Individual metering of energy in existing buildings: potential and critical aspects

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Nomenclature Symbols

$\dot{Q}$	Thermal power (Watts)
U	U value (Watts per square meter Kelvin)
A	Area (square meters)
θ	Temperature (degrees Celsius)
t	Time (seconds)

Subscripts

in	Input
out	Output
ext	Outside
int	Inside
near	Near
we	External walls
wi	Internal walls (between flats)

Introduction

Energy retrofit of existing building stock is a real opportunity to promote the green economy in the sectors of energy efficiency and renewable energy sources; it is also a good strategy for reducing the use of conventional energy sources. Improving the energy efficiency of buildings helps to reduce energy costs for heating and electricity use, which is a real problem in times of crisis, such as the present day, especially for socially disadvantaged sectors of the population. The transition towards a green economy in this manner is not simply an energy or environmental issue but is principally an economic and a social issue, particularly for vulnerable populations.

So far as the housing market in Europe is concerned, recent national and regional legislation, enacted for the transposition and assimilation of the Energy Performance Building Directive (EPBD) (EC 2002), inevitably results in a significant energy performance gap between new and existing buildings. The Lombardy region, which is the most densely populated region of Italy, is the furthest ahead in the application of the EPBD European directives. In this, the data from the energy certification of buildings, which has been mandatory since 2007, indicate that the average value of the primary energy indicator for winter heating of the existing building stock is 197.4 kWh/m^2 year. This figure is much higher than the average value for new buildings, which lies between 30 and 40 kWh/m^2 year; this is not only owing to the new rules on energy efficiency, but also because of a real estate market that rewards existing buildings.

With the current increase in energy costs, energy retrofit works are a good investment; however, users often do not have the capital available to effect these changes.

Another obstacle is that, in collective-ownership buildings such as condominiums, refurbishment projects are subject to the approval by the majority of the owners, which is not always easy to obtain. It should be noted that in Italy, approximately 40 % of flats/dwellings are in collective-ownership buildings.

In such collective-ownership buildings with a centralised heating system, the sharing of costs for winter heating is usually not made based upon the individual energy consumption but by merely assessing geometrical parameters of the dwelling (e.g. the area or the volume of the flat) or as a function of thousandths of a property involved. Obviously, this policy does not encourage responsible energy management by users.

In Italy, the transposition of the EPBD into national laws (IT 2005) requires that, when replacing old boiler with new one, local control systems must be installed in addition to the central regulation systems. This choice, although technically correct, does not produce tangible benefits in energy saving because users have no incentive to control their individual energy consumption.

The Italian Constitution considers energy a competing matter between the State and the Regions; hence, the regional assemblies may approve independent laws on energy issues. A recent council resolution of the Lombardy region (LR 2011) states that all the existing buildings, although not subject to replacement of boilers, must be equipped with single zone or room temperature controls and heat metering systems to provide an incentive for the reduction of energy consumption through the allocation of costs for winter heating based upon the actual consumption for each unit.

The reference standard for the division and allocation of heating costs for central systems is the UNI 10200 standard (UNI 2005), currently under review, which provides the principles and guidelines for the allocation of costs as a function of the heat consumption of each user. The reference standard for indirect accounting systems is UNI EN 834/1997 (UNI 2007).

The application of this resolution allows significant energy savings for at least two reasons as follows:

– The possibility for each owner–occupier or tenant to pay a share of the energy bill (contract structure in Italy is usually such that, on average 70 % of the global heating costs is based on actual consumption which represents a major incentive and will no doubt limit energy wastage)
– In residential condominium buildings, each occupier could implement energy-saving refurbishment (e.g. replacement of windows or internal insulation of the walls) without having to ask permission of a formal general meeting of the condominium, and the savings will directly benefit the occupier

The diffusion of local control systems and heat metering will encourage the energy efficiency market. However, the application of these new useful rules could generate critical issues that must be duly addressed.

The first problem is that those flats located at building extremities, such as bottom floors, top floors or corner zones, will have specific energy consumption greater than the specific energy consumption of the central flats. This is because the amount of their surface area distributed along the heat rejection surfaces (e.g. of the external envelope) is larger, and hence, heat losses are higher. Those living in these unfavourably situated dwellings thus risk an incremental increase in heating costs compared to those of the latter case.

Furthermore, independent energy management allows each user to adjust both the temperature and the heating periods. In existing collective-ownership residential buildings, the walls that separate the flats normally have poor insulation; therefore, different internal air temperatures may generate unwanted heat flux between them; in technical jargon, this is referred to as "theft of heat".

The allocation methods contained in UNI (2005) do not account for these factors. The Federal Energy Authority of the Swiss Confederation (CH 2008) proposes a more sophisticated calculation model in order to partially compensate for the disadvantage. This model starts from a more detailed analysis of different situations. It then introduces some correction factors that, whilst guaranteeing the independence of the mode of management by users and so maintaining the incentive to save, tend not to penalise flats that have a greater heat-loss/rejection surface owing to their geometrical shape.

The topics covered in this paper involve a number of interrelated aspects; some are technical (e.g. technology used for energy control and accounting), while others are behavioural (e.g. the abilities of the users to operate these technological items, such as control devices or thermostats).

The scientific community has addressed the issue of thermal energy accounting control in the residential sector using different approaches, but with a common assumption: good energy management can significantly reduce energy wastage and thereby improve the overall efficiency of buildings.

A study by Jin Woo Moon and Seung-Hoon Han (2011) has identified the impact of thermostat strategies on heating and cooling energy usage, suggesting the importance of a database for understanding the effect of thermostat settings and deciding on the appropriate energy-conscious strategies.

The analysis, which was performed using a computer simulation for two typical single-family homes located in a cold- and a hot-humid climate zones, revealed that heating and cooling systems were significant energy-consuming equipment/components in both climate zones. The study confirms that a proper setback period, set-point and setback temperature need to be established to achieve energy efficiency in residential buildings. The issue of the control of heating systems in residential buildings in Belgium has been treated in a paper by Peeters et al. (2008). The authors state that the primary energy consumption of heating systems is determined not only by the efficiency of the equipment but also by the way in which they are used by the occupiers.

Shipworth (2011) has addressed the subject of thermostat settings in English houses. The author raises a question of why home energy use has not declined over time, although dwellings appear to have become more energy-efficient. The study shows that energy consumption has not decreased owing to poor management of facilities and, in particular, the incorrect use of thermostats. In short, internal air temperatures have risen during heating seasons. Other authors have addressed the problem of poor management of control systems in residential heating systems. A. Meier et al. (2011) state that residential thermostats control 9 % of the total energy use in the US and similar amounts in most developed countries. Their study reports the results of five parallel investigations related to the usability of residential thermostats. Personal interviews revealed widespread misunderstanding of thermostat operation. Online surveys found that most thermostats were selected by previous residents, landlords or other agents. In the same journal, Peffer et al. (2011) provide a review of how people in the US use thermostats at home. The review covers the evolution in residential thermostat technologies but, at the same time, describes how people currently use thermostats, finding that nearly half do not use the programming features. There is then a confirmed real-world problem; the gap between the technological innovation in thermostats (and generally in energy control devices) and the users' lack of knowledge about how to employ them properly.

So far as heat metering issues are concerned, a group of researchers has conducted studies correlating the use of heat accounting systems and energy efficiency measures. A paper by Zhao et al. (2009a) introduced the heat metering and energy efficiency background of existing residential buildings in the northern heating area of China. They summarised the technological experiences that constitute a basis for promoting energy retrofit measures related to the installation of heat metering systems. The same issues are treated in other papers by D. Yan et al. (2011), Bao et al. (2012) and Zhao et al. (2009b), with each paper taking a different approach and providing different insights.

The theme of correct energy use is exciting because the potential for energy savings and avoiding wastage is remarkable. It is also interesting to track the analysis of user behaviour in order to identify possible strategies for informing user–occupiers about the intelligent use of modern technological and advanced energy control and metering devices.

In view of the diffusion of individual energy metering devices, which will be compulsory in the Lombardy region and in Italy, the study-paper addresses two aspects of the same issue, on the basis of a monitoring campaign carried on in a typical residential building of the 1970s located in Milan, Italy. On the one hand, it confirms the validity of this choice, which could boost the shares of energy retrofits in the apartments, but on the other hand, it highlights the critical aspects, particularly the problem of "heat theft". The study is also intended to observe the effect of temperature reduction on expenses by means of the extreme case of total shutdown of the heating system in a dwelling.

A metering system and a room temperature control system were installed in this building in the last winter season. It was therefore possible to evaluate the effects of the application of these technologies.

Description of the case study

Characteristics of the building and its plant

The case study is a typical medium-sized residential building situated in Milan and built in the 1970s. The building technology involves a reinforced concrete structure of beams and pillars clad with an external double brick wall enclosing an air cavity. The windows have wooden frames and double glazing, which was a high-quality choice at the time of construction.

Two sides of the building are adjacent to other heated buildings; the two main facades are oriented, respectively, to the north (street) and to the south (inner private courtyard).

The building is seven storeys high, with the ground floor occupied by commercial activities and the other floors occupied by residential flats. Each floor is divided into a variable number of flats, ranging from 1 to 4. There are 15 flats in the building in total. Table 1 lists the flats with the position and the usage during the heating season under evaluation.

The building is equipped with a central heating plant that uses radiator terminals installed in each room of the flats for heating. During the summer of 2010, the heating plant was partially renovated as follows:

Table 1 Position of the flats and conditions of usage

Flat code	Position (floor)	Usage
1	1	Not heated
2	1	Heated
3	2	Heated
4	2	Heated
5	2	Heated to 15 °C
6	2	Heated
7	3	Heated
8	3	Heated
9	4	Heated
10	4	Not heated
11	4	Heated
12	5	Heated
13	5	Heated
14	5	Heated
15	6	Heated

- Replacement of the obsolete boiler with a new high-efficiency condensing boiler
- Change in the type of boiler fuel from oil to natural gas
- Replacement of the central control system
- Replacement of the old circulation pumps with new high-efficiency pumps equipped with inverter control
- Installation of a thermostatic valve in each radiator instead of the old manual valve
- Installation of indirect metering/accounting devices (one for each radiator)

The difference in the system control before and after the retrofit is significant. Before retrofit, the entire system was centralised for all the building: the water temperature to the heating terminals of the heating system (radiators) was regulated by the control unit installed in the boiler/heating plant room on the basis of the outside air temperature. With the installation of the new control systems, the climatic control for each room is guaranteed by means of the thermostatic valves which, through an air temperature sensor, vary the flow rate of heat transfer fluid (in our case hot water) of each terminal. In the new configuration, each user is able to regulate, by turning the knob of the thermostatic valve, the air temperature inside each room of the flat. Thanks to the installation of indirect metering/accounting devices, the user is also able to measure the thermal energy actually consumed.

Table 2 shows the geometric and thermo-physical characteristics of the building. In this paper, only the residential part of the building is considered.

Energy consumption survey in winter heating season

For the case study, two different situations were compared: the 2009–2010 winter heating season and the 2010–2011 winter heating season. The comparison between the two winter heating seasons permitted the evaluation of the increase in thermal performance due to the plant renovation and partially due to changes in user behaviour after the installation of the individual control and accounting systems.

The consumption data were normalised with reference to the heating degree-days of the location supplied by Agenzia Regionale per la Protezione dell'Ambiente (ARPA) for the two winter heating seasons. The analysis examined both the total costs and the specific costs for each flat. For the 2009–2010 season, the allocation of the costs was made as a function of thousandths of the property, approximately proportional to their heated volumes. Whereas for the 2010–2011 season, after the plant revamp, it was decided to subdivide; 70 % of the global costs were shared-out based on the consumed thermal energy of each flat, which was measured indirectly (this method is known as indirect accounting or allocation) by heating cost distributors/allocators on each radiator (heating cost distributor Kundo mod. HKVE202R, thermostatic valve with liquid sensor HERZ mod. 9.200). In this case, the calculation was made in accordance with the procedure outlined in the EN 834 standard. The remaining 30 % was subdivided on a thousandths of property basis.

In Italy, oil is more expensive than natural gas. To make a valid comparison between the two cases, the costs of energy were normalised to the cost of natural gas in 2012.

Table 2 Geometric and thermo-physical characteristics of the building (after renovation)

Description	Data
Location	Milano (Italy)
Winter degree days	2404
Climatic zone	E
Gross heated volume	4,920.5 m^3
Envelope dispersant surface	2002 m^2
S/V ratio	0.41 m^{-1}
EPH	140 kWh/m^2 year
Energy class	E
U values of the building structures (according with appendix C of standard UNI TS11300)	
Opaque walls	1.15 W/m^2K
Windows	2.80 W/m^2K
Walls below the windows	1.47 W/m^2K
Basements	1.25 W/m^2K
Roofs	1.35 W/m^2K
Internal walls	2.50 W/m^2K
Slabs between flats	1.25 W/m^2K
Characteristics of heating plant (after renovation)	
Heating boiler type	Condensing boiler
Heating capacity	160 kW
Heating terminals	Cast iron radiators
Control type	Climatic centralised control and local control (thermostatic valves)

Monitoring of the air temperature inside the unheated flat

During the 2011–2012 winter heating season, a monitoring survey was conducted in the unoccupied, unheated flat (cod. 10) in which all heating terminals were closed.

During the monitoring period, which lasted from January 29, 2012 to April 15, 2012, the values for internal air temperature and relative humidity were acquired using two mini data-loggers, onset mod. U12.

The first device was installed inside the kitchen whilst the second device was installed inside the living room. The data were acquired every 15 min for the entire duration of the monitoring period.

During the survey, the flat was unoccupied by users and the window shutters were closed around the clock. External climatic data (i.e. air temperature, relative humidity, wind speed) were provided by ARPA.

For the entire monitoring period, the air temperature of the adjacent apartments was controlled to verify variations during the day. The thermostatic valves of the adjacent rooms were set, using the knobs, with the objective of maintaining an internal air temperature of 20–21 °C. The value of the internal air temperature was checked using mini data-loggers installed inside the rooms.

Results and analysis

Utilising the real, measured consumption data, normalised in accordance with the procedure previously described, the overall heating management costs have been calculated for the 15 dwellings which the building comprises.

For each flat, three scenarios were compared as follow:

1. Cost based on the sharing according to the thousandths of property prior to the renovation works (season 2009–2010)
2. Cost based on 70 % of consumption measured using heating cost distributors and for 30 % on thousandths of property, in accordance with UNI 10200 standard, the method actually utilised (season 2010–2011)
3. Same as point 2, but conducting the calculation in accordance with the method proposed by Conteggio Individuale Spese Riscaldamento=*Individual Calculation of Heating Expenses*, which applies a reduction coefficient to the consumption of the dwellings in unfavourable locations within the building [6].

The cost indicators, expressed in euros per square meter, also cover the 30 % which is a fixed cost. For this reason, flats 1 and 10, which are unoccupied and unheated, still pay a portion of winter heating costs for winter heating in scenarios 2 and 3.

The values obtained are presented graphically in Fig. 1. The graph shows that the savings obtained are very variable. This variability could be due to many factors, such as thermostatic device settings, individual set-backs, amounts of cooking, physical exercise or other behaviour, window opening, varying ventilation levels from one flat to the next. Nevertheless, we found that there was consistency between the specific consumption of the flats and their position, which corresponds to a different heat loss/dissipation from their surrounding surfaces. As indicated in Table 1, several dwellings are not heated or are maintained at a lower temperature than the nominal value of 20 °C. An examination in greater depth of these aspects will be the subject for specific consideration in a future paper.

If we compare the energy costs due to winter heating for the whole building before and after the retrofit measure (scenario 2), we have a net reduction of 50.4 % obtained exclusively through plant-modification works. The costs indicated in the graph of Fig. 1 were calculated normalising the cost of fuels and the winter seasons, i.e. considering the standard degree-days. The global benefit is derived from three factors as follows:

1. Increase in the efficiency of the central heating plant (boiler replacement, centralised control system replacement, replacement of the circulation pump)
2. Installation of individual metering and regulation system (indirect metering/accounting devices and thermostatic valves)
3. Modification of user behaviour thanks to the possibility of independently managing energy consumption

It is not possible to apportion the energy benefits between the three factors, since only one flat was monitored and the internal air temperatures of all the flats in the building are not known. In-depth examination of this aspect will be covered specifically in a future paper.

The graph in Fig. 2 highlights the effect in terms of increase in the energy consumption, i.e. the closeness to unheated flats for 2010–2011 heating season. On the *y*-axis, the shared cost for winter heating (based on the data acquired from the energy accounting devices) is reported while the *s*-axis reports the surfaces of the global external envelope (both opaque and transparent).

Figure 2 highlights that for all flats, there is a consistency between cost and heat-loss surface area with the exception of the two flats on the left of the graph for which the cost is markedly higher. The higher consumption is due of the thermal energy transferred to the adjacent unoccupied, unheated flats. The quantitative evaluation of the phenomenon of heat theft is complex and requires monitoring of the mean temperature of the air inside all rooms. Although that was not the objective of the study, the great interest in this aspect suggests that we should pursue this issue further: it will be addressed in a forthcoming paper.

In the same graph unoccupied, unheated flats, or flats maintained at a very low temperature, are highlighted. As shown in Fig. 2, the effect of heat transmission between the flats is not negligible. To

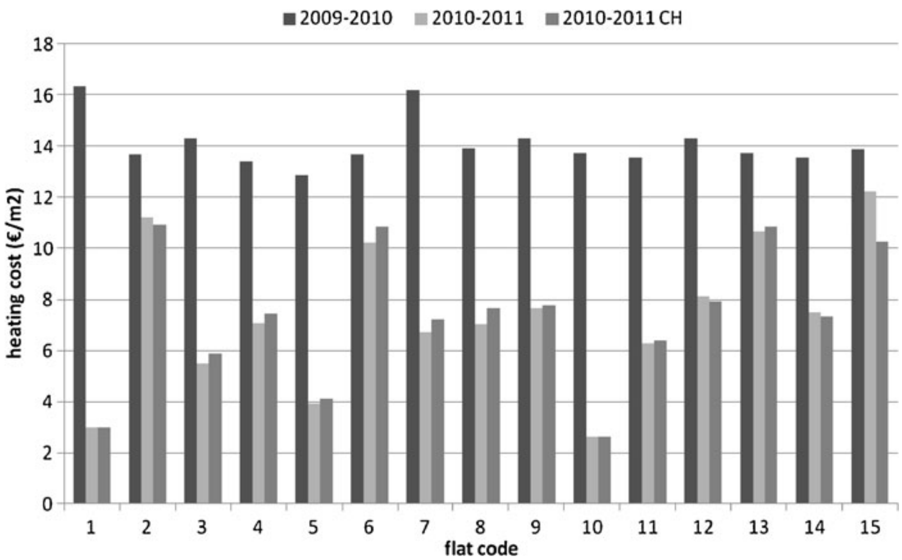

Fig. 1 Cost sharing for winter heating in three different scenarios: *1* sharing based on volumetric thousandths, *2* sharing based on measured consumptions proportionate to the share of the share of 70 % of total costs, *3* the same as scenario *2* but according to CISR model

evaluate the effect of inter-flat heat transmission, data obtained in the monitoring survey from January 29, 2012 to April 15, 2012 have been processed.

Figure 3 shows the internal air temperature of the monitored flat. This flat is unheated, and hence, the internal temperature depends upon the heat fluxes coming from the adjacent heated flats (internal walls, ceiling, floor) and from the outside surrounding environment through the building envelope.

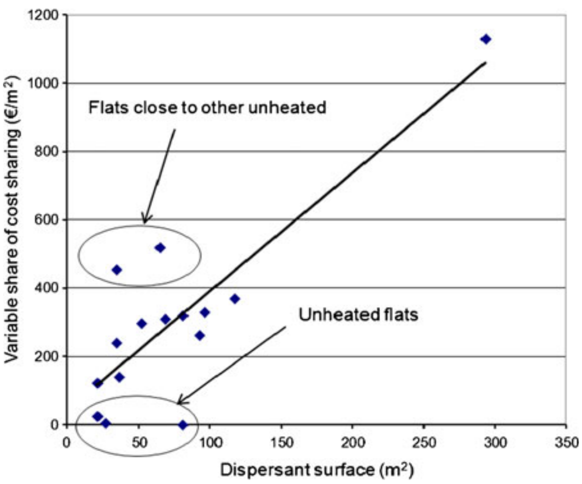

Fig. 2 Consistency between indirect accounting shared cost for winter heating and envelope surface of the flats

The values of the internal air temperature could be calculated in an analytical manner by comparing the heat flux balance equations, evaluating thermal energy coming from each of the other heated flats, Q_{in}, and the thermal losses through the building envelope, Q_{out}.

The calculation is greatly simplified by considering the laws of heat transmission under steady-state conditions, thus neglecting the effect of the thermal inertia of the building structure.

At a time *t*, the output thermal power can be calculated from the following equation:

$$\dot{Q}_{out}(t) = \sum (U_{we}A_{we}) \cdot (\theta_{int}(t) - \theta_{ext}(t)) \quad (1)$$

While the input thermal power can be calculated with the following equation:

$$\dot{Q}_{in}(t) = \sum (U_{wi}A_{wi}) \cdot (\theta_{near}(t) - \theta_{int}(t)) \quad (2)$$

Using $\dot{Q}_{out}(t) - \dot{Q}_{in}(t) = 0$, one can obtain the value of the internal air temperature θ_{int} at time *t* with the following equation:

$$\theta_{int}(t) = \frac{\sum (U_{we}A_{we})\,\theta_{ext}(t) + \sum \left(U_{wi}A_{wi}\right)\theta_{near}(t)}{\sum (U_{we}A_{we}) + \sum (U_{wi}A_{wi})} \quad (3)$$

The graph in Fig. 4, which considers the same period, comparing the values of the measured internal dry bulb

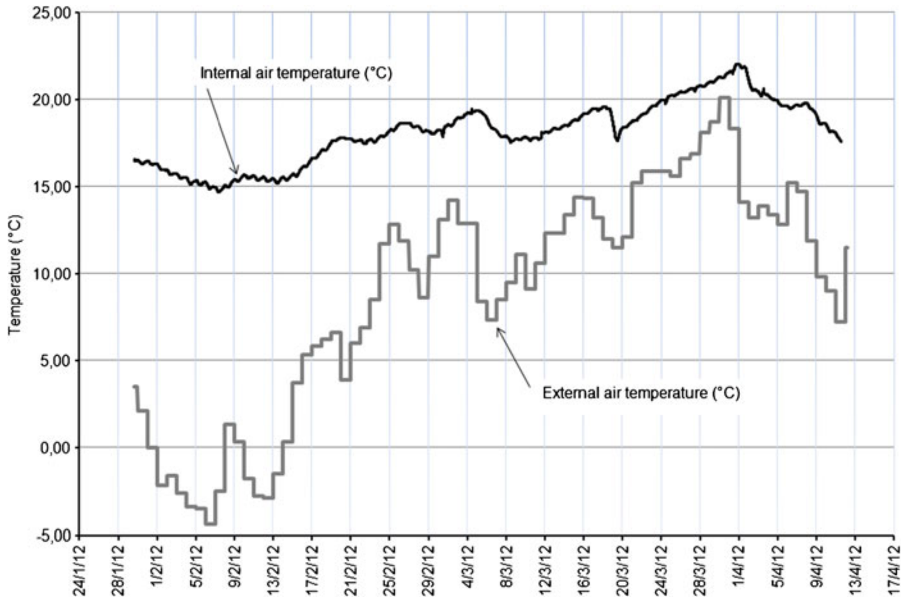

Fig. 3 Comparison between the internal air temperature of the monitored flat and the external air temperature for the same period

air temperature with the internal dry bulb air temperature calculated from Eq. (3).

The values of the air temperature of the adjacent flats, provided by a monitoring survey, were between 20 and 22 °C.

Data in Fig. 4 shows that the two graphs are quite consistent if one excludes the phase shift, as one should since in the simplified calculation, the effects of the thermal inertia of the building structure were not considered.

Basic steady-state equations may be used, with acceptable margins of error, if the objective is limited to better understanding the effects of the heat fluxes in evaluation studies on how to allocate costs for heating services.

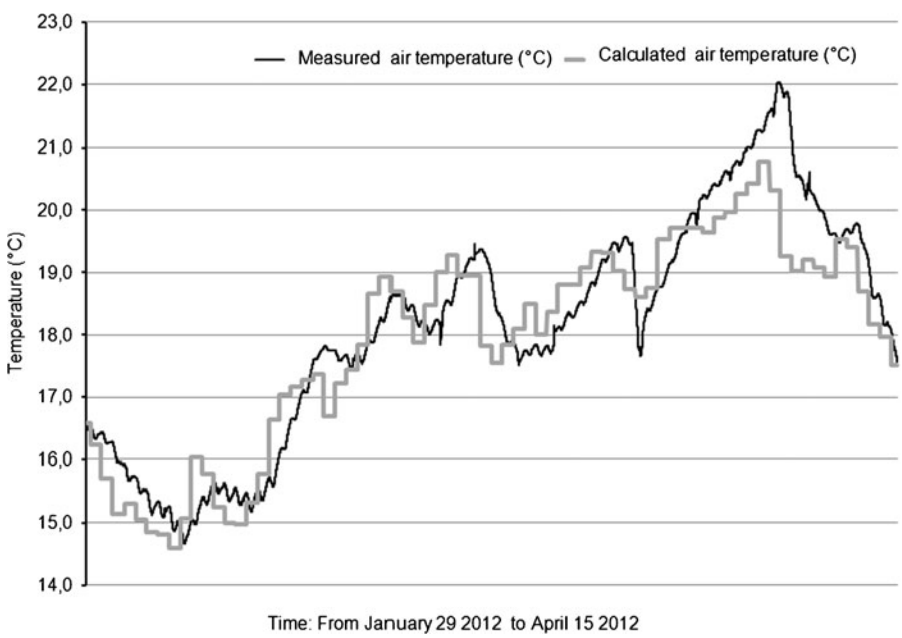

Fig. 4 Comparison between monitored and calculated values of the internal air temperatures

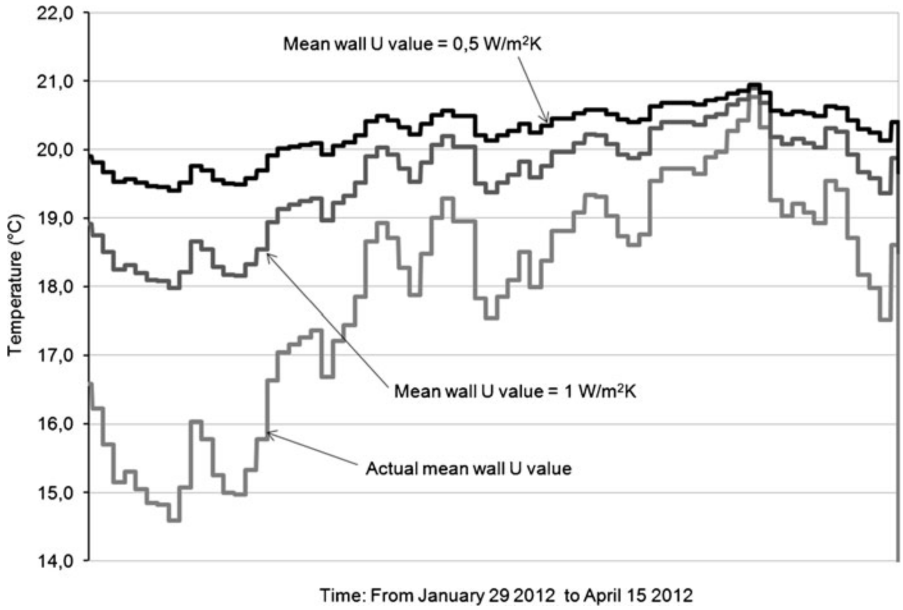

Fig. 5 Comparison between the values of the calculated internal air temperature with different average *U* values of the building envelope

The graph of Fig. 4 provides a comparison between monitored and calculated values of the internal air temperatures of an intermediate flat, i.e. a flat surrounded by other apartments. The same calculation considering building–boundary or extremity flats (i.e. flats #1, 2, 12, 13, 14, 15) would be more complex.

In the case considered, for a flat with its heating system switched off, when retrofit measures are applied, there is no reduction in energy consumption. There will, however, be an increase in the internal temperature.

The graph in Fig. 5 simulates the variation of the internal air temperature inside the flat under study with the heating system switched off, for different average *U* values for the outside envelope, with the actual *U* values (*U* value=1 W/m^2 K and *U* value=0.5 W/m^2 K). The three simulations were calculated using Eq. (3).

The situation shown in the graphs in Fig. 5 is extreme, since it clearly shows that when the surrounding walls are well insulated, the dwelling attains comfortable temperatures by benefiting from the "heat theft". In any case, the reduction of the heat losses due to retrofit measures is an advantage not only for the user of the flat but also for the users of the flats adjoining the extreme situation flat. The benefit accrues to these flats because an increase in the air temperature of the unheated flats corresponds to a reduction in thermal fluxes and the "theft of heat".

Conclusions

In this paper, it was possible to compare two situations using the energy consumption monitoring for winter heating in a typical 1970s building, with and without autonomous heating controls. An analysis has been made of the effects of the application of the recent resolution passed by the Lombardy Regional Council, which states that all the existing buildings must be equipped with local temperature controls and accounting systems for heating appliances; this is intended to facilitate the reduction of energy consumption through the division and allocation of costs for winter heating based upon actual consumption of each unit.

This case study demonstrates that the obligation to equip buildings with thermoregulatory systems and heat metering/accounting can bring significant savings.

A net reduction of 50.4 % in the global costs for winter heating, obtained exclusively through plant-modification works, represents an optimum goal for energy savings. It depends not only upon the increased performance of the heating system but also on different user management strategies that shift the liability for energy to the end-user. For example, the owners of empty dwellings have kept radiators shutoff, avoiding a useless wastage of energy.

The positive effect on the environment of this compulsory resolution is very great, especially in urban areas where the number of condominiums is very high. Associated reductions of greenhouse gases and pollutant emissions from fossil fuels are also expected.

Moreover, critical aspects have been investigated, namely the problem of the increasing the specific costs for the flats with a greater S/V ratio and the "heat theft" phenomenon.

Our analysis highlights several suggestions to improve the implementation stage of this interesting regulation as follows:

– The allocation and distribution of consumption usually is based on two factors: the fixed component and the component directly linked to energy consumption. For apartments located at the extremities of the building (e.g. the top or basement floor), it would be appropriate to apply correction factors; and
– Situations where air temperatures inside some flats are too low, for example below 17 °C, are not acceptable and can cause significant heat theft from adjacent dwellings. One solution could be setting thermostatic valves to prevent an excessive lowering of temperature or modifying the fixed heat rate. Nonetheless, for energy saving purposes, it would be appropriate to maintain the temperature of the unoccupied dwellings at a minimum level. The most appropriate solution would consist of insulating the partition walls between dwellings, thus also improving acoustic comfort.

A final consideration concerns the information provided to the users about the best way to utilise energy control devices and energy metering devices. These technologies do have great potential when not viewed as a mere fulfilment of a rule, but rather as a turning point for more energy-conscious building usage.

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