Simple solutions first—energy savings for domestic hot water through flow restrictors

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ORIGINAL ARTICLE

Simple solutions first—energy savings for domestic hot water through flow restrictors

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Abstract Domestic hot water production is the second most important energy use in the European residential sector, nowadays accounting for 14% of the sector's total final energy consumption. Despite its importance, the energy efficiency improvement rates for domestic hot water are lower than for other residential energy services, hence calling for energy-saving measures. One key measure is to install flow restrictors. Their advantages are the low upfront cost, easy installation, and suitability for integration into energy efficiency programs. Focusing on flow restrictors, this paper presents different methods for quantifying the energy savings using ex-ante and ex-post approaches: deemed savings (DES), dedicated measurements (DMs), and monthly and yearly billing analysis (SMBA and ABA). These methods were tested using information based on measurements (water flow, temperatures), historical billing analysis, a survey among inhabitants, and interviews with field experts. While measurements made at individual faucets or showerheads show significant water savings (20% and 33% respectively), energy savings associated with hot water production in the boiler (final energy) are significantly lower (around 10%) but far from being negligible. The main reasons for the difference are thermal losses related to hot water distribution in central heating systems, usages not affected by flow restrictors, and inhabitants removing them. We conclude that flow restrictors offer promising potential for short- to medium-term implementation. Given the simplicity of this solution, we recommend including it systematically in energy efficiency programs, as well as implementing a ban on fixtures with flow rates beyond a predefined level.

Keywords Domestic hot water · Flow restrictors · Efficient showerheads · Energy savings · Energy conservation · Energy efficiency · Reduction of carbon emissions · Residential sector · Energy efficiency program evaluation · Ex-ante estimations · Ex-post evaluation

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Introduction

To tackle the depletion of non-renewable energy resources and climate change, several European countries have set ambitious targets to reduce energy consumption and carbon dioxide (CO_2) emissions by 2035 and 2050 (European Commission, 2020). To reach these objectives, a fast-paced strategy that allows for realizing significant energy savings in the short to medium term becomes compelling, alongside measures that are implemented over longer timeframes. This reasoning is reinforced by the energy crisis due to the Russia-Ukraine war.

Buildings are the largest energy-consuming sector in Europe, accounting for 40% of the total final energy consumption (IEA, 2013), with almost two-thirds corresponding to residential buildings (Santamouris, 2015). Domestic hot water (DHW) in Europe (EU27 plus UK, Switzerland, and Norway) is the second most important energy usage in the residential sector after space heating, and it represents 14% of the sector's total final energy demand (ODYSSEE, 2019). DHW-related energy use per dwelling began to decrease in Europe approximately 20 years ago (ODYSSEE, 2019); however, this trend has slowed down significantly since 2014 in some countries (e.g., France, Italy, and Spain) and has even reversed in others (e.g., Austria, Belgium, and Romania) (ibid.). In the last two decades, DHW usage shows the lowest improvement in energy efficiency among all end-uses (ibid.).

From the production perspective, DHW is often considered in the context of analyses on heating systems and their full or mostly partial decarbonization (e.g., by solar hot water systems (Panaras et al., 2013), by biomass-fired systems (Demirbas, 2005), or by the installation of central heat pump systems (Montero et al., 2023)). For retrofit, increased attention is also paid to dedicated heat pumps for DHW supply (e.g., Tammaro et al. 2017). From the demand perspective, DHW is receiving less attention than space heating although the associated energy consumption and the potential for energy savings are far from being negligible, particularly in the residential sector. Several studies have focused on the reduction of total (hot and cold) water consumption (Willis et al., 2013; Beal et al., 2010, Mengshan et al., 2011); some of them have analyzed specifically DHW through simulations (Hadengue B. et al 2022), but hardly any also addressed the related energy savings and reduction of CO_2 emissions based on real implementation. This study aims to close the knowledge gap concerning the actual energy savings potential that can be achieved through the reduction of DHW consumption.

Energy savings for DHW can be obtained by implementing simple measures in the short to medium term, thereby contrasting with the heavy burden related to the thermal insulation of building envelope, the installation of heat recovery in the ventilation system, or changing the heat supply system. Among various options to improve the energy efficiency of DHW systems (Hadengue et al. 2022), a simplest solution consists of installing water flow restrictor devices on faucets and showerheads (see Appendix 1) to reduce water consumption and informing users about its benefits in order to ensure its acceptance. This consequently reduces the energy required to produce DHW and the associated CO_2 emissions when fossil fuels are used.

To assess the effectiveness of this energy efficiency measure (EEM), we develop and test a methodology to determine the water and energy savings as well as the reduction of CO_2 emissions related to water flow restrictors. The required information was collected in the context of energy efficiency programs (EEPs) for the residential sector in Switzerland and was complemented by a survey and interviews.

The present study is structured as follows: the "Saving DHW using flow restrictors" section describes the EEMs pertaining to water flow restrictors implemented by the EEP's campaigns covered by our case study; the "Methodology" section explains the methodology (based on one ex-ante and three ex-post methods) that is used to estimate the energy savings; the "Ex-ante deemed energy savings (DES method)—analysis and results" and "Ex-post methods—analysis and results" sections cover the analysis and results for the energy savings and the CO_2 emissions; and finally, the "Discussion" and "Conclusions" sections contain the discussion and conclusions of the present study.

Saving DHW using flow restrictors

The EEM studied in this paper includes the installation of flow restrictors (also called flow reducers or flow regulators) in faucets and the replacement of existing showerheads by efficient ones (see Appendix 1).

DHW fixtures affected by flow restrictors

Flow restrictors are installed on toilet (washroom or bathroom) faucets and kitchen sink faucets but not on bathtubs and washing machines because the amount of required water for the latter is predefined. Water flow restrictors for faucets reduce, according to manufacturers, the flow rate by 50% (Aquaclic, 2022). For the efficient showerheads, the flow reduction is close to one-third according to manufacturers' brochures (ibid.).[1] Instead of replacing the showerheads, some

[1] In addition to manufacturer data, this study includes a literature review and our own measurements, detailed in Appendix 4 "Flow rates."

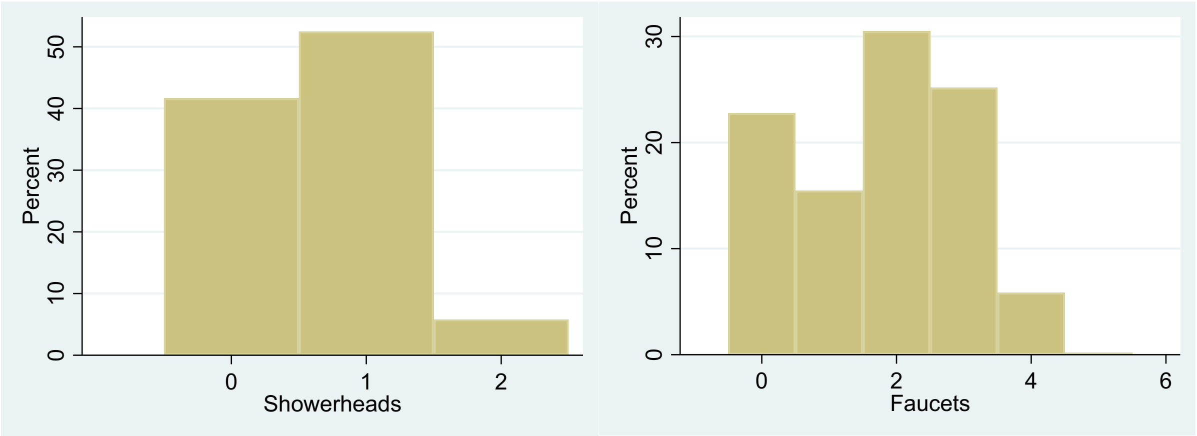


Fig. 1 Distribution (histogram) of the installed number of efficient showerheads (left) and flow restrictors in faucets (right) in dwellings (n=6005) in Geneva, 2010–2018 (totals add up to 100%).

of the flow restrictors installed in faucets can also be installed in showers.

The campaigns

As part of the EEP in the canton of Geneva, the campaigns on DHW savings were ramped up from pilot scale to full scale in 2014, and they were subsequently implemented by three other utilities in the canton of Vaud (Cabrera Santelices et al., 2019). From 2014 to the beginning of 2019, 25 campaigns targeting 14,825 dwellings were carried out (see Appendix 3 for more details). A total of 13,038 dwellings participated in the EEPs.

During each campaign lasting 2 to 3 weeks, energy advisors paid visits to the dwellings. These energy advisors were previously trained by the EEP and tried to convince the inhabitants to install (among other efficient devices for saving electricity) the water flow restrictors and the water-saving showerheads. At the beginning of 2019, 22,390 flow restrictors were installed in faucets and 8813 showerheads were either replaced by efficient ones or were equipped with a flow restrictor. Detailed information is available for a sample of 6005 dwellings (representing more than 40% of all participating dwellings): faucet flow restrictors were installed in 77% of the dwellings (4637/6005) and showerheads in 58% (3502/6005). Figure 1 shows the distribution of number of devices installed per dwellings.

As displayed in Table 1, the most common cases (besides no replacement at all) are one showerhead with either two faucets (bathroom and kitchen) or one showerhead with three faucets (bathroom, toilet, and kitchen). In dwellings where more showerheads were replaced, also a larger number of faucets were equipped with flow restrictors.

As shown in Table 2, there is also a correlation between the number of showerheads installed and the size of the household. One showerhead was mostly installed in apartments with one or two occupants, while two showerheads were primarily installed in apartments with three or four occupants.

The share of flow restrictors installed in bathroom faucets and kitchen faucets is unknown for the whole sample. For a small sample of dwellings (n=1534), we obtained the share of installed restrictors among kitchen faucets (36%) and bathroom (or toilet) faucets (64%).

Table 1 Number of faucets equipped by flow restrictors versus efficient showerheads per dwelling (n=6005).

No. of faucets	No. of showerheads			
	0	1	2	Total
0	931	423	14	1368
1	382	532	16	930
2	610	1151	70	1831
3	477	854	181	1512
4	99	189	64	352
5	4	4	4	12
Total	**2503**	**3153**	**349**	**6005**

Table 2 Number of showerheads intervened and number of habitants per dwellings for a sample of dwellings (n=5765).

No. of household members	No. of showerheads			
	0	1	2	Total
1	803	890	23	1716
2	651	870	60	1581
3	404	555	73	1032
4	361	509	100	970
5	126	178	53	357
6	35	52	22	109
Total	**2,380**	**3054**	**331**	**5765**

Methodology

We propose a combination of methods to determine the energy and CO_2 savings, i.e., a deemed energy savings method (an ex-ante method that we will refer to as DES method) and three complementary ex-post methods for the purpose of calibration of the ex-ante method and validation of the energy savings. The three proposed ex-post methods are the annual billing analysis (ABA method); the summer months billing analysis (SMBA method); and the analysis based on dedicated measurements (DM method).

Ex-ante method—deemed energy savings method (DES method)

Some former DHW saving programs, like in Ohio (USA) and in the Mid-Atlantic (USA), calculate the energy savings based on a complex algorithm involving flow rate, number of people, showerheads per home, water temperature, and DHW efficiency (Mass Save, 2012). While this information increases the precision of the savings estimates, it is very demanding to compile the values pertaining to all these variables for every single participating dwelling. Other programs, like in Massachusetts (USA), use a simpler approach based solely on the number and type (shower or faucet) of devices installed (National Grid, 2011). The number of flow restrictors and/or efficient showerheads installed is readily available from the programs addressing water and energy usage with these devices and the savings can be then calculated straightforward.

As in the Massachusetts program, we aim to determine the energy savings per type of installed device by means of ex-ante methods (or so-called deemed energy savings methods). However, we differentiate between faucets installed in the kitchen as opposed to the bathroom or toilet.

The variables allowing to determine the heat savings are the annual water consumption, the flow rates (before and after the installation of the flow restrictors), the share of water consumption for the different usages of DHW, and the temperatures of cold and hot water. We conducted both a literature review to determine typical ranges found in dwellings and random measurements to corroborate the chosen values for three different types of fixtures: showerheads, bathroom (or toilet) faucets, and kitchen faucets (see Appendix 4). The energy savings (useful energy) per installed flow restrictor and per inhabitant are calculated as follows.

$$e_{\mathrm{P\_Fix}} = \underbrace{\left(\underbrace{V_{\mathrm{total}} * P_{\%\mathrm{Fix}}}_{V_{Fix}} * \frac{T_{\mathrm{Fix}} - T_{\mathrm{c}}}{T_{\mathrm{h}} - T_{\mathrm{c}}} \right)}_{V_{Fix\_\mathrm{Prod}}} * \underbrace{\left(\frac{D_{\mathrm{Fix}_{\mathrm{before}}} - D_{\mathrm{Fix}_{\mathrm{after}}}}{D_{\mathrm{Fix}_{\mathrm{before}}}} \right)}_{\mathrm{Flowrate reduction}} * \frac{Cp}{3600} * 10^{-3} * \left(T_{\mathrm{h}} - T_{\mathrm{c}}\right) * 365] \tag{1}$$

where:

^{e}P_Fix Annual useful energy savings per person obtained by the reduction of DHW flow rate through the fixture *Fix* (kWh/person/year)

Fix Suffix indicating one of the three fixtures: showerhead, bathroom faucet, or kitchen faucet

V_{total} Average initial daily water consumption (liters/person/day)

$P_{\%Fix}$ Share of water used per fixture *Fix* (%)

V_{Fix} Average daily amount of water consumed through the fixture *Fix* (liters/person/day)

V_{Fix_Prod} Average daily DHW produced by the central heating system to be consumed through the fixture *Fix* (liters/person/day)

Tfix Average temperature of (warm) water in fixture *Fix* (°C)

Tc Annual average temperature of the cold water (°C)

T_h Temperature of DHW distributed to the building (°C)

D_{before} Average water flow rate through the regular showerhead or faucet *(before the intervention)* (liters/minutes)

D_{after} Average water flow rate through the reduced flow showerhead or faucet (after the intervention) (liters/minutes)

c_p Specific heat capacity of water (4.2 kJ/kg/°C)

Omission of the value for D_{after} in Eq. (1) (i.e., no reduction at all) allows to determine the useful energy usage before the intervention.

In Eq. (1), the term $\left(T_h - T_c\right)$ appears in the numerator and denominator to account for the difference between the volume of (warm) water at the level of the fixtures (showerhead or faucet) and the volume of produced DHW (passing through the storage tank). Since the hot water leaving the showerhead and faucet is the result of mixing hot and cold water, the volume of this mixed hot water is larger than the amount of hot water leaving the central heating system (DHW storage tank connected to boiler) (see Figure 14).

The following equation is then used to estimate the final energy savings in the central heating system:

$$E_d = e_{P\_Fix} * N_h * \frac{1}{\eta} * F_P * F_s \tag{2}$$

where

E_d Energy savings (final energy) obtained through flow reduction (kWh/year)

e_{p_Fix} Annual useful energy savings per person obtained through the reduction of water flow at the fixture *Fix* (kWh/person/year), from Eq. 1

N_h Total number of inhabitants living in the participating dwellings

η Efficiency of the central heating system (boiler) (see Appendix 2 "Heat production—boiler efficiency" and Appendix 4 "Efficiency of the central heating system")

F_p Persistence factor (considers that only part of dwellings keeps the efficient showerheads and flow restrictors while others decide to remove them)

F_s Factor representing behavioral change (e.g., if the program incentivizes savings by changed behavior like shorter showers or taking showers instead of baths)

The final energy savings are estimated by multiplying the number of installed restrictors by the volume of savings per type of fixture (bathroom faucet, kitchen faucet or showerhead) equipped with the water-saving devices. In our case study, the number of installed restrictors by type of fixture is known for each campaign. It is important to note that the calculated volume of savings per installed device is unlikely to yield an accurate estimate for a given single fixture and neither for a dwelling nor a building. Instead, it represents the statistical mean. To validate the DES method, the results obtained are compared to the savings found with the ex-post methods described in "Ex-post methods" section. The DES method can also be used to estimate the potential of energy savings at a regional level (e.g., a country) provided the variables used are adapted to the local conditions.

Ex-post methods

Ex-post methods for the estimation of savings are typically based on the measurement of the energy consumption as well as explanatory variables (e.g., number of inhabitants or weather conditions). Since it is time-consuming to install measurement equipment, it is advisable to use data that is readily available. We will use two methods based on data from utility invoices and weather statistics (e.g., meter readings, dates, ambient temperatures) and one method that generally requires installing additional meters and frequent readings to obtain complementary information. The three ex-post methods are:

– Annual billing analysis (ABA method)
– Summer months billing analysis (SMBA method)

– Analysis with dedicated measurements (DM method)

Annual billing analysis (ABA method)

Utility meters for fuel consumption are read at regular intervals (monthly or yearly) for billing purposes. In our sample, fuel consumption on an annual basis[2] is available for several buildings. The savings (final energy) are estimated basically as the difference in consumption during a given year prior to the intervention (the baseline) and a given year after the intervention. However, there is a challenge related to the use of annual fuel consumption data of the central heating system for quantifying the energy savings associated with DHW production: As a simple approach, we could assume that the difference in fuel consumption before and after the campaign corresponds to the energy savings. This is correct if the fuel consumption for space heating does not vary from 1 year to another (central heating systems provide both DHW and space heating, with the latter dominating the former). However, energy use for space heating is strongly correlated with weather. In general, it is not straightforward to apply a correction for weather conditions because the exact share of the heat dedicated to space heating is unknown. To overcome this difficulty, we chose years or periods (one before and the other after the campaign) with very similar weather conditions based on the heating degree days (HDDs).

The ABA method is subject to uncertainty as a consequence of technical interventions (e.g., optimization of the heating and distribution system, improvement of the building envelope). To increase the accuracy of our estimates, we choose 2 years which are as close as possible to each other, and we aim for conditions where the DHW savings are relatively high compared to the total heat consumption. This can occur under the following circumstances: (i) high savings of DHW (due to a high share of fixtures newly equipped with flow restrictors); (ii) low share of space heating due to the high-energy performance of the building envelope (in new, well-insulated buildings, the share of energy use for hot water amounts to around 50% (Pomianowski et al., 2020); and (iii) mild winters resulting in a low energy use for space heating (selection of years with low HDD).

Summer months billing analysis (SMBA method)

For some buildings, bills containing monthly energy consumption are available. The advantage of monthly data is that during summer months, the thermal consumption in a residential building is exclusively related to DHW needs. The months of the year to be chosen depend on the weather conditions of the location where the study is carried out. It should also be considered that DHW consumption during summer is lower than in winter for the following reasons: (i) the temperature of cold water entering the building is lower in winter, (ii) thermal losses are higher in winter than in summer, and (iii) the occupancy of residential buildings is lower during summer vacations. We can consequently expect the energy savings to be lower during summer, calling for a correction factor when establishing annual energy savings. The annual final energy savings are hence calculated as the difference in energy consumption before and after the intervention during the summer months, corrected with a seasonal factor.

As is the case for the ABA method, the SMBA method is also subject to some uncertainty as a consequence of technical interventions (e.g., improving insulation of the DHW storage and distribution pipes). However, the improvement of the building envelope can be assumed to not affect the precision of the savings obtained with this method. The analysis of cases with high savings of DHW can help to improve the precision of the SMBA method.

Analysis with dedicated measurements (DM method)

While the two previous methods focus on the final energy savings, the DM method can distinguish the impact of the savings at different levels (production and distribution) of the DHW supply chain. Our DM method relies on measurement of the energy consumption in the boiler room (central heating system) where the DHW is produced and stocked for later use. The energy consumption (and consequently the energy savings) is measured at two levels (see Appendix 2): at the production level (produced heat) and at the distribution level (distributed heat).

[2] Since the readings are typically not made exactly on the same date every year, the energy demand is scaled to 365 days.

Table 3 Summary of the variables (and intermediate results) with the values used to estimate the energy savings with the ex-ante deemed savings method (DES method). Based on a total tap water consumption of 142 liters/person-day.

	Showerhead	Kitchen faucet	Toilet faucet
Average daily tap water consumption V_{total} (liters/person-day)	142		
Proportion of tap water used by type of fixture $P_{\%Fix}$ (%)	16.8%	15.5%	11.3%
Daily warm water consumed by type of fixture V_{Fix} (liters/person-day)	23.9	22.0	16.0
Average temperature of water T_{Fix} (°C)	39	37.9	35
Annual average temperature of the cold water T_c (°C)	13	13	13
Temperature of the hot water distributed to the building T_h (°C)	55	55	55
Daily hot water produced by the central system V_{Fix_Prod} (liters/person-day)	14.8	13.0	8.4
Average water flow rate before the intervention D_{before} (liters/minute)	12	11	11
Average water flow rate after the intervention D_{after} (liters/minute)	8	8.8	8.8
Flow rate reduction	33%	20%	20%
Annual useful energy per person (kWh/person-year)	263	233	150
Annual useful energy savings per person (kWh/person-year)	88	47	30
Efficiency of the central heating system (boiler) η	0.85	0.85	0.85
Annual final energy consumption per person by type of fixture (kWh/person/y)	310	274	176
Annual final energy savings per person E_d (kWh/person-year)	103	55	35
Total number of inhabitants living in the participating dwelling N_h	2.3	2.3	2.3
Persistence factor accounting for dwelling removing the devices F_P	0.7	0.9	0.9
Factor taking into account additional savings F_s	1.15	1.15	1.15

An additional purpose of this method is to establish the thermal losses associated with DHW storage, including the connection pipes between production and distribution. These losses are in first instance not affected by flow restrictors. The proposed method makes use of dedicated measurements of thermal energy consumption (at the two levels) in regular intervals (twice per month) during a period of at least 2 years. Since interventions on the system (e.g., optimization of the heating and distribution system) are usually recorded in a booklet kept in the boiler room, they can be taken into consideration, which is an advantage compared to the two previously described ex-post methods.

Given that the annual energy consumption at the production level (produced heat) includes not only DHW but also space heating, the energy savings are estimated using the SMBA method. The difference between the energy consumption at the production (produced heat) and distribution (distributed heat) is attributed to the thermal losses. We can expect thermal losses to be slightly smaller in summer than during winter due to the difference in ambient temperature in the boiler room. If the ambient temperature varies considerably, this should be considered.

Ex-ante deemed energy savings (DES method)—analysis and results

Table 3 presents a summary of the variables and the values used for the estimation of the energy savings with the DES method. As described in the "Ex-ante method—deemed energy savings method (DES method)" in the "Methodology" section, the values given here were obtained through a literature review and some measurements during the campaigns of our case study. A more detailed description about how these values were chosen is given in Appendix 4.

If we insert the values reported in Table 3 into Eqs. (1) and (2) given in the "Ex-ante method—deemed energy savings method (DES method)" in the "Methodology section," we obtain the results given in Table 4.

A study carried out by the Energy Saving Trust (EST 2008) and Chmielewska (Chmielewska et al. 2017) found that there is a clear correlation between DHW consumption of a household and the number of inhabitants. We can consequently expect that there is also a correlation between energy savings and the number of inhabitants. Figure 2 shows this relationship for a group of 5765 dwellings in our study.

Table 4 Annual produced heat and final energy savings (in kWh/y) per type of fixture

	Useful energy savings (kWh/y)	Final energy savings (kWh/y)
Showerhead	162	191
Kitchen faucet	111	130
Toilet faucet	71	84

If we apply the final energy savings obtained with the DES method (Table 4) for each one of the 6005 dwellings for which we have detailed information about the interventions by type of fixture, we obtain the distribution shown in Figure 3. The intervals chosen in Figure 3 are designed to reflect the discrete nature of savings in this study. Given the ex-ante method employed, there is a fixed value of saving per fixture, and the number of fixtures per dwelling follows a discrete distribution. The specific intervals capture this unique characteristic, providing a precise representation of the savings distribution across different dwellings. The first bar in Figure 3 represents the non-participants. The prominent bar at 500 kWh/year can be explained by the frequent combination of flow restrictors in one showerhead and two faucets. The bar at 650 kWh/year represents the combination of flow restrictors in one showerhead and three faucets.

If we apply the final energy savings given by the DES method (Table 4) to the total of 25 campaigns, the mean final energy savings per participating dwelling is 301 kWh/year.

Ex-post methods—analysis and results

In this section, we apply the three proposed ex-post methods, namely, the ABA method (annual billing analysis), the SMBA method (the summer months billing analysis), and the DM method (analysis with dedicated measurements). As described in the "Ex-post methods" in the "Methodology" section, we first select the campaigns from which we draw the data for the ex-post analysis.

Our total database contains 25 campaigns (see Appendix 3 for the details). Based on the criteria mentioned in the "Ex-post methods" in the "Methodology" section, we first select a group of seven campaigns. The first six are characterized by a high implementation rate of flow restrictors, and the seventh corresponds to the last campaign in our database where we had the opportunity to take additional measurements for the DM method. Table 5 shows, for the seven pre-selected campaigns, the average final

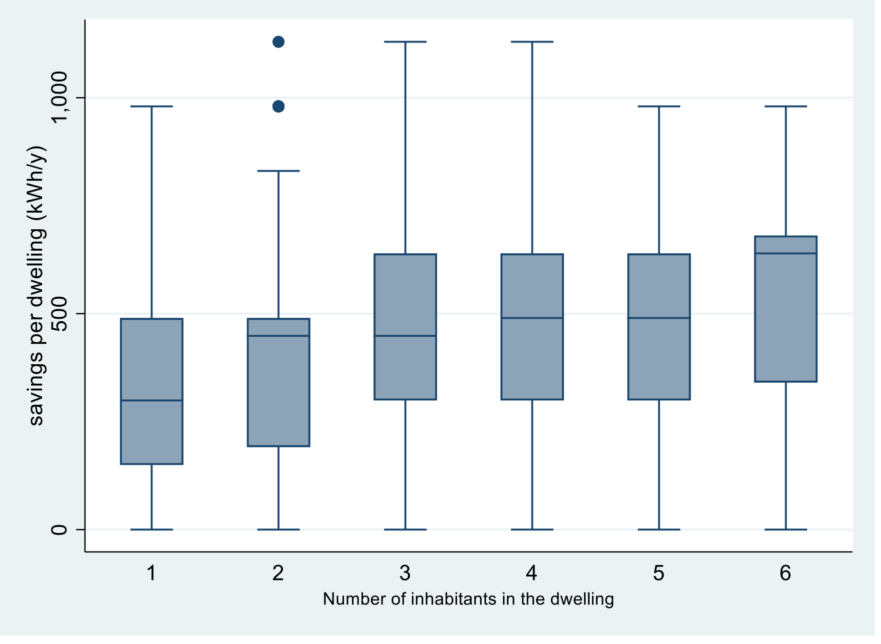


Fig. 2 Correlation between the final energy savings per dwelling estimated with the DES method (in kilowatt hours/year) and the number of dwelling members (n = 6005)

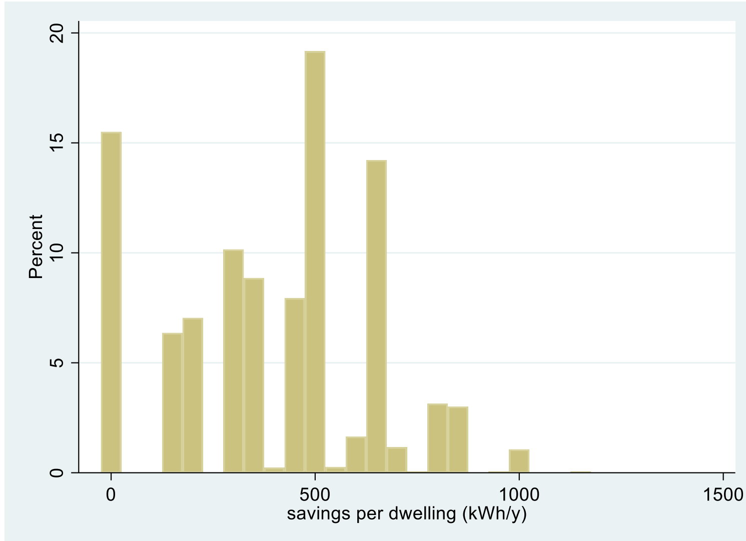


Fig. 3 Distribution of final energy savings per dwelling (in kilowatt hours per year) for the sample (n = 6005)

Table 5 Key data for the seven campaigns. Average energy index (final energy) of the buildings, number of buildings, number of targeted/participating dwellings, and number of intervened faucets/showerheads

Campaign	Energy index (kWh/m^2/y) (final energy)	Buildings (no.)	Targeted dwellings (no.)	Participant dwellings (no.)	Intervened faucets (no.)	Intervened showerheads (no.)
Saconnex 2014	141	542	542	487	980	430
Carouge 2015	114	592	592	506	1125	351
Onex 2015	109	513	513	479	1050	428
Vernier 2016	118	638	638	538	1275	310
Carouge 2016	108	576	576	546	1488	442
Lancy 2017	134	621	621	568	1171	417
Meyrin 2019	142	617	617	538	799	331
Total		4099	4099	3662	7888	2709

energy index for the period 2011–2018 (in kilowatt hours/square meter/year), the number of buildings and dwellings (targeted and participants) involved, and the number of fixtures installed/replaced.

Annual billing analysis (ABA method)

Selection of campaigns

As mentioned in the "Annual billing analysis (ABA method)" in the "Methodology" section, campaigns in buildings with low-energy performance are not convenient for the annual billing method. In the method used in this section, as explained in the "Annual billing analysis (ABA method)" section, we specifically aim for conditions where the domestic hot water (DHW) savings are relatively high compared to the total heat consumption. We have chosen, as a general guideline, for the DHW energy consumption to be higher than one-third of the total energy consumption. This amount aligns with the regulations set by the Canton of Geneva,[3] where a threshold of 450 MJ/m^2/an (125 kWh/m^2/an) is established for energy expenditure (IDC), and buildings exceeding this threshold must undergo specific energy assessments and improvements. The ABA method is then applied to four campaigns (two in 2015 and two in 2016; see Table 5).

[3] https://www.ge.ch/nouvelle-reglementation-bati-qu-est-ce-qui-change/abaissement-du-seuil-idc

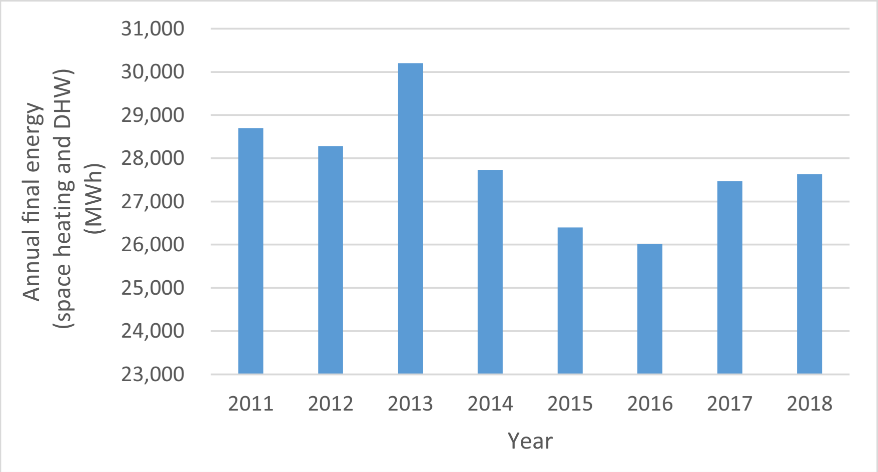


Fig. 4 Annual final energy (space heating and DHW) consumption from 2011 to 2018 (without any climate correction) for the four selected campaigns

Selection of comparison years—weather variation analysis

The selection of the most suitable couple of years (before and after the intervention) is crucial for the accuracy of the savings estimation with the ABA method. Based on the explanation given in the "Annual billing analysis (ABA method)" in the "Methodology" section and in Appendix 5, we choose the following pairs of years, i.e.

- 2011 and 2018 (since HDD are somewhat higher in 2011 than in 2018, the calculated energy savings can be expected to be somewhat higher than the actual savings)
- 2012 and 2017 (since HDD are somewhat lower in 2012 than in 2017, the results for energy savings can be expected to be somewhat lower than the actual savings)

The actual savings will therefore be bounded by the results for the two couple of years described here above.

Energy savings—ABA method

Figure 4 shows the evolution of the annual final energy consumption (for space heating and DHW) for the four selected campaigns. The variation from one year to the next, mainly due to weather differences, is on average close to 9% (as shown in Appendix 6, Figure 21).

Table 6 shows in the first two rows the main results of the ABA method (for the two couple of years selected for the comparison) and (in the third row) a comparison with the DES method for the chosen sample.

As expected, the annual final energy savings per dwelling estimated by the DES method (398 kWh) are bounded by the two values found with the ABA method (393 kWh and 517 kWh). The reduction compared to the baseline (the total final energy consumption for space heat and DHW in initial year) is relatively small (between 2.9 and 3.7%). The reduction is smaller than the annual variations that are on average close to 9%. This confirms the necessity of selecting years with similar weather conditions to reduce the inaccuracy of the savings calculated (ex-post) with the ABA method. As we will see in the "Summer months billing analysis (SMBA method)" section, choosing the energy consumption only for DHW (the summer months method) improves the accuracy.

Summer months billing analysis (SMBA method)

For the SMBA method, we select months without space heating needs (see "Summer months billing analysis (SMBA method)" in the "Methodology" section). Based on the analysis presented in Appendix 6 for our case study, the months of July and August are chosen for the estimation of the savings. We analyzed the monthly energy consumption during the two selected summer months for 16 central heating systems comprised in the seven pre-selected campaigns. While they do not cover the totality of the heat consumption for all the buildings included in the campaigns, the sample size is significant

Table 6 Results for the annual billing analysis (ABA method)—baseline final energy consumption for space heating and DHW in the initial year (2011 and 2012), final energy savings (between 2011–2018 and 2012–2017, respectively), the reduction (in %), and the final energy savings per dwelling (in kWh/y). The savings obtained with the DES method are given in the last row

Comparison years	Baseline final energy in initial year (MWh/y)	Final energy savings (MWh/y)	Reduction (%)	Final energy savings per dwelling (kWh/year)
2011–2018	28,702	1,069	3.7%	517
2012–2017	28,285	813	2.9%	393
DES method		824		398

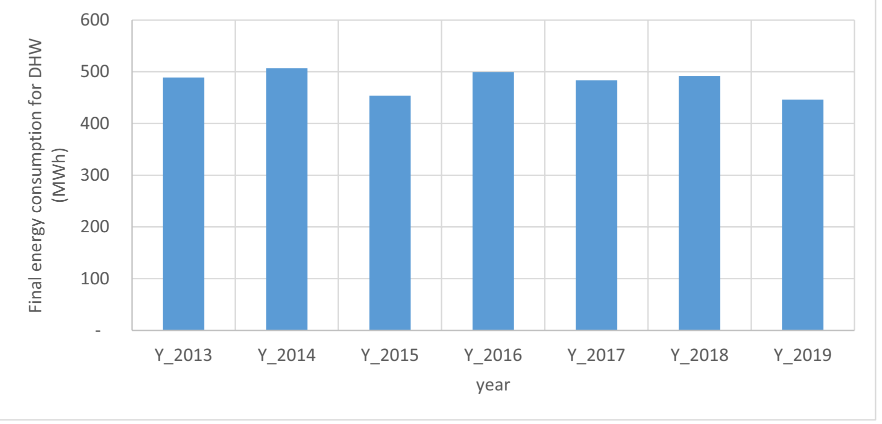


Fig. 5 Annual (from 2013 to 2019) final energy consumption (in megawatt hours) during summer months (July and August) to produce the DHW (1270 dwellings)

(1270 targeted dwellings). Figure 5 shows the final energy consumption for the two summer months from 2013 to 2019. As commented in the "Summer months billing analysis (SMBA method)" in the "Methodology" section and in Appendix 6, the ambient temperature has an impact on the energy consumption and the low value observed for the summer 2015 is due to a severe heat wave that occurred in early July 2015 (see Figure 6).

Since the first campaign was carried out in October 2014 and the last one in February 2019, we chose 2013 and 2014 as the baseline (situation before the improvements) and 2019 to represent the situation after improvements. Since the ambient temperatures in 2013 are closer to those of 2019 (compared to the 2014 temperatures), the results obtained with these years should be more accurate.

Table 7 shows the main results of the SMBA method for the two chosen baselines (2013 and 2014) and a comparison with the DES method (last row). The annual savings are calculated by scaling, thereby considering that the final energy demand for DHW

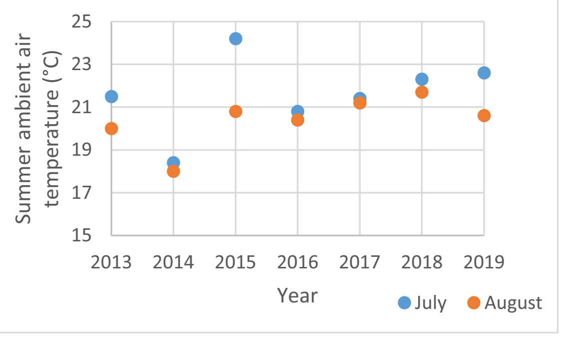


Fig. 6 Average monthly ambient temperature (in °C) from 2013 to 2019 in the summer months of July and August. The month of July 2015 is characterized by a severe heat wave

represents 10.6% of the annual consumption (see Appendix 6). The final energy savings compared to the baseline (DHW production before the intervention) amounts to around 10%. As expected, given the fact that we only measure the energy used for DHW, the reduction is higher than the one found with the

Table 7 Results for the summer months billing analysis (SMBA method)—baseline of final energy consumption for DHW for 2013 and 2014, savings (reduction in final energy consumption between the baseline and the energy consumption in 2018), the reduction (in %), and the savings per participating dwellings. A comparison with the DES method is shown in the last row

Baseline year	Baseline final energy (MWh/year)	Final energy savings (MWh/year)	Reduction (%)	Final energy savings per dwelling (kWh/year)
2013	4401	387	8.8%	344
2014	4560	546	12.0%	485
DES method		393		349

ABA method ("Energy savings—ABA method" section). Also, the reduction is higher than the annual variations that are close to 6%. The results of the DES method are closest to the SMBA results obtained for 2013 as baseline year which is reassuring.

The final energy savings per dwelling obtained here with the DES method (349 kWh/y) are slightly different than those calculated in the "Energy savings—ABA method" section (397 kWh/y) because the number of interventions per dwelling also differs for the two samples.

Analysis with dedicated measurements (DM method)

Due to its technical complexity compared with the previous methods, the DM method was implemented only for the last campaign where three centralized heating systems serve a group of 27 buildings with 617 dwellings out of which 538 (87%) participated in the program. The analysis focuses on one of the three central heating systems where a heat meter measured the produced heat. This energy production and the volume of DHW consumption were recorded twice per month by the personnel in charge of the heating system. This information was available for a period of approximately 4 years. In addition, we installed loggers to measure the temperatures of cold and hot water. To determine the heat content of the DHW distributed to the building, the volume of DHW consumption and the water temperatures (cold and hot) were used.

Figure 7 shows the profiles for useful energy (produced heat in blue) and the heat content of the DHW distributed to the buildings (distributed heat in orange). The shape of these two load profiles is very similar during the summer months but the produced heat is higher than the distributed heat. The (almost constant) difference between the two profiles during summer is attributed to the thermal losses of the storage, pipes, and valves.

As described in the "Analysis with dedicated measurements (DM method)" in the "Methodology" section, the savings at the levels of DHW production (produced heat) and DHW distribution (distributed heat) are measured during the summer periods. If we consider the savings as the difference between 2019 and 2018 (the campaign was carried out at the beginning of 2019), they equal 218 kWh/day at the production level and 240 kWh/day at the distribution level; i.e., the daily savings at these two levels are almost the same. However, the daily thermal losses measured during summer are very significant (724 kWh/day in 2018 and 746 kWh/day in 2019) and do not change significantly after the intervention. These results are summarized in Table 8.

The relative savings at the distribution level (12.8 %) are higher than at the production level (8.4 %). The main reasons for the difference are thermal losses related to hot water distribution in central heating systems and usages that are not affected by flow restrictors. It should be noted that the savings at the production level (8.4 %) are smaller than the savings found with the SMBA method (8.8 to 12.4%) because the replacement rate in this campaign is also smaller.

The thermal losses in our case study are between 28% (724/2600) and 31% (746/2382) relatively to the produced heat. Assuming a production efficiency of 90%, these thermal losses would represent 25 to 28% relatively to the final energy.

Discussion

We proposed an ex-ante method (DES) to estimate the final energy savings for DHW. The parameter values (temperatures, water volumes, flow rates, etc.) had mostly been taken from the literature. As a first validation, these values had been contrasted with measurements made with small samples of our case study that are detailed in Appendix 4. In addition, we compare in Figure 8 the results of our DES

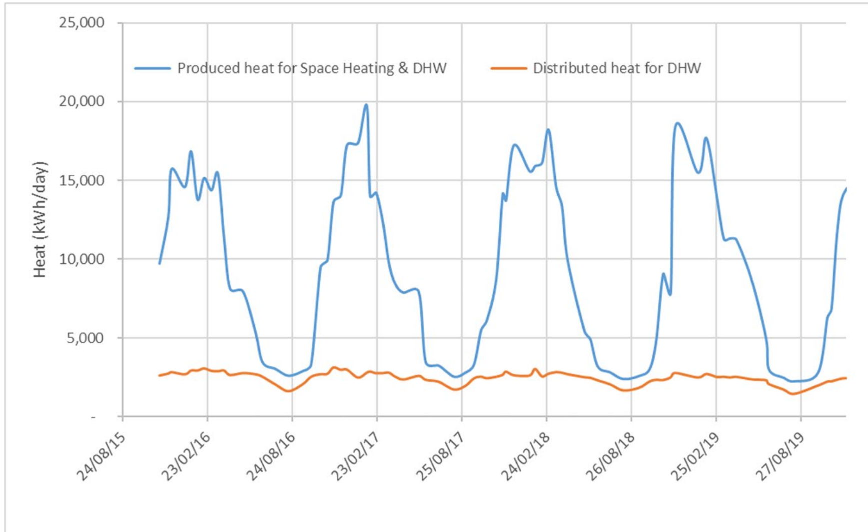


Fig. 7 Load profiles of the produced heat (for space heating and hot water, in blue) and distributed heat leaving the hot water storage tank (in orange) for one of the three heating systems of the 7th campaign (2015–2019)

Table 8 Results for the dedicated measurements (DM method)—daily energy demand, savings, and losses.

Year	Produced heat (kWh/d)	Distributed heat (kWh/d)	Thermal losses (kWh/d)
Demand 2018 (baseline)	2600	1876	724
Demand 2019	2382	1636	746
Savings	218	240	
Savings (%)	8.4%	12.8%	

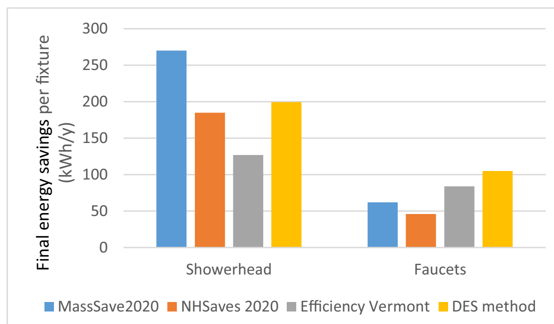


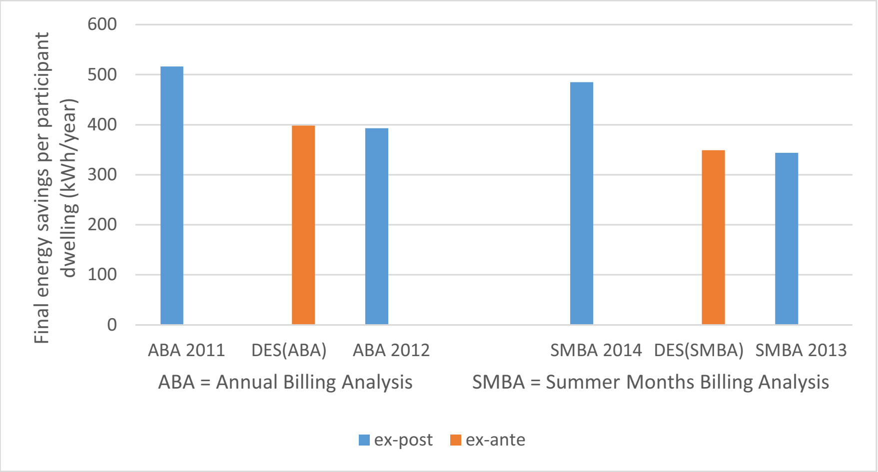
Fig. 8 Comparison of DHW final energy savings obtained with the DES method with those used by three other programs

method with the ex-ante estimation of the following three programs[4]: the Massachusetts EEP (Mass Save, 2020), the New Hampshire EEP (NHSaves, 2020), and the Vermont EEP (Efficiency Vermont, 2018). These programs base their calculations on default savings per type of fixture. For showerheads, the savings of these programs range from 127 to 270 kWh/year per showerhead, with our estimate of 191 kWh/year lying within this range. Concerning the faucets, the savings of the three programs range from 46 to 84 kWh/year per faucet (they do not distinguish between toilet and kitchen faucets). If we apply the share found in a small sample of faucet interventions from our study (36% for kitchen faucets and 64% for toilet faucets), our DES estimation is equivalent to 105 kWh/y per faucet, which is somewhat above the estimates of the three US programs.

Upon comparing our findings with the French standard outlined in BAT-EQ-133, we observe significant parallels. The BAT-EQ-133 benchmarks estimate that “Classe Z” showerheads achieve annual savings of 200 kWh/year, whereas “Classe ZZ or Watersense” variants save around 333.33 kWh/year. This is in close agreement with our showerhead savings of 191 kWh/year. Moreover, for aerators, BAT-EQ-133 data projects savings of 57 kWh/year for non-regulated and 105 kWh/year for auto-regulated types, aligning well with our faucet estimations. Such congruence underscores the robustness of our ex-ante method when

[4] Since no studies about programs for energy saving on domestic hot water were found in Europe, we selected three programs in the USA.

Fig. 9 Comparison of DHW final energy savings calculated with the two ex-post methods (ABA, SMBA) with the ex-ante method (deemed energy savings, DES)



benchmarked against established standards (BAT-EQ-133, 2023)[5].

The two ex-post methods (ABA and SMBA) complement the validation of the ex-ante DES method. We calculate the ex-ante savings per dwelling, denominated as DES (ABA) and DES (SMBA), respectively. Figure 9 summarizes the results obtained. In both cases, the DES method gives savings that are close to the lower range. The DES results are hence be considered to be rather conservative.

In the "Ex-post methods" in the "Methodology" section, we detail how the samples for the first two ex-post methods, ABA and SMBA, were selected. These samples were chosen based on campaigns where a high rate of fixtures was replaced or installed, potentially leading to relatively high energy savings (DES (ABA) = 398 kWh/year and DES (SMBA) = 349 kWh/year). While this selection process might suggest a bias towards overestimating the savings, a comparison with other ex-ante savings methods (such as Mass Save, NHSave, and Efficiency Vermont) indicates that any such bias is likely minimal.

The thermal losses for storage and distribution of DHW are considerable as shown with the DM method. In our case study, they are between 25 and 28% (relative to the final energy). Montero (Montero et al., 2022a, 2022b) found that these thermal losses are close to 25%, while a local standard (SIA 385/2 2015) assumes them to amount to 30%. These losses should be reduced by other types of EEMs, like better insulation of the storage tank, pipes, and valves. As explained in Appendix 2 and confirmed by our measurements, flow restrictors do not have any effect on the thermal losses.

DHW represents the second largest usage of energy in the residential sector and the associated energy saving potential is significant. This contrasts with the slow pace of improvement made in this area. While energy labels already exist for faucets and showerheads, there is no policy in place banning inefficient fixtures (see Appendix 4 "Flow rates labels and obligations"), as it is the case for other devices (e.g., light bulbs).

As Figure 9 indicates, the DES method yields realistic yet conservative estimates. We therefore choose this method to estimate the CO_2 emissions that can be avoided with flow restrictors. For the two most widely used fossil fuels, natural gas and fuel oil, the emission factors (based on final energy) are 203 kg CO_2 per MWh and 265 kg CO_2 per MWh, respectively (OFEV, 2022). If the savings per participating dwelling are close to 301 kWh/year (see results of the deemed approach for all 25 campaigns in the "Ex-ante deemed energy savings (DES method)—analysis and results" section), this represents an annual reduction of 61 and 80 kg of CO_2 per participating dwelling and year for natural gas and fuel oil, respectively.

Conclusions

Domestic hot water production is the second most important energy use in the European residential

[5] BAT-EQ-133. (2023). Systèmes hydro-économes (France métropolitaine). Retrieved from https://calculateur-cee.ademe.fr/pdf/display/149/BAT-EQ-133.

sector, accounting for 14% of the sector's total final energy consumption. A pivotal measure is the incorporation of flow restrictors, which are lauded for their low upfront cost, ease of installation, and seamless integration into energy efficiency programs. Such a measure could also impact non-residential buildings. This paper studied flow restrictors, offering four methods to gauge energy savings via both ex-ante and ex-post analyses. It explores three ex-post methodologies (ABA, SMBA, and DM) alongside a deemed energy savings (DES) method, an ex-ante approach, employing the latter to project savings across all campaigns in our dataset. The ex-ante method can also be adapted to other regions provided that local data is used.

The installation of flow restrictors in faucets and efficient showerheads represents an attractive potential for energy savings. According to our case study (see Figure 9 in the "Conclusions" section), final energy savings amount to close to 300 kWh/year per dwelling (for a baseline close to 3400 kWh/year per dwelling), corresponding to around 10% of the final energy used for DHW. These savings represent a reduction of 60 to 80 kg of CO_2 per dwelling and year (for natural gas and heating oil respectively). Considering the typical characteristics of Swiss dwellings, which have an average heated surface area of approximately 99 m^2 and 2.2 inhabitants (refer to Appendix 4.5), the energy savings translate to about 3 kWh/year/m^2 of heated surface area and 137 kWh/year per person (calculated as 301 kWh/year/99 m^2 and as 301 kWh/year/2.2 inhabitants). Thermal losses of the storage and distribution system are significant (>25% of the final energy for DHW production), representing more than 850 kWh/y per dwelling. This issue needs to be addressed by improving thermal insulation of the storage and the distribution system.

Table 9 Summary of results

	Baseline (kWh/y per dwelling)	After implementation of flow restrictors (kWh/y per dwelling)
Final energy	3400	3100
Storage and distribution losses (greater than)	850	850
Useful energy	2040	1785

Table 9 summarizes our results (baseline consumption, thermal losses, and consumption after the installation of flow restrictors by the program).

To accelerate the energy transition, energy efficiency policies should also address DHW. One option is to conduct energy efficiency programs including water flow restrictors in their portfolio. Another relatively simple measure would be to ban showerheads and faucets with a flow rate beyond a given threshold, by analogy to the EU's successful ban on incandescent bulbs under the Ecodesign Directive (2009/125/EC), which reduced significantly the energy consumption for lighting in households (Schoenmacker et al., 2022). In view of the potential savings (10% of final energy demand for DHW supply), we strongly recommend such a ban on inefficient fixtures. Finally, following the 2012 Energy Efficiency Directive, the EU saw a rise from six to 15 energy efficiency obligation schemes (EEOS), as member states were urged to adopt these to meet energy-saving objectives(Fawcett et al., 2019). The significance of EEOS is further highlighted in a 2020 European Commission report, revealing that EEOS is the most crucial policy measure regarding cumulative energy savings, delivering more than one-third (35.59%) of all cumulative energy savings during the period from 2014 to 2017 (Blumberga et al., 2021). The role of utilities is paramount in this context as they can play a critical role in promoting energy-saving measures within the framework of EEOs (e.g., the installation of flow restrictors for domestic hot water systems). White certificates could be used as a mechanism to prove and quantify the energy savings achieved by the obligated parties.

Saving water also conserves energy in water distribution and treatment (Spang et al., 2020). Given the growing scarcity of water, its conservation is as imperative as saving energy. Furthermore, offering consumers clear feedback, through detailed billing or by showcasing the cost difference between efficient and inefficient showerheads, can help to mobilize the potential savings.

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Declarations

Conflict of interest The authors declare no competing interests.

Appendix 1

Flow restrictors and Swiss water consumption

Flow restrictors

Figure 10 shows a picture of the flow restrictors that have been used in our case study to reduce the water consumption.

Figure 11 shows four of the most common inefficient showerheads and Figure 12 two efficient ones. For these showerheads, we measured the water flows as basis for applying the DES method (see the "Ex-ante deemed energy savings (DES method)—analysis and results" section).

Potable (cold and hot) water consumption in Switzerland

As shown in Figure 13, per capita tap water consumption in Swiss households and small businesses has been decreasing since the 1990s. This evolution is largely due to the diffusion of water-saving measures

Fig. 10 Flow restrictors

(SSIGE, 2018). Washing machines and dishwashers are much more efficient, while bathrooms and kitchens are increasingly equipped with water-saving faucets (ibid.). However, since 2017, this progression seems to stagnate although there is still a significant potential for savings.

Given that per capita water consumption did not change significantly since 2017, we consider that at the time of the present study, the volume of water consumption is at the same level and is chosen as the baseline for our savings estimation.

DHW consumption

According to SwissEnergy, a person in Swiss homes consumes an average of 142 l of water per day, including about 50 l of DHW (SwissEnergy, 2017). SwissEnergy does not specify if the volume for DHW is at the level of storage, distribution pipes or taps (see Appendix 2 for more details).

Another study carried out in Geneva (Switzerland) confirms that DHW consumption is close to 50 l per person per day which represents around one-third of the total water consumption (Zgraggen, 2010). In Zgraggen's study, the DHW volume is measured at the storage level. The hot (or rather warm) water consumption at the fixture level is higher because it is mixed with cold water to obtain the desired temperature in order to shower or wash hands and dishes.

Appendix 2

Production, storage, distribution, and consumption of DHW

DHW has some particularities that need to be considered as they are important to correctly estimate the energy savings. Typical usages such as handwashing require temperatures between 30 and 40 °C (Yao & Steemers, 2005). For sanitary reasons (i.e., to avoid legionella growth), it is important to increase the water temperature above 60 °C (Legionella control, 2021). DHW production and distribution systems are then characterized by different temperature levels, with hot and cold water being mixed to obtain the desired temperatures. To avoid energy peaks, especially related to showering

Fig. 11 The most common inefficient showerheads removed from participating households

Fig. 12 Two efficient showerheads: Three years old (left) and a new one (right)

during early hours in the morning, hot water storage is typically part of the DHW supply system. The present appendix describes the details of a DHW system that are important to consider to correctly evaluate the savings.

Potable water (cold and hot water)

Tap water (called also potable water, running water, city water, town water, municipal water, sink water, etc.) is water supplied to a tap (i.e., valve). Its uses include drinking, washing, cooking, flushing of toilets, and watering plants. For some of these, washing in particular, it is better if the water has a higher

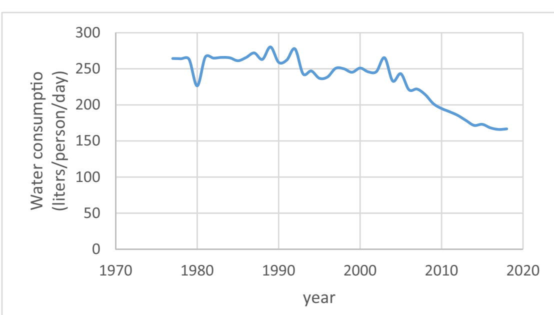

Fig. 13 Evolution of potable water consumption in dwellings and small and medium enterprises in Switzerland (in liters per person per day) from 1977 to 2018. Graph produced with data from SSIGE (La Société suisse de l'industrie du gaz et des eaux)

temperature (Zélem and Beslay, 2015). For this purpose, cold tap water is heated using in general one of the systems described below.

DHW production systems

There are different ways to produce DHW. The cold tap water can be heated (i) in a centralized way using a central heating system (e.g., a boiler that feeds the DHW for one or a group of buildings; (ii) almost directly using a small heater (e.g., at a household level); or (iii) directly using electricity (e.g., at the showerhead level) (Kulay et al. 2015).

In most multifamily buildings in Europe, DHW is provided by a central production system in combination with a large storage tank and a distribution system that keeps the DHW at the required temperature. In our case study, this is also the type of system that we found in all participating buildings.

Central production systems

Residential buildings in Europe are in general equipped with a central heating system that provides heat for the two following thermal usages: space heating and DHW. Nowadays, a large part of these systems are composed of fossil fuel boilers. Those use in general natural gas and heating oil as their main energy source (ECDGE, 2016).

We distinguish in our study the final energy, produced heat, distributed heat, and useful energy. Final

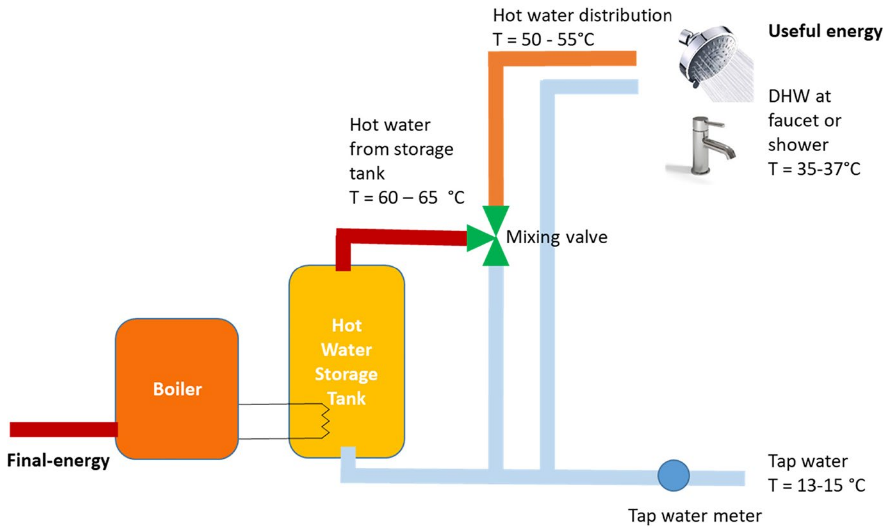

Fig. 14 Schematics of production, storage, and distribution of DHW with usual temperatures for storage, distribution, and consumption

energy is the energy supplied to end users (Eurostat, 2018), i.e., the energy content of the fuel delivered to the building. The heat content of the fuel, the final energy, is calculated in the present study using the gross calorific value. The main reason for this is that in Switzerland, most boilers are condensing units allowing to recover the latent heat from the vapor that has been originated from combustion.

We refer to produced heat as the heat produced by the boiler. Boilers have a given efficiency and heat losses occur. The produced heat will consequently be lower than the final energy.

The heat produced by the boiler is transferred to one or several storage tanks. Even though those are thermally insulated, heat losses occur. We refer to distributed heat as the heat content of the DHW leaving the storage tank.

From the storage tanks, DHW is distributed to the building through pipes and additional heat losses take place. Finally, when a given user opens the tap, the hot water is available and contains a given amount of heat, the useful energy.

Figure 14 shows the schematic of the DHW production, storage, and distribution system for a residential building and the associated temperatures at the different levels. Figure 15 shows the corresponding energy flow chart from production to consumption.

Heat production—boiler efficiency

Boilers produce heat through the combustion process of a given fuel (final energy). Combustion gases escape through the stack to the atmosphere with some

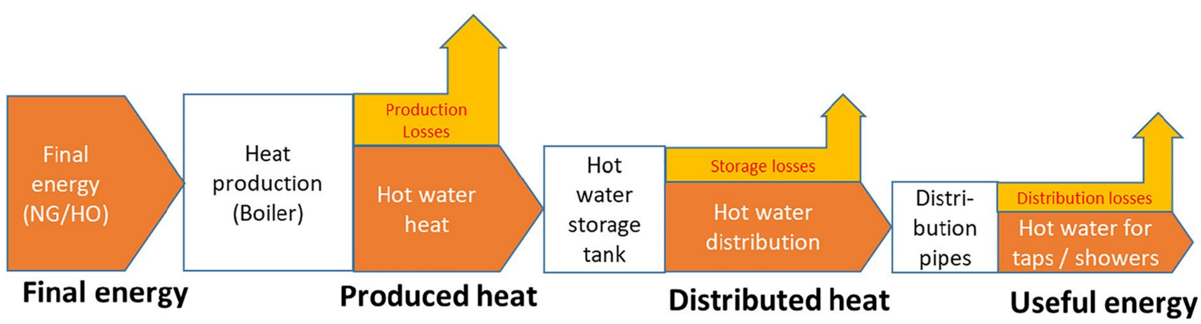

Fig. 15 Energy flow diagram (Sankey chart) from final energy to useful energy showing heat losses in DHW production, storage, and distribution. NG = natural gas, HO = heating oil

energy that could not be transferred to the heat transfer fluid (usually water). Production losses correspond then to the difference between final energy and the produced heat. In order to obtain the final energy savings, it is important then to apply a factor to take into account the efficiency of the boiler.

DHW storage thermal losses

DHW consumption usually presents demand peaks during the morning. In order to overcome the risk of insufficient supply, central heating systems come with a large storage tank. Some thermal losses occur through the walls of the storage tank and its connection pipes and valves. Those depend on the thermal insulation and the temperature difference between the hot water and the boiler room. They do not depend on the volume of used DHW, and the reduction of its consumption will not then have any effect on them.

DHW distribution thermal losses

In multifamily buildings, faucets and showerheads can be far away from the storage tank. Even if the distribution system is thermally insulated, heat losses occur in distribution pipes, connectors, and valves. Swiss standards, for example, require water systems to provide hot water not later than 10 s after the corresponding faucet or showerhead has been opened (SIA 385/1). To guarantee hot water availability shortly after the inhabitants require its usage, distribution pipes must keep the temperature of the DHW at the required level. The distribution system therefore needs to compensate the losses in order to maintain this temperature. This is usually carried out constantly recirculating the DHW inside the pipes or using electrical cables around the pipes to heat them (Haller, 2020; SIA 380/1 2020). Thermal losses for DHW and the recirculation loop account for 30% (SIA 385/2). Messmer reported that thermal losses in central systems (for DHW and space heating) are close to 24% (Messmer et al., 2022).

As mentioned in Appendix 2 "DHW storage thermal losses," the thermal losses do not depend on the volume of the DHW used and the reduction of its consumption will therefore not have any effect on them.

There is hardly any literature on storage and distribution losses for DHW even though they seem to be important. This is hence a topic that needs to be addressed as it probably presents an interesting potential of energy savings.

Energy balance from production to consumption

The heat content of DHW at the faucet or showerhead level (useful energy) is lower than the content of the energy source (final energy). This is depicted in Figure 15. Thermal losses associated with the storage and distribution of DHW are significant; they are estimated to be on average close to 35% (SIA 380/1). Thermal losses depend on the level of insulation of the storage and distribution pipes and can vary considerably from one building to another.

Thermal losses are crucial in our analysis in order to understand the differences we find between water and energy savings (Schmidt, 2008). Energy losses in the storage and distribution pipes remain unchanged with the installation of flow restrictors.

Temperatures of DHW from production to consumption

The DHW temperature differs from production to consumption. As a first step, we describe here the reasons behind the different temperature levels, and we give an overview of typical temperatures that are encountered.

The required temperature of DHW at the tap or shower rarely exceeds 40 °C. However, at this temperature, the risk of legionella growth is relatively high. In order to avoid the associated risks, the temperature is increased in the storage tank to around 60 °C (55 to 65 °C).

According to the American Burn Association, at the temperature of 60 °C, it would take 3 s to burn the skin and cause serious enough injury requiring surgery (American Burn Association, 2018). The association recommends not to exceed 48 °C (ibid.).

A three-way valve is installed after the storage tank to mix the hot water with cold water in order to reach a lower distribution temperature (see Figure 14). However, the temperature cannot be reduced too much to avoid legionella growth inside the distribution pipes. It is therefore maintained between 50 and 55 °C. Constant recirculation of DHW is also used to keep the temperature homogenous across the building.

Measurements made by Zgraggen (Zgraggen, 2010) show that the temperature of hot water leaving the storage is close to 52 °C, with spikes reaching 59 °C. The DHW, after mixing at the three-way valve, is then distributed at a relatively constant temperature of 50 °C.

We have measured the higher temperatures available at the faucets during one of the campaigns and found temperatures ranging from to 46.2 to 58°C with 53.8 °C on average, i.e., values that are higher than those recommended by the American Burn Association.

Appendix 3

Description of campaigns

We have in our database 25 campaigns with information corresponding to the total number of targeted dwellings, the total number of dwellings that participated in the program, and the total number of showerheads and faucets intervened (see Table 9). The table also contains the rate of fixtures intervened per targeted dwelling, an indicator that is used to select the campaigns where higher savings are expected.

Appendix 4

Complementary details for the ex-ante DES method

This appendix describes in more detail the values used for applying the DES method according to Eqs. 1 and 2 for the estimation of the energy savings per fixture installed/replaced. We first discuss cold and hot water consumption, followed by flow rates (before and after the intervention) and temperatures of cold and hot water (see also Appendix 1). We then consider the number of inhabitants per dwelling, the persistency factor, and change behavior factor to end up with the deemed savings per fixture.

Water consumption

Potable (cold and hot) water consumption in Switzerland

According to SSIGE (SSIGE, 2018) and SwissEnergy (SwissEnergy, 2017), the average daily potable water consumption per capita in Swiss households is 142 l, which is considered for the deemed savings. Based on a survey (SSIGE, 2018), potable water is used as follows (Table 10):

Hot water consumption—at the fixture level

According to the usage share found by SSIGE (SSIGE, 2018) in Switzerland, shower and bathtubs represent 35.9 l of water per day per person. This volume will be reduced with the flow restrictors but only for the part used for showering. M. Lee (Lee, 2011) and P.W. Mayer (Mayer, 1999) give a share[6] for showers of 16.8%. Applying this share to our deemed savings calculations, we calculate the volume of water consumed through showerheads to be to 24 l/person/day, which decreases with the flow restrictors or efficient showerheads. The rest, 11.9 l, corresponds to the usage for baths and is not expected to change with the flow restrictors assuming that people will continue to fill the bath at the same level.

According to SSIGE (SSIGE, 2018), the volume of water consumed through kitchen faucets (mainly used for washing dishes and hands) represents 22 l per person per day (i.e., 15.5% of the total tap water demand). The volume of water consumed through bathroom faucets (mainly used for washing hands and face) amounts to 16 l per person per day (11.3 % of the total tap water). In summary, the share of warm water consumption that would be affected by the flow restrictors should be close to 62 l per person per day distributed in the following way:

- Showerheads: 24 l per day per person
- Kitchen faucets: 22 l per day per person
- Bathroom faucets: 16 l per day per person

Adding the bath consumption to the previous three usages, the total warm water consumption should then be close to 74 l per day per person. To our knowledge, most dish washers and washing machines are connected to cold water in Switzerland; i.e., these machines do not consume hot water from the central heating system.

[6] We did not find a recent study giving the share among bathtubs and showers.

Table 10 The 25 campaigns. The table shows when the campaign was carried out, the number of targeted and participating households, the number of fixtures intervened (faucets and showers), and the rate of intervened devices per targeted dwelling

Municipality	Date	Dwellings (no.)	Participants (no.)	Faucets (no.)	Showers (no.)	No. of devices/ dwelling
Meyrin	Feb 14	593	519	200	100	0.51
Vernier	Mar 14	576	539	534	288	1.43
Lancy	Mar 14	607	529	517	247	1.26
Carouge	Oct 14	497	445	660	415	2.16
Onex	Oct 14	533	496	710	447	2.17
Gd-Saconnex	Oct 14	542	487	980	430	2.60
Meyrin	Feb 15	604	508	808	315	1.86
Carouge	Mar 15	592	506	1125	351	2.49
Vernier	Apr 15	699	614	845	264	1.59
Gd-Saconnex	Sep 15	786	668	1430	470	2.42
Lancy	Oct 15	627	518	943	294	1.97
Onex	Nov 15	513	479	1050	428	2.88
Meyrin	Feb 16	874	741	1517	464	2.27
Vernier	Oct 16	638	538	1275	310	2.48
Carouge	Dec 16	576	546	1488	442	3.35
Gd-Saconnex	Feb 17	719	611	1212	541	2.44
Lancy	Apr 17	621	568	1171	417	2.56
Carouge	Oct 17	781	709	741	433	1.50
Vernier	Dec 17	646	560	1155	362	2.35
Carouge	Jan 18	379	337	633	256	2.35
Avully	Feb 18	478	430	808	327	2.37
Pregny-Chambésy	Sep 18	115	101	127	91	1.90
Meyrin	Sep 18	664	554	815	411	1.85
Bernex	Nov 18	548	497	847	379	2.24
Meyrin	Jan 19	617	538	799	331	1.83
Total		**14,825**	**13,038**	**22,390**	**8813**	**2.10**

Flow rates

The flow rates assumed to estimate the energy savings were established based on a literature review and some measurements using a chronometer and a bucket (0.5 l for faucets and 2 l for showers).

(i) Shower flow rates

Flow rate measurements were conducted in our lab with a sample of 95 showerheads removed from participating households and a sample of two efficient showerheads. The same position of the valve was used to measure the water flow rate of all the showerheads. Figure 16 shows the distribution of the flow rates for the inefficient showerheads, ranging from 10.6 to 13.2 l/min with a mean of 11.8 l/min and a median of 11.9 l/min. A large part of the showerheads had visible limestone deposits.

The water flow in two efficient showerheads (valve opened at the same position as previously) were the following: in a new one 9.2 l/min and in a 3-year-old one 8.1 l/min. The older efficient showerhead had some limestone deposits explaining the lower flow rate.

A. Fidar (Fidar, 2010) reports flow rates in showers spanning from 3.4 to 15 l/min. All of our measurements are within this range. According to C. Clarke (Clarke et al., 2009), a standard flow rate for an inefficient showerhead is 12 l/min and an efficient one 8 l/min, very close to the values we found with our measurements. Considering that the study made by Clarke is focused on water consumption, we will take his values for our calculations (i.e., 12 l/min before placing an efficient showerhead (or flow restrictor) and 8 l/min after). The expected reduction rate is then 33%.

According also to C. Clarke (Clarke et al., 2009), while it has been hypothesized that people spend longer time in low flow showers, a robust relationship between flow rate and duration has not been observed in studies and there is no definitive evidence for or against this hypothesis (ibid.). Hence, we are going to assume that shower duration does not change after the installation of flow restrictors.

(ii) Faucet flow rates

A set of measurements was made on a small group of households where the flow rate was measured on thirteen faucets. Inhabitants were requested to open the taps to obtain the flow of water as they usually do. For comparison, we measured the flow rate for the completely opened tap and we found that the flow rate was not too different. Out of the 13 faucets, three already had flow restrictors installed and presented a water flow rate ranging from 5.3 to 7.6 l/min. The other ten had flow rates ranging from 7.5 to 13.8 l/min with an average of 11.0 l/min. Flow restrictors were subsequently installed on eight of the ten taps. The new flow rates with the flow restrictors (same position for the tap) ranged from 6.2 to 10.6 l/min with an average of 8.8 l/min.

According to our measurements in households, the average flow rates amount to 11.0 l/min before restrictors and 8.8 l/min afterwards, representing a reduction of 22%. This is less than what is announced by the manufacturer (50%).

As previously, we assume that the time during which the tap is open to wash hands or dishes does not change with the installation of flow restrictors. The reduction of volume of DHW consumption then corresponds to the flow reduction.

(iii) Flow rates labels and obligations

We have observed that some dwellings are already equipped with low flow devices, but it is rather marginal at present time. The introduction of an energy label[7] for these devices is certainly helping for its adoption but still at a very slow pace. It must be noted that there is no obligation in Switzerland requiring a given efficiency for DHW fixtures. Some standards, like the standard W3/C3 (SSIGE, 2020), defines minimum flow rates (for sanitary reasons) and maximum speeds (to avoid noise problems), but no maximum flow rates.

A brief survey was conducted among Swiss organizations addressing energy and water in buildings who confirmed that there is no obligation at present time for a maximum flow rate limit.

[7] See, for example, ENERG - Energy labels for sanitary products SVES (https://en.etiquetteenergie-sanitaire.ch/Information-2) or the Unified Water Label from Unified Water Label Association UWLA http://www.europeanwaterlabel.eu/thelabel.asp

Temperature of cold water

The temperature of mains inlet tap water (cold) varies as a function of the source providing the water, treatment to make it potable, the distribution system and the characteristics of the soil (Agudelo-Vera et al., 2020). In order to accurately estimate the energy use related to DHW preparation, it is important to obtain the local temperatures of cold water (Fuentes E. et al, 2018). Measurements made in the past by our group found an annual average cold water temperature of 13 °C (Zgraggen, 2010; Khoury, 2014). We measured the water temperatures for one of the campaigns of our case study. We considered only measurements during periods when tap water was demanded because the temperature slowly approaches the room temperature when there is no flow in the pipes. The lowest temperature found was 8 °C (in February), while the highest temperature was 19.4 °C (in July). The average temperature was 12.9 °C, which is very close to the values found in the previous mentioned studies.

Based on the previous studies and our measurements, we use 13 °C as the annual average temperature of cold water in our analysis.

Temperature of DHW

Shower temperatures

Several studies (Clarke et al., 2009; Kawahara et al., 2005; Herrmann, 1994) find that the average shower temperature is close to 39 °C which we also take for our analysis.

Faucet temperatures

We measured the maximum temperature available at the faucets during one of the campaigns and found temperatures ranging from to 46.2 to 58 °C with 53.8 °C as average. Based on the share of hot/cold water consumption for kitchens (hot 35 l/day, cold 24 l/day) and toilets (hot 22 l/day, cold 20 l/day) found by Clarke (Clarke et al., 2009) and our measurements of cold and hot water (13°C and 55°C respectively), we deduct the average temperatures for both fixtures, i.e., 37.9 °C for the kitchen (and 35°C for toilets).

Efficiency of the central heating system

According to SwissEnergy (SwissEnergy, 2015), a program operated by the Swiss Federal Office for Energy, the efficiency of fossil fuel boilers, based on the higher heating value, range between 75 and 95% (see Table 11). At present, heating oil remains the most widely used fuel for central heating systems in the regions under study. However, it is essential to recognize that the use of heating oil has been gradually decreasing, giving way to alternative fuels such as natural gas. In the context of our study, we have chosen to take the average efficiency between heating oil and natural gas. This decision is not meant to represent the exact current state of fuel usage but rather to provide an order of magnitude that captures the transitional phase between these two prevalent fuels. We choose for our estimates the average of these ranges, i.e., 86.25% for natural gas and 83.75% for heating oil.

Characteristics of dwelling

Our survey (see next section) results in 2.3 inhabitants per dwelling, which is quite representative of the Swiss average. We use the result of our survey for the calculation of the savings. However, for the extrapolation of our results at the country level, the official statistics should be used. In Switzerland, the current occupancy rate is 2.21 inhabitants per dwelling. Concerning the surface of dwellings, the Swiss federal statistics estimates an average surface of 99 m^2 per dwelling (Federal Statistical Office, 2022).

Table 11 Usage of potable water (SSIGE, 2018)

Usage	Liters/day	Percent
Toilet flush	41.0	28.9%
Shower and bathtub	35.9	25.3%
Kitchen sink	22.0	15.5%
Laundry	17.0	12.0%
Wash room faucets	16.0	11.3%
Washing machine	3.0	2.1%
Outdoors	7.0	4.9%
Total	**142.0**	100.0%

Persistency factor

For different reasons, some residents remove or replace flow restrictors and/or the efficient showerheads, consequently leading to lower savings than expected. We define as persistency factor the share of households that keep the flow restrictors and/or efficient showerheads in the long term. The persistence factor was determined based on the responses to an online survey. This survey was sent in September 2018 to nearly 12,000 households. More than 4000 people reacted to it, but we finally collected somewhat less than 3000 fully completed questionnaires (n=2840). The main objective of this questionnaire was to collect data in order to analyze the persistency of electricity and water savings related to EEPs. Somewhat more than 200 responses (n=216) concerned the water saving program. When asked "Are the flow restrictors still installed in your taps at home?", close to 12% of respondents reported that they removed or replaced them by a new one. As a result, 88% of households are retaining the equipment (see Table 12).

For showerheads, the situation is somewhat more critical. In response to the question "are you still using the showerhead installed by the program," close to 1/3 declared that they had replaced it by the previous one or by a new one. Thus, only 68% of the households retained the efficient showerheads installed by the program (see Table 13). We can deduct from the dates of the campaigns and the survey, as well as interviews with energy auditors, the program manager, and technicians, that the households which removed the flow restrictors, did it shortly after they had been installed. This happens usually in buildings with some problems concerning the water pressure (Table 14).

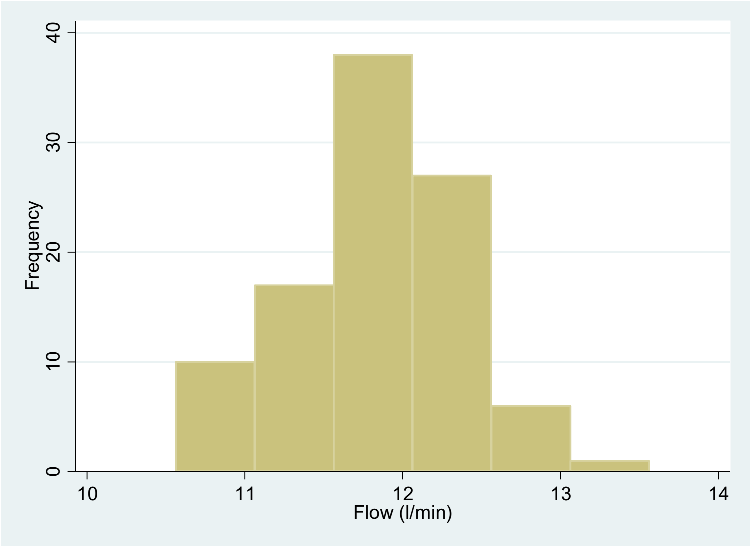

Fig. 16 Distribution of water flow rate in existing (inefficient) showerheads ($n = 95$). Flow rates range from 10.6 to 13.2 l/min with a mean of 11.8 l/min and a median of 11.9 l/min

Table 12 Fossil fuel boilers efficiency based on the higher heating value (SwissEnergy 2015).

Fuel	Age	Efficiency
Natural Gas	New boiler (condensing boiler)	85 to 95%
Natural Gas	Old Boiler	80 to 85%
Heating Oil	New boiler (condensing boiler)	85 to 95%
Heating Oil	Old Boiler	75 to 80%

For the deemed saving calculations, we will use persistence factors of 88% for faucets and 66% for showerheads.

Table 13 Share of flow restrictors (without showerheads) remaining in place, removed or replaced (n= 216).

Response	No.	Percent
No, but it has been replaced by a new one	7	3%
No, it has been removed	18	8%
Yes, it is still installed	191	88%
Total	**216**	**100%**

Table 14 Share of flow restrictors in showerheads remaining in place, removed, or replaced (n= 103).

Response	No.	Percent
No, I replaced it by the older one	13	13%
No, I replaced it by a new one	22	21%
Yes, it is still in place	68	66%
Total	**103**	**100%**

Change behavior factor

One of the characteristics of the program is that the energy auditors spend between 1 and 2 h in the households implementing EEMs (installing flow restrictors, changing light bulbs, etc.). During their visit, they spend also some time explaining to the inhabitants about behaviors that could help increase the savings. For DHW, reducing the temperature or shortening the time of showers can have an additional saving impact. Psychosocial, behavioral, sociodemographic, infrastructure, and contextual variables all have a role in determining household water conservation intentions and water use (Russell et al., 2020; Fielding, 2012). Attitudes, norms, and habits play an important role in determining the intention to conserve water, and habits are the single most important predictor of water conservation intentions. It is likely, that the energy auditors, who explain to the inhabitants the environmental benefits of flow restrictors, contribute to enhanced water and energy savings achieved by the installation of flow restrictors.

The analysis of electricity savings under the same program (Cabrera et al., 2019) showed that households which interacted with the energy auditors obtained higher electricity savings. It is likely that some inhabitants change their habits and achieve additional savings also for DHW. One interesting outcome of the survey carried out among participants is that they are more interested in the environmental benefits of energy savings rather than the financial benefits. V. Tiefenbeck finds that behavior change (induced by real-time feedback) can reduce the energy consumption for DHW from 11.4 to 23% (Tiefenbeck et al., 2014, Tiefenbeck et al. 2018).

It is not straightforward in our case to estimate how much savings are obtained in addition, thanks to the change of habits. We assume that they represent an additional 15% (relative to the savings enabled by the technical measures), which could seem to be a high value but is justified when comparing the deemed savings to the ex-post results (see the comparison in the "Conclusions" section).

Appendix 5

Complementary details for the ABA method

Selection of years for the ABA method

The right selection of a couple of years (before and after the campaign) is crucial for the accuracy of the savings estimation with the ABA method. Figure 17 shows an example for one of the seven campaigns that were analyzed with this method. The year 2013 shows a higher energy consumption since it had a particular cold winter and the reduction in 2014 is justified by a rather warmer winter (see Figure 18). The campaign was carried out in 2015, and an additional reduction is seen shortly afterwards. The energy consumption increases again in 2017 partly because the winter was colder than the previous year and because some households probably removed some devices (see section Appendix 5 "Persistency factor" pertaining to the persistence of savings).

As shown in the previous example and discussed in the "Annual billing analysis (ABA method)" in the "Methodology" section, it is important to choose a couple of years with similar weather conditions and preferably with warmer winter months in order to avoid the noise caused by the variation of space heating consumption. We chose a pair of years with similar weather conditions based on the comparison of annual HDD.

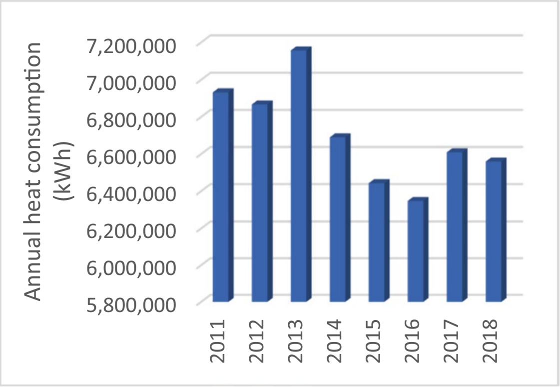

Fig. 17 Annual heat consumption from 2011 to 2018 for one of the campaigns carried out in 2015. The high consumption in 2013 is due to a cold winter (high HDD)

Figure 18 shows the annual HDD (January to December) in °C-days for Geneva, Switzerland[8], from 1994 to 2019 and its absolute variation (in %) between two consecutive years. The annual HDD are in average 2461 °C-days, and the variation between two consecutive years is in average 9%. Extreme variations might occur; HDD varied from 2753 (in 2013) to 2072 °C-days (in 2014—1 year later), a reduction of around 25%. The reduction of the heat consumption from 2013 to 2014 is assumed to be mainly due to the drastic change of weather, representing a reduction of space heating needs close to 25%. This amount of energy reduction is of the same magnitude as the whole heat consumption of DHW, and it would then be very difficult to measure the energy savings if these two years were taken for the comparison.

In our analysis, we consider the period 2011 to 2019. To choose the most favorable years for the estimation of the savings, we sort them by their HDD in ascending order. Figure 19 shows the HDD in ascending order and the variation with the closer lower HDD (in %). As seen with the DES method ("Ex-ante deemed energy savings (DES method)—analysis and results" section), the savings that we are expecting to see are lower than 5% of the total energy consumption. We choose therefore for the comparison, pairs of years with HDD that do not vary by more than 5%.

[8] This information has been retrieved in May 2021 from the web site of the Cantonal Energy Office of Geneva (https://www.ge.ch/document/energie-degres-jour).

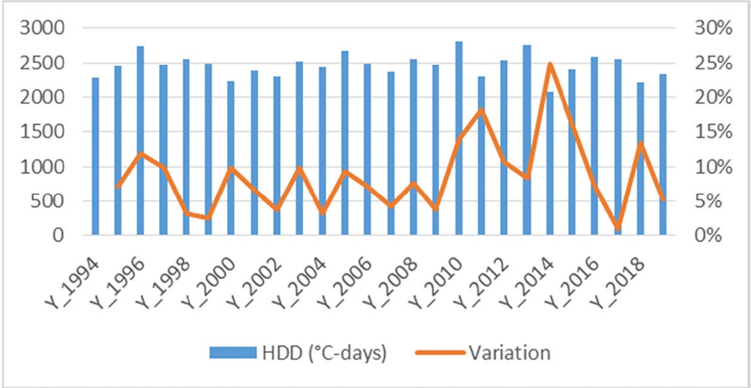

Fig. 18 Annual HDD (°C-days) for Geneva, Switzerland, from 1994 to 2019 (in blue) and the variation with the previous year in % (in orange)

Based on the explanation given in the "Annual billing analysis (ABA method)" in the "Methodology" section and in the previous paragraphs, the most favorable pairs of years are the following two:

– 2011 and 2018: They are characterized by low HDD, and the difference is 3.6%. They can be used for all the campaigns between 2012 and 2017. Considering that HDD are higher in 2011 than in 2018, the difference of the energy consumption between these two years should be higher than the actual savings.
– 2012 and 2017: They have the smallest difference in HDD (1 %). They can be used for all the campaigns between 2013 and 2016. Considering that HDD are lower in 2012 than in 2017, the difference of the energy consumption between these two years should be lower than the actual savings.

The actual savings will therefore be bounded by the differences found using the two couples of years described here above.

Appendix 6

Complementary details for the SMBA method

Selection of months

We choose the months without heating needs based mainly on the monthly HDD. Figure 20 shows the monthly HDD from 2010 to 2020 (left from January to December and right a zoom from May to September). The months of July and August are the only two months that never show space heating needs.

The month of June could be also a candidate for some years. However, we have noticed that in some buildings, the space heating system seems to still work during the first days of this month despite the fact that heating is not necessary. Figure 21 shows, for a small group of buildings of our sample, the monthly heating consumption (space heating and DHW) for several years (from 2010 to 2019). We can see that during the month of June 2013 (characterized by positive HDD—cold spring season), there is still a consumption for heating, but also for some other years where HDD equal zero. Hence, only July and August are considered in the SMBA analysis.

July and August are also vacation months, and the occupancy level of residential buildings decreases during this period. However, we consider that for a large sample and before COVID-19, the occupancy level equally decreases each year.

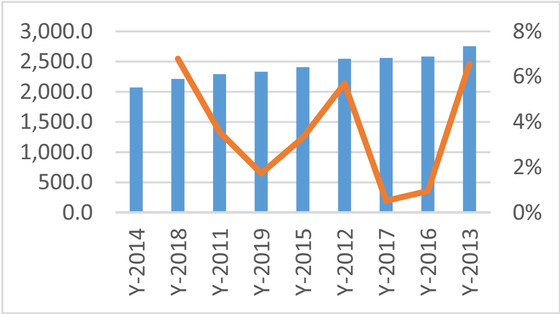

Fig. 19 Annual HDD (from 2011 to 2019) in ascending order and the difference in % with the precedent one

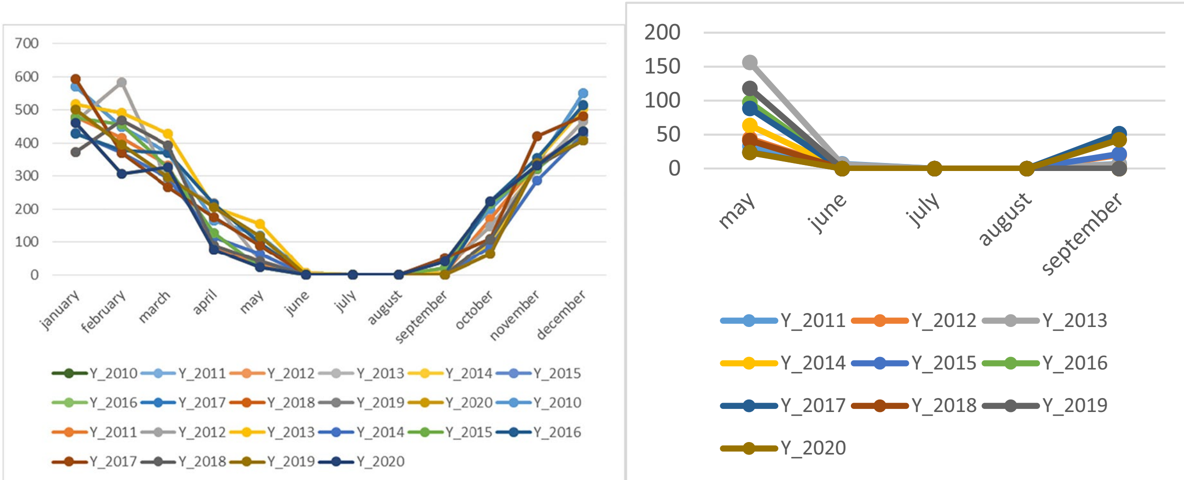

Fig. 20 Monthly HDD in Geneva from 2010 to 2020 (right figure: zoom for the months May to September)

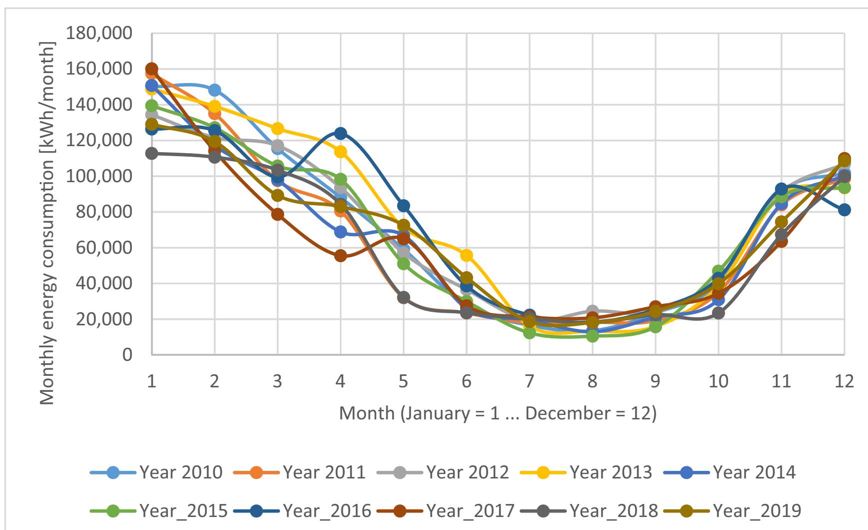

Fig. 21 Monthly (January = 1… December = 12) final energy consumption for space heating and DHW from 2010 to 2019 for a group of buildings of our sample

Hot water seasonal factor

The consumption of hot water is influenced by seasonal weather changes, which affect the temperature of the main water supply (Fuentes et al. 2018, Ahmed et al. 2015), and building occupancy, which can be observed during vacation periods.

Figure 22 shows the monthly profile of the energy for DHW production for a group of buildings in Geneva. The energy consumption during the months of July and August together represents 10.6% of the annual consumption. The ratio between the annual consumption and the summer months used for the calculations of the savings is then 9.4.

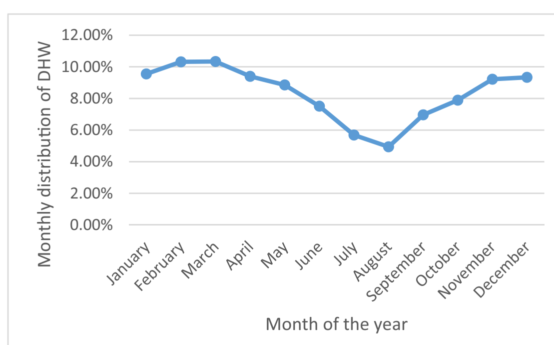

Fig. 22 Monthly distribution of final energy for the production of DHW

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