UCLouvain

epl

École polytechnique de Louvain

Study of the flexibility potential of an aggregation of electric storage water heaters in order to participate in electricity or balancing markets

Author : **Louis Fichefet**
Supervisors : **Emmanuel De Jaeger**
Readers : **Francesco Contino**, **Cathy Crunelle**, **Matthijs Doclo**, **Hervé Jeanmart**
Academic year 2019–2020
Master [120] in Electro-mechanical Engineering

Table of Contents

1. Introduction

Global warming has become a very real problem and no longer needs to be proven. Faced with this urgency and in order to reduce the production of greenhouse gases, renewable energies have experienced considerable growth since the 2000s in Europe, with an increase of installed capacity of 150GW for the wind turbines and 100GW for solar photovoltaic panels (Eurostat, 2019). Indeed, the increase in decentralised electricity production by the advent of "prosumers" (i.e. electricity consumers and producers), attracted to become so by the reduction of their electricity bill, as well as the increase in the number of wind or photovoltaic farms, has meant that the share of renewable energy has become substantial in some countries.

However, the drawback is that renewable energies are subject to the local climate (sun, wind) and are therefore difficult to control because they are highly variable and difficult to predict. They are categorized as an inflexible power source. This inflexibility can be particularly stressful for the power grid. Indeed, at present, it is difficult to store large volumes of electricity efficiently. As a result, different electricity markets exist to ensure a constant balance between production and consumption. However, on particularly windy and sunny days, production can become much higher than consumption, with the result that electricity can have negative prices on the markets in order to force producers to stop production. These negative prices, which can be interpreted as a measure of network inflexibility, are becoming increasingly common. In 2019, a total of 211 hours of negative prices were recorded on the day-ahead market in Germany, an increase of 44% compared to 2017 (146 hours) (Epex Spot, 2020) (Amelang & Appunn, 2018). Faced with this increasing inflexibility, energy producers and consumers are seeking to create flexibility.

The domestic sector was long considered to be a variable and inflexible consumption because technology was limited, households were poorly equipped with electronic devices and the risk of impacting the consumer was high. However, the electrification of households as well as the rise of home automation and the emergence of "smart" technologies have removed this barrier. Since then, a great deal of research has been carried out on the potential flexibility of certain household appliances (Darby, Higginson, Topouzi, Goodhew, & Reiss, 2018) (Da Silva, 2011) (Fischer, Integrating Heat Pumps into smart grids, 2017) (Wong & Negnevitsky, 2013). Among the latter, electrical appliances are good candidates due to the high consumption of heat in households via space and water heating. In addition, these appliances are usually equipped with a heat storage system, making them the first choice for flexibility.

The purpose of this report is to identify devices that can potentially provide flexibility in terms of what can be offered in electricity markets and to try to quantify that flexibility. First, Section 2 will look at the different energy markets and their specificities. Then, the characteristics of space and water heating will be identified in Section 3. Section 4 will be devoted to a listing of the different appliances with potential flexibility to be offered and at the end of this section the electric storage water heater will be chosen.

Subsequently, in order to be able to quantify the flexibility of the chosen device, a synthetic aggregated consumption profile will be created in Section 5. The device itself and the physical phenomena applying to it will be modelled in Section 6. Section 7 will look at a method of controlling the synthetic pool with the objective of minimizing the potential discomfort that the user may experience. Sections 8 and 9 will be dedicated to the use of the synthetic pool to carry out a parametric study of two control cases, the baseload and the peaker case. Finally, in light of the results obtained, a strategy will be proposed to put this flexibility on the electricity markets.

2. The electricity markets

Electricity behaves like any consumer good and is traded on exchanges. However, unlike other products, electricity must be produced and consumed at the same time, since means of large scale storage are limited and expensive. This is why it is important to balance electricity production and consumption at any time. On this purpose, several markets, which all have their own timescale (see Figure 1), are available in Belgium (De Jaeger, 2018), (KULeuven Energy Institute, 2015):

1. The Forward and Future Markets, where bidders can make their bids up to several years before delivery day.
2. The Day-Ahead Market (DAM), where bids are concluded one day before the delivery day.
3. The Intra-Day market (IDM), where bidders can adapt their consumption and/or production to unpredictable events, like the weather for renewable energies or mechanical problems for turbines. The bids are concluded from the day before up to 5 minutes before delivery time.
4. Finally the Balancing Market, managed by the Transmission System Operator (TSO), exists to regulate imbalances that happen in real time and to help the TSO keeping the grid frequency around its nominal value.

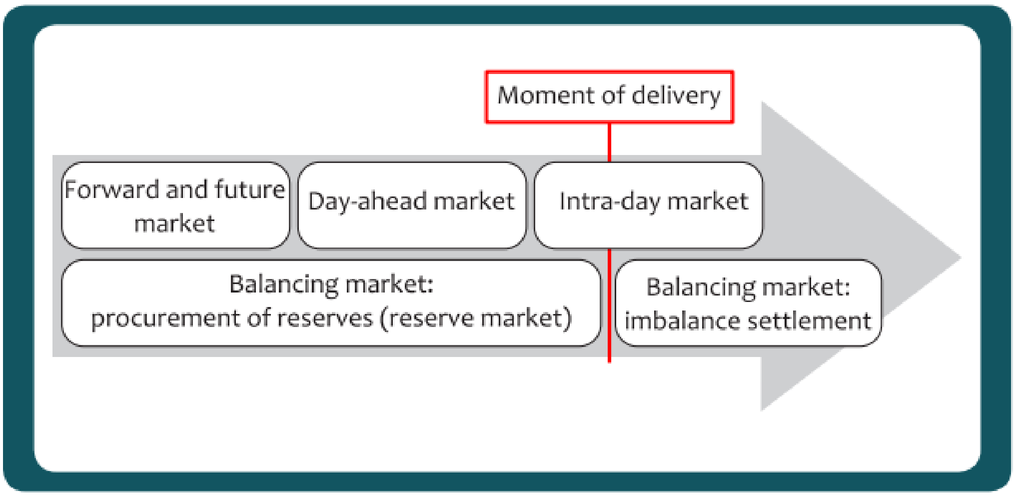


Figure 1 : Timeline of the different markets (KULeuven Energy Institute, 2015)

Bids on the different markets are made via web-based platforms. The EPEX Spot is the central platform on which bids for DAM and IDM from many European countries are made. Also, the TSO of each country has its own platform for balancing market. Finally, the EEX platform, similar to EPEX, is used for forward market.

All these markets participate directly or indirectly to the global balance of the grid. Precisely, bidders are allowed to sell or buy volumes (i.e. a quantity of electricity, generally in MWh) as long as they do not create imbalances. If it is the case, there will be a penalization for this behaviour. This penalization typically aims at recovering the costs of balancing the system and generally include incentives for the market to reduce imbalances as much as possible.

The TSO (which is Elia in Belgium) has a central role concerning the grid; it ensures that the grid (the high voltage – 150+kV – infrastructure, the quantity of energy circulating on the grid, the balance between production and consumption, etc.) remains functional and that the frequency stays stable around its nominal value of 50Hz. As a consequence, every player on any market has first to be authorized by the TSO to be a Balancing Responsible Party (BRP, also called Access

Responsible Party in Belgium) by establishing a contract with the TSO. The conditions included in the contract are for example the obligation to prove financial solvency to the TSO throughout the duration of his contract and to be equipped with an equipment able to measure the volume of electricity sent and/or received. Among these conditions, the most important one is the financial responsibility for their imbalances. Precisely, if the BRP does not comply with the volume initially contracted on any market, he must pay back the TSO a compensation for the imbalance he created on the grid. This will be seen in Section 2.5.

A BRP can take many forms: large producers or consumers (Electrabel, Coo power plant) are their own BRP, while for small end-consumers, the suppliers (Luminus, Electrabel, etc.) take the BRP responsibilities. Traders may also be BRPs.

2.1. Forward and Future Markets

The forward and future markets are made to conclude contracts for the consumption or production of energy years before the day of delivery, at a price fixed when the contract is signed. The difference between the two markets is that for the future market, the contracts are standardized and anonymous, whereas the forward market is made up of non-standardized bilateral contracts known as "over-the-counter" (i.e. the settlement of the contract is made between the two parties) and not via a central regulated platform. The forward market therefore offers additional flexibility in terms of the price or conditions that accompany the contract, whereas the future market offers a certain degree of security via standardised contracts (De Jaeger, 2018) (KULeuven Energy Institute, 2015).

Electricity producers who sell their energy volumes on the forward and future markets do so to ensure their future sales and to reduce their vulnerability to a potentially lower market price. A good example of these producers are nuclear power plants which are particularly non-flexible due to the core of the reactor and must therefore maintain their production. Conversely, large consumers could use this market to purchase their electricity at a price known today, protected from significant increases in the future (KULeuven Energy Institute, 2015).

In 2017, the total volume traded in forward and future markets was equivalent to 67% of the Belgian grid load (De Jaeger, 2018). Moreover in 2014, the traded volumes in future market represented only 0.05% of the Belgian grid load (European Commission, Frontier Economic, 2019). This means that more than the half of Belgian yearly electricity consumption is traded over-the-counter.

2.2. Day-ahead market

The Day-Ahead Market (DAM) takes place from 45 days before delivery day D until 12:00 am at D-1. Transactions are made on the EPEX SPOT platform wherein it is possible to make bids and trade electricity with other bidders in Belgium or even in UK, France, Germany, etc. The electricity is traded by a double-sided auction, allowing producers, consumers and distributors to submit their bids anonymously (EPEX spot, 2020), (De Jaeger, 2018). In 2017, the total volume traded in Belgian DAM was 17.9 TWh, representing 23.1% of the Belgian grid load (CREG, 2018).

Once the market closed, an algorithm will clear the price according to the merit order. This is called the clearing price principle. Afterwards, the 24 clearing prices (for the 24 hours of the next day) are published by EPEX SPOT. The clearing price principle is an economic principle consisting of sorting offers according to their increasing price (called the merit order curve), and requests according to their decreasing price. The price is then decided as the intersection of the two curves, and allows the maximization of the surplus. An example is illustrated in Figure 2.

This market is in principle quite regular in terms of the clearing price, and liquidity of the market due to high number of players makes it reliable. However, the increasing presence of renewable energies and their low marginal cost is disrupting stability in this market, especially when the weather is particularly sunny and windy, leading to negative prices – you get paid for your consumption. These phenomena are, more and more common, particularly in countries where the renewable energies are developed, like in Germany.

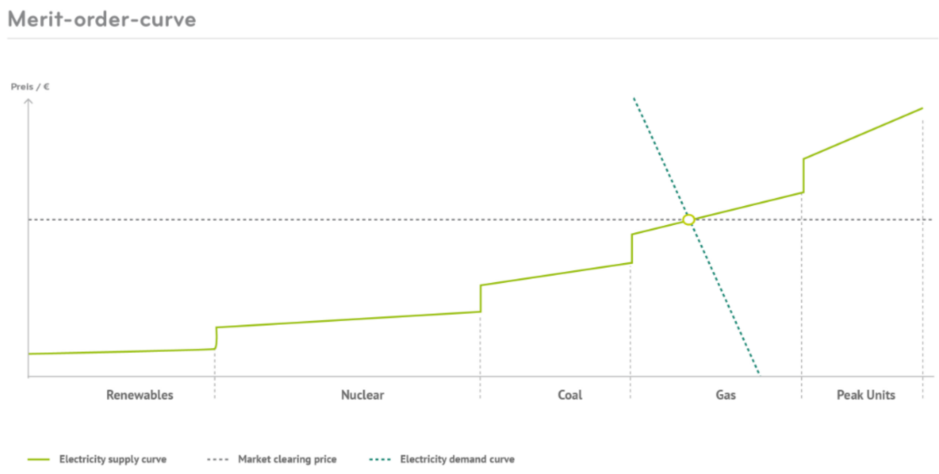


Figure 2 : Merit order curve and clearing price illustrated source: Next Kraftwerke

2.3. Intra-Day Market

The Intra-Day market is used to trade electricity on the day of delivery. This allow players to take into account recent forecasts or big events, and correct their production/consumption in order to control their potential imbalances (see Section 2.5). This market is much more flexible, as it is possible to bid for windows of hours or quarter hours. Trading closes either 60 min before delivery on the XBID platform, or 5 min before delivery on the LTS platform. The major difference between XBID and LTS is that XBID was the first platform resulting on the desire to create a joint integrated cross-border market. LTS was created after, and is linked to national market, thus dealing only with national bids.

As opposed to the DAM, there are as many prices for one market time unit as trades. Thus there will be multiple prices for each market time unit and no overall clearing price. This is a "first come first served" (or Paid-as-bid) process. At the closure of each quarter hour, the bidders are nominated. Due to the nature of this market, volumes traded are mainly small. In 2017, the volume traded on the IDM was 2 TWh, representing 2.6% of the Belgian grid load (CREG, 2018). However, regarding the prices, they can sometimes strongly differ from the DAM, especially when producers or consumers have to react rapidly to a sudden change of consumption/production, like sudden changes of the weather or technical problem. Figure 3 shows the hourly difference between the intraday and the day-ahead prices in 2017. Finally, a summary of the DAM and IDM characteristics is available in Table 1.

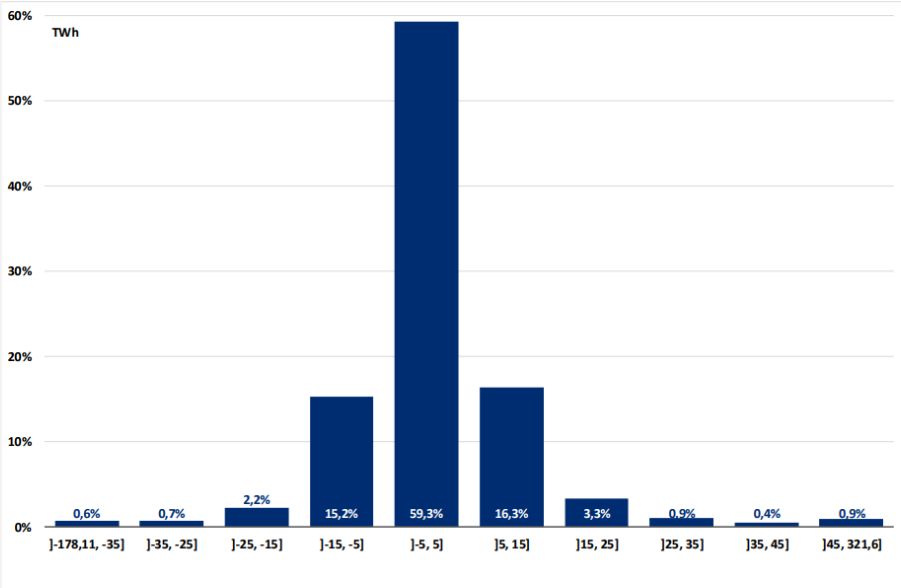


Figure 3 : Hourly difference between the day-ahead and intra-day prices (CREG, 2018)

Table 1 : Summary of characteristics of the Day-Ahead and Intra-Day markets

Specifications	**DAM**	**IDM**
Trading contracts	1h blocks	1h or 15 min blocks
Trading window	45 days before delivery until 12:00 am day ahead of the delivery	Opens at 15:00. Trades close 60min before Delivery (XBID) or 5min before Delivery (LTS)
Block bounds	Max. 40 block orders per delivery day per BRP	None
Volume bounds	[1, 400[MWh for a single block	[1, ∞[MWh
Volume accuracy	0.1 MWh	0.1 MWh
Fixing process	Clearing price	Paid-as-bid
Price bounds	[-500, 3000] €/MWh	[-9999.90 , 9999.90] €/MWh
Gate closure time : Elia nomination	14:00 pm day-ahead	Continuous
Average price (2017)	44.6 €/MWh	45.73 €/MWh
Volume traded (2017)	17.9 TWh	2 TWh

2.4. Strategic Reserve Market (SRM)

The Strategic Reserve Market is a specifically Belgian market that operates from 1st November to 31 March included. The goal of the SR is to cover eventual shortage in generation during winter period. This market is entirely under the governance of the TSO who has to organise, manage and, if needed, activate the reserve.

The nomination is made directly by the TSO. Players publish on D-1 their bid which contains, depending if it is a Strategic Demand or Generation Reserve, several prices like cold/warm start [€/activation], reservation of the power contracted [€/MW/h], power contracted [€/MW] and so on. The TSO nominates the bidders on D-1 and a clearing price is made. The nominated become thus the daily strategic reserve. Due to its seasonality, this market will not be considered in this work.

2.5. Imbalance settlement

The TSO has to maintain the balance in its control area. Hence, the TSO verifies the balance of any BRP, defined by the difference between all its injections (generation or buy-orders) and its offtakes (consumption or sell-orders). This balance is checked twice:

- Right after Day-Ahead nomination, to ensure that each BRP is balanced.
- After the delivery time, based on measurements.

The imbalance is determined on quarter-hourly basis. Depending on the NRV (Net Regulation Volume, the power activated by TSO to restore balance), and the nature of the imbalance (surplus or shortage), 4 cases may occur. They are summarized in Figure 4.

		Elia Net Regulation Volume (NRV)	
		Negative (production surplus)	Positive (production shortage)
BRP imbalance	Positive (production surplus)	$\text{MDP} - \alpha_1$	$\text{MIP} - \beta_1$
	Negative (production shortage)	$\text{MDP} + \beta_2$	$\text{MIP} + \alpha_2$

Figure 4 : Different cases of imbalance (De Jaeger, 2018)

Coefficients β are both null, and coefficients α are non-zero if the value of the imbalance is greater than 140 MW. MIP and MDP can be seen respectively as the highest price paid by the TSO for an upward regulation and the lowest price receive for a downward regulation. The 2 cases with coefficient β are the one where it is possible to earn money from an imbalance. However, the potential gains from this method are much lower than the possible fees, in order to oblige BRPs to respect their initially bid volumes.

2.6. Balancing market

Even if market participants are forced to pay a monetary penalty for their imbalances, these kind of events happen each and every day. As the TSO is responsible for the stability of the national grid, it must build up reserves to compensate for these imbalances. These reserves have different characteristics and different purposes (Elia, 2017):

- The Frequency Containment Reserve (FCR or R1) is a reserve that will automatically and very quickly (within seconds) react to small variations of the frequency, in order to limit the drop/rise of the latter.
- The automatic Frequency Restoration Reserve (aFRR or R2) will then, within minutes, be activated in order to take the frequency back to its nominal value.

- Finally, if the problem persists through time or if it is too significant, the manual Frequency Restoration Reserve (mFRR or R3) will then be activated to free the load initially supported by the aFRR.

As example, Figure 5 shows the imbalance of May 30th 2020 between 15:20 and 16:20 pm. This was a particularly sunny and windy day and thus an overproduction came from renewable energies. The resulting system imbalance (SI) was therefore almost 400 MW higher than expected (the expectation was the sum of volumes traded in DAM, IDM, future and forward markets). The aFRR is then activated by Elia to counterbalance. However, as the SI was too high and too long to be maintained by the aFRR, Elia activated a certain volume of mFRR in order to release the counterbalance maintained by aFRR. The sum of aFRR and mFRR volumes is called the net regulation volume (NRV). When $NRV = -SI$, the system is balanced.

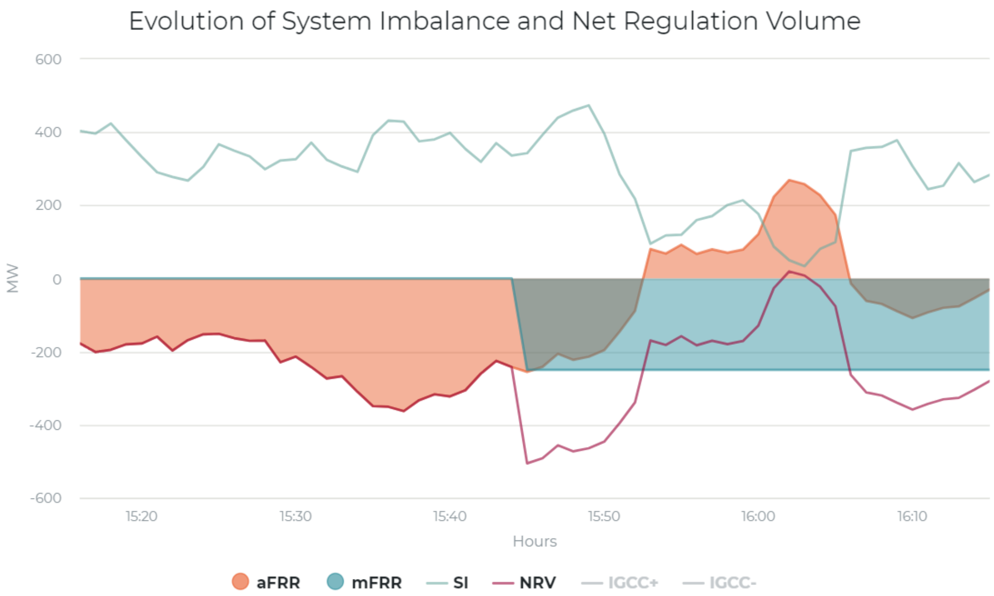


Figure 5 : Real-time system imbalance, available on Elia's website

These reserves do not directly belong to the TSO. In facts, there are established through another market organised by the TSO, wherein bidders called Balancing Service Providers (BSP) can propose their services.

2.6.1. Frequency Containment Reserve

This reserve (also called primary reserve) is in the frontline and acts first when an imbalance occurs; when there is a sudden drop (or rise) of power the frequency deviates from its nominal value, which may lead to instability or worse to a blackout if the drop is large and long enough. To ensure the stability, this reserve has to counterbalance the effect by increasing (resp. decreasing) its load within 30 seconds. The TSO therefore uses multiple BSP whose offer this kind of service to ensure the grid stability. In 2017, Elia contracted 68 MW for R1 (Elia, 2017).

The BSP must however meet certain criteria in order to be able to offer its services to Elia (Elia, 2017):

- The BSP must have some equipment or an industrial process to be able to detect frequency variations in the grid and to react by activating the primary reserve;
- The system must be able to read the frequency locally;
- Half of the contractual of the primary reserve must be activated within 15 seconds; the whole primary reserve must be activated within 30 seconds and must be able to stay activated for at least 15 minutes.

If these conditions are fulfilled, the BSP is a potential candidate. In order to become an eligible candidate, the BSP must pass several tests (a communication test and a series of real-time test) to prove its reliability to the TSO. Once these tests approved by the TSO, the BSP may bid on the TSO's market. The different offers that a BSP can make to the TSO are summarized in Figure 6 (Elia, 2017):

- R1 Sym 200 mHz: The BSP agrees either to increase its consumption (or reduce its injection) or to reduce its consumption (or increase its injection) in the event of a change in frequency in one direction or the other. Elia will expect the BSP to react in proportion to the deviation within a frequency range of 200 mHz.
- R1 Sym 100 mHz: This is the same as the previous offer, but the BSP do not have to react proportionally to the frequency above 100 mHz deviation.
- R1 Up: The BSP agrees to reduce its consumption (or increase its injection) if the frequency falls below 49.9 Hz.
- R1 Down: The BSP agrees to increase its consumption (or reduce its injection) if the frequency rises above 50.1 Hz.

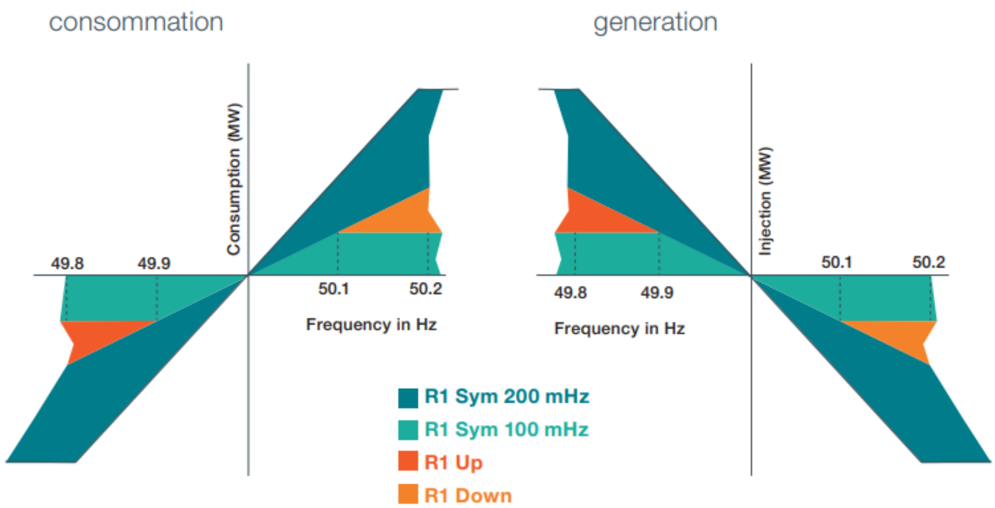


Figure 6 : The 4 different types of offers available on the R1 balancing market [ELIA ANCI SERVICES]

Concerning the bids, as of 1st July 2020, BSPs may offer services for blocks of 4h, independent to each other (0-4h, 4-8h, …, 20-24h) (Elia, 2020). The market follows the clearing price principle.

2.6.2. automatic Frequency Restoration Reserve

This reserve is placed on the second line for the imbalance regulation. Its particularity is that Elia has a total control on this reserve: the TSO sends each 8 seconds a signal saying whether it has to be activated or not, as well as a setpoint that the reserve must reach. In 2017, 144 MW were contracted by Elia (Elia, 2017).

Some conditions are needed for a BSP to be eligible on the R2 market. The BSP must:

- Present a CIPU (Contracts for the Injection of Production Units, in other words actors which produce electricity) symmetrical unit;
- Be able to activate the upward or downward volume requested by the TSO within 7.5 minutes;
- Be able to maintain bilateral communication with Elia.

If these conditions are fulfilled, the BSP must pass a communication test and a real-time test, like for FCR eligibility, in order to enter the R2 market. The major constrain relative to this market is the obligation to present a CIPU. This means that non-CIPU (like aggregators) cannot enter the market. However, Elia is going to open the market to non-CIPU units between 1st July and 1st October 2020 (Elia, 2020). In fact, new regulations will accompany these changes to make R2 market look like R1 market. Thus, bids may be symmetrical or asymmetrical (i.e. doing R2 sym, down or up like R1), and bids are made of 4 hours blocks. As for the remuneration, the BSP is paid for the volume reserved (if it has been nominated by Elia) and for the total volume that has been activated during the 4h period (Elia, 2020).

2.6.3. manually Frequency Restoration Reserve

Finally, if the product of R1 and R2 still cannot counterbalance the current imbalance, the tertiary reserve may be activated by Elia. This latter, as opposition to R2, is activated manually, meaning that Elia has to send beforehand a message to the BSP asking if the latter is ready to activate its reserve. If it is the case, the BSP must fully activate it within a maximum of 15 minutes. In 2017, Elia contracted in average 780 MW for the tertiary reserve (Elia, 2017).

There are 3 types of products (Elia, 2017), (Elia, 2020):

- R3 Reserved Standard: This is a reservation product. During the length of the contract, the TSO may activate this reserve an unlimited amount of time for a maximum of 8h per day. During the reservation, the reserve must be completely available for Elia.
- R3 Reserved Flex: This is also a reservation product. The number of activation is also unlimited but with a maximum time duration of 4 hours and with a period of neutralization (inactivity) of 8h minimum between each activation.
- R3 Non-Reserved: This can be seen as a "unique" bid with the duration, the price and the time of availability set by the bidder.

The R3 Standard is generally prioritized. In fact, the TSO nominates approximately half of its future R3 reserve with standard products. The rest may be either of the 3 types of products as they are nominated based on the merit order (Elia, 2020). Regarding the remuneration, the BSP is remunerated for 2 different things:

- On one hand, the BSP get paid for the fact that it has been nominated by Elia, following the "paid-as-bid" principle (so they get paid the price they initially set). The remuneration is therefore function of the volume bid, the price set and the number of hours they are nominated.
    - The R3 non-reserved makes however an exception: the BSP receive a fee for its activation, and not for the reservation. This fee is not the same as the fee described right below.
- On the other hand, in the case where the volume bid by the BSP is activated, it get remunerated for the volume activated and the activation duration following a clearing price (i.e. the price is defined as the highest price of the pool of BSP that activated their products on the TSO request).

Naturally, in order to enter the R3 market, the BSP also has to do beforehand real-time tests proving its reliability to the TSO. These tests vary whether the BSP wants to bid his product as a standard, flex or non-reserved one.

An important remark is that, for now, even if it is possible for aggregators to bid in R3 markets, the DSOs refuse potential bidders unless they are connected to the high voltage of the DSO grid (>1kV) (Synergrid, 2017). Therefore, the market is currently unavailable for aggregation of domestic devices.

2.7. Summary and mid-term horizon

To summarize up, balancing market offers a lot of possibilities and ways to bid. Summary of R1, R2 and R3 market's characteristics is shown in Table 2. Generally speaking, the balancing market is becoming more and more open to flexibility and therefore to aggregators. At present, only R1 service is open to aggregators, but it is quite possible that R2 will also open at the same time as the new regulation is adopted. As for R3, there is no indication that DSOs will allow the possibility of aggregating at low voltage, but there is every reason to believe that Elia is pushing in this direction.

Table 2 : Summary of the three main reserves of the balancing market

Specification	**R1**	**R2**	**R3**
Type of products	- Sym 200 - Sym 100 - Up - Down	- Down - Up - Down & Up	- Standard - Flex - Non-reserved
Minimum bid (MW)	1	1	1
Bid accuracy (MW)	1	1	1
Contract duration	4h blocks (July 2020)	4h blocks (July-October 2020)	From 15 min to 4h blocks
Remuneration	For reservation and for volume activated	For reservation and for the volume activated (July-October 2020)	For reservation and for volume activated (except for non-reserved bids)
Remuneration type	Clearing price	Paid-as-bid	Paid-as-bid for reservation, clearing price for activation
Open for low voltage aggregators	Yes	Work In Progress[1]	No
Price range[2]	[5 - 20] €/MW/h	[5 - 15] €/MW/h	[1 - 10] €/MW/h
Volume contracted in 2017 (MW)	68	144	780

To finish this chapter, it would be interesting to look at Elia's medium-term plans. Indeed, several projects are now in discussion and summarized in Figure 7. Here is a non-exhaustive list:

- Changes on mFRR (R3) market: Expected in 2021-2022, a standardization of the reserved capacity should appear, meaning that R3 Standard Flex will be merged into a new type of product.
- Voltage & Reactive power control ("MVAr service"): Nowadays it's an obligation for new connections to the grid to ensure being within standardized bounds to not deregulate the voltage quality. In the future there should be less regulation, and a new market to bid reactive power injection/absorption could make its appearance.

[1] *Synergrid is currently working on the regulations. See C08/06 and C08/07 on their website: http://www.synergrid.be/index.cfm?PageID=16832#*
[2] *This is a rough estimation based on recent contracted volumes to only give an idea of the prices.*

- The internet of Energy (IO.Energy): The project’s purpose is to develop new services by exchanging data between all energy market players. The focus is made on end users, who will be able to tailor their generation and consumption by using a digital platform. This could lead to a whole new market. The kick-off of this project was in March 2019.
- PICASSO project: The Platform for International Coordination of Automated frequency Stable System Operation is a European project aiming to create a platform for international management of R2 market. This platform will allow the exchange of aFRR balancing energy between participating TSOs. PICASSO will improve the efficiency of the European balancing system and benefit both TSOs and BSPs. On the one hand, TSOs will have access to competitive aFRR balancing energy offers from other countries. On the other hand, BSPs will be able to sell their aFRR balancing energy to all participating TSOs.
- MARI project: The Manually Activated Reserve Initiative project is another European project aiming for a common European platform for R3. Roughly speaking, it has the same purpose as the PICASSO platform, but for R3.

As the reader can see, the balancing market is in perpetual evolution. Therefore, the reader should be careful regarding the content of this chapter: it may well be completely out of date in a few years' time. For this reason, the interested reader is advised to continue to consult the Elia website, where the information is available and public.

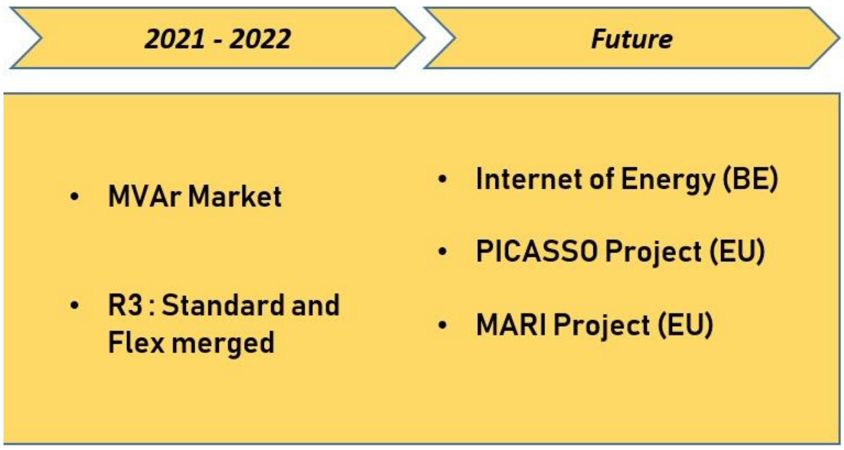


Figure 7 : Overview of the future of balancing market

3. Space and water heating characteristics

Heating is an important part of the energy consumption in the residential sector. According to a European study (Eurostat, 2017) on the energy consumption, the residential sector represents 27.2% of the final energy consumption in Europe. For Belgium, the repartition of the consumption is shown on Figure 8. Space heating represents the great majority of the energy consumption (74%) in front of lighting and appliances (13%) and water heating (11%). It is also interesting to notice that, in Belgium, the consumption related to the cooling demand is negligible (0.1%) and won't be further investigated.

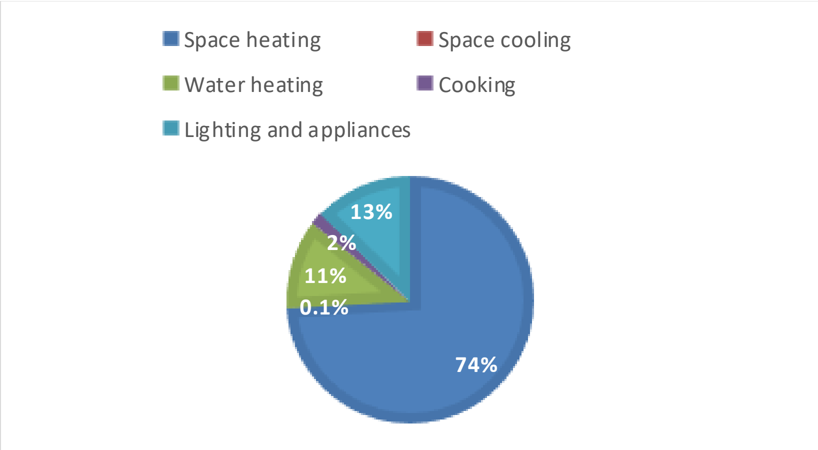


Figure 8 : Share of final energy consumption in the residential sector by type of end-use in Belgium (Eurostat, 2017)

The question is to know how this demand is fulfilled. The Figure 9 based on the results given by Eurostat (Eurostat, 2017) shows the repartition of the space and water heating energy demand between the different sources in Belgium – the denomination "derived heat" stands for the heat generated on the purpose to distribute it directly like a Combining Heat and Power (CHP) power plant or by a heat only natural gas power plant. The natural gas dominates largely, with more than 45% for both space and water heating. The main reasons are that Belgium is well connected to gas and that the price of the natural gas for the end user is less expensive than any other fuel. From (EHPA, 2018), the price of the natural gas in 2018 was €0.06/kWh, which is less compared to oil (€0.09/kWh) or compared to electricity (€0.27/kWh). The high price of electricity explains why it is not preferably used for space heating (3%). Still, electric space and water heating share the same overall consumption, with 2.2% and 2.0% respectively.

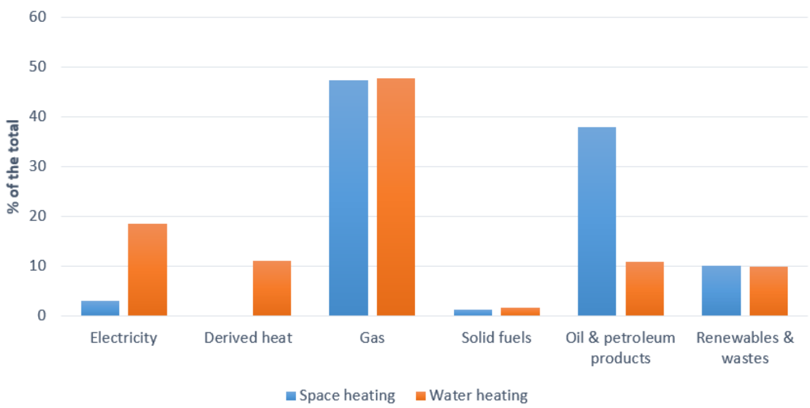


Figure 9 : Share of fuels in the final energy consumption in the residential sector in Belgium (Eurostat, 2017)

Since the focus is on electricity and balancing markets, only the devices that are running on electricity will be considered. In order to be able to estimate the flexibility potential of space heating and water heating, it is necessary to go beyond the first estimations, deeper into the analysis. The purpose of this chapter is to try to define as well as possible the most influential parameters for space heating and water heating in order to see the constraints and limits of these two fields.

3.1. Space heating

The space heating represents the fact to rise the air temperature of one or several rooms in a dwelling by injecting energy under the form of heat. Commonly, the air is sucked through a device by natural or forced convection. Into this device, the air is heated up either directly by the heating device or indirectly by a heating fluid. The heating fluid is usually water, due to its remarkable heat capacity, its non-dangerousness and its cheap cost but one may also find other fluids like oil or synthetic heating fluid.

The use of water as heating fluid is the most common way of space heating in Belgium and can take several forms: the water can pass through radiators which can be designed for hot temperatures (inlet 90°C / outlet 70°C), medium temperatures (inlet 70°C / outlet 50°C) or through a heating floor which can accept low temperatures (inlet 45°C / outlet 35°C). As the installation has a non-negligible cost due to the pipes and the need to seal the connections, these systems are always centralized, meaning that there is only one heating device which provides the heat for the whole dwelling.

On the other hand, the air may be directly heated by the heating device. The latter is often a resistance which heat the air up thanks to Joule effect. As there is no heating fluid to transport the heat generated, these types of system are commonly low-cost and decentralized, meaning that each heating device is used to heat up one room only.

In any case, at some point, the room air is receiving energy from either the heating device or the heating fluid. A simple way to estimate it is to look only the energy Q transferred from the device (or the heating fluid) to the air. This can be translated into the following energy balance equation:

$$Q_{heat} = m_{air} C_{p,air} \Delta T_{air}$$

Here Q may have different mathematical definitions whether the heat comes from the heating device itself or from the heating fluid. This equation looks only to simple thermodynamics, it does not take into account more complex effects linked for example to fluid mechanics. In fact, it can be compared to put the entire room (or dwelling) into a box and look its energy gained from the heating device like in Figure 10. But the heating device is not the only one which plays a role in the room temperature. It is possible to split it into several main factors:

- The heat provided by heating device(s) Q_{heat};
- The heat provided directly by the sunrays Q_{solar};
- The heat coming from occupants Q_{occ};
- The heat resulting from the use of electric devices (computer, lighting, cooking plates etc.) Q_{misc};
- Finally, the heat lost through the walls, roof, floor and ventilation Q_{loss}.

With these factors, if we assume that the room/dwelling temperature has to be maintained at a constant temperature, the result is the following balance equation:

$$Q_{heat} + Q_{loss} + Q_{solar} + Q_{occ} + Q_{misc} = 0$$

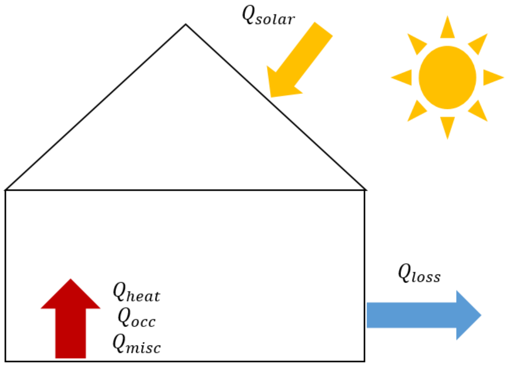


Figure 10 : A very simple way to estimate space heating

All these terms are greater or equal to 0 by nature, except for Q_{loss} which is less than 0. However, the situation is more complex. Actually, there are a lot of parameters that will affect these factors. Among these, one may cite:

- The outside temperature and more generally, the local climate;
- The isolation quality of the different parts of the dwelling;
- The total surface and net heated surface of the dwelling;
- The occupancy rate;
- The glazed surface exposed to the sun as well as their orientation;
- The nature of the ventilation system (mechanical, natural);
- The level of comfort required by the consumer.

These may affect more or less the total consumption. A study has been made in a district of Antwerp (Oregi, Prieto, Hermoso, & Izkara, 2018) where they analyzed the sensitivity of some of these parameters regarding space heating consumption. This is based on the "influence coefficient (IC) which represents the variation of the output (OP) due to a small perturbation at the input (IP), referred to a certain baseline (Westphal & Roberto, 2005) :

$$IC = \frac{\Delta OP/OP_{baseline}}{\Delta IP/IP_{baseline}}$$

With the output being the consumption related to space heating, the IC shows the sensitivity of energy consumption with certain factors. Oregi *et al.* tried to estimate the sensitivity of certain parameters based on a model created with data from dwellings in Antwerp by varying inputs of +-15%. These are some of the studied parameters:

- <u>The base temperature</u> (IC = 1.8). The base temperature of a building is the outside air temperature below which the building needs to heat (BizEE, n.d.). It is a convention that may vary from country to country and from one to another usually within a range of 15-20°C.
- <u>The solar gains</u> (IC = 0.14).
- <u>The internal gains</u> (IC = 0.11).
- <u>The conduction transfer coefficient (U-value)</u> (IC = 0.84) is a very useful coefficient that quantifies the heat flux going through a surface, expressed in [W/m²/K]. This coefficient is used to characterize the heat loss through walls, roof and ceiling.

What this sensitivity analysis underlines is the importance of the base temperature and the U-value, which are the two most influencing parameters. Neither the solar gains nor the internal gains seem to have a significant influence over the consumption. However, these should not be neglected. Elsand *et al.* (Elsland, Peksen, & Wietschel, 2014) estimated the averaged internal gains from a more dynamic point of view for each EU-27 country, based on data collected in 2008. The results showed that these gains are usually underestimated and may differ in a range from 20-

50%. Also, households get more and more electric devices, which will emphasis this underestimation.

From this sensitivity analysis, we see that the base temperature (and thus the outside temperature) and the U-value are two crucial parameters. In other words, the heating consumption will be strongly affected by the weather and the building's isolation. The occupancy and internal gains may be considered constant as a first approximation, and will lower the consumption with a fixed amount. For the solar gains, it is expected that it reaches its maximum in June-July and its minimum in January-February.

So how do the space heating needs evolve throughout the year? Zangheri *et al.* (Zangheri, Armani, Pietrobon, & Pagliano, 2014) studied this question in different cities of the European Union. From reference buildings with fixed geometry, they fitted parameters like the U-values or the construction materials regarding the country's standards. Also, they applied the local climate of the city inder study to the building model. Figure 11 show the results for a single house located in Paris. The x-axis is on an hourly basis while the y-axis shows the hourly heating needs in [Wh/m²] (with a base temperature of 20°C). We see that the heating needs are substantial between October and April – called "the heating season" - with in average a heating need of 176 kWh/m² over the year for a single house in the local climate of Paris. On the contrary, during the summer, there is almost no heating needs.

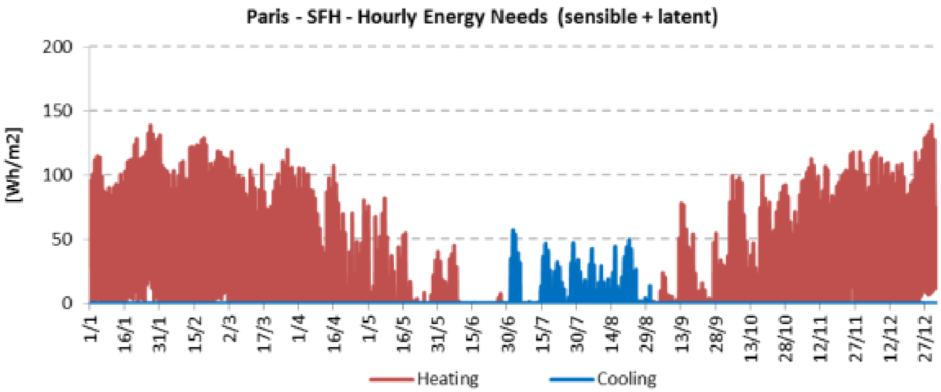


Figure 11 : Heating and cooling needs of a single house in Paris, on an hourly basis (Zangheri, Armani, Pietrobon, & Pagliano, 2014)

Occupants also play a role in the consumption. Guerra Satin *et al.* (Guerra Santin, Itard, & Visscher, 2009) have studied the effects of occupancy and building characteristics on space heating based on data of 2800 households in the Netherlands. They showed that building characteristics such as the insulation level, the presence of a garage/basement/thermostat etc. determine a large part of the energy used in a dwelling (42%), but occupants characteristics and behaviour also have a significant impact (4.2%) which might be greater, according to the authors, depending on the size of the dwelling or the household income. Another longitudinal study (6 years) made by van den Brom *et al.* (van den Brom, Hansen, Gram-Hanssen, Meijer, & Visscher, 2019) looked at two pools (around 900 000 houses) of housing, one in the Netherlands and another in Denmark. The study showed that approximately 50% of the variation in residential can be attributed to differences between buildings and the other 50% to differences in occupant behaviour. These variations relative to occupant behaviour may play against aggregation because it may introduce inaccuracies regarding a consumption forecast. Moreover, differences between buildings may worsen this forecasting.

To summarize, space heating is an important part of the residential consumption, and the latter can play a positive role in aggregation, since there is more energy at stake and thus more flexibility potential. However, the seasonality of space heating forbid aggregation in summer, and space cooling is negligible in Belgium. Moreover, the variability of the space heating need is function of the building's characteristic and occupants' behaviour. This introduces uncertainties in the consumption and makes consumption forecasting harder, which may be risky regarding electricity markets (imbalances).

3.2. Domestic hot water

The term domestic water is defines the supply water used in the dwelling: tap (kitchen, bathroom & others), shower, bath, washing machine and dishwasher are the main devices using domestic water. Domestic water can be divided into 2 categories: the domestic cold water (DCW) which is the supply water and the domestic hot water (DHW) which is the supply water that has been heated by a heating device.

Only a part of the devices cited use DHW. In fact, in Europe, washing machines and dishwashers only use the DCW, which the appliances can heat as needed thanks to a small built-in heater, compared to US appliances that most of the time require a hot water connection (Chateau & Lapillonne, 1982). The reason for using only DCW seems that, for washing machines, the frontload models used in Europe are much more energy efficient in terms of energy and water used than the topload US washing machine (Samsung, 2019) and thus connecting the machine to hot water leads not only to additional connections but also to losses in the pipes. The case is more complex with dishwashers since they are usually placed next to the kitchen sink, and therefore to hot water connection. Moreover, actual dishwashers all have a possibility to connect hot water supply to it. But the real profit (max. 20%) that can be made by connecting the device to hot water supply depends on the source that heat the water up (Michel, Bush, & Nipkow, 2017). As this report focus on electrical source equipment, we will therefore assume that dishwashers and washing machines are both connected to cold water supply only.

The domestic hot water temperature is subject to 2 main regulations. The first is to avoid legionella, a bacteria that proliferates in water when it is in the range of 20-45°C, with an optimum range around 35-41°C and may cause severe diseases like pneumonia to end-user who get exposed to contaminated water (Van Kenhove, Dinne, Janssens, & Laverge, 2019). This leads to temperature control of supply water from both sides: on one hand, government has to make sure that DCW does not reach 25°C and ideally stays <20°C (Agudelo-Vera, et al., 2020) and on the other hand the water heater cannot heat the water to high temperatures to prevent scalding. Therefore, domestic water has to stay ideally below 20°C for cold water, and between 60-65°C for hot water (at least 1h per day) (Van Kenhove, Dinne, Janssens, & Laverge, 2019).

Usually, hot water is not needed at 60°C. Therefore, the hot water is almost always mixed with cold water through a manually adjustable three-way valve that can be found on all DHW output devices. Therefore, 4 important parameters in the DHW consumption can be distinguished: The inlet cold temperature, the inlet hot temperature (the hot water stored into the DHW heating device) and finally the outlet temperature and the flow rate desired by the user. This can be resumed in the following equations:

$$P = \dot{m}_{mix} C_{p,water} (T_{mix} - T_c) \; [W]$$

$$T_{mix} = \frac{\dot{m}_c}{\dot{m}_c + \dot{m}_h} * T_c + \frac{\dot{m}_h}{\dot{m}_c + \dot{m}_h} * T_h \; [°C]$$

Where $\dot{m}$ is the mass flow rate, T the temperature, P the power needed by the user and C_p the specific heat of water is assumed constant. The subscripts h, c and mix represents respectively hot, cold and mixed water. The power is computed using the cold inlet temperature as a reference: if the user's demand is only cold water, $P = 0$. Inlet cold temperature is an important parameter of

DHW consumption because it will have an influence on the energy required to heat inlet water to its desired temperature. This inlet temperature is influenced by the distance between the pumping station and the end-user, the ambient temperature and the local climate. Put simply, inlet temperature is subject to seasonality and variates between 5-25°C (Agudelo-Vera, et al., 2020) with an average of 10°C in Brussels (Gerin, Bleys, & de Cuyper, 2014). According to Gerin *et al.* who studied the seasonality of hot and cold water consumption in buildings, variations in inlet temperature may lead to an increase of DHW consumption of 12% in winter (compared to the average consumption) and a decrease of 13% in summer (Gerin, Bleys, & de Cuyper, 2014). On top of that, other factors may play a role: First, the fact that people usually go on vacation in summer give additional contribution to the decrease of DHW consumption. Also, in case of very low or very high ambient temperatures, people tend to respectively increase or decrease their shower/bath temperature. Nevertheless, in general, the user temperature is quite regular. According to a review made by Jacobs *et al.* (Jacobs, Botha, & Blokker, 2018), several studies all underlined the regularity of shower and bath temperature with an average temperature that seems to be 40°C, with variations limited to +-2°C. This range of temperature correlates with VDI 2067 European guideline (Fischer, Wolf, Scherer, & Wille-Haussmann, 2016). However for kitchen and bathroom faucets, due to the wide variety of uses linked to them (dishwashing, cleaning, cooking, drinking…), it is likely to assume that temperature fluctuates more (Ritcher & Stamminger, 2012).

Additionally, the water consumption naturally depends on the number of people living inside the dwelling. In France, a report made by (COSTIC, 2016) on a total of 15 500 dwellings showed that the average total water consumption in France per capita is about 130 litres/day. This can be combined with the other claim from COSTIC, which is that in average, between 28-35% of the total water consumption is DHW, which makes the consumption of hot water between 35 and 45 litre per day per occupant.

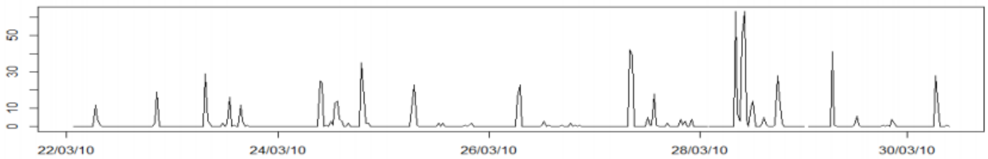


Figure 12 : Consumption of a single house during 8 days. No clear pattern observed. (Lomet, Suard, & Chèze, 2015)

In parallel to these factors that influence daily consumptions, another important aspect is the hourly consumption of DHW. Hot water consumption is highly stochastic from a day to another, and from a dwelling to another. Figure 12 shows an example of DHW consumption through a week for a single residential house. One can observe the stochastic behaviour of the profile by the fact that no pattern are recognizable. However, aggregating individual profiles makes the consumption more predictable. Gelazanskas & Gamage (Gelazanskas & Gamage, 2015) have studied predictability of aggregated profiles based on 120 households over 9 months. From these datasets, they extracted the DHW hourly consumption curve for all the days of the week, as shown in Figure 13. In this figure, the Y-axis is expressed in seasonal factor, which they defined as the average of the same hours from different weeks normalized to mean consumption. The figure shows a repetitiveness during workdays and the profiles are composed of 2 maxima at the beginning and the end of the day. Between these maxima, during the day, the consumption is below the average whereas during the night, the consumption decreases to almost 0. During the weekend, the first peak happens 2 hours later. The authors suggest that supposedly people tend to start their day later during weekends. Moreover, the dip between the 2 peaks is less marked on Saturday and Sunday.

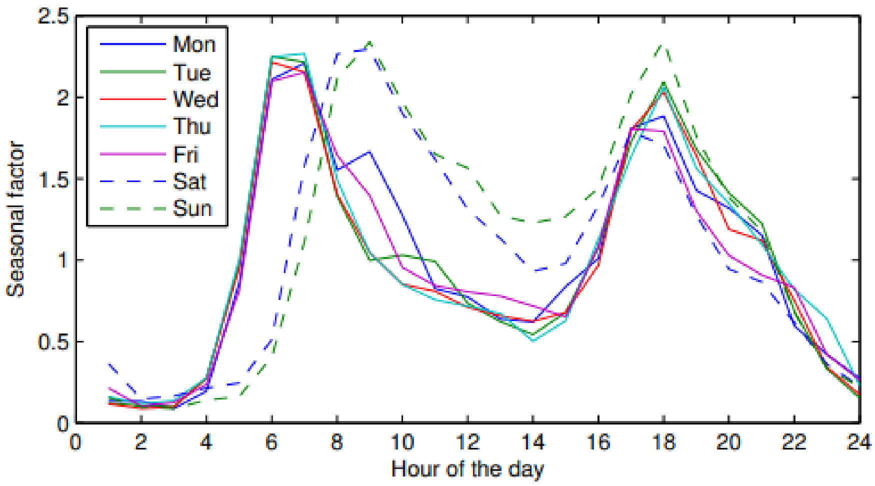


Figure 13 : DHW load profile for each day of a week. The seasonal factor on Y-axis is the ratio between the actual hourly consumption and the mean daily consumption, normalized hour by hour. (Gelazanskas & Gamage, 2015)

Other studies were focused on establishing an hourly profile. Fischer *et al.* (Fischer, Wolf, Scherer, & Wille-Haussmann, 2016) have built, based on daily diaries of 7200 households and with a granularity of 10 minutes, the probability distribution of a draw event's starting time within a day for weekday, Saturday and Sunday (see Figure 14). Although the consumption itself is not described, the characteristics of the profiles are similar to those from Gelazanskas & Gamage's work: the 2 peaks and the dip in between, the offset of the first peak in weekend. Ferrantelli *et al.* (Ferrantelli, Ahmed, Pylsy, & Kurnitski, 2017) have built an hourly DHW consumption wherein they plotted the consumption of reference groups of different sizes, until reaching the whole dataset they used (191 people in 86 Finnish apartments). The result, showed in Figure 15, highlights the fact that consumption seems to be predictable even with a small amount of households.

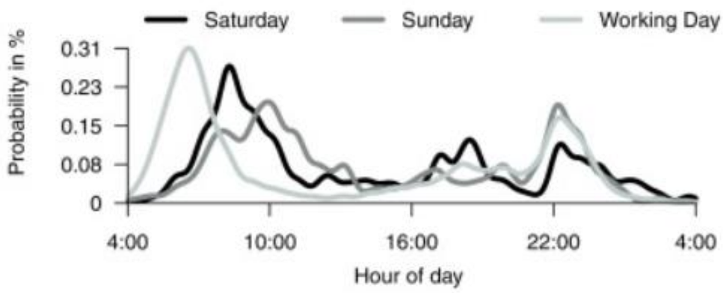


Figure 14 : Probability distribution of the starting hour of a draw event (Fischer, Wolf, Scherer, & Wille-Haussmann, 2016)

To summarize, domestic hot water consumption represent a significant part of the residential final energy consumption (11%) and a significant part of this consumption is achieved *via* electric devices (20%). The DHW is affected by seasons for a small part (+-15% of the average value), but stays relatively constant throughout the year. The 3 main uses of DHW in Europe is the tap, the shower and the bath event. For those last two, the outlet temperature is relatively constant with 40°C +- 2°C. The number of occupant per household play a great role in the consumption with in average 35 to 45 litres at 40°C per occupant. Although the hourly consumption vary with occupant's habits, local climate, culture etc. the aggregated hourly profile present similarities and a strong regularity through time. This therefore is a key factor, making aggregation interesting.

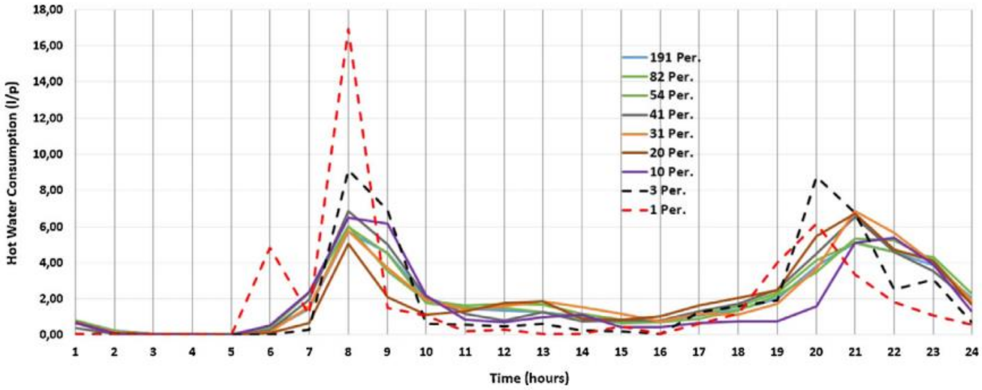


Figure 15 : DHW consumption for different pool sizes. Profiles get rapidly superposed (Ferrantelli, Ahmed, Pylsy, & Kurnitski, 2017)

4. Heating devices and their flexibility potential

Space heating and water heating have both their strengths and weaknesses regarding aggregation, but not all the devices have the potential to be aggregated. In fact, the heating devices have to comply with the following two rules:

- The device must be driven by an acceptable amount of electrical power: As the purpose is to play on electricity markets, the device must achieve its heating objective through electrical means. Moreover, since each aggregated device will be connected to aggregator through a small embedded system in order to exchange communications, the electrical input must be consistent (>1 kW). Otherwise, the price of installation would be too high compared to the volume of energy available. This rule excludes directly devices like mechanical ventilation or fridge, although the availability or the regularity of these devices is very good.
- The device must be able to store energy: As the concerned devices are related to space and water heating it is likely that, if there is a lack or a surplus of energy, the consumer will consequently feel a discomfort. This has to be avoided because it may lead the consumer to refuse aggregation. Hence, the device must have the ability to store energy and to give it back later.

In this section, the focus will therefore be on identifying the main heating devices and their potential for flexibility. First, a quick selection will reduce the scope and a comment will be made on PVs and electric vehicles which are also potential candidates but will not be analyzed in this report. Then, potential devices shall be more deeply described and analyzed in order to choose the best candidate(s). The summary of potential candidates are available in Annex 1 under the form of SWOT analysis.

4.1. First selection

Heating devices using electricity are very often decentralized, which means that they are used to heat only a portion of the dwelling, like a room or two. This is mainly to avoid a too high current flowing through a single cable or fuse, and to limit electricity consumption. Nevertheless, some systems like heat pumps may be centralized thanks to its capacity to produce more heat than its electricity consumption (see heat pumps in Section 4.2). The major advantages of electrical source heating devices are the ease to install and to handle, and the cheap installation cost. However, the electricity price makes this kind of devices long-term expensive. Therefore, they are ideal products when combined with housing rental.

There exists a lot of heating devices driven by electrical power:

- Instantaneous Electrical Water Heater: This is a conduct surrounded by electrical resistances which provides **domestic hot water**. The resistances are designed to directly heat the inlet water up to desired temperature. The activation/deactivation is therefore directly under the user control and there is no storage vessel which prevent any flexibility.
- Heat pump: This is a device which takes profit of its environment (ground, air, water) to provide heat, in exchange of electrical power used to drive a compressor. The latter may take different rotation speeds (the input/output power may vary), and the activation/deactivation is controlled by a thermostat (for **space heating**). There is most of the time a storage vessel linked to it. This is thus a potential flexible device.

- Electric Storage Water Heater: This is a tank of **domestic hot water** wherein one or two electrical resistances are used to heat the water. The device regulates itself to maintain the water temperature of the tank within boundaries predetermined by the manufacturer through a temperature sensor. The water tank and the incapacity of the user to control it makes it a good candidate for flexibility.
- Heat Pump Water Heater: This device is a combination of the two previous ones. A heat pump heats the **domestic hot water** in a tank until the water reaches a medium temperature (40-45°C). Then water is heated up to 50-60°C with an electrical resistance. Although the power involved is relatively smaller than Electric Storage, the flexibility potential is the same.
- Electric Heater: This is an electric radiator, often used for the **space heating** of small spaces like bathrooms. It is fully controlled by the user, and for short periods of time. Therefore it does not constitute a flexible device.
- Electric Storage Heater: This is an electric radiator used for **space heating**, and equipped with bricks that have a high thermal density. The electrical resistances inside accumulate heat which is stored in the bricks, and a valve controls the air flowing into the device, which will transfer its heat by convection. This device is often activated for long period of time, and may be controlled by the user and/or by an integrated temperature sensor. The power involved as well as its capacity to store heat makes it a good candidate for flexibility.

4.1.1. Other devices

Among uncommon heat source, one can mention solar types of heaters, like electric storage water heaters assisted with solar panels. The water circulates into tubes inside a panel on the roof acting like a greenhouse. The lack of heat is then compensated with an electrical resistance. The erratic behavior of the sun, especially in non-Mediterranean countries like Belgium, makes it more complicate to predict when the electrical resistance will be active, and therefore the flexibility is strongly reduced. Another heat source is the hybrid heat pump; a heat pump combined with a gas boiler, optimized to run one or the other in function of the ambient temperature. The heat pump will hence be mostly used in summer, and the gas boiler will be active in the most part of the heating season. Even though it is interesting for the consumer, it is uninteresting for flexibility.

Finally, some domestic devices have an interesting potential for flexibility. One can cite electric vehicles (EV) - only cars are considered - and photovoltaic panels (PV):

- Electric vehicles have a great flexibility potential because they can carry a lot of energy in the batteries. The batteries are, by nature, very fast to respond in power variations. Moreover, the power involved is very high for a domestic device, and patterns are predictable (people usually go to work in the morning, and connect them to the domestic network back home). Nevertheless, EV is a relatively new technology, and some drawbacks are the lack of regulation concerning the subject, the high initial cost, and a mitigated public opinion regarding these new vehicles, precisely regarding the battery of the vehicle. Also, the actual grid is not ready to host a lot of EVs. Finally, in Belgium the tendency of EVs are more on hybrid vehicles because they are cheaper and less electricity dependent[3].
- Photovoltaic panels are well-known products to users. The affordable installation cost coupled with electricity bill reduction make the technology attractive for dwellings. The concept is based on photodiodes producing a current. This low voltage – high current will be transformed by power electronics (a DC-DC buck

[3] *The number of electric cars in Belgium in 2018 was estimated at 15500, which is much lower compared to hybrid cars (92500)*
https://www.statista.com/statistics/698294/number-of-electric-passenger-cars-in-use-in-belgium/
https://www.statista.com/statistics/1060016/number-of-hybrid-vehicles-on-the-road-in-belgium/

followed by a DC-AC inverter), making the control of the output possible. But in standard installations, the electronics are defined to function in maximum power point tracking (MPPT), thus always searching to provide the maximum power available from any situation. There is a possibility of conflict between the economic optimization and the fact to use another control than the MPPT. However, the incoming MVAr market (see Section 2.7) could maybe make aggregation of PVs more profitable.

4.2. Heat pump

Although the first heat pump (HP) has been developed and built around 1850, it is only since 1970's that heat pumps has begun to be present on the market. This technology is based on a closed loop where a fluid with particular thermodynamic properties – the refrigerant - flows into it. This refrigerant passes through 4 different stages: a compression where the refrigerant evaporates, followed by a condensation, then an expansion where the refrigerant becomes liquid and finally the evaporation. The condensation and evaporation parts are the moments when the refrigerant has an interaction outside the heat pump. In other words, there will be a heat transfer between the environment and the fluid. In the condensation part, the heat transfer is supposed to operate from the refrigerant to the environment and *vice-versa* for the evaporation part.

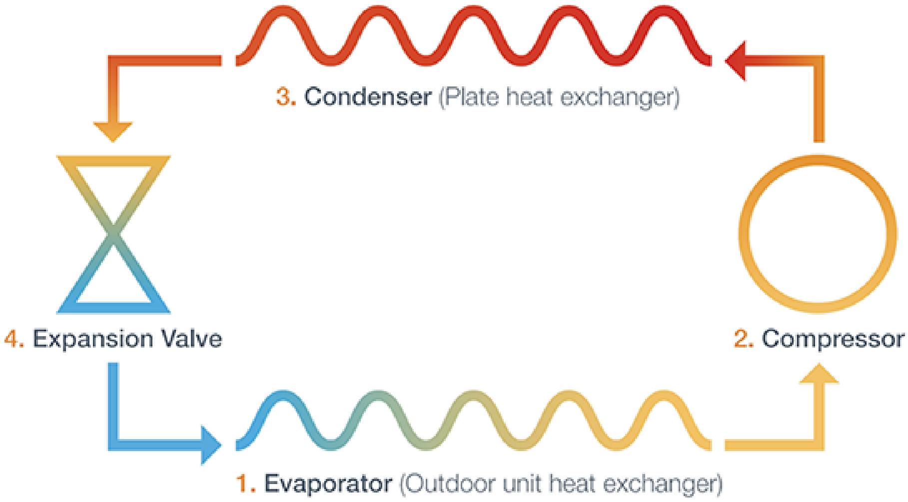


Figure 16 : Heat pump heating cycle. The primary circuit is the environment and the secondary is inside the building. [Source: RHI energy savings]

The compressor is the only non-passive element of the heat pump, and therefore the weakest piece. As every rotating machine, the compressor is subject to friction and to a starting current up to several times its nominal value. The compressor thus undergoes a mechanical and electrical stress that reduces its lifetime. It is thus not recommended to often start. In his book about HP, Béranger (Béranger, 2008) says that cycles of less than 10 minutes are greatly unadvised. This in confirmed in a report made by Green (Green, 2012) where the conclusion says that the minimum cycle time is between 6 and 10 minutes, depending on the technology. This is due to the fact that the compressor is a non-instantaneous device. So at the activation, the power consumption will grow for 6 to 10 minutes until it reaches its setpoint. Regarding the storage vessel, the latter is sometimes not mandatory but often installed for comfort purposes. For example, in Germany, approximately 90% of the existing and 50% - 80% of the newly built buildings are equipped with thermal storage tanks when using a heat pump (Fischer, Integrating Heat Pumps into smart grids, 2017). A good rule of thumb is to install a buffer vessel sized for 10 litres per kW of output heat (Kensa heat pumps, 2014).

Heat pumps are defined by a dimensionless coefficient of performance (COP) which represents the ratio between the power provided as heat at the condenser (in kW_{th}) and the power injected as electricity into the compressor (in kW_{el}):

$$COP = \frac{Thermal\ power\ provided}{Electrical\ power\ needed}$$

The COP is always greater than 1 when the HP is used for heating, and generally between 3…4…5 in practice. The value of the COP is greatly dependent on the temperature difference between the 2 heat exchangers: a higher temperature difference will induce that the compressor must provide more work to elevate the refrigerant temperature[4]. Also, the heat pump may be characterized by another coefficient, the Seasonal Performance Factor (SPF), which is a more practical factor computed experimentally. It expresses the heat/electricity ratio, but averaged for an entire year, thus taking into account temperature variations through the year. Hence, the SPF is always lower than the COP and more representative of the actual performances of the heat pump.

The "environment" may take several forms: at the condenser, it is generally circulating water or air while at the evaporator, it may be circulating water, air or soil. So the HPs are divided in several categories:

- Ground source heat pumps (GSHP), where the primary circuit is either the soil (ground-water) or water from a lake or groundwater (water-water). The secondary circuit is always water in this case, because the power and the cost involved are too high to be worth with low heat capacity fluids like air.
- Air-to-water heat pumps (AWHP), which are either designed to DHW or/and space heating.
- Air heat pumps (AHP), have always a low power input (< 3 kW_{el}) and are easy to install. There are mostly designed for air-conditioning, or to heat one room.
- Absorption heat pumps are air-source heat pumps not driven by electricity, but by a heat source such as natural gas, propane, solar panels etc. Due to the latter characteristic, this kind of heat pump won't be investigated in this report.
- Hybrid heat pumps stand for a combination of an electrically-driven heat pump and a traditional space heater like natural gas boiler. These two are both linked to a controller whose purpose is to choose between one and another heating device, depending on the outside temperature and the inside desired temperature, in order to maximize the efficiency.
- Others can be named, like ground-ground HP (the refrigerant circulates in ducts inside the walls), brine water-to-water, etc. But these cases are not common and thus won't be analyzed in this report.

4.2.1. Ground source

Ground source HP is the most profitable, and also the most expensive and constraining type of heat pump. In fact, as the evaporator needs a large contact surface with the source, conducts are buried. There are 2 main options: either to dig horizontally (wide, shallow trench) or vertically (long, narrow bore). The first one has the advantage to be not too expensive but will have its temperature varying a little during the seasons. Moreover, the surface needed is quite large and bad repercussions may happen at the surface due to constant lower soil temperature. The other one is

[4] The heat pump is then designed for a particular temperature difference. These nominal temperatures are generally given by the manufacturer along with the HP denomination. For example, A15/W45 refers to an Air-to-Water HP with nominal refrigerant temperatures of 15°C at the evaporator entrance and 45°C at the condenser exit.

more expensive because it requires a drilling machine and the possibility to install the tubes depends on the type of soil it is drilled into. The major advantages are that, starting from 15-20 meters deep the soil temperature is constant and usually between 10-15°C depending on the country, which makes the heat pump reliable at any time and that only a low horizontal surface is needed to install the heat pump.

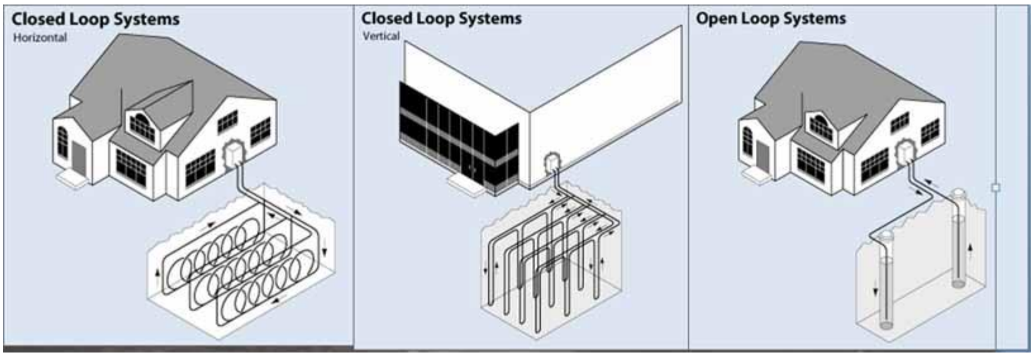


Figure 17 : Types of installation of the evaporator for ground source HP [Source: Tom's Mechanical]

In the case of a groundwater or a lake in proximity of the dwelling, there is a possibility to place an open loop system: instead of a lot of tubes or spirals, the water can be pumped to the heat pump and then ejected back a bit further into the water after the heat transfer. A permit is needed (due to the risk of water contamination) but the initial cost is less expensive.

In each case, this kind of heat pump is sized to heat the whole dwelling, and may sometimes be combined to the heating of the Domestic Hot Water (DHW). The input power is generally between 1-10 kW_{el} (Fischer, Integrating Heat Pumps into smart grids, 2017) depending on the surface to heat, but common cases are between 3-5 kW_{el}.

4.2.2. Air-to-water

Air-to-water HPs are used for space heating but also for DHW (this type of HP is explained later in this report, see section 4.3.2), and represents the most common type of HP bought by Belgian (EHPA, 2018). The installation is rather easy for the primary circuit, since it is easy to bring air to the heat exchanger with a fan. On the water side, the ducts imply higher cost. The primary circuit is thus the main difference with the ground source. The fact that the calories are extracted from the air implies that this kind of heat pump is strongly dependent on the outside temperature. As a consequence, the COP decreases in cold days, when the demand of heat is the highest.

In space heating, the range of power is between 1 and 10 kW_{el}, generally a bit more oversized than the ground source due to a less good COP in winter.

4.2.3. Air-to-air

Air-to-air HP is the most affordable HP, due to its low cost and its fast implementation into the house. This type of heat pump is generally "single-zone", which means that the heat pump is sized to heat only one room. It strongly minimizes the length of duct needed to link the indoor and outdoor equipment. However, it is possible for the heat pump to be sized as "multi-zone", where there is only one outdoor equipment linked to several indoor ones, placed in different rooms. The heat demand is independent from a room to another, by controlling the flow going through the ducts.

A great advantage is the capability to respond quickly to the demand, due to the low thermal inertia of air (more than 4 times less than water). But this can be also a constraint because the heat restitution doesn't last long and consequently, the equipment have to stay switched on almost as long as the heat demand. Its electric power input is lower than air-to-water or ground source.

4.3. Water heaters

4.3.1. Electric storage water heater (ESWH)

The electric storage heater is the most common electric device concerning the DHW. The reservoir is classically equipped with 1 (at the bottom) or 2 (bottom & top) immersion heaters, depending on the size. An immersion heater (or electrical resistance) is composed of several metal bars that provide heat thanks to the Joule effect which causes a heat transfer from the heater to the fluid by convection. The heater has generally a power input of 1.5…3 kW for each heating device and is coupled with an integrated thermostat. The reservoir is sized between 100 and 300 litres (BRG, May 2018), to have the capacity to better respond to most of the demands, regarding the number of occupants.

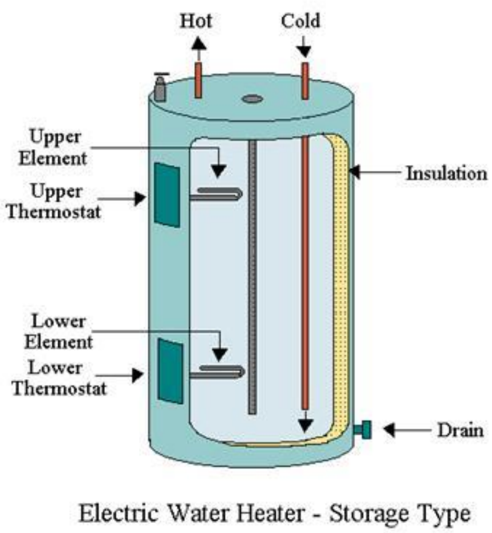


Figure 18 : A typical electric storage water heater [Source: energydepot.com]

The storage is a water tank thermally insulated and often designed to enhance stratification. The inlet of cold water is placed at the bottom and the outlet at the top of the tank to avoid to mix the two liquids. But despite the insulation, it implies losses due to the temperature gradient. Manufacturers will often give an estimation of losses, which is around 1 … 2 kWh/24h for storages of these sizes.[5] If there is a need to estimate losses when the tank contains higher temperature than the nominal one (to 60…65°C), a rule of thumb is to increase the losses by 2.5% for each degree Celsius higher.[6]

Each ESWH has its own program, created by the manufacturer and incorporated to the device, to maintain the water temperature at an acceptable value for sanitary reasons. Also, the device has sometimes an interface to interact with the consumer, where he can set programs to heat the water in advance in order to better respond to the demand when the latter is high (for example in the morning). The flexibility potential is rather large, because the resistances have a quasi-instantaneous response time, and a large nominal power. Furthermore, it is not affected by the serial activation or by a long time of activation. Finally, a large part of the Belgian water heater devices are ESWH (42% i.e. 183,000 ESWHs bought in 2017) (BRG, May 2018).

[5] *Example of datasheet p27 : http://www.nabaki.com/uploads/spec_sheets/Electric_Water_Heaters_2015.pdf*
[6] *The approximation consists to consider only the conduction through the walls of the tank. This results to a linear relation between losses and temperature difference between the ambient air and the water inside the tank.*

4.3.2. Heat pump water heater (HPWH)

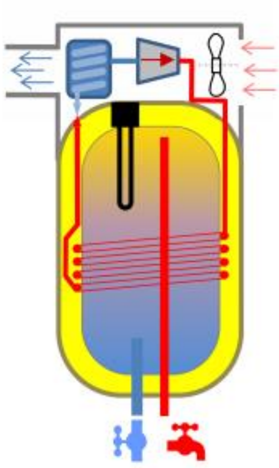


Figure 19 : An integrated HP water heater (above the tank), combined with an immersion heater (in black)

Water heater heat pumps are small units of less than 5 kW output power (BRG, May 2018), generally associated to a buffer vessel between 200 and 300 litres (BRG, May 2018). The heat pump itself is usually an air-to-water (built-in or in combination with space heating) and less commonly a ground-to-water where the heat of DHW is in parallel of the space heating. Due to the temperature limitations of the HP to keep a good COP, the buffer is often associated to another input, like a resistance of 1 … 2 kW or a small traditional boiler combined with a smaller reservoir to reach the desired temperature of 60°C. Depending on the buffer actual temperature and the hot water demand, there is a possibility for the device to activate either the heat pump, or the resistance, or both. The heat pump has a small to medium electrical input power (0.4…2 kW).

This device is ruled by the DHW load profile, with the advantages and inconvenient of a heat pump. But the flexibility potential is difficult to quantify due to the complementary use between the two sub-devices (resistance and HP), meaning that the power involved can suddenly change with the activation/deactivation of 1 of the sub-device.

4.4. Electric storage heaters

Electric heating is an old technology, discovered in parallel to first researches on electricity. It uses the Joule effect in order to generate heat that will be transmitted to the fluid by radiation and convection. Electric heating has numerous application examples, like immersion heaters like in ESWH as seen before. The Electric Storage Heaters (ESH) is a sub-branch of electrical heaters, and consist of an electric radiator that stocks heat generated by an electrical resistance into bricks with a high thermal inertia. The heat is then gradually released from the bricks to the surroundings. Therefore, the main difference with direct electrical heaters is that ESH have storage capacity, which allows the device to be flexible. In fact, this kind of heating is complementary to the two-tariff electricity meter. The storage is charging heat at night in order to restitute it gradually the next day, and to take profit of the night tariff of the electricity. These ESHs are thus either manually or digitally programmable to operate essentially at night.

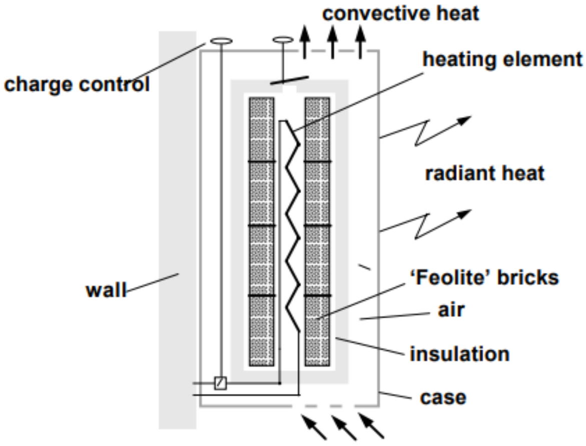


Figure 20 : Cross section of an electric storage heater. The heating element is a resistance. (Da Silva, 2011)

The programmability of ESH is variable, depending on the technology. The most widespread is the manual one, which entered the market first. The controllability is in essence based on 2 commands: the input commands the time the resistance has to stay activated and the output controls the fan which shall heat the air by forced convection. More complex behaviors can be achieved by having a timer to activate the ESH automatically at a given time, or a temperature sensor to adapt its input/output with the temperature of the room etc. to enhance the comfort of the user. The high-end technology is even controllable through Wi-Fi.

Figure 21 : An example of an ESH controller. From the very basic (left) to the high-tech (right)

Recently, the European Union has adopted a regulation (European Commission, 2018) for local space heaters like ESHs. This Ecodesign Directive, which has entered into force on 1 January 2018, imposes a minimum seasonal efficiency (38.5%), based on the active efficiency at 30% and 100% of the rated power, and on several correction factors which depend on the type of technology. For instance, the fact that the ESH is electronically controlled by the energy supplier increases the correction factor by 3.5%. In other words, the regulation impose the local space heaters to be smarter. This implies that basic ESHs are not allowed to be manufactured anymore.

Regarding technical specificities, the power input varies between 0.5-3.5 kW and the maximum energy storable is generally designed to be equivalent to the rated power times the number of hours of the off-peak period. This period is imposed by the local DSO or the country. For example, the off-peak period in Belgium is 9 hours, while the off-peak period in the UK is 7 hours. Consequently, a 3.3 kW storage heater may have a capacity between 23-30 kWh, depending on the country of the manufacturer. As the heating device is a resistance, the time of activation and deactivation is quasi-instantaneous. The control of the device may be either entirely done by the user or partially by the user and partially by another device like a thermostat or the ESH itself, with the help of temperature sensor(s) placed in the room and/or outside of the house. Some ESH can be controlled directly by the supplier like in the study made by RealValue (Darby, Higginson, Topouzi, Goodhew, & Reiss, 2018) where they implemented in several dwellings electric storage heaters that were mainly controlled by an aggregator unless the consumer directly want to modify the program.

To summarize the behaviour of the ESH, one have first to summarize the behaviour of the user:

- First, the behaviour of the user may vary with seasons. A study from Wright (Wright, 1997) underlines that the relationships between outside temperature and the user setpoint was different during the heating seasons. For instance, the control set by the user has a tendency to respond strongly to the external temperature in spring but less in autumn, for the same temperature. Also, the study tells that the user switch on their heating device after the first cold snap in autumn and switch it off after the first warm spell in spring. Furthermore, a qualitative study of what UK inhabitants want from their heating device done by Rubens (Rubens, 2013) showed that several types of user profiles exist among the population. These profiles are either predictable or unpredictable, sensitive to outside temperature or not etc. Thus, it is rather complicated to establish a precise load curve. Furthermore no recent studies on electric storage heaters have been published.
- Secondly, one can establish that an ESH is mainly used at night, but it can also be used at day in the case of a great cold or depending on the personal thermal comfort of the user.
- Finally, there is a progressive automation of the controller. In other words, there exists various types of controller, which can optimise the activation duration with prices, or with temperature curves and so on. This signifies that the power "activated by the controller" (injected in the resistance) may vary, but also that the load profile cannot be determine in advance. Depending on the potential control the aggregator may have on the device, this can be an advantage.

To summarize, ESHs have a great potential in terms of power (0.5…3.5 kW) and capacity storage (up to 30+ kWh), and a negligible time response. Furthermore, the time window where there is a great possibility of flexibility is high (from 7 to 9 hours duration). However, the flexibility may be quite narrowed by the dynamic of the programs that the consumer defined. These latter's introduce then an unknown regarding the power input at any time. Moreover, one have to take into account that ESH are not well seen compared to other "greener" heating device like heat pumps, solar heaters, micro-CHP and so on (Should I get new storage heaters?, 2017). This implies that there is a risk that the market share of ESH will steadily drop. But with the burst of renewable energies, it will maybe be again a device of choice.

4.5. Device selection

Based on the information collected, what device could be interesting? To answer to this question, devices' characteristics are summarized in Table 3 and their main advantages are highlighted in green. For the storable energy, either the value is directly given like for ESHs or it has a storage tank. To estimate the maximum storable energy from the latter, the following equation is used:

$$E = \frac{mC_{p,water}\Delta T}{3600} \cong \frac{LC_{p,water}\Delta T}{3600} = L * 0.058\ [kWh]$$

With $\Delta T = (60 - 10)$ assuming an inlet temperature of 10°C and a desired temperature of 60°C, $C_{p,water}$ the specific heat of water (4.18 kJ/kg/K), L the volume of water in litres and m its mass in kg. To make things simpler, the density of water is assumed constant and equal to 1 kg/L, thus $m = L$. Finally, the division by 3600 is to transform from kJ to kWh. However, the HP used for space heating is often connected to underfloor heating and runs in closed loop. Hence, the temperature difference is adapted to $\Delta T = (45 - 20)$.

The values regarding Belgium market in the Table 3 is either given by (BRG, May 2018) or (EHPA, 2018). One may observe that heat pumps market is growing in Belgium but the initial stock is still very low. This is due to the high installation cost. Moreover, in addition to the initial price, the new installation of space heating HP requires either underfloor heating or radiators adapted to low temperatures. Therefore, they are often bought for new housing but muss less for replacement (BRG, May 2018). On the other hand, ESWH are very common with a stock of more than one million devices but these devices are mainly bought for replacement (BRG, May 2018), which explains why sales are stagnating. As for ESH, there is little to no information available regarding the market. This shows that ESH is not a privileged device (for researches and consumers) and to bet on this device could be risky.

The device selected will be ESWH for several reasons: first of all, the device is strongly present in Belgian households and it is therefore easier to compose a large pool of devices. Secondly, the response time is really fast, which makes it a device with potential regarding every electricity market, and the device does not suffer from chain switches. Finally, the ESWH is used for DHW, and the latter is strongly predictable (see Section 3.2), which ease the aggregation.

Nevertheless, it could be a good strategy to keep an eye on heat pumps evolution: more and more heat pumps are bought each year in Belgium, some of them are even “smart grid ready” (designed to be controlled by the user or the aggregator) and R&D may lead to more flexible compressor. A good strategy could be for the future aggregator to begin with ESWH in order to gain in experience in aggregation while HP market is growing and then include HPs in their pool. For more information, David Fischer (Fischer, Integrating Heat Pumps into smart grids, 2017) has worked deeply on this subject and it could be an interesting document to start.

Table 3 : Summary of potential devices' characteristics

Characteristics	ESWH	HPWH	ESH	HP
Type of heating	Water heating	Water heating	Space heating	Space heating
Electric input (kW)	1.5-3	0.4-2 (+ 1-2)	0.5-3.5	<10 (3-5)
Heating output (kW)	1.5-3	<5	0.5-3.5	<20
Storable energy (kWh)	5.8-17.4	11.6-17.4	<35	2-10
Response time	seconds	6-10 minutes	seconds	6-10 minutes
Initial cost	Low	Medium	Low	Medium to high
Initial stock in Belgium	>1'000'000	25'000	<100'000	49'000
Units sell in Belgium (2017)	180'000	5'000	<<200'000[7]	11'000
Comparison with sells of 2016	+0%	+25%	+0.35%[7]	+15%

[7] *This value includes all types of electric radiators (BRG, May 2018). ESH sells is expected to be much less.*

5. Stochastic approach of DHW load profiling

Now that the device has been chosen, realist profiles are needed in order to quantify the flexibility potential of this device. As the finality is to play on electricity or balancing markets, it is important to have a large pool of profiles. Moreover, these profiles should be as detailed as possible in order to be realistic enough. But there is little to no data of this type available to the public. Hence, one has to create a synthetic pool of individual profiles.

On this subject, Scheepers and Jacobs (Sheepers & Jacobs, 2014) published a probability based end-use model which is based on the REUWS database that collected water (hot and cold) offtakes from 1188 households in 12 study sites in USA/Canada by the American Water Works Association Research Foundation (AWWARF). This end-use model is capable to generate realistic individual load profiles, although not completely representative of the population and more specific to US consumption. This work inspired other works like the thesis of Morné Richard (Richard, 2016). His work was focused on the building of an average load profile with 5 minutes granularity based on the probabilistic data from Scheepers and the Monte Carlo method. The resulting load profile was analyzed and the author found that the daily DHW involved is sensitive to the number of occupants as well as the water heater temperature setting and the cold water inlet temperature. In the report of Hendron *et al.* (Hendron, Burch, & Barker, 2010), also inspired by Scheepers, more parameters have been taken into account in order to generate more precise and realistic individual profiles. The authors integrated parameters such as the duration of the tap according to its type, the volume involved and the probability distribution the latter follows, the seasonal factor and so on. This database has thus been used as a reference for several works and this seems legit since, according to Scheepers, this database is the largest known available collection (the second largest is based on 250 homes). Therefore, this database (precisely, the formatted database in Scheepers' work) will be used in this report.

The REUWS database is composed of indoor and outdoor end-used data from 12 sites of approximately 100 homes in USA and Canada. At each home, a data logger was attached to the water meter and recorded samples of water flow rates every 10 seconds for 2 weeks in summer and 2 weeks in winter. The recorded flow were disaggregated in water consumption events and the start time, stop time, flow rate, volume etc. were calculated for each event. Combined to surveys from each household, the resulting parameters were range of possible values for volume, flow rate and duration for the type of events. An analyst repeated the routine and fine-tuned the parameters to build a file that identifies as much as possible the events and their parameters (Sheepers & Jacobs, 2014). Hence, the results are under the form of:

- Discrete cumulative distribution function (CDF) for the <u>starting hour</u> of each type of event, the <u>number of time</u> the event may happen during the day and <u>the number of occupant per household</u> (PPH, Person Per Household;
- Continuous probability density functions (PDF) for <u>volumes and flow rates</u> for each type of event

The devices used to produce DHW are, however, not mentioned. This could greatly affect the overall hot water consumption. For instance, gas boilers can respond to any demand of any duration since the boiler is connected to the gas network. Households with gas boilers are thus more likely to consume more hot water. Besides, hot water consumption of US households are in average greater than European households (E. Fuentes, 2017). Since the profiles will be based on the fact that the households are equipped with an ESWH, some parameters will be modified to better correspond to European consumption. Finally, the data do not distinguish weekdays or weekends.

5.1. Modelling individual profiles

In order for the REUWS database to better correspond to European hot water consumption and precisely Belgian consumption, different parameters will be modified:

- The number of occupant per household (PPH, People Per Household) will be a combination of Belgian data from Statbel and assumptions about the distribution of 3, 4 and 5+ PPH;
- The number of events probability, the starting hour of these events according to their nature (shower, bath & tap) and the volume probability distribution will be taken from REUWS database (Richard, 2016), (Sheepers & Jacobs, 2014);
- However, the probability distribution of tap (kitchen and basin) given in REUWS is relative to the domestic total water consumption. Hence the data are biased and one must take another source to model more correctly the tap demand. According to Richard (Richard, 2016), only 57% of the total water consumption in taps are hot water consumption. Therefore, the number of tap events as long as their probabilities shall remain as in the REUWS database, but to take into account the 57% of hot water, the model shall multiply each tap volume by a factor 0.57.
- As the REUWS data are based on USA/Canada consumption, the average volume of hot water used may be different compared to Europe. In order to be more realistic the probability distributions of volumes of the different events shall be controlled in order to fit the French data (COSTIC, 2016), closest country to Belgium with reliable and detailed data on their water consumption and hence less subject to differences.
- Shower and bath outlet temperatures are in average around 40°C. Therefore the assumption will be that, for shower, bath and tap events, the outlet temperature is always constant and equal to 40°C.

As the reader can see, the output of this stochastic modelling looks like a patchwork of different models, data and countries. The consequence is of course that the household profiles will not be representative of the Belgian DHW consumption behavior. However, the purpose is to create profiles realistic enough to create a sufficient pool in order to try forecasting on the aggregated one.

5.1.1. Cumulative distribution of the starting hour and the number of events

People have their own habits, but looking at the aggregated curve, it is possible to see trends. For instance, showers usually start at the beginning of the day before people go to work. On the contrary, bath often start at the end of the day because people usually want to take their time for a bath. This effect is visible in Figure 22 which shows the cumulative distribution of the starting hour for each type of event. There is a significant rise in the CDF from 6h to 9h for showers and from 18h to 23h for baths. Regarding the tap events, the CDF is relatively constant throughout the day. Finally, one may observe that, for every event, the probability of any draw-off between 0 and 5h is very low.

As for the number of event of each type, the latter are available under the form of CDF but linked to the PPH, the number of occupant in the household. Indeed, the number of events occurring in a same day is strongly dependent on the PPH. So, from 1 to 5+ PPH, each one has its own cumulative for each type of event. An example is shown in Table 4 for bath events. For the complete tables of each event, the reader is invited to see the work of Richard (Richard, 2016).

Table 4 : CDF values regarding the number of occurrences within the day for bath events (Sheepers & Jacobs, 2014)

Number of events: BATH	Person per household				
	1	2	3	4	5+
1	0.6121	0.1282	0.2192	0.0995	0.3301
2	0.8772	0.7654	0.7861	0.7898	0.8010
3	0.9612	0.9297	0.9580	0.9558	0.9450
4	0.9914	0.9829	0.9895	0.9893	0.9871
5	1	0.9924	0.9974	0.9933	0.9903
6	---	1	0.9987	0.9973	0.9951
7	---	---	1	0.9987	0.9984
8	---	---	---	1	1

It is quite surprising to see that, for some households, certain occurrences may be considered as very high (5 baths within the same day for 1 PPH for instance), but it confirms first that some households of the database may have gas boilers and thus do not look at their hot water consumption and second that the initial data has been processed to identify the type of event, leading to potential errors. Finally, one has to keep in mind that the data were recorded during weekdays and weekends, without distinction.

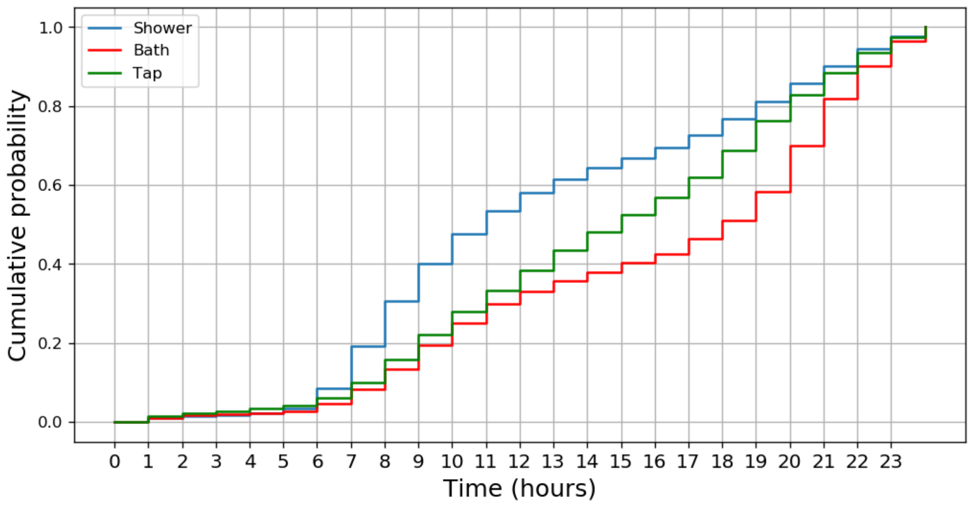


Figure 22 : Cumulative probability function of the starting hour for the 3 different events (Based on the work of Scheepers & Jacobs)

The starting hour and the number of event will be determined with random numbers. Let $x \in [0,1]$ be a random number. Considering an iterator i, The following condition will be tested from the beginning of the CDF $F(y)$:

$$x \geq ?\ F(i)$$

If the condition is true, the iterator's value is the discrete value (starting hour or number of events) corresponding to the random variable.

Finally, it is essential to gain in time resolution regarding the starting hour. For now, the time resolution is too low and thus non-realistic. To go from a granularity of 1 hour to 1 minute, a random integer between 0 and 59 will be generated using a uniform distribution to determine the minute at which the event will start. It would also have been possible to directly increase the resolution of the CDFs linked to the starting hour but, as the distribution of the generated integer is uniform, it comes to the same.

5.1.2. Event's flow rates and volumes probability distribution

Along with the starting hour of the event and the number of times this event occurs, the two other important parameters are the flow rate and the total volume of the event. These two parameters will decide for how long the event will occur. Scheepers & Jacobs have defined these parameters using continuous PDFs that match as much as possible the data. The distributions as well as their parameters are shown in Table 5. Since these are continuous PDFs, it is possible that a high random number (>0.99) will potentially result to a very high flow rate or volume. Even if it is quite possible for the latter, a huge or tiny flow rate is not realistic. So, to avoid these situations, a condition will be imposed on the flow rate. The latter (FR) has to be within these boundaries:

$$\mu - 2\sigma \leq FR \leq \mu + 2\sigma$$

With μ and σ respectively the average and the standard deviation of the PDF considered. Furthermore, in order to limit the cumulated output flow rate, one will make the hypothesis that there is only one bathroom, whatever the PPH. In this bathroom, there is a probability of 80% that there is a bath (Waterwise, 2015) but in any case, one will make the hypothesis that there is only one place in each dwelling where people can shower and bathe. This means to re-randomize shower or bath events that take place during another existing shower/bath event. The tap events are not affected by this constraint since there are minimum 2 taps (kitchen and bathroom) in each dwelling.

Table 5 : Table of the event's distribution functions, as well as their parameters (Sheepers & Jacobs, 2014)

Event	Type	Distribution	Distribution parameters
Shower	Flow rate (L/s)	Log-Logistic	Shape = 4.158 Scale = 0.127
	Volume (L)	Log-Logistic	Shape = 2.828 Scale = 55.2
Bath	Flow rate (L/s)	Rayleigh	Scale = 65.98
	Volume (L)	Weibull	Shape = 2.578 Scale = 0.34
Tap	Flow rate (L/s)	Lognormal	Shape = 3.262 Scale = 0.023
	Volume (L)	Gamma	Shape = 1.064 Scale = 0.276

Finally, as previously discussed, these data are relative to US/Canada consumptions and may be too large compared to European consumption. To regulate this, the total hot water volume composed of all the events generated will have to follow a constraint relative to French hot water consumption. In the report from COSTIC (COSTIC, 2016), averages and standard deviations of total daily volumes of hot water consumption for French households are available for each PPH. Therefore, the total volume will have to comply with the condition:

$$V_{tot} \leq \mu_{PPH} + 2\sigma_{PPH}$$

With μ_{PPH} and σ_{PPH} being respectively the average and standard deviation of hot water consumption relative to the PPH given by COSTIC. This is only an upper limit and not a lower limit since it is entirely possible that almost no hot water is draw for a day. These values are given in Table 6 for information.

Table 6 : Values of the final condition, function of the PPH

PPH	1	2	3	4	5+
$\boldsymbol{\mu_{PPH} + 2\sigma_{PPH}}$ **(L)**	80+70	120+90	150+100	170+140	220+210

5.1.3. Summary of the profile generation procedure

As a reminder, each profile is created with the following procedure summarized in the flow chart in Figure 23:

1. The number of people per household (PPH) is randomly determined between 1 and 5, according to the Belgian repartition of people per household. The fact that the household is equipped with a bath or not is also randomized and implicitly included in the case "Set its PPH". Higher PPH are neglected.
2. Then, for each type of event (shower, bath and tap), the number of time the event occurs is randomly determined, according to the cumulative distribution of these events.
3. For each event, the hour at which it starts is randomly determined using the starting hour cumulative distribution related to each type of event. The minute at which it starts is random following a uniform distribution.
4. Then, a volume (in litres) and a flow rate (in litres/sec) is assigned for each event, using the probability distributions shown in Table 5. The assignment verifies that two events of shower or bath type are not placed in the same time and that the flow rate is not too low or too high regarding their respective PDF, otherwise it re-randomize the last event generated until it fits.
5. Finally, the total volume of water is computed by summing each draw-off, and compared to typical volumes according to their PPH. If the value of the total volume generated is too high compared to the typical one ($\leq \mu_{PPH} + 2\sigma_{PPH}$), the complete consumption profile is re-randomized (step 2 to 5).

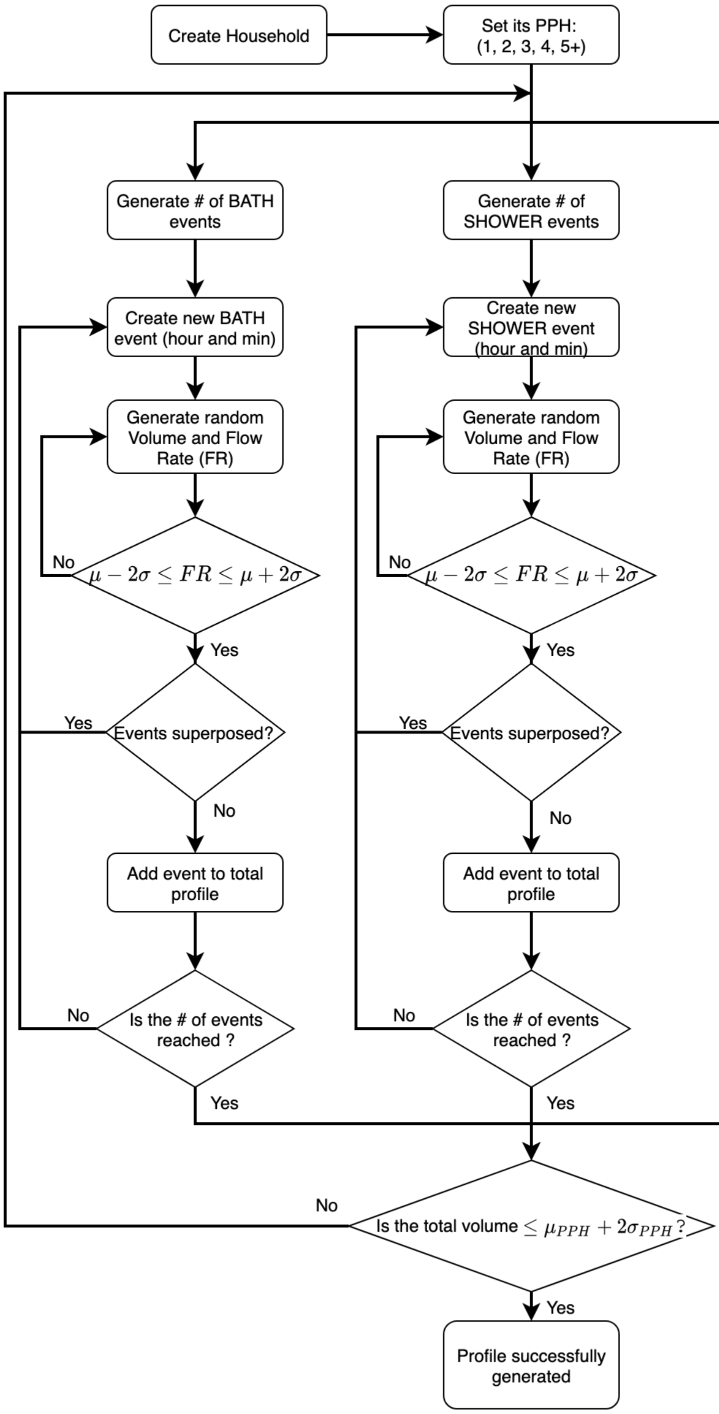


Figure 23 : Flow chart used to create household profiles

An example of generated consumption profile of a single household of 4 occupants is shown in Figure 24. This profile is composed of 3 showers at approximately 9h30, 11h30 and 20h30 as well as a bath at 18h. All the very small consumptions throughout the day are tap events. Bath events are often characterized by a large consumption for a short time while shower events are characterized by a medium consumption for a longer period. Tap events are always composed of very small numerous volumes.

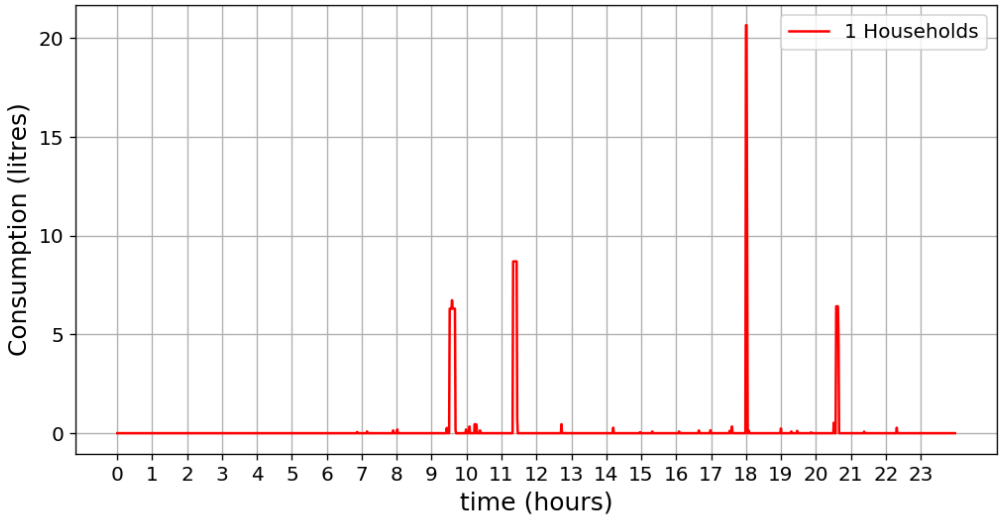


Figure 24 : Random generation of a single profile. Here, the PPH is equal to 4.

The result for different pool size generation are shown in Figure 25. The y-axis is the normalized consumption i.e. the total volume of hot water consumed by the pool divided by the number of households composing this pool. The main observation is that the larger is the pool, the smoother is the normalized consumption profile. One can also see that there are 2 peaks of consumption: one at 6-8h, and another at 19-21h. Finally, the hot water consumption is really low at 1-4h. The distribution of volumes according to the type of event is as follows: The shower represents on average 70% of the total volume, the bath 22% and the tap 8%.

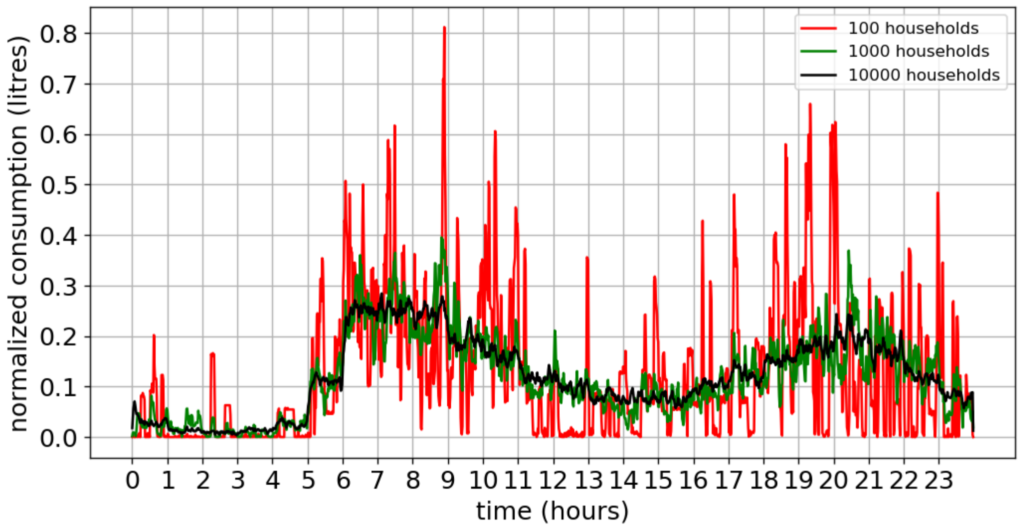


Figure 25 : Normalized consumption for different pool sizes

It is also interesting to compare the shapes between Figure 25 and Figure 13 in Section 3.2. There are similarities between the two, like the two peaks at the morning and the evening of the day or the very low consumption during the early hours of the night (0-4h). However, the first peak in Figure 25 happens one hour later compared to Figure 13. This is again due to the fact that the REUWS data were taken for 4 weeks without distinction between weekdays and weekends. This is the major drawback of these data. Still, the individual and aggregated profiles can be assumed to be realistic enough for the rest of this report.

6. Modelling the ESWH's hot water tank

The other important part of the modelling is the device itself. As a reminder, the chosen device for flexibility is the electric storage water heater (ESWH). This is a storage vessel composed of 1 (or 2) resistance(s) placed at the bottom (and the top) of the tank. The inlet cold water get in from the bottom of the tank while the outlet hot water get out from the top. The resistance at the bottom may be placed vertically or horizontally if there is only one resistance and only horizontally if there are two. A bit above the resistance is placed a sensor that will send probed temperature to the PCB integrated to the ESWH. This PCB drives the activation or deactivation of the resistance(s) based on simple rules. Generally, the ESWH will try to keep its storage tank (precisely the temperature probed) in a range of temperatures, for instance between 50 and 60°C. If the temperature goes below the lower limit, the resistance is activated and runs until it reaches the upper limit. These upper and lower temperature limits are function of the manufacturer.

The temperature inside the tank is function of different phenomena. The first and the most influent one is the stratification: As hot water is slightly less dense than cold water, the hot water will take place at the top of the tank, creating a natural stratification. Stratification is a sought-after phenomenon in hot water tanks, as it allows more demand to be satisfied (the temperature of the upper layer can remain close to 60°C while 80% of the balloon is at the inlet temperature, right after a long draw-off like a bath). On the other hand, natural phenomena will contribute to destroying this stratification (Kepplinger, Huber, Preißinger, & Petrasch, 2019):

- The losses to the environment, which will be greater at high temperature layers;
- The natural convection resulting from a temperature gradient at the tank wall;
- The conduction between the different layers of the tank, which will tend the tank towards a uniform temperature;
- The mixing between layers due to the energy brought in the form of heat by the electrical resistance. If the layers that are at the level of the resistance see their temperature being higher than the temperature of the top layer, the water in the lower layers will then move towards the upper layers, creating a natural convection phenomenon.

This last point leads to the fact that, if all the energy in the tank has been drawn from it, the hot water from the top layer will only reach its maximum temperature again after the resistance has brought the entire tank to this temperature. This is the reason why there are tanks with two resistances: the top resistance is used to reduce the heating time before hot water at the top layers is available for drawing.

There exist several models that all rely on the same basic assumption: at a given height, the temperature is considered uniform along the other axes. Doing so highly simplifies the model, by transforming a 3D problem (x, y and z axis) into a 1D problem (only z axis), where the temperature is function of height. This simplification therefore neglects side effects like natural convection due to the temperature difference between the water and the tank wall. However, although these effects participate to stratification destruction, the phenomena will be assumed negligible compared to the mixing effect and the conduction between layers.

6.1. Literature review : existing models

Several models exist to describe the temperature evolution in the tank. Each one has its own specificities, its degree of precision and its necessary calculation time. On this subject, Kepplinger *et al.* (Kepplinger, Huber, Preißinger, & Petrasch, 2019) have published a paper comparing, in terms of accuracy and calculation time, the different usual methods used to model hot water storage tanks. This section will be entirely based on their work to describe the different models except for the Multi-Node model, which is also based on (Wong & Negnevitsky, 2013).

Two of the four nodes will be described much less than the two others because there are not interesting to investigate in this report for reasons explained in Section 6.1.5.

6.1.1. Single-Node Model

The single node model (SN) consists of taking the entire hot water tank as a single layer. As a result, there are no conduction terms between the layers, making calculations simple. The evolution of the temperature in the tank is governed by the following formula:

$$m c_p \frac{dT}{dt} = P(t) - Q(t) - UA(T - T_{amb})$$

Where m is the mass of water in the storage tank, C_p the specific heat of water [J/kg/K], P the power supplied by the resistance [W], Q the power withdrawn [W], U the heat transfer coefficient [W/m²/K], A the surface area of the storage tank shell [m²] and T_{amb} the ambient temperature in the surroundings of the storage tank. Here, the terms $P(t)$ and $Q(t)$ are piece-wise continuous and have a rectangular window shape over time. One solution is to solve this equation analytically, assuming that P and Q are constant when these terms are non-zero. This gives:

$$T(t) = T_0 e^{-\frac{UA}{C_p}(t-t_0)} + (1 - e^{-\frac{UA}{C_p}(t-t_0)})(\frac{P}{UA} - \frac{Q}{UA} + T_{amb})$$

This equation is valid only for the time interval $[t_0, t_0 + t]$ when there is no changes in P or Q. If it does, the term t_0 must reset at 0. Another possibility is to solve the initial equation with a numerical integration tool, such as Runge-Kutta of order 4 (RK4).

In both cases, the SN model excels in its simplicity, which greatly reduces the computation time and thus becomes an ideal candidate for embedded systems or systems with low computing power. The drawback is the lack of information: it is impossible to know the temperature of the upper layer, neither the real temperature that the probe senses.

6.1.2. Multi-Node Model

In contrast to the single node, the multi node will divide the hot water tank into n layers of the same height h, as shown in Figure 26. Each layer i has a uniform temperature T_i. Heat exchanges by conduction will take place from layer i to the upper $(i + 1)$ and lower $(i - 1)$ layers, which is represented by conduction terms such as $\frac{kA(T_{i-1}(t) - T_i(t))}{h}$, where k is the thermal conductivity of the water, assumed to be constant and equal to 0.6 [W/m/K] and A is the cross-section of the tank, assumed to be cylindrical. The drawing of hot water from the first layer and the filling of cold water from the bottom of the tank will induce a translation of the layers upwards. In order to model this translation with defined and fixed layers, one will introduce the term $\dot{m} c_p (T_i(t) - T_{i+1}(t))$ in the energy balance of the layer i, with $\dot{m}$ the flow rate and c_p the specific heat of the water. It can be observed that in the case where the draw-off is zero or the layers are at the same temperature, the term is equal to 0. The last term represents the wall losses, $US_e(T_i(t) - T_{amb})$, where U is the heat transfer coefficient in [W/m²/K] and S_e is the surface of the layer in contact with the cylinder wall.

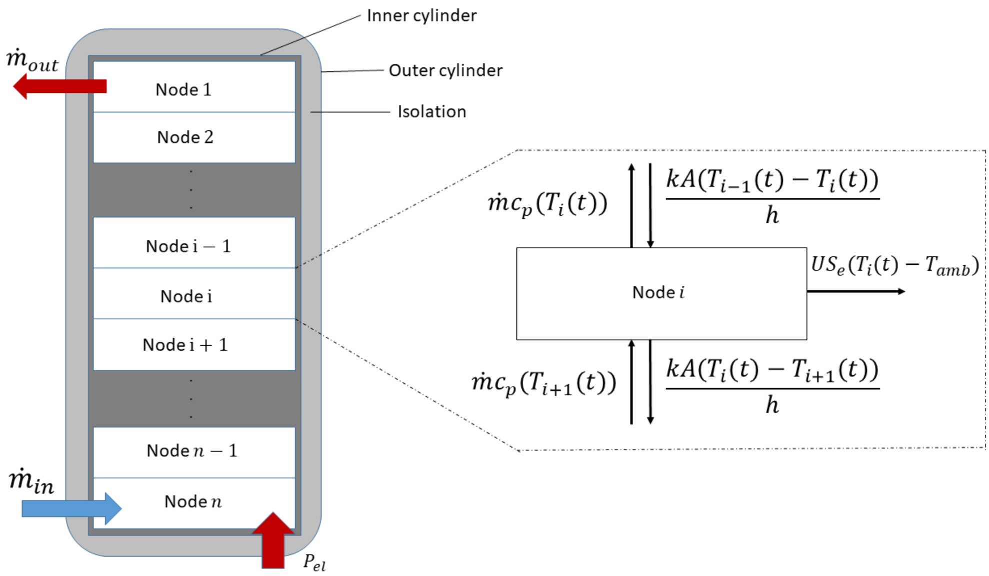


Figure 26 : Graphical representation of the multi-node model

The presence or not of a part or the whole of the electrical resistance will induce an additional term related to it: δP_{el} with $\delta = \{0,1\}$ the Kronecker delta, set to 1 in the layer with the resistance, and P_{el} the electrical power of the resistance. This leads us to the general equation for a layer i:

$$mc_p \frac{dT_i}{dt} = \dot{m}c_p\big(T_i(t) - T_{i+1}(t)\big) + \frac{kA(T_{i-1}(t) - T_i(t))}{h} + \frac{kA(T_i(t) - T_{i+1}(t))}{h} - US_e(T_i(t) - T_{amb}) + \delta P_{el}$$

It should be noted that $\delta = 0$ in all circumstances for layers not in direct contact with the resistance. The first and last layers have an equation adapted due to the absence of an upper and lower layer, respectively. For the first, it becomes:

$$mc_p \frac{dT_i}{dt} = \dot{m}c_p\big(T_i - T_{i+1}(t)\big) + \frac{kA(T_{i+1}(t) - T_i(t))}{h} - U(S_e + A)(T_i(t) - T_{amb}) \quad , \quad i = 1$$

And for the last:

$$mc_p \frac{dT_i}{dt} = \dot{m}c_p\big(T_{in} - T_n(t)\big) + \frac{kA(T_i(t) - T_{i-1}(t))}{h} - U(S_e + A)(T_i(t) - T_{amb}) + \delta P_{el} \quad , \quad i = n$$

Finally, it is necessary to incorporate the phenomenon of de-stratification, which will be seen in the model as the fact that, for a layer i, its temperature turns out to be lower than that of the layer just below it $(i + 1)$, which can be the case when the resistance injects energy into the lower layers. In this case, the hotter water will rise in the tank and a mixing phenomenon will occur. This will be mathematically translated as (Wong & Negnevitsky, 2013):

$$T_{i,new} = mean\{T_{i,old} + T_{i+1} + .. + T_{n-1} + T_n\}$$

This verification will be done for each couple of layers, starting with the layers $\{n, n-1\}$, and the equation above will be applied as long as there is an upper layer higher in temperature than a layer below. All these differential equations therefore form a system of interdependent equations, which can be solved by numerical integration methods, such as the RK4.

The multi-node method has the major advantage of being of good precision compared to other methods, this precision being proportional to the number of layers that make up the tank. On the other hand, the equation system is the heaviest, which significantly increases the calculation time.

6.1.3. Two-mass composite model

The two-mass composite (2MC) model is based on switching from the SN model to a two-node model in the case where hot water is drawn, then calculating the relative height $0 \leq h_2 \leq 1$ of the remaining part of the tank that is at high temperature, as shown in Figure 27. This gives the following differential equation:

$$mc_p \frac{dh_2}{dt}(T_2 - T_1) = P_{el} - \dot{m}c_p(T_2 - T_1) - (1 - h_2(t))UA(T_1 - T_{amb}) - h_2(t)UA(T_2 - T_{amb})$$

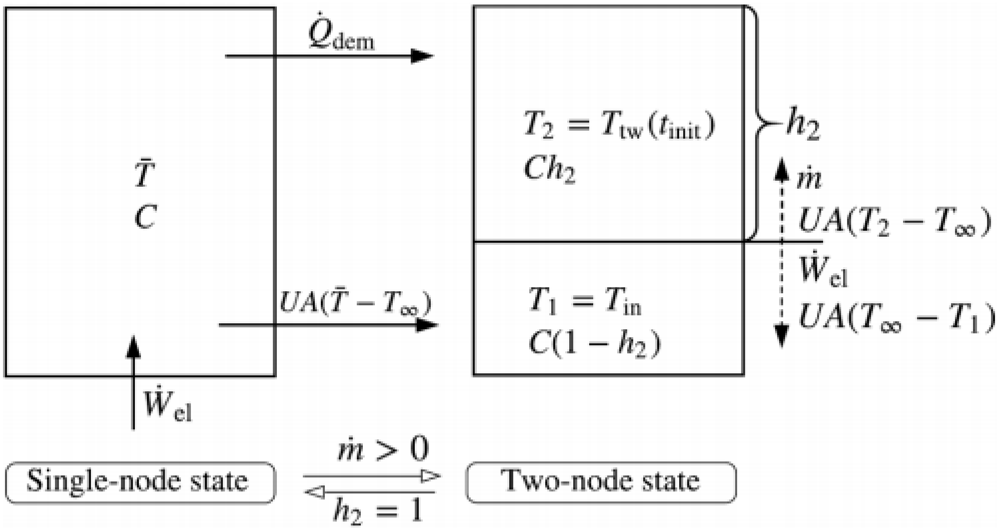


Figure 27 : Two-mass composite model. (Source: Kepplinger *et al.*)

Note that conduction effects between the two layers are neglected in this model. In addition, the temperatures of the two layers are considered constant during a draw. The estimation of the state of charge of the storage tank is calculated only via the equivalent height of the hot layer. When the model switches back to the SN model, the equation used is the one showed in Section 6.1.1.

6.1.4. Two-node hybrid model

The latest model is greatly inspired by the 2MC model, but this time it incorporates the heat exchange by conduction between the two layers. There is thus an additional equation into the system and the additional term $\frac{2kA_c}{h}(T_2 - T_1)$.

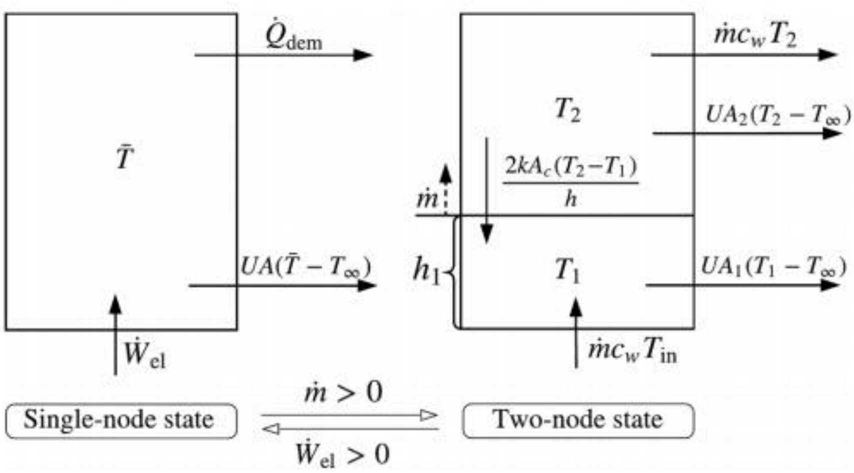


Figure 28 : Two-node hybrid model. (Source: Kepplinger *et al.*)

This model is a bit more complex and a bit more precise than the two-mass composite model. It gives, like its predecessor, an estimation of the state of charge via the equivalent height of the hot layer.

6.1.5. Comparison of the different models

The four models described can give an estimation of the average temperature of the tank as well as an estimation of the outlet temperature. However, according to the authors of the comparison study (Kepplinger, Huber, Preißinger, & Petrasch, 2019), only two models are really relevant:

- The SN model: This model excels by its simplicity and the fast computation time, making this model an ideal candidate for cheap embedded systems. Moreover, if the initial conditions are correctly defined, this model becomes more accurate than the two-mass composite and the two-node hybrid model.
- The MN model: This model is the most accurate of the 4 models in every domain. Its accuracy is function of the number of layers it is composed. However, the computation time is the largest of the four models.

The major advantage of the MN model is the multi-layers fact. This allows to know the temperature of each layer and thus, if there is enough layers, allows the possibility to model the temperature sensor of the ESWH.

6.2. Comparison between single-node and multi-node

The objective here is to compare the two models and define the impacts they have on water tank behaviour. To do so, a profile will be determined randomly. From the profile's PPH, certain characteristics of the tank will be tuned, notably its dimensions and volume. The latter will be determined as follows: 150L for 1 or 2 PPH, 200L for 3 PPH and 250L for 4 or 5+ PPH. The choice may be surprizing by the large sizes of these boilers, which take into account only water heaters from single houses and not ESWHs present in most rental apartments with smaller volumes (100…150 L). This is due to security reasons regarding the aggregator. The latter is more likely to deal with ESWH with larger energy content in order to avoid as much as possible the risk of leading to any discomfort.

In terms of dimensions, height is generally favoured in relation to the ground surface. Thus, the inner diameter (D) of the tank will be fixed at 0.5 [m] regardless of its volume (V). Next, a typical 50mm thick layer of rigid polyurethane foam (for a U-value of 0.7 W/m²/K) is considered for the insulation (Armstrong, Ager, Thompson, & McCulloch, 2014). Finally, the height (h) can be determined from the equation of the volume of a cylinder:

$$V\ [m^3] = \frac{\pi D^2 h}{4} \leftrightarrow h = \frac{4V}{\pi D^2}\ [m]$$

These characteristics may define therefore the standing losses of each tank type and the energy efficiency class associated following the EU standards is also given for information (Kenma, van Elburg, & Aarts, 2019) as shown in Table 7. Finally, the resistance will be assumed unique, placed horizontally at the bottom of the tank and with a nominal power of 2 kW. The summary of the boiler characteristics is summarized in Table 8.

Table 7 : Characteristics of boilers based on the PPH of the household and several assumptions

PPH	VOLUME [L]	LOSSES (kWh/24h)	Energy efficiency class
1 or 2	150	1.2	B
3	200	1.5	C
4 or 5+	250	1.81	C

Table 8 : Summary of tank characteristics. Some values are function of the PPH

Tank characteristic	Volume (L)	Inner diameter (m)	Height (m)	U-value (W/m²/K)	Resistance power (kW)	Resistance position
Value	150 / 200 / 250	0.5	0.76 / 1.01 / 1.27	0.7	2	Bottom, horizontal

Consumption data are initially expressed in litres of water at 40°C. However, the water temperature at the top layers will not be at this temperature. As a result, the amount of water taken from the tank will be more or less important, i.e. a smaller volume of water at 55°C will be necessary to fulfil a fixed amount of water at 40°C that the consumer will need for his shower/bath/tap. In order to adapt this consumption, this volume can be converted back into energy demand:

$$\dot{m}_1 c_p (40 - T_{in}) = \dot{m}_2 c_p \left(T_{up} - T_{in}\right)$$

With $\dot{m}_1$ the quantity of water requested by the consumer at 40°C, $\dot{m}_2$ the quantity of water to be drawn from the storage tank, T_{up} the temperature of the top layer of the storage tank and T_{in} the temperature of the inlet water (injected at the bottom of the storage tank). This temperature may vary over the seasons (see Section 3.2), but will be considered here as constant and equal to 10°C. The quantity of water drawn from the tank is thus defined as:

$$\dot{m}_2 = \dot{m}_1 \frac{(40 - T_{in})}{(T_{up} - T_{in})} \left[\frac{kg}{s}\right]$$

From this last equation, it can be noticed that once $T_{up} < 40$°C, it means in concrete terms that the user is at the maximum of the three-way valve and still feels a temperature below 40°C and decreasing, which will be defined as a discomfort feeling.

The major difference will be the reference temperature with which the boiler will decide to switch on or off. For the SN model, the decision is made with the average temperature while for the MN model, the temperature of the layer right above the layer containing the resistance will be the reference. The number of layers for the MN model will be 7. This choice gives enough precision and not too much computation time. Moreover, it allows the layer containing the temperature sensor to be close enough to the resistance. The two boilers will have to keep the temperature (the average for SN model and the temperature of the sensor's layer for the MN model) in the bandwidth of [50, 60] °C.

6.2.1. Results of the comparison

Results are presented in Figure 29. The two boilers start at 60°C and follow a random consumption of a households of 4 occupants (4 PPH) in green. The solid lines are the average temperatures of the two models, and the dashed lines represent the activation/deactivation of the resistance. It can be observed that the time of activation may strongly differ. Precisely, the MN model activates its resistance earlier than the SN model. However, the total duration of activation is the same for both models (509 minutes) which seems logical since the energy demand through water draws and the wall losses are in both cases correctly estimated. Besides, the SN model goes back to an almost correct estimation after an important draw like the one at 10h. Regarding the computation time, the MN model achieve its calculation after 0.787 seconds while the SN models did it in less than 0.007 seconds.

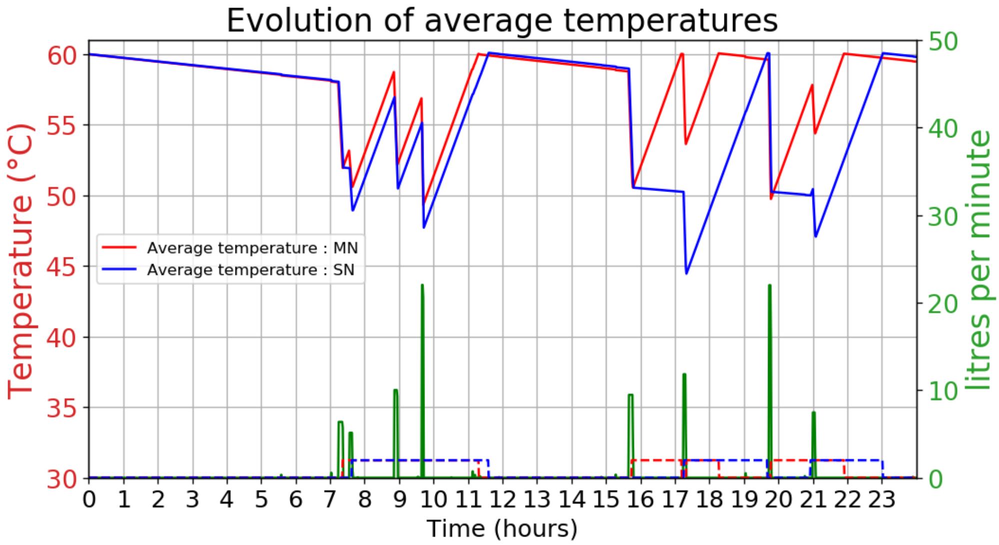


Figure 29 : Results of the comparison between SN and MN models, the two boilers following the same consumption profile of 4 PPH in green.

This shows than the SN model is quite capable to give a good estimation of the tank evolution with a much lower computation time. However, large difference may appear regarding the activation time, especially with small draw-offs. Still, this model could be interesting if the tank concerned has a low volume (less than 100 litres) because each draw would be large enough to drop the average temperature lower than its dead band. Finally the low computation time allows cheaper embedded systems.

6.2.2. Looking deeper into the MN model

In order to analyse the results of the MN model, the same profile and initial conditions as for the Figure 29 is used. As reminder, the MN model will be here composed of seven layers, the last of them (layer 7) will includes the resistance and the one just above (layer 6) contains the temperature sensor. The result are presented in Figure 30. It can be seen that the lower layers are more sensitive to draw-offs, but their temperature rise rapidly when the resistance is activated. On the contrary, the upper layers are mostly influenced by wall losses. However, when their temperature drops, the layer has to wait that lower layers go back to their temperature to rise anew. This is due to the mixing effect. Moreover, due to the same effect, it takes more and more time for the boiler to reach 60°C.

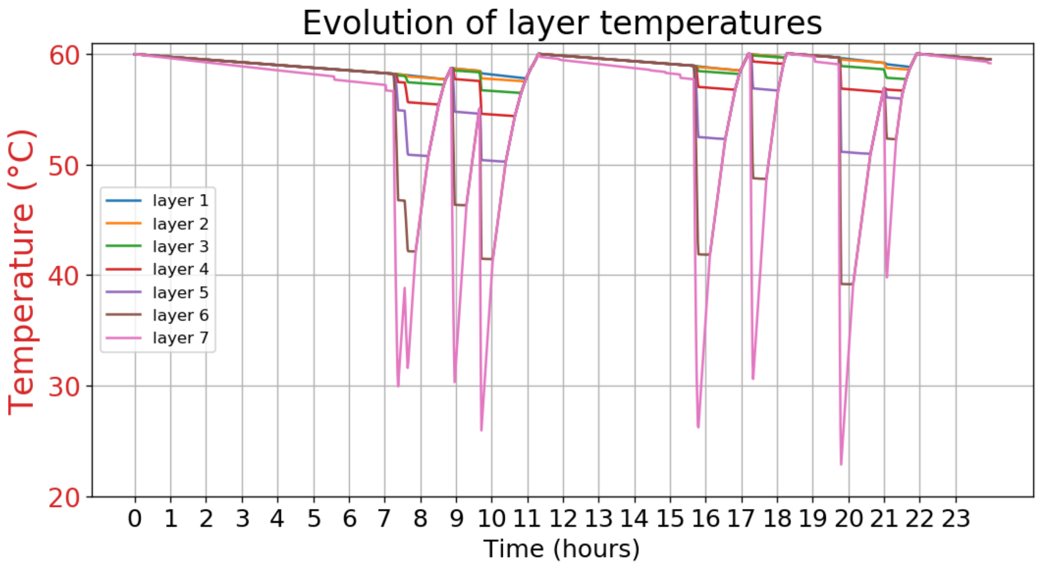


Figure 30 : MN model with each layer. The lower layers (5-7) are much more sensitive to draw-offs, while the upper layers (1-4) stay at a relative constant temperature.

6.3. Definition of the SoC for the MN model

Rather than looking at the temperature of the layers, it would be more interesting to look at its state of charge (SoC), which is then more flexible in relation to the accepted guidelines. The SoC will be defined as follows:

$$SoC_{layer}[\%] = 0 \leq 100 * \frac{T - 40}{T_{max} - 40} \leq 100$$

This SoC is always defined under the assumption that the requested temperature is constant and equal to 40°C. The advantage of expressing the storage tank according to its SoC is that it is possible to clearly define what energy is left in the storage tank. Figure 31 shows the different SoC of some layers, as well as two types of averaged SoC (dashed lines). The first, in red, is the SoC of the average temperature in the tank. The second, in black, is the average of the SoC of all layers. The major difference is visible when one or more layers go below 40°C. Taking the example of the major draw at 7h, the average temperature in the tank is close to 40°C, leading to a SoC of almost 0%. However, the upper layers still have energy available. As a result, the actual SoC of the storage tank is a bit below 40%. In summary, the total SoC of the tank will be defined as follows, where n is the number of layers:

$$SoC_{avg} = \frac{\sum_{i=1}^{n} SoC_i}{n}$$

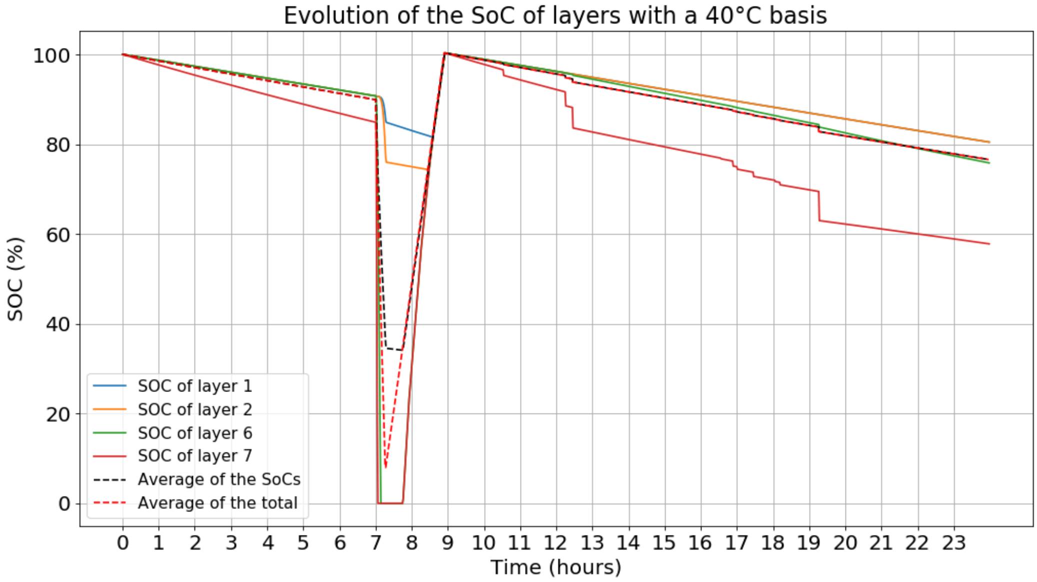


Figure 31 : This figure highlights the difference by taking only the SoC of the average or the SoC of each layer

6.4. Summary

Different models have been explored in this section, particularly the SN and MN models. The SN model reveals to be quite efficient especially regarding the computation time, which makes it a good model to use in case of small tanks (<100 litres) or if the focus is on the cheap cost of embedded systems. The MN model appears to represent more the reality of the boiler with a lot of precision and the possibility to simulate the temperature sensor as well as the mixing effect. Moreover, using a right definition of the layers' SoC, it is possible to give a good estimation of the energy remaining into the tank. The MN model will therefore be used for the rest of the report.

7. Towards control and aggregation

Now that the model (MN) has been chosen to simulate each hot water tank and that a pool of profiles can be randomly generated, this section will look at the control of this pool in order to respond to a setpoint. This setpoint may be defined as a certain power (fixed or variable) in kW that has to be reached by the pool and maintained for a certain period of time. In view of the different possibilities of participation in the energy market and the services to be offered to the TSO, one may seek different characteristics, like to have a constant setpoint for a long period of time (15...60... min) for markets such as DAM or IDM, to be able to respond very quickly for R1 ancillary services or to be able to modify its consumption volume for a longer period for R2 or R3 ancillary services. In any cases, a control method must be implemented in order to respond to the demand while minimizing the discomfort of the households participating in the pool.

7.1. Implementation of a control method

7.1.1. Definitions and assumptions

In order to make good use of the pool of households, an effective control method is essential. This control will be based on the information that each hot water tank will be able to provide, i.e. its average SoC and the current status of its resistance (operating or not). However, the reader should keep in mind that the SoC information and the layers' temperature in general are not readily information. They must be estimated, for instance with an identification procedure (De Ridder & Coomans, 2014). This will not be analysed in this report and it will be assumed that the temperatures are always known.

The control will be assumed achievable in only one direction: Currently, the control of a hot water tank by retrofitting is only possible by playing on the direct supply of the resistance. As a matter of fact, turning the device on would only be possible by overriding its internal thermostat, which would require modification of the device and it would therefore make the device unwarranted by the manufacturer anymore. Thus, it is impossible to directly control the switching on of the appliance, which is a function of the personal temperature setpoint, but it is possible to force the appliance to switch off by cutting off the power to it (an example is shown in Figure 32). This only leads to upward regulation (i.e. to reduce the power consumed by the pool and therefore to rise the frequency of the grid). However, as EU regulations are more and more pushing towards smart devices (European Parliament, 2018), it is likely that smart storage tanks (remotely controllable) will constitute a significant part on the ESWH market[8] in several years. There would then be compatible with a control system directly on the resistance, making bilateral regulation (up and down) possible. Here, the focus will be on the retrofitting of existing ESWH but a small test will be done with the hypothesis of bilateral regulation.

The control can only be done on a reduced temperature band. Indeed, the temperature cannot exceed 60°C ($SoC = 100\%$) to avoid scalding risks and should not be controlled if the temperature is below 40°C ($SoC = 0\%$), because any draw would cause discomfort. This feeling of discomfort will therefore be defined as follows: For each time step t, if $SoC(t) = 0\%$ or less (if the temperature of each layer is $\leq 40°C$) AND if there is a hot water draw at this moment, the consumer will feel discomfort. This discomfort will be quantified according to whether or not a household has

[8] *Some models "smart grid ready" already exist: http://www.uscraftmaster.com/products/electric/energy-smart-electric-water-heater/*

experienced discomfort at least once during the day under the form of a Boolean for each household.

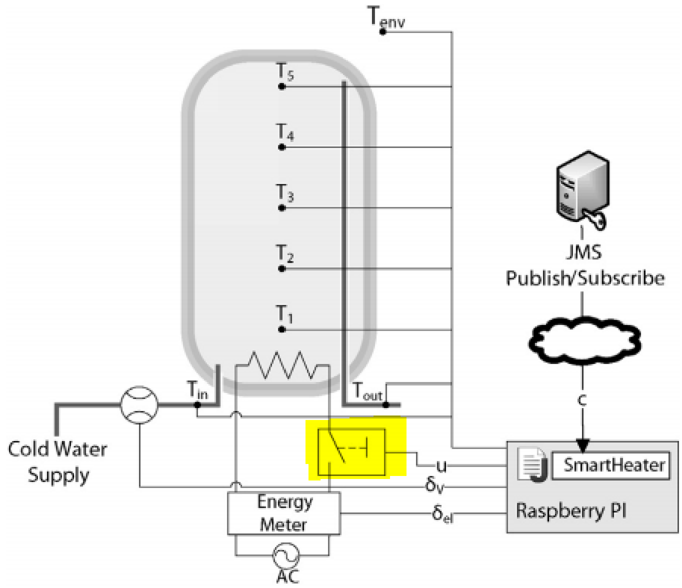


Figure 32 : Example of how to control the resistance. The controller, highlighted in yellow, is external to the water heater. (Kepplinger, Huber, & Petrasch, 2016)

Since we want to avoid any consumer discomfort, two rules will be applied at each timestep to each tank in order to define if the latter is available for flexibility:

- The average tank SoC must be high enough: The tank has to have a security margin before any control because a sudden large draw-off event may appear the next minute;
- The tank must not be used during the control: If the tank is already solicited by a large draw-off event like a shower of a bath, it would be dangerous to impose a control.

These two rules will take slightly different forms whether the regulation is unilateral (upward only) or bilateral. Furthermore, each tank has to first intrinsically refresh its status (see below) before applying these rules. All these information will be sent to the "controller", which is here defined as the aggregator.

7.1.2. Individual status refreshing

At each timestep, so after each minute, the tank will probe its temperature. Depending of the result, the tank will activate or deactivate its resistance. The upper and lower limit of temperature is generally function of the manufacturer but it is reasonable, considering the scalding risk, the legionella risk and the consumer's desired temperature, to assume these limits to be 50°C and 60°C for the lower and upper limit respectively. This corresponds to a SoC of 50% and 100% at the probed layer (at the bottom of the tank).

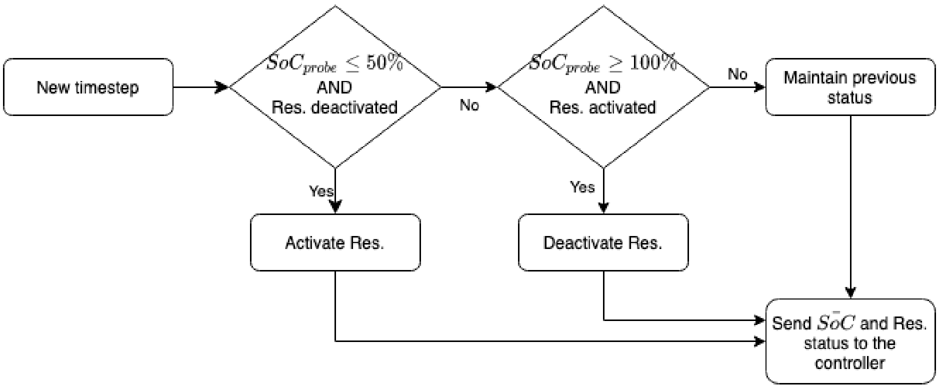


Figure 33 : Flow chart of the tank's status refreshing. Here, "Res." stands for resistance.

The device wants thus to keep the probe layer within the bandwidth of [50°C, 60°C]. To do so, the simplest method is a hysteresis control, consisting of activating the resistance when the temperature at the probe goes below 50°C and to keep the resistance activated until the probe temperature reaches 60°C. Considering the mixing effect, this is equivalent to say that the resistance stops when the full tank is at 60°C. The flow chart is shown in Figure 33. Finally, each tank will send its new status to the controller, i.e. its average SoC (as defined in Section 6.3) and its resistance status.

It has to be noticed that the status refreshing of the tank's resistance is a simple model of the intrinsic behaviour of the water heater. The fact to send the SoC and the resistance status is a part of the control system, like an embedded device connected to the tank.

7.1.3. Setting availability for upward regulation only

The tank has now to apply the two rules previously cited (i.e. a SoC high enough and a device not solicited) to minimize the risk for the consumer of feeling a discomfort. Since here only the upward regulation is considered (i.e. the controller may only force the device to switch off), the first rule is only a lower limit condition:

$$40\% \leq \overline{SoC}(t)$$

The lower limit set at 40% is a compromise between having a security margin and having a pool of energy large enough to be consequent, but this lower limit will be studied later in the report. Regarding the second rule, it will be mathematically translated as:

$$\overline{SoC}(t-1) - \overline{SoC}(t) \leq 2.5\ [\%]$$

In other words, if the SoC freshly calculated at the timestep t is 2.5% lower than the SoC one minute before, it means that the ESWH is being solicited by a shower or a bath and therefore it is risky to switch off the resistance. The threshold of 2.5% is set to be large enough to neglect small draw-offs like tap draws – a tap draw is in average 1 litre at 40°C, but small enough to detect the two other events. Moreover, when the tank upper layer's temperature begin to fall, the volume of water necessary to fulfilled the event is larger (there is more water at 55°C needed to fulfilled the demand than for water at 60°C). This implies that the less energy there is in the tank, the more sensitive to small draw-offs this rule becomes. The resulting flow chart is illustrated in Figure 34.

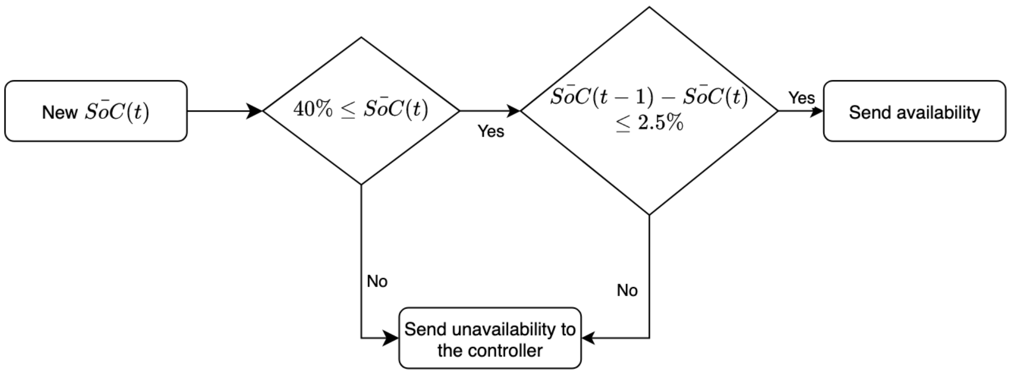


Figure 34 : Flow chart regarding the (un)availability of the water heater at each timestep

7.1.4. Setting availability for bilateral regulation

The case of bilateral regulation is a bit more complex because it is possible to control the water heater in both ways. Therefore, some circumstances may lead to an unavailability for a regulation, but not for the other. For example, if the water heater just began to be solicited by a shower event, this water heater will become unavailable for upward regulation. However, it would reduce the risk of discomfort if the resistance is rapidly activated after the event beginning. There is thus an additional priority factor to take into account.

Regarding the first rule (having a SoC high enough), the lower limit stays the same. Nevertheless, one must put also an upper limit to avoid rapid switching perpetuated by the controller. For example, if the controller needs that a great part of the pool stays activated, it could force some tanks that have a SoC of 99% to switch on, but right after the tank has to switch off because its SoC reached 100%. Therefore, to avoid these situations, a hysteresis is implemented under the form of an upper limit:

$$40\% \leq \overline{SoC}(t) \leq 95\%$$

For the second rule, it has the same definition as the one for upward regulation:

$$\overline{SoC}(t-1) - \overline{SoC}(t) \leq 2.5\ [\%]$$

However, if this rule is not respected, a priority marker will be also sent to the controller to have the activation priority. As the bilateral case allows to activate the resistance, it is no possible to help the solicited tanks by directly maintain (or switch on) the resistance.

The flow chart is shown in Figure 35. Four cases may be distinguished from the two conditions. For each case, the regulation availability is written in green while the unavailability is shown in red. Finally, the priority marker is displayed in blue. From this flow chart, it can be said that bilateral regulation offers a lot more flexibility than upward regulation only, but also more complexity.

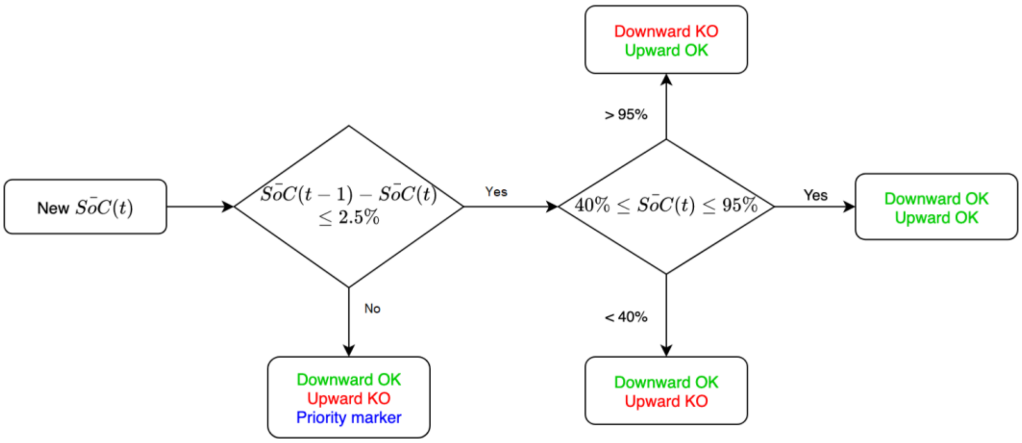


Figure 35 : Flow chart for bilateral regulation.

7.1.5. Control methodology

At this stage, the controller just received the SoC, the resistance status (activated or deactivated), the (un)availability for the different regulations and eventually a priority marker from each ESWH. The control method, summarized in Figure 36, will be based on a setpoint, noted P_{set} which can be constant or variable. At each time step it will count the current power consumed by the pool, noted P_{pool}, and compare it to the setpoint. The comparison of the two values can then lead to several scenarios:

- If $P_{pool} = P_{set}$, then the setpoint is reached so no control is made.
- If $P_{pool} > P_{set}$, the pool's power consumption must be reduced to meet the setpoint. The controller will then sort the different available storage units in the pool in **descending order of SoC**. The controller will then deactivate the ESWH units starting from the beginning of the list (and therefore from the highest SoC) until the setpoint is reached or until there is no available device left for upward regulation.
- If $P_{pool} < P_{set}$, the pool's power consumption must be increased to meet the setpoint. The controller will first activate the eventual marked devices until P_{set} is reached or there is no more marked devices not activated. Then, it will sort the rest of available storage tanks in the pool by **increasing order of SoC**. The controller will then activate the storage tanks starting from the beginning of the list (and therefore from the lowest SoC) until the setpoint is reached or until there is no available device left for downward regulation.

If at the end of the day the setpoint is nevertheless not respected, which can happen when the majority of the tanks are unavailable, the controller will then record the difference between the current power consumption and the requested setpoint. The fact to sort available devices by increasing or decreasing order of SoC is here to minimize the risk of user discomfort.

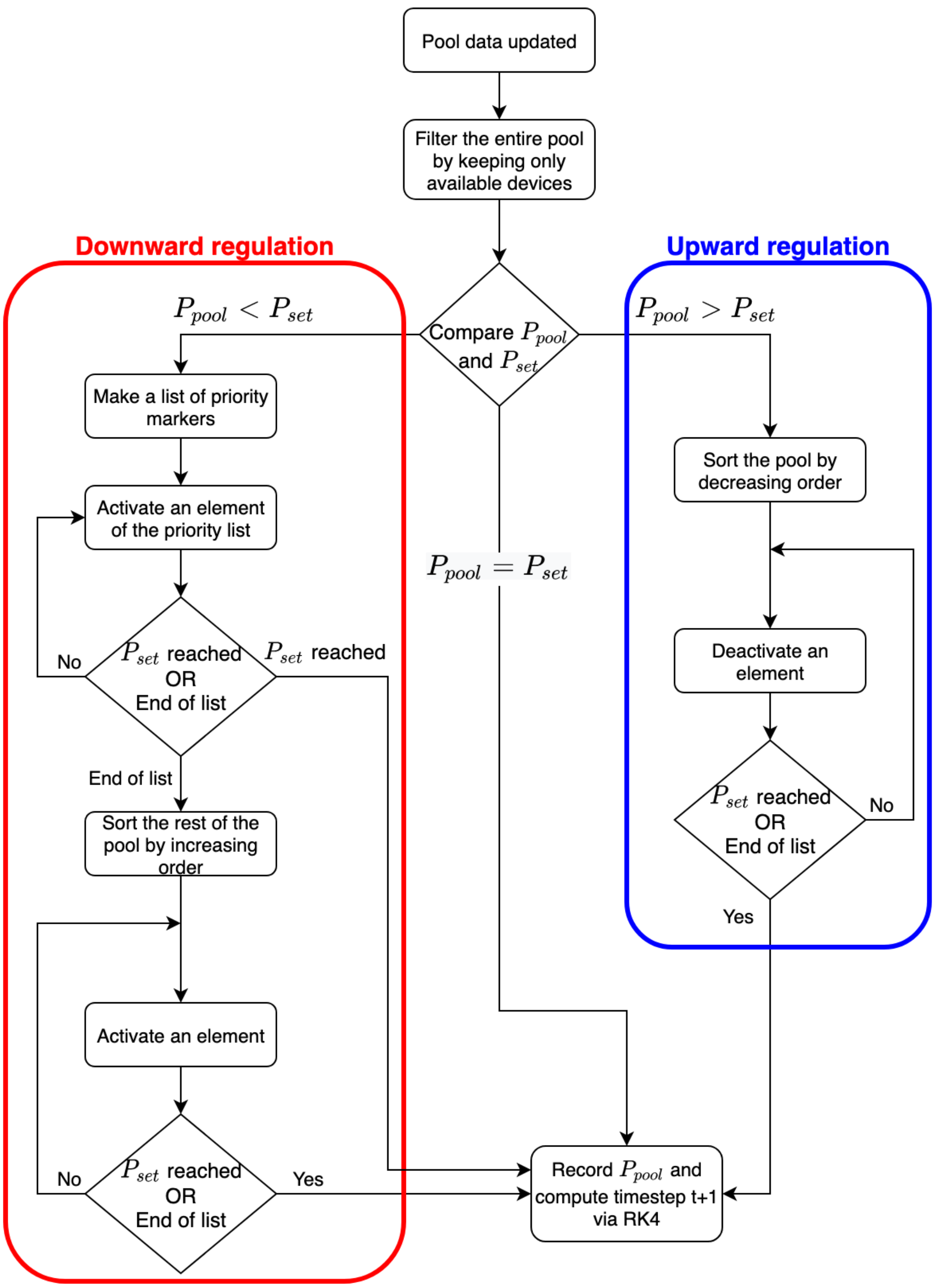


Figure 36 : Decision tree of the controller in order to reach the setpoint P_{set} from the current power P_{pool}. In the case of an upward regulation only, only the central and the right branches are considered.

It should be noted that, in the decision tree shown in Figure 36, the condition that $P_{pool} = P_{set}$ is possible in the simulations that will be made due to the constant value (2 kW) of the resistances but is not realistic in practice. This is because not only do the tanks have different resistances of different power ratings depending on the manufacturer, but also because the resistance provides a power that may vary slightly over time due to inrush currents for instance. The condition can then be adapted to become:

$$|P_{pool} - P_{set}| \leq \epsilon$$

With ϵ defined as an arbitrary small positive value. The other two conditions will also have to be adapted accordingly. For the downward and upward regulations, we have respectively:

$$P_{pool} + \epsilon < P_{set}$$

$$P_{pool} - \epsilon > P_{set}$$

7.2. Investigated cases

Now that the control methodology is defined, different cases will be simulated to evaluate the flexibility potential of an aggregation of ESWH devices. With regard to the requirements demanded by the various electricity markets and their bid possibilities, two types of control will be investigated:

- The baseload case: A first interesting case is to control the power consumed by the pool by imposing a constant setpoint throughout a day that the pool has to follow continuously. If the baseload case functions well, it would allow the aggregator to place a well-defined volume on the market, leading to the possibility of bidding this volume on DA and ID markets without any risk of creating imbalances.
- The "peaker" case: As a reference of gas peaker power plants, this case is defined as a **relative and sudden** increase or decrease in the consumption of the pool in relation to what the pool would normally have consumed, for a defined period of time (30min…1h…3h). It is important to notice that this change is relative. This means that, during the control, the difference between the consumption forecasted and the actual consumption is constant. The reason is that the volumes bid on electricity markets must be constant (except for R1 and R2 ancillary services), at least for the bid duration. Moreover, the aggregator has to prove somehow to the TSO that he respected his bid, and this can be done by comparing the actual and forecasted consumptions (if the aggregator have passed the tests to prove its reliability). The fact of proving that the aggregator provided its flexibility is a whole subject on itself and is out of the scope of this report.

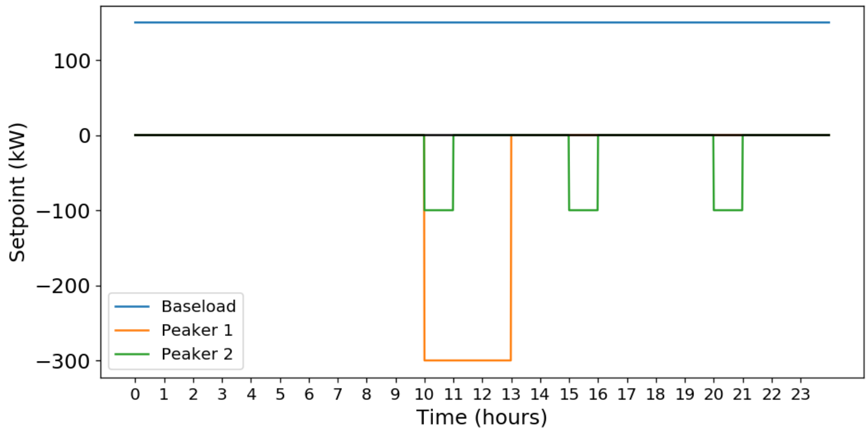


Figure 37 : Example of the baseload and peaker cases. Peaker cases are represented only for upward regulation because the bilateral regulation will not be investigated.

The two cases are illustrated in Figure 37. The peaker case may take multiple forms: it can happen once or several times in a day, with different or equal volume sizes. From these two cases, there are multiple variation possible that won't be investigated in this report in order to reduce the scope. For example, one could take the baseload case and do an optimization with the DAM price. This would result in a baseload case with slightly different setpoints (1 per hour). Another thing would be to do peaker cases with upward and downward regulation, which could lead in a lot of possibilities. Finally, another case interesting case will not be investigated: the tracker case. This consists on the fact that the pool has to continuously follow a setpoint variable through time. This case could help to determine the pool flexibility potential in R1 market.

7.2.1. Initialization of the pool

First, a sufficiently large pool has to be created. To do so, the following procedure is applied:

1. A pool of 1000 households is stochastically generated the same way as explained in Figure 23 in Section 5.1.3. All the profile data (i.e. the consumption of each household at each minute and their respective PPH) are stored.
2. In a second step, each profile will be assigned to a tank and each tank volume is determined on the household's PPH. The profile of each tank is completed based on the Table 8 in Section 6.2. It is important to notice that, regardless of their volume, each tank is equipped of a single resistance of 2 kW placed horizontally at the bottom of the tank.
3. Random initial (t=0) temperatures are assigned for each layer of each tank.
4. Then, at each timestep t (1 minute), starting at t=0, the next temperature values for each tank are computed with the RK4 method. Eventual draw-offs are taken into account.
5. At the end of the computations, the final temperatures of each layer as well as the state of the tank resistance (ON/OFF) are kept and reinjected back as initial conditions into another simulation (step 4).
6. At the end of computations, the resulting aggregated consumption profile is finally kept as a reference.

In a nutshell, the pool is created in steps 1-2. However, the initial conditions of step 3 are not realistic. Therefore, the program runs once (step 4) and take the final values of temperature plus the resistance state in order to set them as more realistic initial conditions. Finally, steps 5-6 are here to extract the "initial" profile, i.e. the profile the pool would have if it wasn't controlled. This profile will be the reference when there will be a need to compare values obtained after control with values without control.

7.2.2. Comparison between water and power consumption profiles

Before any aggregator control, the first interest is to see whether it is possible to link efficiently the water consumption from the pool with the power consumption from the ESWH's resistance composing the pool as shown in Figure 38 shows this comparison for a pool of 1000 households. The most relevant information is that there is an observable delay between draw-offs and ESWH activations. Precisely, the delay between minima and maxima of the two curves is generally 1 hour but it may extend up to 2 hours. This is due to the fact that the tanks act as a buffer. This buffer effect is also visible into the smoothness of the resistance consumption curve while the water consumption curve, composed of sudden draws, is more chaotic. Finally, the resistance consumption is always slightly higher (10-100 kW) than the water power consumption. This relates to the wall losses that every tank is subject to.

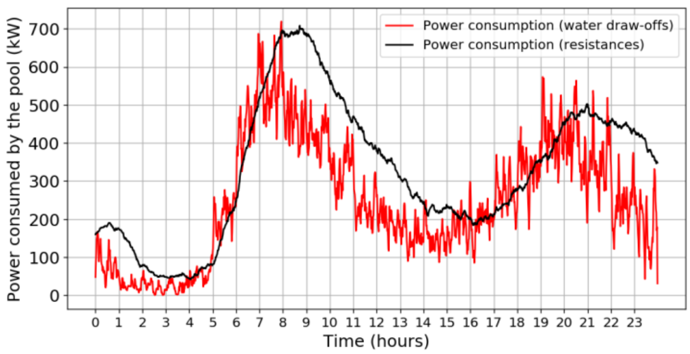


Figure 38 : Comparison, for a pool of 1000 households, between the power-equivalent of the pool's draw-offs (red) and the power consumed via the ESWH (black)

8. Parametric study : Baseload case

The baseload case is defined as the fact to control the consumption of the pool by imposing to the latter to follow a setpoint. This setpoint is thus a fix amount of kW. This section aims to quantify the efficiency of the baseload and to define the influent parameters. At first, only the upward regulation will be considered but at the end of this section, a chapter is reserved for bilateral regulation.

8.1. Overview of the baseload effect on the consumption

Let us first look at the effect the baseload has on the consumption profile. Figure 39 shows a comparison between the reference curve – without any control – in black and the baseload curve in red for a pool of 1000 households. The blue curve represents the flexibility potential i.e. the power that the aggregator can switch off. The baseload setpoint is here set at 256 kW.

Three effects are visible in this figure. Between 0-6h, since only upward regulation is considered, the aggregator is powerless to act and therefore the power consumption is the same as the reference. Once the consumption of the pool reaches the setpoint value, the aggregator may act on the consumption. Between 6h and 19h30, the aggregator controls efficiently the pool consumption and maintains it at the setpoint. However, after 19h30, a lot of tanks are lacking of energy and send their unavailability to the aggregator. Therefore, the latter cannot withstand anymore and the setpoint is not respected anymore. Still, the aggregator keep its influence to approach the setpoint as much as possible.

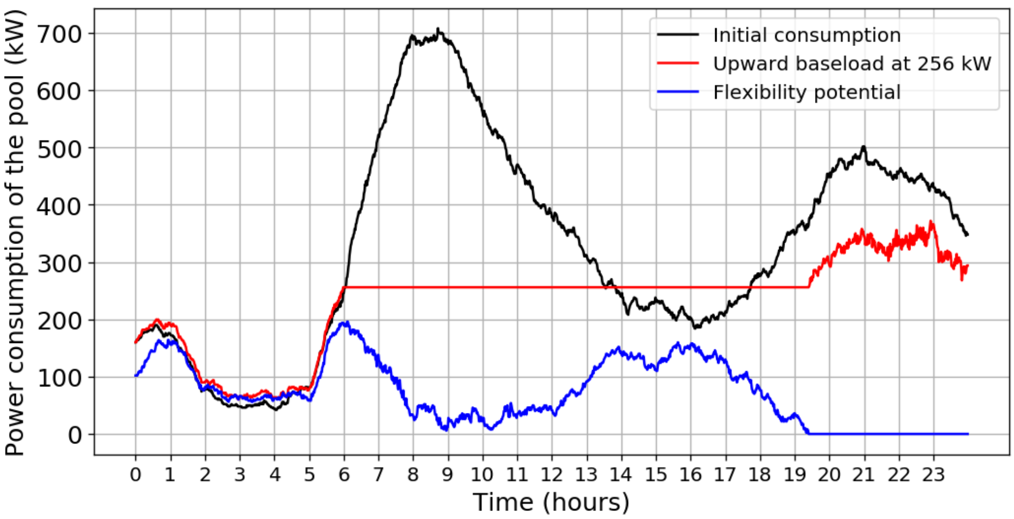


Figure 39 : Example of consumption of a pool of 1000 households in two cases: without any control (black) and with an upward baseload control (red)

This example shows the risks of having a too low or a too high setpoint: too low would lead to situations like the one that happens after 19h30, but a too high setpoint will increase the dips as the one between 0-6h. However, this could also mean that an optimum exists, which minimize the two effects.

8.2. Definitions

Before entering into the parametric study, two concepts have to be beforehand defined: the "level of imbalance" and the definition given to the discomfort.

8.2.1. Level of imbalance

The baseload may be seen as a sort of contract from the aggregator point of view. The latter has to keep the power consumption at the setpoint. When the aggregator cannot reach this objective in a way or another, the gap between the setpoint and the actual consumption will be called an "imbalance". This means that, at a certain timestep t and during one minute, there was a gap of X kW. However, the imbalance is quantified in kWh since this gap have been maintained for a whole minute.

There are two sorts of imbalances: the one resulting from a lack of consumption and the other one resulting from a too large consumption. These two imbalances are always positive values. Doing the sum of the two for the whole day will give the total, the level of imbalance (LOI). Mathematically, it can be expressed as:

$$LOI = \frac{1}{60} * \sum_{i=1}^{1440} |P_{set} - P_{pool,i}| \ [kWh]$$

Where the factor 60 is there to transform initial data (kW for a minute) into kWh and the sum counts each minute composing the day (1440 minutes per day).

However, during the parametric study, a lot of runs will be performed with different setpoints. Therefore, one needs to quantify the LOI computed in each run relatively to its setpoint. By imposing a constant setpoint, the aggregator has "bid" a volume of energy evaluated at $24 * P_{set}$ kWh for the entire day. Therefore, one can define the relative level of imbalance (RLOI) as:

$$RLOI = \frac{1}{60 * 24 * P_{set}} * \sum_{i=1}^{1440} |P_{set} - P_{pool,i}| * 100 \ [\%]$$

Taking back the Figure 39 showed above as example, Figure 40 shows the graphical representation of the RLOI. The latter is thus defined as the ratio between the LOI – the blue areas – and the volume "bid" by the aggregator – the green area.

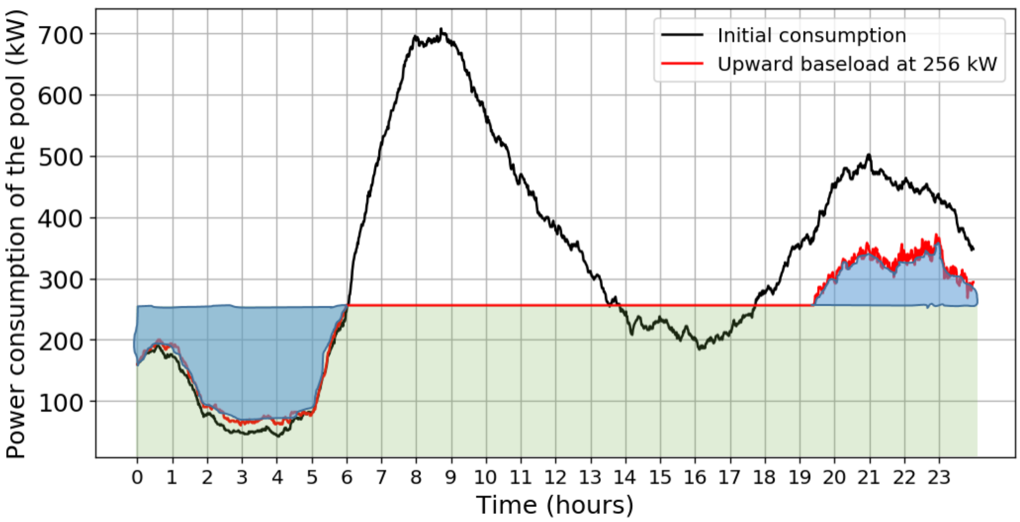


Figure 40 : Graphical representation of the RLOI, which is the ratio between the blue and the green areas

8.2.2. Discomfort

The discomfort is an important parameter to analyze because it will impact the user willing to participate to the aggregation or not. As it has been assumed that the draws always have a temperature of 40°C, the sensation of discomfort will be defined as the moment the outlet temperature (i.e. the temperature of the top layer) goes below 40°C. Due to the mixing effect, this means that the entire tank is below this temperature.

Once it is detected in a household, the latter will be flagged with a Boolean. If more discomfort feelings happen after that the household has been flagged, these discomforts are not taken into account. Therefore, at the end of the day, the discomfort parameter has the size of the pool as maximum limit.

8.3. Parametric study

As explained in the Section 3.2, the domestic hot water consumption is sensitive to two main parameters: the size of the pool which will play a role on the smoothness of the consumption and the inlet temperature which induce the consumption to be slightly seasonal. Regarding the control methodology, the SoC lower limit of controllability is also an important factor. Finally, it could be interesting to keep an eye on the effect the aggregator has on the total consumption of the pool. The reference value for these parameters are as follows:

- Pool size: 1000 households;
- SoC lower limit: 40%;
- Inlet temperature: 10°C.

The parametric study consists of a series of runs with different setpoints. To cover a wide range of possibilities, the setpoints will vary from 5-25% of the total pool's deployable power (i.e. the power the pool would consume if every boiler was activated at the same time). This means that, for a pool of 1000 households, the setpoints will go from 100 to 500 kW. Higher and lower setpoints are impossible to respect for the aggregator. This series of runs will be repeated for different values of the studied parameter shown above.

8.3.1. Pool size

The first parameter to check is the influence that the pool size may have. To do so, several runs of different pool sizes (200, 400, 600, 800 and 1000) will be done. These runs are however function of the total power deployable by the pool. It would be useless to run with a setpoint of 400kW with a pool size of 200 households, because it represents the totality of the pool's deployable power. However, it would make sense for a pool of 1000 households. Therefore, the runs will check for setpoints from 5 to 25% of the maximum pool consumption, with a step of 6kW. For instance, with the pool of 200 households, the setpoints tested will be [20, 26, 32, …, 98] kW. The reader must pay attention that the maximum deployable power of the pool of 200 households is 400 kW, 2kW per resistance.

Figure 41 shows the RLOI variation of this simulation. The setpoints are expressed in % of the total pool deployable power. It can be seen that, proportionally to their setpoints range, the RLOI is not really influenced. Moreover, with pool sizes of 600 households and above, the different curves become indistinguishable. This means that the predictability is enhanced for pools larger than 600 households. It is thus advised for the aggregator to have a reasonable pool in order to be efficient.

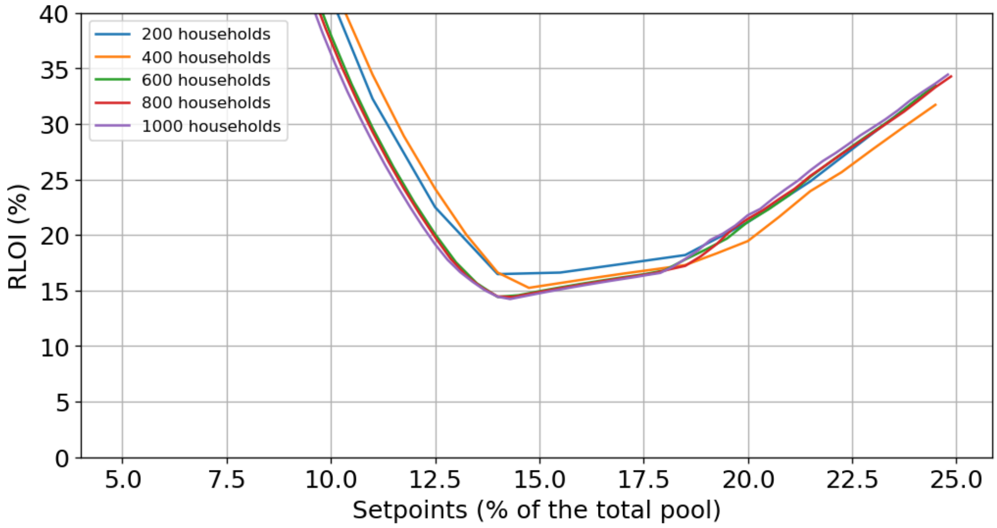


Figure 41 : RLOI in function of the setpoints attributed for different pool sizes.

8.3.2. SoC lower limit

The SoC lower limit is an important parameter for upward regulation: a higher limit narrows the aggregator's scope of action but a lower limit increases the risk of feeling a discomfort. Figure 42 shows the impact it has on the RLOI for a SoC lower limit of 30, 40 and 50%. The minimum of each curve is not affected by this parameter. However, the range of setpoints at which these minima occur are significantly affected. For a lower limit of 50%, the optimal range of setpoints is 350-370 kW (i.e. a constant control of 17.5-18.5% of the pool) while for a lower limit of 40%, the range of setpoints is a bit larger (270-310 kW, i.e. 13.5-15.5% of the pool). The lower limit of 30% (and lower) is the best option for aggregators, which offers the widest range (250-320 kW i.e. 12.5-16% of the pool) and with which the lowest RLOI is reached (15%). The lower limit of 40% gets almost the same result. Thus, we can say that the upper is the limit, the narrower are the possibilities (a loss of 20 kW range per 10% increase of SoC lower limit.

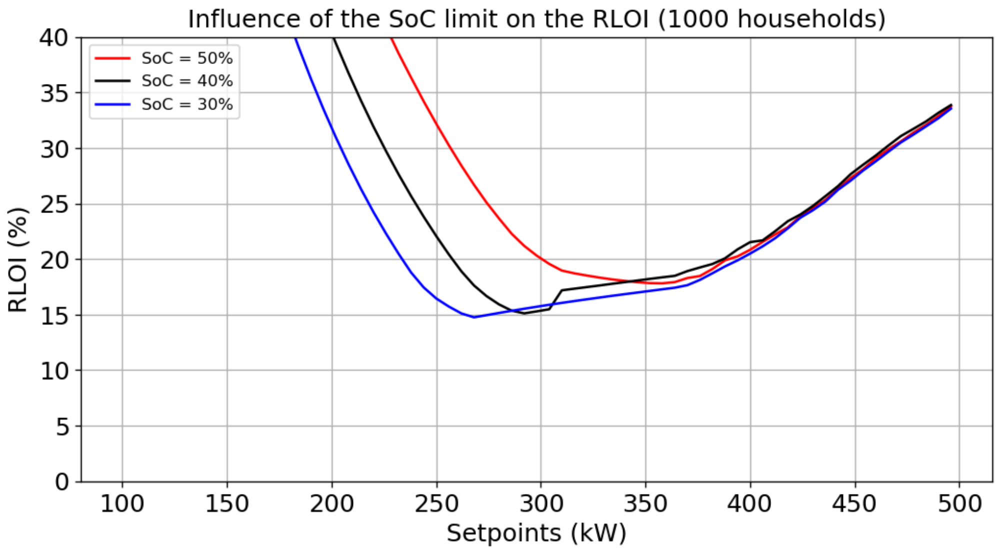


Figure 42 : Influence of the SoC lower limit on the RLOI. A higher SoC limit reduces the aggregator scope.

On the other hand, to decrease this limit is equivalent to increase the risk of discomfort. Figure 43 shows the resulting number of households that felt a discomfort for the three limits tested. It can be seen that, for setpoints above 300 kW, there is no clear difference in the discomfort between the three limits. Moreover, the curves seem to tend to a non-zero value (~10) for very high setpoints. This is due to the stochastic generation of individual profiles. It means that some profiles in the pool have either a very large consumption regarding their tank size, or a lot of events happening one after the other. For setpoints below 300 kW, the influence of the lower limit is really significant, especially for the lower limit of 30%, where it can go up to 70 households feeling discomfort (7% of the pool).

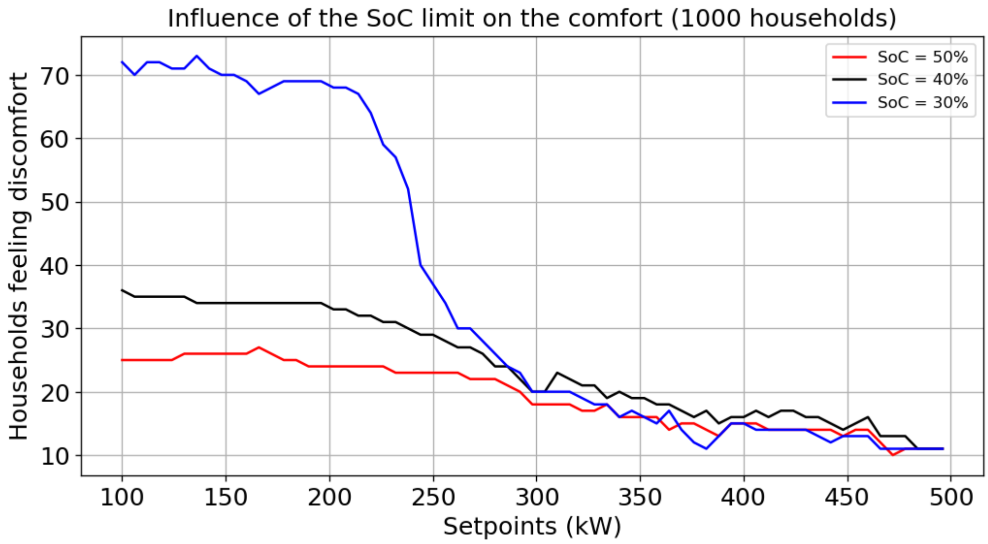


Figure 43 : Impact on the comfort for the three different limits. The difference between the curves are negligible for setpoints higher than 300 kW.

Thus, it can be said that the lower limit of the SoC has a non-negligible influence on the results. However, starting at setpoints of 300 kW, this effect is largely reduced. The SoC lower limit of 40% seems to be an optimum, especially around 300 kW.

8.3.3. Aggregator influence on pool consumption

By definition, the upward regulation reduces the consumption of the pool. In order to quantify this reduction, the consumption for different setpoints of a standard pool is shown in Figure 44. It can be seen that, effectively, the consumption is reduced by a maximum of 2.5 MWh compared to the initial consumption. However, the result is mitigated by the fact that the RLOI is at minimum 15%. For instance, with a setpoint of 300kW for a standard pool of 1000 households, the RLOI is at 15% which means a LOI of 1.08 MWh. Thus, although the consumption was reduced by 1.8 MWh, the level of imbalance created was 1.08 MWh.

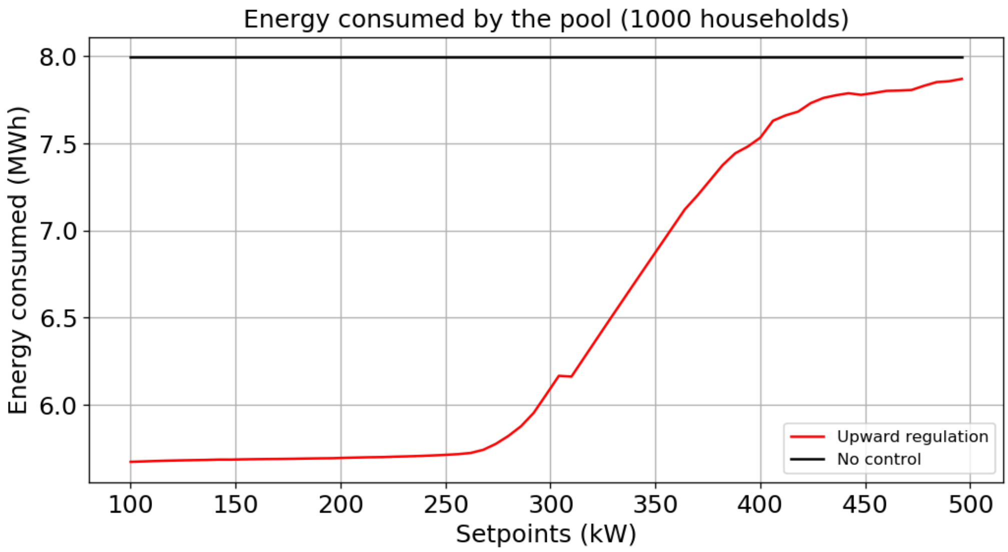


Figure 44 : The upward regulation may reduce the pool consumption for more than 2 MWh compared to the initial consumption.

8.3.4. Inlet temperature

The inlet temperature is a seasonal parameter that can have an influence on the consumption. As a matter of fact, it costs more energy to rise a litre of water from 5 to 60°C than from 15 to 60°C. This will influence the time each resistance has to stay switched on for the tank to reach 60°C.

In Figure 45, it can be shown that the RLOI will not be significantly influenced by the inlet temperature, with only an increase of 2% of the RLOI with an inlet between 15°C and 5°C, but it influences the minimum localization. Precisely, the minimum of each curve is offset of 50 kW for each decrease of 5°C at the inlet temperature.

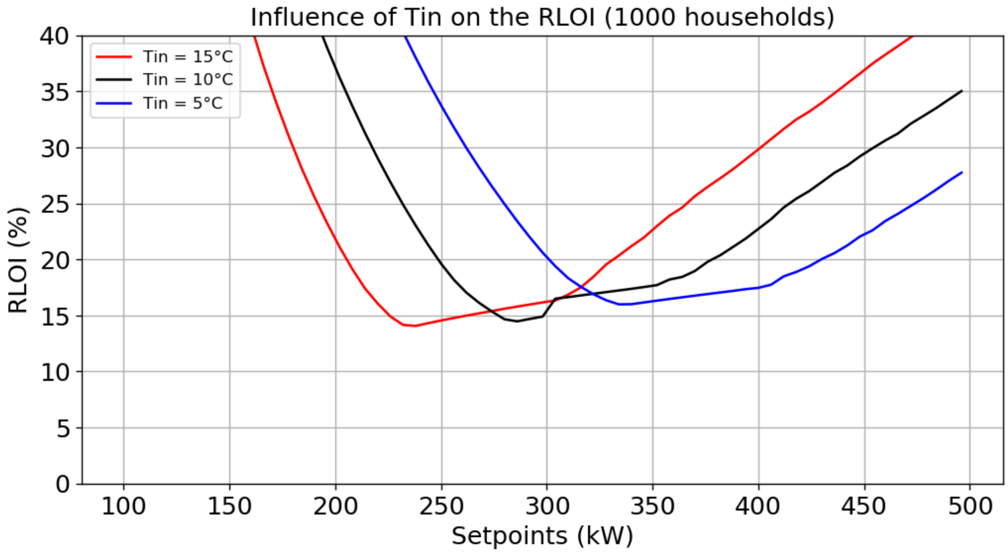


Figure 45 : The inlet temperature does not influence the RLOI, but it does offset the curves.

As for the comfort, Figure 46 shows that it will be largely variable to the inlet temperature, especially at 5°C where, even for high setpoints, there is still more than 3% of the pool feeling discomfort. Fortunately, these water temperatures are uncommon, even in winter, and thus can be seen as an upper limit. On the other hand, the discomfort risk is heavily reduced when the inlet temperature goes above 10°C. It could be even said that, for an inlet temperature of 15°C, the discomfort reach a “zero” value for setpoints higher than 370 kW. It means that, past this limit, the households still feeling a discomfort are the one with extreme consumptions and can therefore be neglected.

Thus, the inlet temperature has a high influence on the minimum localization and on the user’s comfort. Therefore, it would be a good strategy to precisely target the minimum of RLOI curve in summer and to sacrifice 1-2% of the RLOI by targeting higher setpoints (~400 kW) in winter in order to minimize discomfort.

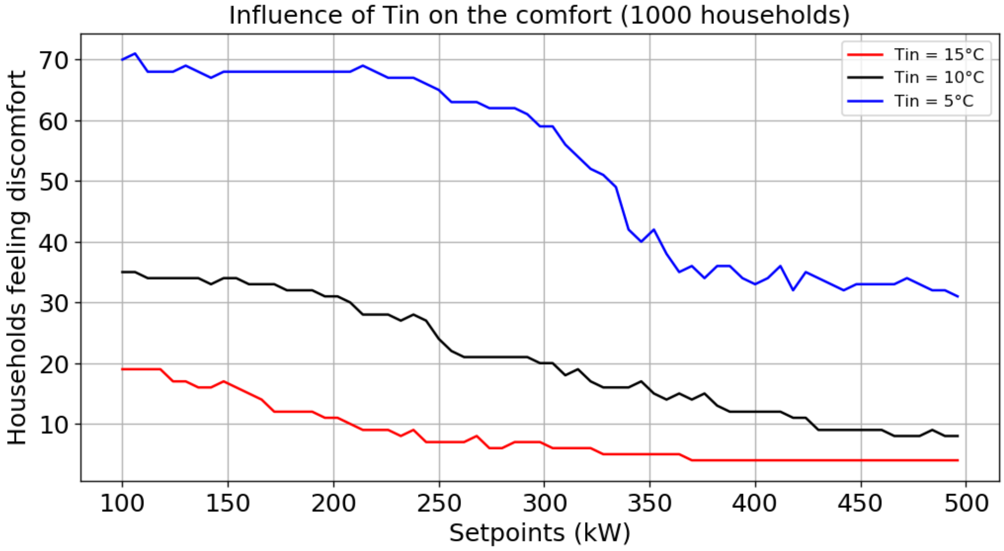


Figure 46 : Comfort is largely influenced by inlet temperature

8.4. Bilateral regulation

The previous studies highlighted that the upward regulation is somehow limited by the fact that the aggregator cannot force any water heater to switch on. This can be seen as the fact that the RLOI cannot go down below 15%. These 15% are always located at the early hours of the day (0-6h), when the demand is very low. Therefore, it is expected that the bilateral regulation would reduce this effect. However, the downward regulation leads also to the fact that the consumption may increase.

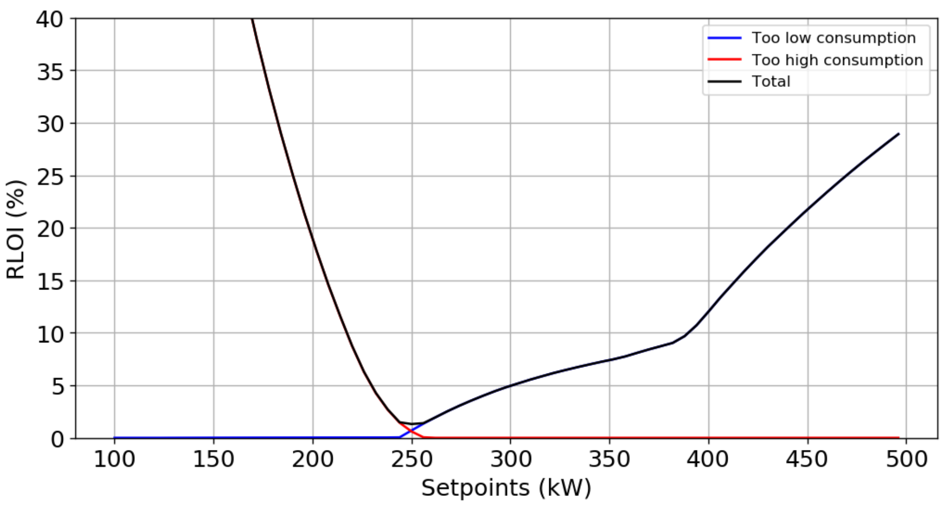


Figure 47 : RLOI in function of the different setpoints for bilateral regulation.

Figure 47 shows the evolution of RLOI for the different setpoints. In addition to the total RLOI (black), the latter is also split in two parts for more details: the RLOI due to a too low consumption compared to the setpoint (blue) and the one due to a too large consumption (red). For low setpoints, the consumption is often too high. However, this effect rapidly decreases until reaching its minimum at 250 kW (12.5% of the total pool) where the RLOI is evaluated at 2%. For higher setpoints, the RLOI is only composed of consumption recorded as too low and essentially located between 0-6h. However, for setpoints higher than 380 kW, this effect also appears at the end of the day (21h+). The reason is that the boilers are all full of energy and therefore cannot be switched on anymore.

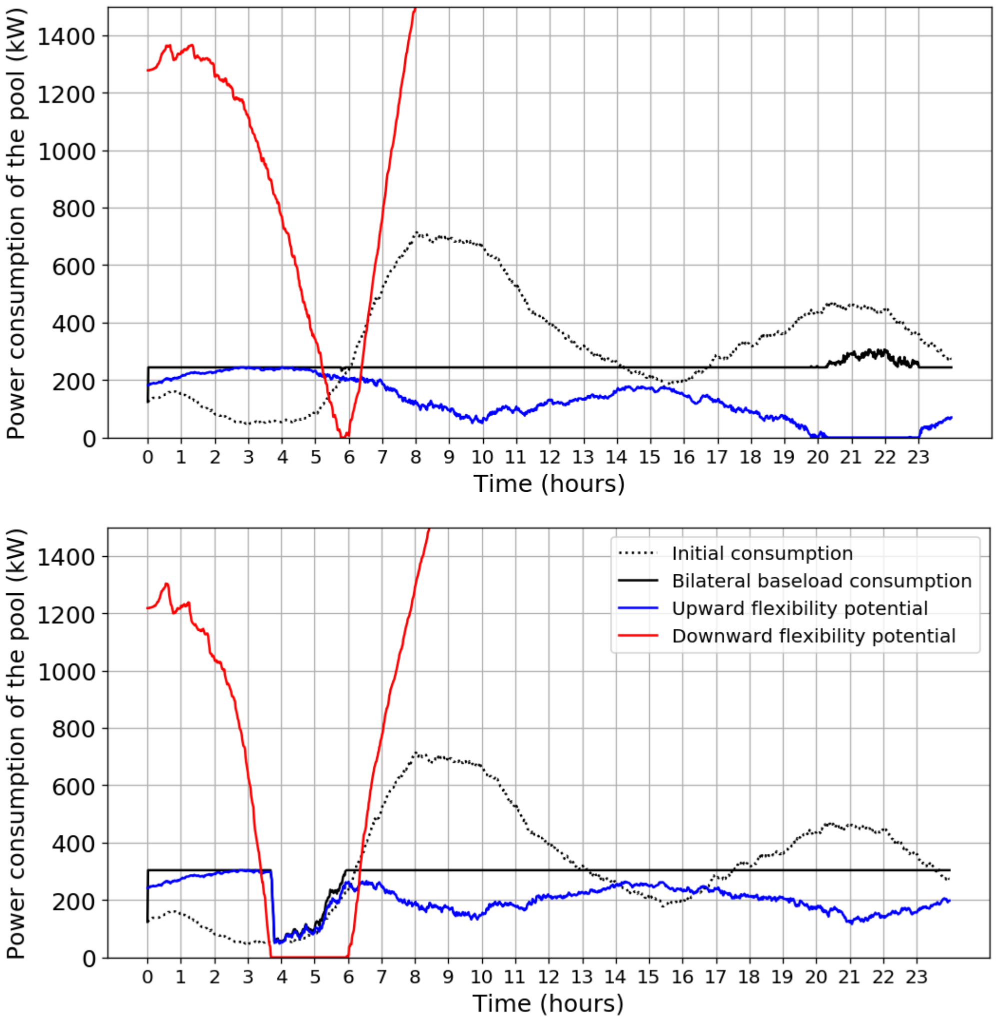


Figure 48 : Evolution of the consumption and the pool's potential for a setpoint of 250 kW (above) and 300 kW (below) with a bilateral baseload

Figure 48 shows, as example, a comparison of the upward and downward potential evolution for two distinct cases: 250 kW and 300 kW. On may observe that, for both cases, at the early morning, the downward flexibility potential of the pool decreases rapidly until reaching zero. This can be translated as the fact that the tanks of the entire pool have their SoC above 95%. Besides, this effect gains in intensity when the setpoints are higher. Finally, a too low setpoint will deplete the upward reserve at the end of the day.

On the subject of the pool's consumption, the Figure 49 shows the comparison between the initial consumption and the one when the aggregator makes a baseload control on it. The major observation is that the pool consumption is still lower for most of the bilateral cases compared to the initial case. Particularly, for a setpoint of 250 kW at which the RLOI is 2%, the economy in energy is 2 MWh at the end of the day. One may also see that the consumption reaches two plateaus. At the lower plateau, it can be considered that the entire pool is mostly uncontrollable because their SoC are all constantly below 40%. The upper plateau is related to the fact that the entire pool's tanks are almost constantly at a SoC of 95% of more.

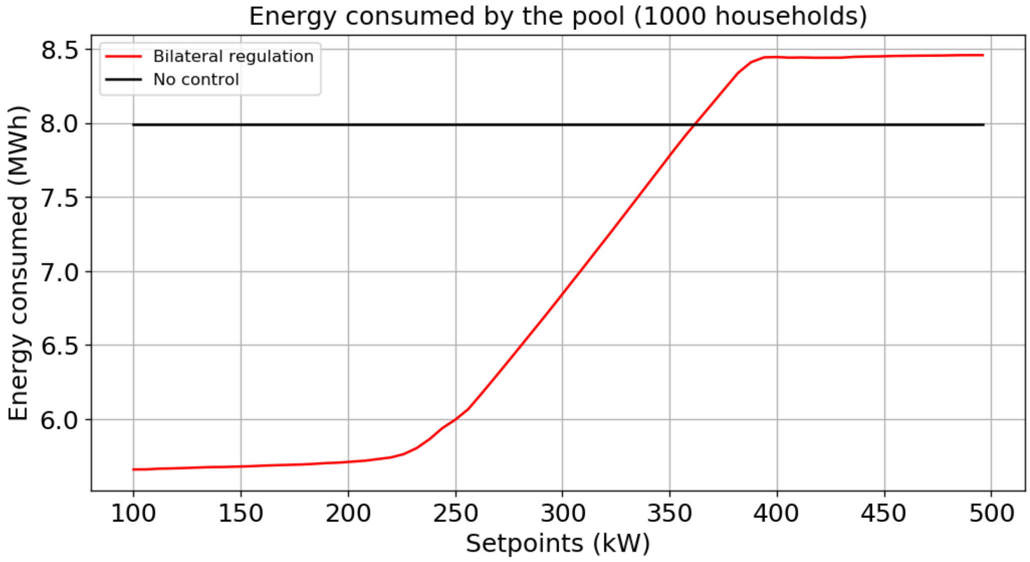


Figure 49 : Comparison between the initial consumption and the one with bilateral regulation.

Finally, the impact on the user's comfort has to be verified. Figure 50 shows the comparison between the bilateral, the upward and the initial cases regarding the number of households that felt a discomfort. It can be seen that the bilateral control has a positive effect on consumer's comfort compared to the initial case (1.4% of the pool) and it can go down to less than 0.5% of the pool that felt a discomfort. However, regarding the upward case, the discomfort increases in each case, except for very high setpoints.

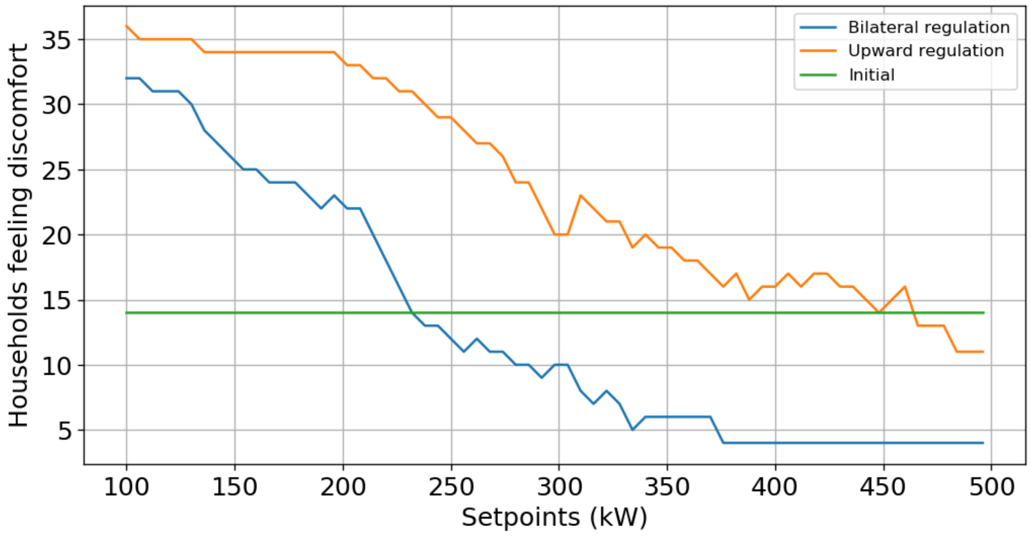


Figure 50 : The number of households that felt a discomfort during the day for different setpoints and different cases

8.5. Summary and positioning with regard to the different markets

The baseload control reveals to be efficient in average. It is always characterized by an optimum whose position depends on the influencing parameters like the inlet cold temperature or the choice of the SoC lower limit. It can be said that this optimum is generally located at the setpoints corresponding to a constant activation of 12 to 20% of the pool (240-400 kW for a pool of 1000 households). Nonetheless, this optimum corresponds also to a RLOI of 15% when talking about upward regulation. The cause is often the early hours of the day, when the pool's consumption is rather low. Moreover, the user comfort is often negatively impacted from this control.

The bilateral regulation offers much more flexibility and better results, with a RLOI of 2% at its optimum. Besides, the user comfort is positively impacted when more than 10% of the water heater pool is constantly activated. This means that the aggregator have a larger spectrum of possibilities with regard to the possible setpoints. Finally, additionally to its reliability, it is even possible to reduce the pool consumption down to 2.5 MWh for a pool size of a 1000 water heaters.

However, only setpoints constant throughout the day were tested, which is not the better solution at the end of the day. Another way would be to impose a setpoints that varies from hour to hour. For instance, to decrease the setpoint at the early hours of the day and to increase it during the peaks. Furthermore, for upward regulation, it should be possible to anticipate the hollows by lowering the setpoint before in order to increase the number of devices that need to switch on. Although it could be risky, the fact that a hollow is following right after could mitigate this risk.

The possibility to reduce the consumption by a significant amount, the reliability in maintaining the pool at a setpoint and the possibility to vary the setpoint from hour to hour are main factors that suggest the possibility for this control to be efficient in the Day-Ahead market. Moreover, it can be coupled with day-ahead prices, which are predictable and also vary from hour to hour. There is thus a possibility to do optimization. It is also possible to bid on the Intra-Day market, but since the IDM is more based on last minute bids, it could be less profitable.

With regard to the ancillary services (R1, R2 and R3), the control is not accessible to R1 and R2 by nature: The setpoint to follow is much more fluctuating through time and thus is not relevant for the baseload control. For the R3 service, assuming that the market is available for low voltage aggregators, it could be possible to propose reserved and non-reserved Flex, with the condition to choose carefully the 4 hours blocks.

9. Parametric study : Peaker case

The peaker case, as a reference for gas peaker power plants which are quick to respond, is based on a sudden change in the consumption for a short period of time. In this report, only upward peaker cases will be analyzed, i.e. a sudden reduction in the pool consumption.

9.1. Overview of the peaker on the consumption

An example of peaker case is shown in Figure 51, where the dashed line is the initial consumption without any control and the solid line is for the consumption with the peaker. The control operates a reduction of 200 kW from 9h to 12h. It is then released and not reiterated. The first thing observable is that the control does not fix the output consumption but instead it follows the initial consumption. The purpose is for the aggregator to have a basis consumption to prove that it efficiently deactivates a volume for a certain time. Therefore, this is more oriented for balancing services.

The other observation is the influence that the control has on the rest of the day. In fact, just after the control release, the consumption rises rapidly and goes beyond the initial consumption. The perturbation then stays for a long period of time but ultimately will disappear. These two features will be studied in this section under the name of rebound effect and recovery time, respectively.

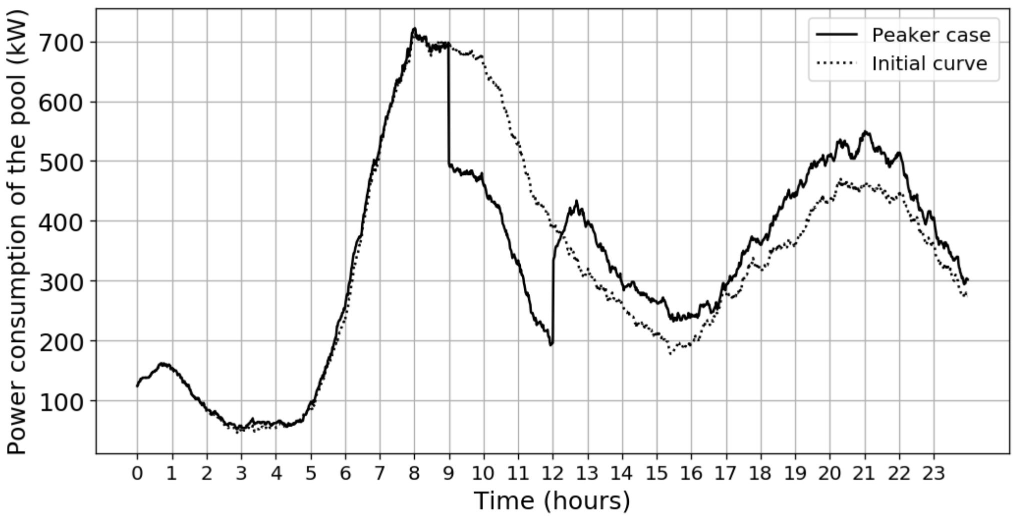


Figure 51 : Example of a peaker case of 200 kW from 9 to 12h.

9.2. The rebound effect and the recovery time

When the aggregator reduces the consumption for some time, water heaters are gradually losing their energy and the temperature at their probe layer goes down the activation limit. Therefore, when the control is released, numerous devices suddenly reactivate their resistance. As the water heaters that have been switched off at the start of the control were already in a situation where they need to switch on, one can say that, at least, the same amount of devices that has been shut off will be reactivated. On top of that, other tanks passed under the threshold in the meantime. Consequently, it is possible that the consumption increase in reaction to the control may be higher than the decrease initiated by the aggregator. This release response will be called the rebound effect. It is characterized by a certain intensity and will be a parameter of this study. This intensity will be quantified by taking the initial curve as the reference. The rebound (R) can thus be translated as the maximum absolute difference between the current consumption and the initial consumption after the release:

$$R = \max(|P_{pool,i} - P_{init,i}|)$$

On the other hand, after the rebound effect, the current consumption curve will progressively go back to its initial state and after a certain time, the difference will be small enough to consider that the initial consumption curve is once again the reference. The time it takes from the end of the release to the state described will be called the reference time. The latter is an important parameter since it determines the time the aggregator has to wait between two activations. Thus, the recovery time is defined as follows: At a time $t_0 + t$ where t_0 is the time when the control has been released, the time period $[t_0, t_0 + t]$ is considered as the recovery time if:

$$\left|\frac{P_{pool,i} - P_{init,i}}{P_{init,i}}\right| \leq 0.05 \quad \forall i \in [t_0 + t, t_0 + t + 60]$$

In other words, if at a time t after the release, the difference between the current and the initial curve is less than 5% of the initial curve for at least the next hour, then the time period between the release time t_0 and the time t is therefore considered as the recovery time.

Figure 52 illustrates the two concepts with two different cases: one control which has been done from 6-9h (red) and the other one from 9-12h (blue). Although they share the same intensity and the same control duration, the consequences are substantially different. For the red curve, the rebound is important with a difference of 300 kW between the current and the initial curves whereas the rebound effect is much smaller (100 kW) for the blue curve. However, it can be seen that the latter takes more time to recover than the red one. Thus, the starting time of the control will have a significant effect on the rebound effect and the recovery time.

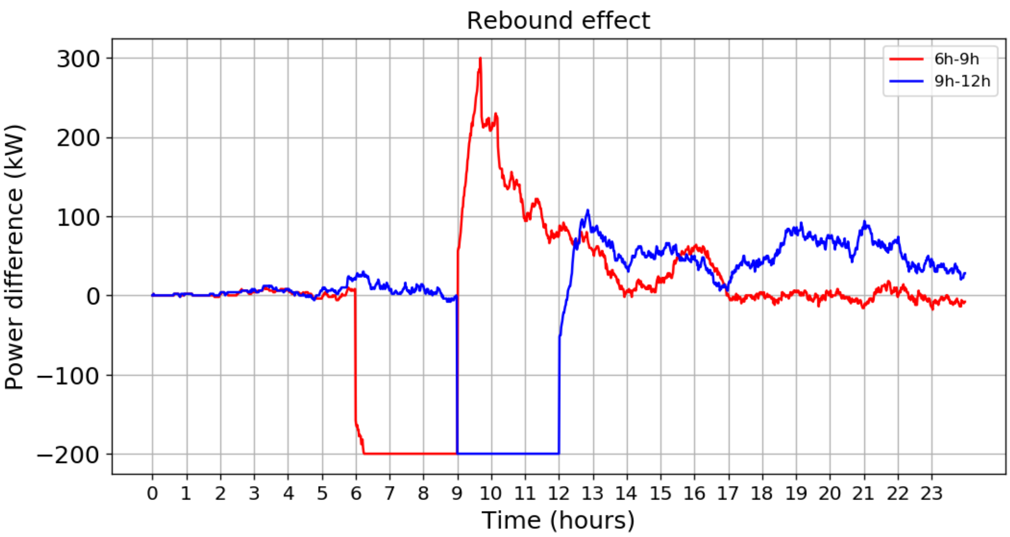


Figure 52 : Illustration of the rebound effect and the recovery time for two different cases: a control from 6 to 9h, and one from 9 to 12h.

9.3. Parametric study

In order to cover the whole spectrum of possibilities regarding the starting time and the control duration, the starting time will vary from 0 to 23h and the duration of the control will range from 30 minutes to 180 minutes in 30-minute increments. Also to limit the computations due to the large number of data, the drop intensity done by the aggregator will be set constant and equal to a reduction of 200 kW. Moreover, due to the fact that the recovery time can be rather long, the simulations will always cover two days.

First of all, Figure 53 gives the level of imbalance for the different cases. Globally, the contracted volume established by the aggregator is perfectly respected. However, a significant level of imbalance is located at the early hours of the day, due to the lack of water heaters switched on. A small imbalance is also located at 15h for the same reasons.

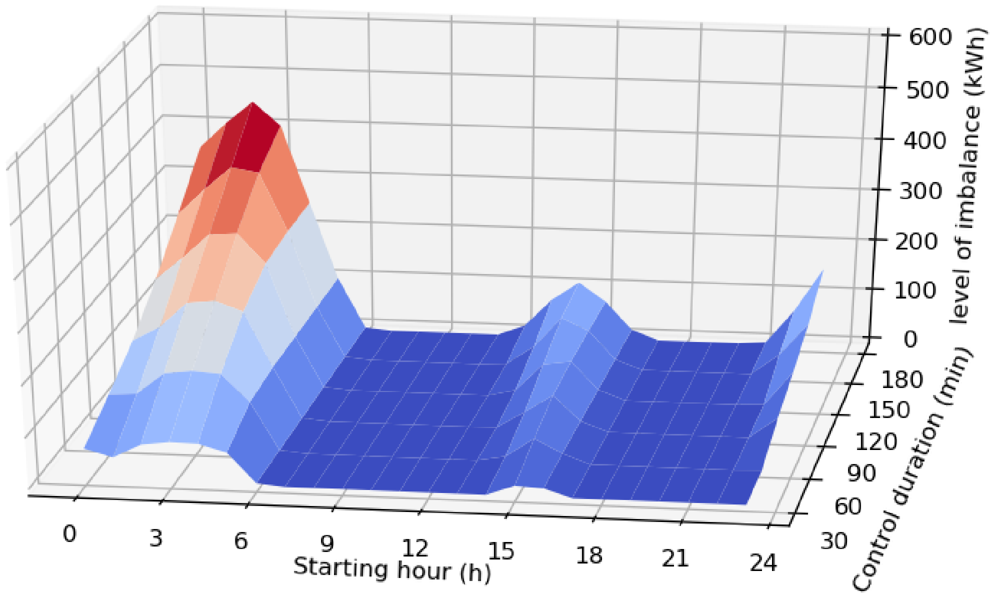
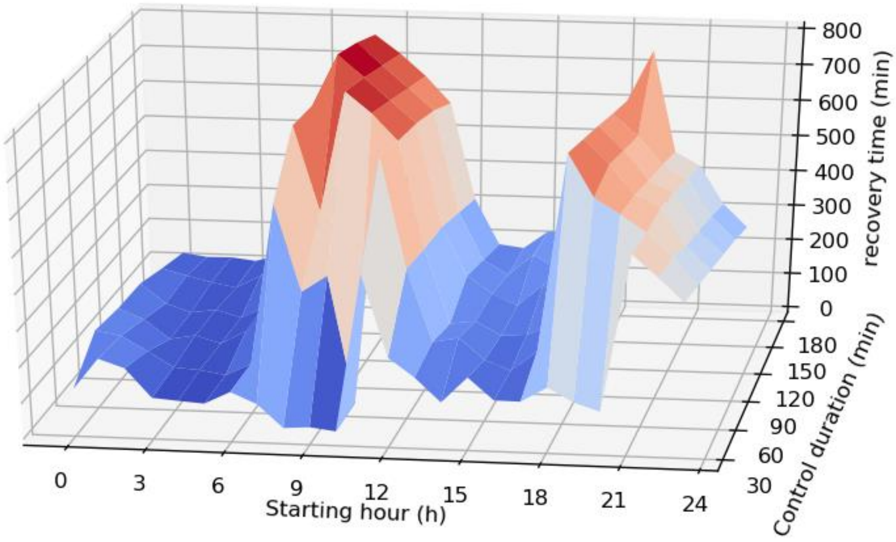


Figure 53 : LOI results for the peaker case.

Looking at the recovery time and the rebound effect, it can be seen in Figure 54 that these two effect are really low at the early hours, but it is linked to the limited pool consumption. For the recovery time, its duration is in general very long with values between 150 and 800 minutes, with duration peaks located at the consumption peaks. This indicates that the consumption curve is particularly sensitive when solicited. It seems also that a good control window exist between 12 and 16 hours, but this is mitigated by the fact that the LOI is non-zero in this window. In any case, controls of small duration have the smallest recovery time and therefore are preferable to other control durations.

Regarding the rebound effect, the latter is proportional to the control duration, with peaks at 400-500 kW, and relatively inflexible regarding the starting time if the results of the 5 first hours are neglected. However, a dip is observable between 9 and 12h, which corresponds to control the pool at the moment where the consumption begins to decrease (see Figure 51). Finally, the user's comfort is not affected by the peaker case, with an exception for at 7h when there is an increase of discomfort of 5 households for the worst case (180 minutes).



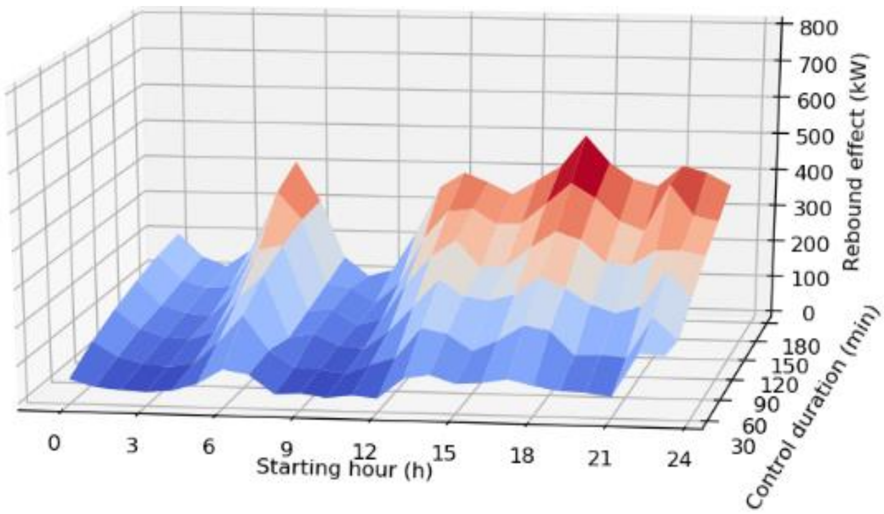


Figure 54 : Results of the recovery time (above) and rebound effect (below) for the peaker case

Finally, the last interesting situation to analyze would be the situation where the peaker control is done multiple times in a single day. Figure 55 shows the pool consumption when the peaker control is done 5 times, starting at 7h, with 2 hours interval between each activation. Two cases are shown, one with 30 minute activations and one with 1 hour activations. From these figures, one may observe that successive controls increase the rebound effect at each release. Furthermore, at the end of the last control, the current consumption curve seems to follow the initial curve with an offset proportional to the total volume deactivated. Finally, in both cases, the consumption is stabilized at the end of the day. However, the major difference is that, since the aggregator controls the volume to reduce relatively to the initial consumption, the volume deactivated is generally larger and up to 300 kW (instead of a constant 200 kW) for the case with activations of 1 hour. Finally, the number of households that felt discomfort is the same (for both cases) as for the initial consumption (1.4%).

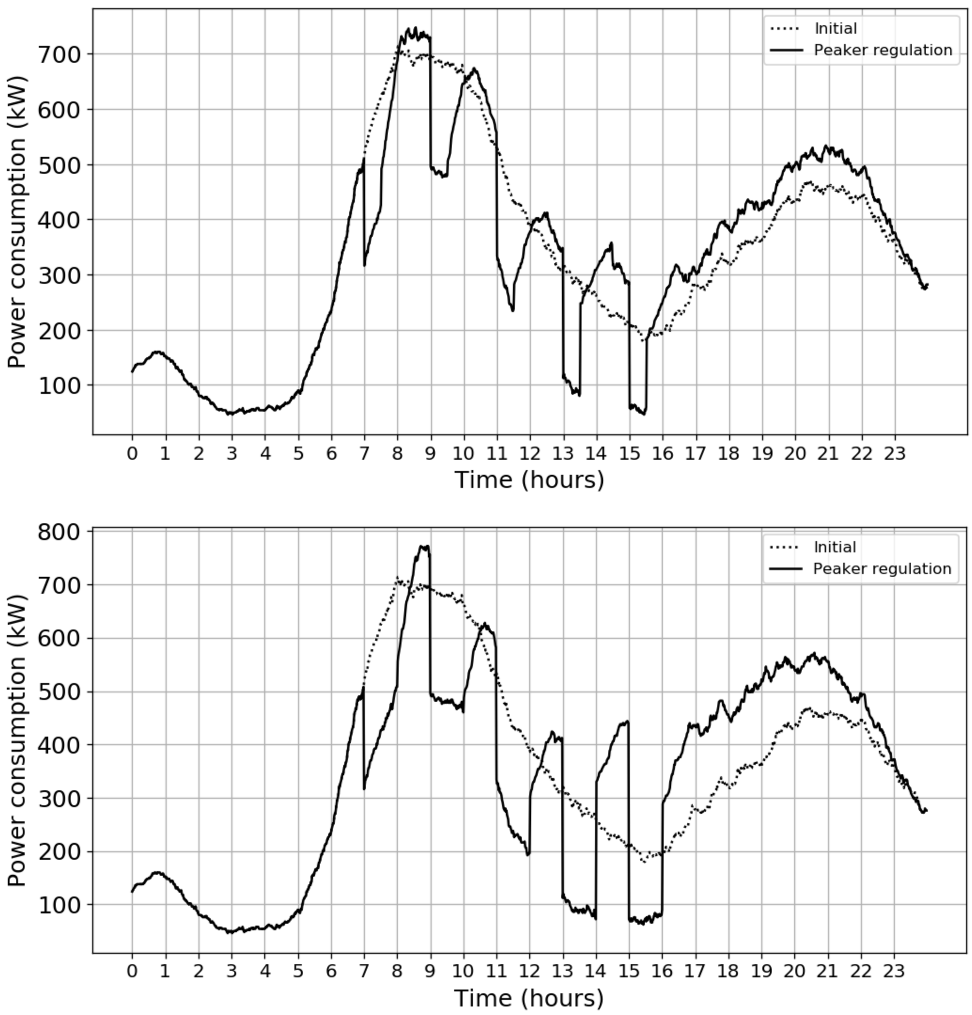


Figure 55 : Multiple peaker cases. The control is done 5 times at 7, 9, 11, 13 and 15 hours. The duration is either 30 min (above) or 1hour (below).

9.4. Summary and positioning with regard to the different markets

The peaker control showed that it can be reliable if the duration time is short (less than an hour). In the 30-minute case, the difference between the current and the initial consumption curves stays relatively small and, as the initial curve is still reliable, it thus allows multiple controls on the same day. However, for durations of 1 hour or more, the initial curve is not reliable anymore because the rebound effect and the recovery time are too high. But it seems that the consumption still follows the reference curve, although with an offset. Hence, it could be maybe possible to forecast this effect. This needs further investigations, but it goes out of the scope of this report.

Furthermore, the peaker control respects very well the volume demanded and is thus reliable during the control. Single or multiple controls do not create more user's discomfort than the initial consumption, except for very long controls at crucial moments, like during the first peak of consumption.

This type of control would be a good opportunity for the R1 and R3 ancillary services. However, the pool's potential is variable through time and a 4 hours bid for R1 must be chosen carefully to avoid large and long demands when the pool consumption is too low. Moreover, even if the peaker is efficient to follow a variable setpoint (in the studied cases, the initial consumption), more tests should be done with a more chaotic setpoint. Regarding the R3 services, assuming that this market will be soon open to low voltage aggregators, the “non-reserved flex” is ideal because the aggregator may choose the time duration and that the bid granularity is 15 minutes. The “reserved flex” is also a good candidate because the time between activations is 8 hours, which could let the time to the pool to regain its initial consumption. However, as for R1, the 4h blocks make that the aggregator should be careful regarding in which block it will bid.

As for R2 services, it is unadvised at first sight since this type of services is frequently solicited and for large volumes and since the reservation will be soon done with 4h blocks. It could therefore involve an increase of discomfort. However, this track should be deeper explored.

The Intra-Day market is another solution since bids can be for 15 minutes. However, the volume is generally too small to be envisaged on the Day-Ahead market. Finally, it is possible for the aggregator to simply readjust its own consumption and thus avoid fees relative to imbalances.

The bilateral peaker has not been studied here in order to reduce the scope of this work. Still, this case should be investigated because it is likely that it gives efficient and better results, just like the baseload case.

10. Discussion and conclusion

The topic of flexibility in the residential sector is very large and partly unexplored. To achieve this work, the scope had to be reduced. On one hand, the fact that the scope was limited to Belgium meant that the subject of heat pumps was not given more attention. Yet, this device is experiencing good sales in other countries such as France, where 245000 units were sold in 2017. On the other hand, some important parts of the topic were not discussed, such as the way and the efficiency of communications between the devices and the aggregator, the methods used to forecast the aggregated consumption profile or the economic aspect of the aggregation. Finally, the bilateral peaker control was not investigated. These subjects should be investigated in future works.

The residential sector is promising for the aggregator, mostly due to the electrification of households and the emergence of new “smart” technologies. Therefore the space heating, which is a non-negligible part of the consumption, should be also envisaged for aggregation. This could greatly increase the flexibility potential of the aggregator because space and water heating profiles are rather different. However, for any of both of them, it demands a large initial investment and a good knowledge of the real (on-the-field) consumption profile. The electric storage water heater is thus an ideal device to begin with: depending on the control method, it can participate to almost every electricity market. However, the ancillary services are not reachable at first because the minimum bid and the granularity of the latter are 1 MW, which therefore require a large pool. A good strategy would then be to start with the DAM and IDM in order to accumulate devices and knowledge about the consumption profile via the baseload control. After, the aggregator could variate his services and bid on the balancing market with the peaker control while doing researches about heat pumps and space heating profiles to further incorporate this device to its pool. Regardless of the strategy chosen, the emergence of smarter electric devices makes investment in aggregation a viable solution.

10.1. Conclusion

This work searched for flexibility in the residential sector through aggregation of domestic devices in the scope of Belgium. It has been found that the electric storage water heater is a good candidate for aggregation because on one hand it is used for domestic hot water whose aggregated consumption is rather predictable, and on the other hand the device is strongly present in Belgian households.

In order to quantify the flexibility, a synthetic pool of consumption profiles was first created on the basis of probability functions from an American database. Then, the devices were modelled using the Multi-Node model and two methods based on simple rules were defined to control the pool: the case of the baseload and the case of the peaker.

The baseload revealed to be effective and its characteristics fit well with electricity markets such as the Day-Ahead and the Intra-Day markets. The peaker on the other hand could be more effective to provide grid-services. But to do so, it would require a larger pool size due to the balancing market’s bid condition. Therefore, it is recommended to aggregate first with the objective to bid on the Day-Ahead or Intra-Day and then, when the pool size is sufficient, to provide grid-services.

Future prospects should look at on-the-field profiles, means of communication between the devices and the aggregator and economic viability of the two control methods.

Works Cited

Agudelo-Vera, C., Avvedimento, S., Boxall, J., Creaco, E., de Kater, H., Di Nardo , A., . . . Blokker, M. (2020, April 7). Drinking Water Temperature around the Globe: Understanding, Policies, Challenges and Opportunities. *Water, 12*, 1049. doi:10.3390/w12041049

Amelang, S., & Appunn, K. (2018, January 5). *The causes and effects of negative power prices*. Retrieved from Clean Energy Wire: https://www.cleanenergywire.org/factsheets/why-power-prices-turn-negative#:~:text=The%20number%20of%20hours%20with,minus%2027%20euros%20per%20MWh.

Armstrong, P., Ager, D., Thompson, I., & McCulloch, M. (2014, November 11). Improving the energy storage capability of hot water tanks through wall material specification. *Energy, 78*, 124-140. doi:10.1016/j.energy.2014.09.061

Béranger, B. (2008). *Les pompes à chaleur.* Eyrolles.

BizEE. (n.d.). *Degree-Day Base Temperature - Choosing the Best Values for Heating and Cooling*. Retrieved from BizEE Degree Days: https://www.degreedays.net/base-temperature

BRG. (May 2018). *The European Heating Product Markets : Belgium.* London: BRG BUILDING SOLUTIONS.

Chateau, B., & Lapillonne, B. (1982). *Energy Demand: Facts and Trends: A Comparative Analysis of Industrialized Countries.* Grenoble: Springer Science & Business Media.

COSTIC. (2016). *Les besoin d'eau chaude sanitaire en habitat individuel et collectif.* Paris: ADEME. Retrieved from https://www.costic.com/sites/default/files/upload/telechargements/ECS_MJL_ADEME/besoin-eau-chaude-sanitaire-habitat-individuel-et-collectif.pdf

CREG. (2018). *Study on the functioning and price evolution of the Belgian wholesale electricity market.* Brussels: CREG.

Da Silva, D. (2011, March 12). *Analyse de la flexibilité des usages électriques résidentiels : application aux usages thermiques.* Master Thesis. Retrieved from Archives ouvertes: https://pastel.archives-ouvertes.fr/pastel-00678316/file/Da_Silva_David.pdf

Darby, S., Higginson, S., Topouzi, M., Goodhew, J., & Reiss, S. (2018). *Getting the balance right : Can smart electric thermal storage work for both customers and grids ?* RealValue.

De Jaeger, E. (2018). Course on Electric Energy System. *Chapter 2 : Structure and mechanisms of the electricity market in Belgium*. Louvain-la-Neuve, Belgium: UCLouvain.

De Ridder, F., & Coomans, M. (2014, June 1). Grey-box model and identification procedure for domestic thermal storage vessels. *Applied Thermal Engineering, 67*, 147-158. doi:10.1016/j.applthermaleng.2014.03.003

E. Fuentes, L. A. (2017, June 8). A review of domestic hot water consumption profiles for application in systems and buildings energy performance analysis. *Renewable and Sustainable Energy Reviews, 81*, 1530-1547. doi:10.1016/j.rser.2017.05.229

EHPA. (2018). *Heat pump sales overview.* Retrieved from stats.ehpa: http://www.stats.ehpa.org/hp_sales/story_sales/

Elia. (2017, May 23). *Keeping the Balance.* Retrieved from Elia website: https://www.elia.be/-/media/project/elia/elia-site/keeping-the-balance/afrr/afrr/eliaby_special_ancillary-services_20170523_eng_lr-en.pdf

Elia. (2020, April 16). *Automatic Frequency Restoration Process.* Retrieved from Elia website: https://www.elia.be/-/media/project/elia/elia-site/electricity-market-and-system---document-library/balancing---balancing-services-and-bsp/2020/20200303_tc-bsp-afrr_en.pdf

Elia. (2020, April 30). *Frequency Containment Reserve.* Retrieved from Elia website: https://www.elia.be/-/media/project/elia/elia-site/electricity-market-and-system---document-library/balancing---balancing-services-and-bsp/2020/20200518tc-bsp-fcren.pdf

Elia. (2020, March 03). *Frequency restoration via manual activation.* Retrieved from Elia ebsite: https://www.elia.be/-/media/project/elia/elia-site/electricity-market-and-system---document-library/balancing---balancing-services-and-bsp/2020/20200203_bsp-contract-mfrr_en.pdf

Elsland, R., Peksen, I., & Wietschel, M. (2014, January 1). Are Internal Heat Gains Underestimated in Thermal Performance Evaluation of Buildings? *Energy Procedia*, pp. 32-41.

EPEX spot. (2020, May). Retrieved from EEX Group website: https://www.eex-group.com/eexg/companies/epex-spot

Epex Spot. (2020). *Negative prices - Q&A*. Retrieved from Epex Spot: https://www.epexspot.com/en/basicspowermarket#negative-prices-q-a

European Commission. (2018, January 1). *Local space heaters*. Retrieved from European Commission: https://ec.europa.eu/info/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/energy-label-and-ecodesign/energy-efficient-products/local-space-heaters_en

European Commission, Frontier Economic. (2019). *METIS Technical Note T4 : Overview of European electricity markets.* Brussels: European Commission.

European Parliament. (2018, May 30). *Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency.* Retrieved from EUR-Lex: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2018.156.01.0075.01.ENG

Eurostat. (2017, March). *Energy consumtion in Households.* Retrieved from EuroStat: https://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_consumption_in_households#Energy_consumption_in_households_by_type_of_end-use

Eurostat. (2019, June). *Electricity and heat statistics*. Retrieved from Eurostat: https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_and_heat_statistics#Production_of_electricity

Ferrantelli, A., Ahmed, K., Pylsy, P., & Kurnitski, J. (2017, May). Analytical modelling and prediction formulas for domestic hot water consumption in residential Finnish apartments. *Energy and Buildings, 143*, 53-60. doi:10.1016/j.enbuild.2017.03.021

Fischer, D. (2017). *Integrating Heat Pumps into smart grids.* Royal Institute of Technology, Department of Energy Technology. Stockholm: Royal Institute of Technology. Retrieved from https://kth.diva-portal.org/smash/get/diva2:1141142/FULLTEXT02.pdf

Fischer, D., Wolf, T., Scherer, J., & Wille-Haussmann, B. (2016, July). A stochastic bottom-up model for space heating and domestic hot water load profiles for German households. *Energy and Buildings, 124*, 120-128. doi:10.1016/j.enbuild.2016.04.069

Gelazanskas, L., & Gamage, K. (2015, November). Forecasting Hot Water Consumption in Residential Houses. *Energies, 8*, 12702-12717. doi:10.3390/en81112336

Gerin, O., Bleys, B., & de Cuyper, K. (2014). *Seasonal variation of hot and cold water consumption in apartment buildings.* Brussels: CIBW062 Symposium 2014.

Green, R. (2012). *The Effects of Cycling on Heat Pump Performance.* EAtechnology, Department of Energy and Climate Change. Capenhust: EAtechnology.

Guerra Santin, O., Itard, L., & Visscher, H. (2009, November 1). The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock. *Energy and Buildings, 41*(11), 1223-1232. doi:10.1016/j.enbuild.2009.07.002

Hendron, R., Burch, J., & Barker, G. (2010). TOOL FOR GENERATING REALISTIC RESIDENTIAL HOT WATER EVENT SCHEDULES. (pp. 1-8). New York: National Renewable Energy L.aboratory.

Jacobs, H., Botha, B., & Blokker, E. (2018). Household Hot Water Temperature – An Analysis at End-Use Level. *WDSA.* Kingston: WDSA / CCWI 2018.

Kenma, R., van Elburg, M., & Aarts, S. (2019). *Task 1 : Scope - Policies and Standards. Final draft report.* Brussels: European Commission. Retrieved from http://solarheateurope.eu/wp-content/uploads/2019/02/20190208_Water-Heater-TASK1-draft-final-report-January-2019.pdf

Kensa heat pumps. (2014, October 17). *Factsheet : buffer vessel.* Retrieved from Kensa heat pumps: https://www.kensaheatpumps.com/wp-content/uploads/2015/11/Factsheet-Buffer-Vessels-V1.pdf

Kepplinger, P., Huber, G., & Petrasch, J. (2016, June 8). Field testing of demand side management via autonomous optimal control of a domestic hot water heater. *Energy and Buildings, 127*, 730-735. doi:10.1016/j.enbuild.2016.06.021

Kepplinger, P., Huber, G., Preißinger, M., & Petrasch, J. (2019, March 1). State estimation of resistive domestic hot water heaters in arbitrary operation modes for demand side management. *Thermal Science and Engineering Progress, 9*, 94-109. doi:10.1016/j.tsep.2018.11.003

KULeuven Energy Institute. (2015). *Fact sheet : The current electricity market design in Europe.* Leuven: KULeuven.

Lomet, A., Suard, F., & Chèze, D. (2015, May). Statistical modeling for real domestic hot water consumption forecasting. *Energy Procedia, 70*, 379-387. doi:10.1016/j.egypro.2015.02.138

Michel, A., Bush, E., & Nipkow, J. (2017). *Dishwashers: Testing the energy variability related to different uses.* Topten International.

Oregi, X., Prieto, I., Hermoso, N., & Izkara, J. L. (2018, May). Automatized and georeferenced energy assessment of an Antwerp district based on cadastral data. *Energy and Buildings, 173*, pp. 176-194. doi:10.1016/j.enbuild.2018.05.018

Richard, M. (2016). *Simulating Domestic Hot Water Demand by means of a Stochastic End-Use Model.* Stellenbosch: Stellenbosch University.

Ritcher, C. P., & Stamminger, R. (2012, April 18). Water Consumption in the Kitchen – A Case Study in Four European Countries. *Water Resources Management, 26*(6), 1639-1649. doi:10.1007/s11269-012-9976-5

Rubens, S. K. (2013). *What people want from their heating controls: a qualitative study.* London: Department for Energy and Climate Change.

Samsung. (2019, December 2). *Differences between the Front Load and Top Load Washing Machine*. Retrieved from Samsung: https://www.samsung.com/in/support/home-appliances/what-are-the-differences-between-the-front-load-and-top-load-washing-machines/

Sheepers, H. M., & Jacobs, H. E. (2014, September). Simulating residential indoor water demand by means of a probability based end-use model. *Journal of Water Supply: Research and Technology - AQUA, 63*, pp. 476-488.

Should I get new storage heaters? (2017, April 4). Retrieved from The Green Age: https://www.thegreenage.co.uk/get-new-storage-heaters/

Synergrid. (2017, December). *Prescriptions techniques électricité : C8/01.* Retrieved from Synergrid: http://www.synergrid.be/index.cfm?PageID=16832#

van den Brom, P., Hansen, A. R., Gram-Hanssen, K., Meijer, A., & Visscher, H. (2019, September 15). Variances in residential heating consumption – Importance of building characteristics and occupants analysed by movers and stayers. *Applied Energy, 250*, 713-728. doi:10.1016/j.apenergy.2019.05.078

Van Kenhove, E., Dinne, K., Janssens, A., & Laverge, J. (2019, August 1). Overview and comparison of Legionella regulations worldwide. *American Journal of Infection Control, 47*(8), 968-978. doi:10.1016/j.ajic.2018.10.006

Waterwise. (2015). *RENEW: Development of concept and offering.* European Commission.

Westphal, F. S., & Roberto, L. (2005). Building Simulation Calibration Using Sensitivity Analysis. *Ninth International IBPSA* (pp. 1331-1338). Montréal: Building Simulation.

Wong, K., & Negnevitsky, M. (2013). Development of an evaluation tool for demande side management of domestic hot water load. *Power and Energy Society General Meeting* (pp. 1-5). IEEE. doi:10.1109/PESMG.2013.6672465

Wright, A. J. (1997). *Electric Storage Heaters in Building Simulation.* Chester: EA Technology Ltd.

Zangheri, P., Armani, R., Pietrobon, M., & Pagliano, L. (2014). *Heating and cooling energy demand and loads for building types in different countries of the EU.* Entranze.

Appendix A. SWOT analysis

Electric storage heater (ESH)

Strengths	Weaknesses
• *Correct input power (0.5…3.5 kW)* • *Large energy capacity* • *High predictability of the pattern at night* • *Time of activation/deactivation quasi instantaneous*	• *Seasonal device* • *Highly dependent on the user's will and comfort* • *Daily energy consumed depends on the building's isolation*
Opportunities	**Threats**
• *Cheaper than other space heating devices (heat pump, solar panel…)* • *Easy to retrofit* • *The EU's Lot 21 regulation forces the manufacturers to build smarter devices*	• *Low yearly sells* • *Too high price of electricity to use it during the day* • *The slow heat release negatively may influence the user's satisfaction*

Electric Storage Water Heaters (ESWH)

<table>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
<tr>
<td>• Patterns are predictable when aggregated (for domestic hot water consumption)
• Presence of a tank (100-300L), which acts as an energy capacity
• Time response quasi-instantaneous
• Power input between 1.5-3 kW</td>
<td>• Only downward regulation (prevent or stop the activation of the resistances only)
• Impossible to get access to the temperature probe of the tank without opening the device
• Has an intrinsic dynamic which vary with manufacturers</td>
</tr>
<tr>
<th>Opportunities</th>
<th>Threats</th>
</tr>
<tr>
<td>• More than 1M devices in Belgium
• Mature technology
• Low initial cost
• Smarter devices, more controllable, enter the market</td>
<td>• Yearly sells are constant
• Most new apartment buildings tend to have a centralized system for space and water heating</td>
</tr>
</table>

Electric Vehicles

<table>
<tr>
<td>

Strengths

- *Large energy capacity (5-15 kWh for hybrid / 20-120 kWh for full electric). Up to 20% are available for flexibility*
- *Large power involved: from 3.7 to 7 kW*
- *Good predictability of availability (function of workhours, low variations from week to week)*
- *Good potential control of the power*
- *Time response between 1 and 10 seconds, depending on technology*

</td>
<td>

Weaknesses

- *State of charge unknown*
- *Time duration is limited by the SOC*
- *Power tends to decrease when the EV is almost fully charged*
- *Up to now, only for downward regulation*

</td>
</tr>
<tr>
<td>

Opportunities

- *Market in constant expansion*
- *High market penetration for hybrid vehicle in Belgium*
- *New EVs become smarter and more grid-oriented*

</td>
<td>

Threats

- *Relatively new market : lack of regulation and norms*
- *Expensive technology*
- *Mitigated opinion about the carbon footprint of electric vehicles*

</td>
</tr>
</table>

Heat pumps

Strengths	Weaknesses
• *Available for upward and downward regulation* • *Variable speed thus variable input power* • *Power involved may be high (3..5 kW)* • *Can be used for heating or for cooling* • *High lifetime (20+ years)*	• *Very sensitive to outside temperature (performance & activation)* • *Seasonal device* • *Time duration cannot be below 6-10 min, and a too long activation will cause a discomfort for the user in absence of a buffer* • *Variable pattern, depending on the building isolation and the ambient temperature* • *The starting current of certain models is high. Therefore, an aggregation of heat pumps may be dangerous for the grid* • *Time response of 6-10 min* • *Ancillaries like circulation pumps lead to less available power*
Opportunities	**Threats**
• *Europe is pushing forward regarding the heat pumps* • *Heat pumps are considered as renewable energy. They have thus more value in this era of decarbonisation* • *Very valuable option for new housings* • *The new heat pumps are already "smart"; possibility to control it with 4 modes* • *Increasing yearly sells*	• *The initial stock and yearly sells are low in Belgium* • *The need for space cooling in Belgium is quasi-null due to its climate* • *Initial cost for the installation may be high* • *Difficult to retrofit* • *New housings in Belgium are low (1% of all dwellings per year)*

Photovoltaic panels

Strengths	Weaknesses
• *Quasi instantaneous response* • *High controllability due to power electronics* • *Can do downward regulation, and upward regulation if a reserve is provided* • *Can do voltage control and thus may be bid on the (future) MVAr ancillary services* • *Mature technology, widely spread in the country*	• *Low power input (1kW peak per 8m² in Belgium)* • *Only available during the day* • *Power reduced to ¼ of its nominal value in winter* • *Small-scale PVs are often equipped with unique MPPT algorithm, thus not flexible without improvements* • *Hard to predict the production*
Opportunities	**Threats**
• *Technology well-known by consumers for being green, easy to implement and at reasonable cost* • *Green certificates makes the technology financially attractive* • *Potential future regulations will require to link the end-user to an aggregator (?)*	• *Reinjection on the grid is not profitable anymore for the end-user* • *Flexibility on PVs has been experimented only on large-scale PV plants* • *Flexibility may be in contradiction with financial aspect (MPPT)*

UNIVERSITÉ CATHOLIQUE DE LOUVAIN
École polytechnique de Louvain
Rue Archimède, 1 bte L6.11.01, 1348 Louvain-la-Neuve, Belgique | **www.uclouvain.be/epl**