A probabilistic approach to include the overall efficiency of gas-fired systems in urban building energy modelling

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Abstract. Urban building energy modelling has an essential role in the estimation of energy demand at urban or neighbourhood scales. However, current modelling methods have limitations in reproducing realistic gross energy usage. Although it is theoretically possible to simulate all components of the heating system in detail, such an extensive approach significantly increases the computational effort, prohibiting a large scale probabilistic analysis. As an alternative, this paper presents a simplified data-driven approach to estimate the overall efficiency for the six most occurring gas-fired heating system configurations in Flemish single-family dwellings. For all configurations, efficiencies of emission, distribution, production, control and storage components are taken into account, of which the efficiency of the production unit is modelled most in detail as it includes the load-dependency. The approach is applied to a sample of 20 dwellings reflecting realistic variation in size, insulation quality and occupancy schedules. For all dwellings and the different heating systems the resulting annual production efficiency, and monthly heating systems’ efficiency as a function of gross energy demand are shown based on the 25th, 50th and 75th percentile.

1. Introduction

The link between the overall dwellings’ energy use and the net demand of space heating (SH) and domestic hot water (DHW) is indispensable in the creation of realistic energy demand profiles in urban building energy modelling (UBEM). In literature, different simplified methods can often be found. One of the most common approaches is the assumption of a unique heating system type with a constant annual efficiency in all dwellings (e.g. 85% in [1]). In studies that assume building typologies, different systems paired with constant efficiencies are usually allocated to dwellings based on construction year and building type (e.g. [2]). More specific approaches suggest the allocation of the constant system efficiency for SH and DHW separately based on the system type (e.g. [3]). Although the system performance at low and high loads often significantly differ, which affects the usage of the energy carrier, examples of approaches which include a dynamic system efficiency could not be found. Thus, this paper introduces that possibility and presents a simplified data-driven approach to estimate and allocate dynamic, load-dependent, system efficiencies for gas-fired heating systems.

In this study, it is assumed that the simulated SH and DHW demand for buildings in an observed district are computed beforehand, as is often the case in UBEM, and the overall losses are allocated in post-processing. In the first step, the simulated SH demand profile and the generated DHW demand profile are loaded. Then, a particular system is chosen, from a selection of the six most occurring heating
systems in Flemish dwellings. In the next step, emission efficiency and distribution efficiency are added to the SH demand. Then, the DHW demand is calculated, including distribution and storage efficiency. Finally, both profiles are added and the production efficiency is implemented, resulting in the overall energy use of the boiler. All steps are also presented in Figure 1 (right) and later discussed more elaborately.

Figure 1. Allocation of efficiencies to SH and DHW subsystem components (left), and an overview of the simplified approach to obtain the overall energy use for gas-fired heating systems (right).

The overall energy use of a gas-fired heating system is equal to the sum of the energy demand for SH and DHW increased by the thermal losses of the heating system. The losses can be attributed to each of the components of the system, and are often expressed as efficiencies, as they depend on the energy demand. Doing so, the total heating system efficiency can be expressed as:

\[
\eta_{\text{total}} = \eta_e \cdot \eta_d \cdot \eta_s \cdot \eta_p \tag{1}
\]

Where \(\eta_e\) is the emission efficiency, \(\eta_d\) is the distribution efficiency, \(\eta_s\) is the storage efficiency, if applicable, and \(\eta_p\) is the production efficiency. These efficiencies can be subdivided for SH and DHW subsystems and are also illustrated in Figure 1 (left). Although distribution and emission efficiency are often considered together, in this work, the emission efficiency is separated from the distribution efficiency. Moreover, the emission efficiency sometimes includes the control efficiency (e.g. [4]), while the control efficiency is excluded in other studies (e.g. [5]). In the presented approach, the control efficiency is taken into account together with the emission efficiency.

2. Method

In this work, the SH demand profile is obtained by simulating a white-box two-zone building energy model using IDEAS [6], assuming an ideal radiator heating system. The nominal power of this ideal system is equal to the design heat load of the dwelling, quantified following NBN EN 12831 [7]. The occupancy profiles which include set-point temperatures for day and night zone, convective and radiative heat gains for the dwelling, electrical loads due to appliances, as well as DHW demand, are generated using the StROBe Python package [8].
2.1. Selection of the heating system configuration and sizing
When defining the heating system configuration two possibilities of heat generators can be selected: condensing and non-condensing gas boiler, paired with three types of DHW production subsystems. The three types are: systems where DHW is not produced by the main heat generator, systems with direct DHW production, or so-called combi boilers, and indirect systems with heated DHW storage tanks. The DHW production efficiency of secondary heat generators (i.e. auxiliary heaters) is not included in the overall energy use of the main system and thus not investigated in this work.

The system components (boiler and, if needed, storage unit) could be sized, as in reality, to satisfy the maximal needed demand. However, it is observed that installed boilers are often not properly sized [9]. Instead, 25 or 32 kW boilers can usually be found in existing dwellings. Therefore, as this work aims at modelling the existing building stock, the nominal power of the heating system is chosen to be 32 kW regardless of the house and its thermal performance. Depending on the production efficiency, the allowable maximum power for gross energy demand varies. The calculation of the allowable maximum power is introduced after discussing the production efficiency.

2.2. Space heating: distribution, emission and control efficiency
After selecting the heating system configuration, the emission and distribution efficiency are added to the simulated energy demand for SH. According to NBN EN 15316-2-1 [10], the emission efficiency accounts for the non-uniform space temperature distribution, embedded heat emission system and control accuracy of the indoor air temperature. Assuming that the heat emission system consists of radiators that are placed in front of external walls, that the temperature regime is 70/55°C and that the system is controlled by a thermostat in the master room space, the emission efficiency is equal to 85%. The constant value for the emission efficiency, including control, is a simplification. As an example, Van der Veken et al. [11] assume that the emission efficiency of radiators, excluding control, is constant and equal to 97%. However, they show that the control efficiency depends on the heat load of the system. For a thermostat combined with thermostatic radiator valves, the control efficiency is just below 100% at high loads but can drop even to below 50% at low loads. This load-dependent effect is not taken into account in this work.

Next, distribution efficiency is taken into account. NBN EN 15316-2-3 [10] prescribes three methods to calculate the thermal energy emitted by the distribution system, however, these methods do not provide efficiency in percentage. The Flemish Energy Performance Certificates calculation method prescribes a distribution efficiency of 100% if the length of uninsulated pipes outside of the heated volume is smaller than or equal to 2 m and of 95% if the length is smaller than or equal to 20 m [10]. According to the work of Van der Veken et al. [11], the distribution efficiency is just below 100% at high monthly loads but decreases to just below 90% at low monthly loads. In this work, 98% is assumed, to include that some of the losses might occur in unheated spaces, whereas most of them will occur in heated spaces.

2.3. Domestic hot water: distribution and storage efficiency
Since StR0Be DHW demand profiles produce energy demand peaks up to 70 kW, while the foreseen power is 32 kW, it is chosen to limit demand peaks to 0.23 kg/s (14 l/min) to be sure that the demand can be supplied. This limit is based on common flow rates in single-family dwellings [12]. Rather than cutting off the peaks in the real demand, the peaks are flattened and the excess is shifted to the very next time step to obtain the same annual total.

In the next step, the energy demand for DHW, including the distribution and storage efficiency, is calculated. Combi boiler units can produce instantly large amounts of hot water, which sometimes requires higher installed boiler capacities. On the other hand, in systems with DHW storage tanks, the regular boiler reheats the stored DHW over time, therefore, a smaller boiler capacity is sufficient and the boiler is turned on less frequently. As a result, the calculation method is different for systems with direct and indirect production and is now discussed respectively.

The energy demand profile for the directly heated DHW is calculated by:
\[ Q_{\text{direct}} = q_w \cdot c_w \cdot (T_{\text{dhw}} - T_w) \cdot t \] (2)

Where \( q_w \) is equal to the instant DHW demand in [kg/s], \( c_w \) is equal to the water heat capacity [J/(kg K)], \( T_{\text{dhw}} \) is equal to the selected DHW draw-off temperature, \( T_w \) is equal to the temperature of cold water on the tank inlet and \( t \) is the length of the time step in [s]. For directly heated DHW, there is no storage unit and thus no storage efficiency to be included. However, distribution losses certainly occur and are calculated based on Annex B of ISO EN 15316-3-2 [10], as follows in equation (3):

\[ \eta_{\text{pipe}} = \frac{1}{\frac{f_{\text{kitchen}}}{\eta_{\text{pipe},k}} + \frac{f_{\text{bath}}}{\eta_{\text{pipe},b}}} \] (3)

Where \( f_{\text{kitchen}} \) is the fraction of DHW demand in the kitchen (here 0.2), \( f_{\text{bath}} \) is the fraction of DHW demand in the bathroom (here 0.8), \( \eta_{\text{pipe},k} \) is the proportion of energy reaching the outlet in the kitchen, and \( \eta_{\text{pipe},b} \) is the proportion of energy reaching the outlet in the bathroom. The pipework efficiency depends on the length of the pipework, type of pipes, recirculation of hot water in pipes and recuperation of losses. In this work, it is assumed that there is no recirculation pump installed in the system and that losses occurring in the heating season are not taken into account (i.e. distribution losses only occur if there is no SH demand). Therefore, only losses during the summer months are calculated with constant values \( \eta_{\text{pipe},k}=0.55 \) and \( \eta_{\text{pipe},b}=0.86 \) which correspond to losses of average pipework with a length between 6 and 8 meters, measured from the production unit. It is important to mention that in this approach the losses are temperature independent. The energy demand with included distribution losses is calculated as:

\[ Q_{\text{demand}} = \frac{Q_{\text{direct}}}{\eta_{\text{pipe}}} \] (4)

For indirectly heated DHW the energy supply to the storage tank is simplified with an ON/OFF regime, where the maximal energy delivered to the storage is equal to the maximal heat output of the coupled boiler. An additional assumption is that the lower temperature limit of the stored water is 50°C, and the upper temperature limit is 60°C. The storage tank \( (M_{\text{tank}}) \) is sized based on the number of household members and an average daily consumption of 50 l/pp day, based on Table B.5 of NBN EN 12831-3 [7]. To satisfy the peak demand (i.e. 14 l/min), a minimal tank size of 140 l is introduced. In this work, the tank dimensions are chosen together with the average daily standby losses for a given tank size, based on Table B.8 of NBN EN 12831-3 [7].

Calculating the energy demand profile for the indirectly heated DHW is not as straightforward as for the directly heated DHW. The model for the simplified single mass tank is based on the idea from [16]. Due to the simultaneous occurrence of the DHW demand, storage losses and heat input from the boiler, the energy balance of the DHW storage over a time step should be calculated and is equal to:

\[ M_{\text{tank}} \cdot c_w \cdot \Delta T_{\text{tank}} = Q_{\text{tank}} - Q_{\text{demand}} - Q_{\text{loss}} \] (5)

Where \( \Delta T_{\text{tank}} \) is the temperature drop between two time steps, \( Q_{\text{tank}} \) is the heat supplied to the storage tank, \( Q_{\text{loss}} \) represents the heat loss and the DHW demand in the observed time step, \( Q_{\text{demand}} \) is defined as in equation (4). The instant demand, in this case, is equal to the DHW demand of the direct system because the latter already includes the distribution losses.

Tank losses through the shell to the surrounding ambient and primary pipework losses are calculated, as previously mentioned, according to Table B.8 [7]. The resulting losses can be compared to what is reported in other studies. Orr et al. [9] report storage or standby losses of 900 kWh annually. This corresponds to a tank of approximately 250 l according to Schweitzer et al. [13].

### 2.4. Production efficiency

Finally, the obtained profiles for SH and DHW are added and the production efficiency is applied to the resulting overall energy demand. However, to avoid unrealistic peaks in the gross energy demand
The nominal power of the heating systems is considered to be 32 kW for all dwellings. The allowable peak power for the gross energy demand is thus equal to 32 kW multiplied by the maximal production efficiency, where the production efficiency is defined as the amount of useful energy delivered by the production unit divided by the amount of energy that is supplied to the production unit. Since the focus in this work is on gas boilers, the energy supplied to the production unit is equal to the energy liberated during the combustion process, based on the higher calorific value. Given that the condensation of water vapour in exhaust gasses is taken into account, as a result, the maximum efficiency is equal to 100%.

Different studies investigated the on-site behaviour of domestic gas boilers. Wolff et al. [14] investigated the operational behaviour of 60 condensing gas boiler and 7 non-condensing gas boilers. They conclude that the annual efficiency of a gas boiler does not only depend on the production system and the heat load but also on the user behaviour, the control of the heating system and the hydraulic integration of the system. Orr et al. [9] studied the operational behaviour of 31 condensing combi boilers, and 10 condensing regular boilers combined with an external DHW tank. They report the mean annual efficiency and its standard deviation for the different types of boilers. Schweitzer et al. [13] present a study of domestic gas boilers over 25 years. However, they do not measure the on-site behaviour, therefore it has been decided not to use these data. Bennet [15] investigated the 10% performance gap related to gas boilers in residential dwellings, through both simulations and on-site measurements. He presents high-resolution data from 4 dwellings as well as lower resolution data for 217 heating systems, where he confirms the observations of Orr et al. [9]. However, in his work, no numerical data is available that can be readily used in this research. Consequently, further calculations are based only on the results of Wolff et al. [14] and Orr et al. [9]. Their findings for the annual efficiency of different production systems are summarized in Table 1. For missing system configurations own estimations based on discussed literature were adopted.

### Table 1. Reported efficiency for domestic gas boilers based on Wolff et al. [14] and Orr et al. [9].

| Source                    | Own estimations | Wolff et al. (2004) | Orr et al. (2009) |
|---------------------------|-----------------|---------------------|------------------|
| Heating system configuration |                 |                     |                  |
| Non-condensing regular boiler – no DHW | 80 | 75.4 | 85.3 |
| Non-condensing combi boiler | 72.5 | 90.6 | 82.5 |
| Non-condensing regular boiler – no DHW | 75.4 | 90.6 | 85.3 |
| Condensing regular boiler – no DHW | 72.5 | 86.2 | 82.5 |
| Condensing regular boiler – DHW tank | 72.5 | 75.4 | 75.4 |
| Condensing combi boiler | 85.3 | 86.2 | 82.5 |
| Condensing regular boiler – DHW tank | 82.5 | 85.3 | 82.5 |

Since for small heat loads the efficiency can be significantly lower than its nominal efficiency, this research considers the load-dependency of the production efficiency. The mathematical formulation of this phenomenon is clearly described by Wolff et al. [14] and is explained below.

To exclude the nominal power of the boiler, but to include the load-dependency of the boiler efficiency, it is useful to define the standardized energy demand \( \beta \), as in (6). Where \( Q_{\text{gross}} \) is the gross energy demand profile, which is equal to the useful energy output profile of the boiler, and \( Q_{\text{nominal}} \) is the nominal power of the boiler. In other words, \( \beta \) is a time-dependent profile presenting the produced power compared to the nominal power. Similarly, the standardized energy use \( w_{\text{on}} \) is defined also in (6).
\[ \beta = \frac{Q_{\text{gross}}}{Q_{\text{nominal}}} \quad \text{and} \quad w_{\text{on}} = \frac{Q_{\text{use}}}{Q_{\text{nominal}}} \quad (6) \]

Where \( Q_{\text{use}} \) is the energy use profile of the boiler. Thus, in other words, \( w_{\text{on}} \) is a time-dependent profile presenting how much power the boiler uses compared to its nominal power. A clear relation between \( \beta \) and \( w_{\text{on}} \) can be observed:

\[ w_{\text{on}} = w_{\text{on},0} + a \cdot \beta \quad (7) \]

Where \( a \) is a conversion factor, \( w_{\text{on},0} \) is the standardized energy use at zero load of the boiler defined as \( q_B / \eta_{\text{nominal}} \) where \( q_B \) are the readiness losses and \( \eta_{\text{nominal}} \) is the nominal boiler efficiency. The nominal efficiency is defined as the inverse of the standardized energy use at full load:

\[ \eta_{\text{nominal}} = \frac{\Delta \beta}{\Delta w_{\text{on}}} = \frac{1}{w_{\text{on}}(\beta=1)} = \frac{1}{w_{\text{on},0} + a} \quad (8) \]

The load-dependent efficiency is equal to:

\[ \eta(\beta) = \frac{\beta}{a \cdot \beta + w_{\text{on},0}} \quad (9) \]

From equation (9) is possible to conclude that \( w_{\text{on},0} \) is the term which causes the efficiency to decrease at low loads. The efficiency drop can be observed if the monthly heating efficiency is visualized as a function of the supplied heat per month. Although such plots are available in both reports, only Wolff et al. [14] report on \( a \) and \( w_{\text{on},0} \) for different systems. Therefore, \( a \) and \( w_{\text{on},0} \) are based on the values found in Wolff et al. [14] for different systems, but are manipulated to better align with the monthly heating efficiency versus heat supplied plots found in both reports and with the reported annual efficiencies and their standard deviations as listed in Table 1. As a result, both the mean value and the standard deviation for \( a \) and \( w_{\text{on},0} \) have been determined for the considered system configurations. These results are listed in Table 2.

### Table 2. Estimated values of \( a \) and \( w_{\text{on},0} \) as used in this work.

|                     | Non-condensing regular boiler – no DHW | Non-condensing combi boiler | Non-condensing regular boiler – DHW tank | Condensing regular boiler – no DHW | Condensing regular boiler – DHW tank | Condensing combi boiler |
|---------------------|----------------------------------------|-----------------------------|------------------------------------------|-----------------------------------|--------------------------------------|--------------------------|
| \( a \) [-] - Mean  | 1.12                                   | 1.25                        | 1.25                                     | 1.11                              | 1.126                                | 1.07                     |
| \( a \) [-] - Standard deviation | 0.05                                  | 0.1                         | 0.08                                     | 0.026                             | 0.062                                | 0.05                     |
| \( w_{\text{on},0} \) [-] - Mean | 0.02                                  | 0.02                        | 0.0139                                   | 0.0015                            | 0.006                                | 0.025                    |
| \( w_{\text{on},0} \) [-] - Standard deviation | 0.002                                 | 0.002                       | 0.005                                    | 0.00005                           | 0.011                                | 0.002                    |

Results for 20 dwellings

|                          | Annual efficiency – Mean [%] | Monthly efficiency at high monthly loads [%] | Monthly efficiency at low monthly loads [%] |
|--------------------------|-------------------------------|---------------------------------------------|--------------------------------------------|
|                          | 80.4                          | 85.0                                        | 36.0                                       |
|                          | 67.1                          | 77.5                                        | 40.0                                       |
|                          | 73.6                          | 78.0                                        |                                            |
|                          | 89.1                          | 90.0                                        |                                            |
|                          | 84.6                          | 87.5                                        |                                            |
|                          | 72.8                          | 89.0                                        |                                            |
|                          |                               |                                             |                                            |

3. Example of the application and results

In this work, in order to show the proposed simplified approach while having sufficient variation in dwelling size, insulation quality, user schedule and others, the approach is applied to 20 dwellings. For each dwelling, the gross energy demand for SH and DHW is calculated separately. Then, \( a \) and \( w_{\text{on},0} \) are sampled from the normal distributions for the chosen heating system. Based on these sampled values
the nominal production efficiency is calculated based on equation (8). Since it is assumed that all buildings have a 32 kW boiler, the allowable peak power for the gross energy demand is calculated by multiplying the nominal power by the nominal production efficiency. The energy demand profiles for SH and DHW are added to get the total gross energy demand profile. This profile is then shifted, using the same approach as for shifting the DHW profile and the calculated peak power for the gross energy demand. This way, the needed energy can be always delivered by the production unit and the annual gross energy demand is conserved. Subsequently, the gross energy demand profile is used to determine $\beta$ based on $Q_{\text{gross}}$, following equation (6). Then, $w_{\text{on}}$ is calculated based on $\beta$ and the sampled $a$ and $W_{\text{on,0}}$ following equation (7). Finally, $Q_{\text{use}}$ is calculated based on $w_{\text{on}}$ following equation (6). The production efficiency is therefore not a fixed number, but rather a time-dependent profile, following equation (9). However, using these formulae, and more specifically because of $W_{\text{on,0}}$, the boiler uses energy while there is no gross energy demand. The difference is fairly small for most systems, but is noticeable for other systems due to regression errors. Therefore, it is chosen to put the energy use equal to zero when the gross energy demand is zero as well.

Figure 2. Annual production efficiency for different heating systems (left), and monthly heating efficiency vs. gross energy demand for SH and different heating systems (right), both based on the 25th, 50th and 75th percentile for $a$ and $W_{\text{on,0}}$ and the 20 dwellings. The distributions $a$ and $W_{\text{on,0}}$ introduce an uncertainty on the annual and monthly production efficiency, this uncertainty is visualized in Figure 2, showing the 25th, the 50th and the 75th percentile for the different heating systems and the 20 dwellings. The mean annual and monthly efficiencies are aligned with the values in Table 1. However, for systems with instant DHW production it is noticed that, even if the monthly efficiencies are aligned, the mean annual production efficiency is significantly lower than reported in Table 1. The difference can be explained due to the differences in the standardized gross energy demand profiles ($\beta$). In this work, $\beta$ has more low values, compared to Orr et al. [9], i.e. the boiler works often on a low load to provide only DHW. Additionally, it should be noted that the heat supplied per month in this work is similar to values reported by Wolff et al. [14] (from 0 to 9000 kWh/month), but is significantly larger than reported by Orr et al. [9] (from 0 to 4500 kWh/month).

4. Conclusion
The presented paper shows a data-driven approach for the creation of total energy use profiles of gas-fired heating systems which supply both the SH and DHW needs of single-family dwellings. With a probabilistic allocation of the parameters which describe the load-dependency of the production
efficiency, it provides a realistic variation in demand profiles attributable to different heating systems installed in dwellings. However, given that the parameters in this work are fitted based on the results found in Wolff et al. [14] and Orr et al. [9], it can be argued that reported performances could be outdated (dating from 2004 and 2009, respectively). This hypothesis can be confirmed based on the work of Schweitzer et al. [13]. Although their work only reports on nominal efficiencies and on real efficiencies calculated by a software called BOILSIM, it can be used to get insight into the evolution of boilers. It is observed that boilers manufactured from 2010 until 2015, perform 2 to 3% better than the boilers considered in this paper. Unfortunately, recent field measurements which reflect the current situation of the building stock in regards to installed boilers, to the author’s knowledge, are not available.

References
[1] Nouvel R, Mastrucci A, Leopold U, Baume O, Coors V and Eicker U 2015 Combining GIS-based statistical and engineering urban heat consumption models: Towards a new framework for multi-scale policy support Energy and Buildings 107 204–212
[2] Cuypers D, Vandevelder B, Van Holm M and Verbeke S 2014 Belgische woningtypologie: nationale brochure over de TABULA woningtypologie (Tech. rep., VITO)
[3] Wang D, Landolt J, Movrmatidis G, Orehoung K, Carmeliet PIJ and Carmeliet J 2018 CESAR: A bottom-up building stock modelling tool for Switzerland to address sustainable energy transformation strategies Energy and Buildings 169 9–26
[4] Maivel M and Kurnitski J 2014 Low temperature radiator heating distribution and emission efficiency in residential buildings Energy and Buildings 69 224–236
[5] Van der Veken J and Hens H 2010 Determination of the heating efficiency at building level Proc. Clima2010 Conf. (Antalya, Turkey)
[6] Jorissen F, Reynders G, Baetens R, Picard D, Saelens D and Helsen L 2018 Implementation and Verification of the IDEAS Building Energy Simulation Library J. Build. Perform. Simul. 11 (6) 669-688
[7] NBN EN 12831 Energy performance of buildings - Method for calculation of the design heat load: Part 1: Space heating load (2017), Part 3: Domestic hot water systems heat load and characterization of needs (2017)
[8] Baetens R and Saelens D 2016 Modelling uncertainty in district energy simulations by stochastic residential occupant behaviour J. Build. Perform. Simul. 9 (4) 431–447
[9] Orr G, Lelyveld T and Burton S 2009 In-situ monitoring of efficiencies of condensing boilers and use of secondary heating (Tech. rep., The Energy Saving Trust)
[10] NBN EN 12831 Heating systems in buildings - Method for calculation of system energy requirements and system efficiencies: Part 2: Space emission systems (heating and cooling) (2017), Part 2-1: Space heating emission systems (2007), Part 3-2 Domestic hot water systems, distribution (2007)
[11] Van der Veken J 2018 Overall efficiency of heating systems in relation to dwelling properties and inhabitant demands NEBPC Workshop Heating System Eiciencies
[12] IEA ETSAP 2012 Water heating (Tech. brief R03)
[13] Schweitzer J 2017 Facts and figures about domestic gas boilers: A compilation of results covering 25 years of testing at DGC’s laboratory (Proj. rep. Danish Gas Technology Centre)
[14] Wolff D, Teuber P, Budde J and Jagnow K 2004 Felduntersuchung: Betriebsverhalten von Heizungsanlagen mit Gas-Brennwertkesseln (Tech. rep., Deutsche Bundesstiftung Umwelt)
[15] Bennett G J 2019 The secret life of boilers: Dynamic performance of residential gas boiler heating systems - a modelling and empirical study (Doctoral thesis, UCL)
[16] Sinha R, Jensen B B, Pillai J R, Bojesen C and Møller-Jensen B 2017 Modelling of hot water storage tank for electric grid integration and demand response control Proc. of the 52nd International Universities Power Engineering Conf. (Heraklion, Greece)