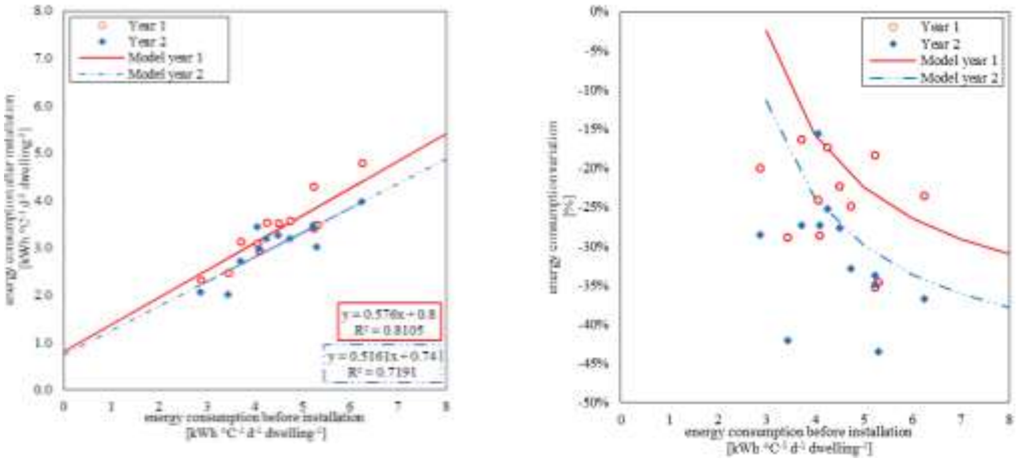
Figure 2.5a highlights that energy consumption data two years after the retrofit are more reliable than the ones before. Referring to the box plot in Figure 2.5b, it is confirmed that the data dispersion is lower for higher energy consuming buildings.



a) b)

Figure 2.5 - Energy consumption of investigated buildings before and after HAT systems installation with boiler replacement: a) Normalized energy consumptions, b) Energy saving.

Figure 2.6a and Figure 2.6b 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 2.6 – 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.

2.4 *Case study #3: Design and application of a novel feedback strategy about energy consumption*

In case study #3 the problem of using data coming metering and sub-metering devices in a way effective for increasing end-user awareness has been investigated. To this aim, a strategic design of the feedback strategy is required together with the development of consumption and benchmark indicators applicable to effectively communicate with end-users in residential buildings. Thermal and electrical energy monitoring systems have been installed in a set of buildings and a new feedback strategy has been designed and discussed basing on the data collected during the experimental campaign. In the following, the activities carried out during the experimental campaign are described, as listed below:

1) installation of metering and submetering systems;
2) administration of surveys aimed at assessing energy use and user satisfaction with respect to the systems installed;
3) design a feedback strategy for presenting energy consumption data to final users;
4) gathering and analysis of energy consumption data for a reference period;
5) validation of the feedback through meetings with the involved end users.

Finally, the suitability of the communication of energy consumption in terms of temporal, spatial and typological aggregation is evaluated.

2.4.1 Methodology

Experimental campaign for user information

For the experimentation of feedback strategies on the consumption of thermal energy for heating, an experimental campaign is currently underway in two social housing buildings belonging to the Italian Territorial Agency for Social Housing (ATER), served by a centralized natural gas system and in a detached house all located in the district of Frosinone (Central Italy). The social housing buildings, built in the '70s, have very low energy performance and would require relevant energy retrofit intervention, both to improve the insulation of the building envelope and to increase the efficiency of the heating plant. End-users are mostly low income and elderly, mainly living in single- or two- family units (see Figure 2.7), with limited ability to interact with automation systems.

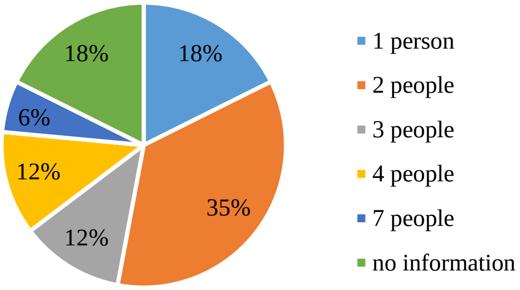


Figure 2.7 – End users living in ATER buildings, sample composition

In each building a thermal energy meter for the direct measurement of the thermal energy produced by the boiler (metering level) and two different indirect heat metering systems have been installed (submetering level): i) insertion time counters compensated with fluid temperature and thermostatic electronic valves controlled by programmable thermostat (*building #1*); ii) two-sensors electronic heat cost allocators, mechanical thermostatic valves and programmable thermostat (*building #2*).

With regards to electrical energy consumption, an experimental campaign is currently underway in a detached house (*building #3*) located in the district of Frosinone (Central Italy) built in the first decade of 2000s and inhabited by a family of four people. The house is a two-floor detached building, divided into two apartments, of which only one actually inhabited by the family, but both served by the main electrical energy meter with a maximum power installed of 4.5 kW. A current clamp meter has been installed on the main power line of the sole inhabited apartment (metering level), whereas, on the submetering level, two different devices were installed: i) current clamp meter on the main light's powerline; ii) smart plugs on the more energy consuming electrical appliances. In Figure 2.8 the investigated buildings are represented.

a) *b)*

Figure 2.8 – a) Heating plant case study building, b) Electrical Plant case study building with location of devices (red dots: smart-plugs, green dots: current clump meters).

Specific survey questionnaires have been administrated to the inhabitants of the buildings, to assess user's attitude to adopt energy saving strategies and to interact with monitoring and control systems.

The survey, the user could assign a vote to 7 statements, attributing a grade from 1 (not at all in agreement) to 10 (fully agreed) based on their level of concordance with the statement. For each question there was also the option "I don't know". Each user was also given the opportunity to express general considerations in a special note field. The questions given to families are listed below:

A. Overall, I feel satisfied with the installation of thermostatic valves and sub-metering devices in my apartment;
B. I do often adjust the temperature using the chrono thermostat;
C. During periods of absence from the apartment, I set the thermostat temperature to minimum to save energy;
D. I think the installation of thermostatic valves and sub-metering devices in my apartment is helping me save on my gas bill;
E. The temperature in my apartment is often too high and I am forced to open the windows;
F. The temperature in my apartment is often too low;
G. I use alternative systems to heat my apartment (for example electric heaters, gas stoves etc.).

Basing on the results of the survey, on the characteristics of the monitored energy systems and user behaviour, and referring to the analysis of the existing scientific literature, two new direct and indirect feedback strategies have been designed.

Design criteria for the information strategy

The evaluation of effective strategies to make end users aware of their energy consumption in "smart homes" is influenced by numerous aspects such as [104]: i) the quality of the perceived interaction (e.g. speed, brevity/easiness); ii) information efficiency (e.g. accuracy and completeness); iii) usability (e.g. ease of use, intuitiveness, user satisfaction); iv) the aesthetics; v) the usefulness (e.g. offered functions); vi) acceptability (e.g. low cost, number of potential users). The feedback of monitored data should reach end users over time and the most adequate way to allow the full understanding of the phenomenon, before it is irreversible or no longer visible, linking it to specific retrofit actions [105]. To identify the most effective feedback, the most relevant features have been analysed, as shown in Table 2.7.

Table 2.7 – Feedback characteristics

Characteristic	***Description***
Frequency	Continuous feedback (1/4 hour, hourly, daily) Deferred feedback (weekly, bi-monthly, half-yearly, yearly)
Content	consumption, kWh (absolute), % (relative) costs, € (absolute), % (relative) environmental impacts, CO2 (absolute), % (relative)
Data aggregation	by location (e.g. room, living / sleeping area, apartment) for use (e.g. heating, cooling, ventilation, ...) for plant / appliance (e.g. refrigerator, washing machine) by energy carrier (e.g. electricity, heating, gas)
Presentation	Analog data (e.g. dashboard) Numerical data (e.g. display) Traffic lights, colours and ideograms Historical trend (e.g. trend, histograms) Diagrams (e.g. pie, bar, ring, …)
Benchmark	Historical consumption Consumption of other users (e.g. building average) Expected theoretical consumption (e.g. based on climatic data, characteristics of energy systems, type of user)
Further information	Diagnosis (e.g. faults and malfunctioning) Retrofit (e.g. indications and tips for rational use and efficiency)

In the technical practice, the simplicity and/or cost of information system is sometimes favoured, in others the completeness and/or the effectiveness of the information. The different types of feedback can have very different costs and customer satisfaction levels, but a crucial issue should be the awareness and immediacy of information to lead users at performing higher energy savings. A unanimous judgment of end users is the greater appreciation of a detailed, frequent and actual feedback. Therefore, differentiation between direct and indirect feedback has been performed: i) by using a frequent, synthetic and immediate information in the case of direct feedback, ii) by providing detailed and disaggregated information for each consumption area (i.e. bedrooms, living, bathroom, kitchen), for each energy carrier (i.e. thermal energy, electrical and natural gas) and for device/system in the case of indirect feedback.

Other aspects positively evaluated in the technical literature are the diagnosis of faults and malfunctions, the comparison with historical consumption, simplicity and effectiveness in understanding user information. Therefore, for indirect feedback and for each consumption area the followings are presented: i) historical consumption benchmark, ii) benchmark with average consumption of other users (building average), iii) theoretical expected consumption obtained on the basis of the specific characteristics of the user (e.g. characteristics of energy systems, type of user) and of climate data. To enhance the communication effectiveness, pie charts (for allocation), bar charts (for comparisons with previous periods and with other users) have been prepared.

2.4.2 Results and discussions

The response rate to the questionnaires provided was 100%. Figure 2.9 shows the list of the questions together with the overall analysis of the answers obtained. With regard to the installation of monitoring and control systems, the users, although they declare themselves satisfied (100%) and quite familiar with such systems (64%), were wary of the potential effectiveness in terms of savings (71%). As for indoor temperature perception, most users feel that they do not perceive too high (71%) or too low (78%) indoor temperatures.

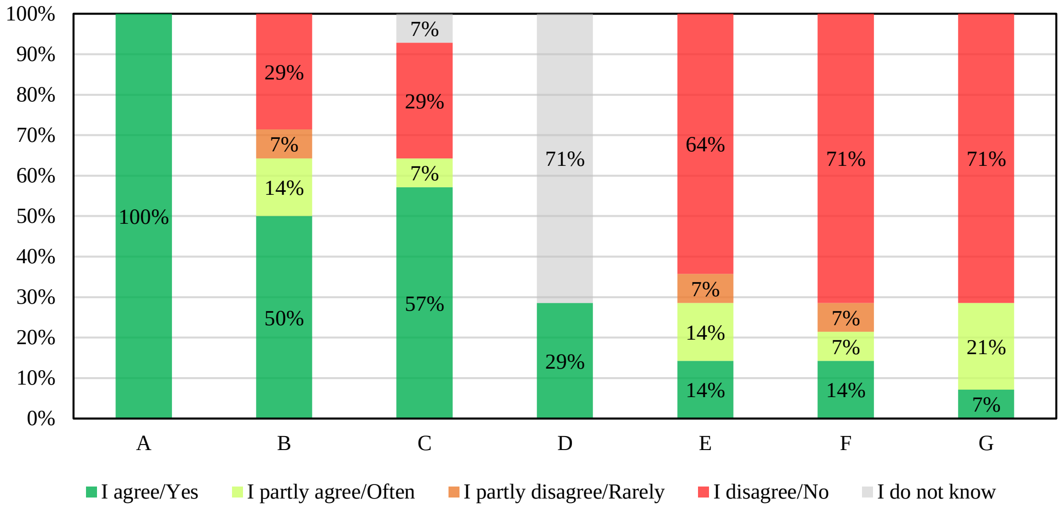


Figure 2.9 – Results of surveys analysis

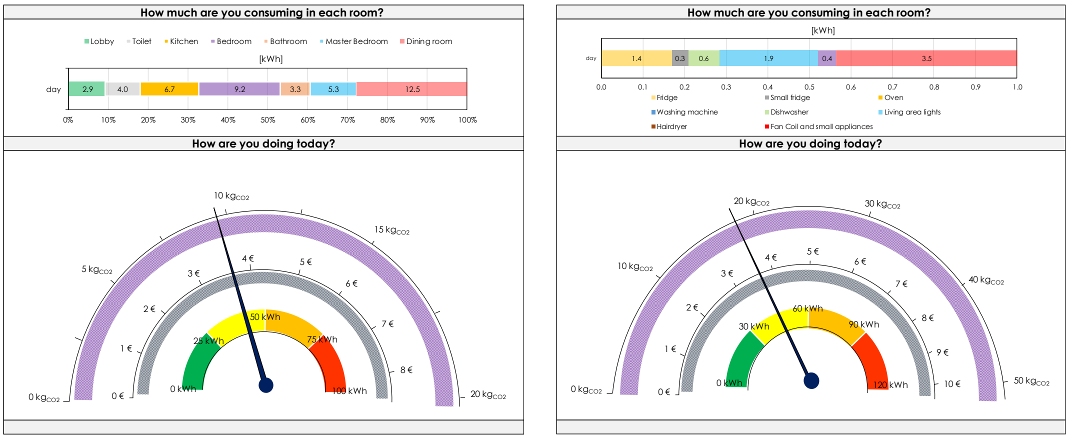
The characteristics of the direct and indirect feedback designed within this work are summarized in Table 2.8.

Table 2.8 - Characteristics of the direct and indirect feedback

Characteristic	***Direct feedback***	***Indirect feedback***
Frequency	Daily	Monthly
Content	Consumed energy (kWh, %) Cost (€) CO_2 emitted (kg)	Consumed energy (kWh, %) Cost (€) CO_2 emitted (kg) Consumption indexes
Aggregation	By room / appliance By apartment	By room /appliance By apartment By building
Presentation	Energy dashboard	Bar charts Ring diagrams Histograms
Benchmark	-	Historical consumption With other users (building) Expected consumption (tailored rating) Share of consumption for appliance
Further information	-	Useful tips for savings and efficiency

The dashboard built for direct feedback (daily frequency) is made up of two sections. The first one for sub-metering shows the energy consumption (kWh and %) of each room, using a bar graph. In the second section (metering), through a multi-scale display, the user can simultaneously access the energy data consumed by the apartment (in kWh and in €) and the corresponding CO_2 emitted (in kg). In this way, the user receives in real time information about his own energy consumption, the related costs and environmental impact, as well as on their distribution among different environments, leading, at the same time, to adopt energetically, economically and environmentally efficient behaviours. A daily frequency of this feedback was chosen due to metering and submetering devices characteristics and to the related costs of data transmission (e.g. battery consumption).

Unfortunately, due to operative constraints, it has not been possible to provide the users with the direct feedback during the experimental campaign, it was therefore not possible to test its effectiveness in terms of reduction in energy consumption during the present experimental campaign. However, impressions and suggestions were collected through direct interaction with the participants, who showed appreciation for the direct feedback design. Figure 2.10 shows the dashboard developed to display the daily energy consumption of a typical user both for heating and for electrical energy consumption.



a) *b)*

Figure 2.10– Direct feedback: a) Heating Plant, b) Electrical Plant

As above reported, through indirect feedback (monthly frequency), users receive information on their consumption also in terms of performance indices, personalized suggestions, comparisons with historic consumption, etc.

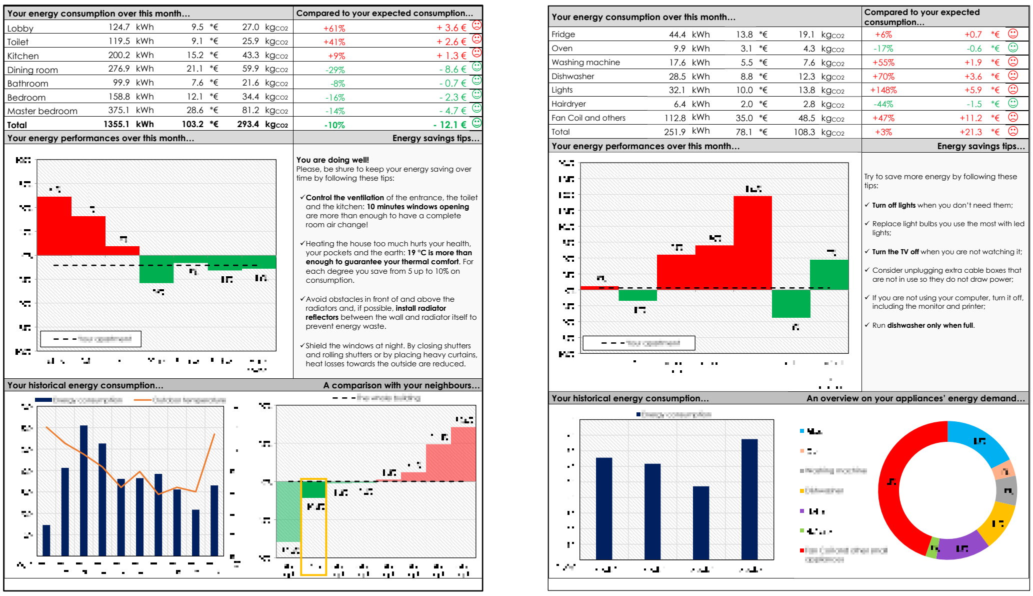
As regard to the heating plant (i.e. for the feedback about thermal energy consumption), the performance benchmarks have been calculated as the ratio between the energy consumption measured at actual conditions of use (i.e. operational rating) and the estimated primary energy consumption adjusted to the actual conditions of use and climate (i.e. tailored rating or expected consumption), for each room, apartment and the whole building, as per equation (2.1).

$$\frac{Measured\ consumption - Expected\ consumption}{Expected\ consumption} \cdot 100 \qquad (2.1)$$

The information has been communicated by using emoticons, colours and “user friendly” tips, so as to capture the user's attention. In order to test the effectiveness of the designed feedback, indirect feedback sheets were periodically provided to all users involved in the experimentation, by organizing periodical meetings in which also impressions and suggestions of the users have been collected.

In particular, from the meetings carried out it emerged: i) a high participation (about 95%) of the users, ii) almost no user was able to understand the non-rated units provided by heat cost allocators, iii) users who had a poorly aware and responsible behaviour generally did not perceive the over consumption since before the experimentation heat accounting was carried out exclusively by floor area and costs due to building inefficiencies were divided into tenants accordingly, iv) not all users were familiar with the control systems perceiving the intervention of thermostatic valves as a malfunction of the same, v) the cultural level of the users strongly affects the understanding of energy consumption data and, consequently, the adoption of retrofit actions, vi) the information received during initial installation was not sufficient to understand operation and use. Figure 2.11a shows the form designed for indirect feedback of heating divided into six sections:

1) aggregate and disaggregated monthly energy consumption for each room (energy consumed and related costs and environmental impact);
2) local consumption indexes in percentage and economic units (i.e. benchmark for each room);
3) total consumption indexes (i.e. benchmark for the entire apartment);
4) personalized advice and tips aimed at saving energy;
5) historical consumption and related average outdoor temperature;
6) benchmark with the other apartments in the building.



Your energy consumption over this month…							Compared to your expected consumption…		
Lobby	124.7	kWh	9.5	*€	27.0	kg$_{CO2}$	+61%	+ 3.6 €	☹
Toilet	119.5	kWh	9.1	*€	25.9	kg$_{CO2}$	+41%	+ 2.6 €	☹
Kitchen	200.2	kWh	15.2	*€	43.3	kg$_{CO2}$	+9%	+ 1.3 €	☹
Dining room	276.9	kWh	21.1	*€	59.9	kg$_{CO2}$	-29%	- 8.6 €	☺
Bathroom	99.9	kWh	7.6	*€	21.6	kg$_{CO2}$	-8%	- 0.7 €	☺
Bedroom	158.8	kWh	12.1	*€	34.4	kg$_{CO2}$	-16%	- 2.3 €	☺
Master bedroom	375.1	kWh	28.6	*€	81.2	kg$_{CO2}$	-14%	- 4.7 €	☺
Total	**1355.1**	**kWh**	**103.2**	***€**	**293.4**	**kg$_{CO2}$**	**-10%**	**- 12.1 €**	☺

Your energy performances over this month…

Energy savings tips…

You are doing well!
Please, be shure to keep your energy saving over time by following these tips:

- ✓ **Control the ventilation** of the entrance, the toilet and the kitchen: **10 minutes windows opening** are more than enough to have a complete room air change!
- ✓ Heating the house too much hurts your health, your pockets and the earth: **19 °C is more than enough to guarantee your thermal comfort**. For each degree you save from 5 up to 10% on consumption.
- ✓ Avoid obstacles in front of and above the radiators and, if possible, **install radiator reflectors** between the wall and radiator itself to prevent energy waste.
- ✓ Shield the windows at night. By closing shutters and rolling shutters or by placing heavy curtains, heat losses towards the outside are reduced.

Your historical energy consumption…

A comparison with your neighbours…

(a) *Heating plant*

Your energy consumption over this month…							Compared to your expected consumption…			
Fridge	44.4	kWh	13.8	*€	19.1	kg$_{CO2}$	+6%	+0.7	*€	☺
Oven	9.9	kWh	3.1	*€	4.3	kg$_{CO2}$	-17%	-0.6	*€	☺
Washing machine	17.6	kWh	5.5	*€	7.6	kg$_{CO2}$	+55%	+1.9	*€	☹
Dishwasher	28.5	kWh	8.8	*€	12.3	kg$_{CO2}$	+70%	+3.6	*€	☹
Lights	32.1	kWh	10.0	*€	13.8	kg$_{CO2}$	+148%	+5.9	*€	☹
Hairdryer	6.4	kWh	2.0	*€	2.8	kg$_{CO2}$	-44%	-1.5	*€	☺
Fan Coil and others	112.8	kWh	35.0	*€	48.5	kg$_{CO2}$	+47%	+11.2	*€	☹
Total	251.9	kWh	78.1	*€	108.3	kg$_{CO2}$	+3%	+21.3	*€	☹

Your energy performances over this month…

Energy savings tips…

Try to save more energy by following these tips:

- ✓ **Turn off lights** when you don't need them;
- ✓ Replace light bulbs you use the most with led lights;
- ✓ **Turn the TV off** when you are not watching it;
- ✓ Consider unplugging extra cable boxes that are not in use so they do not draw power;
- ✓ If you are not using your computer, turn it off, including the monitor and printer;
- ✓ Run **dishwasher only when full.**

Your historical energy consumption…

An overview on your appliances' energy demand…

(b) *Electrical plant*

Figure 2.11 - Indirect feedback

Table 2.9 and Table 2.10 show the absolute variation between the energy consumption indicators (see equation (2.1)) calculated before and after the realization of the information campaign in buildings #1 and #2 (which is the variation between the two heating seasons 2017/2018 and 2018/2019). It is clear how the periodical meetings, combined with the delivery of indirect feedback sheets, has led to significant changes in the management of single rooms/radiators by almost users involved in the experimental campaign.

Table 2.9 – Variation of energy consumption indexes in building #1 calculated before and after the information campaign

	dwel. 1	dwel. 2	dwel. 3	dwel. 4	dwel. 5	dwel. 6	dwel. 7	dwel. 8
Lobby	-52%	-75%	4%	-42%	48%	-18%	-15%	-36%
Toilet	-72%	-100%	1%	-94%	-287%	-7%	-11%	-60%
Kitchen	-51%	-51%	8%	-35%	-94%	-20%	8%	-79%
Dining room	-14%	-33%	47%	24%	11%	94%	-15%	-21%
Bathroom	11%	-2%	2%	97%	275%	-11%	14%	-28%
Bedroom	-10%	-52%	-21%	9%	-41%	-60%	-33%	-88%
Master bedroom	-50%	-23%	-6%	-36%	10%	-6%	25%	21%

Table 2.10 – Variation of energy consumption indexes in building #2 calculated before and after the information campaign

	dwel. 1	dwel. 2	dwel. 3	dwel. 4	dwel. 5	dwel. 6	dwel. 7	dwel. 8	dwel. 9
Lobby	-20%	-93%	-44%	0%	-286%	-288%	0%	-44%	-74%
Toilet	-38%	-37%	-22%	-22%	-25%	-28%	-19%	-23%	-13%
Kitchen	0%	-43%	-78%	-55%	-77%	-81%	-78%	-100%	-78%
Dining room	64%	99%	216%	194%	83%	215%	138%	62%	126%
Small bedroom	-33%	-25%	-78%	-59%	-82%	-111%	-2%	-52%	-59%
Master bedroom	52%	39%	34%	13%	0%	58%	23%	53%	47%
Bedroom	-61%	-98%	-95%	-94%	-133%	-126%	-103%	-88%	-99%

With regards to the feedback for electrical energy consumption (Figure 2.11b), no comparison with other user was possible, as the family lives in a detached house, thus the dedicated section in the feedback sheet was replaced with a ring chart showing the share of energy usage for each monitored appliance in a reference period (month).

The benchmarking indicators have been built as the ratio between the measured and the expected energy consumption of the analysed appliance. It is well known that energy consumption of an appliance strongly depends on its use, which in turn, rely on the number of family components, characteristics of the house (e.g. floor area, outdoor spaces etc.) and on end-user (e.g. income, work, age, presence of children and/or elderly people). Thus, in order to determine the expected energy consumption of each electrical appliance, a preliminary analysis of statistical data about electrical energy use from the Italian National Institute of Statistics (ISTAT) and the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) has been performed. Specific data were obtained about: i) number of cycles per week for given electrical appliances (dishwasher and washing machine); ii) lights turn-on period; iii) expected expenditure for different numbers of family components.

Figure 2.12 shows the data about dishwasher and washing machine usage per week and the trend of the expenditure for electrical energy of different family sizes. These data were used to determine energy usage coefficients as function of the family components and used as base to determine, for each electrical appliance, the time of use (in hours) in the reference period. Table 2.11 shows the usage coefficients determined by normalizing all data in respect to the ISTAT reference family (2.4 components). The reference energy consumption was then calculated by multiplying the above-mentioned calculated hours and the electrical energy consumption per cycle of the appliance declared by the manufacturer.

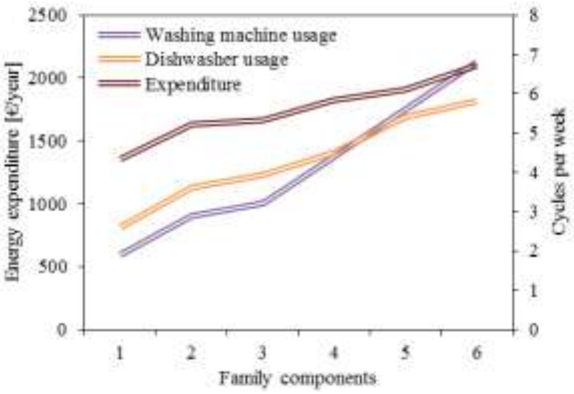


Figure 2.12 – Data usage for main appliances (ISTAT, 2014)

The benchmarks have been calculated as the ratio between the measured energy consumption of the appliance and the estimated energy consumption adjusted to the conditions of use of the appliance.

Table 2.12 shows the calculated energy consumption of appliances.

Table 2.11 – Calculated usage coefficients (ISTAT, 2014)

Family components	***Expenditure coeff.***	***Washing machine coeff,***	***Dishwasher coeff.***
1	*0.80*	*0.37*	*0.61*
2	*0.96*	*0.87*	*0.92*
2.4	*1.00*	*1.00*	*1.00*
3	*1.05*	*1.16*	*1.10*
4	*1.12*	*1.37*	*1.23*
5	*1.17*	*1.53*	*1.32*

Table 2.12 – Calculated energy consumption of appliances (ISTAT, 2014)

Appliance/device	*No.*	*Max.Power [W]*	*Energy label [kWh/year]*	*Usage coefficient*	*Expected consumption [kWh/year]*
Refrigerator Rex FI 22/10 H	1	n.a.	511	1.12	511
Oven Rex FR63	1	1865	105	1.12	146
Microwave Panasonic NN-k-108 WM	1	1000	n.a.	1.12	25
Washing mach. Electrolux EWF1286	1	2200	134	1.37	138
Dishwasher Bosch SMV 46 KX 01 E	1	2400	262	1.23	204
Iron De'Longhi PRO1847	1	2200	n.a.	1.12	60
Hairdryer Bosch PHD9760/01	2	2000	n.a.	1.12	139
Television Sharp, LC-40LE630E	2	108	70	1.12	15
Laptop HP 15-bc014nl	3	120	n.a.	1.12	328
Energy saving fluorescent lamps	46	9	n.a.	1.12	158
Fluorescent lamps	5	11	n.a.	1.12	
LED strips	1	13	n.a.	1.12	
LED lamps	14	7	n.a.	1.12	
Fan-coils	6	50	n.a.	1.12	462

The family was also provided with a dedicated app for remote management of the electrical appliances and analysis of its energy consumption in terms of real-time energy consumption and statistical consumption for each appliance and for the entire apartment.

Nevertheless, the family has shown limited interest in the feedback provided and low interaction with the app, and no significant behavioural changes were observed.

CHAPTER 3. POLICIES FOR INDIVIDUAL METERING

In this Chapter, the issue of individual metering is addressed from a policy perspective. The goal will be to answer the question: is it possible to guide the success of the action about individual metering in residential buildings at a political/regulatory level? In particular, two different case studies concerning the energy policies of individual metering will be analysed and discussed at different scales:

1. *Case study #4*, in which a new energy-efficient policy about heat cost allocation is presented and applied to a single building scale;
2. *Case study #5*, in which the potential impact of the policy about individual metering is evaluated at a Country-scale for the Italian nation through scenarios simulation.

The following subjects will be first discussed in order to allow a further understanding about the context in which the case studies are embedded:

- the heat cost allocation rules currently in use within EU (paragraph 3.1),
- the cost-benefit analysis of individual heat metering and accounting systems (paragraph 3.2)
- the models for estimating the consumption of building stocks for the projection of energy policy scenarios (paragraph 3.3).

3.1 Allocation rules in Europe

As known, in multi-apartment buildings supplied by district heating or cooling, or where centralized heating or cooling sources are prevalent, EED [9] requires MSs to introduce transparent rules on the allocation of the cost of thermal or hot water consumption to ensure transparency and accuracy of accounting for individual consumption. However, to date (2019) only 16 out of 28 MSs (see Table 3.1) had defined official rules for allocating heating costs among tenants, and only 2 set regulations for allocation of cooling costs [106]. In the remaining, rules have not yet been set or are currently under definition and only a general framework has been established. Where allocation rules have been set, energy costs for space heating are generally shared taking into account voluntary and involuntary energy consumption (Figure 3.1). Thus, the total energy expenditure is divided into:

- *variable share*, which is generally allocated basing through individual DHMs or IHASs,
- *fixed share*, accounting for energy consumption of common heated area or for running costs such as the maintenance of the heating system, energy for auxiliary devices, billing services etc.; this is shared among the tenants according to shares of ownership, heated surfaces, installed heat output etc.

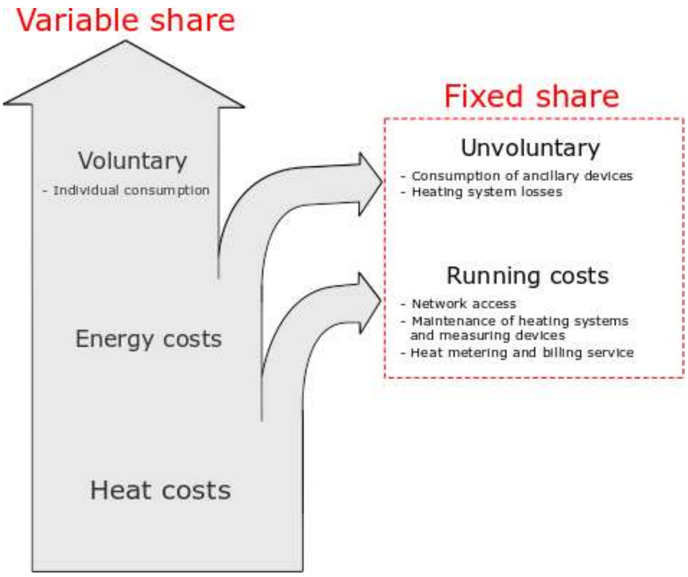


Figure 3.1 – Fixed and variable share of heating and cooling energy cost

Among EU MSs the share of fixed costs varies between 25% and 60%. This variability may rely on different characteristics of EU building stocks and on unfavourable climate conditions. In fact, Eastern EU MSs assign higher shares of fixed costs due to the generally low thermal performance of the buildings in order to avoid undesirable disputes between low-income tenants, especially in social housing buildings. The majority of the other EU MSs has set the share of fixed costs at 30%-50%, whose choice is left to different players (landlords, service companies, professionals etc.). Table 3.1 and Figure 3.2 provide an overview of the ranges defined for variable shares of heat cost allocation in EU MSs.

Table 3.1 – Heating costs allocation rules in Europe [27]

MS	*Ref.*	*Rules before EED*	*Rules after EED*	*Variable share*	*Notes*
Austria	[107]	Yes	Yes	55-75%	The percentage of variable share is set at 65% if specific agreements between companies and users are not reached. Fixed costs are allocated basing on floor area.
Belgium	[108]	No	No	-	-
Bulgaria	[109]	Yes	Yes	60-75%	-
Cyprus	[106]	No	No	-	-
Croatia	[76]	No	Yes	10-50%	-
Czech Republic	[110]	No	Yes	50-70%	Total costs per m^2 cannot be lower than 20% or more than 100% of the average cost.
Denmark	[111, 112]	No	Yes	50-70%	-
Estonia	[113]	No	Yes	40-60%	-
Finland	[114]	No	No	-	-
France	[115-117]	No	Yes	70%	The share for variable and fixed costs is regulated by law.
Germany	[118]	Yes	Yes	50-70%	-
Greece	[106, 119]	No	No	Calcul. case by case	Variable costs calculated as specified in Greek technical standard. Rules for fixed costs are not provided
Hungary	[120]	Yes	Yes	50-70%	-
Ireland	[106]	No	No	-	-
Italy	[37, 77, 78]	No	Yes	> 70%	The percentage of variable share can be set by the building assembly if the difference between minimum and maximum energy need between the apartments within the building is greater than 50%
Malta	[121]	No	No	-	The provision of common energy sources for heating and cooling, and hot water remains is deemed economically unfeasible.

MS	*Ref.*	*Rules before EED*	*Rules after EED*	*Variable share*	*Notes*
Latvia	[122]	No	Yes	-	There is no obligation to adopt allocation rules based on actual consumption. Conversely, the choice of the calculation method is decided in the building assembly.
Lithuania	[123, 124]	No	Yes	-	The owners of apartments/buildings can decide the method of sharing the thermal energy consumption. The method must be authorized/validated by the National Energy Control Commission.
Luxembourg	[106]	No	No	-	-
Netherlands	[125, 126]	No	Yes	-	If requested by one or more tenants, a professional verifies the heating costs allocation rules performed by the heating service company.
Poland	[127, 128]	No	No	-	Only general rules are in Energy Law. The percentage of variable share can be set by the building owner/manager in the form of individual rules of heat cost allocation for a specific building.
Portugal	[106]	No	No	-	-
Romania	[129, 130]	Yes	Yes	-	The adoption of a percentage for variable costs of 40% is under discussion.
Slovakia	[131, 132]	Yes	Yes	40%	The adoption of a percentage for variable costs of 40% is fixed by law, but it can be modified upon agreement between involved parties.
Slovenia	[133, 134]	No	Yes	50-80%	Consumption per m^2 should not be below 40% and over 300% with respect the average consumption.
Spain	[88, 135]	No	No	-	-
Sweden	[119]	No	No	-	-
UK	[22, 136, 137]	No	No	Not regulated	The Government did not propose to mandate rules on the allocation of costs after national consultation

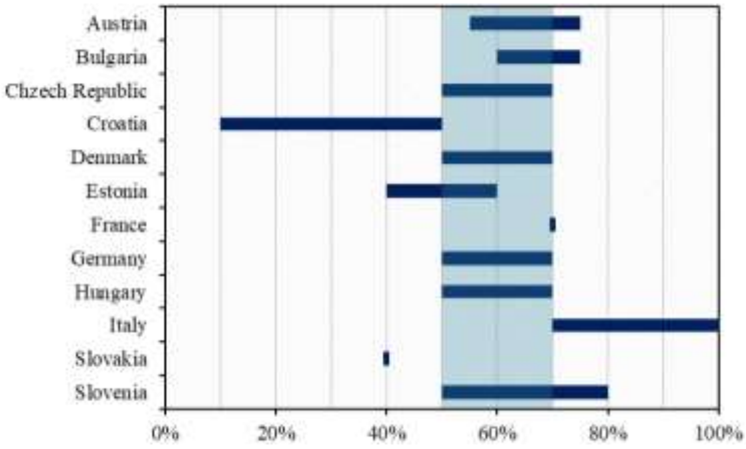


Figure 3.2 - Range for variable share of heat cost allocation in some EU Member States

Heat flows between adjacent apartments

Especially in old and existing buildings, the lack of insulation of walls between adjacent apartments determines thermal energy flows between apartments differently heated. This phenomenon is referred within the scientific literature as “stolen heat” or “heat thefts” and represents the cause for which, if a dwelling is surrounded by numerous unheated spaces, it will have involuntary over-consumptions even when energy-efficient behaviours are adopted. In some very unfavourable situations Lukić, et al. [138] demonstrated that an unheated and unoccupied dwelling in a fully insulated building with heated surrounding units can gain about 80% of its total energy need for heating through “heat thefts”. In this regard, Gafsi and Lefebvre [29] showed that an apartment may “steal” up to approximately 90% of heat from adjacent apartments. Whereas, Andersson [139] demonstrated the possibility to obtain more than 95% of the thermal energy need from surrounding apartments. The above-mentioned problem, causes issues related to the allocation of heating costs among tenants [140]. For this reason, different compensation strategies have been proposed also based on calculation of heat flowing through adjacent apartments.

Compensation factors

When installing individual metering and accounting systems, “fairness” and the “responsibility” of heat cost allocation should also be considered. In fact, in multi-apartment buildings, some dwellings may have an unfavourable location [141, 142]. As for example, Ling, et al. [141] estimated that a corner unit on the top floor has a space heating consumption per floor area 26.1% higher than a centre unit in middle floors. Hence, the heating cost allocation might not be perceived fair if based exclusively on individual readings [143], especially considering that in new high insulated buildings warmer apartments would pay a disproportionate part of the total heating costs if other dwellings are heated at lower temperatures [144, 145].

According to EED, tenants should be "responsible" for their energy consumption, that would require allocation rules mainly based on actual energy consumption. However, “fairness” of heat cost allocation, would rely the above-mentioned disadvantaged situations to be tackled through specific Compensation Factors (CFs), accounting for: i) largest dispersing surfaces with the same heated area; ii) presence of adjacent unheated rooms/apartments; iii) different orientation (for example, houses facing north or with large shadings etc.).

Two different kinds of compensation strategies have been identified based on: i) energy use and ii) thermal-comfort.

The compensation based on energy use is widely spread in different EU countries, where specific CFs are given depending on apartment location, orientation etc. CFs can be applied either to the entire apartment or to single disadvantaged rooms. Such compensation is currently adopted in Hungary [120], Lithuania [123, 124], Romania [129, 130] (see

Table 3.3) and, among non-EU MSs, in Switzerland [146]. Denmark allows compensation based on the calculation of heat loss percentage of each apartment with some exemptions [111, 112]. Ling, et al. [141] also determined local CFs based on building types and age through a calibrated simulation method. Compensation based on the stolen-heat between adjacent apartments has been also proposed by Siggelsten [103] for estimating heat transfers between adjacent apartments and for compensating energy bills taking these into account. This method has been experimented in an existing multi-apartment building with 16 apartments and assessed with computer-based simulations. Michnikowski [147] presented a variation of the method proposing a correction based on indoor temperature measurement and on the analytical determination of the energy need for heating. Gelegenis, et al. [148] and Nikos Gkonis [149] refer that heat cost allocation based on stolen heat is spread in Greece, where the use of CFs is allowed without being mandatory. Compensation is then allowed through the calculation of the residual heat loss through the surrounding envelope when the dwelling is not heated. In Table 3.2 the main advantages and disadvantaged of the available compensation strategies are summarized.

Table 3.2 – Advantages and disadvantages of different compensation strategies

Compensation Strategy	*Method*	*Advantages*	*Disadvantages*	*Reference*
Energy use	Fixed CFs for disadvantaged rooms/dwellings	Simplicity of application	Limited accuracy of the method. It can lead some users to detachment	Hungary [120] Lithuania [123, 124] Romania [129, 130] Switzerland [146]
	Heat loss percentage	Very accurate	Complexity of calculation. It can lead some users to detachment and to disputes between tenants	Denmark [111, 112] Ling, et al. [141]
	Stolen-heat between adjacent apartments	It prevents too low set-point temperatures	Complexity of calculation	Siggelsten [103] Michnikowski [147] Nikos Gkonis [149]
Thermal comfort	Set-point temperatures and operating hours	Good accuracy	It requires specific additional devices. Inefficient users' behaviour (e.g. windows and doors left open) not considered	Liu, et al. [150]
	Ratio between measured differences in indoor/outdoor temperatures and comfort	Good accuracy	It requires specific additional devices. Inefficient users' behaviour (e.g. windows and doors left open) not considered	Darvariu [70]

Table 3.3 – Ranges of CFs in different countries.

Rooms/apartments	*Hungary*	*Lithuania*	*Romania*
Lower floors	0.85-0.95	0.85-0.90	0.77*-0.90
Intermediate floors	0.90-0.95	0.85-1.00**	0.90-1.00**
Higher floors	0.80-0.90	0.75*-0.90	0.72*-0.90
North orientation	0.95	-	0.95-0.97
South orientation	-	-	1.03-1.05

**Lower values (high compensation) assigned to corner rooms at higher floors;*

***Higher values (low or no compensation) assigned to intermediate apartments with adjacent heated surroundings.*

Regarding compensation through thermal-comfort, Darvariu [82] proposed a correction based on the measured difference between the indoor comfort temperature and the outdoor one, while Liu, et al. [81] proposed compensation though the measured cumulative on-time of zone thermostatic valves.

Other MSs adopt different approaches for CFs. In three countries, such as in Italy, Austria and Germany, they are forbidden, while CFs are mandatory in Czech Republic, Denmark and Lithuania. A general overview on CFs use is given in Table 3.4.

Table 3.4- Compensation factors in EU MSs

Member State	***Compensation***	***Notes***
Austria	Forbidden	
Bulgaria	Allowed	CFs rarely used
Croatia	n.a.	CFs are not used
Czech Republic	Mandatory	
Denmark	Mandatory	
Estonia	Allowed	CFs widely used
France	Allowed	CFs managed by the building assembly
Germany	Forbidden	
Greece	Allowed	CFs managed by the building assembly
Hungary	Allowed	Compensation allowed for single rooms within the dwelling
Italy	Forbidden	
Latvia	Allowed	CFs are estimated by independent technicians.
Lihtuania	Mandatory	
Netherlands	Allowed	
Poland	Allowed	CFs managed by the building owner/manager and/or by independent technicians.
Romania	Allowed	Compensation allowed for single rooms within the dwelling
Slovakia	Allowed	
Slovenia	Allowed	CFs are estimated by independent technicians.

Indeed, this topic is still very debated on both policy-makers and research levels. In fact, although the use of CFs could reduce the inequalities of heat accounting, it is also believed that this is fully functional to the objectives of the EED Directive to improve building energy efficiency [150]. In any case, the adoption of CFs and the socialization of energy losses could also increase the number of detachments from centralized heating systems.

Risk for energy poverty

An important and arising issue regarding heat cost allocation is represented by its potential for worsening the economic conditions of final users at risk for energy poverty. As known, households under energy poverty are more likely unable to keep their home adequately warm [151, 152]. Energy poverty affects differently the EU MSs, with some countries having very high percentages of population under such risk (up to 30-36% in Bulgaria, Greece, Lithuania, see Figure 3.3 [153]).

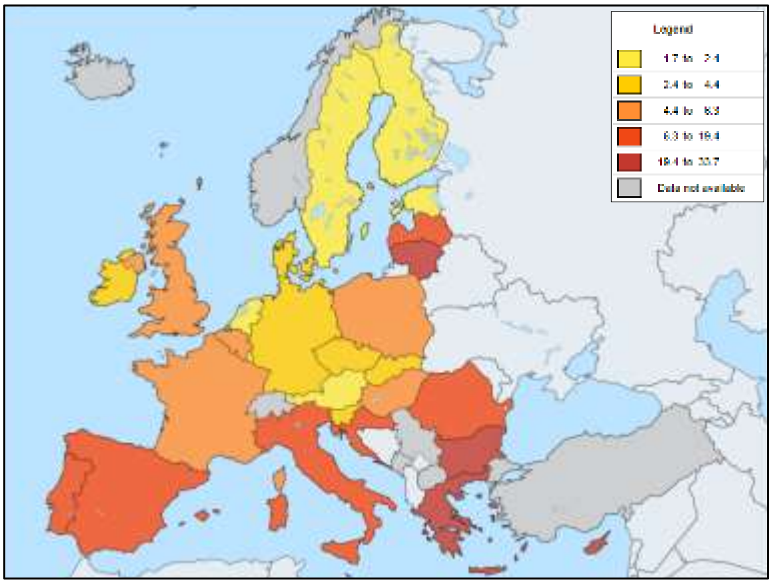


Figure 3.3 – Population unable to keep home adequately warm by poverty status (% of population, year 2018, exceptions: CZ, AT, LU, SE, LT, SK, RO, TR, MT, PL, RS, MK, ES, IE (2017), CH, IS (2016))

In England and Wales, energy poverty is likely to be a significant contributor the excess winter death with about 27 000 cases each year over the last decade. Energy poverty also causes a large number of ill-health and a wider range of problems of social isolation and poor outcomes [154]. Moving from an allocation of energy costs based on the area of ownership (and similar) to the adoption of a scheme fixed/variable share, could cause an excessive increase in costs for some particularly disadvantaged apartments (low insulated attics or basements etc.). Hence, the introduction of individual metering in residential buildings with low-income users could cause a series of undesirable consequences whose effects have to be carefully taken into account. Indeed, social housing apartments are often randomly assigned and first and top floors not always have further advantages especially in cases of absence of lifts, yards or similar [155]. Moreover, social housing buildings are often represented by old buildings with poor thermal energy performances and obsolete heating systems and tenants tend to have low energy consumption regardless the presence of individual metering devices, as heating costs represent a great part of the users' income. In such cases, the socialization of the heating expenses could represent a way for disadvantaged end-users to afford the winter heating costs. Opaina [156] reported that customers who intended to have savings of 30-40% of the heating bills received higher invoices than before the HCAs were installed because there were customers who closed totally their radiators. This causes also technical issues (condensation, mould and dampness in flats and in the joint resistance structure), health problems of residents of the buildings (asthma, bronchitis, lung colds) and other unexpected risks of explosions and fires caused by improvised and illegal alternative heating systems (e.g. with natural gas from the cooker, electric power from their own undersized facility or firewood and burning coal). Kuyumdjiev [157] highlighted that in Bulgarian buildings thousands of radiators equipped with HCAs and Thermostatic Radiator Valves (TRVs) are permanently closed and that many apartments are inhabited by single people heating only one room. Moreover, many Bulgarian people refuse to pay for heat from the building installation in uninhabited apartments, or with disconnected or sealed radiators.

3.2 Cost-benefit analysis of individual heat metering and accounting systems

With respect to the obligation about individual metering set by EU with the Energy Efficiency Directive, Member States (MSs) adopted different approaches at the policy level [27] due to the numerous open questions on the technical and economic feasibility of these systems. Despite the requirement 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).

In this regard, Empirica GmbH [119] has developed a Guide to provide support to MSs Authorities and to the owners of buildings for the implementation of articles 9-11 of EED on the consumption of thermal energy for heating, cooling and domestic hot water. In the Guide, MSs are recommended to determine reference costs to assess which metering and information measures might be cost-effective in a particular building. In this respect, some National Authorities promoted surveys among various suppliers of instruments and services, in order to obtain information on competitive costs through market analysis. In Table 3.5 and Figure 3.4 the results of market analyses carried out in representative MSs are reported.

Table 3.5 - Total running and capital costs of individual heat metering and accounting systems in EU

	IT [27]	**SE [16, 17]**	**DE [27]**	**UK [22, 27, 28]**	**PL [71, 82]**
DHM (installation included)	235 €/piece	n.a.	314 €/piece	336 €/piece	n.a.
Annual costs (DHM)	10 €/dwelling	n.a.	24 €/ dwelling	94 €/ dwelling	n.a.
HCA (installation included)	34 €/piece	190-348 €/dwelling	39 €/piece	52 €/piece	4-13€/piece
TRV (installation included)	40 €/piece	n.a.	n.a.	58 €/piece	32 €/piece
Annual costs (HCA)	7 €/piece	24-64 €/dwelling	5 €/piece	41 €/ dwelling	3 €/piece

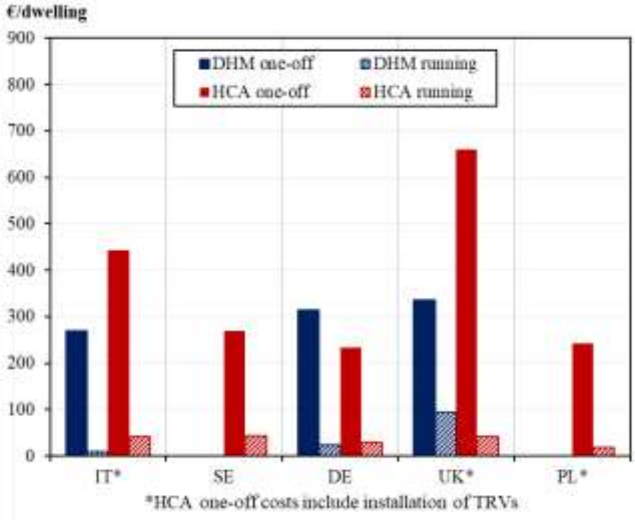


Figure 3.4– Total one-off and running costs of DHMs and HCAs installation per dwelling

In Figure 3.4 the total capital (one-off) costs are calculated hypothesizing a mean number of 6 radiators per dwelling and any accessory installations, adjustment on the heating system (i.e. installation of variable speed pumps, heating system balancing, de-aerators, strainers etc.) or masonry works are not included. However, masonry works are almost unavoidable, especially for DHMs installation in old buildings, while the installation of additional repeaters, central acquisition system and the balancing of the heating system is often required when installing HCAs and TRVs. Thus, the installation costs to equip a single dwelling with an individual metering system is estimated varying between 300 and 3000 €/dwelling, depending also on the type of user’s feedback system adopted, with an operational cost between about 20-60 €/year/dwelling.

According to these figures, it is clear that the result of cost-effectiveness analysis of heat metering and accounting systems is strictly related to the expected benefit and also to fiscal policies incentivizing the installation of individual metering and temperature control devices. This is also the reason why, in EU:

- only ten MSs (Italy, Germany, Austria, Czech Republic, Denmark, Romania, Bulgaria, France, Netherlands and England) obliged the installation of individual heat metering systems with some differences: in some cases, e.g. in Germany and Austria, very few exemptions to the obligation are allowed, while in others, i.e. Italy, a specific economical assessment according to the standard EN ISO 15459 [20] has to be performed for each building when technical feasibility is demonstrated; in France, Netherlands and England some exemptions have been allowed in a mandatory installation scenario;

- two MSs (i.e. Sweden and Finland) have decided to not proceed with the obligation to install as the evaluation of the economic feasibility at large scale has resulted negative;
- in the remaining MSs the directives are unclear or the transposition has not yet taken place.

An overview of the relevant literature regarding cost-benefit analysis of individual metering and temperature control systems is given in Table 3.6.

Table 3.6 - Overview of the relevant literature regarding cost-benefit analysis of individual metering and temperature control systems at national scale

Subject	***Main outcomes***	***Reference***
Cost-benefit analysis commissioned by the Finnish Ministry of Employment and the Economy and performed	For 99% of existing Finnish multi-apartment buildings individual heat measurement or indirect cost allocation would not be cost-effective. It would be more cost effective to invest in controlling and balancing the heating system and network (Finland, 2014).	Koski [18]
Cost-benefit analysis at national level taking into account the uncertainties regarding benefits as well as costs of investments	Monte Carlo simulations performed in order to analyse whether individual heat metering would be cost-effective. Investment in individual metering and charging using HCAs or temperature metering would generally be not cost-effective in existing buildings (Sweden, 2015).	Carlsson, et al. [16]
Cost-benefit analysis on reference buildings	Significant dependence of the economic effectiveness of such devices also on the energy performance of the analysed building (i.e., its primary energy consumption) and on its net floor area, besides on capital and running costs and on the expected benefits. Payback time variable between 3 and 16 years when the building energy need ranges from 300 to 100 kWh m^{-2} $year^{-1}$ (Italy, 2016)	Celenza, et al. [27]

3.3 Modelling energy consumption of building-stock to project policy scenarios

In order to estimate the impact of an energy policy, the complex issue to investigate energy consumption of large-scale building stocks has to be carefully 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 types of Urban Building Energy Models (UBEMs) 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 so-called bottom-up engineering models simulate the energy consumption of buildings through suitable physically based equations with a number of parameters such as thermo-physical characteristics of the urban building stock, installed heating systems and their real operation, human behaviour, climate data etc. [158]. These models generally produce fixed “building typologies” [159], also called “archetypes” or “reference buildings”, in which it is possible to classify the existing building stock. These, by relying on physical features of the buildings, are able to determine the total energy demand of a residential building stock showing also flexibility to model possible scenario’s changes.

On the other hand, top-down models typically estimate the aggregate energy consumption of a building stock by establishing a relationship between the energy use and different drivers such as socio-economic indicators, household size, technologies and practices, weather condition, etc. [160]. The aggregate building energy demand of a region is increasingly subdivided into smaller sections, being suitable only for particular purposes, i.e. at estimating increased energy consumption of new buildings or reduced energy consumption before or after retrofit interventions [161].

An overview of UBEMs approaches is shown in Figure 3.5 and their characteristics are summarized in [160].

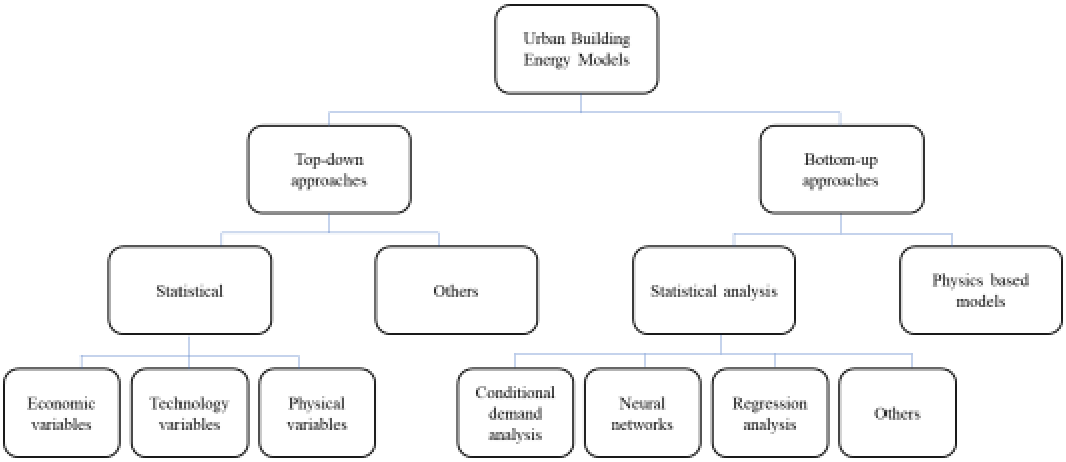


Figure 3.5 – UBEMs classification overview [160]

Table 3.7 – Advantages and disadvantages of UBEMs [160]

		Advantages	Disadvantages
Top-down	Statistical	a) Socio-economic drivers considered b) Do not require detailed technology and actual energy consumption data c) Relatively simple finding of aggregate econometric data	d) Strongly depends on historical trends e) Long term historical data required f) Lack in technological details
Bottom-up	Statistical analysis	a) Socio-economic effects considered b) Simulation of energy use at end-use and/or building level c) Individual end uses considered	d) Billing, weather, and/or survey data required e) Large number of data required f) Possible multicollinearity g) Depends on historical trends and/or on quality of training data (for neural networks)
	Physics based	a) Socio-economic data not required b) Simulation of energy use at end-use and/or building level at different temporal scales c) Individual end uses considered	d) Detailed data about buildings' thermo-physics and technology required e) Socio-economic factors not considered f) High computational capacity/time

In the present paragraph, the attention will be focused on the bottom-up engineering (physics based) of UBEMs, as this methodology will be applied to determine the energy consumption of the Italian building stock as *case study #5.*

Bottom-up UBEMs make predictions using general data of existing building stock retrieved by official databases, reports etc., with variable level of accuracy and detail.

These models are becoming increasingly important in energy modelling practices as they offer a method of assessing the energy demand and the environmental impact of building stocks, and can help simulating different actions to reduce their energy and environmental impact. For this reason, they are expected to become one of the main planning tools for energy utilities, municipalities, urban planners, policy makers and other professionals [162]. They have been used to evaluate policy scenarios [163, 164], the potential for renewable energy sources [165, 166] and energy planning on an urban scale [161, 167, 168]; assess life cycle performance [169]; and study the heat island effect [170], refurbishment strategies [171], and health impacts [172]. For the Italian Country, these have been applied mainly on regional level [173-175].

However, these models have a series of limitations, especially considering that the details of building systems are rarely available for a large number of buildings at the urban/country scale, thus the building systems and their efficiency are often determined or hypothesized based on the building type, age and size.

Thus, results of this kind of models will be strongly affected by the quality of the available data and by the reliability of the assumption underlying the model. The uncertainty of results can be substantial, although this is not often reflected or assessed in modelling practices [161], thus, any bottom-up energy model needs to be calibrated in order to increase confidence in its predictions. Kavgic, et al. [158] identified three major issues which still need to be addressed when referring to bottom-up building stock models: a) the lack of publicly available detailed data relating to inputs and assumptions, as well as underlying algorithms, b) the lack of data on the relative importance of input parameter variations on the predicted demand outputs, and c) the uncertainty as to the socio-technical drivers of energy consumption.

As mentioned, within this Chapter, the author will try to overcome these issues by developing, validating and calibrating a bottom-up physics-based model which has been functional to estimate the potential energy saving deriving from the application of the individual metering on the whole Italian Country.

3.4 *Case study #4: A new heat cost allocation method for social housing*

In this paragraph, an energy-efficient heat cost allocation policy based on the estimation of extra-consumptions related to building inefficiencies and not only to users' behaviour is proposed and detailed. The main novelty of this method relies in charging the expenses related to the building energy inefficiency (the so called "extra-consumptions") to all tenants in order to encourage building assembly to promote energy efficient retrofit interventions. The proposed policy has been experimented in a typical social housing building in Italy and compared to other methods currently applied in relevant EU countries, evidencing some advantages and weaknesses.

3.4.1 Methodology

The developed method for energy-efficient heat cost allocation

The adoption of heat cost allocation rules aims to promote both end users' virtuous behaviour and to achieve energy saving and efficiency in thermally underperforming buildings. In this context, the proposed method is based on the punctual estimation of extra-consumptions, which represents the share of energy consumption due to the lack of thermal insulation of the common parts of a building, and of the related costs. The allocation of extra-consumptions and of the related costs to all tenants in the building is then performed and this should be a driver to promote energy retrofits in the building. The proposed method is briefly highlighted as follows:

a) extra-consumptions and the related extra-costs are estimated in the building;
b) all tenants are charged for extra-cost and, consequently, condominium meeting should be encouraged to promote energy retrofit interventions;
c) once the energy retrofit intervention has been effectively carried out, the extra-costs are zeroed and tenants start paying only for their individual consumptions.

The estimation of the heat losses coming from inadequate insulation of single dwellings and common parts of a building is performed through the calculation of the heat flow exceeding the corresponding one at reference conditions, which are provided by current technical regulation. To this aim the energy performance of single building elements and of common areas of the building (e.g. walls, windows, floor, ceiling, roof, …) are considered. On the other hand, the proposed method does not take into account both internal and external heat gains since it is not possible to modify them to improve building energy efficiency. Furthermore, internal heat gains depend on the users' habits and not on the building characteristics, whereas the external ones depend on uncontrollable variables such as the presence of new constructions and natural vegetation. Therefore, voluntary and involuntary extra-consumption are allocated to the *i-th* dwelling through a specific “efficiency correction” factor $f_{ext,i}$, calculated as described in equation (3.1).

$$f_{ext,i} = \frac{HDD \cdot 0.024 \cdot \sum_j \left[\left(U_{com,j} - U_{com,j}^{ref} \right) \cdot b_j \cdot A_{com,j} \right]}{Q_{H,ls,i}} \tag{3.1}$$

Where:

- HDD are the Heating Degree Days, defined by the current regulation for the location, K;
- $U_{com,j}$ is the actual thermal transmittance of the *j-th* common building element, W m^{-2} K^{-1};
- U_{com}^{ref} is the reference thermal transmittance of the *j-th* common building element, defined by the current regulation as a function of the climatic zone), Wm^{-2}K^{-1};
- b_j is the correction factor due to heat dispersions of unheated spaces, dimensionless [176];
- $A_{com,j}$ is the surface of the *j-th* common building element, m^2;
- $Q_{H,ls,i}$ is the total heat loss for transmission and ventilation [177] for space heating of the *i-th* dwelling, kWh.

Correction factor $f_{ext,i}$ is set to zero when $U_{com,j}$ is lower than U_{com}^{rif}. Correction factors $f_{ext,i}$ are then used to allocate voluntary and involuntary extra-consumption for space heating of each *i-th* dwelling, respectively $EQ_{v,i}$ and $EQ_{u,i}$, through equations (3.2) and (3.3).

$$EQ_{v,i} = Q_{v,i} \cdot f_{ext,i} \tag{3.2}$$

$$EQ_{inv,i} = Q_{inv,i} \cdot f_{ext,i} \tag{3.3}$$

The total voluntary and involuntary extra-consumption, respectively $EQ_{v,tot}$ and $EQ_{u,tot}$, are finally estimated through equations (3.4) and (3.5).

$$EQ_{v,tot} = \sum_i EQ_{v,i} \tag{3.4}$$

$$EQ_{inv,tot} = \sum_i EQ_{inv,i} \tag{3.5}$$

The final energy extra-consumption is then allocated among tenants through equations (3.6) and (3.7), where m_i is the percentage of heated gross volume of the *i-th* dwelling.

$$Q_{com,v,i} = -EQ_{v,i} + m_i \cdot EQ_{v,tot} \tag{3.6}$$

$$Q_{com,inv,i} = -EQ_{inv,i} + m_i \cdot EQ_{inv,tot} \tag{3.7}$$

As for example, in Table 3.8 the informative scheme of heat sharing and of the related voluntary and involuntary consumptions estimations is presented, highlighting extra-consumptions due to the roof, the building envelope and floors not effectively insulated.

Table 3.8 – Calculation and accounting scheme of Extra-Consumptions

Voluntary Consumption							
Dwelling	*Measured Voluntary Consunption*	*Extra-Consumption*			*Extra-Consumption Share*		*Share for Voluntary Consumption*
		Common Roof	*Common Walls*	*Common Floor*	*Share, %*	*Share, kWh*	
Top floor	$Q_{v,i}$	$-EQ_{v,j,i}$	$-EQ_{v,j,i}$		m_i	$+m_i \cdot EQ_{v,tot}$	$Q_{v,i} + Q_{com,v,i}$
...	$Q_{v,i}$		$-EQ_{v,j,i}$		m_i	$+m_i \cdot EQ_{v,tot}$	$Q_{v,i} + Q_{com,v,i}$
...	...		...		…	...	…
First floor	$Q_{v,i}$		$-EQ_{v,j,i}$	$-EQ_{v,j,i}$	m_i	$+m_i \cdot EQ_{v,tot}$	$Q_{v,i} + Q_{com,v,i}$
Total	$\sum Q_{v,i}$		$-EQ_{v,tot}$		100%	$EQ_{v,tot}$	$\sum Q_{v,i}$
Involuntary Consumption							
Dwelling	*Estimated Involuntary Consumption*	*Extra-Consumption*			*Extra-Consumption Share*		*Share for Involuntary Consumption*
		Common Roof	*Common Walls*	*Common Floor*	*Share, %*	*Share, kWh*	
Top floor	$Q_{inv,i}$	$-EQ_{inv,j,i}$	$-EQ_{inv,j,i}$		m_i	$+m_i \cdot EQ_{inv,tot}$	$Q_{inv,i} + Q_{com,inv,i}$
...	$Q_{inv,i}$		$-EQ_{inv,j,i}$		m_i	$+m_i \cdot EQ_{inv,tot}$	$Q_{inv,i} + Q_{com,inv\ i}$
...	...		...		…	...	…
First floor	$Q_{inv,i}$		$-EQ_{inv,j,i}$	$-EQ_{inv,j,i}$	m_i	$+m_i \cdot EQ_{inv,tot}$	$Q_{inv,i} + Q_{com,inv,i}$
Total	$\sum Q_{inv,i}$		$-EQ_{inv,tot}$		100%	$EQ_{inv,tot}$	$\sum Q_{inv,i}$

The proposed method allows to highlight the building inefficiency in terms of extra-consumption and of the related extra-costs. Since such inefficiency is allocated to all tenants, possible retrofit interventions on the common parts of the building should be encouraged and promoted. This is even more applicable for social housing buildings in which tenants should push the Public Institution (which is often the owner of the building or of the most part of the building) to implement energy retrofit interventions. Extra-consumption and the related compensation costs are then zeroed when the building is well insulated in compliance with applicable laws in force and heat cost sharing should be based only on effective individual consumptions, in agreement with EED. On the other hand, in certain conditions the heat cost sharing through the proposed method may generate almost similar bills among tenants (i.e. a sort of flat-rate) and this should lead to maintain the status quo in the building, avoiding the EED intended goal.

In the following, the developed method is experimented in a typical social housing building in Italy and compared with other applicable methods available for heat cost sharing, which are respectively:

- methods based on *fixed proportionality* principle, still spread in some MSs, in which the whole energy consumption should be charged with flat-rate; the following flat-rate shares will be considered within the analysis: floor area, primary energy need, installed heat output;
- methods based on *responsibility* principle, based on the actual energy measured through direct or indirect measuring systems basing on calculation variable and fixed cost shares; the following methods will be considered within the analysis: heat costs shared basing 100% on individual consumption, heat costs shared basing on calculation of voluntary and involuntary energy consumption (Italian method [37]) and heat costs shared with a fixed/variable share respectively of 30 and 70%;
- methods based on *fairness principle,* which make use of specific compensation factors in order to account for higher consumption of some dwellings within the building; among these, two methods will be considered for the comparison: the Greek method [148, 149] which applies compensation basing on calculation of stolen-heat and the Swiss method [146] which applies compensation basing on expected energy use.

The building

The case study investigated by the author is represented by a social housing building located in Anagni, Central Italy. The building was constructed in 1979 by ATER, the Territorial Agency for Social Housing, and it is composed by eight dwellings served by a central heating system supplied by natural gas, whose consumption is measured through a G16 class 1.5 MID approved diaphragm smart gas meter. The heating plant has been equipped with programmable thermostats in each dwelling and electronic thermostatic radiator valves (TRVs) on each radiator. Voluntary and involuntary consumptions are gathered through an indirect allocation system and a direct class 2 MID approved heat meter in the boiler room. The system is remotely accessed through a GSM communication system allowing frequent readings and billing. Natural gas for hot water production and cooking purposes is supplied by individual boilers to each dwelling. The building is part of a social housing complex of three buildings currently undergoing a larger investigation by the Department of Civil and Mechanical Engineering of the University of Cassino in cooperation with ENEA and ATER.

The building consists of two connected blocks. The first one, made up of two dwellings on two floors, is located above the front porch (dwelling type C). The second one, located above garages, consists of six dwellings (two for each floor) of which three North-West oriented (dwelling type A), and 3 South-West oriented (dwelling type B). In Figure 3.6, Figure 3.7 and Figure 3.8 some pictures, the layout schemes and the cross-section of the investigated building are represented, respectively.

Figure 3.6 – The investigated building

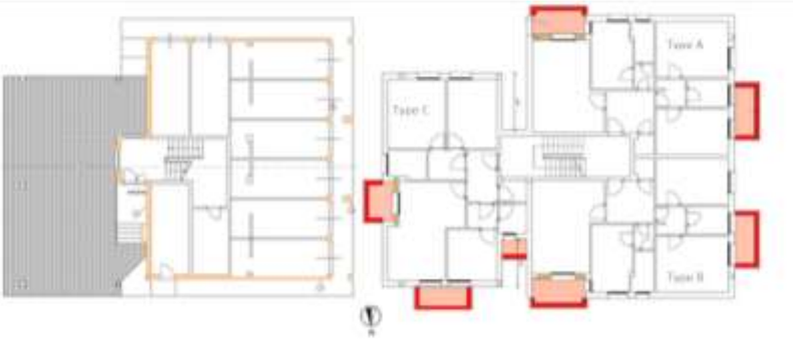


Figure 3.7 - Layout schemes of the building (basement and typical floor)

Figure 3.8 - Cross section of the investigated building

The investigated building is a typical Italian social housing building in terms of thermo-physical characteristics, and maintenance status. As most of social housing buildings in Italy, the investigated building would require a major renovation both for improving the building envelope insulation and the efficiency of the heating plant. Most tenants are low-income and elderly people and their attitude to interact with automation systems such as programmable thermostats and TRVs is quite low.

Type A and B apartments present a net floor area of about 79 m^2, whereas type C apartments of about 86 m^2. The net ceiling height in dwellings is 2.7 m. It is important to point out that the two type C apartments present both a large external envelope component towards unheated space (the under-roof and the porch). On the other hand, type A and type B apartments present large heat fluxes towards unheated space only at first (towards the garages) and top floor (towards the under-roof), whereas apartments of the mid floor are sandwiched between adjacent heated apartments. With regard to the heating plant, the distribution of the heat carrier fluid is performed through vertical mains. Pipes are uninsulated and mainly run into the external walls. All dwellings are equipped with cast iron radiators. U-values of single building elements have been estimated through data obtained by historical analysis or analogies with similar buildings using specific technical databases [178]. The main thermal and physical characteristics of the investigated building are listed in Table 3.9.

Table 3.9 – Thermal and Physical Characteristics of the investigated building

Building Element	***Description***	***Layers (from indoor to outdoor)***	***Thickness [m]***	***Estimated U-value [Wm^{-2}K]***	***Reference* U-value [Wm^{-2}K]***
Ceiling	Uninsulated pitched roof on unheated space	Lime/gypsum plaster	0.02	1.67	0.26
		Concrete	0.20		
		Waterproofing layer (bitumen)	0.004		
		Tiles	0.015		
External walls	Uninsulated concrete/hollow brick wall with air gap	Lime/gypsum plaster	0.02	1.12	0.32
		Hollow clay bricks	0.10		
		Air gap	0.08		
		Hollow concrete bricks	0.10		
Internal walls	Uninsulated hollow brick wall	Lime/gypsum plaster	0.01	1.77	-
		Hollow clay bricks	0.10		
		Lime/gypsum plaster	0.01		
Floors	Single fired wall and floor tiles	Lime/gypsum plaster	0.02	1.30	0.32
		Hollow core concrete	0.18		
		Lean concrete	0.05		
		Floor tiles	0.01		
Windows	Single-glazed windows with wooden frame	---	---	4.90	1.80

* referred to the Climatic Zone “D” for retrofit requirements (see Annex 1 of Decree of Ministry of Economic Development (MISE) on date 2015/06/26)

The building has been equipped with an indirect heat cost allocation system and thermostatic radiator valves, since the obligation set by Italian Legislative Decree 102/14 and subsequent modifications [77, 78]. The indirect heat accounting system installed is represented by insertion-time counters compensated with the inlet temperature of the heating fluid [32], compliant with national technical standard UNI 11388 [49], while temperature control of single rooms is obtained through electronic TRVs controlled by a programmable thermostat. In this way, each apartment is autonomous and consisting of a single thermal zone. Finally, an external temperature probe allows continuous monitoring of the outdoor temperature.

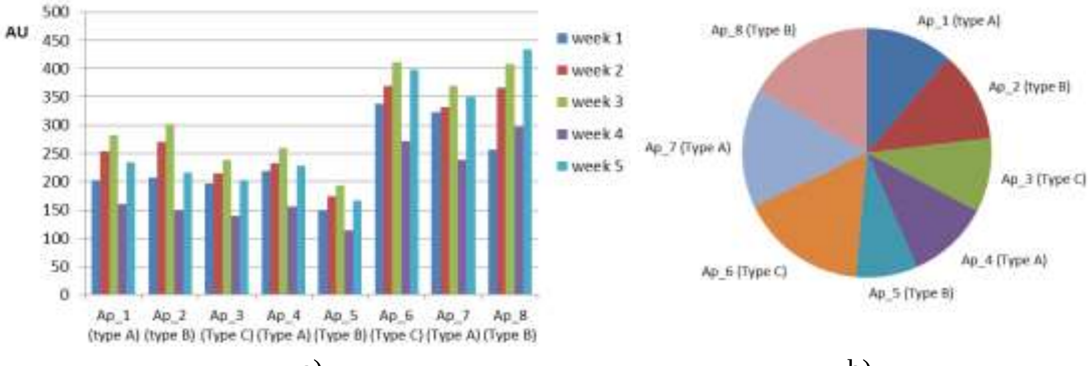
3.4.2 Results and discussions

In the following the results in terms of share for only variable energy consumption according to the above described fixed proportionality, responsibility and fairness allocation principles are presented. To this aim, in Table 3.10 the total cost for heating registered in the whole heating season 2016-2017 is reported.

Table 3.10 - Energy costs for space heating for the whole heating season 2016-2017

Description		***Cost***
Natural Gas Consumption	€	5.498,80
Maintenance (boiler and circulating pumps, TRVs etc.)	€	766,00
Electrical Energy for circulating pumps and boiler	€	100,00
Heat accounting service and billing	€	242,00
Total cost for space heating (2016-2017)	€	6.606,80

The individual consumption has been gathered with a two-weekly frequency and the related trends of a typical month and of the whole heating season hare represented in Figure 3.9.



a) b)

Figure 3.9 - Individual consumptions trend: a) a typical month, b) the whole heating season

In Table 3.11 the extra-consumptions estimated are reported for the case study social housing building.

Table 3.11 - Voluntary and involuntary extra-consumptions according to the proposed method

Floor	*Dwelling*	*Floor Area [m2]*	*Measured Consump. [kWh]*	*Extra-Consumption [kWh]*		*Extra-Consumption Share*		*Consumption Share [kWh]*
				Common Roof	*Common Floor*	*%*	*[kWh]*	
1st	Ap_1 (type A)	78.98	9128		-1576	12.2%	+2565	10117
	Ap_2 (type B)	78.98	9496		-1846	12.2%	+2565	10215
	Ap_3 (Type C)	85.73	7752		-1981	13.3%	+2784	8555
2nd	Ap_4 (Type A)	78.98	8613			12.2%	+2565	11178
	Ap_5 (Type B)	78.98	6461			12.2%	+2565	9026
3rd	Ap_6 (Type C)	85.73	13342	-4645		13.3%	+2784	11480
	Ap_7 (Type A)	78.98	12391	-5157		12.2%	+2565	9798
	Ap_8 (Type B)	78.98	13416	-5750		12.2%	+2565	10231
	Total	***645.34***	***80599***	***-15553***	***-5403***	***100%***	***+20956***	***80599***

In Table 3.12, Table 3.13 and Table 3.14 and in Figure 6 the heat cost shares calculated according to methods belonging to the above described proportionality, responsibility and fairness principles are respectively presented.

Table 3.12 – Fixed Proportionality principle: Heat costs share 2016-2017 in the investigated building

Floor	*Dwelling*	*Floor Area*			*Energy Need*			*Installed heat output*		
		m^2	*Share, %*	*Share, €*	*MWh*	*Share, %*	*Share, €*	*kW*	*Share, %*	*Share, €*
1st	Ap_1 (type A)	79.0	12.2%	672.97	18.7	10.7%	586.97	9.6	12.9%	707.05
	Ap_2 (type B)	79.0	12.2%	672.97	16.7	9.6%	525.25	9.1	12.2%	669.51
	Ap_3 (Type C)	85.7	13.3%	730.49	30.3	17.3%	951.59	8.8	11.8%	649.94
2nd	Ap_4 (Type A)	79.0	12.2%	672.97	13.4	7.7%	421.62	7.6	10.1%	557.35
	Ap_5 (Type B)	79.0	12.2%	672.97	12.7	7.3%	400.02	7.4	9.9%	546.38
3rd	Ap_6 (Type C)	85.7	13.3%	730.49	31.4	18.0%	987.38	11.0	14.7%	808.39
	Ap_7 (Type A)	79.0	12.2%	672.97	26.2	15.0%	823.79	10.2	13.7%	752.31
	Ap_8 (Type B)	79.0	12.2%	672.97	25.5	14.6%	802.19	11.0	14.7%	807.87

From data in Table 3.12 it can be pointed out that the flat-rate charging based on the floor area (even with the same floor area) differs considerably with the ones based on the energy need and on the installed radiators' heat output. This should not be surprising since the same floor area corresponds to different external envelope components and thermal loads, depending on the floor, the exposure and the transmittance of single building elements. The huge deviation between energy need and installed radiators' heat output methods is also particularly interesting. In fact, such deviation may seem incomprehensible if we do not take into account that the former is representative of the average energy load in standard conditions, the latter of the peak load (and therefore without considering free heat gains). Moreover, since such estimations are often carried out by different technicians and often through different reference standards for the radiators' heat output estimation, they lead to huge deviations (e.g. in Ap_1, Ap_2 and Ap_3). The comparison is particularly interesting since, although the fixed proportionality principle is no longer allowed in numerous MS, it is the most common for fixed costs sharing and, often, for involuntary ones. Comparing these methods, it emerges that, despite the simplicity and uniform distribution of costs, the floor area method is not representative neither of the potential individual consumptions nor of the heat output, favouring above all the more dispersing apartments (i.e. AP_6, Ap_7 and Ap_8, located on the top floor).

Table 3.13 - Responsibility principle: Heat cost share 2016-2017 in the investigated building

Floor	*Apartment*	*Individual consumptions*			*Voluntary/Involuntary (Italy)*				*70/30 (EU)*	
		AU	*Share, %*	*Share, €*	*Vol. Share, %*	*Unvol. Share, %*	*Share, %*	*Share, €*	*Share, %*	*Share, €*
1st	Ap_1 (type A)	3651	11.0%	607.18	11.3%	10.7%	11.2%	613.25	11.4%	626.92
	Ap_2 (type B)	3798	11.1%	609.28	11.8%	9.6%	11.2%	615.36	11.4%	628.39
	Ap_3 (Type C)	3101	9.4%	519.13	9.6%	17.3%	11.7%	640.91	10.6%	582.53
2nd	Ap_4 (Type A)	3445	10.5%	578.69	10.7%	7.7%	9.9%	543.64	11.0%	606.98
	Ap_5 (Type B)	2584	7.8%	431.02	8.0%	7.3%	7.8%	429.99	9.2%	503.61
3rd	Ap_6 (Type C)	5337	17.0%	934.28	16.6%	18.0%	16.9%	930.67	15.9%	873.14
	Ap_7 (Type A)	4956	15.5%	851.03	15.4%	15.0%	15.3%	839.62	14.5%	797.61
	Ap_8 (Type B)	5367	17.6%	968.19	16.6%	14.6%	16.1%	885.35	16.0%	879.62

From data in Table 3.13 it can be pointed out that allocation methods based on the responsibility principle (i.e. on the actual consumptions of each dwelling) penalize on average the more unfavourable dwellings in terms of energy need (e.g. those on the top or on the first floor). An exception is represented by those users who, thanks to the reduced use in terms of on-off hours or to the higher propensity to save energy in terms of lower set point temperatures (e.g. Ap_3), behave intentionally to consume less. This results in a high economic load, leading to charge some tenants up to twice the energy costs (e.g. Ap_8 compared with Ap_5), and it is only partly mitigated by the "Voluntary/Involuntary" and by the percentage reduction "70/30" methods aimed to balance actual consumption with the expected needs. Finally, it is interesting to highlight that the less critical apartments from the thermal losses point of view (i.e. Ap_4 and Ap_5) are also those that never present a share of actual consumption lower than potential ones. This is probably due to the oversized heating plant and/or to the stolen heat issue.

Table 3.14 - Fairness principle: Heat cost share 2016-2017 in the investigated building

Floor	*Dwelling*	*Swiss Method (reduction factor)*				*Greek Method*			
		CF	*AUc*	*Share, %*	*Share, €*	*Fixed share*	*Var. Share*	*Share, %*	*Share, €*
1st	Ap_1 (A)	-13.1%	3747	11.6%	639.11	3.3%	8.2%	11.5%	632.77
	Ap_2 (B)	-12.0%	3944	12.2%	672.70	3.0%	8.5%	11.5%	631.82
	Ap_3 (C)	-23.3%	2807	8.7%	478.71	4.5%	7.0%	11.5%	630.29
2nd	Ap_4 (A)	-3.1%	3943	12.2%	672.47	2.8%	7.7%	10.5%	577.19
	Ap_5 (B)	-2.0%	2989	9.3%	509.74	2.6%	5.8%	8.4%	463.11
3rd	Ap_6 (C)	-23.3%	4830	15.0%	823.86	3.8%	12.0%	15.8%	866.28
	Ap_7 (A)	-17.0%	4854	15.1%	827.86	3.9%	11.1%	15.0%	826.14
	Ap_8 (B)	-19.1%	5126	15.9%	874.35	3.8%	12.1%	15.8%	871.20

Table 3.15 - The proposed method: Heat cost share 2016-2017 in the investigated building

Floor	*Apartment*	*Proposed Method*			
		Extra-Cons. factor	*AUc*	*Share, %*	*Share, €*
1st	Ap_1 (A)	-17.3%	4047	12.6%	690.20
	Ap_2 (B)	-19.4%	4086	12.7%	696.88
	Ap_3 (C)	-25.6%	3422	10.6%	583.65
2nd	Ap_4 (A)	0.0%	4471	13.9%	762.61
	Ap_5 (B)	0.0%	3610	11.2%	615.77
3rd	Ap_6 (C)	-34.8%	4592	14.2%	783.24
	Ap_7 (A)	-41.6%	3919	12.2%	668.45
	Ap_8 (B)	-42.9%	4092	12.7%	698.00

Regarding the use of "fairness” principle in a typical social housing building, data in Table 3.14 and Table 3.15 show that compensation methods available in literature (e.g. the Swiss and Greek methods) do not allow an effective compensation of inequalities within the building. These inequalities are mainly due to the energetic inefficiencies of the building, if compared to the “voluntary/involuntary” and to the “70/30” sharing methods. To this aim, the method proposed seems to be much more effective, while maintaining the principle of responsibility and awareness of consumption and sharing among different tenants the costs related to the energy inefficiency of the common parts. The deviations between different compensation methods shows that the effects of compensation of the proposed method are much more incisive on the apartments at the top floor (about -40%) making the share of energy costs comparable between apartments with similar floor area and of the same type (with the same on-off hours and set point temperatures).

In Figure 3.10 an overview of the results in terms of heat share for each apartment in the investigated building is presented.

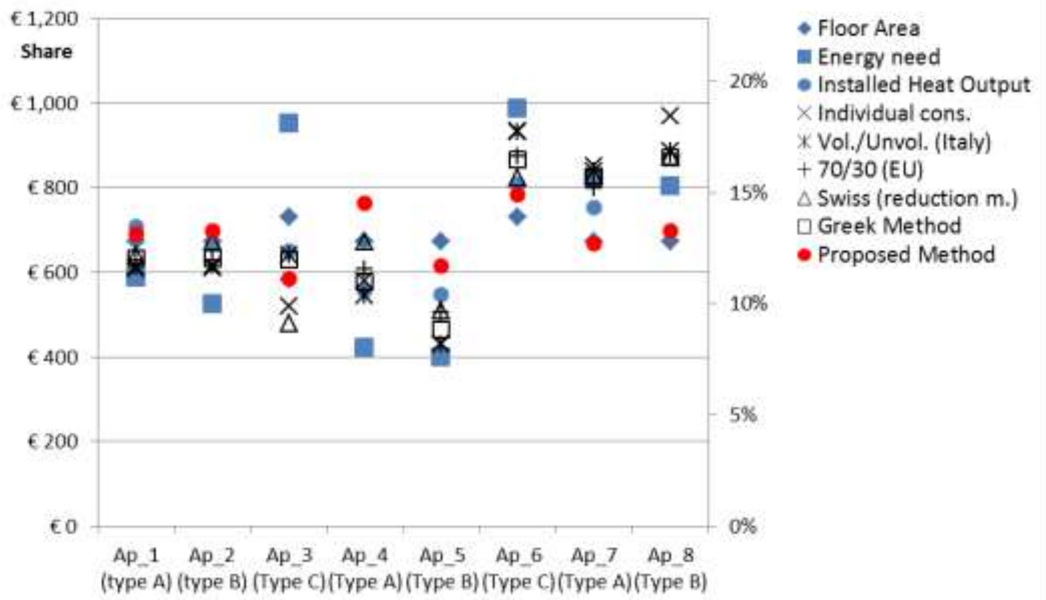


Figure 3.10 - Comparison between different cost allocation methods in the investigated social housing building

From the analysis of Figure 3.10 it can be highlighted that huge deviations clearly emerge among different allocation methods, especially for those apartments presenting higher propensity to heat saving (e.g. Ap_3) or larger heat losses (e.g. Ap_6, Ap_7 and Ap_8). The proposed method seems to be fairly sustainable since shares for disadvantaged apartments are corrected and the propensity to heat saving of single tenants is however encouraged.

3.5 *Case study #5: Estimating the impact of heat accounting on Italian residential building stock*

In this paragraph, the development, calibration and validation of a model to predict energy consumption in Italian residential sector has been developed, calibrated and validated is presented. This work, has the main aim to assess, at the policy level, the effectiveness of the European energy policy about individual heat metering and accounting systems in terms of potentially achievable national energy saving. The model has been also used to evaluate the effect of different fiscal incentive measures in increasing the spread rate of these systems on the Italian territory, by carefully considering their climatic and typological features.

With the necessary adjustments, the results of this 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.

3.5.1 Methodology

To estimate the Italian energy consumption for space heating, a calculation method based on the classification of the building stock in building typologies [159, 179, 180] has been developed. The modelling scheme followed five subsequent phases, as shown in Figure 3.11.

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 [175, 180]. To this aim, a Building Typology Matrix (BTM) has been developed 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 <u>*phase 3*</u> 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 [181, 182]. Data on actual energy consumption of each region have been obtained from the available European databases and from REBs (provided by ENEA).

In <u>*phase 4*</u> 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 <u>*phase 5*</u> 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.

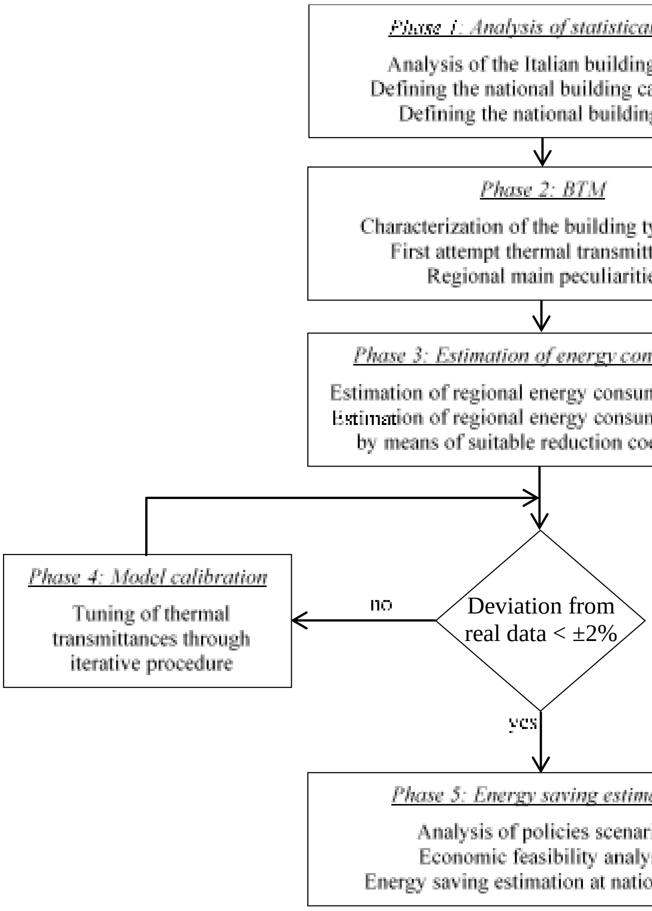


Figure 3.11 – Flow chart of the developed model.

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 4.5 and Figure 3.12. 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 3.16 - Italian dwellings occupied by residents classified by category and construction age.

Building category	*Num. of dwellings*	*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%

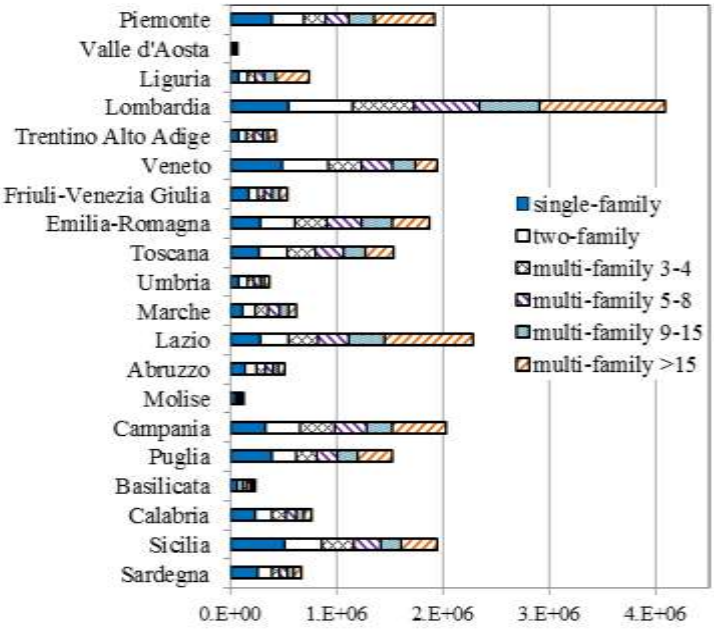


Figure 3.12 - Number of dwellings per region and per building type.

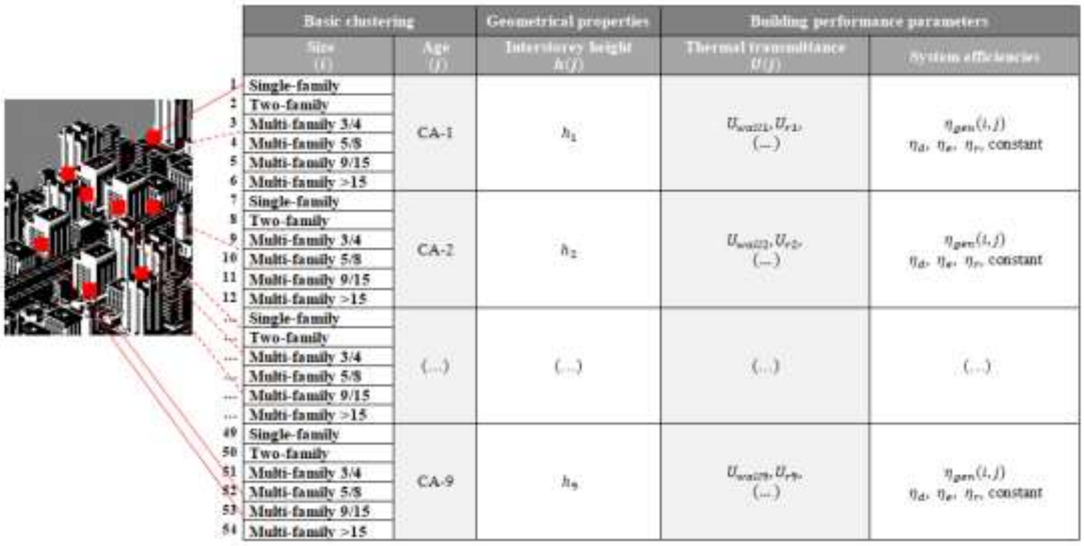
The same classification has been applied to the BTM, which consists of 54 rows (9 CA and 6 dimensional categories). Geometrical and thermo-physical properties have been assigned to each row as a function either of the CA or of the building dimensional category as follows:

i) inter-storey height (*h*), variable as a function of the CA; in absence of national statistical data of the residential buildings, values in [183] 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 [175];
iii) generation system efficiency, η_{gen} , as a function of the building category and CA [184].

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 author assumed the average value of the corresponding efficiencies in UNI 11300-2 [185]. 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 [186, 187] 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 they will refined 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 [102]. A graphic representation of BTM is given in Figure 3.13. 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 3.13 – 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 [188];
- the mean number of building floors by building size, obtained through a dwellings-weighted average, variable as a function of the building size [188].

Finally, historical data of HDD for each region have been obtained from Eurostat database [153].

The estimation of the building energy need for space heating has been performed according to the standard EN ISO 13790 [189]. 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 [190]. 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 [181, 182] 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 [191] and NEBs [192]. 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 [192]. 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 [193] 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 [20] 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 [27] 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 paragraph 2.3 of this thesis) has been considered and the following assumptions have been made [119, 188, 194, 195]:

- 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 [177].

The calculated $EP_{H,min}$ has 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.

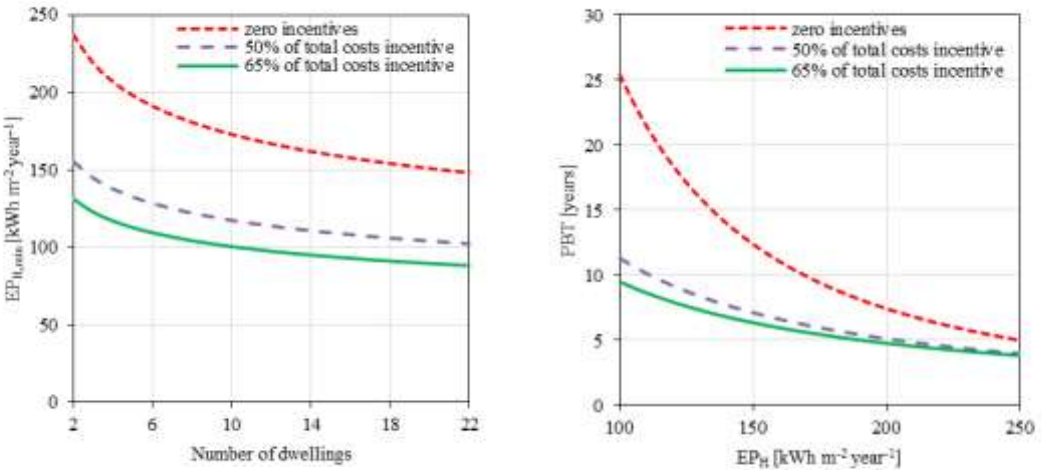
3.5.2 Results and discussions

Table 3.17 presents the results of the calibration and validation of the model described in the previous paragraph, 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 3.17- 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-Ven. 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 3.14a) shows the EPH,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 3.14b), 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 3.14 – 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 3.18 the estimated energy saving obtainable through different incentive policies and obligation approaches is reported. From data in Table 3.18, 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).

Table 3.18 –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-Ven. 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

CHAPTER 4. FORECASTING CONSUMPTION IN ENERGY NETWORKS

In this Chapter, the problem of measuring and profiling the energy consumption of domestic users is addressed giving focus on rules and modelling tools employed for natural gas networks, since these show high potential to make accurate predictions using simple regression-based models and few easily retrievable inputs.

The three different allocation methods for natural gas consumption will be described and their performances will be evaluated as part of the discussions carried out as case study #6 by examining the energy balance of a real natural gas network located in Italy. An innovative view is provided on the possibility of using these models, mainly employed for energy network management, as a support tool for simulation and forecasting of the consumption of urban building stocks.

4.1 Overview on Natural Gas Networks rules and regulations

With European (EU) Natural Gas (NG) market liberalization (first Gas Directive [196]), the organisation and management of the gas market has radically changed and its reform is still an ongoing project (Figure 4.1).

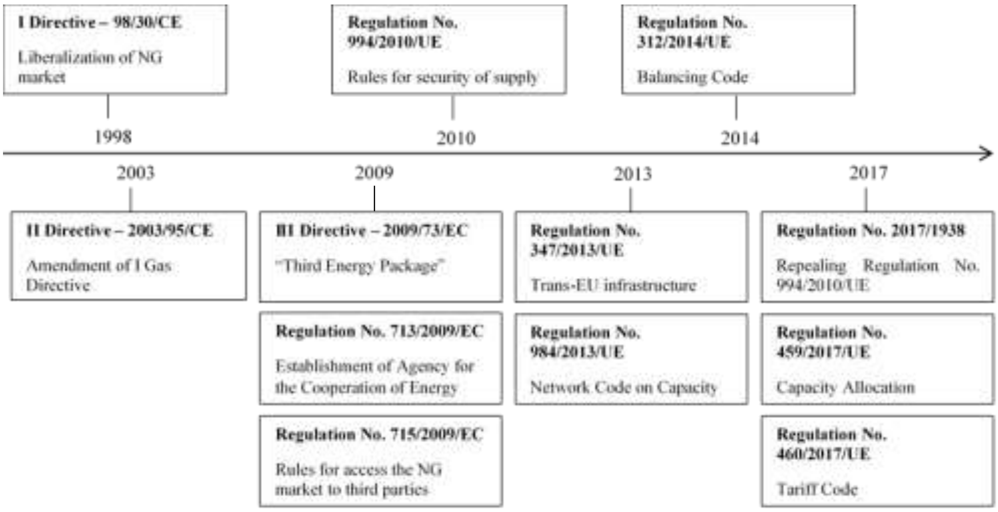


Figure 4.1 –NG regulation evolution in Europe

In the competitive gas market, many different actors – such as shippers, Transmission System Operators (TSO), distribution companies etc. – must be properly coordinated in order to ensure security and efficiency of the NG system.

Despite the common goal set by Member States (MS) to achieve a single common market, as a matter of fact EU gas market is constituted by the union of small national or even local networks.

Moving towards a greater market integration, rules on gas balancing of transmission networks have been established with EU Commission Regulation No. 312/2014 [197], in order to facilitate gas trading across balancing zones and to guarantee correct balancing activities across the EU borders.

Balancing represents, in particular, the instrument that TSO must use to ensure the network operation within given pressure limits and to achieve an end-of-day line-pack position that allows the transport network to operate economically and efficiently. By performing network balancing, in particular, the network operators ensure the equilibrium over time between NG entries and withdrawals. This is essential for the operation of the network and to guarantee the security of the system and the continuity of supplies.

Every network user has its own balancing portfolio, a balancing equation whose result is the user imbalance for a given gas day. Every gas-day, the network users are required to make a forecast of the withdrawals for the following gas-day in order to ensure the achievement of a neutral (balanced) position at the end of the day. An imbalance position also results in an economic compensation to be paid. This obligation requires the definition of proper demand estimation models for final users.

In fact, in many EU Countries the vast majority of final users is represented by small residential and commercial utilities with heating, cooking, hot water production and cooling purposes [198]. Their consumption is usually metered only few times a year and for this reason they are identified as Non-Daily Metered (NDM). In fact, despite the Third Energy Package [199, 200] requires Member States to ensure implementation of smart metering systems for all final users, this obligation is conditional on a positive economic assessment of the long-term cost-benefit analysis and a specific implementation program for smart metering in the gas sector has not even been set [201]. In this direction, only five EU Member States (Ireland, Italy, Luxembourg, Netherlands and UK), decided to carry out smart meters rollout in the gas sector by 2020 to allow a daily metering of final users, while twelve will not even proceed with the gas meters rollout, as the results of the cost-benefit analysis were negative. In this context, estimation, forecasting and profiling energy demand and consumption at both urban and larger scales (neighbourhoods, cities, energy networks etc.) are, undeniably, fundamental tools for energy management. In fact, they represent a key issue in numerous contexts, such as planning building retrofitting strategies and energy production, reducing CO_2 emissions, capacity allocation, price estimation, continuity of supply, estimation of unaccounted gas etc..

Allocation and forecasting represent an issue not only in NGN, but also in district heating and cooling networks, in cases where the heat is only metered at a building level and the delivered energy need then to be subdivided into the heating and hot water consumption, or allocated to single tenants. Besides, forecasting and estimating models may be useful tools also for building stocks fully metered by means of smart gas meters, when energy consumption loads have to be reconstructed due to failures of the measurement or the transmission systems.

Methods established in the scientific literature to simulate the building energy consumption at urban scale belong to different categories: the so-called *bottom-up* engineering models, with which the energy consumption on macro-scales is built by simulating the energy consumption of the buildings of the selected area through physically based equations, and the *top-down* models, which typically estimate the aggregate energy consumption of a building stock by establishing a relationship between the energy use and different drivers [160]. Within top-down models, *data-driven* approaches start from real energy consumption data coming from smart-metered district or cities, and by means of suitable techniques (machine learning algorithms, regression methods etc.) they make predictions by learning from historical data [202, 203]. These last usually require the use of a huge amount of data (i.e. smart meters data) during training phase, which are of course not always available for NDM customers.

In the following, emphasis will be given to description of methodologies mostly applied in NGNs for allocation purposes, since these show high potential to make accurate predictions using simple regression-based models and few easily retrievable inputs. These models could be useful for both the initial calibration and the validation phases of simulation models of residential building stocks, whose characteristics may be mainly unknown (e.g. thermo-physical building parameters, plant configuration, behavioural aspects and so on), and could stand as useful tools also for energy simulators in different working phases.

4.2 Profiling energy consumption in Natural Gas Networks

In the gas industry, alternative methods can be found to model gas consumption for general forecasting and gas management purposes, including: regression models [204, 205]; auto-regressive integrated moving-average or autoregressive models including exogenous variables [206, 207]; neural networks [208, 209]; and generalised additive models [210]. A review paper on the topic of forecasting natural gas consumption was prepared by Soldo [211], who summarised the approaches used by researchers based on the forecasting area (world, national, individual consumer), forecasting horizon (hourly, daily, monthly), gas data measurements used and the model applied.

In relation to NDM consumption estimation and profiling, regression-based models are considered to offer a more transparent methodology compared to the alternatives. This is an important consideration when there are stakeholders such as energy regulators and energy suppliers who are concerned with methodological transparency [212]. In fact, energy regulators and network managers, as well as the competent authorities, are required to make estimates with a limited number of significant parameters and with a high level of accuracy, in order to continuously supply industrial and domestic consumers and to avoid dangerous service interruption.

In Europe, simple, lumped-parameters models are used to estimate gas consumption for general forecasting and gas management of NDM customers (allocation for balancing purposes). These represent a sort of "hybrid" models, a cross between the bottom-up and the data-driven approaches (also referred as “bottom-up statistical” [158]). These models are generally employed for consumption allocation purposes in energy balancing of the NGN and make energy consumption estimates and forecasts in a given period (month, year etc.) by means of: *i)* energy consumption within a random period, *ii)* climatic variables (outdoor temperature, wind speed, temperature of the previous days etc.) and *iii)* Standard Load Profiles (SLP) obtained from samples of frequently read users (day/intra-day frequency) clustered by end use category.

SLP curves are built quite differently within European Countries, since they need to suit the characteristics of the particular building stocks and the peculiarities of different consumers, which also depend on numerous economic and cultural aspects. Two main methodologies have been identified in the current European regulatory context to develop SPLs:

- Linear, exponential and polynomial regressions, making use of climate-related variables and particular dummy variables for weekends, holidays, holiday seasons etc.; these are used for the estimation of NDM consumption for the Irish [204], English [205] and Italian [213] gas markets for example;
- Sigmoid curves, currently applied in German NGN, which are tilted S-shaped curves suitable for modelling the gas consumption characteristics: gas usage is high and constant at low temperatures, decreases approximately linearly with

increasing temperature for mid-range temperatures, and is constant and low at high temperatures [214].

In [214] the authors state that, after comparing linear, parabolic, exponential and sigmoid models for a single consumer, they observed best performance using the sigmoid model for virtually all consumers of the Slovenian NGN. However, whether the use of the first or the second type of SLPs is preferable is not completely clear, and it is in the opinion of the author that a dedicated and systematic study should be undertaken in order to compare the performances of several NDM forecasting methodologies in different countries and climatic conditions.

In the following, three methods for allocating the NG consumption of NDM consumers for balancing purposes are briefly described and analysed, as representative of the above mentioned SLPs definitions. The methods investigated are currently in use in Italy, Germany and United Kingdom, which are the main countries for NG consumption within Europe and are therefore also considered representative of the technical and regulatory state of the art on this subject.

In all the three investigated methods each NDM customer is first assigned with an end-use category, which identifies either the final use of the natural gas (heating, cooking, hot water production, cooling, technological use etc.) or the size, in terms of natural gas consumption of the customer [205, 213, 215-217]. The estimation of the annual NG consumption ($\mathrm{NDM_{AC}}$) and daily NG consumption ($\mathrm{NDM_{DC}}$) of each NDM user is then performed as reported in equations (4.1) and (4.2).

$$NDM_{DC} = CV \cdot SLP_d \cdot CF_d \tag{4.1}$$

$$NDM_{AC} = CV \cdot \sum_{d=1}^{365} SLP_d \cdot CF_d \tag{4.2}$$

Where CF is the correction factor for weather conditions, day of the week, holidays etc., SLP_d is the Standard Load Profile defined by the national regulation and CV represents the Customer Value, which is a measure of the “amplitude” of the load profile of the customer, being directly related to two meter-readings at days 1 and n (L_1 and L_n), as per equation (4.3).

$$CV = \frac{L_n - L_1}{\sum_{d=1}^{n} SLP_d} \tag{4.3}$$

The three analysed methods, although presenting methodology similarities, differ for SLP and climate definition as described in Table 4.1.

Table 4.1 –End-use categories of the analysed sample

IT	**SLP**	SLPs are given via a specific equation, whose parameters are fixed by the National Authority as a function of climate, of the customer type etc.
	Climate	There is no explicit weather variable in the equation. Weather is however taken into account in the equation parameters which are defined by climatic zone.
UK	**SLP**	SLPs are defined as a proportion of the average seasonal normal demand. Seasonal cut-offs and turn-on are used to better manage seasonal conditions. SLPs are defined and updated by a third party basing on samples of smart-metered users.
	Climate	A Composite Weather Variable (CWV) is defined to linearize the daily NDM Demand. The weather data used for the CWV are temperature and wind speed and a set of parameters that provide a linear relationship to demand.
DE	**SLP**	Two different variations of SLPs are given, which are both temperature-dependent sigmoid-like curves to which seasonal specific space heating and water heating terms are added to account for seasonal peculiarities.
	Climate	An “allocation temperature” is defined, calculated as geometric series of the temperatures measured within the forecasting day and the previous 3 days, to consider the heat capacity of buildings.

In the following, major details about the single methodologies are given. Due to a non-disclosure agreement between the third party and the network operators, it has not been possible to access to the UK regression coefficients of the defined customer profiles. However, in the presented case study new profile have been developed by applying the UK methodology to the real natural gas consumption of residential customers for the year 2017.

Italy

In Italy the rules to perform the balancing of NG networks are defined by the Regulatory Authority for Energy, Networks and the Environment (ARERA) in dedicated documents [213]. For a first customer categorization, Italy applies a classification (based on Rénard series) of the gas-meters depending on their flow rate from G1.6 (nominal flow rate of about 1.6 m^3/h) to G6500 (nominal flow rate of about 6500 m^3/h) [52]. Gas-meters for domestic and small-technological utilities (NDM customers) mainly belong to G4 and G6 categories. Industrial customers, depending on their annual consumption, belong to the class from G10 and above and currently all DM. For balancing purposes, NDM customers are segmented in different final-use customers categories depending, as described in Table 4.2.

Table 4.2 – End-use categories

Code	**Final use**	**Thermal component**
C1	Space heating	Yes
C2	Cooking and hot water production	No
C3	Space heating, cooking and hot water production	Yes
C4	Air conditioning use	No
C5	Air conditioning use and space heating	Yes
T1	Technological use (artisanal and industrial)	No
T2	Technological use and space heating	Yes

Depending also on the number of days per week in which the customers need NG availability (mainly for technological purposes), customers are also given with a "withdrawal class", as per Table 4.3.

Table 4.3 – Withdrawal classes

Code	**Days of NG use, per week**
1	7 days
2	6 days (excluding Sundays and official holidays)
3	5 giorni (excluding Saturdays, Sundays and official holidays)

With reference to domestic customers, the final-use categories are assigned as follows:

- for NG consumption below 500 Smc, the use category C2 is associated;
- for NG consumption between 500 and 5.000 Smc, the use category C3 is associated;
- for NG consumption above 5,000 Smc the use category C1 is associated.

The SLP for each customer is then calculated as per equation (4.8).

$$SLP = \beta 1_{prof}\, c1^{\%}_{i,j,k} + \beta 2_{prof}\, c1^{\%}_{k} + \beta 3_{prof}\, t1^{\%}_{j,k} + \beta 4_{prof}\, c4^{\%}_{k} \qquad (4.4)$$

$$\forall\, i\, \in \{A, B, C, D, E, F\}, \forall\, i\, \in \{1,2,3\}$$

where:

- A, B, C, D, E and F are the Italian climatic zones;
- 1, 2 and 3 are the "withdrawal classes" as defined above;
- $c1^{\%}_{i,j,k}$ is the percentage value, in the day *k*, of the standard NG consumption for heating purposes associated to the climatic zone *i* and to the withdrawal class *j*;
- $c2^{\%}_{k}$ is the percentage value, in the day *k*, of the standard NG consumption for cooking purposes and/or to hot-water production;
- $t1^{\%}_{j,k}$ is the percentage value, in the day *k*, of the standard NG consumption associated to the technological use and to the withdrawal class *j*;
- $c4^{\%}_{k}$ is the percentage value, in the day *k*, of the standard NG consumption for cooling purposes;
- $\beta 1_{prof}, \beta 2_{prof}, \beta 3_{prof}, \beta 4_{prof}$ are specific coefficients defined to characterize each profile.

Germany

In Germany, for the purpose of balancing the entry and exit quantities on each day and for each gas transmission customer, entry and exit quantities belong to given balancing groups. These last are coordinated by the operators of the two market areas GASPOOL Balancing Services GmbH and NetConnect Germany GmbH & Co. KG. The balancing group managers have responsibility for actual balancing. The two market area coordinators manage activities within their market areas, focusing on operating the virtual trading point, on balancing group management and on control energy management.

In the actual regulation, the use of sigmoid SLPs is prescribed to forecast and correctly allocate NG consumption of NDM consumers, although this has been in use since the early 2000s for similar purposes [218]. According to the German Federal Network Agency, SLPs shall be defined at least for three types of final consumers, which are: business entities, cooking gas and heating gas customers.

The distribution system operator can choose between two different variations of SLP calculation: the synthetical and the analytical ones. The first variation uses a "bottom-up" approach in which the representative load profiles of end users are calculated basing on the individual customer value, forecasted temperature, day of the week etc., and whose result is a forecasted consumption for the following gas day. The second one makes use of a "top-down" approach in which the "residual load" of the previous day, calculated as difference between the total entries in the distribution system and all metered consumption, is divided upon individual suppliers using suitable decomposition factors [219]. In the case of the analytical procedure, the allocation is also based on load profiles calculated with the synthetic load profile method.

To reduce the forecasting errors and the consequent occurrence of deviations in gas network balancing, the German Association of Energy and Water Industries (BDEW) makes available specific guidelines [216].

SLPs are frequently updated and modified to meet higher standards of forecasting and allocation purposes. At present, the official guidelines refer to profiles developed by the *Technical University on Munich* (TUM) and to the so called SigLinDe profiles, developed by *Forschungsgesellschaft für Energiewirtschaft mbH* (FfE) as further improvement of the TUM profiles with a specific project commissioned by the BDEW [217]. SigLinDe profiles represent, in particular, the composition of the sigmoid profiles, which account for the temperature sensitiveness of the NG consumption, and a linear term, whose function is to adjust the profiles for the cold and the high temperatures and are intended to face the problem related to the summer-winter effect (over-allocations in summer and sub-allocations in winter). A qualitative representation of SigLinDe profiles is given in Figure 4.2.

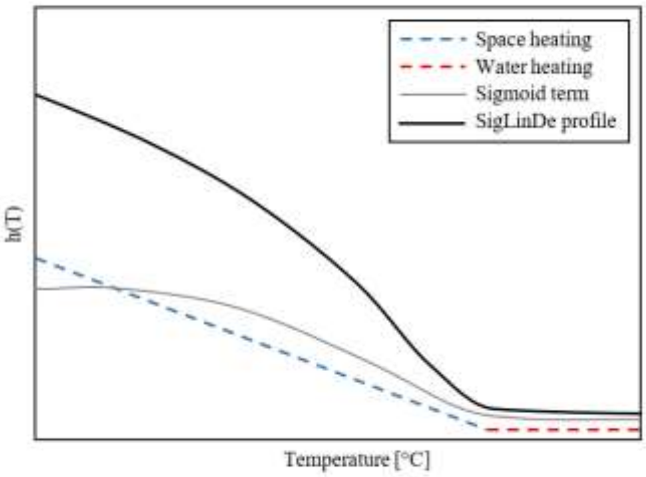
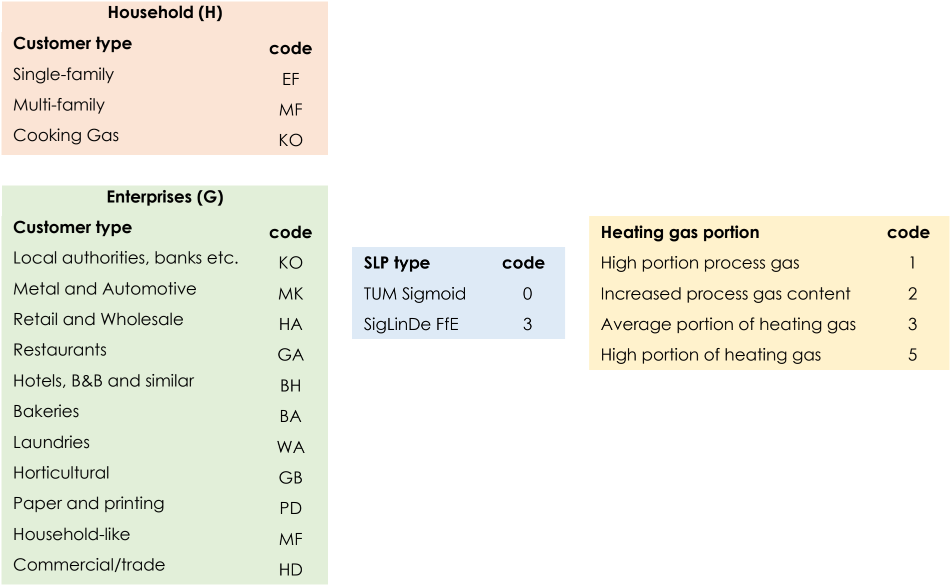


Figure 4.2 – Qualitative representation of sigmoid SLPs

BDEW has specified three household/heating gas profiles (H-type) and a wide range of SLP types in the commercial/trade/service (G-type) sector. In order to account for diverse temperature sensitiveness of different consumption profiles, three profile variants (codes from 03 to 05 with increasing heating gas portion) are available in the household sector, while in the commercial one, five variants (codes from 01 to 05 with increasing heating gas portion) are available. An overview is given in Figure 4.3.



Household (H)

Customer type	**code**
Single-family	EF
Multi-family	MF
Cooking Gas	KO

Enterprises (G)

Customer type	**code**
Local authorities, banks etc.	KO
Metal and Automotive	MK
Retail and Wholesale	HA
Restaurants	GA
Hotels, B&B and similar	BH
Bakeries	BA
Laundries	WA
Horticultural	GB
Paper and printing	PD
Household-like	MF
Commercial/trade	HD

SLP type	**code**
TUM Sigmoid	0
SigLinDe FfE	3

Heating gas portion	**code**
High portion process gas	1
Increased process gas content	2
Average portion of heating gas	3
High portion of heating gas	5

Figure 4.3 – German classification of end users

SLPs are calculated as a function of the temperature as per equation (4.5).

$$SLP(T) = \left[\frac{A}{1+\left(\frac{B}{T-40}\right)^{C}} + D\right] + \left[max\begin{Bmatrix} m_H \cdot T + b_H \\ m_W \cdot T + b_W \end{Bmatrix}\right] \tag{4.5}$$

Where:

- A, B, C and D are coefficients of the sigmoid,
- the second term of the summation in (4.5) modifies the sigmoid profile by adding a space heating (H) or a water heating (W) correction (with coefficients m and b representing, respectively, the slope of the lines and the intercept at 0 °C)
- T is the allocation temperature calculated as geometric series as per equation (4.6) given that d, d-1, d-2, d-3 subscripts stand for allocation day and relative previous days, allowing to consider the heat capacity of buildings.

$$\overline{T_d} = \frac{T_d + 0.5\,T_{d-1} + 0.25\,T_{d-2} + 0.125\,T_{d-3}}{1 + 0.5 + 0.25 + 0.125} \tag{4.6}$$

United Kingdom

In UK, the Uniform Network Code (UNC) represents the reference point for the gas industry, comprising a legal and contractual framework to supply and transport gas. In the last years, the UNC has undergone modifications due to the implementation of the so called “Project Nexus”, whose aim is to modify the approach involving an annual estimate of unidentified gas to address the misallocation of unidentified gas that occurred under the previous regime [220].

NDM demand estimation, with particular reference to small NDM, represents a key instrument when it comes to balancing the Gas Network and estimating unidentified gas. In the actual regime, every NDM supply point belongs to a given End User Category (EUC) for which specific demand models are defined. At present, 9 EUC bands have been defined. Small NDM are grouped in consumption bands from 1 to 4 (up to 2196 MWh/year), while large NDM pertain to EUC bands from 5 to 9. Each band is also characterized for 13 English local distribution zones. An overview of the defined EUC bands is given in Table 4.4.

Table 4.4 – End User Categories of English NG customers

Consumption range [kWh/year]		**EUC band**
0	73200	1
73201	293000	2
293001	732000	3
732001	2196000	4
2196001	5860000	5
5860001	14650000	6
14650001	29300000	7
2930001	58600000	8
58600001		9

The NDM demand estimation methodology is defined in the homonymous document [205] as per equation (4.7).

$$SLP_d = \frac{SNDE_d}{\left(\frac{\sum_{d=1}^{n} SNDE_d}{n}\right)} \tag{4.7}$$

Where $\mathrm{SNDE_d}$ is seasonal normal demand for the EUC for day *d*, determined by applying the averaged results of the regression analysis (constant and slope) to the seasonal normal values of the Composite Weather Variable (CWV), combined with any other relevant adjustments (e.g. day of week, holiday factors, summer reductions).

Demand models are developed for EUC based on a statistical relationship between the aggregate demand for a sample of NDM meter points for one or more years, actual weather data and other relevant factors, including day of the week.

The weather data currently used in the development of the CWV are temperature, at two-hourly intervals throughout the day and night, and wind speed, at four-hourly intervals throughout the day and night and a set of parameters designed to provide a strong linear relationship to NG demand. A qualitative representation of the UK SLPs is given in Figure 4.4.

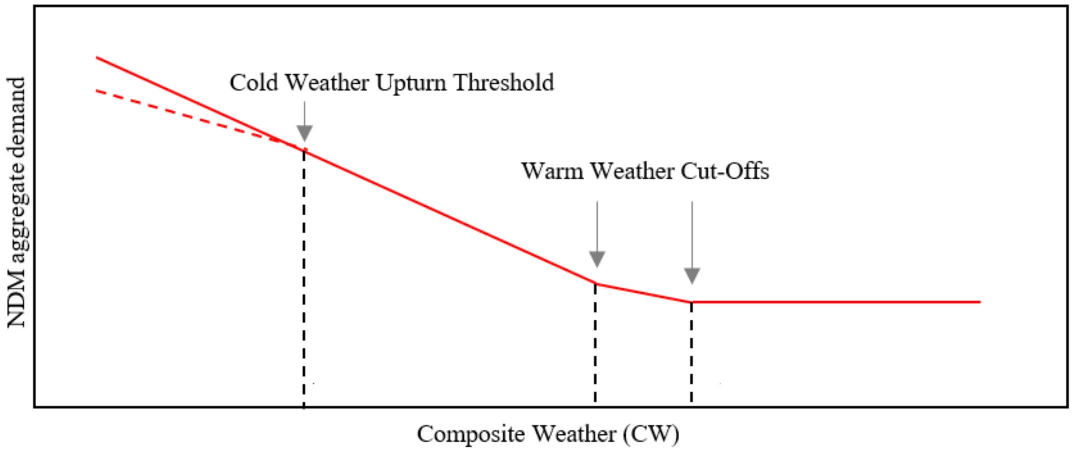


Figure 4.4 – Qualitative representation of UK SLPs

4.3 *Case study #6: Standard Load Profiles for Natural Gas consumption simulation at urban scale*

In the following, the three different NG allocation methods described previously have been investigated with the aim of assessing the accuracy of using these last to effectively predict the energy consumption of a building stock at urban scale. To this end, the case study of a building stock in Southern Italy with about 16000 NDM and 4000 buildings is presented and discussed. The performances of the investigated methods have also been evaluated at two different spatial scales, city and neighbourhood, by determining the monthly and yearly errors from the real measured values.

4.3.1 Materials and methods

NGN and dataset description

The author investigated a local distribution NGN located in Southern Italy supplying 3828 residential buildings (climatic zone C, 1134 Heating Degree Days). The NGN is made up of 15980 NDM customers equipped with G4 gas meters and about 80 Daily-Metered (DM) customers equipped with smart gas meters (i.e. all greater than G4, according to the rollout program). These latter measure NG consumption of small and medium industries and public offices including also few apartment buildings equipped with centralized heating system. In detail, 48 DM users are large and medium industrial users and the remaining 32 are public offices and apartment buildings equipped with centralized heating system (domestic use). For sake of simplicity, in the present analysis, the author will refer to the energy consumption of NDM users, DM public offices and domestic users as “Residential”, identifying with this label utilities with heating, cooking, hot water production and cooling purposes. An overview of the analysed urban building stock is given in Figure 4.5.

Figure 4.5 - The analysed building stock

For this study, three sets of data, provided by the distribution company, were available:

1. NDM meter readings within a period of about three years between 2015 and 2017;
2. DM meter readings from smart gas meters within the year 2017 on a daily basis;
3. total natural gas supplied to the network, in the year 2017 on a daily basis.

Regarding NDM readings, although Italian regulation establishes a minimum requirement of two attempts of meter reading per year, the actual availability of data for each NDM users is conditioned to the accessibility to the gas meter in absence of the customer (i.e. gas meter inside or outside the property). Thus, within the given period, the number of readings is not the same for all users and some readings are also missing in the considered period. In these cases, an average customer value has been assigned basing on the end user category.

The application of the described methods, of course, required an effort to adapt the Italian end user categories, which were already assigned to each customer of the dataset, into German and English ones. This has been possible thanks to additional information provided by the distribution company, which allowed to identify the type of use of both technological and residential customers.

Only 3% of end user category was not known and it has not been possible to get this information elsewhere. For this limited set of users, it was chosen to replicate the sample distribution and to allocate the end user categories by preserving the same proportion observed in the assigned dataset.

Climatic data (temperature, solar radiation, wind speed, relative humidity etc.) are weather historical simulation data, and have been provided by the Swiss weather service provider *meteoblue AG* (www.meteoblue.com).

Estimate of NG consumption & model performance evaluation

The real natural Gas Consumption of Residential customers (RGC) for space heating, cooking, hot water production and space cooling purposes in the given period (days from 1 to 365 of the year 2017), has been measured as the difference between the Total natural Gas Consumption (TGC) of the network and the Industrial natural Gas consumption (IGC) as per equation (4.8).

$$RGC_{meas} = \sum_{d=1}^{365} TGC_d - \sum_{d=1}^{365} IGC_d \tag{4.8}$$

The total RGC has been estimated as the summation of two contributions: the total NDM load, estimated by means of the methods above-described, and the total, known, residential DM load as per equation (4.9).

$$RGC_{est} = \sum_{d=1}^{365} \sum_{i=1}^{15980} NDM_{DC_{i,d}} + \sum_{d=1}^{365} \sum_{i=1}^{12} DM_{i,d} \qquad (4.9)$$

Finally, the knowledge of the real RGC allowed to calculate the relative error (e) of the natural gas consumption estimated by means of the investigated method on a monthly, seasonal and yearly basis, as per equations (4.10), (4.11) and (4.12) to evaluate the model performance when applied at urban scale.

$$e_{month} = \frac{RGC_{est,month} - RGC_{meas,month}}{RGC_{meas,month}} \qquad (4.10)$$

$$e_{season} = \frac{RGC_{est,season} - RGC_{meas,season}}{RGC_{meas,season}} \qquad (4.11)$$

$$e_{year} = \frac{RGC_{est,year} - RGC_{meas,year}}{RGC_{meas,year}} \qquad (4.12)$$

Figure 4.6 shows an overview of the methodology applied to determine the error of the analysed methods.

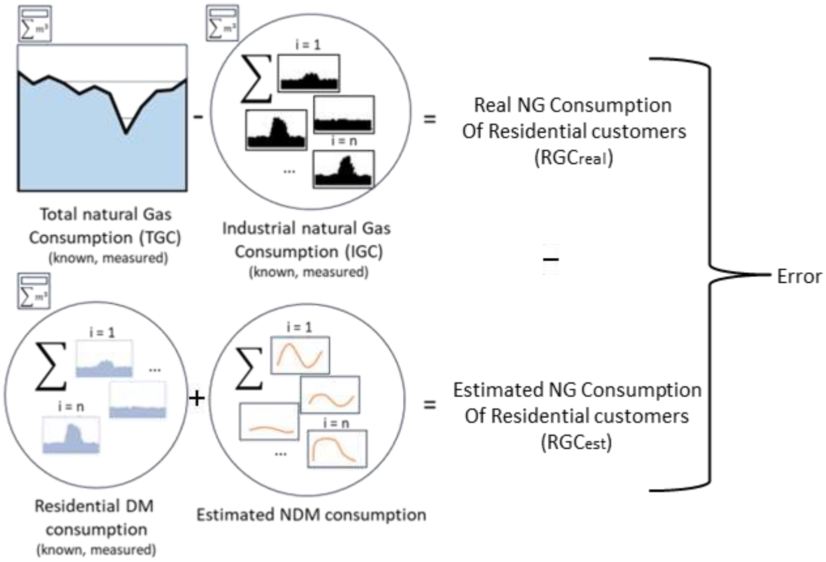


Figure 4.6 - Overview on the methodology applied to determine the error of the analysed methods

4.3.2 Results and discussions

Building-stock scale

Results of the application of the described methodologies are shown in Figure 4.7 and in Table 4.5, respectively on monthly and yearly basis. In Table 4.5, the same analysis is also shown aggregating the data for both the heating and the non-heating season.

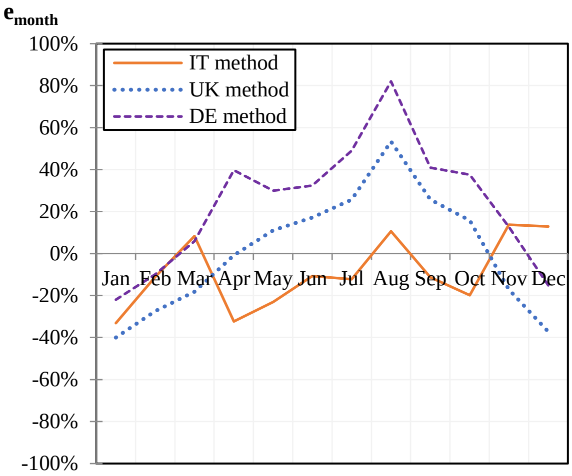


Figure 4.7 – Monthly relative error of the analysed methods applied to an urban scale

Table 4.5 –Errors of the analysed methods for: Heating Season (HS), non-Heating Season (nHS), year 2017

	Method	**IT**		**UK**		**DE**	
	RGC_{meas} [MWh]	**RGC_{est} [MWh]**	***e* [%]**	**RGC_{est} [MWh]**	***e* [%]**	**RGC_{est} [MWh]**	***e* [%]**
HS*	76 320	70 519	-8%	47 677	-38%	67 139	-12%
nHS*	31 797	25 245	-21%	38 441	+21%	47 765	+50%
Year	**108 117**	**95 764**	**-11%**	**86 118**	**-20%**	**114 903**	**+6%**

As highlighted in Figure 4.7 and Table 4.5, the investigated methods present high errors, which however, were smoothed on yearly basis resulting in far smaller values.

A consideration has to be done regarding the month of January 2017. In this case, in fact, all the methods greatly under-estimated the measured energy consumption of the building stock due to an exceptionally cold weather that occurred in Europe, affecting Central-Southern Italy as well. For the way it is defined (i.e. accounting for meter reading of previous years), the model is not capable to effectively describe extreme weather conditions.

As expected, Italian method performs better if compared to the other ones, as a result of the fact that the methods are applied to an Italian urban energy network. In fact, the application of SLPs defined for building stocks located in continental or cold climates (such as the German and the English ones) to Mediterranean ones, can result in lower quality. This should also explain why both the German and the English methods greatly over-estimate the energy consumption during summer months (from June to September), where also the gradual emptying of cities during July and August should be considered as one of the main uncertainty contributions.

Nevertheless, it has to be highlighted that, considering only the heating season, the German method presents performances comparable with those of the Italian one, sometime giving better results. This could strictly depend on the fact that the German SLPs are temperature-dependent curves, whereas for the Italian ones the climatic dependence is based only on the climatic zone and not on punctual temperature data.

On the other hand, the UK method always: i) under-estimated the energy consumption of the urban network during heating months (January to March, November, December), ii) over-estimated the energy consumption of the urban network during non-heating months. The low performance of the English method is probably due to the composite weather variable, which is built on the specific continental climate (i.e. wind and temperature) and not on Mediterranean one (i.e. temperature and solar radiation).

In Figure 4.8 the results of the energy simulation performed with the described methods are shown, highlighting their error from the measured residential energy consumption.

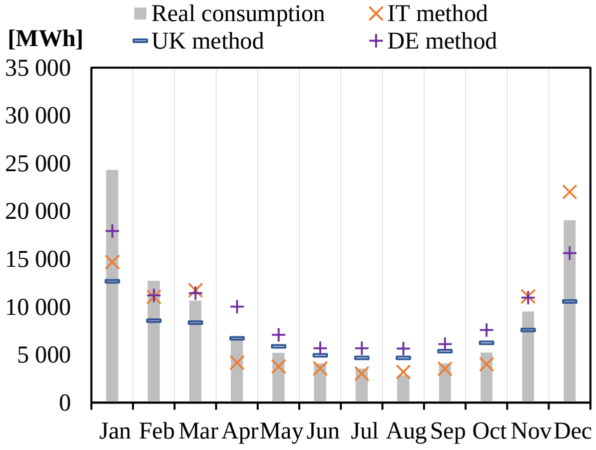


Figure 4.8 – Monthly consumption and relative error of the analysed methods

The application of these models was possible since, for the analysed case study, industrial users were all DM. This, however, represents a fairly replicable condition on most of the European natural gas networks as, generally, users with great energy consumption, as the industrial ones, are DM. Definitely, the greater the number of DM users (both industrial and residential), the lower will be the estimation error of the proposed methodology.

Regarding the estimated energy consumption errors, these are mainly due to DM users and NDM users. Regarding the first one, errors are mainly related to different devices and completeness of the measurement chain and could be statistically neglected; on the contrary, NDM users' systematic errors are due to:

- to the drift of the meters, that in some cases are very old meters;
- inaccurate user categorization;
- accuracy of SLPs given by national regulations and used to model final users' behaviour;
- number and accuracy of climatic data;
- frequency of successful meter-readings and period in which these have been performed.

Among all the above-mentioned contributions, the one related to the frequency of meter-readings has the greatest weight. In fact, the energy consumption of the users is extremely variable over time and depends on numerous variables, such as the weather conditions within the readings, the number of people and the occupancy coefficient, the propensity to energy saving.

Data in Figure 4.8 and in Table 4.5 have been calculated with almost one meter-reading per year per final user. The estimation error greatly decreases with increasing number of readings per year and simultaneously performing "reconciliation" sessions. For this reason, four scenarios of successful meter-readings attempts were simulated: i) almost one meter-reading per customer, per year, without reconciliation (scenario #0); ii) two meter-readings per customer, per year (scenario #1); iii) four meter-readings per customer, per year (scenario #2) iv) six meter-readings per customer, per year (scenario #3).

The different scenarios have been simulated under the hypothesis of 100% successful meter-readings, evenly distributed among the entire year 2017. This implicitly means that, on monthly basis:

- in scenario #0, none of the users presents error equal to zero;
- in scenario #1, one sixth of the users presents error equal to zero;
- in scenario #2, one third of the users presents error equal to zero;
- in scenario #3, half of the users presents error equal to zero.

In the following, Figure 4.9 shows the monthly standard deviation (σ) for each applied method, while Figure 4.10 shows the yearly error under the defined scenarios.

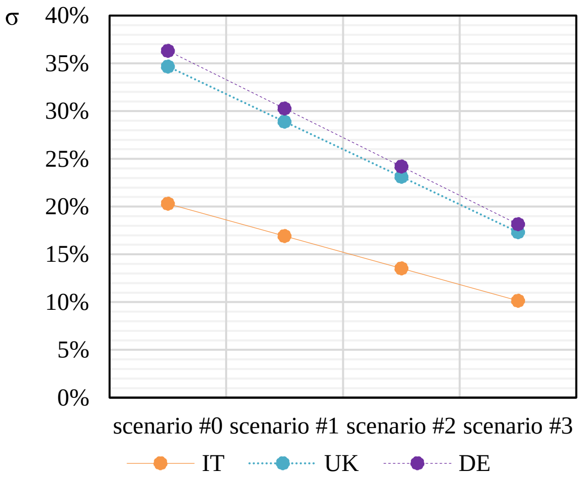


Figure 4.9 –Mean monthly standard deviation of the methods in each scenario, year 2017

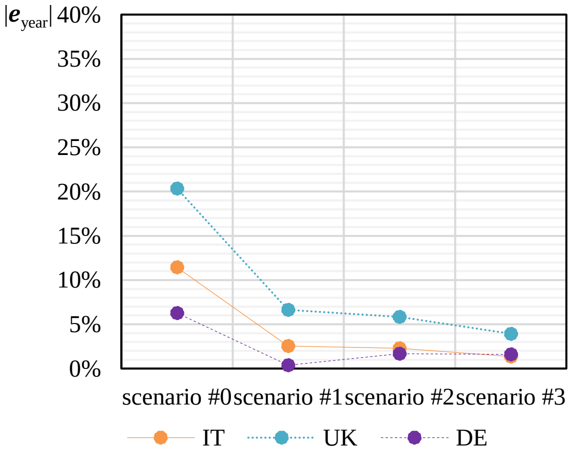


Figure 4.10 –Year error of the methods in each scenario, year 2017

Both the monthly standard deviation and the yearly error strongly decrease with increasing number of meter-readings, reaching absolute values respectively of about 10% and 2% with the Italian method. In fact, under the mentioned hypothesis, the yearly forecasting errors under scenario #0 (which were about -11%, -20% and +6% respectively for the Italian, English and German methods) all decrease below 5%, as shown in Figure 4.10.

Thus, the high potential of these methods for forecasting purposes is evident. This is particularly true if one considers that in Italy, and even in most of EU Countries, NG distribution companies are obliged to perform at least 2 meter-reading attempts per year (scenario #1).

Neighbourhood scale

Finally, the Italian method (that showed the best performance at the urban scale) was applied at a neighbourhood scale, by simulating the energy consumption of 5 buildings, whose energy consumption was remotely read by suitable smart gas meters and heating, cooking and hot water production services were available. The investigated buildings are shown in Figure 4.11.

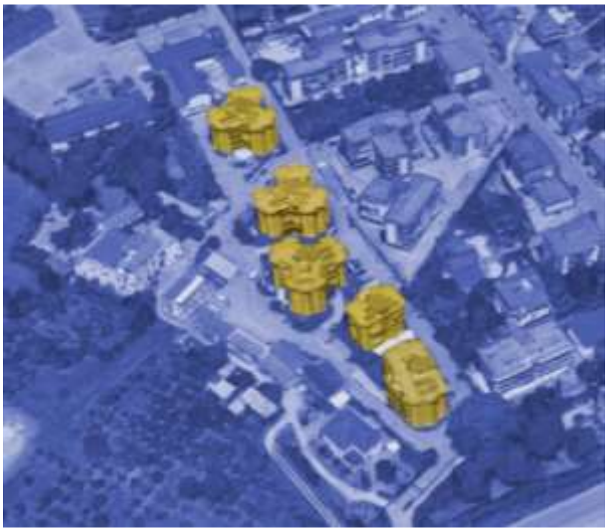


Figure 4.11 – Analysed neighbourhood

A number of one meter-reading during the forecasting year has been used for the investigated buildings. This allow to update the CV, calculated as per equation (4.3).

Figure 4.12 shows the results in terms of monthly error between the estimated and the measured energy consumption.

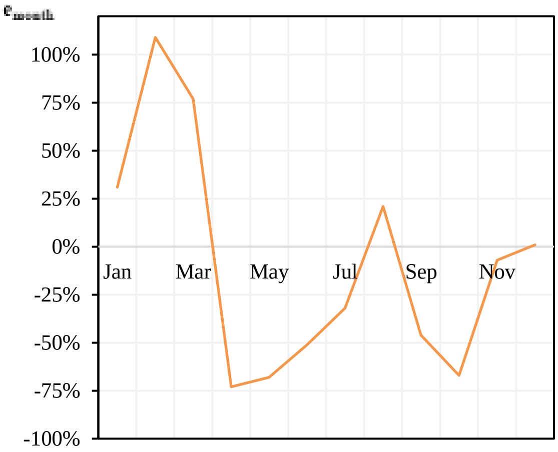


Figure 4.12 – Monthly error of the analysed method applied to a neighbourhood scale

In Table 4.6 measured and estimated energy consumption of the analysed neighbourhood are shown in terms of seasonal absolute energy consumption and error.

Table 4.6 – Measured and estimated energy consumption with relative seasonal errors, year 2017

	Method	**IT**	
	RGC_{meas} [kWh]	**RGC_{est} [kWh]**	***e* [%]**
HS*	213 374	303 443	+42%
nHS*	78 295	32 691	-58%
Year	**291 669**	**336 133**	**+15%**

* Heating Season (HS), non-Heating Season (nHS)

As expected, when reducing the scale of application of the model to a limited number of buildings, the error considerably increases, as a result of the lack of compensation effects, with a quietly different trend respect to the one observed at urban scale. Nevertheless, the seasonal error seems to be higher during the non-heating season, where the expected energy consumption of the five buildings is greatly under-estimated. This is due to the fact that the selected neighbourhood consists of new buildings with better thermal performance than the average ones. On the contrary, during the heating season, the model tends to over-estimate the energy consumption. This is probably due to the fact that some users may have started to heat their houses in October (i.e. before the official beginning of the heating season, which is 15th November for climatic zone C).

With the aim to evaluate more precisely the accuracy of the model with reference to the SLP, for the specific case of the neighbourhood, also the daily trend of the load profile estimates of the Italian method have been analysed. This allowed to highlight the effect of a meter-reading during the forecasting year on the estimated consumption profile (i.e. the effect of the CV update during the forecasting year) as shown in Figure 4.13. This last, in particular, shows the results of the performed analysis in terms of both measured and estimated daily energy consumption, respectively with and without CV update.

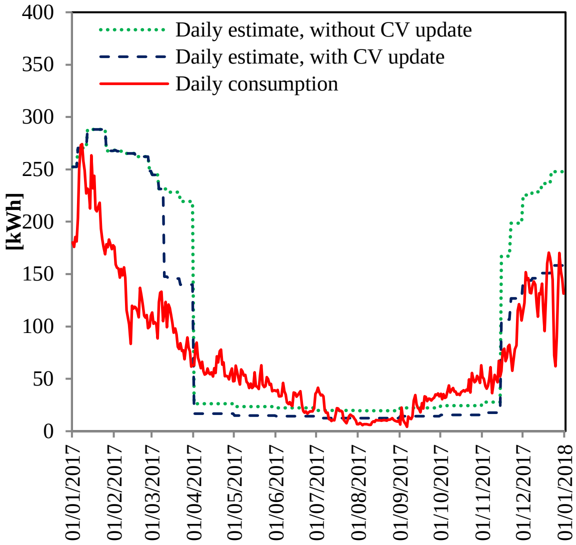


Figure 4.13 – Comparison between the real and estimated consumption of the neighbourhood under the defined scenarios

By analysing the data in Figure 4.13, it is clear that the application of the model is strongly affected by the frequency of meter-readings and also by the period in which the meter-reading is performed. In fact, a meter-reading within the simulated year (March 2017) strongly improves the performance of the model, reducing the gap between the measured and the estimated energy consumption.

CONCLUSIONS

In this work the complex issue of energy metering has been addressed with particular reference to individual energy metering and accounting in residential building sector. The subject has been treated in a multidisciplinary manner, allowing the reader to have a broader view of the problem in its different facets. To this aim, numerous research experiences have been reported in the present thesis as case studies.

The subject of energy metering in residential buildings is first tackled from a technical point of view in ***Chapter 1***, highlighting the major criticalities relating to the measurement of thermal energy on-field through the devices currently available on the European market. In respect to the reliability of direct and indirect heat accounting systems, some important limitations emerged with the analysis provided through this work, which are:

i. for direct heat meters: the drift over time, the influence of installation methods, the lack of periodic in-service verification standardized procedures, the huge uncertainties related to some operative conditions;
ii. for indirect heat accounting systems: the lack of standardized installation procedures, the uncertainty of rating factors for existing and old radiators, the need to displaying the rated allocation rules (instead of non-rated ones), the initial and periodic verification of the on-field reliability.

The analysis also highlighted the need to further improve on-field verification procedures of thermal energy meters in service. In fact, a very limited knowledge about long-term accuracy of direct heat meters exists. A number of operational issues affects the in-service meter accuracy and a common standardized approach should be useful in terms of in-service verification frequency and procedures. On the other hand, the possible incompatibility between different metering and sub-metering methods together with the lack of specific standards for the installation of IHASs can cause the metrological performance of these systems to be strongly dependent from the ability and competence of the installer and from the proper management of the plant, which are not always guaranteed. As a direct consequence, the development of dedicated shared installation protocols at a regulatory level for both DHMs and IHASs should be useful together with new innovative heat measurement and allocation techniques and/or the improvement of existing ones to overcome limits related to accuracy, drift over time and the need to measure the energy actually consumed. The main aim of Chapter 1 was to answer the question: *What are the expected on-field metrological performances of distributed individual metering and sub-metering systems with respect to consumer protection?* In this context, the metrological performance and installation issues of indirect heat accounting systems in residential buildings have been analysed and a statistical model for the estimation of the uncertainty and reliability of such systems has been proposed and experimentally validated in different representative buildings as *case study #1*. The application of the proposed model to specific buildings allowed to estimate the uncertainty of heat sharing in residential buildings under variable installation conditions (critical conditions, i.e. a two-family building heated in a different way during heating season and with radiators almost different between apartments and optimal conditions, i.e. a large building with similar radiators and related installation conditions) ranging, respectively, from 3% to 12%. The developed model represents a useful tool for both the design of new buildings, allowing the choice of more reliable accounting systems, and to define possible improvements of existing buildings (i.e. the more accurate estimation of the radiators thermal output). The main weakness of the model is represented by the fact that significant changes in installation and operative conditions in the apartments and in the building may affect the expected uncertainty estimation. Therefore, the application of the model at regular intervals is suggested in order to get a fair heat sharing over time.

In ***Chapter 2***, the author provided an analysis about the energy saving potentially achievable through the use of individual metering devices together with the use of temperature control systems with the aim to answer the main question: *What is the potentially achievable energy saving through the installation of individual metering devices?* For this purpose, the analysis has been carried out at two different levels:

b1 - A statistical estimation of the expected energy saving in different climatic conditions has been obtained through performing an experimental campaign in a high number of dwellings (*case study #2)*;

b2 - A study aimed to design a feedback strategy to increase end-user's awareness on own energy consumption has been designed and experimentally performed, with particular focus on the determination of possible influence factors on potentially achievable energy saving (*case study #3)*.

As regards to the experimental campaign carried out as *case study #2*, the energy consumptions of 3047 dwellings in 50 buildings, located in the major Italian regions and equipped with individual heat accounting systems and temperature control devices have been investigated before and after their installation. The experimental results showed that:

a total mean benefit of 11.0% is potentially achievable as a result of the summation of the energy saving in the first two years from the installation;

i. an additional energy saving of about 2% may be expected at the second year from the installation of metering devices, which could be the result of a better knowledge of the devices by the users;
ii. there exists a huge variation of energy consumption after the installation of the investigated systems, due to the building characteristics and to the operative conditions of the heating plant but also on the climatic conditions in which the installation is performed on the level of user's engagement and awareness.

For this reason, a special focus was given to user's awareness, in relation to adopted feedback and to the development of specific consumption indicators for benchmarking purposes, in the experimental campaign carried out as *case study #3*.

Basing on the available scientific literature, a personalized feedback strategy has been designed and tested on a set of final users belonging to: *i)* two old social housing buildings, for feedback on thermal energy consumption, and *ii)* a detached house for feedback on electrical energy consumption. Results have been presented and discussed related to heating and electrical energy consumption in residential buildings, highlighting that:

i. the huge number of measured data and the complexity of the monitored systems make analysis and feedback particularly complex for non-skilled users;
ii. in the case of direct feedback, impressions collected on field with direct interaction with the participants suggest that simplicity and immediacy of information is highly appreciated;
iii. in the case of indirect feedback, detailed data sheets of user consumption were presented, emphasizing the comparison based on performance indicators and personalized suggestions on user energy consumption behaviour, resulting in significant changes in energy behaviour of the social housing users;
iv. additional dedicated research is needed in order to develop specific consumption indicators for household electrical appliances, which today is still missing in the available scientific literature.

The adopted feedback strategy demonstrated high potential in terms of energy savings, as effective and frequent feedback contributes significantly to motivate and support the change in occupant behaviour. The analysis of the data showed some incorrect behaviour that users were not aware of, such as excessive ventilation of some rooms (e.g. entrance, bathrooms and kitchens), incorrect management of the thermostatic valves, incorrect management of some domestic appliances. End users were allowed to know precisely how much energy is actually consumed together with the estimate of their impact and comfort, to evaluate more effectively alternative technological solutions for heating, ventilation, lighting and choice of household appliances. It is clear that the so-called Building Energy Management Systems should not only allow the management and the control of the systems installed within a building, but also allow detailed information to the user. In this sense, the integration and development of systems based on information and communication technologies in buildings and, more specifically, on the Internet of Things (IoT), could be enabling factors for a wide range of communication applications with the end user. The IoT enables the interaction between intelligent objects and the effective integration of information and real-world knowledge into the digital world. Intelligent objects with detection and interaction capabilities or identification technologies provide the means to acquire real-world information in great detail.

In ***Chapter 3***, the issue of individual metering has been addressed from a policy perspective with the main goal of answering to the question: *is it possible to guide the success of the action about individual metering in residential buildings at a political/regulatory level?*

To this end, two different case studies concerning the energy policies of individual metering have be analysed and discussed at different scales:

c1 - Case study #4, in which a new energy-efficient policy about heat cost allocation is presented and applied to a single building scale;

c2 - Case study #5, in which the potential impact of the policy about individual metering is evaluated at a Country-scale for the Italian nation through scenarios simulation.

With regard to *case study #4*, the author found that very different approaches have been adopted in EU and some Member States still do not even have a general framework concerning heat accounting. As for example, variable costs range between 50 and 70% of total energy costs and the use of specific factors to compensate dis-advantaged situation is not homogeneous, since in some Member States it is mandatory and in others forbidden. The analysis of the wide scientific literature available on this subject shows that, despite the peculiarities deriving from different climates, building stock characteristics and management practices among EU, it should be possible to set some common pillars to achieve fairness and transparency in heat cost allocation and to improve user awareness about energy consumption. To this end fixed/variable costs should be tuned in order to maximize user awareness (thus leading to higher energy savings), taking into account the need to promote energy retrofit interventions which advantage all tenants (avoiding split incentives issues) and limiting the influence of stolen heat especially for apartments not continuously occupied. Furthermore, compensation factors for unfavourable location and for users under the risk of energy poverty should be introduced also taking into account particular situations such as social housing. Heat cost allocation has been little investigated in literature as a driver to achieve energy efficiency in buildings, despite also particularly impacting on the low-income social classes and determining issues related to fuel poverty. For this reason, a newly developed method has been proposed, which is based on the estimation of energy consumption due to energy inefficiency of buildings and on the compensation of the heating bill basing on it. The method has been applied to a typical social housing building in Central Italy showing, moreover, the potential to reduce the gap between who has the charge to implement energy efficiency interventions and the beneficiary of the interventions (often only few dwellings). The use of the proposed method brings to the attention of landlord/tenants the building thermal inefficiency and may encourage possible retrofit interventions on the common parts of the building. On the other hand, in certain conditions the heat cost sharing through the proposed method may generate almost similar bills among tenants and this should lead to maintain the status quo in the building, being in contrast with the EED intended goal. The method has also been proposed as standard method to the Italian Standardization body UNI-CTI and to the Italian Authority (MISE).

With regard to *case study #5*, 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. A model has been developed 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 fiscal incentive scenarios (i.e. 0 – 50 – 65 % of related costs) and two obligation approaches (i.e. economic feasibility calculation based on asset or operational rating). The application of the model to the Italian residential building stock showed that, considering the Italian panorama, the installation of individual heat accounting devices together with temperature control systems in the residential building stock can lead to a potential energy saving ranging from 0.3 to 1.9% of the estimated energy consumption for space heating. The analysis highlighted that, from a policy perspective, the installation of such systems would be ineffective in the South Italian regions (i.e. in warmer climates) regardless of applied incentives, while applying these last in Central/North Italy could lead to significantly higher energy savings.

Thus, results presented in Chapter 3 suggest that, if designed properly and applied to both micro- and macro-scales, policies about individual metering could have a great impact on the potential energy saving within both single buildings and large building stocks. Results should also 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.

In ***Chapter 4***, the author tried to answer to the question: *What is the impact of metering devices in management and regulation of energy networks? M*easuring instruments play a key role in the context of managing energy networks transporters and transmission systems operators strongly need to guarantee an efficient balancing of the network and the minimization of the quantities of unaccounted for energy. In natural gas networks, the entire system of consumption billing and network balancing is based on the measurement of conservative quantities such as mass or energy. Thus, forecasting energy consumption through periodical meter-readings can guarantee that the energy network operates in balanced conditions, which not only has important economic implications, but above all determines whether the network operates safely and ensuring the continuity of supply. In this context, in *case study #5*, the author described and applied the Italian, English and German natural gas allocation methods to estimate the energy consumption of an urban building stock at city and neighbourhood scales. The investigation has been performed in a natural gas distribution network located in Southern Italy having about 16000 NDM customers and about 4000 buildings. The selected neighbourhood was made up of 5 buildings supplied by centralized heating system for heating, cooking and hot water production purposes, remotely read.

The results of the present analysis suggest that the German method, which profiles energy consumption basing on sigmoidal energy signatures, presents high potentialities to give high quality forecasts. Referring only to the Italian method, which showed the best performances, at urban scale the proposed methodology, in case of less than one meter-reading per year, predicted the entire energy consumption of the network within an error of -11% on a year basis. Under the hypothesis of increased number of meter readings per year, the error decreased below 2%, showing the potential of using smart-metering technologies in managing energy networks. The proposed modelling approach to residential energy consumption at urban scale has the main limitation to not providing high flexibility to energy consumption simulation. SLPs are, in fact, suitably built on large samples of DM users chosen as representative of the urban building stock and usually updated at large interval of times. Also, they rely on historical energy consumption, which means that are not capable to account for extreme weather scenarios, for changes in the building stock energy efficiency and for end-user' behaviour. For the same reason, they have limited capacity to assess the impact of energy conservation measures.

Due to the extent and to the complexity of the topic, many of the gaps highlighted in this work, both in terms of official European regulations and of scientific literature, are still open topics to date and then represent "fertile ground" for future research projects. Some food of thought is provided below:

- ✓ It is now clear that the future scenarios of the energy sector are and will be strongly influenced by the widespread smart-energy technologies. Will we be able to maximize their potentialities in the future outlook of energy networks?

- ✓ What is the real potential of existing buildings, not designed with current predisposition to integration with smart technologies (and which represent the vast majority of the building sector), to become smart?
- ✓ How can the energy, environmental and performance monitoring sensors, with extremely diversified communication protocols, communicate in a single effective infrastructure with low economic impact?
- ✓ What will be the impact of the new IoT technologies on energy efficiency in the residential sector with particular reference to smart metering, smart-home and smart-grid technologies and to the relative data management as a distinctive element that allows the consumer awareness, energy diagnosis and efficiency in network management?
- ✓ Will it really be possible the integration of data-driven technologies for real-time estimation and the forecast of average and peak consumption for the energy balancing of the networks to energy metering technologies?
- ✓ How will the new blockchain technologies be handled in the management of direct energy transactions between electricity, thermal and gas users?

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