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Methodology of building a water heater aggregated model for evaluating energy flexibility for domestic hot water

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SUMMARY

Domestic hot water (DHW), due to their connection to the thermal energy storage, can act as an effective tool to gain the flexibility-oriented power system services such as primary frequency control, voltage balancing or power call from the grid. Its flexibility brings balance and stability to the electrical system. Thus, it is important to have an aggregated model, which represents a large number of domestic hot water systems instead of repeating a unit model of only one system. The contribution of this paper consist in developing a methodology to construct an aggregated model representing domestic hot water demand, which is equivalent to a large amount of water heater units. The objective is to assess the energy flexibility. The water heater using an electric resistance element is investigated in order to test the methodology. First, a multi-layer stratified temperature model is built and is simulated. Secondly, the mentioned methodology to provide an aggregated model is developed. Then, the results obtained are presented and show the relevance of the aggregated model behavior for a large amount of hot water heater. These results provide a first building block for the development of an energy consumption flexibility model.

KEYWORDS

Domestic Hot Water, Energy Flexibility, Demand Response, Energy Model, Electric Water Heater.

1. Introduction

Thermostatically controlled loads such as domestic hot water heaters are considered a useful source of flexibility for the power system. Due to their correlation with energy storage, domestic hot water can act as an effective tool to gain the flexibility-oriented power system services such as primary frequency control, voltage balancing or power call from the grid. The energy used for heating the water accounts for 14.8% and 12.1% of the residential energy consumption in Europe and France, respectively [1], [2]. According to Electricité de France (EDF), there are more than 13 million electric water heater systems installed in France [3], with approximately 46.5 percent for the residential sector. Natural gas and oil-fired systems supply the rest. Domestic hot water demand can be considered as a flexible load since it can be turned off sometimes without sacrificing consumers' comfort.

There are various studies looking for the potential of electric water heaters in providing demand-side flexibility services [4]-[6]. A single residential household has only a negligible contribution to demand-side flexibility services, but a group of such tiny loads becomes a major energy consumption. This leads to a need for an aggregated model, which can represent a large number of domestic hot water systems instead of repeating the unitary model of only one system. Using an aggregated model allows evaluating and quantifying the flexibility for the aggregation of multiple water heater units by testing different control strategies on it. It helps to measure the impact of these control strategies on domestic hot water energy consumption and can be applied at different spatial scales, from a district to a city then to a region with less time-consuming and more efficient computation.

The contribution of this paper is to develop a methodology to construct such an aggregated model for domestic hot water demand, with the objective of evaluating the energy flexibility.

2. Water heater model

2.1. Electric water heater

Electric water heaters use electricity to operate. The cold water is injected through a dip tube at the bottom of the water tank and is heated by an electric heating element. Then the hot water is moved through the heat-out pipe at the top of the tank. Depending on the volume of the water tank, each electric water heater has a specific nominal power P_{EWH} , which is supplied to the heating elements.

2.2. Water tank model

In reality, the water temperature inside the tank is never uniform, which means that there exists a stratified phenomenon across it. This leads to the fact that the temperature of the coldest water displaces at the lower layers of the tank while the warmest water is at the higher layers. For this case, the multi-layer model is required to obtain the water temperature dynamics accurately inside the tank. The multi-layer model proposed in this paper considers the stratified water tank with N layers (Figure 1). There are several assumptions applied to it:

- A uniform temperature in each layer
- Thermal losses are defined for each layer
- All layers have the same thickness

The water temperature of each layer is calculated at any given time. According to Kizilers et al. [7], the position of the thermostat at the bottom of the water tank shows a better performance than other positions inside the tank. Hence, the water temperature at the

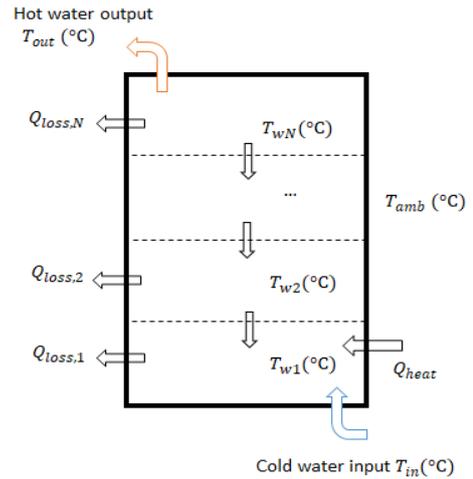


Figure 1: Multi-layer water tank model

bottom layer (layer 1) of the water tank is chosen to control the switching actions. They can be designed as follows:

If $T_{w,1} \leq T_{set} - T_{db}$ then turn on the water heater

If $T_{w,1} \geq T_{set}$ then turn off the water heater

If $T_{set} - T_{db} < T_{w,1} < T_{set}$ then do the same action as previous time step

With $T_{w,1}$ the water temperature at the bottom layer of the water tank. T_{set} the setting temperature of the thermostat. T_{db} the dead band temperature.

3. Unit model and aggregated model of the electric water heater

3.1. Unit model of electric water heaters

The unit model is built by repeating the simulation of the physical model of many water heater units, in order to obtain the energy consumption curve for domestic hot water. This energy consumption curve acts as a base to evaluate the methodology for the aggregated model. Hence, each water heater is simulated to get the domestic hot water's energy consumption profile for each household.

In this paper, we call the set of the simulations for each electric water heater using the physical model as an **unit model**, in order to distinguish it from the aggregated model using methodology, which is presented in the next part.

For the unit model, each water heater operates as described in figure 2.

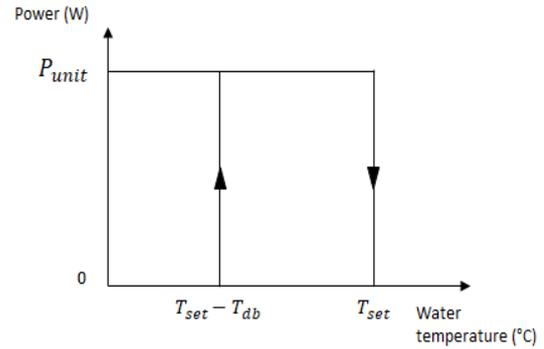


Figure 2: The relation between the power and the temperature of the water tank of the unit model

Each water heater has a specific thermal power P_{unit} which is supplied to the water tank to heat the water. If there is no water demand, the water temperature keeps raising until it meets the thermostat setting temperature T_{set} . At this moment, the thermostat controls the water heater to turn off. Due to the energy loss to environment or the demand of the hot water, the water temperature then decreases and if it falls down at a temperature lower than $T_{set} - T_{db}$, the thermostat once again controls the water heater to turn it on.

3.2. Aggregated model of the electric water heater

Amongst the difficulties faced in a large spatial scale such as a city, the availability of data is one of the most relevant. Normally, it is not easy to find the information regarding the city's characteristics to find out the electricity consumption for domestic hot water. In order to avoid such an issue and also save time, the methodology proposed in the next part helps to generate an aggregated model which is used to define the energy consumption of the hot water without the need of detailed data of each household.

Within this methodology, the requirements for this aggregated model are the average values regarding the water heater systems in the region considered including: the setting temperature T_{set} , the average power rating P_{avg} , average volume V_{avg} and average height H_{avg} of all water heater tanks in that region. The aggregated model of electric water heaters requires to have a number of households which are equipped with electric water heaters. With the methodology applied, instead of simulating each small water heater, a new big aggregated water heater, which is equivalent to numerous water heaters, is considered. This aggregated water heater is then characterized by several parameters as follows:

- The maximum power rating of this aggregated water heater equals the sum of all water heater units' maximum power rating.
- Its volume is equal to the sum of all water heater units' volume.
- Its height is given by taking the average of all water heater units' height.
- The insulation characteristics are identical to those of individuals.

The inputs of the aggregated model are the domestic hot water demand in time series and the water temperature of each layer inside the aggregated water tank. The output of the model is the power consumption used by the aggregated electric water heater for the number of households chosen and the water temperature of each layer, which is updated at each time step.

4. Methodology

4.1. Domestic hot water demand

The hot water profiles used in this paper are generated from a calculator named Load Profile Generator (LPG) [8]. This calculator is capable of synthesizing the hot water consumption of a household, by integrating the “psychological” dimension of its residents. LPG takes into account human behaviors, for example the time to cook, eat and sleep, time range for going to work... The main objective is to create different realistic scenarios for the users, based on their database providing to LPG.

By using LPG, we generate a database of domestic hot water demand profiles for 600 and 6000 households, which represent different spatial scales with an interval of 1 minute during 1 year.

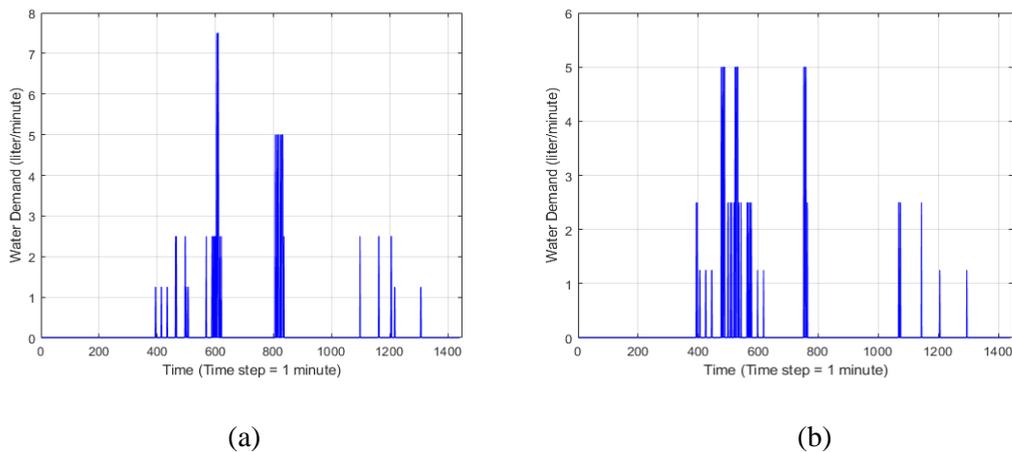


Figure 3: (a), (b) The water consumption data obtained from LPG in 1 day (1440 minutes) of 2 different households

The figure 3a and 3b show some examples for the domestic hot water consumption profile during 1 days (1440 minutes) of two different households, with an interval of 1 minute by using LPG.

4.2. Methodology for generating the aggregated water heater

First, the simulation of the unit model for 7 days (10080 minutes) with the time step of 1 minute is done for 6000 households. Each household is randomized with a particular type of electric water heater with a specific power rating, volume and height of the water tank, which are provided by a manufacturer. The setting temperature for thermostats is 60°C.

The unit model is simulated using two different laws of control.

- Case 1: Only thermostat regulates the switch of the water heater.
- Case 2: Using peak and off-peak hour signal in addition to the thermostat control.

For case 2, along with the thermostat control, at peak hours, all electric water heaters are turned off and are only turned on at off-peak hours. Within these simulations, each household then has its own energy consumption profile for domestic hot water. Hence, at each time step, a value of total power consumed and values of average water temperature inside the tank at each layer are obtained for 6000 households.

As mentioned in the section 2, the water temperature at the bottom layer (layer 1) of the water tank is chosen to control the switching actions. The figure 4 illustrates the relationship between the total power consumed and average water temperature at the bottom layers of 6000 electric water heater units at each time step

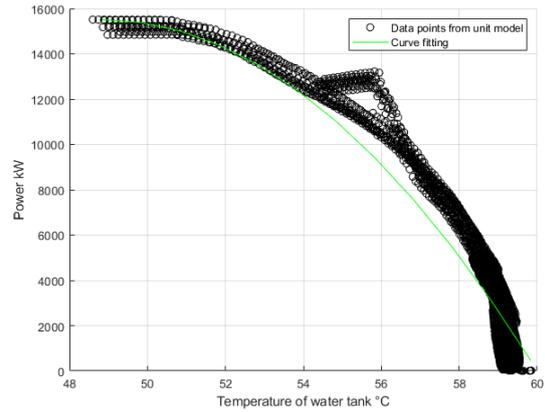


Figure 4: The relationship between the total power consumed (kW) and average water temperature at the bottom layer of 6000 houses in each time step

obtained from the simulation results of the unit model in 2 cases. It shows that the total power and average water temperature at bottom layer have a relation that follows a form of a quadratic equation. Based on this curve from the figure, the total power consumed never exceeds the summation of maximum power of all water heaters and the total power equals 0 if the average temperature is higher than or equal to the thermostat setting temperature. For others, total power consumed seems to have a quadratic relationship with average water temperature at the bottom layer.

Hence, the idea for generating the aggregated model is to define the relationship curve between total power consumed and average water temperature as a quadratic function with some additional constraints. This function is described by the curve in the figure 5, with the aggregated power P_{agg} is the sum of maximum power of all electric water heaters, the lower bound temperature T_{lb} and the higher bound temperature T_{hb} act as the constraints for the relation curve. It can be seen that the water temperature is set by thermostat setting temperature, hence, T_{hb} is defined as the setting temperature of the aggregated water tank. T_{lb} is the threshold where decides whether the total power consumed is equal to the aggregated power P_{agg} .

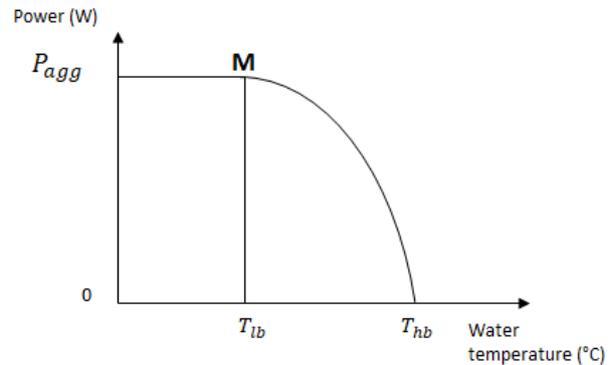


Figure 5: The relation curve between the power and the temperature of the water tank defined in the methodology for the aggregated model

From the simulation result of the unit model (Figure 4), we can always get a set of values for P_{agg} , T_{lb} and T_{hb} and now the question is how to calculate them with a shortage of the information concerning detailed characteristics of each electric water heater. One of the solutions is to calculate them from some parameters regarding the water heater systems in the region considered including: the temperature setting T_{set} , the average power rating P_{avg} , average volume V_{avg} of all water heater tanks in that region and the number of electric water heaters considered.

With that idea, P_{agg} is calculated by the average power rating P_{avg} (W) multiplies by the number of households considered (Nbhouse).

$$|P_{agg}| = P_{avg}Nbhouse$$

T_{hb} is defined by the temperature setting of the water tank T_{set} (°C).

$$|T_{hb}| = T_{set}$$

T_{lb} is given by the linear function of the average power rating P_{avg} (W), the average volume V_{avg} (m³) and temperature setting of the water tank T_{set} (°C).

$$|T_{lb}| = \text{function}(P_{avg}, V_{avg}, T_{set})$$

In order to find the coefficients for the function of T_{lb} , the simulations of the unit model for different numbers of households and different values of P_{avg} , V_{avg} and T_{set} are done so as to get the different values of T_{lb} . We investigate 10 cases corresponding to 60, 120, 240, 600, 1200, 1800, 2400, 3000, 6000 and another 6000 households. Values for P_{avg} and V_{avg} vary regarding the number of households. For each case, the value of T_{set} is varied from 55 to 64 °C with 10 values (Table 1).

Case	Number of households	P_{avg} (W)	V_{avg} (m ³)	T_{set} (°C)
1	60	2543	0.201	[55,64]
2	120	2087	0.161	[55,64]
3	240	2179	0.168	[55,64]
4	600	2161	0.168	[55,64]
5	1200	2104	0.162	[55,64]
6	1800	2109	0.162	[55,64]
7	2400	2099	0.161	[55,64]
8	3000	2106	0.162	[55,64]
9	6000	2110	0.163	[55,64]
10	6000	2500	0.25	[55,64]

Table 1: The values of P_{avg} and V_{avg} and T_{set} of different numbers of households

From the simulations of 10 cases along with the variation of T_{set} (10 values), 100 values of T_{lb} are obtained. A fitted linear regression model is used to identify the coefficients for the relationship between T_{lb} and (P_{avg} , V_{avg} , T_{set}). The figure 6 demonstrates 100 values of T_{lb} . The black line shows 100 values of T_{lb} obtained from simulations of the unit model while the red line represents the results obtained from a fitted linear regression model.

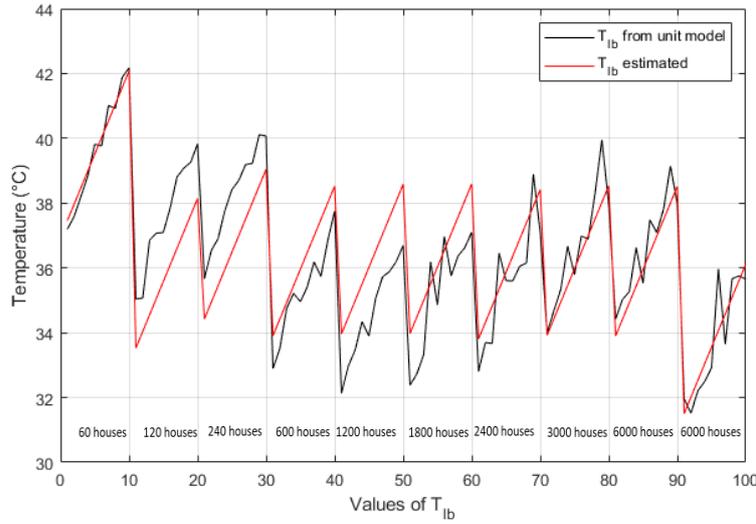


Figure 6: The value of T_{lb} when changing the value of P_{avg} , V_{avg} and T_{set}

Hence, the coefficients for P_{avg} , V_{avg} , T_{set} are found and the final equation of $|T_{lb}|$ is then shown as follow:

$$|T_{lb}| = -19.775 + 0.0362 P_{avg} - 313.4 V_{avg} + 0.513 T_{set}$$

Now, as described above, we can define P_{agg} , T_{lb} and T_{hb} from P_{avg} , V_{avg} and T_{set} . Besides, a hypothesis is made in order to determine the functions of the relation curve between the total power consumed and water temperature: The point M on the figure 5 is the maximum of the quadratic function, which represents the relation between the power and the temperature of the water tank (Figure 5).

To summarize, with P_{agg} , T_{lb} and T_{hb} defined and the point M as the maximum of the quadratic curve, the quadratic relation between the total power consumed and the average temperature for the aggregated water heater can be determined.

5. Simulation settings of the aggregated water heater model

5.1. Simulation process

The simulation of the aggregated model is done in MATLAB and has a one-minute sampling time. 7 days (with 10080 minutes) simulation is chosen. The inlet water temperature is set at 15°C and the ambient temperature is assumed to be 20°C. The temperature setting of the thermostat is 60°C. The water demand used for the aggregated model is the summation of all water demand profiles within the number of houses chosen (600 and 6000 houses).

5.2. Parameters

The parameters of the model chosen for simulation are shown as follows:

- The number of houses
- The average power rating P_{avg} of all water heaters (W)
- The average volume V_{avg} of all water heaters (m^3)
- The average height H_{avg} of all the water heaters (m)
- The temperature setting T_{set} for water tank (°C)
- The inlet water temperature T_{in} (°C)
- The ambient temperature T_{amb} (°C)
- Thermal transmittance coefficient U (W/m^2K)

- The conductivity coefficient of water k (W/mK)
- Heat capacity of water C_p (J/kgK)
- Water density μ ((kg/m³)
- The number of layers N

6. Simulation of aggregated model for electric water heater

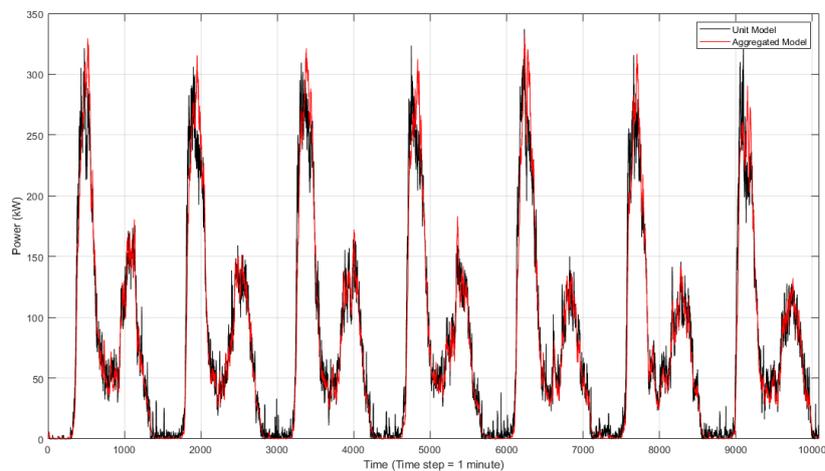
The simulation of the aggregated model is done for 7 days (10080 minutes) with the time step of 1 minute for different numbers of households (600 and 6000 houses).

As mentioned above, each household has its own type of electric water heater, parameters of the aggregated model are then determined including the average power rating P_{avg} , average volume V_{avg} and average height H_{avg} for different numbers of households. The value of thermostat setting point T_{set} is set at 60°C.

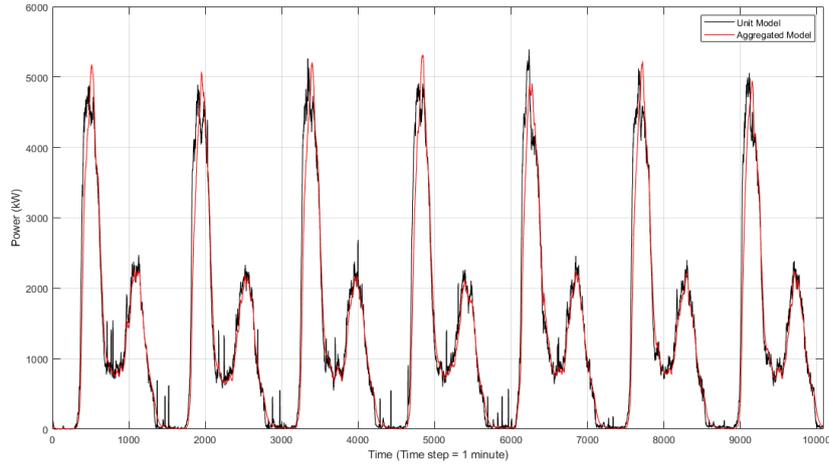
Number of households	600	6000
P_{avg} (W)	2258	2805
V_{avg} (liter)	153	250
H_{avg} (m)	1.18	1.61
T_{set} (°C)	60	60

Table 2: The values of the average power rating P_{avg} , average volume V_{avg} , average height H_{avg} and setting temperature T_{set} for 600 and 6000 households, respectively.

Table 2 describes the values of the average power rating P_{avg} , average volume V_{avg} , average height H_{avg} and setting temperature T_{set} for 600 and 6000 households, respectively. With the methodology applied, the aggregated model for electric water heater is built and the simulation result is presented in figure 7.



(a)



(b)

Figure 7: (a,b) The electrical power consumption for domestic hot water using the electric water heater multi-layer model in 7 days (kW). (a) and (b) represent the simulation for 600 and 6000 households, respectively.

In order to assess the methodology, a comparison of energy consumption between the result of the unit model and the aggregated model is necessary. Figure 7 illustrates the power consumption for domestic hot water of different numbers of households during seven days with the time interval of 1 minute. The black and red curves represent the energy usage generated by the unit model and the aggregated model, respectively. This figure shows that the methodology of generating an aggregated model is capable of describing the behavior of energy usage for domestic hot water of the unit model.

Model type	600 households (%)	6000 households (%)
Multi-layer aggregated model	2.96	3.29

Table 3: Normalized Root Mean Squared Error (r.m.s.e.) (%) of the aggregated model with multi-layer model, compared to the unit model for 600 and 6000 households, respectively.

Table 3 shows normalized r.m.s.e. of the aggregated model with multi-layer model (4 layers), compared to the unit model in different spatial scales (600 and 6000 households).

7. Conclusion

The methodology for generating the aggregated model for domestic hot water using electric water heaters is able to describe the behavior of energy usage for domestic hot water. The generated aggregated model allows to assess and to quantify the flexibility for the aggregation of multiple water heater units by testing different control strategies on it. It helps to measure the impact of these control strategies on domestic hot water energy consumption and can be applied at different spatial scales, from a district to a city then to a region with less time-consuming and more efficient computation. For our future research,

we plan to study how to minimize the error of the methodology for aggregated water heater models. Another research way could also be to find a method to build aggregated model but can optimize the user's comfort.

BIBLIOGRAPHY

- [1] Energy consumption in households by type of end-use (Eurostat, Europe, June 2021)
- [2] Agence de la transition écologique, “L’eau chaude sanitaire,” (ADEME, France, 2016).
- [3] Demand-side flexibility for power sector transformation (International Renewable Energy Agency, Abu Dhabi, 2019).
- [4] T. Peirelinck, C. Hermans, F. Spiessens, and G. Deconinck, “Domain Randomization for Demand Response of an Electric Water Heater” (IEEE Transactions on Smart Grid, vol. 12, no. 2, March 2021, pages 1370–1379).
- [5] A. Haider, W. Stark, and T. K. A. Brekken, “Electric Hot Water Heater Primary Frequency Control” (IEEE Energy Conversion Congress and Exposition (ECCE), September 2018, pages 2670–2675).
- [6] M. Pied, M. F. Anjos, and R. P. Malhamé, “A flexibility product for electric water heater aggregators on electricity markets” (Applied Energy, vol. 280, December 2020, pages 115-168)
- [7] C. Kizilors and D. Aydin, “Effect of thermostat position and its set-point temperature on the performance of a domestic electric water heater” (International Journal of Low-Carbon Technologies, vol. 15, no. 3, August 2020, pages 373–381).
- [8] Noah Pflugradt “Load Profile Generator” (<https://www.loadprofilegenerator.de/>).