A comprehensive review on heat accounting and cost allocation in residential buildings in EU

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Abstract

Since 2002, the European Union (EU) 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 present, when technically feasible and cost efficient. As a consequence, EU Member States adopted different allocation rules mainly due to differences in building stocks and climatic conditions. This measure has led to a series of technical, legal and consumer protection issues which still need to be solved. In this paper, more than 130 publications have been analysed and critically reviewed, highlighting the different approaches adopted in EU Member States concerning heat accounting and the related issues. To this aim, the authors focussed the following subjects: *i)* the allocation rules adopted by EU Member States, *ii)* the heat metering and sub-metering technologies, *iii)* the cost-benefit analysis of individual heat metering and accounting systems. This review is useful for researchers since the existing regulation and technologies for heat accounting and their related potential are discussed together with the analysis of the existing gap in terms of technical standard and consumer protection. Finally, the analysis provides policy makers with several suggestions to improve transparency and reliability of allocation rules.

Keywords:

Heat metering; energy efficiency; heat cost allocation; compensation factor; stolen heat; energy poverty.

1. Introduction

The estimation of energy consumed in individual dwellings certainly represents a very debated topic, given the multi-disciplinary nature of the subject which involves metrology, policy, energy management together with social and behavioural aspects.

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) [1] 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 [2] and 2010/31/UE [3]. Indeed, these directives state that the billing of heating, air conditioning and domestic hot water production based on individual consumption contributes to energy savings in the residential sector, thus also identifying in the end-user's awareness about energy consumption a functional tool to achieve the 20-20-20 goals. In 2012 the Energy Efficiency Directive (EED) [4] 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 and encouraged MSs to adopt transparent rules on consumption-based and informative billing.

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 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. As a direct consequence, 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 [5-7].

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). Within this paper, authors will refer to these last also as, respectively, “voluntary” and “involuntary” energy consumption. 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" [8] 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 [9]. 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. To this regard, in several MSs the use of compensation factors is 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. 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 [10]. Unfortunately, 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 an overall 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. However, despite EED requirement about individual metering is subject to technical feasibility and cost-effectiveness [11, 12], current legislation within MSs lacks official indications regarding the reference energy saving and standard costs. Nevertheless, some efforts have been made to provide tools and/or guidance about how to perform the economic feasibility analysis of individual heat metering and accounting systems (e.g. in

Italy, United Kingdom and Spain [13-15]). 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% [16-18] whereas more recent studies in Mediterranean countries found lower benefits: i) variable between 10-20% [19], ii) in average of about 11% but highlighting also increased consumptions in some investigated buildings (up to 24%) [20], iii) variable between 21-36% and in average 25% (with 16% of investigated apartments showing increased consumptions) [21]. Besides, standard figures of cost related to the installation of individual metering systems are available only for few markets [5, 6, 22, 23]. 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% [22].

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). As well known, EED sets as a priority of the installation of DHMs if 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 [24, 25] constraints, DHMs installation is often not feasible, while IHASs installation is almost always technically feasible in existing buildings with conventional radiators. The alternative use of DHMs and IHASs implies some consequences in terms of consumer protection. Accuracy of IHASs could range from 3.0% to 12.4% [26] and up to 30% [27] while in different operating conditions it ranges from about 2.7 % to about 11.7 % [28]. Moreover, only DHMs are currently regulated by legal metrology [29], 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. Vice versa, IHASs are lacking from a regulatory point of view in terms of consumer protection and of the related metrological performance, since in most MSs, DHMs are also subject to on-field verifications, while IHASs have no legal verification constraints of the on-field performances.

In this paper, authors present a comprehensive review of more than 130 publications, in which the different approaches of EU MS concerning heat accounting and related issues have been analysed and critically discussed. The analysis was focused on European legislative and normative documents (46%), scientific papers (35%), official reports issued under commission of EU MSs (13%), data presented during official meetings organized by the European Union in the framework of Concerted Action for the EED (4%) and conference proceedings (2%). Analysed documents are dated between 1978 and 2019, with particular focus on the ones published after 2012, year in which the EED was issued (about 76% of the documents). Concerning research papers published in this field by the main indexed journals, authors used specific keywords (e.g. individual metering; heat meters; heat metering; heat accounting; heat cost allocation; heat cost allocators; stolen heat). Search for European legislative and normative documents and official reports issued by EU MSs was made through the institutional web-sites of the European Union and of the MSs competent authorities in the field of energy.

This review is organized as following: *section #2* provides a review of the allocation rules adopted by EU MSs, *section #3* provides an insight into the heat metering and sub-metering systems and devices currently available and spread on EU markets, *section #4* presents the cost-benefit analysis of individual heat metering and accounting systems.

2. Allocation rules

As known, in multi-apartment buildings supplied by district heating or cooling, or where centralized heating or cooling sources are prevalent, EED [30] 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 1) had defined official rules for allocating heating costs among tenants, and only 2 set regulations for allocation of cooling costs [31]. 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 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.

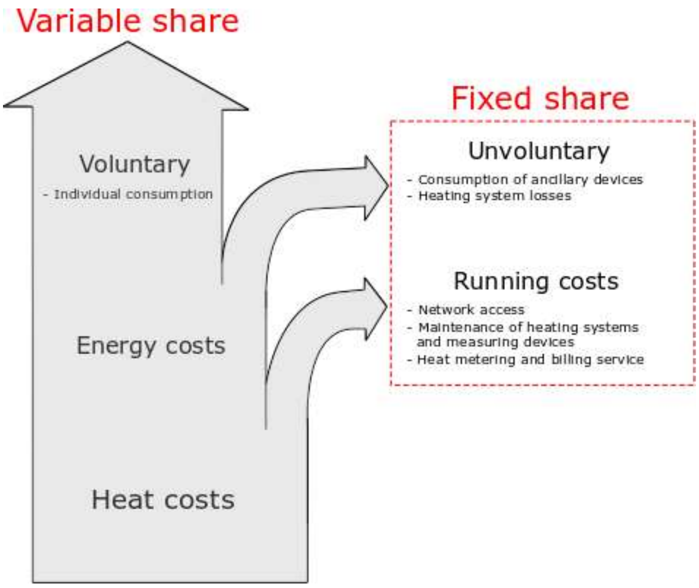

Figure 1 – Fixed and variable share of heating and cooling energy cost

Among EU MSs the share of fixed costs varies between 25% and 60%. According to Dell'Isola *et al.* [32] this variability relies 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 1 and Figure 2 provide an overview of the ranges defined for variable shares of heat cost allocation in EU MSs.

Table 1 – Heating costs allocation rules in Europe [27]

MS	*Ref.*	*Rules before EED*	*Rules after EED*	*Variable share*	*Notes*
Austria	[33]	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	[34]	No	No	-	-
Bulgaria	[35]	Yes	Yes	60-75%	-
Cyprus	[31]	No	No	-	-
Croatia	[36]	No	Yes	10-50%	-

MS	*Ref.*	*Rules before EED*	*Rules after EED*	*Variable share*	*Notes*
Czech Republic	[37]	No	Yes	50-70%	Total costs per m^2 cannot be lower than 20% or more than 100% of the average cost.
Denmark	[38, 39]	No	Yes	50-70%	-
Estonia	[40]	No	Yes	40-60%	-
Finland	[41]	No	No	-	-
France	[42-44]	No	Yes	70%	The share for variable and fixed costs is regulated by law.
Germany	[45]	Yes	Yes	50-70%	-
Greece	[31, 46]	No	No	Calculated case by case	Variable costs calculated as specified in Greek technical standard. Rules for fixed costs are not provided
Hungary	[47]	Yes	Yes	50-70%	-
Ireland	[31]	No	No	-	-
Italy	[48-50]	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	[51]	No	No	-	The provision of common energy sources for heating and cooling, and hot water remains is deemed economically unfeasible.
Latvia	[52]	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	[53, 54]	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	[31]	No	No	-	-
Netherlands	[55, 56]	No	Yes	-	If requested by one or more tenants, a professional verifies the heating costs allocation rules performed by the heating service company.
Poland	[57, 58]	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	[31]	No	No	-	-
Romania	[59, 60]	Yes	Yes	-	The adoption of a percentage for variable costs of 40% is under discussion.
Slovakia	[61, 62]	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	[63, 64]	No	Yes	50-80%	Consumption per m^2 should not be below 40% and over 300% with respect the average consumption.
Spain	[19, 65]	No	No	-	-
Sweden	[46]	No	No	-	-
UK	[14, 66, 67]	No	No	Not regulated	The Government did not propose to mandate rules on the allocation of costs after national consultation

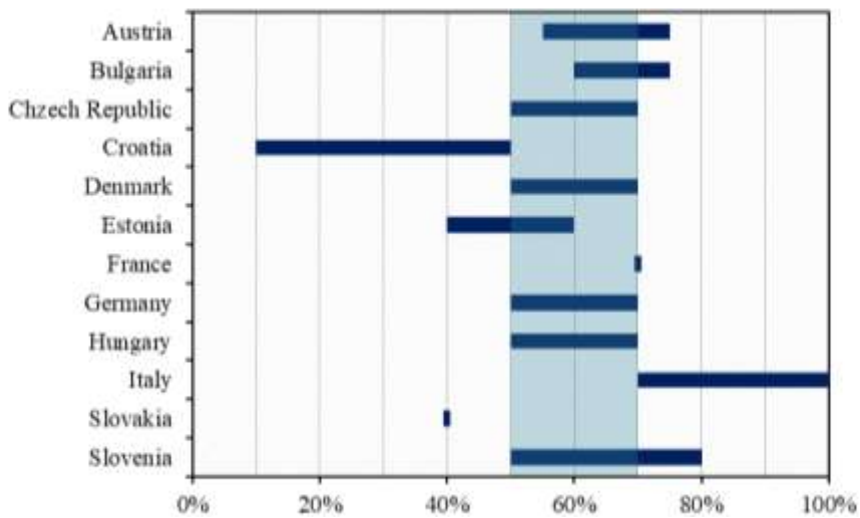

Figure 2 - Range for variable share of heat cost allocation in some EU Member States

2.1 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.* [68] 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 [8] showed that an apartment may "steal" up to approximately 90% of heat from adjacent apartments. Whereas, Andersson [69] 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 [70]. For this reason, different compensation strategies have been proposed also based on calculation of heat flowing through adjacent apartments.

2.2 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 [71, 72]. As for example, Ling *et al.* [71] 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 [73], 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 [74, 75].

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.).

Authors have identified different kinds of compensation strategies mainly based on energy use, stolen heat and 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 [47], Lithuania [53, 54], Romania [59, 60] (see Table 3) and, among non-EU MSs, in Switzerland [76]. Denmark allows compensation based on the calculation of heat loss percentage of each apartment with some exemptions [38, 39]. Ling *et al.* [71] 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 [77] 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 [78] 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.* [79] and Nikos Gkonis [80] 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. Regarding compensation based on *thermal-comfort*, Liu, et al. [81] proposed compensation though the measured cumulative on-time of zone thermostatic valves, while Darvariu

[82] proposed a correction based on the measured difference between the indoor comfort temperature and the outdoor one.

In Table 2 the main advantages and disadvantaged of the available compensation strategies are summarized.

Table 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 [47] Lithuania [53, 54] Romania [59, 60] Switzerland [76]
	Heat loss percentage	Very accurate	Complexity of calculation. It can lead some users to detachment and to disputes between tenants	Denmark [38, 39] Ling *et al.* [71]
	Energy efficiency factors	Very accurate. It overcomes the contrast toward the energy efficiency in the building	Complexity of calculation	Dell'Isola *et al.* [32]
	Stolen-heat between adjacent apartments	It prevents too low set-point temperatures	Complexity of calculation	Siggelsten [77] Michnikowski [78] Nikos Gkonis [80]
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) are not considered	Liu *et al.* [81]
	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) are not considered	Darvariu [82]

Table 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.

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 4.

Table 4- Compensation factors in EU MSs

Member State	*Compensation*	*Notes*
Austria	Forbidden	
Bulgaria	Allowed	CFs rarely used

Member State	*Compensation*	*Notes*
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 [81]. In any case, the adoption of CFs and the socialization of energy losses could also increase the number of detachments from centralized heating systems.

In this regard, Dell'Isola *et al.* [32] proposed a compensation method representing also a driver for improving building energy efficiency without leading to discomfort conditions and to imbalances of the heating system. The method is based on the estimation of the consumption exceeding those that would occur if legal limits of energy performance of buildings (e.g. thermal transmittances) would be respected, by temporarily re-allocating the extra-costs due to building inefficiency to all tenants proportionally until a retrofit intervention is carried out. The method seems to be particularly promising also to address the issue of split incentives, as the extra costs would be removed after the retrofit intervention is carried out, thus allocating the economic benefit among all dwellings in the building.

2.3 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 [83, 84]. 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 [85]).

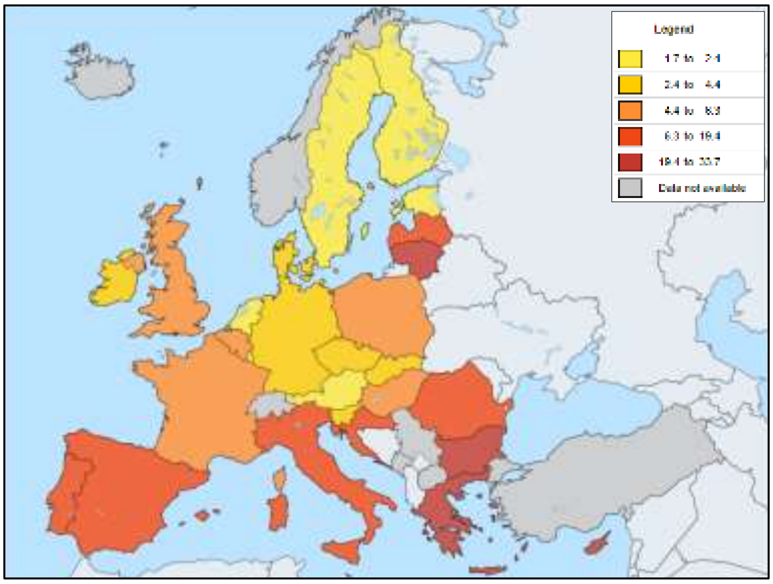

Figure 3 – Population unable to keep home adequately warm by poverty status (% of population) (year 2018, exceptions: CZ, AT, LU, SE, LT, SK, RO, TR, MT, PL, RS, MK, ES, IE (2017), CH, IS (2016)

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 [86]. Moving from the allocation of energy costs based on surface area (and similar) towards a fixed/variable cost sharing scheme, 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 [87]. 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 [88] 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 [89] 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. Metering and sub-metering systems for heat accounting

Heat metering and sub-metering systems are classified: DHMs and IHASs.

DHMs measure the thermal energy delivered to a building or an apartment through a simple thermal energy balance by multiplying the volume flow-rate of the heating fluid leaving and entering a closed heat exchange circuit by the enthalpy difference between the inlet and outlet section of the circuit itself. A calculator module provides the value of a thermal coefficient depending on the average fluid density and specific heat capacity calculated at operative conditions and acquires flow and temperatures signals to get the amount of thermal energy supplied. According to the MID Directive on measuring instrument [29] and related harmonized technical standards [90-98], a thermal energy meter (see Figure 4a) is either a complete instrument or combined consisting of sub-assemblies (i.e. flow sensor, temperature sensor pair and calculator).

As highlighted by Choi *et al.* [99] by summing sales data between 2002 and 2006 from Germany, Denmark, UK, Finland and Sweden the main types of flow-meters used in heat energy metering are turbine, electromagnetic and ultrasonic, with average market shares of respectively 37.6%, 38.4% and 24.0%. Recently, ultrasonic meters are more and more spreading especially for residential use. In almost all cases, complete meters are installed at smaller apartments (e.g. for sub-metering purposes) and they are generally not remotely read, with mechanical single-jet flow meters and with short-stem temperature sensors. On the other hand, combined meters are installed at larger user's premises (e.g. commercial buildings, light industries, large residential buildings directly supplied by district heating) often with static flow meters and long-stemmed temperature sensors. 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 (see Table 5).

Conversely, existing and historical buildings normally present heating plants with rising mains [25] and in such configuration the installation of IHASs is strongly recommended. For the sake of completeness, also hybrid DHMs recently patented [100] are available, consisting in a miniaturized static flow sensor installed in the return pipe and a remotely read temperature sensor pair embedded in the thermostatic valve and in the holder of the heating element. Such devices allow the "direct" measurement of energy consumption at each heating element and therefore, according to the EED [4, 30], their installation should be a priority when DHMs are not technically feasible. In Table 5 a summary of technical and economic feasibility of direct and indirect heat accounting devices is presented.

Table 5 - Direct and indirect accounting systems feasibility in space heating and cooling plants.

	Direct Systems		*Indirect Systems*	
	DHM	*Hybrid DHM*	*HCA*	*ITC*
1. Legal metrology requirement				
Applicable Technical Standard	EN 1434 [90-95]	EN 1434 [90-95]	EN 834 [101]	UNI 11388 [102] UNI 9019 [103]
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
2. 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
3. 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

	Direct Systems		*Indirect Systems*	
	DHM	*Hybrid DHM*	*HCA*	*ITC*
1. Legal metrology requirement				
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 are considered for single device, then the final cost depends on the number of HEs within the apartment

On the other hand, IHASs provide an estimation of heat consumption, based on the measurement of some parameters closely related to it. Among IHASs, two-sensors electronic HCAs are nowadays the most widespread especially in East-European market [104]. According to the EN 834 standard [101], one temperature sensor registers the temperature of the radiator surface and the second sensor registers the room temperature or a temperature in a defined relation to it. A crucial element of this device is represented by the coupling plate which assure the proximity of the radiator surface temperature with the heating fluid temperature, through a specific rating factor (see Figure 4b).

HCAs can be used exclusively on heating elements (HE) whose heating surface is accessible, being directly applied in a suitable position to detect its average temperature by the calculation of the temperature difference integral with respect to time. This last is then related to the displayed reading trough suitable rating factors taking into account the thermal output of heating surface, the thermal contact between the sensors and the surfaces and the way in which the indoor temperature is estimated (see Table 6).

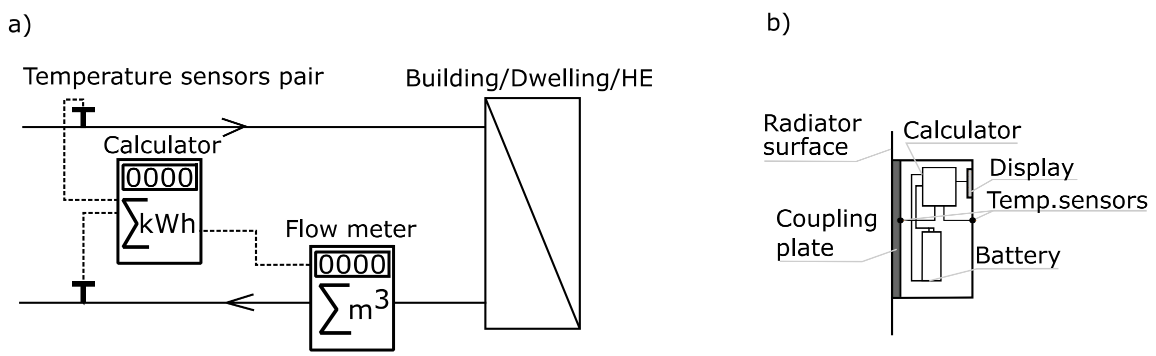

Figure 4 - a) DHM and b) HCA functioning scheme

Insertion Time Counters (ITC) have been among the first IHASs to appear on the Italian market [105], as well as the first ones to be regulated by national standards [102, 103]. Such devices are based on the registration of the opening times of a single thermal zone or of the TRV of a single radiator. The opening times of each valve or TRV are then compensated with the average temperature of the heat transfer fluid (ITC-TC [102]) or with the actual heating degree days (ITC-DD [103]). The heat exchanged during the transient of the valve closure is also considered for the estimation of heat consumption. Recently, a novel indirect heat cost allocation method has been proposed by Saba *et al.* [106]. The method, based on steady-state indirect estimation of radiator thermal output, showed a maximum deviation of about 10% respect to the heat cost allocation provided through the use of EN 442 [107, 108] model for radiator thermal output estimation.

In Table 6 the basic equation of the above described direct and indirect heat metering and sub-metering devices provided by the related standard documents are reported.

Table 6 - Basic equation for heat consumption calculation of DHMs and IHASs.

Device	*Basic equation*	*Reference*
DHM	$E = \int \rho \, \bar{c}_p \, q \, \Delta T \, d\vartheta$ Where: i) ρ is the flow density (kg m^{-3}), ii) $\bar{c}_p$ is the average specific heat capacity of the heating thermal fluid (kWh kg^{-1} K^{-1}), iii) q is the volumetric flow rate (m^3 h^{-1}), iv) ΔT is the fluid temperature difference between the flow and return pipes (K).	EN 1434 [90-95]
HCA	$AU = K_C K_Q K_T \int_{\vartheta} \left(\frac{\Delta T}{60}\right)^n d\vartheta$ Where: i) ΔT is the temperature difference between the ambient temperature and the HE surface (K); ii) n is the characteristic exponent of the HE (-); iii) K_C, K_Q, K_T rating factors respectively for thermal contact between HCA and HE, thermal output of the HE, indoor temperature (only for single-sensor HCA).	EN 834 [101]
ITC	$AU = K \, \dot{Q}_{HE} \int_{\vartheta_{OV}} \left(\frac{T_{m,i} - T_{a,i}}{T_{m,c} - T_{a,c}}\right)^n d\vartheta + K \, \dot{Q}_{HE} \left(\frac{T_{m,i,c} - T_{a,i}}{T_{m,c} - T_{a,c}}\right)^n \int_{\vartheta_{CV}} e^{-n\left(\frac{\vartheta}{\tau}\right)} d\vartheta$ Where: i) ϑ_{OV} is the opening time of the valve; ii) $T_{m,i}$ is the average temperature of the heating fluid during ϑ_{OV}; iii) $T_{a,i}$ is the ambient temperature (measured or calculated); iv) $T_{m,c}$ and $T_{a,c}$ are the reference values for the heating fluid temperature and the ambient temperature; v) $\dot{Q}_{HE}$ is the nominal heat power of the HE; vi) K is the coefficient of proportionality between the AU and the actual heat used; vii) n is the characteristic exponent of the HE; viii) τ is the time constant; ix) ϑ_{CV} is the closing time of the valve; x) $T_{m,i,c}$ is the average temperature of the heating fluid measured at ϑ_{CV}.	UNI 11388 [102]
	$AU = K \sum_{k=1}^{n} \dot{Q} \left(\frac{HDD_i}{T_{a,c} - T_{e,c}}\right) \left[\vartheta_{OVk} + \tau \left(1 - e^{-\frac{\vartheta_{CV,k}}{\tau}}\right)\right]$ Where: i) ϑ_{OV} is the opening time of the valve; ii) $T_{a,c}$ and $T_{e,c}$ are the reference values for the heating fluid temperature and the ambient temperature, iii) HDD are the heating degree days; iv) K is the coefficient of proportionality between the AU and the actual heat used; v) τ is the time constant; vi) ϑ_{CV} is the closing time of the valve.	UNI 9019 [103]

3.1 Accuracy of heat accounting systems

Maximum permissible errors for the approval and initial verification of DHMs are set by [29]. Furthermore, subsequent verification and in-service inspection are regulated by law in several EU MSs (e.g. Austria, Germany, Italy, France [109]) which frequency, as for example: i) in Italy varies between 6 and 9 years depending on the type of flow sensor, ii) in Poland is 5/10 years, iii) in Lithuania, Romania and Slovakia is 4 years. In other MSs subsequent verification and in-service inspection is still not regulated (e.g. Belgium, Finland, Norway, Spain and United Kingdom). Finally, when in-service inspections are applied, several MSs (e.g. Austria, Denmark, France, Germany, Netherlands, Slovakia, Slovenia and Sweden) allow to adopt maximum permissible errors higher than the corresponding ones in initial verification or re-verification [109]. There are specific installation and management issues affecting in service metrological performance of DHMs [110-116], as following: *i)* installation effects (fluid-dynamic disturbances upstream and downstream of the flow sensor or thermal disturbances affecting the temperature sensors pair); *ii)* the presence of air bubbles or impurities in the heat transfer fluid (due to chemical reactions, corrosion phenomena, biological phenomena, fouling etc.); *iii)* calculation errors due to the characteristics of the heat transfer fluid which in some application is mixed with anti-freeze fluid; *iv)* frequency of critical operating conditions (e.g. low flow and low temperature difference). Accuracy of single DHMs, as a consequence, varies between 3.3 % and 8.4 % with a typical value of 5.5% [28]. On the other hand, devices for IHASs are not regulated by Legal Metrology, thus lacking clear rules regarding legal seals, type approval tests, initial and subsequent verifications, quality assurance of the production process etc. The accuracy of this kind of systems is affected mainly by: *i)* the estimation of the rated heat outputs of radiators which could greatly differ from the actual ones depending on the operating temperatures, the type of installation, the hydraulic connections and the painting, that have to be considered through suitable corrective factors [117]; *ii)* the inaccuracy of temperature measurement depending on both on the installation parameters and on the position of the sensor itself, on the functioning of the heating element, on the coupling between the sensor and the radiator and on the calculation model; *iii)* the drift of the temperature sensors. Accuracy of single IHASs, consequently, varies between 4.9 % and 37.7 % with a typical value of 8.1% for HCA and between 5.7 % and 37.1 % with a typical value of 10.3 % for ITCs [28].

However, the accuracy of the whole heat accounting system should be very different from that of the single device, due to compensation effects and correlation between radiators in the apartment and in the building and between apartments in the building itself [28]. When the same type of radiators and the same installation conditions are used, the uncertainty of heat sharing is greatly reduced, ranging from 2.7% to 4.9% in optimal conditions (i.e. a large building with similar radiators and installation conditions). Finally, compensation effects are more relevant in small buildings, due to the autocorrelation effect on heat shares. In recent scientific literature several studies dealing with accuracy issues of DHMs and IHASs are available and they are summarized in Table 7.

Table 7 – Scientific literature on direct and indirect heat accounting accuracy and reliability

Subject	*Main outcomes*	*Reference*
DHMs installation effects, recalibration periods, accuracy over time	Meters correctly installed are accurate within EMP of MID. Flow meter is relatively resilient to incorrect installation Installation of temperature sensor pair is critical	Butler *et al.* [116]
DHMs on field test accuracy, accuracy over time	Significant reductions in the heat meters performance	AGFW [118]
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.* [99]
Accuracy of DHMs over time	Need of correction factors specifically designed for local plant installation characteristics.	Celenza *et al.* [119]
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 [120]
Optimum installation of HCAs	Optimum installation position of HCAs at a radiator height of about 60% has been demonstrated	Bozzini *et al.* [121]
Test on HCAs in a "vertical" hot water distribution network of 10 radiators of different types, materials and installation conditions	Authors found relative deviations with respect to the reference share of radiator heat consumption, up to 30% When heat consumptions are shared, compensation of systematic errors occur as far as the radiators within the same building are similar for type, material, shape, dimensions, installation, operative conditions	Saba *et al.* [27]
Metrological reliability of HCAs and ITCs	Uncertainty of heat sharing of about 11% at critical conditions could decrease to about 3% in optimal ones	Dell'Isola *et al.* [28]
On field experimental comparison of direct and indirect heat accounting systems (HCAs and ITCs)	HCA accuracy is comparable with the one of DHMs (share error in the whole heating season of about 3.0% for HCAs vs 1% for DHMs), Share error in the whole heating season of about 7.1% for ITC-DDC and of about 8.2% for ITC-TC, error becomes unacceptable (up to 12.4%) for heating plants handled differently or in case of very low energy consumption.	Ficco *et al.* [26]

4. Cost-benefit analysis of individual heat metering and accounting systems

4.1 Benefit estimation from individual 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 [122]. Celenza *et al.* [22] highlighted that the installation of DHMs is almost technically unfeasible and not cost effective in old buildings and heating plants, whereas HCAs are almost always technically feasible and cost effective, thus resulting the most spread individual heat accounting system in EU MSs.

The installation of HCAs is often performed together with TRVs and in some countries (such as Croatia, Italy, England, France [36, 49, 123, 124]) this is reversely mandatory when installing IHASs. 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 attributable to the use of TRVs (about 60% according to [125]). Other studies demonstrated TRVs accounting alone for about 10-20% energy consumption reduction depending on installation conditions and balancing of the heating plant [126, 127]. 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 authors best knowledge, no experimental study about the benefits induced by the sole installation of DHMs was performed.

As a matter of fact, non-physical factors [18] 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 [128]. 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 [129, 130]. 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 [16, 131, 132]. Felsmann *et al.* [16] 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. 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 [133, 134]. Long-term experimentations are almost lacking in scientific literature. Cholewa and Siuta-Olcha [135] 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. Two studies experimentally evaluated the potential for energy saving of heat accounting and temperature control devices in temperate climates: the first [20], conducted in about 3000 apartments in three Italian cities, highlighted a wide variability of energy consumption variation (ranging from -24% to +15%, on average 11%) showing a higher potential for energy saving in temperate climates rather than in cold ones; the second [19], conducted in Spain, found a 15–20% reduction of normalized energy consumption during the first two years after HCAs and TRVs installation. In [21] a saving ranging between 21-36% and in average of 25% has been found in Croatia, thus ensuring a positive net present value if the specific energy requirements of the apartment are lower than 170 kWh/m^2 and 95 kWh/m^2 in Continental and Mediterranean Croatia, respectively. This is due to the difference in heat energy price between cities in Continental and Mediterranean Croatia.

Figure 5 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.

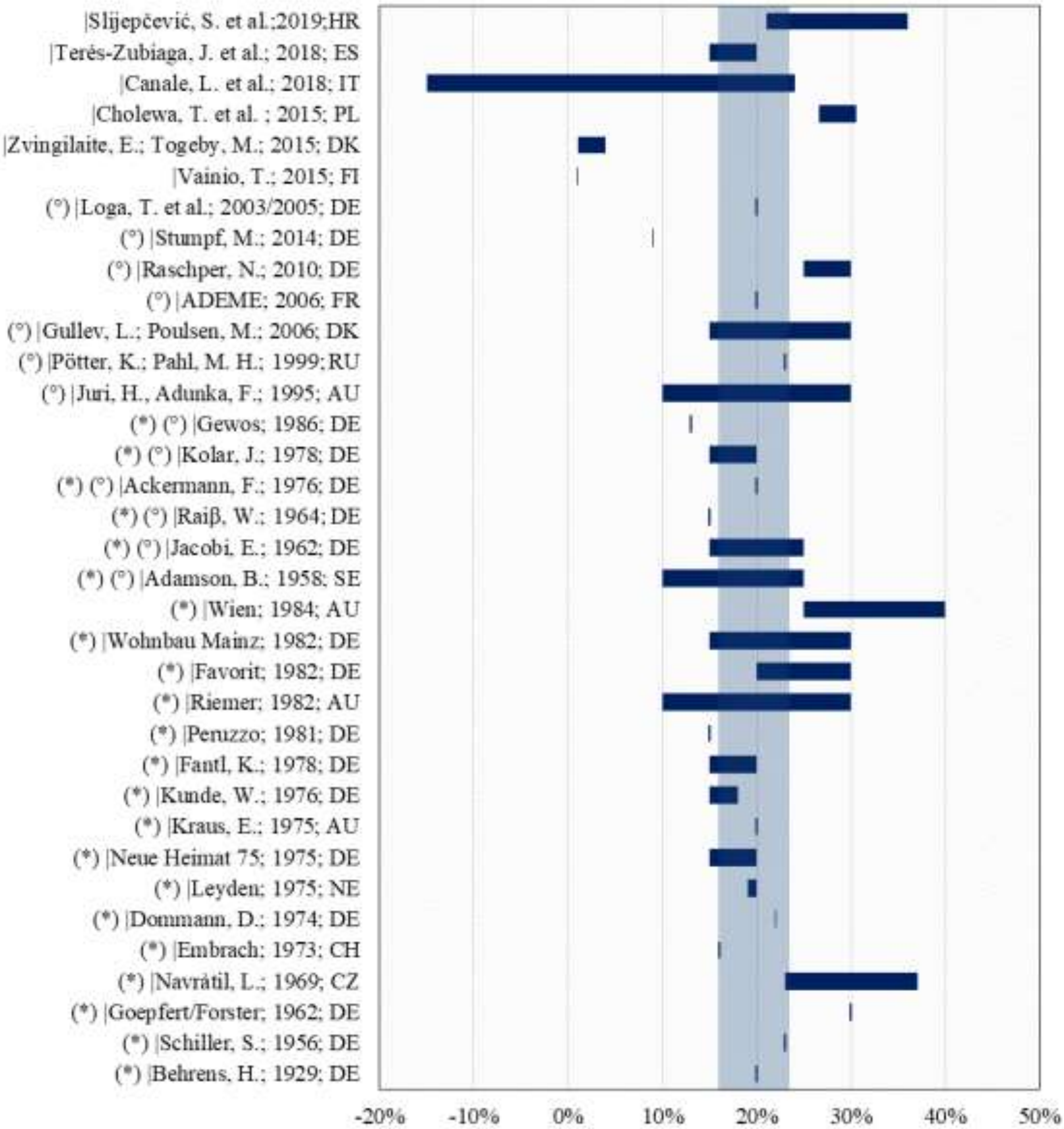

Figure 5– Existing scientific literature regarding individual metering systems' energy saving, (°) papers reviewed in [17]; (*) papers reviewed in [16]

4.2 Cost-benefit analysis

Empirica GmbH [46] 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 8 the results of market analyses carried out in representative MSs are reported, whereas in Figure 6 a comparative analysis of one-off and running costs per dwelling in different MSs is presented.

Table 8 – Total running and capital costs of individual heat metering and accounting systems in EU

	IT [22]	*SE [5, 6]*	*DE [22]*	*UK [14, 22, 23]*	*PL [126, 135]*
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

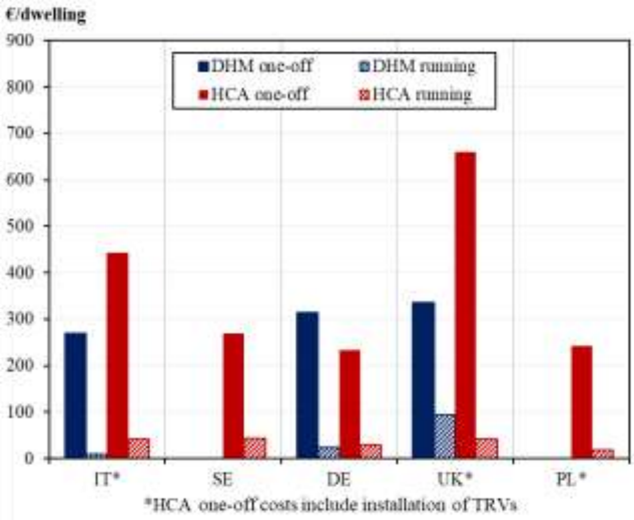

Figure 6 – Total one-off and running costs of DHMs and HCAs installation per dwelling

In Figure 6 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-areators, 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 sistems 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 [12] has to be performed for each building when technical feasibility is demostrated; 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 economical 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 9.

Table 9 - 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 [7]
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.* [5]
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.* [22]
Cost-benefit analysis on building typologies used to model the Italian building stock	The potential for energy saving and efficiency of the analysed obligation is strongly dependent on the fiscal incentives applicable. The minimum value of primary energy need for space heating above which buildings should be obliged to install individual metering systems ranges from 90 to 150 $kWhm^{-2}$ corresponding to maximum fiscal incentive and to zero incentives respectively (Italy, 2018)	Canale *et al.* [20]

5. Conclusions and future research developments

In this paper, authors presented a comprehensive review of more than 130 publications, in which the different approaches concerning heat accounting and the related issues have been analysed, compared and critically discussed considering: *i)* the allocation rules adopted in EU Member States, *ii)* the heat metering and sub-metering technologies, *iii)* the cost-benefit analysis of individual heat metering and accounting systems.

In respect to allocation rules, authors found that very different approaches have been adopted in EU and some MSs 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 disadvantaged situation is not homogeneous, since in some MSs 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.

An essential constraint to the installation of individual heat metering and sub-metering systems is represented by the cost benefit analysis. The results of the experimental campaigns available in the literature show a high variability of both expected benefits obtainable from heat accounting (which can be assumed to range from 16% to 23% by averaging minimum and maximum benefits found in 35 research papers) and of the related one-off and running costs. Such variability demonstrates the need to further investigate the potential benefits of individual heat accounting considering the following aspects: *i)* climatic differences; *ii)* buildings characteristics in terms of thermal insulation, performance of heating systems and so on; *iii)* social, cultural and economic conditions of tenants; *iv)* combined effects with other energy retrofit interventions; *v)* the duration of experimental campaign.

In respect to the reliability of direct and indirect heat accounting systems, from the review analysis some important limitations emerge, which are: *i)* for DHMs: 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 (e.g. low temperature differences between flow and return and low flow rates); *ii)* for IHAS: 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) to improve user awareness, the initial and periodic verification of the on-field reliability.

The review 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 DHMs emerges. In fact, 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.

Finally, 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.

Nomenclature

AU	Allocation Unit
CFs	Compensation Factors
DHMs	Direct Heat Meters
EED	Energy Efficiency Directive
EU	European Union
HCA	Heat Cost Allocator
HE	Heating Element
HDD	Heating Degree Days

IHASs	Indirect Heat Accounting Systems
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
TRVs	Thermostatic Radiator Valves

Symbols

$\bar{c}_p$	average specific heat capacity of the heating thermal fluid
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
$\dot{Q}_{HE}$	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
$T_{m,i}$	average temperature of the heating fluid during ϑ_{OV}
$T_{m,i,c}$	average temperature of the heating fluid measured at ϑ_{CV}
ΔT	temperature difference
ϑ_{CV}	closing time of the valve
ϑ_{OV}	opening time of the valve
ρ	flow density
τ	time constant

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