The role of individual metering in reducing domestic hot water consumption in residential buildings: A long-term evaluation

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Highlights

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Detailed quantitative analyses of the effect of individual metering on DHW consumption.

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Long-term field observation of DHW production and consumption in 3rd gen DH network.

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16 thermal substations supplying 137 multi-family buildings.

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Reduction in heat consumption for DHW production at the DH side.

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Reduction in hot water volume consumption at the demand side.

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Individual metering among the influencing factors in DHW consumption reduction.

Abstract

Within the residential sector, Domestic Hot Water (DHW) production represents the highest energy-intensive end-use after the space heating. Energy consumption for DHW production in residential buildings depends not only on the efficiency of the production, distribution and supply systems, but also on the occupants' behaviour and characteristics. For this reason, it is crucial to increase users' awareness in order to induce virtuous behaviours and reduce excessive uses of DHW. In this context, individual metering and consumption-based billing can be extremely useful and low-cost tools for reducing energy and water wastes and increasing the end-use energy efficiency in buildings. This paper is aimed at investigating the effect of individual metering systems on DHW consumptions in the residential sector. For this purpose, the operating parameters of 16 substations of a high-temperature district heating (DH) network supplying 137 multi-family buildings were monitored daily for over 14 years, during which individual DHW meters were installed and consumption-based billing was introduced. It has been found that after the installation of individual DHW meters the average daily heat consumption for DHW production decreased by 14% and that the DHW volume withdrawn by the buildings decreased by 32%. Those variations were found to be statistically significant.

Introduction

The building one is among the main energy-intensive sectors in European Union and increasing its energy efficiency is expected to contribute significantly to the EU achieving its carbon neutrality goal by 2050. As well known, energy in buildings is used for different end-uses, depending on several factors, including the type of building (residential or commercial). According to EUROSTAT estimates, on average about 85% of the energy in residential buildings is consumed for space heating (70%) and water heating (15%) [1].

While the space heating need of newly built and renovated buildings is progressively diminishing with increasing energy performances of the envelope and of the technical systems, as a result of increasingly stringent design requirements towards nearly Zero Energy Building (nZEB) [2], the energy need for the domestic hot water (DHW) production has remained quite constant over the years, with the consequence that this is becoming a significant share of the total energy balance of buildings. Indeed, the analysis of surveys data on nZEB and recently built energy-efficient dwellings show that DHW production is already reaching 40–50% of the total energy usage in these cases [[3], [4], [5]].

The final uses of DHW in the residential sector can be manifold. Although DHW is mainly used for personal hygiene, its use is also relevant for washing dishes, clothing and cleaning of domestic environments. Almost 70% of the total hot water volume is used in baths and showers, followed by bathroom basin and kitchen sink [6]. According to Ref. [7], in US 51% of total DHW consumption occurs for showers, 23% for baths, 10% for dishwashers and 16% for washing machines.

DHW consumption is made up of a deterministic and a random component: end-users tend to use DHW more or less at the same time every day (with some differences in working days compared to non-working days). However, the consumption of DHW varies stochastically depending on occupants' characteristics and behaviour and on events that are difficult to predict (e.g., holiday/non-occupancy periods, number of showers per person per day, number and temperature of washing cycles, frequency use of dishwashers etc. [8]). Indeed, end-user behaviour is a driving factor affecting energy consumptions for DHW production. This depends not only on geographical and climate conditions, but also on cultural habits, education and socio-economic background, which all greatly affect energy use practices. Socio-economic and demographic factors include dwelling size, number and age of adults, gender, income and education [9]. Fuentes et al. [8] summarized the findings in several studies regarding the influence of socio-economic factors on DHW consumption and included the following factors among those having an increase effect on DHW consumption: i) the occupancy rate, ii) the presence of females, teenagers and children, iii) the number of generation systems, iv) the occupants' age, v) the household income, vi) the higher education level, vii) the household size etc.

Another non-secondary aspect, with a potential significant impact on the residential DHW consumption, is the ever-growing trend towards better comfort and hygiene (e.g., immediate availability of DHW upon delivery request, more frequent and longer showers etc.) of the end-users, both in developed and developing countries. These have been demonstrated to affect not only the DHW production, but all the energy consumption in the residential sector. As for example, the total electricity consumption of domestic appliances in the residential sector is growing, despite the specific consumption of the devices is progressively decreasing as a consequence of increasing energy efficiency. In the space heating sector, the so-called rebound effect has also been observed, which happens when end-users increase their energy consumption after an energy renovation of the building looking for greater comfort [10]. Similarly, Pomianowski et al. [3] report that, over the last 20 years, the annual DHW consumption per capita in Denmark increased from 10 m^3/year to around 15 m^3/year. As a consequence, the occupants' behaviour and characteristics should be carefully considered in building energy management systems, as a part of grid-connected microgrids implementing demand management features via distributed control and human-in-the-loop optimization [11]. As for example, Baldi et al. [12] showed that increasing the occupant-building interaction via smart zoning of thermostatic loads (switched self-tuning approach) can allow to save more than 15% energy consumption for space heating. Similarly, Korkas et al. [13] demonstrated that an occupancy-based control strategy accounting for occupants' schedules and thermal comfort can improve renewable energy exploitation up to 22%. Similarly, in the DHW sector, Zhou et al. [14] proposed an information-driven stochastic DHW usage model that interacts with solar hot water systems and studied the effects of occupants' sensitivity to water temperature and their energy-saving awareness on the energy performance of solar hot water systems. They showed that optimal design and control strategies based on the actual DHW profile can increase the annual solar energy utilization rate by 11.5%.

Numerous efforts have been made to encourage the EU Member States to implement measures to empower the consumers toward energy efficiency actions in the sectors of heating and of DHW production in buildings. In 2012, the first Energy Efficiency Directive (EED) [15] introduced the obligation to install individual metering and sub-metering systems in buildings, where centralized heating, cooling or DHW production systems were installed. Indeed, individual metering systems had been proven to be an effective tool to reduce energy wastes by increasing end-users' awareness and inducing positive changes in end-users' behaviour [16]. In December 2018, the amended EED (2018/2002) [17] strengthened the provisions in the sector of individual metering, specifically by: i) introducing the unconditional requirement of installing individual meters in new multi-occupancy buildings, ii) obliging Member States (MS) to publish transparent cost allocation rules; iii) introducing new remote reading requirements for individual metering systems; iv) requiring more frequent billing or consumption information, where remotely readable devices are installed; v) requiring a more frequent and complete billing information (climate corrected data, comparisons, energy mix and GHG emissions, complaints procedures ... [18]).

Some Member States officially opposed to the EED provisions on individual metering (e.g., Sweden, Finland), while in others serious doubts in the public opinion specifically regarding cost efficiency have been raised [19,20]. The main question regards the actual efficacy of individual metering and behavioural changes as an energy retrofit action, compared to other interventions on the envelope and on the technical systems. Indeed, the installation of individual metering devices alone may not be perceived as an actual retrofit intervention, since the achievable energy saving relies on the assumption that the more the users are aware of their consumptions, the more they will try to avoid unnecessary energy wastes. In other words, the energy saving deriving from individual metering depends on occupants' behaviour, which is stochastic and therefore very variable by definition. This leads some Member States to prefer other technical interventions, whose resulting energy saving is more easily predictable (thermal insulation, replacement of the generator, etc.). Furthermore, it should also be argued that, although many papers in the scientific literature studied the effects of individual metering, the majority concern the effects of individual metering on space heating consumption in few years of observation. As for example, Canale et al. [21], performed an experimental campaign on a sample of about 3000 dwellings in 50 buildings located in the Italian regions where heat cost allocators and thermostatic radiator valves were installed. They found an average energy saving of about 11% in space heating consumption. Cholewa and Siuta-Olcha [22] investigated the effects of heat cost allocation on space heating consumption in 40 apartments in a multifamily building located in Poland for over 17 heating seasons and estimated an average benefit of about 26.6% at the second year from installation. In Ref. [20], the authors performed the analysis of the space heating consumption of 250 buildings with over 20 000 apartments in nine Croatian cities prior to and after the installation of individual metering devices. The analysis of the consumption of cumulative standardized heat energy showed an average reduction of 27.7% after the implementation of individual metering devices in the space heating service. Canale et al. [10] provide detailed statistical analyses of the effect of in-home displays and individual metering on more than 200 apartments in four Danish buildings where the average consumption of cold water, hot water, electricity and heating decreased by 17%, 23%, 12% and 17%, respectively as an effect of the information on consumptions.

On the other hand, the literature regarding the effects of individual metering on DHW consumption is almost lacking. In Ref. [23] the authors analysed of DHW consumption data in 14 households provided with detailed information about hot tap water consumption. The recorded changes in DHW consumption varied widely across the households, ranging from reduced (−75.9%) to increased consumption (+126.1%) during the monitoring period. An average increase of DHW consumption was observed in all the sample (+13.4%). A study conducted in Spain [24] found a 15–20% reduction of normalized energy consumption during the first two years after the implementation of individual metering on space heating and DHW production services. In Ref. [25] a saving of 11.4% was observed in a sample of guests of 6 hotels who were given direct feedback on the use of water for the shower through a water meter with display directly installed on the hand shower. In Ref. [26], the authors reviewed 21 papers to assess the evidence base for the effectiveness of water-usage feedback technology in water conservation and found a decrease in water use between 2.5 and 28.6%, with an average of 12.2%, after providing user's feedback.

The analysis of the existing scientific literature highlighted two research gaps: *i)* the effectiveness of individual metering systems in reducing energy consumptions is still unclear, if compared to other technical interventions, and *ii)* there is a lack of detailed experimental studies, on relevant building samples and on extended time horizons, analysing the effect of individual metering on DHW consumptions. In this context, this paper aims to overcome the above described limitations, by providing a detailed quantitative analysis on the effectiveness of individual metering in reducing the DHW consumption in the residential building sector. For this purpose, data of DHW production and consumptions over 14 years related to 16 thermal substations supplying 139 buildings in a high temperature district heating (DH) network have been analysed before and after the installation of individual water meters for DHW.

This paper adds a relevant contribution to the current scientific literature on individual metering, presenting a series of innovative aspects compared to the existing literature, namely:

- i)

a detailed quantitative analysis of the effects of individual metering on DHW in a large sample of buildings (i.e., 139 buildings) is provided;

- ii)

a long-term experimental monitoring campaign (i.e., 14 years) was carried out, while most of the existing studies focus on a few years in single case studies;

- iii)

both DHW consumptions (demand side) and DHW production operating parameters (supply side) were analysed, thus providing a complete overview on the investigated effect.

In the following, both the experimental campaign and data processing are first described (Section 2), then the analysis of the substations operating parameters (supply side) and DHW consumptions (demand side) is provided in Section 3 and the main general discussions are drawn in Section 4. Finally, the main conclusions of this paper are given in Section 5.

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Section snippets

Experimental campaign and data processing

A long-term experimental monitoring campaign was carried out at 16 substations serving 137 residential multi-family buildings and 2 non-residential buildings (i.e., a school and a post office) supplied by a high-temperature district heating (DH) network located in Poland in Lublin Voivodeship, for over 14 years (i.e., from 01 June 2005 to 31 May 2019).

As regard the characterization of Lublin Voivodeship building-stock and DH network [27], almost 91% of apartment buildings in cities have access

Effect of individual metering on DHW: supply side

Table 2 shows the average (avg) and standard deviation (stdv) values of the daily heat consumption for DHW production [kWh] in the non-heating season. The table also shows the relative variation, calculated as relative difference between the average values measured before and after (respectively, avgbefore and avgafter) as per equation (5).Relativevariation=avgafter−avgbeforeavgbefore·100

As shown in Table 2, in all the substations daily average heat supplied for DHW production decreased in the

Conclusions

The aim of the present paper was to investigate the effectiveness of individual metering in reducing DHW consumptions in a district heating network located in Poland. For this purpose, the authors provided statistical analyses of 14 years of daily data of DHW production and consumptions of 16 thermal substations supplying 139 buildings in a high temperature district heating network in Poland, comparing the data measured before and after the installation of individual DHW meters in the single

Author statement

Laura Canale: conceptualization, data curation, formal analysis, writing - original draft, writing - review & editing; **Tomasz Cholewa**: conceptualization, data curation, writing- original draft, writing - review & editing; **Giorgio Ficco**: conceptualization, methodology, supervision, writing- review & editing; **Alicja Siuta-Olcha:** investigation, data curation, writing- review & editing; **Biagio Di Pietra:** resources, visualization, writing- review & editing; **Piotr Kołodziej:** data curation, writing-

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Citation Excerpt :

Recent experimental research [11] conducted in multifamily buildings shows energy saving potential of up to 49,5% depending on the specific methods (integration of TCV’s, DHW temperature reduction in the night etc.) applied. Also, increasing user awareness and enhancing analyses of DHW consumption through installation of individual DHW meters can lead to significant savings, namely 14% for the average daily heat consumption for DHW production as described in Ref. [12] in a long-term monitoring study of DHW supply in multi-family buildings. Concerning demand-based DHW system control, several publications [13–16] reveal energy efficiency increase potential using probabilistic/analytical modelling for, e.g., predicting occupancy as well as DHW use in residential dwellings [13], predicting future heat losses in the circulation system [15] so as to dynamically adjust the DHW target temperature [14] or predicting the future DHW demand utilizing BAS based on neural networks in residential buildings [16].

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