Integration of heat demand and demand response in power systems to cover the flexibility requirements linked to high shares of variable renewable energy

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Integration of heat demand and demand response in power systems to cover the flexibility requirements linked to high shares of variable renewable energy

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Abstract

Increasing the share of renewable energy generation in the generation mix is one of European's objectives. Increasing renewable generation sources complicates the power grid management. In particular, the variability of such energy sources increases the complexity of maintaining the demand-supply balance. More flexibility is needed.

The goal of this master thesis is to assess the potential of residential heating demand management to meet the flexibility needs linked to high shares in renewable generation. To that end, a heat demand model is developed and coupled to an existing unit commitment and dispatch model of the power system. The residential heating demand considered consists in the space heating demand and the domestic hot water demand and is coupled to the power system through flexible electric heating devices (heat pumps and domestic hot water heaters).
Several simulations are performed for Belgium. The potential benefits in 2015 are assessed. Then a parametric analysis is performed assessing the influence of the flexible devices penetration, the renewable capacity and the flexibility of the capacity mix.

Results show operational cost benefits up to 35M€ and curtailment reduction up to 1 TWh with 1 million flexible electric heating systems. These benefits are reduced significantly when non-flexible units are replaced by flexible units and are increased when more renewable capacity is added. Moreover, when the number of flexible heating systems are increased, a saturation effect of the flexibility is observed.

In conclusion, the heat demand is able to provide non-negligible flexibility to the power system through flexible electric heating devices. The benefits due to the additional flexibility are increased when the flexibility need of the system increases and especially when more renewable energy is available. Results show that non negligible curtailed energy can be captured by the thermal storage when high shares of renewable capacity exist.

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Chapter 1

Introduction

1.1 General context

Increasing the share of renewable energy generation in the generation mix is one of European's objectives towards 2020 and beyond. Scenarios for renewable energy integration in the EU28 show that up to 43% of the electricity will be generated from renewable sources by 2030 from which more than 50% will be provided by nondispatchable, intermittent sources (solar and wind). [1]

Although increasing the share of renewable sources in the power production mix has many advantages, increasing non-schedulable generation sources complicates the power grid management. In particular, the unpredictability and variability of such energy sources increases the complexity of maintaining the demand-supply balance and decreases the global efficiency of the power system. More flexibility is needed. Up to now, most of the flexibility was provided by the supply side through reserves and storage facilities but recently, interest in flexibility at the demand side has grown and the concept of demand side management (DSM) has progressed.

The goal of this master thesis is to assess the potential of residential heating demand management to meet the flexibility needs linked to an increase in renewable generation. To that end, a heat demand model is developed and coupled to an existing unit commitment and dispatch model of the power system. The residential heating demand considered consists in the space heating demand and the domestic hot water demand and is coupled to the power system through flexible electric heating devices (heat pumps and domestic hot water heaters).

1.2 State of the art

The term of DSM was used for the first time in 1984 and was defined as "the planning, implementation and monitoring of those utility activities designed to influence customer use of electricity in ways that will produce desired changes in the utility's load shape" [2].
Potential benefits of DSM are: reduction of the generation margin, improved power system efficiency, more efficient managing of intermittent generation, etc. [3]
Different electric demand side management strategies exist, in particular demand response (DR) which focuses on load flexibility and short term customer action [4].

In the literature, a large amount of studies assessing the benefits of DSM on the power system operation exists. Dupont et al. [5] show its benefits in terms of cost reduction, higher reliability, and emission levels reduction. Pina et al. [6] and Moura et al. [7] show the possible impact of DR on enabling the integration of high shares of intermittent renewable generation in the power system. Finally, Gils [4] presents an assessment of the theoretical DR potential in Europe and identifies potential flexible loads in all demand sectors. In particular, the residential sector has been pointed out to have a large potential for both load increase and decrease.

Since the residential sector accounts for 26% of the final energy demand in EU28 and a substantial electrification of this sector is expected, there is a significant potential for energy savings and demand-side management in this sector, in particular for space heating and domestic water heating which account for more than 70% of the total residential energy consumption [1]. Therefore, demand response management by controlling and adapting space heating (SH) and domestic hot water (DHW) demands may provide the flexibility needed to cope with intermittent renewable generation.

However, modifying the load pattern of the residential heating demand affects the consumers' comfort that has to stay within an acceptable range. This is achievable through the use of thermal energy storage. Thermal energy storage allows decoupling the heat demand from the electric demand in time allowing the modification of the residential electric load pattern without affecting significantly the comfort of the consumers.

A broad range of thermal energy storage technologies exists for demand side management. However, no specific installation is needed for thermal energy storage in the residential sector. In fact, inherent thermal storage exists for both space heating and domestic hot water as the building envelope and the hot water tank respectively.
Reynders et al. [8] and Hedegaard et al. [9] show the strong potential of the structural storage capacity.
Kepplinger et al. [10] show the potential for DR of resistive domestic hot water heaters.

As no additional thermal energy storage is needed to implement residential demand response management and because of the expected electrification of the residential sector, DSM by means of flexible electrical heating systems coupled to the inherent thermal energy storage in the buildings could be very beneficial for the power grid in terms of integration of renewable sources, cost reduction, etc.
Electric individual heat pumps and domestic resistance water heaters are good candidates to DSM.
In 2015, more than 2 million aerothermal heat pumps where sold in the EU increasing the total number of units in operation to almost 30 millions [11]. Considering heat pumps potential for energy savings and CO2 emission reduction [12], their market share is expected to increase further in the European residential and tertiary sector. Due to this expected increase especially in the building sector, they are good candidates for heating demand management.
The potential of resistance electric waters heaters as DSM techologies has been shown by Kepplinger et al. [10].

- The aim of this work is to assess the flexibility potential of the residential heating demand. Heat pumps and resistance water heaters are considered as flexible loads and are coupled to thermal energy storage in the building envelope and the domestic hot water tank through a so-called integrated model.

As emphasized by Bruninx et al. [13, 14], the use of an integrated model for modelling purpose of demand response with electric heating systems coupled to thermal energy storage is of significant importance. In fact, this model has to consider all technical and comfort constraints

present at the demand side and at the supply side. Patteeuw et al.
Patteeuw et al. [15] present such an integrated model for short term demand response of flexible electric heating systems. The integrated model describes an centrally controlled optimisation problem minimizing the overall operational cost of the system subjected to both electricity supply and heating systems constraints.

Few studies were found assessing the benefits of coupling electric heating systems coupled to thermal energy storage using integrated models.
Patteeuw et al. [16] show that demand response with heat pumps has significant benefits in reducing costs, peak shaving and CO2 emissions reduction. Hedegaard et al. [17] assesses the influence of heat pumps in the integration of high shares of wind power in Denmark by applying an energy system model that optimizes both investments and operation costs. Results show that the heat pumps can contribute significantly to reduce wind power investments costs, fuel consumption and CO2 emissions. The main benefit is peak demand reduction ranging from 300 to 600 MW, and leading to a socio-economic cost reduction of 60-200€per year and per dwelling.

Similarly to this work, Arteconi et al. [18] made a Belgian case study of active demand response with electric heating systems coupled to thermal energy storage. Heat pumps and electric resistance heaters are coupled with building envelope and hot water tank storage. The study evaluates the benefits of demand response market penetration in terms of electricity consumption and operational costs. The final user's and the overall system's benefits are assessed.
The model that is used minimizes the operational cost of the system combining a merit order model of the electricity generation side with a detailed representation of the demand side. At the supply side, the minimum and maximum capacities of the generation units are taken into account but ramping constraints, start-up costs and minimum on and off-times are neglected. The generation mix is based on a future energy mix scenario consisting in gas fired power plants and renewable sources.
Results show the benefits of increasing the participation rate to active demand response: reduction in total operational costs (up to 35M€/year) and CO2 emission (0,29Mton/year), significant peak demand reduction (up to 2GW), reduction in curtailment and peak electricity pricing reduction. Moreover, an increase in the demand with the increase in the participation to demand response is shown and a 'saturation of the usefulness of the flexibility' effect is pointed. As the renewable generation increases, results show an increase in operational cost benefits and in the total electric demand.

1.3 Objective and structure

The objective of this work is to develop an integrated model of the power system coupled to the heat demand and to assess the potential benefits of demand response through this heat demand. For the results analysis, emphasis is put on the supply side and especially on renewable generation. A Belgian case study is performed.

The supply side model is an existing unit commitment and dispatch model: the Dispa-SET model [19]. This highly detailed model minimizes the total operational cost of the system and takes into account the following parameters: minimum and maximum capacities of power plant, ramping constraints, reserves, hydro storage, etc. This model is detailed in the next chapter. (Chapter 2)

The demand side is coupled to the supply side through electric air-to-water heat pumps and electric resistance water heaters. A heat model is developed coupling the heating demands for space heating and domestic hot water to the final heat demand through state space models (thermal storage). (Chapter 3)

For the coupling, the heat model is implemented in the Dispa-SET interface and coupled to the unit commitment and dispatch model. (Chapter 4)

In order to assess the potential benefits of the flexible heat demand, several simulations are performed from the integrated model for different capacity mixes and different flexible electric heating system penetrations. (Chapter 5)

Finally, the main results are resumed and ideas for future work are developed. (Chapter 6)

Chapter 2

Dispa-SET

The aim of the Dispa-SET model [19] is to represent with a high level of detail the short-term operation of large-scale power systems, solving the unit commitment problem. To that aim, it is considered that the system is managed by a central operator with full information on the technical and economic data of the generation units, the demands in each node, and the transmission network.

The model is released as an open-source tool. It is structured in such a way that potential users can easily modify the input data to run their own simulations with limited knowledge in programming languages.

In this section, the Dispa-SET tool is partly described. The description is a condensed and modified version of [19] and focusses on the characteristics directly linked to this master thesis. The optimisation model is first described. The Dispa-SET interface is then described and finally, the input data is explained.

2.1 Model description

The model is expressed as an optimisation problem written in GAMS [20]. It is a mixed-integer linear program (MILP) for which the binary variables are the commitment status of each unit. The main model features can be summarized as follows:

- Minimum and maximum power for each unit
- Power plant ramping limits
- Reserves up and down
- Minimum up/down times
- Load shedding
- Curtailment
- Pumped-hydro storage
- Non-dispatchable units (e.g. wind turbines, run-of-river, etc.)
- Start-up, ramping and no-load costs

The demand is assumed to be inelastic to the price signal. The MILP objective function is therefore the total operational cost over the optimisation period.

Table 2.1: Dispa-SET sets

Name	Description
f	Fuel types
h	Hours
i	Time step in the current optimisation horizon
l	Transmission lines between nodes
mk	{DA: Day-ahead, 2U: Reserve up, 2D: Reserve down}
n	Zones within each country (currently one zone, or node, per country)
p	Pollutants
t	Power generation technologies
tr	Renewable power generation technologies
u	Units
s	Storage units (including hydro reservoirs)

2.1.1 Variables

Sets

The sets are the basic building blocks of the optimisation model, corresponding exactly to the indices in the algebraic representations of models. The sets defined in Dispa-SET are listed in Table 2.1.

Parameters

The parameters correspond to the exogenous data provided to the model. They result in the constant coefficients of the optimisation model. The list of Dispa-SET parameters is provided in Table 2.2.

Optimisation variables

The optimisation (decision) variables are the variables that need to be adjusted to minimize the objective function. They are defined in Table 2.3.

2.1.2 Optimisation model

The unit commitment problem explained in this section is a simplified instance of the problem faced by the operator in charge of clearing the competitive bids of the participants into a wholesale day-ahead power market. In the present formulation the demand side is an aggregated input for each node, while the transmission network is modelled as a transport problem between the nodes (that is, the problem is network-constrained but the model does not include the calculation of the optimal power flows).

The unit commitment problem consists of two parts:

1. scheduling the start-up, operation, and shut down of the available generation units
2. allocating (for each period of the simulation horizon of the model) the total power demand among the available generation units in such a way that the overall power system costs is minimized

The first part of the problem, the unit scheduling during several periods of time, requires the use of binary variables in order to represent the start-up and shut down decisions, as well as the consideration of constraints linking the commitment status of the units in different periods. The second part of the problem is the economic dispatch problem, which determines the continuous output of each and every generation unit in the system. Therefore, given all the features of

Table 2.2: Dispa-SET parameters

Name	**Units**	**Description**
AvailabilityFactor(u,i)	%	Percentage of nominal capacity available
CommittedInitial(u)	n.a.	Initial commitment status
CostFixed(u)	EUR/h	Fixed costs
CostLoadShedding(n,h)	EUR/MWh	Shedding costs
CostRampDown(u)	EUR/MW	Ramp-down costs
CostRampUp(u)	EUR/MW	Ramp-up costs
CostShutDown(u)	EUR/h	Shut-down costs
CostStartUp(u)	EUR/h	Start-up costs
CostVariableH(u,i)	EUR/MWh	Variable costs
Curtailment(n)	n.a.	Curtailment {binary: 1 allowed}
Demand(mk,n,i)	MW	Hourly demand in each zone
Efficiency(u)	%	Power plant efficiency
EmissionMaximum(n,p)	EUR/tP	Emission limit per zone for pollutant p
EmissionRate(u,p)	tP/MW	Emission rate of pollutant p from unit u
FlexibilityDown(u)	MW/h	Available fast shut-down ramping capacity
FlexibilityUp(u)	MW/h	Available fast start-up ramping capacity
Fuel(u,f)	n.a.	Fuel type used by unit u {binary: 1 u uses f}
LineNode(l,n)	n.a.	Line-zone incidence matrix {-1,+1}
LoadMaximum(u,h)	%	Maximum load for each unit
LoadShedding(n,h)	MW	Load that may be shed per zone in 1 hour
Location(u,n)	n.a.	Location {binary: 1 u located in n}
OutageFactor(u,h)	%	Outage factor (100 % = full outage) per hour
PartLoadMin(u)	%	Percentage of minimum nominal capacity
PowerCapacity(u)	MW	Installed capacity
PowerInitial(u)	MW	Power output before initial period
PowerMinStable(u)	MW	Minimum power for stable generation
PowerMustRun(u)	MW	Minimum power output
PriceTransmission(l,h)	EUR/MWh	Price of transmission between zones
RampDownMaximum(u)	MW/h	Ramp down limit
RampShutDownMaximum(u)	MW/h	Shut-down ramp limit
RampStartUpMaximum(u)	MW/h	Start-up ramp limit
RampUpMaximum(u)	MW/h	Ramp up limit
Reserve(t)	n.a.	Reserve provider {binary}
StorageCapacity(s)	MWh	Storage capacity (reservoirs)
StorageChargingCapacity(s)	MW	Maximum charging capacity
StorageChargingEfficiency(s)	%	Charging efficiency
StorageDischargeEfficiency(s)	%	Discharge efficiency
StorageInflow(s,h)	MWh	Storage inflows
StorageInitial(s)	MWh	Storage level before initial period
StorageMinimum(s)	MWh	Minimum storage level
StorageOutflow(s,h)	MWh	Storage outflows (spills)
StorageProfile(u,h)	MWh	Storage long-term level profile
Technology(u,t)	n.a.	Technology type {binary: 1: u belongs to t}
TimeDownInitial(u)	h	Hours down before initial period
TimeDownLeftInitial(u)	h	Time down remaining at initial time
TimeDownLeftJustStopped(u,i)	h	Time down remaining if started at time i
TimeDownMinimum(u)	h	Minimum down time
TimeDown(u,h)	h	Number of hours down
TimeUpInitial(u)	h	Number of hours up before initial period
TimeUpLeftInitial(u)	h	Time up remaining at initial time
TimeUpLeftJustStarted(u,i)	h	Time up remaining if started at time i
TimeUpMinimum(u)	h	Minimum up time
TimeUp(u,h)	h	Number of hours up
VOLL ()	EUR/MWh	Value of lost load

Table 2.3: Dispa-SET decision variables

Name	Units	Description
Committed(u,h)	n.a.	Unit committed at hour h {1,0}
CostStartUpH(u,h)	EUR	Cost of starting up
CostShutDownH(u,h)	EUR	cost of shutting down
CostRampUpH(u,h)	EUR	Ramping cost
CostRampDownH(u,h)	EUR	Ramping cost
CurtailedPower(n,h)	MW	Curtailed power at node n
Flow(l,h)	MW	Flow through lines
MaxRamp2U(u,h)	MW/h	Maximum 15-min Ramp-up capbility
MaxRamp2D(u,h)	MW/h	Maximum 15-min Ramp-down capbility
Power(u,h)	MW	Power output
PowerMaximum(u,h)	MW	Power output
PowerMinimum(u,h)	MW	Power output
ShedLoad(n,h)	MW	Shed load
StorageInput(s,h)	MWh	Charging input for storage units
StorageLevel(s,h)	MWh	Storage level of charge
Spillage(s,h)	MWh	Spillage from water reservoirs
SystemCostD	EUR	Total system cost for one optimisation period
LostLoadMaxPower(n,h)	MW	Deficit in terms of maximum power
LostLoadRampUp(u,h)	MW	Deficit in terms of ramping up for each plant
LostLoadRampDown(u,h)	MW	Deficit in terms of ramping down
LostLoadMinPower(n,h)	MW	Power exceeding the demand
LostLoadReserve2U(n,h)	MW	Deficit in reserve up

the problem mentioned above, it can be naturally formulated as a mixed-integer linear program (MILP).

Objective function

The goal of the unit commitment problem is to minimize the total power system costs

$$min \sum_{i} \Big(SystemCost_i \Big) \tag{2.1}$$

which are defined as the sum of different cost items:

$$\begin{aligned}
&SystemCost_i = \sum_{u,n} \\
&\Big[CostStartUp_{u,i} + CostShutDown_{u,i} + CostFixed_u \cdot Committed_{u,i} \\
&+ CostVariable_{u,i} \cdot Power_{u,i} + CostRampUp_{u,i} + CostRampDown_{u,i} \\
&+ PriceTransimission_{i,l} \cdot Flow_{i,l} + (CostLoadShedding_{i,n} \cdot ShedLoad_{i,n}) \\
&+ VOLL_{Power} \cdot (LostLoadMaxPower_{i,n} + LostLoadMinPower_{i,n}) \\
&+ VOLL_{Reserve} \cdot (LostLoadReserve2U_{i,n} + LostLoadReserve2D_{i,n}) \\
&+ VOLL_{Ramp} \cdot (LostLoadRampUp_{u,i} + LostLoadRampDown_{u,i}) \Big]
\end{aligned} \tag{2.2}$$

The costs can be broken down as:

- Fixed costs: depending on whether the unit is on or off.
- Variable costs: stemming from the power output of the units.
- Start-up and shut-down costs: due to the start-up or shut-down of a unit.

- Ramp-up and ramp-down costs : emerging from the ramping up or down of a unit.
- Shed load costs: due to necessary load shedding.
- Transmission costs: depending of the flow transmitted through the lines.
- Loss of load costs: power not matching the demand, ramping or reserve.

Fixed costs The fixed costs of the power plants are given as exogenous parameters in the Dispa-SET database.

Variable costs The variable production costs are determined by fuel and emission prices corrected by the efficiency (which is considered to be constant for all levels of output) and the emission rate of the unit:

$$\begin{aligned}
&CostVariable_{u,h} = \\
&Markup_{u,h} + \sum_{n,f}\left(\frac{Fuel_{u,f} \cdot FuelPrice_{n,f,h} \cdot Location_{u,n}}{Efficiency_u}\right) \\
&+ \sum_{p}\left(EmissionRate_{u,p} \cdot PermitPrice_p\right)
\end{aligned} \tag{2.3}$$

The variable cost includes an additional mark-up parameter that can be used for calibration and validation purposes.

Start-up and shut-down costs The start-up and shut-down costs are positive variables, active when the commitment status between two consecutive time periods is modified:

$$\begin{aligned}
&i = 1: \\
&CostStartUp_{u,i} \geq CostStartUp_u \cdot (Committed_{u,i} - CommittedInitial_u) \\
&CostShutDown_{u,i} \geq CostShutDown_u \cdot (CommittedInitial_u - Committed_{u,i}) \\
&i > 1: \\
&CostStartUp_{u,i} \geq CostStartUp_u \cdot (Committed_{u,i} - Committed_{u,i-1}) \\
&CostShutDown_{u,i} \geq CostShutDown_u \cdot (Committed_{u,i-1} - Committed_{u,i})
\end{aligned} \tag{2.4}$$

In the previous equation, as in some of the following, a distinction is made between the equation for the first and the subsequent periods. The equation for the first period takes into account the commitment status of the unit before the beginning of the simulation, which is part of the information fed into the model.

Ramping costs Ramping costs are computed in the same manner:

$$\begin{aligned}
&i = 1: \\
&CostRampUp_{u,i} \geq CostRampUp_u \cdot (Power_{u,i} - PowerInitial_u) \\
&CostRampDown_{u,i} \geq CostRampDown_u \cdot (PowerInitial_u - Power_{u,i}) \\
&i > 1: \\
&CostRampUp_{u,i} \geq CostRampUp_u \cdot (Power_{u,i} - Power_{u,i-1}) \\
&CostRampDown_{u,i} \geq CostRampDown_u \cdot (Power_{u,i-1} - Power_{u,i})
\end{aligned} \tag{2.5}$$

Loss of load costs In order to facilitate tracking and debugging of errors, the model considers some variables representing the capacity the system is not able to provide when the minimum/maximum power, reserve, or ramping constraints are reached. These lost loads are a very expensive last resort of the system used when there is no other choice available. The different lost loads are assigned very high costs (with respect to any other costs). This allows running the simulation without infeasibilities, thus helping to detect the origin of the loss of load. In a normal run of the model, without errors, the *LostLoad* variables are expected to be equal to zero.

Demand-related constraints

The main constraint to be met is the supply-demand balance, for each period and each zone, in the day-ahead market. According to this restriction, the sum of all the power produced by all the units present in the node (including the power generated by the storage units), and the power injected from neighbouring nodes is equal to the load in that node, plus the power consumed for energy storage, minus the shed load:

$$\begin{aligned}
&\sum_{u} (Power_{u,i} \cdot Location_{u,n}) \\
&+ \sum_{l} (Flow_{l,i} \cdot LineNode_{l,n}) \\
&= Demand_{DA,n,h} + \sum_{r} \left(StorageInput_{s,h} \cdot Location_{s,n}\right) \\
&\quad - ShedLoad_{n,i} \\
&\quad - LostLoadMaxPower_{n,i} + LostLoadMinPower_{n,i}
\end{aligned} \tag{2.6}$$

Besides that balance, the reserve requirements (upwards and downwards) in each node must be met as well. In Dispa-SET, the reserve requirements are defined as an aggregation of secondary and tertiary reserves, which are typically brought online in periods shorter than an hour, the time step of this model. Therefore, additional equations and constraints are defined to account for the up/down ramping requirements, by computing the ability of each unit to adapt its power output within a period of 15 min. Since this master thesis does not focus on reserve provision, the details are skipped.

Power output bounds

The minimum power output is determined by the must-run or stable generation level of the unit if it is committed:

$$\begin{aligned}
&PowerMustRun_{u,i} \cdot Committed_{u,i} \\
&\leq Power_{u,i}
\end{aligned} \tag{2.7}$$

On the other hand, the output is limited by the available capacity, if the unit is committed:

$$\begin{aligned}
&Power_{u,i} \\
&\leq PowerCapacity_{u} \cdot AvailabilityFactor_{u,i} \\
&\cdot (1 - OutageFactor_{u,i}) \cdot Committed_{u,i}
\end{aligned} \tag{2.8}$$

The availability factor is used for renewable technologies to set the maximum time-dependent generation level. It is set to one for the traditional power plants. The outage factor accounts for the share of unavailable power due to planned or unplanned outages.

The power output in a given period also depends on the output levels in the previous and the following periods and on the ramping capabilities of the unit. If the unit was down, the ramping capability is given by the maximum start up ramp, while if the unit was online the limit is defined by the maximum ramp up rate. Those bounds are given with respect to the previous time step by the equation:

$$\begin{gathered}
i = 1 : \\
Power_{u,i} \leq \\
PowerInitial_u \\
+ CommittedInitial_u \cdot RampUpMaximum_u \\
+ (1 - CommittedInitial_u) \cdot RampStartUpMaximum_u \\
+ LostLoadRampUp_{u,i} \\
i > 1 : \\
Power_{u,i} \leq \\
Power_{u,i-1} \\
+ Committed_{u,i-1} \cdot RampUpMaximum_u \\
+ (1 - Committed_{u,i-1}) \cdot RampStartUpMaximum_u \\
+ LostLoadRampUp_{u,i}
\end{gathered} \tag{2.9}$$

where the $LoadMaximum$ parameter is calculated taking into account the availability factor and the outage factor:

$$LoadMaximum_{u,h} = AvailabilityFactor_{u,h} \cdot (1 - OutageFactor_{u,h}) \tag{2.10}$$

Similarly, the ramp down capability is limited by the maximum ramp down or the maximum shut down ramp rate:

$$\begin{gathered}
i = 1 : \\
PowerInitial_u - Power_{u,i} \leq \\
Committed_{u,i} \cdot RampDownMaximum_u \\
+ (1 - Committed_{u,i}) \cdot RampShutDownMaximum_u \\
+ LostLoadRampDown_{u,i} \\
i > 1 : \\
Power_{u,i-1} - Power_{u,i} \leq \\
Committed_{u,i} \cdot RampDownMaximum_u \\
+ (1 - Committed_{u,i}) \cdot RampShutDownMaximum_u \\
+ LostLoadRampDown_{u,i}
\end{gathered} \tag{2.11}$$

Minimum up and down times

The operation of the generation units is also limited by the amount of time the unit has been running or stopped. In order to avoid excessive ageing of the generators, or because of their physical characteristics, once a unit is started up, it cannot be shut down immediately. Reciprocally, if the unit is shut down it may not be started immediately.
That is, the value of the time counter with respect to the minimum up time and down times

determines the commitment status of the unit. In order to model theses constraints linearly, it is necessary to keep track of the number of hours the unit must be online at the beginning of the simulation:

$$\begin{gathered} \mathit{TimeUpLeftInitial}_u = \\ \mathit{min}\left\{N, \left(\mathit{TimeUpMinimum}_u - \mathit{TimeUpInitial}_u\right) \cdot \mathit{CommittedInitial}_u\right\} \end{gathered} \tag{2.12}$$

where N is the number of time steps in the current optimisation horizon.

If the unit is initially started up, it has to remain committed until reaching the minimum up time:

$$\sum_{i=1}^{\mathit{TimeUpLeftInitial}_u} \left(1 - \mathit{Committed}_{u,i}\right) = 0 \tag{2.13}$$

If the unit is started during the considered horizon, the time it has to remain online is *TimeUp-Minimum*, but cannot exceed the time remaining in the simulated period. This is expressed in the next equation and is pre-calculated for each time step of the period:

$$\begin{gathered} \mathit{TimeUpLeftJustStarted}_{u,i} = \\ \mathit{min}\left\{N - i + 1, \mathit{TimeUpMinimum}_u\right\} \end{gathered} \tag{2.14}$$

The equation imposing the unit to remain committed is written:

$$\begin{gathered} i = 1: \\ \sum_{ii=i}^{i+\mathit{TimeUpLeftJustStarted}_{u,i}-1} \mathit{Committed}_{u,ii} \geq \\ \mathit{TimeUpLeftJustStarted}_{u,i} \cdot \left(\mathit{Committed}_{u,i} - \mathit{CommittedInitial}_u\right) \\ i > 1: \\ \sum_{ii=i}^{i+\mathit{TimeUpLeftJustStarted}_u-1} \mathit{Committed}_{u,ii} \geq \\ \mathit{TimeUpLeftJustStarted}_{u,i} \cdot \left(\mathit{Committed}_{u,i} - \mathit{Committed}_{u,i-1}\right) \end{gathered} \tag{2.15}$$

The same method can be applied to the minimum down time constraint:

$$\begin{gathered} \mathit{TimeDownLeft}_u = \\ \mathit{min}\{N, \left(\mathit{TimeDownMinimum}_u - \mathit{TimeDownInitial}_u\right) \\ \cdot\left(1 - \mathit{CommittedInitial}_u\right)\} \end{gathered} \tag{2.16}$$

Related to the initial status of the unit:

$$\sum_{i=1}^{\mathit{TimeDownLeft}_u} \mathit{Committed}_{u,i} = 0 \tag{2.17}$$

The $TimeDownLeftJustStopped$ parameter is computed by:

$$\begin{gathered} \mathit{TimeDownLeftJustStopped}_{u,i} = \\ \mathit{min}\left\{N - i + 1, \mathit{TimeDownMinimum}_u\right\} \end{gathered} \tag{2.18}$$

Finally, the equation imposing the time the unit has to remain de-committed is defined as:

$$
\begin{gathered}
i = 1 : \\
\sum_{ii=i}^{i+TimeDownLeftJustStopped_{i,u}-1} (1 - Committed_{u,i}) \geq \\
TimeDownLeftJustStopped_{u,i} \cdot (CommittedInitial_u - Committed_{u,i}) \\
i > 1 : \\
\sum_{ii=i}^{i+TimeDownLeftJustStopped_{u}-1} (1 - Committed_{u,i}) \geq \\
TimeDownLeftJustStopped_{u,i} \cdot (Committed_{u,i-1} - Committed_{u,i})
\end{gathered}
\tag{2.19}
$$

This formulation avoids the use of additional binary variables to describe the start-up and shut-down of each unit.

Storage-related constraints

Generation units with energy storage capabilities (mostly large hydro reservoirs and pumped hydro storage units) must meet additional restrictions related to the amount of energy stored. Storage units are considered to be subject to the same constraints as non-storage power plants. In addition to those constraints, storage-specific restrictions are added for the set of storage units (i.e. a subset of all units). These restrictions include the storage capacity, inflow, outflow, charging, charging capacity, charge/discharge efficiencies, etc. Discharging is considered as the standard operation mode and is therefore linked to the *Power* variable, common to all units.

The first constrain imposes that the energy stored by a given unit is bounded by a minimum value:

$$StorageMinimum_s \leq StorageLevel_{s,i} \tag{2.20}$$

In the case of a storage unit, the availability factor applies to the charging/discharging power, but also to the storage capacity. The storage level is thus limited by:

$$StorageLevel_{s,i} \leq StorageCapacity_s \cdot AvailabilityFactor_{s,i} \tag{2.21}$$

The energy added to the storage unit is limited by the charging capacity. Charging is allowed only if the unit is not producing (discharging) at the same time (i.e. if the Committed variable is equal to 0).

$$
\begin{gathered}
StorageInput_{s,i} \leq StorageChargingCapacity_s \\
\cdot AvailabilityFactor_{s,i} \cdot (1 - Committed_{s,i})
\end{gathered}
\tag{2.22}
$$

Discharge is limited by the level of charge of the storage unit:

$$
\begin{gathered}
\frac{Power_{i,s}}{StorageDischargeEfficiency_s} + StorageOutflow_{s,i} \\
+Spillage_{s,i} - StorageInflow_{s,i} \\
\leq StorageLevel_{s,i}
\end{gathered}
\tag{2.23}
$$

Charge is limited by the level of charge of the storage unit:

$$\begin{aligned}
& \mathit{StorageInput}_{s,i} \cdot \mathit{StorageChargingEfficiency}_s \\
& -\mathit{StorageOutflow}_{s,i} - \mathit{Spillage}_{s,i} \\
& +\mathit{StorageInflow}_{s,i} \\
& \leq \mathit{StorageCapacity}_s - \mathit{StorageLevel}_{s,i}
\end{aligned} \tag{2.24}$$

Besides, the energy stored in a given period is given by the energy stored in the previous period, net of charges and discharges:

$$\begin{gathered}
i = 1 : \\
\mathit{StorageLevelInitial}_s + \mathit{StorageInflow}_{s,i} \\
+\mathit{StorageInput}_{s,i} \cdot \mathit{StorageChargingEfficiency}_s \\
= \mathit{StorageLevel}_{s,i} + \mathit{StorageOutflow}_{s,i} + \frac{\mathit{Power}_{s,i}}{\mathit{StorageDischargeEfficiency}_s} \\
i > 1 : \\
\mathit{StorageLevel}_{s,i-1} + \mathit{StorageInflow}_{s,i} \\
+\mathit{StorageInput}_{s,i} \cdot \mathit{StorageChargingEfficiency}_s \\
= \mathit{StorageLevel}_{s,i} + \mathit{StorageOutflow}_{s,i} + \frac{\mathit{Power}_{s,i}}{\mathit{StorageDischargeEfficiency}_s}
\end{gathered} \tag{2.25}$$

Some storage units are equipped with large reservoirs, whose capacity at full load might be longer than the optimisation horizon. Therefore, a minimum level constraint is required for the last hour of the optimisation, which otherwise would systematically tend to empty the reservoir as much a possible. An exogenous minimum profile is thus provided and the following constraint is applied:

$$\begin{gathered}
\mathit{StorageLevel}_{s,N} \geq min(\mathit{StorageProfile}_{s,N} \\
\cdot \mathit{AvailabilityFactor}_{s,N} \cdot \mathit{StorageCapacity}_s, \\
\mathit{StorageLevel}_{s,0} + \sum_{i=1}^{N} InFlows_{s,i})
\end{gathered} \tag{2.26}$$

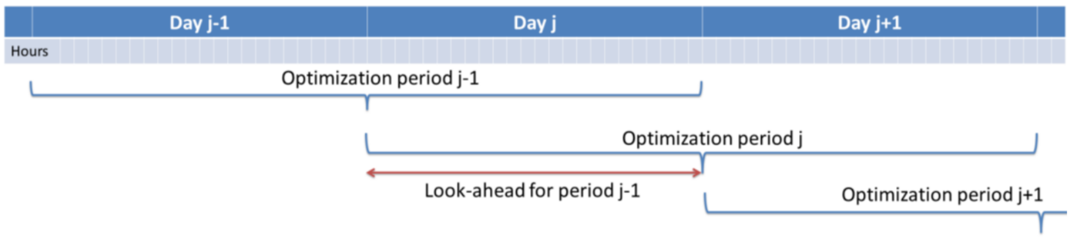
where $StorageProfile$ is a non-dimensional minimum storage level provided as an exogenous input. The minimum is taken to avoid infeasibilities in case the provided inflows are not sufficient to comply with the imposed storage level at the end of the horizon.

Curtailment

If curtailment of intermittent generation sources is allowed in one node, the amount of curtailed power is bounded by the output of the renewable (tr) units present in that node:

$$\begin{gathered}
\mathit{CurtailedPower}_{n,i} \\
\leq \sum_{u,tr} \left(\mathit{Power}_{u,i} \cdot \mathit{Technology}_{u,tr} \cdot \mathit{Location}_{u,n} \right) \cdot \mathit{Curtailment}_n
\end{gathered} \tag{2.27}$$

Figure 2.1: Principle of the rolling horizon optimisation



Load shedding

If load shedding is allowed in a node, the amount of shed load is limited by the shedding capacity contracted on that particular node (e.g. through interruptible industrial contracts)

$$ShedLoad_{n,i} \leq LoadShedding_n \tag{2.28}$$

2.1.3 Rolling horizon

The mathematical problem described in the previous sections could in principle be solved for a whole year split into time steps of one hour, but with all likelihood the problem would become extremely demanding in computational terms when attempting to solve the model with a realistically sized dataset. Therefore, the problem is split into smaller optimisation problems that are run recursively throughout the year.

Figure 2.1 shows an example of such approach, in which the optimisation horizon is one day, with a look-ahead (or overlap) period of one day. The initial values of the optimisation for day j are the final values of the optimisation of the previous day. The look-ahead period is modelled to avoid issues related to the end of the optimisation period such as emptying the hydro reservoirs, or starting low-cost but non-flexible power plants. In this case, the optimisation is performed over 48 hours, but only the first 24 hours are conserved.

Although the previous example corresponds to an optimisation horizon and an overlap of one day, these two values can be adjusted by the user in the Dispa-SET configuration file.

2.1.4 Power plant clustering

For computational efficiency reasons, it is useful to cluster some of the original units into larger units. This reduces the number of continuous and binary variables and can, in some conditions, be performed without significant loss of simulation accuracy.

The clustering occurs at the beginning of the pre-processing phase (i.e. the units in the Dispa-SET database do not need to be clustered).
The units that are either very small or very flexible are aggregated into larger units. Some of these units (e.g. the turbojets) indeed present a low capacity or a high flexibility: their output power does not exceed a few MW and/or they can reach full power in less than 15 minutes (i.e. less than the simulation time step). For these units, a unit commitment model with a time step of 1 hour is unnecessary and computationally inefficient. They are therefore merged into one single, highly flexible unit with averaged characteristics.
The condition for the clustering of two units is a combination of sub-conditions regarding their type, maximum power, flexibility and technical similarities. Only very similar units are aggregated (i.e. their quantitative characteristics should be similar), which avoids errors due to excessive aggregation.

2.1.5 Optimisation precision

In order to reach an MILP solution within an acceptable time frame, the model is not forced to find the exact optimal solution but has to find a solution that is close enough to the better relaxed (linear) solution obtained. An optimum criteria is fixed as the distance between the best relaxed solution and the MILP solution. In this master thesis, the optimum criteria is set at 1%. The optimal objective value obtained is thus between 0 and 1% higher than the actual optimal objective value.

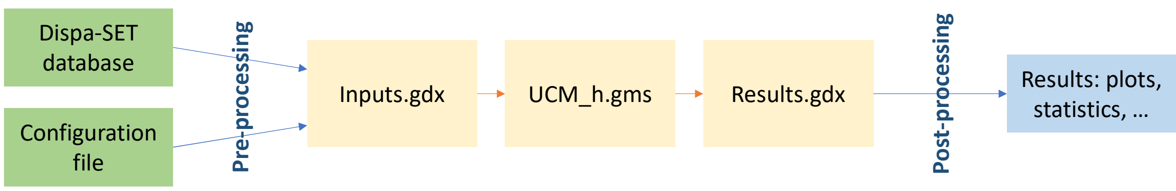
2.2 Implementation and interface

The typical step-by-step procedure to parametrize and run a Dispa-SET simulation is the following:

1. Fill the Dispa-SET database with properly formatted data (time series, power plant data, etc.)
2. Configure the simulation parameters (rolling horizon, data slicing) in the configuration file.
3. Generate the simulation environment which comprises the inputs of the optimisation
4. Open the GAMS simulation files (project: UCM.gpr and model: UCM_h.gms) and run the model.
5. Read and display the simulation results.

This section provides a detailed description of these steps and the corresponding data entities which are illustrated in Figure 2.2.

Figure 2.2: Implementation and interface of Dispa-SET



2.2.1 Dispa-SET database

The Dispa-SET input data is stored as csv files in a directory structure. A link to the required data is then provided by the user in the configuration file.

2.2.2 Configuration file

The excel configuration file is read at the beginning of the pre-processing phase. It provides general inputs for the simulation as well as links to the relevant data files in the database. Especially, it provides

- the optimisation period
- the horizon length and the lookahead period

- the countries to be simulated
- input modifiers

The input modifiers are multiplication factors for the load, the solar power capacity, the wind power capacity and the storage units (power and storage capacity). They are useful to simulate various scenarios without to have to modify the database.

2.2.3 Simulation environment

This section describes the principal simulation files, templates and scripts used when running Dispa-SET.
For each simulation, these files are included into a single directory corresponding to a self-sufficient simulation environment. This simulation environment directory is generated by the pre-processing in Python.

UCM_h.gms is the main GAMS model described in Section 2.1. A copy of this file is included in each simulation environment, allowing keeping track of the exact version of the model used for the simulation. The model must be run in GAMS and requires a proper input file (Inputs.gdx).

All the inputs of the model must be stored in the Inputs.gdx file since it is the only file read by the main GAMS model. This file is generated from the Dispa-SET database and the configuration file.

After optimisation in GAMS, all the results of the model are stored in the simulation environment in the Results.gdx file.

2.2.4 Post-processing

Post-processing is implemented in the form of a series of functions in Python to read the simulation inputs and results, to plot them, and to derive statistics. Some functions and type of results provided by the post-processing are given hereunder:

- the *GetResults* function : loads and formats the results from the Results.gdx file.
- the *dispatch_plot* function : plots the power dispatch for each simulated zone with the units aggregated by fuel type. The power consumed by storage units and the exportations are indicated as negative values. (Figure 2.3)
- the *EnergyBarPlot* function : plots the yearly energy balance per fuel or per technology for all the simulated zones. (Figure 2.4)
- the *ResultsAnalysis* function : returns some aggregated statistics on the simulation results including the total consumption, the peak load, the curtailment, etc. In addition, per power plant indicators can also be computed like the number of start-ups and the capacity factor.

2.3 Input data

In this section, "Input data" refers to the data stored in the Dispa-SET database. The format of this data is pre-defined and imposed, in such a way that it can be read by the pre-processing tool.

Figure 2.3: Example result: power Dispatch for Belgium, disaggregated by fuel type

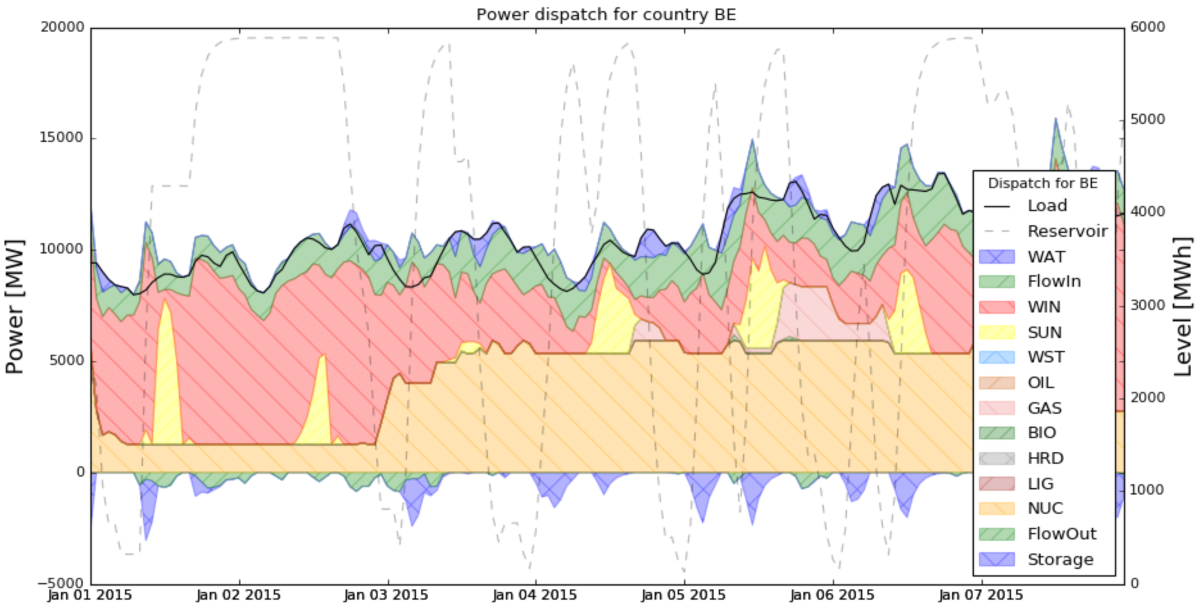


Figure 2.4: Example result: energy balance per simulated country

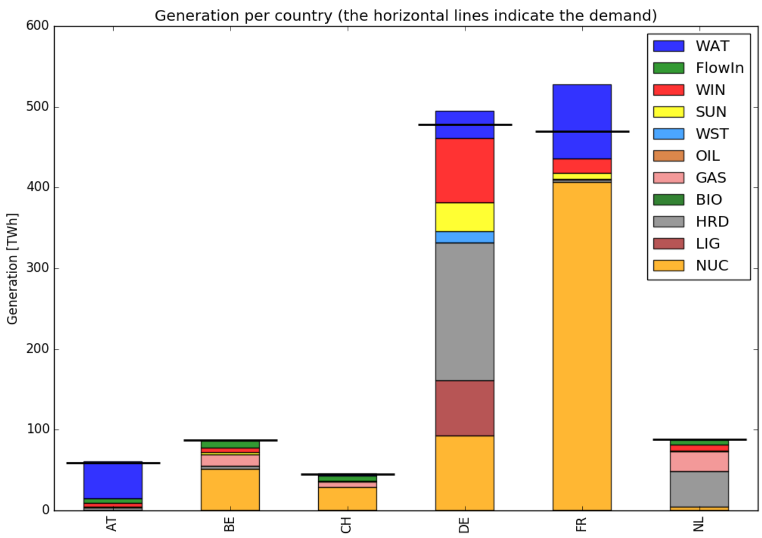


Table 2.4: Dispa-SET technologies

Technology	**Description**	**VRES**	**Storage**
COMC	Combined cycle	N	N
HPHS	Pumped hydro storage	N	Y
PHOT	Solar photovoltaic	Y	N
STUR	Steam turbine	N	N
WTOF	Offshore wind turbine	Y	N
WTON	Onshore wind turbine	Y	N

2.3.1 Technologies

The Dispa-SET input distinguishes between the technologies defined in Table 2.4. The VRES column indicates the variable renewable technologies (set "tr" in the optimisation) and the Storage column indicates the technologies which can accumulate energy.
Only the technologies used in this master thesis are described.

2.3.2 Fuels

Dispa-SET only considers a limited number of fuel types. They are summarised in Table 2.5, together with some examples. Only the fuel types used in this master thesis are described.

Table 2.5: Dispa-SET fuels

Fuel	Examples
BIO	Bagasse, Biodiesel, Gas From Biomass, Gasification, Biomass, Briquettes, Cattle Residues, Rice Hulls Or Padi Husk, Straw, Wood Gas (From Wood Gasification), Wood Waste Liquids Excl Blk Liq (Incl Red Liquor, Sludge, Wood,Spent Sulfite Liquor And Oth Liquids, Wood And Wood Waste
GAS	Blast Furnace Gas, Boiler Natural Gas, Butane, Coal Bed Methane, Coke Oven Gas, Flare Gas, Gas (Generic), Methane, Mine Gas, Natural Gas, Propane, Refinery Gas, Sour Gas, Synthetic Natural Gas, Top Gas, Voc Gas & Vapor, Waste Gas, Wellhead Gas
HRD	Anthracite, Other Anthracite, Bituminous Coal, Coker By-Product, Coal Gas (From Coal Gasification), Coke, Coal (Generic), Coal-Oil Mixture, Other Coal, Coal And Pet Coke Mi, Coal Tar Oil, Anthracite Coal Waste, Coal-Water Mixture, Gob, Hard Coal / Anthracite, Imported Coal, Other Solids, Soft Coal, Anthracite Silt, Steam Coal, Subbituminous, Pelletized Synthetic Fuel From Coal, Bituminous Coal Waste)
NUC	Uranium, Plutonium
SUN	Solar energy
WAT	Hydro energy
WIN	Wind energy

Different fuels may be used to power a given technology, e.g. steam turbines may be fired with almost any fuel type. In Dispa-SET, each unit must be defined with the pair of values (technology,fuel).

2.3.3 Countries

Dispa-SET allows to simulate different European countries at the same time.

2.3.4 Power plant data

The power plant database may contain as many fields as desired, e.g. to ensure that the input data can be traced back, or to provide the id of this plant in another database. However, some fields are required by Dispa-SET and must therefore be defined in the database.

Common fields

The common fields that are required for all units are listed in Table 2.6.

Table 2.6: Common fields for all units

Description	Field name	Units
Unit name	Unit	
Commissioning year	Year	
Technology	Technology	
Primary fuel	Fuel	
Zone	Zone	
Capacity	PowerCapacity	MW
Efficiency	Efficiency	%
Efficiency at minimum load	MinEfficiency	%
CO2 intensity	CO2Intensity	TCO2/MWh
Minimum load	PartLoadMin	%
Ramp up rate	RampUpRate	%/min
Ramp down rate	RampDownRate	%/min)
Start-up time	StartUPTime	h
Minimum up time	MinUpTime	h
Minimum down time	MinDownTime	h
No load cost	NoLoadCost	EUR/h
Start-up cost	StartUpCost	EUR
Ramping cost	RampingCost	EUR/MW

Storage units

Some parameters (Table 2.7) must only be defined for the units equipped with storage. They can be left blank for all other units.

Table 2.7: Specific fields for storage units

Description	Field name	Units
Storage capacity	STOCapacity	MWh
Self-discharge rate	STOSelfDischarge	%/h
Maximum charging power	STOMaxChargingPower	MW
Charging efficiency	STOChargingEfficiency	%

In the case of a storage unit, the discharge efficiency should be assigned to the common field "Efficiency". Similarly, the common field "PowerCapacity" is the nominal power in discharge mode.

2.3.5 Fuel Prices

Fuel prices vary both geographically and in time. They must therefore be provided as a time series for each simulated zone. One table is provided per fuel type, with as column header the zone to which it applies. If no header is provided, the fuel price is applied to all the simulated zones. If no table is available, the fuel price is set to its default value. This default value is set in the configuration file.

Chapter 3

Heat model

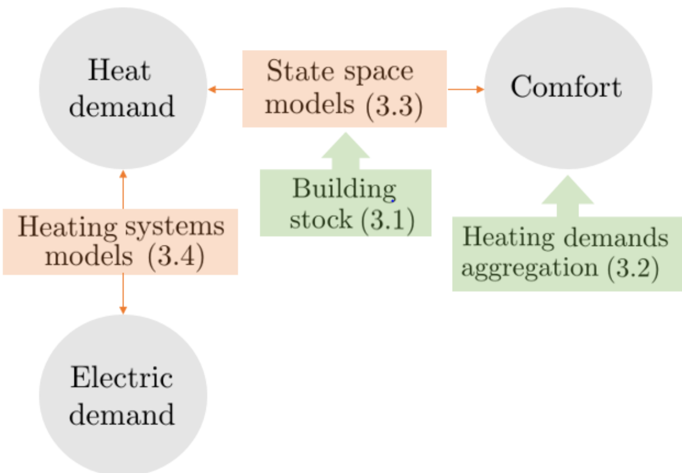
For the demand side management part, the residential heat demand for space heating (SH) and domestic hot water (DHW) is used. The heat demand is provided by two different heating systems: electric heat pumps providing both SH and DHW and electric water heaters providing only DHW.

The aim of this section is to develop a model able to couple the electric consumption for heating and the comfort required the dwellings. These are linked through the heat demand. Figure 3.1 shows how these three variables are linked.

First, comfort constraints are fixed through the aggregation of the space heating and the domestic hot water demand (Section 3.2). Then, state space models are developed for SH and DHW in order to represent the heat transfers occurring in the building envelope and the hot water tank (Section 3.3). The state space models parameters are derived from a Belgian building stock representation (Section 3.1). Finally, the heat demand is coupled to the electric demand through models of the heating systems (Section 3.4).

In the heat model, 40 different model typologies are defined, each consisting in a house typology (geometry, insulation, ...), a space heating demand and a hot water demand.

Figure 3.1: Heat model



3.1 Belgian building stock

In order to have a good representation of the heat demand in Belgium, the residential Belgian building stock has to be modelled.

Gendebien et al. [21] developed a tree-structure used for the characterization of the residential building stock of Belgium. Following a bottom-up approach, dwellings are clustered according to their geometry, year of construction, insulation level, etc.

From this tree structure, two different house typologies are considered. A specific branch of the three structure is selected, characterized by the same geometry, representative of a typical two-story free-standing house with a heavy concrete structure and built after 1991. Two relatively high insulation levels and air tightness are considered accounting for 75% and 25% of the building stock represented:

- $U = 0.458$ $[W/m^2K]$ and $n_{50} = 6ACH$ (75%)
- $U = 0.305$ $[W/m^2K]$ and $n_{50} = 3ACH$ (25%)

This choice of building stock representation was made since heat pumps are usually installed in recent well isolated free-standing houses.

The insulation characteristics (thermal resistance, infiltration rate, ...) of the dwellings derived from this representation are be used as parameters in the SH state space models.

3.2 Aggregation of heating demands

In addition to the thermal characteristics of the dwellings, the model also needs to represent the space heating and domestic hot water demands.

First, heating demand profiles have to be generated.
The space heating demand consists in temperature set point profiles. These profiles are generated randomly according to three conventional types of profiles and a random profile.
The domestic hot water demand consists in minimum and maximum temperature levels in the hot water tank and in water consumption profiles. These water consumptions profiles are generated from a database developped by Georges et al. [22].

Then, the heating demand profiles are clustered for each insulation level using the validated methodology proposed by Georges et al. [23].
The space heating demand profiles are aggregated in four clusters and the domestic hot water profiles are aggregated in five clusters. This gives a number of 20 pairs of aggregated demands per house typology.

The remaining of this section describes briefly the aggregation method used for the space heating demand and the aggregation method used for the domestic hot water demand.

3.2.1 Space heating demand aggregation

Temperature set point profiles can be gathered under three conventional types of profile and a random profile:

- Constant profile

- Night set-back profile, in which set point temperature is lower during the night
- Intermittent profile, in which set point temperature is lower during the night and unoccupied hours
- Random profile

Temperature set points are generated randomly for each building of the building stock represented according to a random percentage of each profile. Then, the set point profiles are clustered in the four categories of profile types and all profiles in a cluster are averaged. Depending on the diversity of the profiles, the number of aggregated models vary between one and four. Here four aggregated models exists for each insulation level (8 different profiles).

The lower and upper temperatures bounds of a cluster c are set to the most restrictive ones within that cluster:

$$T_{t,c}^{min} = \max_{i \in c} x_{i,t}^{min} \tag{3.1}$$

and

$$T_{t,c}^{max} = \min_{i \in c} x_{i,t}^{max} \tag{3.2}$$

Occupancy profiles are generated from the space heating demand profiles.

3.2.2 Domestic hot water demand aggregation

The admissible tank temperature range is constant and ranges from 50°C for sanitary reasons to 65°C for thermal resistance reasons. This temperature range is used as constraints on the DHW temperature variable in the model.

The hot water consumption is fixed by an aggregation of the domestic hot water demand profiles.
The clustering of the water heating demand is done by the so-called random sampling method in which five representative profiles are determined. A pairwise comparison of all profiles is performed and to each profile i is associated the closest profile j. The four profiles with the higher number of occurrence are chosen to be the representative profiles.
The corresponding DHW use profiles are the average of the profiles that fall in each category. Profiles that are not associated to one of the four representative profiles are averaged in a separated category.

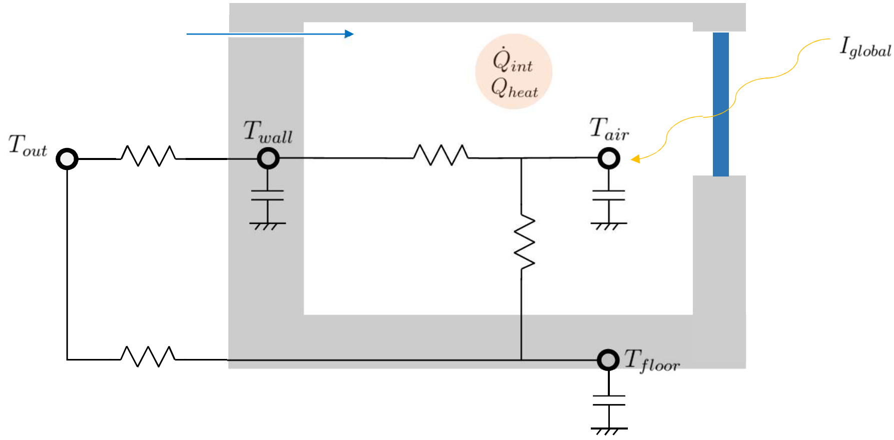
The hot water consumptions are used as fixed influence variables in the DHW state space models.

For all profiles, the tank volumes are set to the average value over the entire set of water tanks (a single tank volume). This hot water tank volume is used to determine the parameters of the DHW state space models.

3.3 State space models

In order to represent the heat transfers that occur in a dwelling and in a hot water tank accurately, state space models are used.
These state space models consist in the actualisation of the temperatures from a time step to another by means of linear equations that take the state space parameters as coefficients and

Figure 3.2: Space heating state space model representation



the previous temperatures T_{t-1} and the influence variables U_t as variables.
The general form of the state space models is

$$T_t = \mathbf{A}T_{t-1} + \mathbf{B}U_t \tag{3.3}$$

where T_t is the vector of temperatures after time step t, U_t the vector of influence variables at time step t and $\mathbf{A}$ and $\mathbf{B}$ are matrices containing the state space parameters.

3.3.1 Space heating

For the space heating part, three temperature are modelled: the inside air temperature, the wall temperature and the floor temperature:

$$T_t = \begin{pmatrix} T^a \\ T^{wl} \\ T^f \end{pmatrix}_t \tag{3.4}$$

and the influence of the outside temperature, the solar irradiation, the internal gains and the heating is taken into account:

$$U_t = \begin{pmatrix} T^o \\ I \\ \dot{Q}^i \\ \dot{Q}^h \end{pmatrix}_t \tag{3.5}$$

The state-space model parameters are defined based on an equilibrium equation for each temperature that can be written as:

$$\dot{Q}_{stored} = \sum \dot{Q}_{transfer} + \sum \dot{Q}_{gains} \tag{3.6}$$

The different heat transfers and heat gains taken into account can be seen in Figure 3.2. The equilibrium equation for each space heating temperature node can be written as:

$$\begin{aligned} C_a \frac{dT^a}{dt} &= R_{a,wl}(T_t^{wl} - T_t^a) + R_{a,f}(T_t^f - T_t^a) + \dot{m}_{inf} c_{p,a}(T_t^o - T_t^a) + \tau A I_t + \dot{Q}_t^i + \dot{Q}_t^h \\ C_{wl} \frac{dT^{wl}}{dt} &= R_{a,wl}(T_t^a - T_t^{wl}) + R_{wl,o}(T_t^o - T_t^{wl}) \\ C_f \frac{dT^f}{dt} &= R_{a,f}(T_t^a - T_t^f) + R_{f,o}(T_t^o - T_t^f) \end{aligned} \tag{3.7}$$

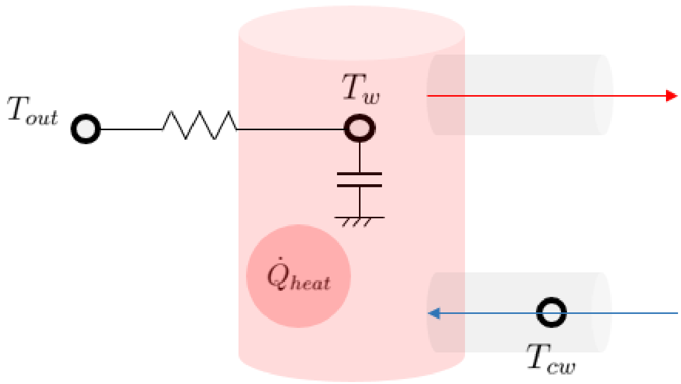


Figure 3.3: Domestic hot water state space model representation

where $R_{x,y}$ is the thermal resistance between x and y, $\dot{m}_{inf}$ is the mass infiltration rate of outside air, $c_{p,a}$ is the specific thermal capacity of air, τ is the transmittance of the windows and A the windows area. All these parameters (except $c_{p,a}$) are function of the house typology of the dwellings.

These conservation equation are non-linear. In order to get a linear state space model, a linearisation of the time derivatives over the desired period is done through the central finite difference method[1].
After linearisation and by rearranging their terms, Equations 3.7 can be set in the form given by Equation 3.3 and thus determine the state space parameters matrices **A** and **B**.

From Equations 3.7, it can be seen that the state space parameters are time-independent[2] but depend on the house typology (insulation, infiltration). There is thus a different pair of matrices (**A**,**B**) for each house typology.

3.3.2 Domestic hot water

For the domestic hot water state space model, only the hot water tank temperature is modelled. In addition, the tank is considered isothermal:

$$T_t = T_t^w \tag{3.8}$$

In the model, the influence of the outside temperature, the city water temperature and the heating is taken into account:

$$U_t = \begin{pmatrix} T^o \\ T^{cw} \\ \dot{Q}^h \end{pmatrix}_t \tag{3.9}$$

The state-space model parameters are defined based on an equilibrium equation that can be written as

$$\dot{Q}_{stored} = \dot{Q}_{loss} + \dot{Q}_{water} + \dot{Q}_{heat} \tag{3.10}$$

where $\dot{Q}_{loss}$ are the thermal losses of the tank and $\dot{Q}_{water}$ the heat losses due to the incoming cold water (both negative). The different heat losses and heat gains taken into account can be

[1] This linearisation is done through Matlab
[2] The infiltration rate and the thermal capacity of air are considered constant.

seen in Figure 3.3. The equilibrium equation for the hot water tank temperature can be written as:

$$C_w \frac{dT^w}{dt} = AU_{loss}(T_t^o - T_t^w) + c_{p,w}\dot{m}_w(T_t^{cw} - T_t^w) + \dot{Q}_t^h \tag{3.11}$$

where C_w is the thermal capacity of the water tank, AU_{loss} the overall heat transfer coefficient between the inside and outside of the tank, $c_{p,w}$ the specific thermal capacity of water and $\dot{m}_w$ the specific hot water consumption determined by the domestic hot water demand.

Because of the time-derivatie, Equation 3.11 is non-linear. Since there is a single temperature modelled, a forward linearisation is performed over the desired period:

$$C_w \frac{T_{t+1}^w - T_t^w}{\Delta t} = AU_{loss}(T_t^o - T_t^w) + c_{p,w}\dot{m}_w(T_t^{cw} - T_t^w) + \dot{Q}_t^h \tag{3.12}$$

By rearranging the terms of this equation, it can be set in the form given by Equation 3.3 and thus determine the state space parameters matrices $\mathbf{A}$ and $\mathbf{B}$:

$$\mathbf{A} = \quad a \quad = 1 - b_1 - b_2 \tag{3.13}$$

$$\mathbf{B} = \begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} = \Delta t \begin{pmatrix} AU_{loss}/C_w \\ c_{p,w}\dot{m}_w/C_w \\ 1/C_w \end{pmatrix} \tag{3.14}$$

As the hot water consumption $\dot{m}_w$ is time-dependent, the state space parameters and matrices cannot be considered constant and there is thus a different pair of matrices $(\mathbf{A}, \mathbf{B})$ for each time step considered and for each house typology.

3.4 Heating systems

Two types of heating systems are considered: electric heat pumps and electric water heaters. This section develops the model for each system.

3.4.1 Heat pumps

Variable-speed heat pumps are considered in the model.
The heat pump model is a linear empirical model based on the ConsomClim method [24]. The same model is used for all the heat pumps. The only difference that exists is the heat pumps nominal capacity which depends on the insulation level and the supply temperature which is different for space heating and for domestic hot water heating.

The nominal characteristics of the heat pumps are the following:

- Outside temperature: $7°C$
- Exhaust temperature: $35°C$[3]
- Capacity: $11,2\ kW$ / $14\ kW$
- COP: $3,95$

[3]The exhaust temperature of the heat pumps is the supply temperature of the heating systems

The heat pumps can work both in space heating mode or in domestic hot water heating mode but not simultaneously. However, for sufficiently long time steps, a simultaneous working of both modes is considered possible (ON-OFF).

The heat pumps full load capacity and COP depend on the outside temperature and on the heating system supply temperatures ($45°C$ for SH and $60°C$ for DHW) according to:

$$DT = \frac{T_{out}}{T_{su}} - \frac{T_{out,n}}{T_{su,n}} \tag{3.15}$$

$$COP_{fl} = \frac{COP_n}{C_0 + C_1 DT + C_2 DT^2} \tag{3.16}$$

$$\dot{Q}_{fl} = [D_0 + D_1(T_{out} - T_{out,n}) + D_2(T_{su} - T_{su,n})]\, \dot{Q}_n \tag{3.17}$$

$$\dot{W}_{fl} = \frac{\dot{Q}_{fl}}{COP_{fl}} \tag{3.18}$$

where C_x and D_x are parameters specific to the heat pump design, T_{su} and $T_{su,n}$ are the heating system supply temperatures (effective and nominal), COP_n the nominal performance and $\dot{Q}_n$ the nominal heat capacity.
The full load parameters are thus different for space heating and domestic water heating and are time-varying.

The part-load electrical consumption model of the heat pumps differs in space heating and in water heating. Operating at part load affects the performance (COP) in SH mode but not in DHW mode.

In space heating mode, the heat pump consumption at part load is modelled using a piecewise linear approximation (Figure 3.4):

$$\dot{W}_r = max \begin{cases} 0,77\dot{Q}_r \\ 0,6881 + ((K_2 - K_1) + 2(1 - K_2) \times 0,75)(\dot{Q}_r - 0,75) \end{cases} \tag{3.19}$$

where $\dot{Q}_r = \dot{Q}/\dot{Q}_{fl}$ and $\dot{W}_r = \dot{W}/\dot{W}_{fl}$ are respectively the heat and electric part load ratios.
In addition, the heat pump comprises an additional electric heater for space heating. The capacity of this additional heater is 3 kW.

In DHW mode, the performance is supposed constant at part load and is equal to the full load performance:

$$\dot{W} = \frac{\dot{Q}}{COP_{fl}} \tag{3.20}$$

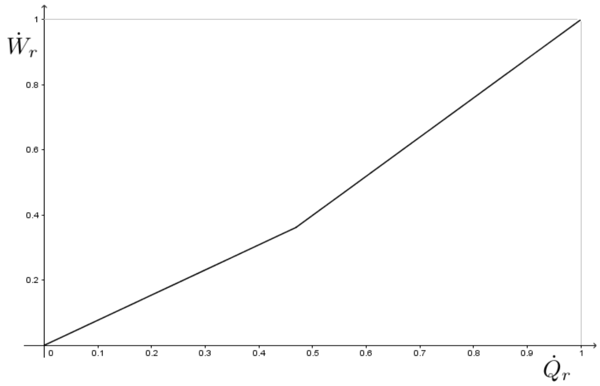
3.4.2 Water heaters

The water heaters are electric resistance heaters and provide only domestic hot water heating. Their capacity and performance do not depend on external parameters and they can work at part load with a constant performance.

The coefficient of performance of the water heaters is thus at all time equal to unity:

$$\dot{W} = \dot{Q} \tag{3.21}$$

Figure 3.4: Part load performance of heat pumps in space heating



Regarding the water heaters capacity, they are supposed to be designed to be able to make their tank temperature stay at its minimum value at all time

$$\dot{Q}^d = max_h \left\{ \dot{Q} : \Delta T_h \|_{T_{w,min}} = 0 \right\} \tag{3.22}$$

but within the limited range $\left[\dot{Q}_{min}, \dot{Q}_{max}\right] = [1kW, 4kW]$:

$$\dot{Q}_n = \begin{cases} \dot{Q}_{min}, & \dot{Q}_d < \dot{Q}_{min} \\ \dot{Q}^d, & \dot{Q}_{min} < \dot{Q}_d < \dot{Q}_{max} \\ \dot{Q}_{max}, & \dot{Q}_d > \dot{Q}_{max} \end{cases} \tag{3.23}$$

where $\dot{Q}_n$ is the nominal (full load) capacity of the water heaters.

3.5 Preprocessing

The aim of the preprocessing is to determine, to format an to store the inputs parameters of the heat model from the building stock, the demands aggregations and the heating systems models raw data. This raw data is given in Table 3.1 and the corresponding sets are given in Table 3.2. The raw data is given for a time period of one day and time steps of 15 minutes.

From this data, the input parameters of the heat model have to be determined. These parameters are resumed in Table 3.3 and have to be written for one year with a time step of one hour[4].
Some model parameters are directly given as raw data while others have to be calculated. In particular, the base case consumptions of the heating systems have to be determined. These base consumptions are indispensable to assess the potential of the heat pumps flexibility.

Thus, two types of manipulations have to be done with the raw data. The inputs parameters have first to be calculated and then put in the right format.

3.5.1 Model parameters calculation

The model parameters that have to be calculated from the raw data can be put in five categories: initial temperatures, state space model parameters (DHW), heat pump parameters, water heater parameters and base case consumption.

[4]Actually, the parameters are written for 375 days allowing a lookahead period of ten days.

Table 3.1: Heat model raw data

Name	Units	Description
$aSH_{xx,xx,ind}$	n.a.	Space heating state space parameters
$bSH_{xx,yy,ind}$	n.a.	Space heating state space parameters
C_i, D_i, K_i	n.a.	Heat pump parameters
$CapacityHeater_{ind}$	W	Nominal additional heater power
$CapacityHpNominal_{ind}$	W	Nominal heat pump capacity
$CopHpNominal$	n.a.	Nominal heat pump performance
$InternalGains_{xx,ind,t}$	W	Internal gains
$ratio_{ind}$	%	Share of the water heaters represented
$TankFlow_{ind,t}$	m3/s	Volumetric hot water consumption
$TankU_{ind}$	W/m2	Hot water tank heat transfer coefficient
$TankVolume_{ind}$	m3	Hot water tank volume
$TemperatureAirLow_{ind,t}$	K	Maximum inside air temperature
$TemperatureAirHigh_{ind,t}$	K	Minimum inside air temperature
$TemperatureSupplySH$	K	Nominal space heating supply temperature
$TemperatureTankLow$	K	Maximum hot water tank temperature
$TemperatureTankHigh$	K	Minimum hot water tank temperature
$TypologyShare_{ind}$	%	Model typology share in the building stock

Initial temperatures

No information exists on the initial dwellings temperatures. Consequently, they have to be fixed at realistic values.
For consumption reasons, temperatures in dwellings are likely closer to their lower limits than to their higher limits especially in winter (when the simulations usually start). The choice was thus made to set the initial temperatures equal to their lower limits.
The wall and floor temperatures (which are not restricted) are respectively set to 18°C and 20°C.

State space model parameters

The state space models parameters that have be calculated are the time dependent DHW parameters. They are calculated by means of Equations 3.13 and 3.14 where

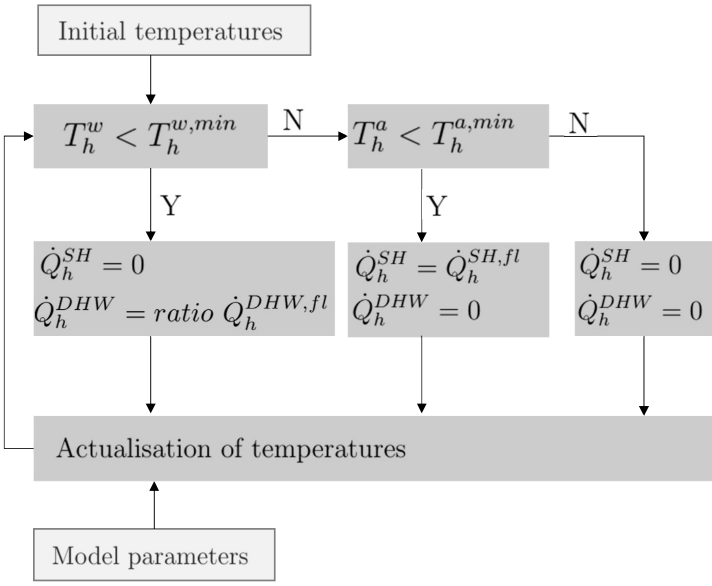
$$\begin{aligned} AU_{loss} &= S \cdot TankU_{ind} && (3.24)\\ c_{p,w} &= 4187 \quad [J/kgK] && (3.25)\\ \dot{m}^w &= \rho_w \cdot TankFlow && (3.26)\\ C_w &= c_{p,w}\rho_w \cdot TankVolume && (3.27) \end{aligned}$$

with $\rho_w = 1000$ kg/m3 the water density and S the area of the water tank given by[5]:

$$\begin{aligned} S &= H * \pi D + \frac{\pi D^2}{4} && (3.28)\\ H &= \frac{4TankVolume}{\pi D^2} && (3.29)\\ D &= 0,508m && (3.30) \end{aligned}$$

[5]where D is an average water tank diameter

Figure 3.5: Base case iteration model



Heat pump parameters

The heat pumps parameters to calculate are the full load parameters:

- *CapacityHpFullLoadSH*
- *CapacityHpFullLoadDHW*
- *ConsumptionHpFullLoadSH*
- *CopHpFullLoadDHW*

which can be determined through Equations (3.15) to (3.18) with the SH and DHW supply temperatures respectively equal to *TemperatureSupplySH* and *TemperatureTankHigh*.

Water heater parameters

The water heater parameters that have to be calculated are their nominal capacities.
The water heaters are supposed designed to fulfil the needs in domestic hot water at all moment while staying at their lower limit. The capacity of a water heater $CapacityWaterHeater_{ind}$ is thus given by Equation (3.23) with

$$\dot{Q}_{ind}^{d} = \max_{h} \left\{ \begin{array}{l} [(1 - aDHW_{h,ind}) \cdot TemperatureTankLow \\ -bDHW_{1,h,ind} \cdot TemperatureOut_h \\ -bDHW_{2,h,ind} \cdot TemperatureCityWater_h] / bDHW_{3,h,ind} \end{array} \right\} \tag{3.31}$$

Base case consumptions

In order to capture the potential of the heat demand to provide flexibility and storage, the baseline consumption must be known. No data on this base consumptions is available for each typology. They thus have to be calculated realistically.

Heating systems in dwellings are usually working in an On-Off mode: the heating system goes

Table 3.2: Heat model sets

Name	**Description**
h	Hours time steps
ind	Model typologies
k	15-min time steps
xx	House temperatures [Air, wall, floor]
	Length of DHW influence variable vector [1,2,3]
yy	Length of SH influence variable vector [1,2,3,4]

ON at full load when the temperature falls below its lower limit and stops after a certain time step when the temperature is back in its valid range.
This working mode is considered for the heat pumps and water heaters baseline consumptions with a time step of 5 minutes. When both space heating and domestic hot water modes are needed, priority is given to domestic hot water.

In addition, in order to increase the diversity of the DHW heating profiles, the parameter *ratio* is introduced as proposed by Georges et al. [23], limiting the full load DHW capacity. This increase of diversity is needed since the hot water tank volume and the temperature bounds are fixed at constant values removing the existing diversity among the tanks. This parameter is proportional to the number of water tanks represented by each aggregated model.

Figures 3.5 gives an illustration of the baseline iteration model. Once the heat demands are known, the electric power consumptions can easily be determined through Equations 3.19 and 3.20 for the heat pumps and through Equation 3.21 for the water heaters.

3.5.2 Format

The raw data is given for one day with a time step of 15 minutes, the baseline consumption is computed on a 5 minutes basis while the final heat model works with an one hour time step for a time period of one year.

The data computed has thus to be adapted for time steps of one hour and for one year.
Firstly, the average of each hour is taken. Then, the data that is given for one day is extended to one year by considering that all days have the same profile.

All the model parameters are then put into a InputsHeat.gdx file that is readable in GAMS. This file is the database of the heat model.

3.6 Model description

The final heat model is written in GAMS in order to be coupled to the Dispa-SET model.

3.6.1 Sets

The sets defined in the heat model are listed in Table 3.2.

Table 3.3: Heat model database parameters

Name	**Units**	**Description**
$aDHW_{h,ind}$	n.a.	DHW state space parameters
$aSH_{xx,xx,ind}$	n.a.	Space heating state space parameters
$bDHW_{xx,h,ind}$	n.a.	Space heating state space parameters
$bSH_{xx,yy,ind}$	n.a.	Space heating state space parameters
$CapacityHeater_{ind}$	W	Additional heater capacity
$CapacityHpFullLoadDHW_{h,ind}$	W	DHW full load heat pump capacity
$CapacityHpFullLoadSH_{h,ind}$	W	SH full load heat pump capacity
$CapacityHpNominal_{ind}$	W	Nominal heat pump capacity
$CapacityWaterHeater_{ind}$	W	Water heater capacity
$ConsumptionHpFullLoadSH_{h,ind}$	W	Full load heat pump electric consumption
$CopHpFullLoadDHW$	n.a.	DHW heat pump full load performance
$InternalGains_{xx,ind,t}$	W	Internal gains
$Irradiation_h$	W/m2	Total horizontal global irradiation
K_i	n.a.	Heat pump parameters
$PowerBaseHpMean_h$	W	Mean power consumed by a heat pump
$PowerBaseWhMean_h$	W	Mean power consumed by a water heater
$TemperatureCityWater_h$	K	City water temperature
$TemperatureInitialDHW_{ind}$	K	Initial DHW temperature
$TemperatureInitialSH_{xx,ind}$	K	Initial SH temperatures
$TemperatureAirLow_{ind,t}$	K	Maximum inside air temperature
$TemperatureAirHigh_{ind,t}$	K	Minimum inside air temperature
$TemperatureOut_h$	K	Outside Temperature
$TemperatureTankLow$	K	Maximum hot water tank temperature
$TemperatureTankHigh$	K	Minimum hot water tank temperature
$TypologyShare_{ind}$	%	Model typology share in the building stock

3.6.2 Parameters

The heat model database parameters are listed in Table 3.3.

In addition to the fixed database, some configuration parameters have to be loaded in the model. That is:

- The number of installed electric heat pumps and water heaters considered in the building stock: $NumberHouses_{HP,Base}$ and $NumberHouses_{WH,Base}$
- The number of flexible heat pumps and water heaters considered: $NumberHouses_{HP,Flexible}$ and $NumberHouses_{WH,Flexible}$

These configuration parameters allow to vary the number of flexible systems in the simulation and to consider an increase in the electric demand arising from the introduction of new electric systems.

3.6.3 Decision variables

The decision variables of the heat model are defined in Table 3.4.

Table 3.4: Heat model decision variables

Name	Units	Description
Positive variables		
$ConsumptionHpSh_{ind,h}$	W	Electric consumption for SH by HP
$ConsumptionHpDhw$	W	Electric consumption for DHW (HP)
$HeatHpDHW_{ind,h}$	W	Heating power forDHW
$HeatHpSH_{ind,h}$	W	Heating power for SH by HP
$HeatSH_{ind,h}$	W	Heating power for SH
$PowerHeater_{ind,h}$	W	Additional heater power
$PowerHp_{ind,h}$	W	HP total electric consumption
$PowerHpMean_{h}$	W	HP mean electric consumption
$PowerWh_{ind,h}$	W	WH power
$PowerWhMean_{h}$	W	WH mean electric consumption
$TemperatureCoolerHpDHW_{ind,h}$	K	Relaxation variable
$TemperatureCoolerSH_{ind,h}$	K	Relaxation variable
$TemperatureCoolerWhDHW_{ind,h}$	K	Relaxation variable
$TemperatureHpDHW_{ind,h}$	K	HP hot water tank temperature
$TemperatureLimitHpDHW_{ind,h}$	K	Bounded tank temperature (HP)
$TemperatureLimitSH_{ind,h}$	K	Bounded inside air temperature
$TemperatureLimitWhDHW_{ind,h}$	K	Bounded tank temperature (WH)
$TemperatureSH_{xx,ind,h}$	K	Space heating temperatures
$TemperatureWarmerSH_{ind,h}$	K	Relaxation variable
$TemperatureWhDHW_{ind,h}$	K	WH hot water tank temperature
$TotalPower_{h}$	W	Total electric power consumption
$TotalRelaxation_{h}$	K	Degree-hours of relaxation variables
$y_{ind,h}$		Share of space heating mode
Free variables		
$PowerDifference_{h}$	W	Power difference with the base case

3.6.4 Equations

Base consumptions

First of all, the baseline power of the simulated flexible devices has to be calculated:

$$\begin{aligned} &BasePower_i \\ &= NumberHouses_{HP,Flexible} * PowerHpMean_i \\ &+NumberHouses_{WH,Flexible} * PowerWhMean_i \end{aligned} \tag{3.32}$$

In addition, the added electric power demand arising from the introduction of new electric heating systems is given by:

$$\begin{aligned} &BasePowerAdd_i \\ &= max\,[0,\ (NumberHouses_{HP,Flexible} - NumberHouses_{HP,Base}) * PowerHpMean_i] \\ &+max\,[0,\ (NumberHouses_{WH,Flexible} - NumberHouses_{WH,Base}) * PowerWhMean_i] \end{aligned} \tag{3.33}$$

Heat pump

As described in Section 3.3, the actualisation of the temperatures from a time step to another are done through the state-space parameter models. For the first time step, the initial temperature stored in the database is used.
The actualisation of the space heating temperatures is written:

$$\begin{aligned} &i = 1: \\ &TemperatureSH_{xx,ind,i} \\ &= \sum_{xxx}(aSH_{xx,xxx,ind} \cdot TemperatureInitialSH_{xxx,ind}) \\ &+bSH_{xx,1,ind} \cdot TemperatureOut_i + bSH_{xx,2,ind} \cdot Irradiation_i \\ &+bSH_{xx,3,ind} \cdot HeatSH_{ind,i} + bSH_{xx,4,ind} \cdot InternalGains_{xx,i,ind} \\ \\ &i > 1: \\ &TemperatureSH_{xx,ind,i} \\ &= \sum_{xxx}(aSH_{xx,xxx,ind} \cdot TemperatureSH_{xxx,ind,i-1}) \\ &+bSH_{xx,1,ind} \cdot TemperatureOut_i + bSH_{xx,2,ind} \cdot Irradiation_i \\ &+bSH_{xx,3,ind} \cdot HeatSH_{ind,i} + bSH_{xx,4,ind} \cdot InternalGains_{xx,i,ind} \end{aligned} \tag{3.34}$$

and for the hot water temperature:

$$\begin{aligned} &i = 1: \\ &TemperatureHpDhw_{ind,i} \\ &= aDHW_{ind,i} \cdot TemperatureInitialHpDhw_{ind} + bDHW_{1,i,ind} \cdot TemperatureOut_i \\ &+bDHW_{2,i,ind} \cdot TemperatureCityWater_i + bDHW_{3,i,ind} \cdot HeatHpDhw_{ind,i} \\ &i > 1: \\ &TemperatureHpDhw_{ind,i} \\ &= aDHW_{ind,i} \cdot TemperatureHpDhw_{ind,i-1} + bDHW_{1,i,ind} \cdot TemperatureOut_i \\ &+bDHW_{2,i,ind} \cdot TemperatureCityWater_i + bDHW_{3,i,ind} \cdot HeatHpDhw_{ind,i} \end{aligned} \tag{3.35}$$

The inside air temperatures and the water tank temperatures have to be limited by their lower and upper bounds. However, relaxations on these limits are introduced in order to allow the model to run in any conditions.
A new temperature is defined for each bounded temperature as the "limited temperature". The maximum and minimum temperature constraints are applied to the limited temperature which equals the real temperature if relaxation is inactivated (relaxation variables equal zero) and equals the overlapped temperature limit if relaxation is activated.

For space heating, the inside temperature can be below its minimum value if there is not enough heating or above its maximum value because of no cooling. Cooler and warmer relaxation variables are defined. For domestic hot water production, no uncontrolled external gains are present and only a cooler relaxation variable is needed.

The actual temperatures are defined by

$$\begin{aligned} TemperatureSH_{1,ind,i} &= TemperatureLimitSH_{ind,i} \\ -TemperatureCoolerSH_{ind,i} &+ TemperatureWarmerSH_{ind,i} \end{aligned} \tag{3.36}$$

and

$$\begin{aligned} &TemperatureHpDhw_{ind,i} \\ &= TemperatureLimitHpDhw_{ind,i} - TemperatureCoolerHpDhw_{ind,i} \end{aligned} \tag{3.37}$$

and the temperature constraints are modelled by:

$$TemperatureLimitSh_{ind,i} \geq TemperatureAirLow_{ind,i} \tag{3.38}$$

$$TemperatureLimitSh_{ind,i} \leq TemperatureAirHigh_{ind,i} \tag{3.39}$$

and

$$TemperatureLimitHpDhw_{ind,i} \geq TemperatureTankLow_{ind,i} \tag{3.40}$$

$$TemperatureLimitHpDhw_{ind,i} \leq TemperatureTankHigh_{ind,i} \tag{3.41}$$

The space heating power is composed of two terms: the heat pumps heating power and the additional heater power:

$$HeatSh_{ind,i} = HeatHpSh_{ind,i} + PowerHeater_{ind,i} \tag{3.42}$$

These heating powers are limited by their full load capacity and the share of time during which the heat pump works in space heating mode:

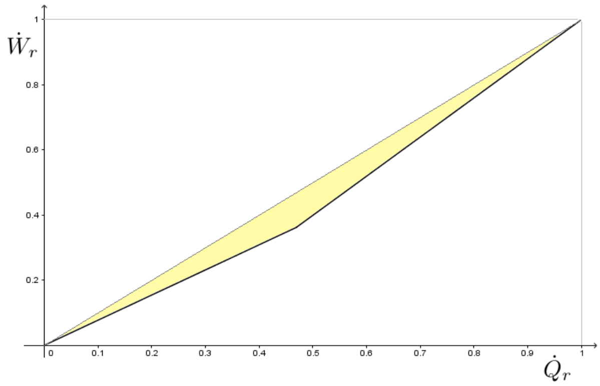
$$HeatHpSh_{ind,i} \leq y_{ind,i} \cdot CapacityHpFullLoadSh_{i,ind} \tag{3.43}$$

$$PowerHeater_{ind,i} \leq y_{ind,i} \cdot CapacityHeater_{ind} \tag{3.44}$$

For domestic hot water:

$$HeatHpDhw_{ind,i} \leq (1 - y_{ind,i}) \cdot CapacityHpFullLoadDhw_{ind,i} \tag{3.45}$$

Figure 3.6: Part load model of heat pumps in space heating



The heat pump consumption depends on the mode of heating: space heating or domestic hot water.

For space heating, consumption is given by Equation 3.19. This equation is a piecewise linear equation and, if the electric consumption has to be minimized at all time, it could be represented in linear optimisation by:

$$\begin{gathered} ConsumptionHpSh_{ind,i} \geq \\ ConsumptionHpFullLoadSh_{i,ind} \cdot 0,77 \cdot \frac{HeatHpSh_{ind,i}}{CapacityHpFullLoadSh_{i,ind}} \end{gathered} \tag{3.46}$$

$$\begin{gathered} ConsumptionHpSh_{ind,i} \geq ConsumptionHpFullLoadSh_{i,ind} \\ \cdot \left[0,6881 + ((K_2 - K_1) + 2 \cdot (1 - K_2) \cdot 0,75) \times \left(\frac{HeatHpSh_{ind,i}}{CapacityHpFullLoadSh_{i,ind}}\right]\right) \end{gathered} \tag{3.47}$$

However, in the final heat model, the system cost is minimized and it does not lead to a minimized consumption at all time steps. Thus, the heat pump consumption has to be limited by an upper bound and the choice is made to limit it by fixing a maximum performance equal to the full load performance. The performance of the heat pumps is thus free to vary in a range (Figure 3.6):

$$\begin{gathered} ConsumptionHpSh_{ind,i} \leq \\ ConsumptionHpFullLoadSh_{i,ind} \cdot \frac{HeatHpSh_{ind,i}}{CapacityHpFullLoadSh_{i,ind}} \end{gathered} \tag{3.48}$$

For domestic hot water, the heat pump performance at part load equals the full load performance and the electric consumption is:

$$ConsumptionHpDhw_{ind,i} = \frac{HeatHpDhw_{ind,i}}{CopHpFullLoadDhw_{i,ind}} \tag{3.49}$$

The additional heater electric consumption equals its heating power.

The total electric consumption of the heat pumps is the sum of all the consumptions:

$$\begin{aligned} PowerHp_{ind,i} &= ConsumptionHpSh_{ind,i} + PowerHeater_{ind,i} \\ &+ ConsumptionHpDhw_{ind,i} \end{aligned} \tag{3.50}$$

The mean electric consumption of a heat pump in the building stock is the weighted average of the consumptions of each model typology:

$$PowerHpMean_i = \sum_{ind} (TypologyShare_{ind} \cdot PowerHp_{ind,i}) \tag{3.51}$$

Water Heater

The equations that model the water heaters are similar to the heat pumps model equations. The actualisation of the water tank temperature is given by:

$$\begin{gathered}
i = 1 : \\
TemperatureWhDhw_{ind,i} \\
= aDHW_{ind,i} \cdot TemperatureInitialWhDhw_{ind} + bDHW_{1,i,ind} \cdot TemperatureOut_i \\
+ bDHW_{2,i,ind} \cdot TemperatureCityWater_i + bDHW_{3,i,ind} \cdot PowerWh_{ind,i} \\
i > 1 : \\
TemperatureWhDhw_{ind,i} \\
= aDHW_{ind,i} \cdot TemperatureWhDhw_{ind,i-1} + bDHW_{1,i,ind} \cdot TemperatureOut_i \\
+ bDHW_{2,i,ind} \cdot TemperatureCityWater_i + bDHW_{3,i,ind} \cdot PowerWh_{ind,i}
\end{gathered} \tag{3.52}$$

Because no uncontrolled external gains exist in the water tank, only a cooler relaxation variable is needed. The actual temperature is given by:

$$\begin{gathered}
TemperatureWhDhw_{ind,i} \\
= TemperatureLimitWhDhw_{ind,i} - TemperatureCoolerWhDhw_{ind,i}
\end{gathered} \tag{3.53}$$

and the temperature constraints are modelled by:

$$TemperatureLimitWhDhw_{ind,i} \geq TemperatureTankLow_{ind,i} \tag{3.54}$$

$$TemperatureLimitWhDhw_{ind,i} \leq TemperatureTankHigh_{ind,i} \tag{3.55}$$

The heating power is limited by its capacity:

$$PowerWh_{ind,i} \leq CapacityWaterHeater_{ind} \tag{3.56}$$

and the electric consumption equals the heating power ($PowerWh_{ind,i}$).

The mean electric consumption of a water heater in the building stock is the weighted average of the consumptions of each model typology:

$$PowerWhMean_i = \sum_{ind} \Big(TypologyShare_{ind} \cdot PowerWh_{ind,i}\Big) \tag{3.57}$$

Total

The total power consumed by the flexible heat pumps and water heaters depends on the number of heat pumps and water heaters simulated:

$$\begin{aligned} &TotalPower_i \\ &= NumberHouses_{Hp,Simulated} \cdot PowerHpMean_i \\ &+ NumberHouses_{Wh,Simulated} \cdot PowerWhMean_i \end{aligned} \tag{3.58}$$

The electric power difference between the base case and the flexible case is given by:

$$PowerDifference_i = TotalPower_i - BasePower_i \tag{3.59}$$

It represents the demand modification induced by the flexible devices.

In order to limit the relaxation variables, a single variable is used. This variable is the sum of all the relaxation variables and over the number of model typologies. It thus does not have any physical representation:

$$\begin{aligned} &TotalRelaxation_i = \sum_{ind} \\ &\Big(TemperatureCoolerSh_{ind,i} + TemperatureWarmerSh_{ind,i} \\ &+ TemperatureCoolerHpDhw_{ind,i} + TemperatureCoolerWhDhw_{ind,i}\Big) \end{aligned} \tag{3.60}$$

Chapter 4

Coupling and implementation

In order to have an integrated model, the heat model is coupled to the Dispa-SET unit commitment and dispatch model. The heat model written in GAMS is added to the Dispa-SET interface.

This section explains how these two models previously described are linked together as a single optimisation model and how the interface is adapted in order to add this new model.

4.1 Model description

4.1.1 Sets, parameters and variables

Most of the sets, parameters and variables in each model is independent of the other model. There are only two sets that are common to the two models: the hour set h and time step set i. Each of these sets is used in the two models and is considered as a same unique set in the final heat model in order to link the periods of each model.

In addition to the time coupling, a locational coupling can also be done through the node (zone) set n. Since the heat model does not include several nodes (only Belgium is taken into account), the final model is written for one zone only and no locational coupling is needed.[1]

4.1.2 Optimisation model

Besides time coupling through sets, the two models has to be coupled through the model equations.
This is done by introducing the modification of the load due to the flexible heating systems ($PowerDifference_i$) in the supply-demand balance equation (Equation 2.1.2). This variable is added at the demand side of the equation.

In addition, the load potentially added by the introduction of new electric heating devices ($BasePowerAdd_i$) is taken into account and added at the demand side.

Attention must be paid to the fact that the heat model is running with power units of watts while the unit commitment model is running with power unit of megawatts. The coupled supply-

[1] The heat model can easily be adapted in order to take several zones into account. The InputsHeat.gdx database has then to be modified as well.

demand equation is given by:

$$
\begin{aligned}
&\sum_u (Power_{u,i} \cdot Location_{u,n}) \\
&+\sum_l (Flow_{l,i} \cdot LineNode_{l,n}) \\
= Demand_{DA,n,h} + &\sum_r \left(StorageInput_{s,h} \cdot Location_{s,n}\right) \\
&-ShedLoad_{n,i} \\
-LostLoadMaxPower_{n,i} &+ LostLoadMinPower_{n,i} \\
&+10^{-6} \cdot PowerDifference_i \\
&+10^{-6} \cdot BasePowerAdd_i
\end{aligned}
\tag{4.1}
$$

where the added terms are written in bold.

As mentioned before, the relaxation variable $TotalRelaxation_i$ must be included to the objective function in order to be minimized. The cost allocated to this relaxation variables is chosen very high in order to avoid non-zeros values when it is possible.

The cost allocated to the relaxation variables has a great impact on the model performance. In fact, since there is no cooling considered in the dwellings, the inside air temperature can not always be kept in its comfort range especially in summer (several degrees higher). Because of the high cost allocated to the relaxation variables, this leads to a high objective function and thus a significant drop in precision. On the other hand, if the cost of relaxation is decreased to a value that does not affect the precision significantly, relaxation can occur without having a significant influence on the optimisation and the relaxation variables are not kept at their minimum. Here, the choice was made to adapt the higher temperature limit in a feasible range.

The new objective function is given by:

$$
min \sum_i \Big(SystemCost_i + 10^6 \cdot TotalRelaxation_i\Big) \tag{4.2}
$$

4.2 Implementation and interface

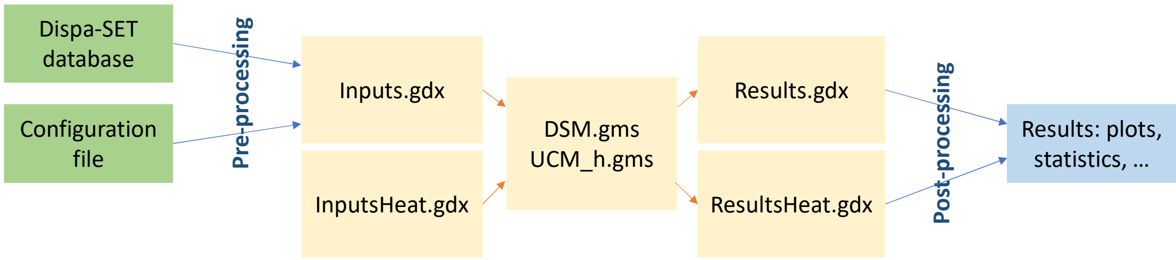
Figure 4.1 gives an illustration of the adapted Dispa-SET interface.

4.2.1 Database

A heat database is added in Dispa-SET containing the InputsHeat.gdx file. The existing Dispa-SET database remains unchanged.[2]

[2]Actually, some power plant data is added in the Dispa-SET database in order to simulate different energy mixes.

Figure 4.1: Adapted implementation and interface of Dispa-SET



4.2.2 Configuration file

The configuration file of the Dispa-SET model is changed in order to add the heat configuration parameters:

- the number of heat pumps in the Belgian building stock
- the number of water heaters in the Belgian building stock
- the number of heat pump simulated as flexible
- the number of water heaters simulated as flexible

These parameters are then loaded with the configuration file and added to the Inputs.gdx file. They are used to simulate different scenarios of flexible electric devices penetration.

On the other hand, some configuration parameters are fixed for all the simulations:

- the optimisation period: year 2015
- the horizon length: 2 days
- the lookahead period: 1 day
- the countries to be simulated: Belgium

The horizon length and lookahead period are chosen short in order to decrease the computational time. Indeed, adding the heat model to an already computational expensive model is increasing the computational time of the model runs furthermore. Decreasing the optimisation periods allows to reduce the computational time significantly.

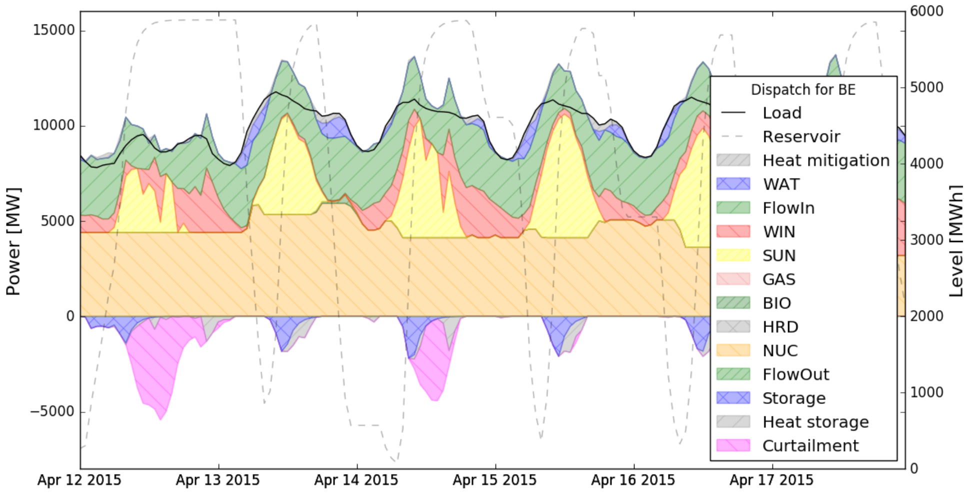
4.2.3 Simulation environment

The preprocessing phase will now copy the following files in the simulation environment:

- The Inputs.gdx file containing the Dispa-SET database parameters and the configuration parameters
- The InputsHeat.gdx files containing the heat model parameters
- The DSM.gms GAMS file containing the heat model
- A modified GAMS file UCM_h.gms that makes the coupling between the two models in the supply-demand balance equation (4.1) and in the objective function (4.2)

The DSM.gms file and de UCM_h.gms are run together as a single file in GAMS.
The results of the simulation are written in a Results.gdx file and a ResultsHeat.gdx file.

Figure 4.2: Dispatch plot example



4.2.4 Postprocessing

Post-processing is adapted to the new results included in the ResultsHeat.gdx file.
First a function *GetResultsHeat* is written in order to load the results stored in this file. Then the different analysis and plot functions are modified.

The $dispatch_{plot}$ function is modified in order to take into account the curtailment and the modification involved by the flexible heating systems.
The *ResultsAnalysis* function is extended in order to return all useful indicators for the scenarios analyses. These indicators will be defined and explained in Section 5.1.

4.3 Illustrative results

This section gives an example of the post-processing results for an arbitrary simulation. The principal useful plots are illustrated and explained

4.3.1 Dispatch plot

Figure 4.2 shows an example of dispatch plot. This plot can be generated over any period and represents the dispatch of the generation aggregated by fuel during this period. The system's load is also represented and is the generation that the system has to reach.
The negative part of the plot contains the consumption for storage and the exported generated power. These consumptions are supplied by additional generation with respect to the system's load.

Curtailment is also represented. It does not represent any generation or consumption but a non-used generation. Given that emphasis is put on curtailment reduction thanks to thermal storage, the curtailment is seen as a potential thermal storage and is represented as being negative.

Thermal storage is represented as hydro storage: power is consumed when heat is stored (heat storage) and is virtually generated when heat is not generated (heat mitigation). Actually, the heat mitigation is not generated and the generation is lower then the load.

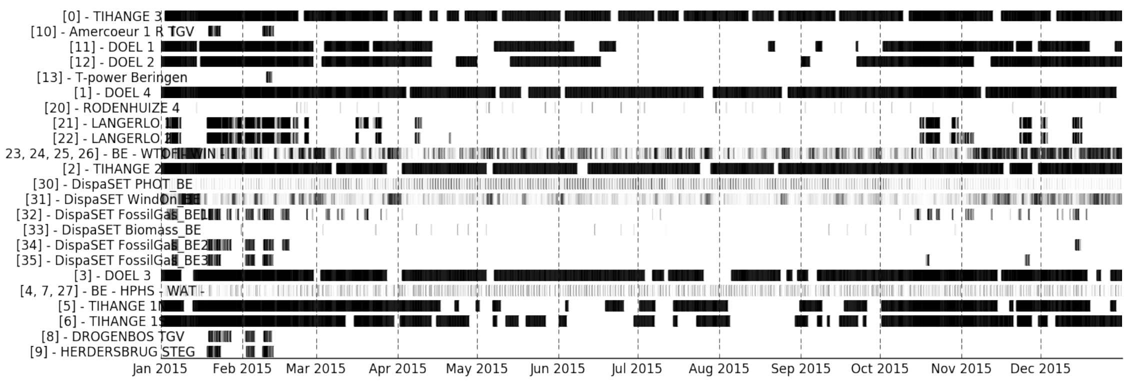
In the example given in Figure 4.2, it can be seen that generation is dispatched between nuclear plants, renewable sources and hydro pumped storage plants. A lot of power is imported. Nuclear generation is the base load generation.
A significant amount of curtailment occurs because of the non-flexibility of the nuclear power plants and storage (hydro and heat) seems to play an important role in curtailment reduction.

4.3.2 Commitment rug plot

Figure 4.3 shows an example of commitment rug plot. This plot gives an overview of the commitment status and power outputs of the system's power plants over the optimisation period. It gives additional information over the system's dispatch.

For example, Figure 4.3 shows which power plants units are participating to the base load (all the year). These are TIHANGE 2, TIHANGE 3, DOEL 3 and DOEL 4. The other nuclear units are participating to the generation essentially in winter because of the load increase.
It also shows differences between different gas fired units. In fact, by comparing the DispaSET FossilGas power plants ([32],[34],[35]), it can be seen that [32] is more participating to the generation and for shorter times (a lot of start-ups). This gas fired unit [32] is more flexible (better ramping capacities) than the two others and is thus a better peak unit. Since nuclear and renewable generation are supplying most of the required generation, gas fired units are used as peak units.

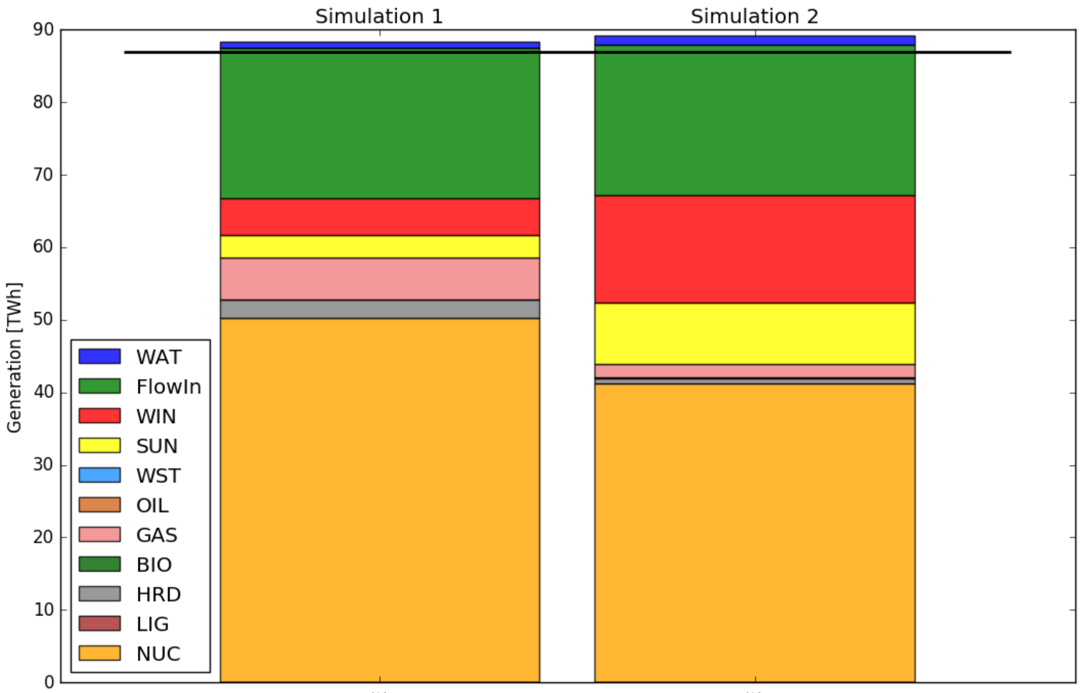
Figure 4.3: Commitment rug plot example



4.3.3 Generation mix plot

Figure 4.4 shows an example of a generation mix plot. This plot gives the generated energy by fuel type, the imports and it also shows the total load of the system (horizontal black line). Due to storage and exports, the total generation is higher than the total load.
The plot allows to compare the generation mix for different simulations easily. For example, Figure 4.4 compares two simulations where the available renewable capacity was higher in Simulation 2 than in Simulation 1. It shows that consequently, more renewable generation occurs in Simulation 2 reducing the generation of nuclear, coal and gas units. It also shows an increase in hydro pumped storage generation and in total generation (due to the increased need in flexibility).

Figure 4.4: Generation mix plot example



Chapter 5

Simulations and results

In this section simulations are performed in order to assess the potential of heat pumps and resistance water heaters in terms of flexibility, RES integration and cost reduction. First, the indicators chosen to analyse the simulation results are defined and explained. Then, the flexibility potential of heat pumps and electric water heaters is assessed for the year 2015. A parametric analysis is then performed in order to asses the influence of the renewable capacity, the generation mix flexibility and the flexible devices penetration.

All the simulations are performed under a "perfect forecast" assumption: all the parameters used are considered to be predicted with no error. Actually if such simulations are made in order to be implemented, several parameters (temperature, demand, etc) would arise from predictions with some error. The benefits of the flexible heating devices assessed hereunder are thus potential benefits under the perfect forecast assumption.

5.1 Indicators description

In this section, the indicators used to analyse and explain the impact of the introduction of flexible electric heating system are defined and explained. These indicators are listed hereunder:

- Operational cost (reduction)
- Marginal cost and generation cost
- Total load variation
- Curtailment
- Renewable generation share
- Global, storage and thermal efficiency
- Hydro capacity factor
- Number of start-up of power plants by fuel

5.1.1 Operational cost (reduction)

The operational cost (OC) is the total cost of the optimisation period (1 year). Since this cost is minimized in the optimisation model, it is expected to decrease when flexibility is added.
The OC reduction represents the benefit in terms of operational cost that is achieved by introducing flexible heating systems.

5.1.2 Marginal cost and generation cost

The marginal cost (MC) is the cost of generating one additional unit of energy at a particular time and with a particular dispatch situation. It is a representation of the real-time price of electricity.

The generation cost (GC) is the cost of generating one additional unit from the more expensive committed unit. It is the variable cost of the most expensive committed unit. It allows to represent the reduction (increase) in high-cost (low-cost) generation.

5.1.3 Total load variation

The total load of a system is given by its electric demand. In the model, this electric demand is fixed (database parameter). When electric devices are made flexible, they can consume more or less power than their base consumption. This consumption variation modifies the electric demand and hence the total load. The total load variation is expressed in percentage and represents the consumption increase or decrease due to the flexible heating systems.

5.1.4 Curtailment

The curtailment (C) is an indicator that represents the unused fraction of renewable energy. It is given by the curtailed energy (unused available renewable energy) divided by the available renewable energy:

$$C = \frac{Curtailed\ energy}{Available\ renewable\ energy} \tag{5.1}$$

5.1.5 Renewable generation share

Increasing the share of renewable generation (RGS) in the generation mix is one of the European's objectives. This renewable generation share is defined by:

$$RGS = \frac{Renewable\ generation}{Total\ generation} \tag{5.2}$$

The total generation is the total generation of the Belgian power plants. It does not take the imports into account[1].

5.1.6 Global, storage and thermal efficiency

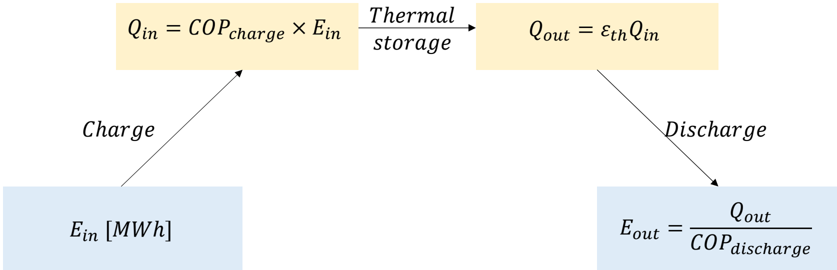
The global storage efficiency is the ratio of the energy not consumed (virtually generated) thanks to thermal storage to the energy used for this storage:

$$\varepsilon_{gl} = \frac{Energy\ generated}{Energy\ consumed} = \frac{\sum_h PowerDifference_h^-}{\sum_h PowerDifference_h^+} \tag{5.3}$$

where $PowerDifference_h^-$ and $PowerDifference_h^+$ are respectively the negative and positive values of the $PowerDifference_h$ variable. They represent the energy discharged and the energy charged respectively.

[1] Since only Belgium is simulated in the model, the imports and exports are fixed. This introduces an error in the results especially when the generation mix is modified.

Figure 5.1: Thermal storage cycle illustration



The storage efficiency is the efficiency of one storage cycle (charge - discharge). Figure 5.1 represents schematically one storage cycle. The storage efficiency can be written:

$$\varepsilon_{st} = \frac{Discharged\ energy}{Charged\ energy} = \frac{COP_{charge}}{COP_{discharge}} \varepsilon_{th} \tag{5.4}$$

where ε_{th} is the thermal efficiency taking into account the thermal losses occurring during storage.
When the charging and discharging coefficients of performance are equal, the storage efficiency equals the thermal efficiency. This is the case for the water heaters where $COP = 1$ at all time.

The global storage efficiency is the weighted average of the storage efficiencies. In the case of water heaters, the global efficiency represents a global thermal efficiency.

5.1.7 Hydro pumped capacity factor

The capacity factor of a power plant is the ratio of the energy produced by the power plant to the energy that could be produced at full load over the entire period considered. The hydro capacity factor (HCF) is thus defined by:

$$HCF = \frac{Hydro\ generation}{Hydro\ capacity \times 8760h} \tag{5.5}$$

This indicator allows to assess the reduction in hydro pumped storage due to the introduction of thermal storage.

5.1.8 Number of start-ups

The number of start-ups of a power plant is the number of time that the power plant has been started (and shut down) within the optimisation period. It is a representation of the stability of the unit.
The power plants starts are aggregated by fuel[2].

5.2 Potential in 2015

In 2015, the energy mix in terms of capacity was composed of around one third of nuclear plants, one third of gas fired plants and one fourth of renewable intermittent sources (Figure 5.2a)[3].

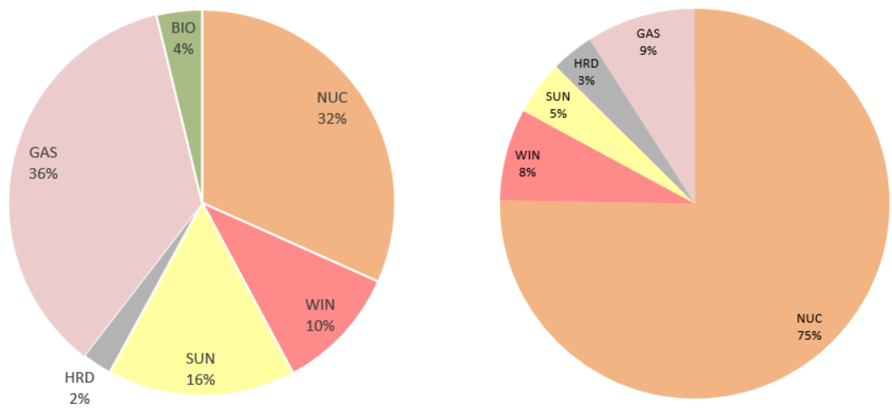
[2] In the remaining of the work, the different fuel types given in Table 2.5 will be designate as: nuclear (NUC), coal (HRD), biomass (BIO), gas (GAS) and hydro (WATER)

[3] The data relative to power capacity was taken from the Dispa-SET database

Figure 5.2: Energy mix of Belgium in 2015

(a) Capacity

(b) Generation



The simulated generation mix is shown in Figure 5.2b[4].

The main results of the base case simulation are given in Table 5.1. A share of 11.9% renewable generation is assessed with 1.2% of curtailment.

Figure 5.3a shows some days the most subjected to curtailment (in summer). It can be seen that curtailment does not arise from an excess in renewable availability compared to the demand but is due to the non-flexibility of the nuclear power plants. In fact, these base load units are unable to follow the load variations induced by renewable generation.
The impact of hydro pumped storage units on the system can also be seen. These units appear to provide non negligible flexibility to the power system as it is able to avoid a lot of curtailment and to achieve peak load reduction.
In addition, although there is more renewable generation in the daytime due to solar plants, it can be seen that curtailment and storage occur during the night. Results show that 60.1% of the curtailment occurs between midnight and 6AM. This can be explained by the load reduction occurring at that time. The net residual load (without renewable and imports) is then entirely produced by nuclear plants which are not flexible enough to follow the renewable variations.

Figure 5.4a shows a typical winter day. Significant differences between summer and winter are observed. First, no curtailment occurs. In fact, results show that no curtailment occurs in winter. Then, the generation of nuclear and coal units is more stable. Finally there is a significant increase in non-nuclear conventional generation in particular gas fired power plants. These effects arise without significant reduction in variable renewable generation. They are explained by the higher demand in winter ranging from 1 to 2 GW. This load increase allows low-cost non-flexible units like nuclear power plants and coal units to work at full load. The flexibility requirement is shifted 'above' the non flexible level and is provided by more flexible power plants like gas fired combined cycle power plants.
In addition, hydro power plants are less used than in summer because of a lower need in flexibility.

To summarize, the base case study already shows a broad range of parameters affecting the flexibility and flexibility requirement of the system. In particular, nuclear units increases the flexibility need of the system while storage units are flexibility providers. The remain of the

[4]The data related to nuclear generation seems to be overestimated. In fact, the database of Dispa-SET (as it was used) takes into account some nuclear power plants that were inactive most of the year (Doel 1, Tihange 2), these accounting for 1500MW of nuclear capacity. Because of the high capacity factor of nuclear plants,this leads to high increases in nuclear generation.

Table 5.1: Potential in 2015: main results

	OC [M€]	**MC** [€]	**GC** [€]	**Load** [TWh]	**C** [GWh]	**RGS** [%]	$\varepsilon_{\mathbf{gl}}$ [%]	**HCF** [%]
Base	712	32.0	30.7	87.0	95.5 (1.2%)	11.9		10,6
Heat pumps	710	32.0	30.5	87.0	85.7 (1.0%)	12.0	119	10,4
Water heaters	703	37.2	29.9	87.3	8.9 (0.1%)	12.1	75.1	6,7

work will assess the potential of flexible electric heating systems to provide such storage flexibility through the thermal building mass and the hot water tank and especially its potential to facilitate the integration of high shares of RES.

5.2.1 Heat pumps

A number 84000 heat pumps (residential and tertiary sector) were in operation in Belgium in 2015 [11] from which 40000 units are assumed to be residential. This corresponds to a market penetration of 0.8%.

The results of the implementation of flexible heat pumps can be found in Table 5.1. Due to the limited heat pump penetration in the building stock, there is no significant effect in their flexible implementation, only slight benefits can be observed. However, as the result in cost reduction is less than the optimisation precision (1%), these slight reductions only show possible benefits of introducing flexible heat pumps in the system. One can thus conclude that the number of heat pumps existing in 2015 does not allow to affect the overall system operation significantly.

5.2.2 Water heaters

In 2013, 30% of the Walloon dwellings has an electric equipment for domestic hot water [25]. This share is assumed to be the same for Belgium and to stay constant until 2015. This leads to a number of 1.6 million of units in 2015. Several effects of the flexible water heaters implementation can be observed in Table 5.1.

The most remarkable effect (Table 5.1) concerns curtailed power. Indeed, flexible heat pumps reduced the curtailed power by more than 90%. Although this reduction seems to be large, the initially curtailed power was of only 1.2% of the total load and the benefit in terms of renewable generation is only of 0,2%. Curtailed power reduction should therefore be regarded in terms of additional RES energy generation added: 87 GWh.

The share of renewable generation has grown from 11.9% to 12.1%. This grow arises from the curtailed power reduction.
However, thermal storage increases the total load of the system. In fact, thermal storage means that higher temperatures has to be reached. Consequently, more thermal losses arise and have to be compensated by an increase in heating. Increase in heating increases the electric consumption for the heating demand and thus the total electric demand.
Since the total load is increased, the total generation of electricity is increased and the share of renewable in this generation is decreased. Thermal storage with electric heating has thus two opposite effects on the share of renewable energy: a positive effect due to curtailment reduction and a negative effect due to total load increase.
It should be kept in mind that neither the curtailment, nor the total load of the system is minimized but its operational cost. To that end, a flexibility increase could lead to a decrease in the

Table 5.2: Differences in generation by fuel type due to flexible water heaters [GWh]

NUC	HRD	BIO	GAS	RES	WAT
140	151	-0,8	-250	87	-445
0.,28%	6,45%	-3,6%	-4,14%	1,1%	-36,6%

share of RES generation.

Figure (5.3b) looks at the generation dispatch for the same time period as Figure (5.3a), that is when the curtailment occurred the most. For this period, thermal storage is able to capture all the curtailed power achieving curtailment reduction, and peak load shifting. Moreover, the stability and generation of low-cost power plants are increased. Generation of more expensive units is reduced. Table 5.2 shows the differences in electricity generation by fuel type induced by flexible water heaters and thermal storage.

A large generation reduction occurs for hydro pumped storage plants.
As can be seen by comparing Figure 5.3b and 5.4b, when no need in additional flexibility exists in the system, thermal storage replaces hydro pumped storage to some extent leading to a lower hydro power utilisation (lower HCF). The fact that thermal storage replaces hydro storage in the power system means that the thermal storage efficiency is better than the hydro storage efficiency. However, it can be seen from Figure 5.3b that the storage capacity in the hot water tank is larger than what is used to replace hydro storage.

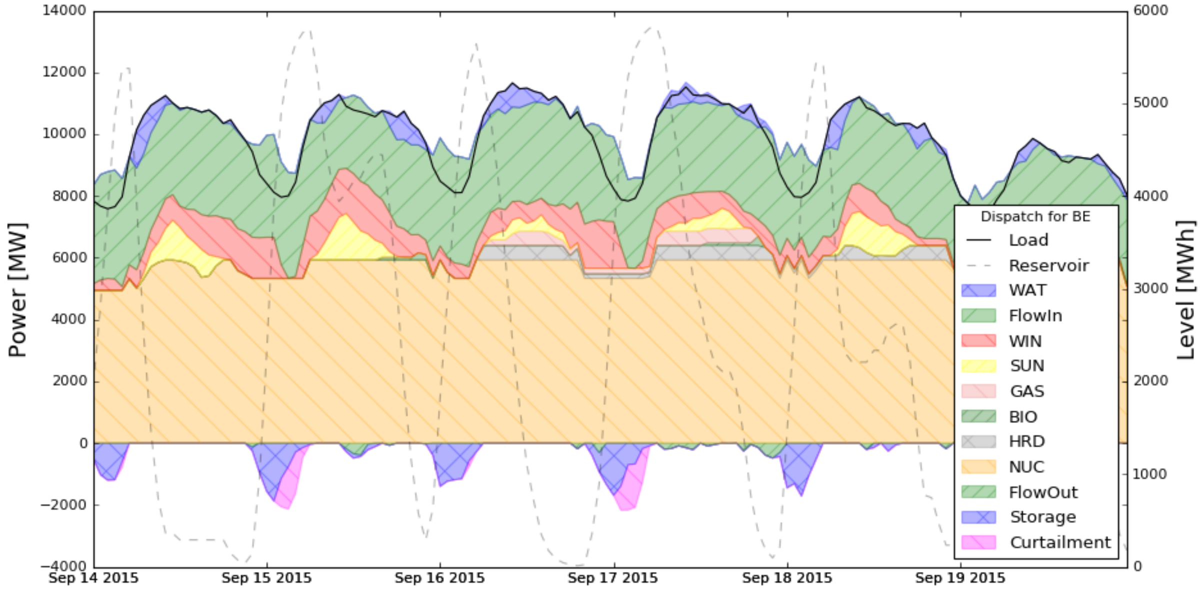
When a unit of electricity is consumed for hydro storage, a part of this energy is turned into potential energy. After some time, this potential energy is released and only a part of it is turned as electric generation in the power system regardless of the time during which water was stored or the storage level. The storage efficiency of the hydro pumped storage system is thus constant.
For thermal storage, things are quite different. Although the same principle of storage and release applies, the dynamics is different. When a unit of electrical energy is consumed by the water heater, a unit of energy is stored as thermal energy in the water tank ($COP = 1$). When a unit of heat energy is not used in the water tank, a unit of electrical energy is not provided by the system and is virtually generated. The thermal storage thus has a charging and release performance of 100%. However, the temperature increase in the tank generates higher thermal losses and the thermal efficiency decreases. Moreover, as longer the system stays at higher temperature levels, as much the thermal losses increases and the thermal efficiency decreases.

Thus, the storage efficiency (thermal efficiency) of the water heaters can reach theoretically 100% but decreases with the storage level and the storage duration while the hydro storage efficiency is fixed and lower than unity (0,74% in the simulations). This explains why only a part of the initial hydro storage is replaced by thermal storage: thermal storage takes the place of hydro storage until their performance are equal. At that equilibrium point, replacing more or less hydro by thermal storage would lead to a less efficient overall storage.
This is true only when all the flexibility needed by the system is already provided by hydro storage. When this is not the case (Figure 5.3b), the water heaters play the role of additional flexibility providers. It has its own storage efficiency. Only when the entire flexibility need of the system is reached can the thermal storage replace the hydro storage, if its storage efficiency is still higher than the hydro efficiency.

A 75.1% global efficiency is reached in the simulation. This is close to the hydro efficiency.

Figure 5.3: Potential in 2015: summer dispatch

(a) Base case



(b) Flexible WH case

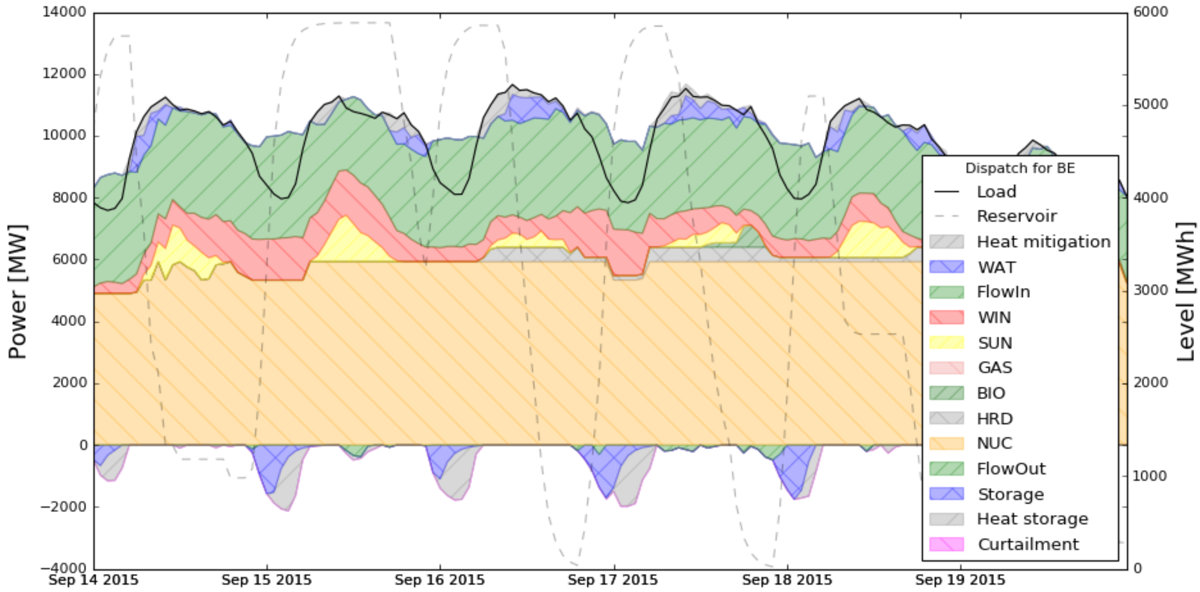
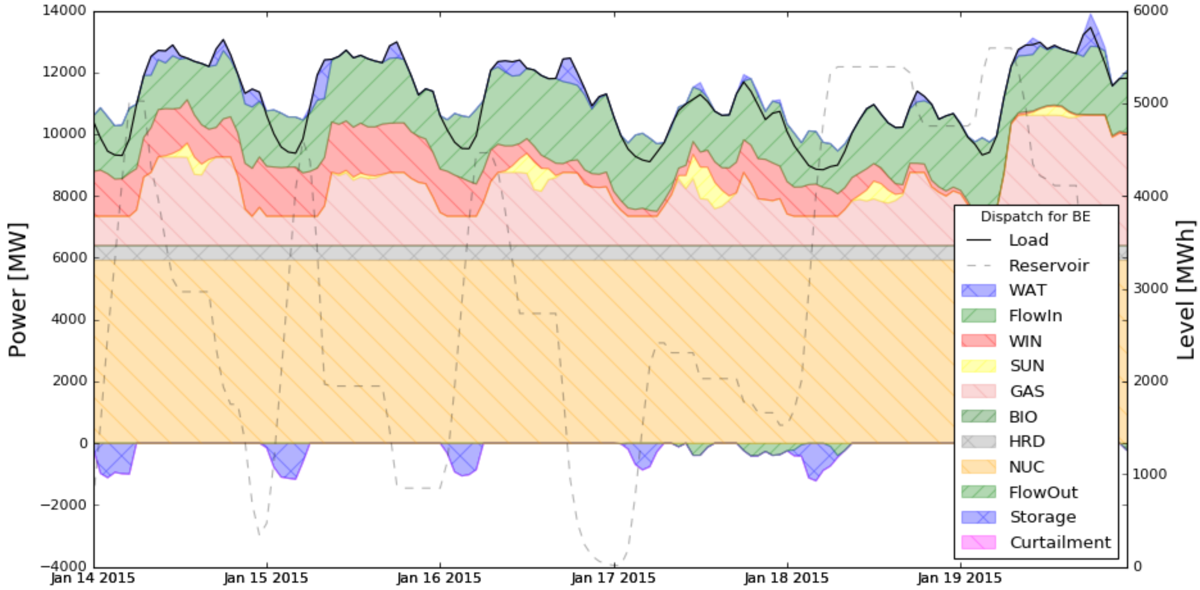
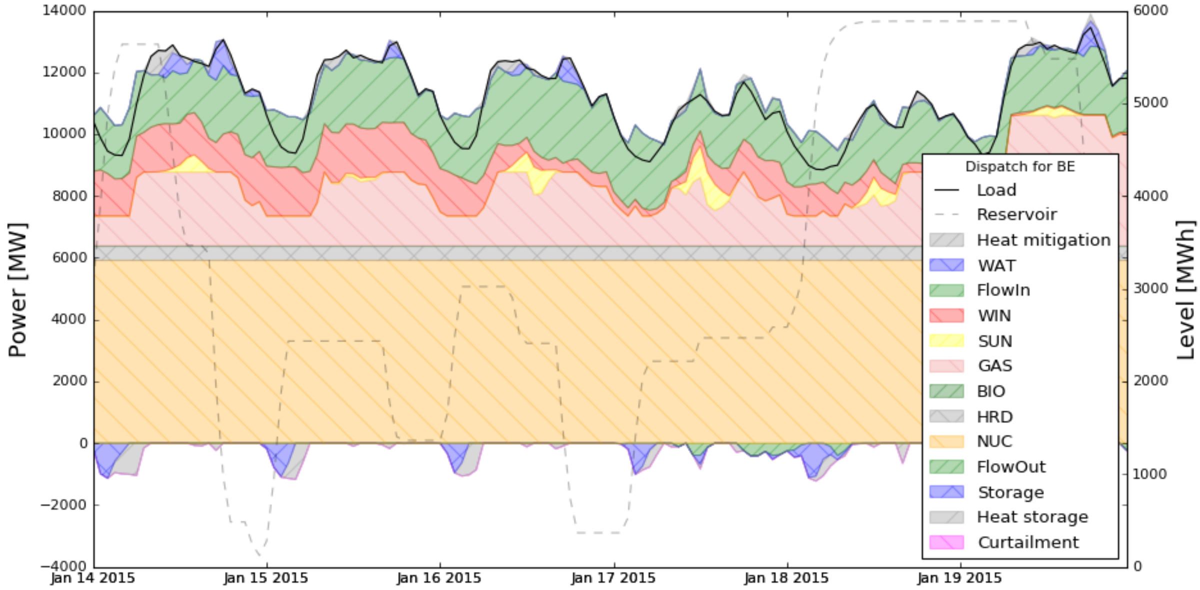


Figure 5.4: Potential in 2015: winter dispatch

(a) Base case



(b) Flexible WH case



The replacement of hydro storage can be represented by the hydro capacity factor (HCF). As more the initial storage is replaced, as more its capacity factor goes down. In this case study, the capacity factor of hydro storage was reduced by one third, representing the fact that one third of the initial hydro storage was replaced by thermal storage. More flexibility than needed was introduced in the power system at some time periods. However, since the flexibility need in the system is varying within a year, hydro storage replacement cannot be completely avoided when thermal storage is introduced.

Since storage duration decreases the thermal storage efficiency of the water tank, it can be assessed that hot water tank storage through electric heating is a short term load shifting technology. This can be seen in Figures 5.3b and 5.4b where storage discharge happens almost immediately after storage charge. In particular, when hydro and thermal storage exists in a system, a typical pattern of charge - discharge is: (i) hydro charge, (ii) thermal charge, (iii) thermal discharge and (iv) hydro discharge. This system behaviour optimizes the storage efficiency by reducing the duration of thermal storage.

In terms of cost, the operational cost of the system is decreased by 9M€(1.3%), the generation cost has decreases by 0.8€and the marginal cost increases by 5.2€.
Since the introduction of flexibility allows an increase in low-cost generation, the generation cost and the marginal cost are expected to decrease. This is not the case for the marginal cost.

Firstly, it should be reminded that the marginal cost is not the cost of generating one additional unit from the more expensive committed unit (GC) but the cost of generating one additional unit at a particular time and with a particular dispatch situation. The difference lies essentially in the accounting of the actual system conditions (dispatch situation, ramping constraints, ...). Figure 5.5 shows and compares the marginal and generation cost duration curves in the base case study and when water heaters are made flexible. It can be seen that the marginal cost is sometimes higher and sometimes lower than the generation. This is most likely arising from positive and negative effects of taking the system conditions into account.

The identified positive effect is curtailment. In fact, when one unit of electricity is curtailed in the system, the price of generating an additional unit of electricity is zero. This effect can clearly be seen in Figure 5.5 where the marginal cost ranges from zero to the minimum generation cost (nuclear cost). The positive effect of curtailment can also occur when more expensive units are committed.
The negative effect is the incapacity of the committed power plants to deliver an additional unit of electricity. When all the committed units are at their full load capacity, they cannot deliver any additional unit of electricity. Consequently, this additional unit has to be found elsewhere. Possibilities are the modification of load through storage units, load shedding or starting up another plant[5]. Since the overall cost is optimized, all these options lead to higher costs than the generation cost. As a results, the marginal cost of a system for which all the committed plants are at (or close to) their full load capacity is higher than the generation cost of the system.

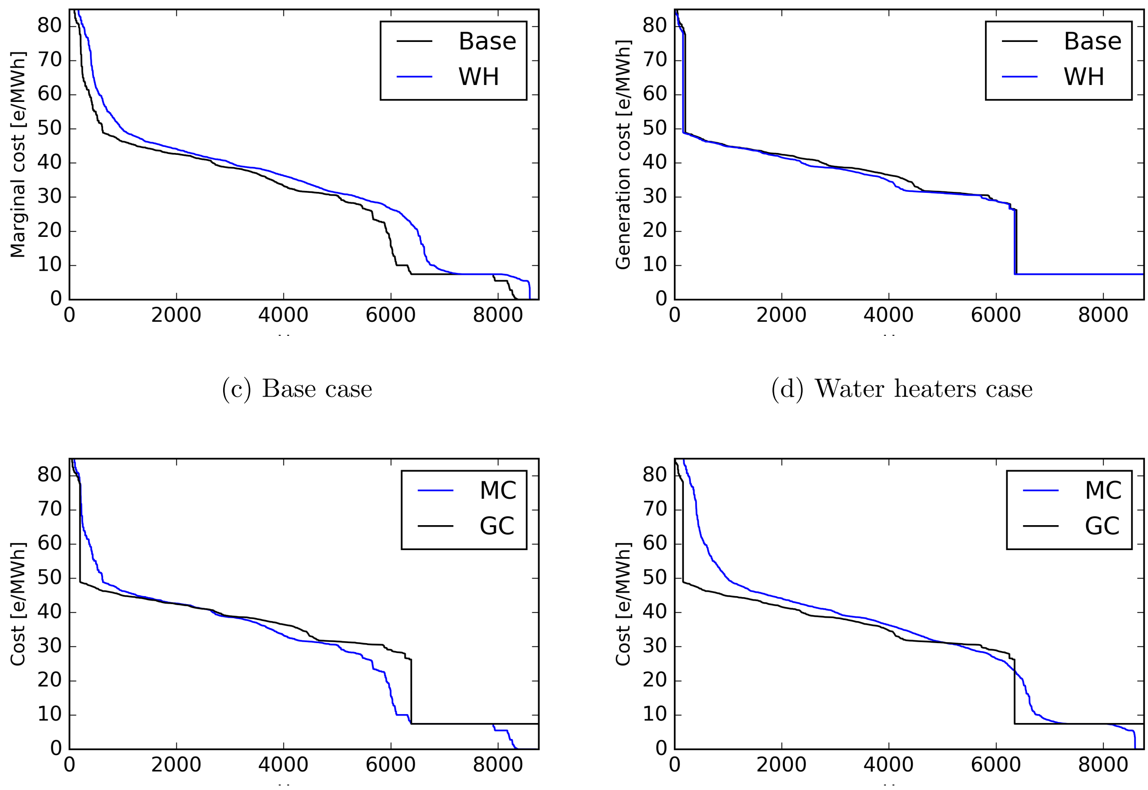
Introduction of flexibility reduces the generation cost, reduces curtailment and increases the generation of low-cost power plants close to their full load (stabilisation). Thus, the positive effects on the marginal cost compared to the generation cost are lowered while the negative effects are increased. However, the generation cost is still lowered. As a consequence, the marginal cost can decrease or rise when the system flexibility is increased.

[5]In the model, the marginal cost calculation is done by fixing the binary variables (commitment) and generating the marginal cost of demand of the remaining linear model. As the start-ups of power plants is done through the use of the binary variables, the optimisation does not take them into account in the marginal cost calculation.

Figure 5.5: Marginal cost and generation cost duration curves

(a) Marginal cost (b) Generation cost

(c) Base case (d) Water heaters case



5.3 Parametric analysis

In this section, an analysis is performed on the influence of the share of renewable sources and the existing flexibility of the system on the benefits achieved by flexible electric heating devices. To that end, several simulations are performed for different capacity mixes and different numbers of electric heating units.

5.3.1 Simulated scenarios

The simulations are carried out for six different capacity mixes.
Starting from the capacity mix of year 2015 (Figure 5.2a), the renewable capacity is varied from one to three times the base renewable capacity (R1, R2, R3). Moreover, the flexibility can be increased by replacing all the nuclear units by gas-fired units.

A number of one million installed electric heating units (heat pumps or water heaters) in the building stock is assumed and the number of flexible units is varied from zero (non-flexible demand) to one million with steps of 0.2M. Table 5.3 shows the parametric analysis parameters that are varied in the simulations.

Table 5.3: Parametric analysis scenarios

Heating system	Number of flexible units	Renewable capacity	Flexibility of the system
HP - WH	0 - 0.2 - 0.4 - 0.6 - 0.8 - 1M	R1 - R2 - R3	Non-flexible - Flexible

In the following, the effect of these parameters on the benefits assessed before are evaluated through the indicators variation. First, the WH heating units scenarios' results are analysed and discussed. Then, a comparison with the HP scenarios is performed and significant differences are pointed out.

All the simulation results can be found in Table A.1 and Table A.2.

5.3.2 Water heaters results

Operational cost

The total operation cost of the system without flexible heating devices in the demand is shown in Table 5.4. It can be seen that an increase the renewable capacity decreases the operational cost significantly. In fact, since renewable generation is free, the cost decreases when more renewable generation is available. On the other hand, increasing the flexibility of the system leads to much higher OC. This is explained by the fact that flexibility is added by replacing low-cost nuclear plants by high-cost gas fired plants.

Since the total operational is minimized, making water heaters flexible is expected to reduce it. Figure 5.6 shows the cost reduction benefit of introducing flexible water heaters.

For the non-flexible system, Figure 5.6a shows that as more water heaters are made flexible, as more the benefit in cost reduction is important. Moreover, increasing the renewable capacity also increases this cost reduction.
The increase in cost benefit seems to follow a sub-linear trend. When water heaters are made flexible, the system flexibility increases and its flexibility need decreases. A further increase in water heaters is applied to a system that has become more flexible and the additional benefits are lower. The same effect arises when renewable generation is made available: the system's need in flexibility increases as well as the cost benefits. This effect can be seen as a saturation of the system's flexibility. When less need in flexibility exists in a system, adding further flexibility has less impact on the system.

For the flexible system, Figure 5.6b shows only a cost reduction in the maximum renewable capacity case. For the other cases, a cost increase is shown. As mentioned before, since the total operational cost is minimized, only a cost reduction is possible.
These results are due to the precision of the optimisation model. In fact, the objective function (total cost) is minimized within a 1% precision range. For the flexible system, this accounts for a 17 to 23 M€ of precision (depending on the renewable capacity). This precision is much higher than the calculated cost reductions and the results are thus highly inaccurate[6].
The introduction of one million flexible water heaters has thus no significant benefit in terms of cost reduction on the considered flexible system. Again, this arises from the fact that the system's flexibility is increased.

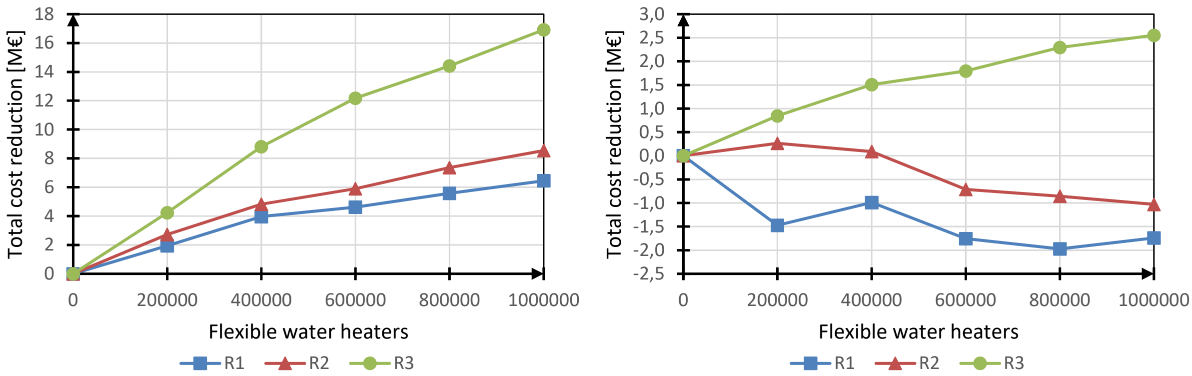
[6]The same precision effect exists for the non-flexible case but since the total operational costs are lower, the precision is better (lower). In addition, the costs reductions are higher.

Table 5.4: Base total operational cost for the different scenarios [M€]

	Non-flexible system	Flexible system
R1	711	2362
R2	544	2026
R3	457	1705

Figure 5.6: Total cost reduction (water heaters)

(a) Non-flexible (b) Flexible



Marginal and generation cost

Figure 5.7b shows the generation cost for the non-flexible system cases. It can be seen that the generation cost is decreasing with an increase in renewable capacity. For the first renewable capacity case (R1), the generation cost is staying almost constant. For the second renewable capacity case (R2), the generation cost decreases and stabilizes. Finally, for the high renewable capacity case (R3), it decreases more significantly. Once again, the benefits of the flexible water heaters are higher when a higher flexibility need exists (more high-cost peak generation to reduce).

The flexible system cases is not represented. In these cases, the generation cost is staying constant at the cost of the gas-fired units. Indeed, as nuclear units are replaced by gas units, the coal units (low-cost but low capacity) and some gas units become the base load units. Other

Figure 5.7: Marginal cost and generation cost in the non-flexible case (water heaters)

(a) Marginal cost (b) Generation cost

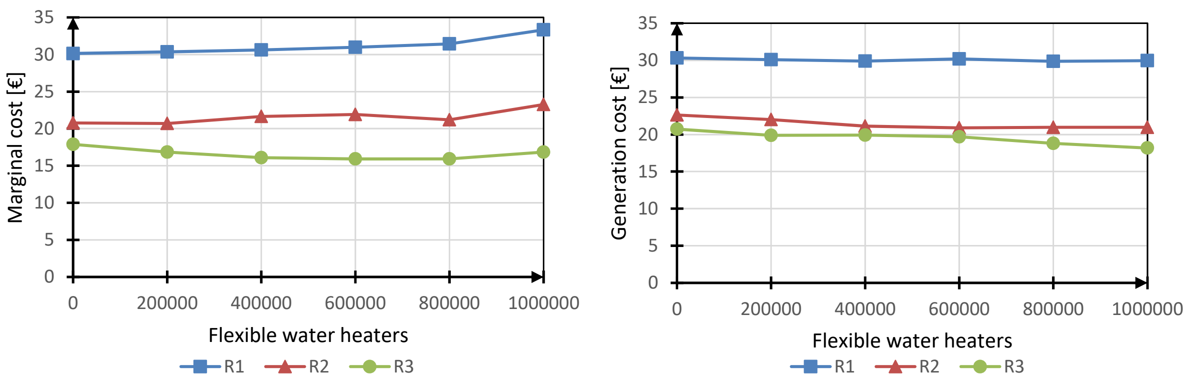
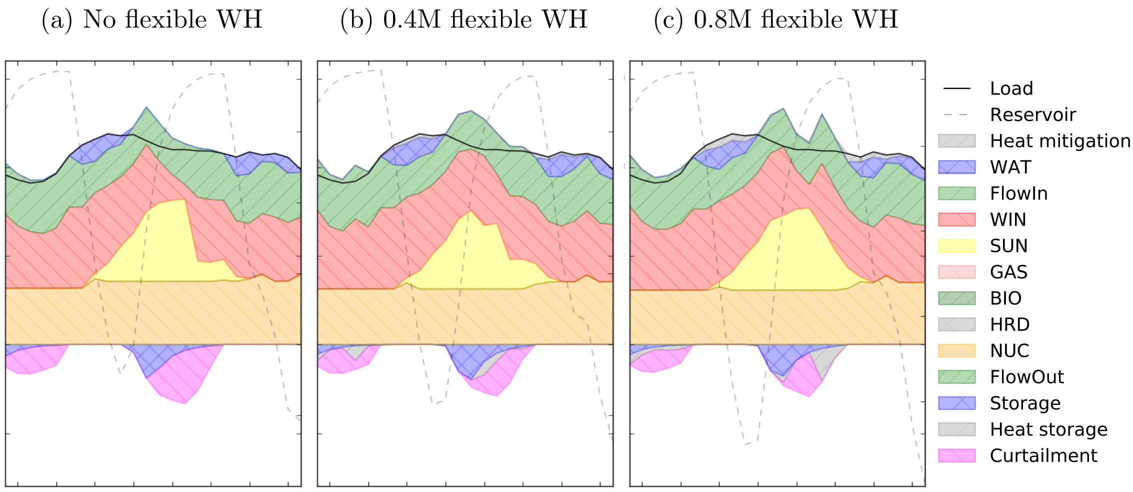


Figure 5.8: Curtailment reduction for different numbers of flexible water heaters (R3, Non-flexible, April 1)



gas units and biomass units are still the peak units. Since gas units generation is cheaper than biomass generation, the gas units are used as peak power plants and the biomass units are used as the last choice. That is never for the R1 and R2 cases and a little for the R3 cases. Actually, the generation cost in the R3 case is slightly higher than in the other cases.

The marginal cost for the non-flexibible system cases is shown in Figure 5.7a. It shows that the marginal cost is decreasing with an increase in renewable capacity. Concerning its dependence to the number of flexible water heaters, several trends are observed. The minimum renewable capacity case seems to show an increase in marginal cost when the maximum renewable capacity case shows a decrease followed by an increase.

It has been shown that the marginal cost can increase when flexibility is added, especially when curtailment is reduced. In the R1 case, an increase in flexible water heaters does not reduce the generation cost. However, it reduces curtailment. The marginal cost is thus increasing. On the contrary, in the R3 case, an increase in flexible water heaters decreases the generation cost while decreasing the curtailment. Opposite effects on the marginal cost are thus occurring. Figure 5.8 shows the R3 case without, with 0.4M and with 0.8M flexible water heaters for a typical summer day. It shows that when 0.4M water heaters are made flexible, it is not able to capture all the curtailment and curtailment is occurring during the same periods. Moreover, the stability of power plants generation is not increased significantly. The negative effects on the marginal cost are negligible and it decreases as the generation cost. When another 0.4M water heaters are made flexible, more curtailment is avoided reducing the periods during which curtailment occurs. This curtailment reduction makes the marginal cost rise.

For the flexible case, the marginal cost is staying almost constant close to the gas generation cost (higher). In fact, as no curtailment occurs, there is almost no effect of the flexible water heaters on the marginal cost.

To summarize, the marginal cost is decreasing with the flexible water heaters penetration when the flexibility need is important and is increasing when the flexibility need becomes lower. When there is almost no need in flexibility in the system, the marginal cost remains unchanged.

Figure 5.9: Total load variation (water heaters)

(a) Non-flexible (b) Flexible

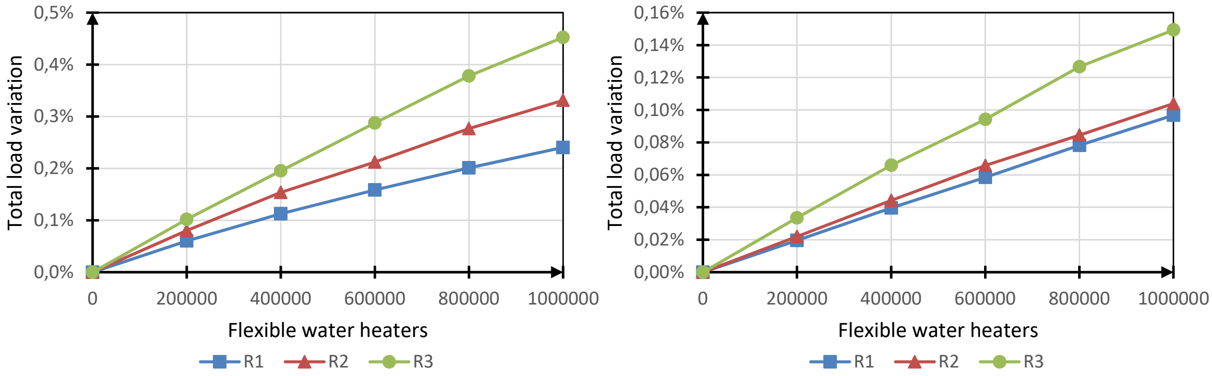
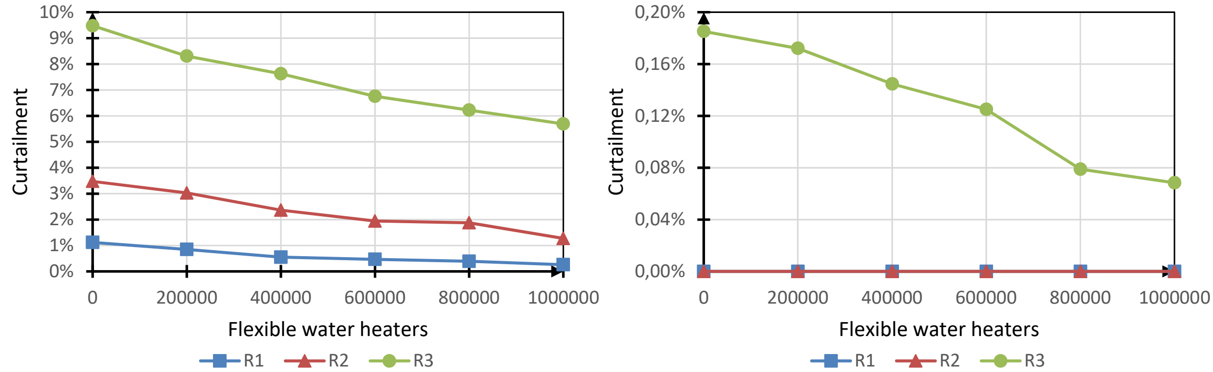


Figure 5.10: Curtailment (water heaters)

(a) Non-flexible (b) Flexible



Total load variation

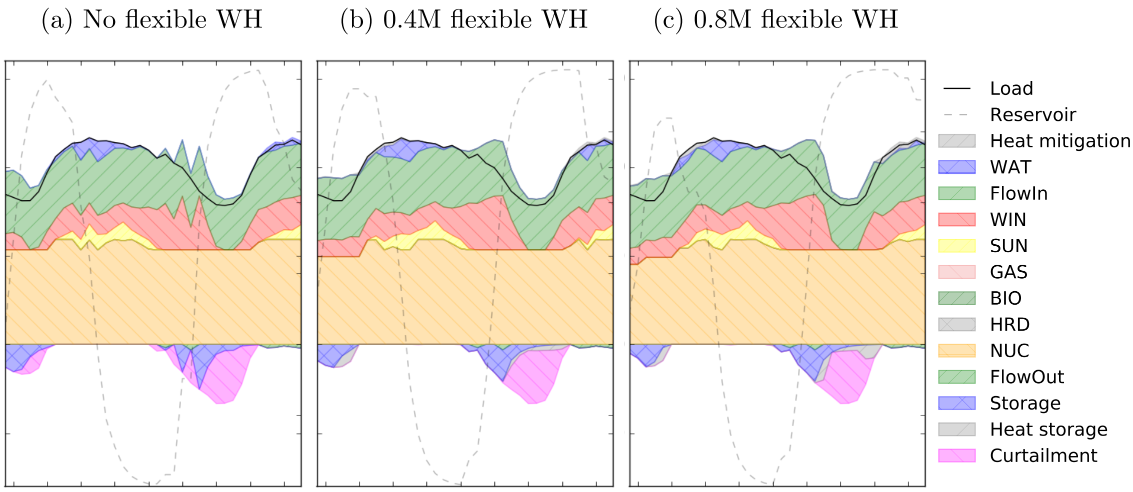
The load variation is shown in Figure 5.9. It shows that the total load increases with the introduction of flexible water heaters. As mentioned before, this increase is due to the higher thermal losses (and thus higher heating needed) that arises from thermal storage. This consumption increase increases with the renewable capacity (more flexibility need) and decreases when the system is made flexible. As for the total operational cost, the higher the flexibility need, the higher the impact of the flexible water heaters. Furthermore, the same saturation effect is observed (sub-linear increase).

Curtailment

Figure 5.10 shows the curtailment variation when flexible water heaters are added. Obviously, curtailment is higher when there is more renewable capacity and it decreases with the introduction of flexible systems. This decrease is more important when more energy is curtailed and follows a sub-linear trend.

Figure 5.11 shows a typical day where curtailment occurs (R2 - N-Flex) for three penetrations of flexible water heaters. It is showing two curtailment periods; the first one containing less curtailed energy than the other.
When 0.4M flexible heaters are introduced, thermal storage is able to capture all the curtailed power of the first period and only a part of the second period. When 0.4 additional heaters are made flexible, there is no more curtailment occurring at the first period and curtailment is only

Figure 5.11: Curtailment reduction for different numbers of flexible water heaters (R2, Non-flexible, September 16)



captured at the second period. Since thermal storage is a short term technology, the storage capacity not used at the first period cannot be added to the storage capacity at the second period and less curtailed power is captured.
This explains the sub-linear trend of the curtailment reduction.

For the flexible system, curtailment is very low for the maximum renewable capacity and is zero for the other cases. This is showing that replacing non-flexible nuclear plants by more flexible gas fired plants reduces significantly the need in flexibility of the system and hence the impact of flexible water heaters.

Renewable generation share

The share of renewable generation is significantly increased when a higher renewable capacity is available. However, it only slightly increases with the introduction of flexible devices and this increase is higher as the renewable capacity is higher. Only a 0.2% increase in renewable generation share is observed with the minimum renewable capacity case while a 1.3% increase is observed for the maximum capacity case for the non-flexible system.

For the flexible system, no increase is observed for the R1 and R2 cases since no curtailment occurs. For the R3 case, the renewable generation share increased by 0.1%.

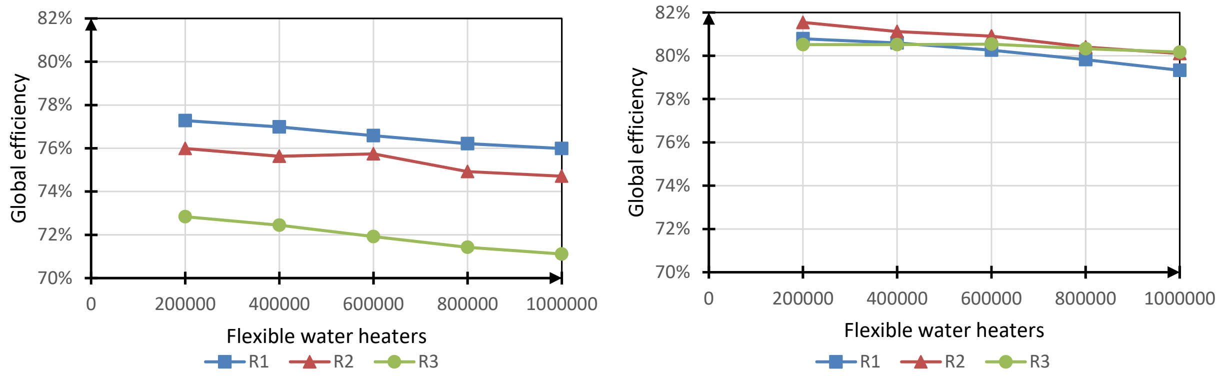
In terms of renewable generation share, the principal beneficial effect of flexible water heaters is to possibly allow the system to own more renewable capacity. The slight increase due to the flexible water heaters penetration is a secondary and less beneficial effect.

Efficiency

Figure 5.12 shows the global storage efficiency variations of the parametric analysis. The global storage efficiency for water heaters has been shown to be the average value of the storage thermal efficiencies. Since this efficiencies are lowered when more storage is used, it also decreases with the system's flexibility need.
Since thermal storage is a short term storage, the charge - discharge periods are close to each

Figure 5.12: Storage efficiency (water heaters)

(a) Non-flexible (b) Flexible



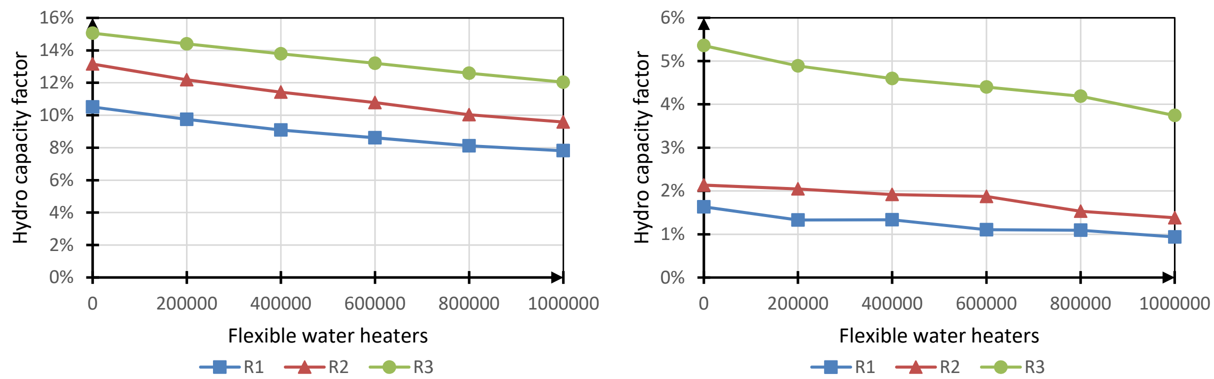
other. When additional water heaters are made flexible, the available periods for charge and discharge are less close to each other and the thermal efficiency decreases. This is why the global efficiency decreases with the flexible water heaters penetration.

Hydro capacity factor

The hydro capacity factor is shown in Figure 5.13. As expected, it decreases when more flexible heaters are introduced. In addition, a higher renewable capacity makes it increase and a higher flexibility in the system makes it decreases. In fact, as more flexibility is needed when renewable sources are added, as more the flexibility of the hydro storage is used.

Figure 5.13: Hydro pumped storage capacity factor (water heaters)

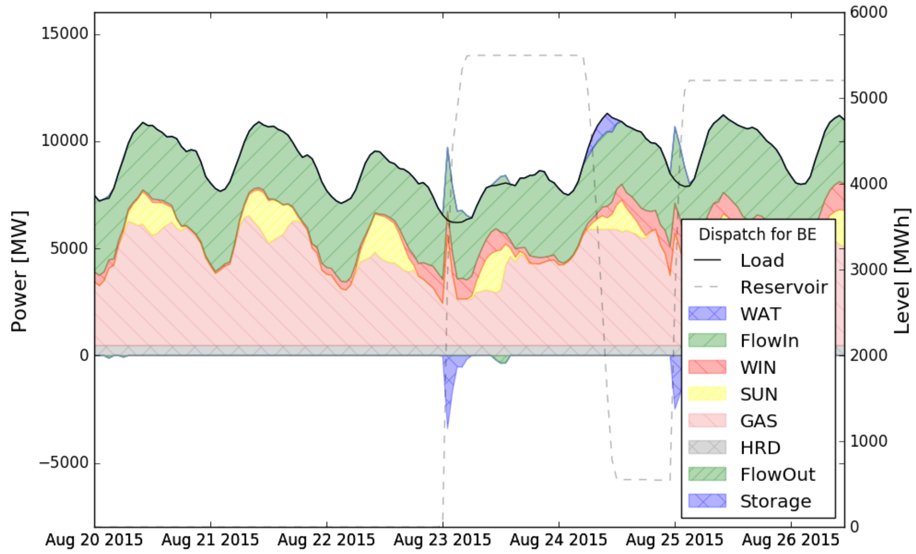
(a) Non-flexible (b) Flexible



Generation by fuel

The generated energy by fuel is shown in Figure A.1. Broadly speaking, when flexible water heaters are introduced, the generation of low-cost power plants is slightly increased (nuclear, coal) and the generation of high-cost plants is slightly decreased (gas, biomass). Besides, adding renewable capacity makes the generation of the other plants decrease except for hydro plants (needed for flexibility) and biomass plants. Indeed, since the renewable generation increases, the generation of the other plants has to decrease. Biomass plants are the most expensive units

Figure 5.14: Flexible case dispatch plot without flexible units (R1, Flexible)



considered in the model, they are thus treated as peak units and are more started when more flexibility is needed.

Starts by fuel

The unit starts by fuel type is shown in Figure A.2. No significant effect can be seen on the base load units like nuclear and coal units. However, for peaking units (gas, biomass), a reduction in the number of start-ups is observed.

In addition, there is no start-up of coal units in the flexible system case for all water heaters penetration.
Since the low-cost nuclear units have been removed from the system, the cheaper remaining units are the coal units. These units are thus base load units (Figure 5.14). Moreover, the coal capacity is low. The coal units are thus committed at all time. Figure A.1 also shows a constant coal generation when no curtailment occurs (R1 and R2) for the flexible system case. This generation corresponds to a nearly full load generation at all time (capacity factor of 99.9%).

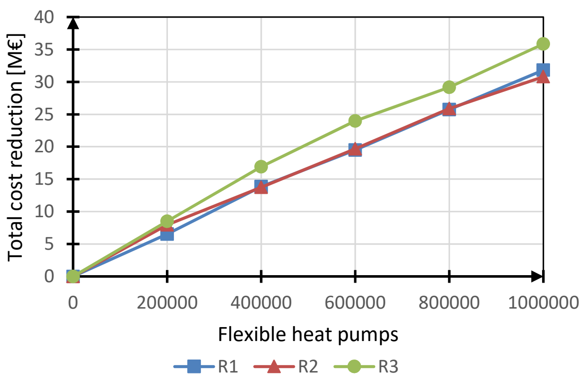
5.3.3 Comparison with heat pumps

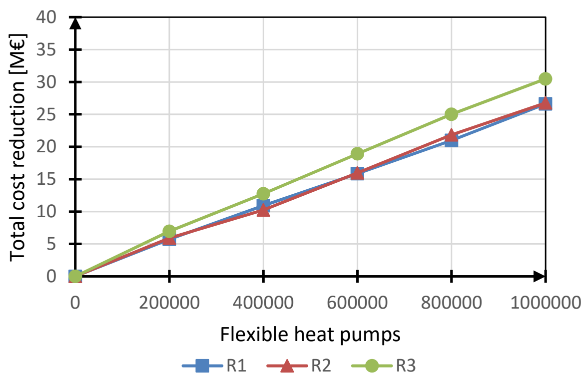
In this section, a comparison is performed between the heat pumps implementation cases and the water heaters implementation cases. Only the results that differ from the water heaters cases are analysed.

Operational cost

The total operational cost reduction is shown in Figure 5.15. Compared with the water heaters cases, the cost reduction is larger and is become more significant in the flexible case.
When heat pumps are made flexible in the system, cost reduction occurs for two reasons: the increase in flexibility (like for water heaters) and the heat pump consumption reduction thanks

Figure 5.15: Total cost reduction (heat pumps)





to a better repartition of the heating with respect to the varying performance of the heat pumps[7].

The lower renewable capacity cases (R1 and R2) have the same increase in cost reduction. For the flexible case, the flexibility provided by the heating systems has hardly no effect on the total cost (Figure 5.6b). In these cases, the cost reduction observed is entirely due to the consumption reduction. This consumption reduction is the same whatever the renewable capacity and the resulting cost benefits follow a sub-linear trend. In fact, a consumption reduction reduced the production of the higher-cost units. As more the consumption decreases, as less the higher-cost units are expensive and as less the cost benefit is important.
For the non-flexible case, the cost reduction due to flexibility is much lower than the cost reduction due to the consumption reduction and the increases are the same. When more renewable is added (R3), the cost reduction due to flexibility becomes significant and the total cost reduction is increased as well.

Total load variation

As explained before, the heat pumps consumption decreases when they are made flexible. This decrease has a lowering effect on the total load being in opposition with the increasing effect due to the thermal storage. Figure 5.16 shows the load variation induced by flexible heat pumps.

The consumption decrease is proportional to the number of flexible heat pumps and follows thus a linear trend while the consumption increase due to thermal storage follows a sub-linear trend. The total load variation is thus the addition of the decreasing linear variation and the increasing sub-linear variation. That leads to the variations observed in Figure 5.16. Only for a high flexibility need is the upward trend prevailing over the downward trend. However, when more flexible heat pumps are introduced, the flexibility of the system increases and the load variation decreases. Because this variation is the addition of a linear decreasing curve and a sub-linear increasing curve, the introduction of a high enough number will always lead to a consumption decrease.

Figure 5.16: Total load variation (heat pumps)

(a) Non-flexible (b) Flexible

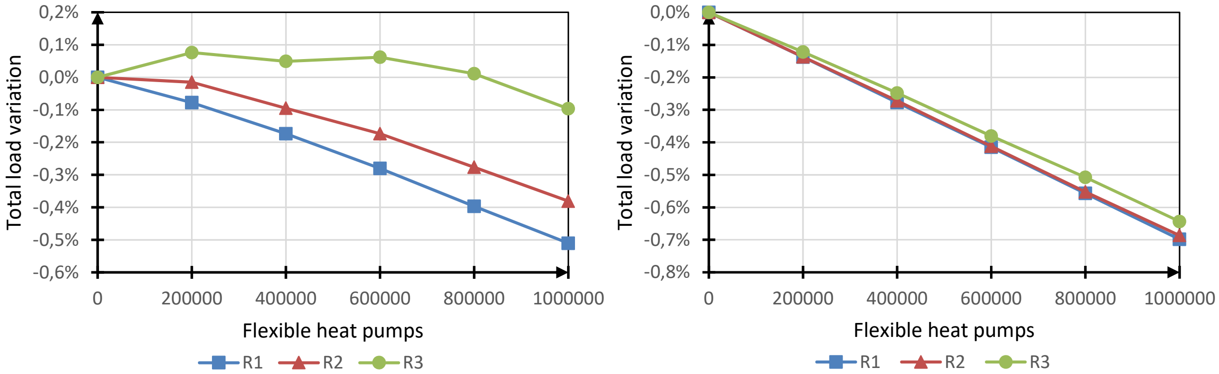


Figure 5.17: Curtailment (heat pumps)

(a) Non-flexible (b) Flexible

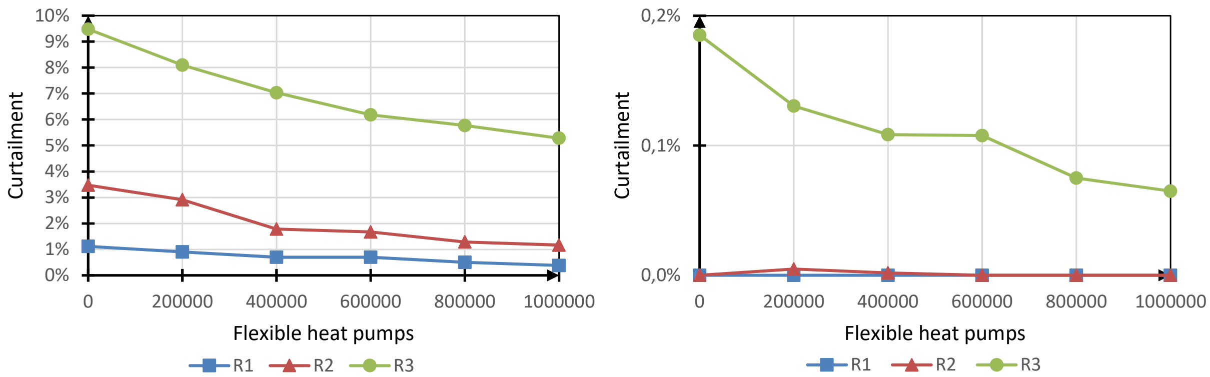
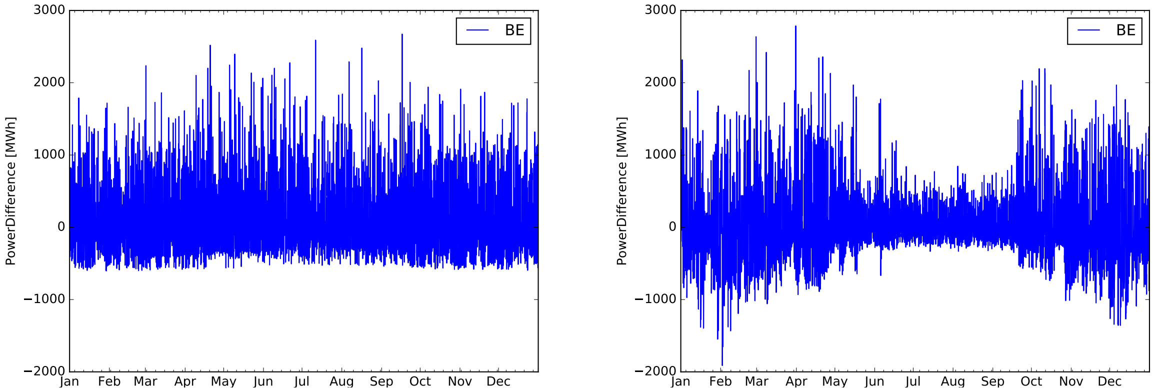


Figure 5.18: Difference in electric heating system consumption

(a) Water heaters (b) Heat pumps



Curtailment

The reduction in curtailment when heat pumps are introduced is almost the same than when flexible water heaters are introduced. Since the heat pumps have a larger heating nominal power and provide both space heating and domestic water heating (more storage capacity), curtailment is expected to decrease further.

The main difference between heat pumps and water heaters is their performance. The COP of the heat pumps ranges from 1 to 5 with a nominal value of 3.95 while the COP of the water heaters is constant and equal to unity. Consequently, for the same heat storage capacity, the storage capacity in terms of electricity is lower for heat pumps.
In addition, as the inside air temperature is influenced by various external factors (like internal gains), the space heating storage capacity is varying with the minimum reachable inside temperature. For example, the space heating capacity is lowered in summer and is even zero when the maximum admissible temperature is reached.

Figure 5.18 shows the storage capacity reduction of the heat pumps in summer compared to the water heaters. It shows the consumption difference ($PowerDifference_h$) during the entire optimisation period. For heat pumps, a distinct difference can be seen between summer and winter.

Renewable generation share

The share in renewable generation is increasing slightly faster by introducing flexible heat pumps than by introducing flexible water heaters. This is due to the load decrease occurring with heat pumps instead of the load increase that occurs with flexible water heaters.

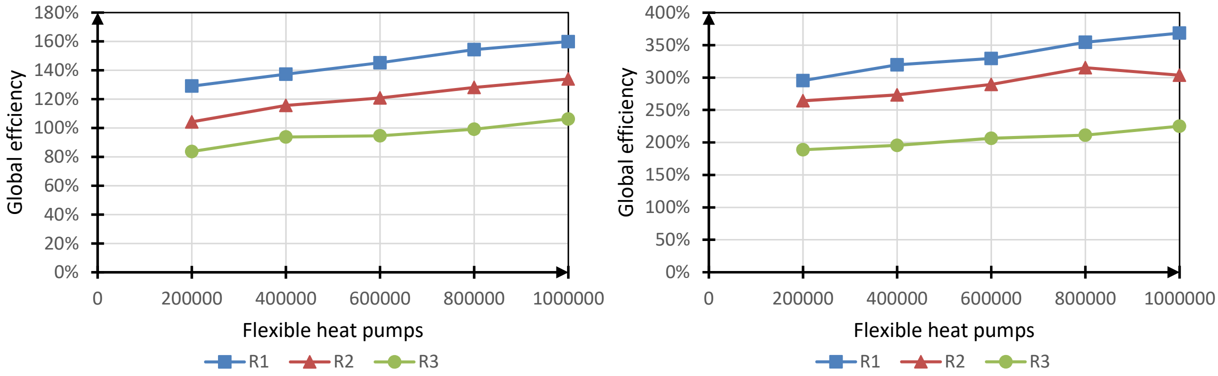
For the non-flexible system, a 0.3% increase is observed for the minimum renewable capacity case and a 1.7% increase is observed for the maximum renewable capacity case.

For the flexible system, although there is no curtailed power reduction in the R1 and R2 cases, the renewable generation share increases slightly. Again, this is due to the load decrease.

[7] Actually, a consumption reduction is possible in both cases (HP and WH) since the base consumption was not taken as the minimum consumption but given that the performance of water is constant, this consumption reduction is negligible compared to the flexibility increase effects

Figure 5.19: Storage efficiency (heat pumps)

(a) Non-flexible (b) Flexible



Efficiency

The global efficiency of storage is shown in Figure 5.19. The efficiency values are higher than with flexible water heaters and are even above unity for some simulations. Moreover, contrary to the water heaters case, the efficiency is increasing when more flexible devices are introduced.

Given Equation 5.4, these differences are arising from the varying performance of the heat pumps. The storage efficiency can be higher than unity if :

$$\frac{COP_{discharge}}{COP_{charge}} \leq \varepsilon_{th} \tag{5.6}$$

When flexible heat pumps are introduced, the charging and discharging periods are chosen in order to satisfy Equation 5.6 and to have a storage efficiency above unity.

When more heat pumps are introduced, the flexibility needs of the system are shared between more devices and allows a better repartition of the needed storage. Because the performance of the heat pumps increases at part load (for SH), more flexible heat pumps and thus more divided storage power allows to increase the charging performance. This can explain why the global efficiency is increased when more flexible heat pumps are introduced.

Chapter 6

Conclusion

The objective of this work was to assess the potential benefits of demand response through electric heating systems under high shares of renewable energy. A Belgian case study is performed.

To that aim, an integrated model coupling the heat demand to an existing unit commitment and dispatch model (Dispa-SET) was developed.
The demand side heat model was developed taking into account the existing Belgian building stock and the Belgian heating demands. The heating demands were linked to the heat demand through accurate state space models and different electric heating systems were modelled: flexible resistance water heaters and flexible air-to-water heat pumps. The obtained demand side heat model was implemented in the Dispa-SET interface and coupled to the supply side model.

Several simulations were performed. First the potential benefits of implementing flexible water heaters and heat pumps in 2015 are assessed. Then a parametric analysis is performed assessing the influence of the flexible devices penetration, the renewable capacity and the flexibility of the capacity mix on these benefits.

Results show that significant benefits can be achieved by making the heat demand flexible. Operational cost benefits up to 16€ per water heater and 35€ per heat pump are assessed. Thermal storage is able to capture up to 1 TWh of curtailment with 1 million electric heating systems when the flexibility needs are the most important (high renewable capacity and non-flexible system). That is 1 MWh of curtailment reduction per electric device.

These benefits are reduced significantly when non-flexible units are replaced by flexible units and increased when more renewable capacity is added. In order to have significant benefits, the flexibility requirements of the system have to be high. Moreover, when the number of flexible heating systems are increased, a saturation effect of the flexibility is observed.

In addition, the heat pumps electric storage capacity is shown to vary during the year. In particular, it is shown to be significantly lower in summer than in winter. The benefits of the flexible heat pumps implementation are thus most likely lower in summer.

In conclusion, the heat demand is able to provide non-negligible flexibility to the power system through flexible electric heating devices. The benefits due to the additional flexibility are increased when the flexibility need of the system increases and especially when more renewable energy is available. Results show that non-negligible curtailed energy can be captured by thermal storage when high shares of renewable capacity exist.

Future work

This work analyses the flexibility potential of the heat demand for demand response through a Belgian case study. The emphasis is put on the supply side and in particular on renewable generation integration. Several future development possibilities exist.

First, the heat optimisation model can be improved by taking ventilation and/or cooling into account. Thanks to this improvement, cooling and ventilation demands flexibility could also be assessed. In addition, adding cooling would limit the higher temperature relaxation variable and avoid the problems linked to the relaxation costs.

Another pathway to development is the extension of the heat model to several zones (countries). Indeed, the heat model has been written for a single zone only. Taking several countries into account could allow to simulate a whole coupled system and to identify additional effects. For example, the effects on the imports and exports or the effects of adding flexible heating in one zone on the other zones.

Since the emphasis was put on the supply side for the results analysis, a analysis on the demand side could be performed in order to assess the benefits and impacts of the flexible heating on the end-users (cost reduction, comfort range, etc). The dispatching of the flexibility provision could also be analysed.

Furthermore, a full cost analysis could be performed in order to assess the cost profitability of the flexible devices introduction with and/or without investment in renewable capacity.

Finally, since the simulation are performed under a "perfect forecast" assumption, the effect of the prediction errors is not taken into account. This prediction error effect could be assessed by first simulate the system with the prediction values and then simulate the same system with the actual values of the parameters and with the fixed load obtained in the previous simulation.

Appendix A

Simulations results

Table A.1: Parametric analysis results: water heaters

Scenarios			OC	MC	GC	Load	PL	PRL	C	RGS	ϵ_{th}	HCF	Generation [TWh]					Starts			
[M]			[M€]	[€]	[€]	[TWh]	[GW]	[GW]	[%]	[%]	[%]	[%]	NUC	HRD	BIO	GAS	REN	NUC	HRD	BIO	GAS
0	R1	N-Flex	711	30.1	30.3	87.0	13.6	11.7	1.1	11.9		10.5	50.2	2.34	0.02	6.01	8.10	22	36	22	89
0.2	R1	N-Flex	709	30.4	30.1	87.0	13.6	11.6	0.9	12.0	77.3	9.8	50.2	2.41	0.01	5.94	8.12	24	33	12	88
0.4	R1	N-Flex	707	30.6	29.9	87.1	13.6	11.6	0.5	12.0	77.0	9.1	50.2	2.45	0.01	5.88	8.15	22	36	9	80
0.6	R1	N-Flex	707	31.0	30.2	87.1	13.7	11.6	0.5	12.0	76.6	8.6	50.2	2.46	0.02	5.85	8.16	23	37	14	73
0.8	R1	N-Flex	706	31.4	29.9	87.1	13.6	11.5	0.4	12.1	76.2	8.1	50.2	2.48	0.02	5.81	8.16	20	36	14	75
1	R1	N-Flex	705	33.3	30.0	87.2	13.7	11.5	0.3	12.1	76.0	7.8	50.3	2.47	0.02	5.81	8.17	22	37	17	64
0	R2	N-Flex	544	20.8	22.6	87.0	13.6	11.6	3.5	23.2		13.2	46.4	1.21	0.03	3.27	15.8	54	27	47	83
0.2	R2	N-Flex	541	20.7	22.0	87.0	13.6	11.6	3.0	23.3	76.0	12.2	46.4	1.24	0.03	3.19	15.9	57	28	39	77
0.4	R2	N-Flex	539	21.6	21.1	87.1	13.6	11.5	2.4	23.5	75.6	11.4	46.4	1.26	0.02	3.13	16.0	57	34	28	71
0.6	R2	N-Flex	538	21.9	20.9	87.2	13.5	11.4	1.9	23.6	75.7	10.8	46.4	1.28	0.02	3.11	16.1	60	33	25	65
0.8	R2	N-Flex	536	21.2	21.0	87.2	13.8	11.4	1.9	23.6	74.9	10.0	46.4	1.25	0.03	3.11	16.1	57	29	26	64
1	R2	N-Flex	535	23.3	21.0	87.3	13.8	11.4	1.3	23.8	74.7	9.6	46.4	1.26	0.03	3.08	16.2	57	31	32	61
0	R3	N-Flex	457	17.9	20.7	87.0	13.6	11.6	9.5	32.5		15.1	41.7	0.73	0.08	2.04	22.3	108	26	93	78
0.2	R3	N-Flex	453	16.8	19.9	87.1	13.6	11.5	8.3	32.9	72.8	14.4	41.6	0.71	0.07	2.01	22.5	107	25	78	76
0.4	R3	N-Flex	449	16.1	19.9	87.1	13.6	11.4	7.6	33.1	72.4	13.8	41.5	0.75	0.07	1.94	22.7	101	25	79	70
0.6	R3	N-Flex	445	15.9	19.7	87.2	13.6	11.4	6.8	33.4	71.9	13.2	41.4	0.77	0.07	1.87	22.9	102	25	78	63
0.8	R3	N-Flex	443	15.9	18.8	87.3	13.7	11.4	6.2	33.6	71.4	12.6	41.4	0.72	0.05	1.89	23.1	102	25	65	62
1	R3	N-Flex	441	16.8	18.2	87.4	13.7	11.4	5.7	33.8	71.1	12.0	41.3	0.70	0.04	1.90	23.2	99	24	54	61
0	R1	Flex	2362	42.9	41.3	87.0	13.6	11.7	0	12.3		41.1	0	4.12	0.00	54.0	8.19	0	0	0	56
0.2	R1	Flex	2363	45.6	41.3	87.0	13.6	11.6	0	12.3	80.8	41.1	0	4.12	0.00	54.0	8.19	0	0	0	53
0.4	R1	Flex	2363	44.6	41.3	87.0	13.6	11.6	0	12.3	80.6	41.1	0	4.12	0.00	54.0	8.19	0	0	0	49
0.6	R1	Flex	2363	44.4	41.3	87.0	13.6	11.6	0	12.3	80.3	41.1	0	4.12	0.00	54.0	8.19	0	0	0	51
0.8	R1	Flex	2364	45.1	41.3	87.0	14.0	11.6	0	12.3	79.8	41.1	0	4.12	0.00	54.0	8.19	0	0	0	49
1	R1	Flex	2363	43.8	41.3	87.1	13.8	11.5	0	12.3	79.3	41.1	0	4.12	0.00	54.0	8.19	0	0	0	49
0	R2	Flex	2026	43.6	41.3	87.0	13.6	11.6	0	24.6		41.1	0	4.11	0.00	45.8	16.4	0	0	0	73
0.2	R2	Flex	2026	43.3	41.3	87.0	13.6	11.6	0	24.6	81.5	41.1	0	4.11	0.00	45.8	16.4	0	0	0	68
0.4	R2	Flex	2026	44.6	41.3	87.0	13.6	11.5	0	24.6	81.1	41.1	0	4.11	0.00	45.8	16.4	0	0	0	64
0.6	R2	Flex	2027	44.5	41.3	87.0	13.6	11.5	0	24.6	80.9	41.1	0	4.12	0.00	45.9	16.4	0	0	0	57
0.8	R2	Flex	2027	43.9	41.3	87.0	13.7	11.5	0	24.6	80.4	41.1	0	4.12	0.00	45.9	16.4	0	0	1	58
1	R2	Flex	2027	44.3	41.3	87.1	13.6	11.3	0	24.6	80.1	41.1	0	4.12	0.00	45.9	16.4	0	0	0	57
0	R3	Flex	1705	43.1	42.1	87.0	13.6	11.6	0.19	36.6		41.0	0	4.03	0.01	37.9	24.5	0	0	16	150
0.2	R3	Flex	1705	43.3	41.6	87.0	13.6	11.5	0.17	36.6	80.5	41.1	0	4.04	0.07	37.9	24.5	0	0	9	142
0.4	R3	Flex	1704	44.6	41.6	87.0	13.6	11.5	0.14	36.6	80.5	41.0	0	4.05	0.06	37.9	24.5	0	0	9	129
0.6	R3	Flex	1704	44.7	41.7	87.1	13.6	11.4	0.13	36.6	80.5	41.0	0	4.04	0.08	37.9	24.6	0	0	13	123
0.8	R3	Flex	1703	45.0	41.6	87.1	13.6	11.4	0.08	36.7	80.3	41.1	0	4.05	0.06	37.9	24.6	0	0	6	115
1	R3	Flex	1703	44.1	41.5	87.1	13.6	11.4	0.07	36.7	80.2	41.1	0	4.06	0.04	37.9	24.6	0	0	6	119

Table A.2: Parametric analysis results: heat pumps

Scenarios			OC	MC	GC	Load	PL	PRL	C	RGS	ϵ_{gl}	HCF	Generation [TWh]					Starts			
[M]			[M€]	[€]	[€]	[TWh]	[GW]	[GW]	[%]	[%]	[%]	[%]	NUC	HRD	BIO	GAS	REN	NUC	HRD	BIO	GAS
0	R1	N-Flex	711	30.1	30.2	87.0	13.6	11.7	1.1	11.9		10.5	50.2	2.34	0.02	6.01	8.10	22	36	22	89
0.2	R1	N-Flex	705	29.8	29.9	86.9	13.6	11.6	0.9	12.0	129	9.93	50.2	2.34	0.01	5.88	8.12	21	34	12	91
0.4	R1	N-Flex	697	31.4	29.9	86.9	13.5	11.5	0.7	12.1	137	9.16	50.2	2.44	0.01	5.64	8.14	22	37	14	78
0.6	R1	N-Flex	692	31.2	29.5	86.7	13.5	11.5	0.7	12.1	145	8.68	50.3	2.41	0.01	5.52	8.14	22	38	14	75
0.8	R1	N-Flex	686	31.9	30.0	86.6	13.6	11.4	0.5	12.1	154	8.35	50.3	2.43	0.02	5.36	8.15	22	36	21	70
1	R1	N-Flex	679	31.6	29.8	86.6	13.6	11.6	0.4	12.2	160	8.81	50.3	2.42	0.02	5.24	8.16	21	34	21	65
0	R2	N-Flex	544	20.8	22.6	87.0	13.6	11.6	3.5	23.2		13.2	46.4	1.22	0.03	3.27	15.8	54	27	47	83
0.2	R2	N-Flex	536	20.2	21.4	87.0	13.6	11.5	2.9	23.3	104	12.5	46.5	1.24	0.03	3.08	15.9	55	28	31	77
0.4	R2	N-Flex	530	21.9	20.8	86.9	13.5	11.4	1.8	23.7	116	11.9	46.3	1.18	0.02	2.99	16.1	63	29	26	68
0.6	R2	N-Flex	524	21.1	20.4	86.8	13.7	11.4	1.7	23.8	121	11.1	46.4	1.18	0.02	2.86	16.1	62	31	24	63
0.8	R2	N-Flex	518	21.7	20.3	86.7	13.8	11.3	1.3	23.9	128	10.5	46.3	1.17	0.03	2.73	16.2	59	32	29	67
1	R2	N-Flex	513	20.7	20.0	86.6	13.8	11.3	1.2	24.0	134	9.89	46.3	1.15	0.03	2.62	16.2	62	36	29	54
0	R3	N-Flex	457	17.9	20.8	87.0	13.6	11.6	9.5	32.5		15.1	41.7	0.73	0.08	2.04	22.3	108	26	93	78
0.2	R3	N-Flex	449	17.4	19.5	87.0	13.6	11.5	8.1	33.0	83.7	14.5	41.6	0.70	0.06	1.92	22.6	108	27	72	69
0.4	R3	N-Flex	440	17.2	19.6	87.0	13.8	11.4	7.0	33.4	93.8	14.0	41.4	0.67	0.06	1.82	22.9	104	22	73	69
0.6	R3	N-Flex	433	15.5	18.8	87.0	13.8	11.3	6.2	33.7	94.6	13.6	41.4	0.60	0.06	1.75	23.1	101	22	71	66
0.8	R3	N-Flex	428	16.1	18.6	87.0	14.0	11.2	5.8	33.9	99.2	13.0	41.3	0.60	0.06	1.65	23.2	110	23	76	49
1	R3	N-Flex	422	15.2	18.1	86.9	14.6	11.2	5.3	34.2	106	12.4	41.2	0.60	0.06	1.56	23.3	98	23	65	49
0	R1	Flex	2362	42.9	41.3	87.0	13.6	11.7	0	12.3		41.1	0	4.12	0.00	54.0	8.19	0	0	0	56
0.2	R1	Flex	2356	43.5	41.3	86.9	13.6	11.6	0	12.4	295	41.1	0	4.12	0.00	53.9	8.19	0	0	0	52
0.4	R1	Flex	2351	43.7	41.3	86.7	13.6	11.5	0	12.4	320	41.1	0	4.12	0.00	53.7	8.19	0	0	0	48
0.6	R1	Flex	2346	43.1	41.3	86.6	13.7	11.5	0	12.4	329	41.1	0	4.12	0.00	53.6	8.19	0	0	0	51
0.8	R1	Flex	2341	43.8	41.3	86.5	13.8	11.4	0	12.4	355	41.1	0	4.12	0.00	53.5	8.19	0	0	0	51
1	R1	Flex	2335	43.1	41.3	86.4	13.8	11.4	0	12.5	369	41.1	0	4.12	0.00	53.4	8.19	0	0	0	53
0	R2	Flex	2026	43.6	41.3	87.0	13.6	11.6	0	24.6		41.1	0	4.11	0.00	45.8	16.39	0	0	0	73
0.2	R2	Flex	2020	43.1	41.4	86.9	13.6	11.5	0	24.7	264	41.1	0	4.11	0.00	45.7	16.39	0	0	2	64
0.4	R2	Flex	2016	43.6	41.3	86.7	13.5	11.5	0	24.7	273	41.1	0	4.11	0.00	45.6	16.39	0	0	0	67
0.6	R2	Flex	2010	43.8	41.4	86.6	13.7	11.4	0	24.8	289	41.1	0	4.11	0.00	45.5	16.39	0	0	2	68
0.8	R2	Flex	2004	43.8	41.3	86.5	13.8	11.4	0	24.8	315	41.1	0	4.11	0.00	45.3	16.39	0	0	0	66
1	R2	Flex	1999	43.5	41.3	86.4	13.8	11.3	0	24.9	304	41.1	0	4.11	0.00	45.2	16.39	0	0	0	62
0	R3	Flex	1705	43.1	42.1	87.0	13.6	11.6	0.19	36.6		41.0	0	4.03	0.01	37.9	24.5	0	0	16	150
0.2	R3	Flex	1699	44.7	41.8	86.9	13.6	11.5	0.13	36.7	189	41.1	0	4.04	0.01	37.7	24.5	0	0	11	139
0.4	R3	Flex	1693	44.0	41.8	86.8	13.5	11.4	0.11	36.8	196	41.0	0	4.04	0.01	37.6	24.6	0	0	11	133
0.6	R3	Flex	1687	43.4	41.6	86.6	13.6	11.3	0.11	36.8	206	41.1	0	4.04	0.00	37.5	24.6	0	0	8	123
0.8	R3	Flex	1680	42.5	41.6	86.5	13.4	11.3	0.08	37.0	211	41.1	0	4.04	0.00	37.4	24.6	0	0	6	122
1	R3	Flex	1675	43.5	41.7	86.4	13.7	11.3	0.06	37.0	225	41.1	0	4.04	0.00	37.2	24.6	0	0	9	117

Figure A.1: Parametric analysis: generation mix (water heaters)

(a) Non-flexible (b) Flexible

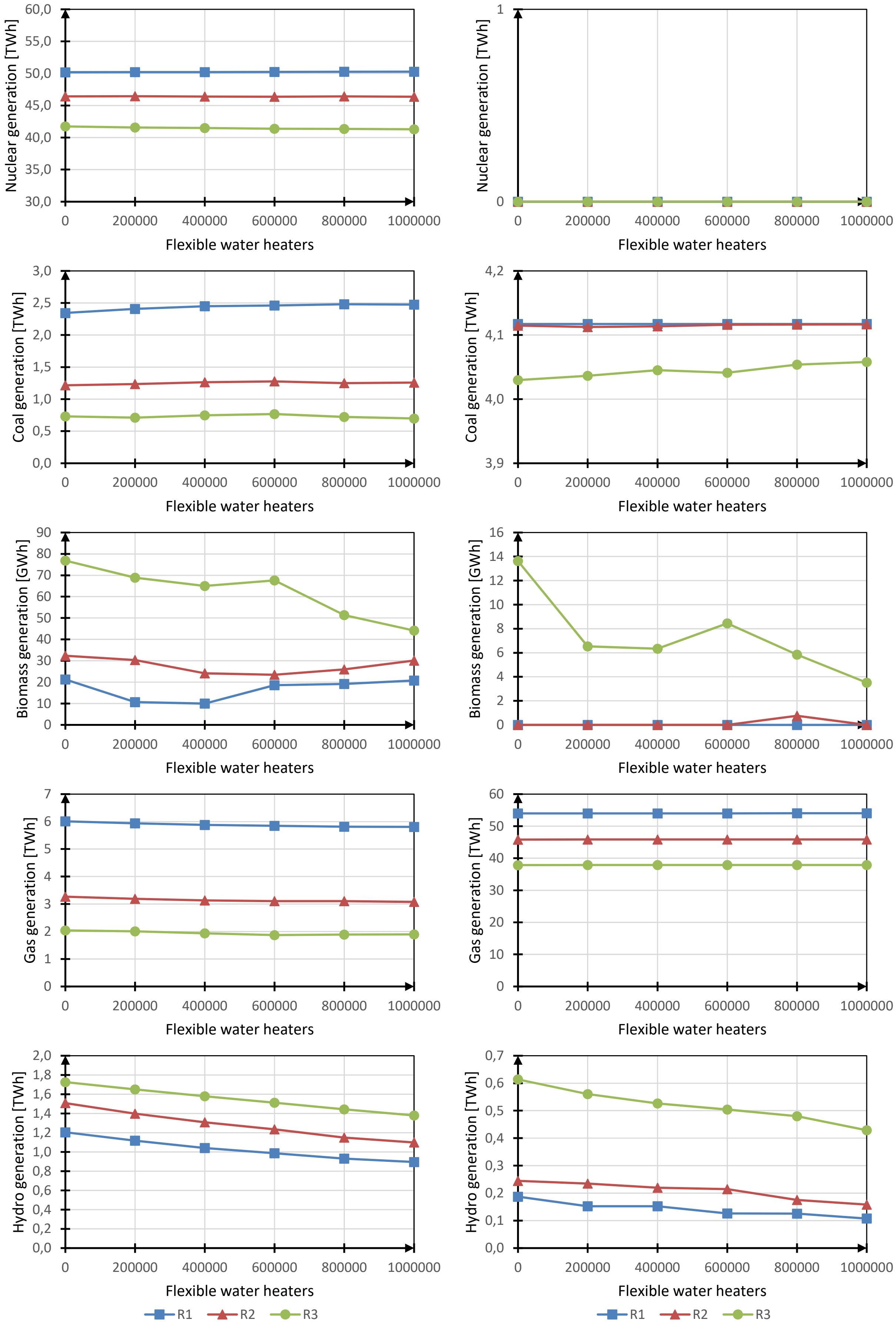
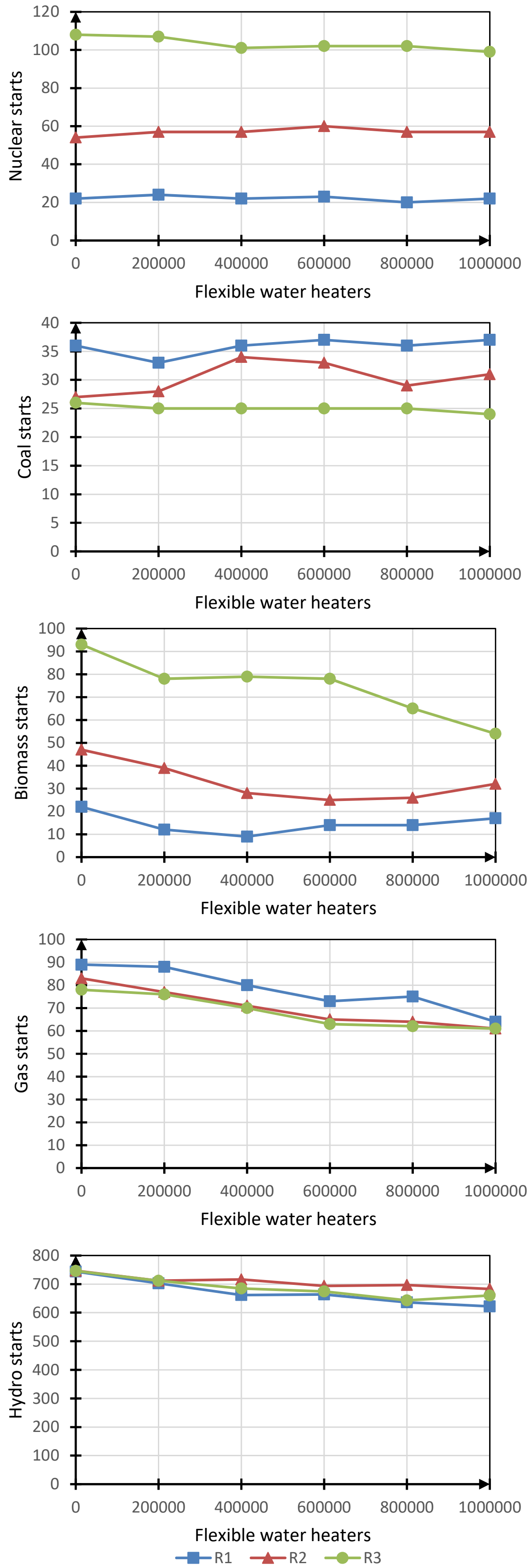
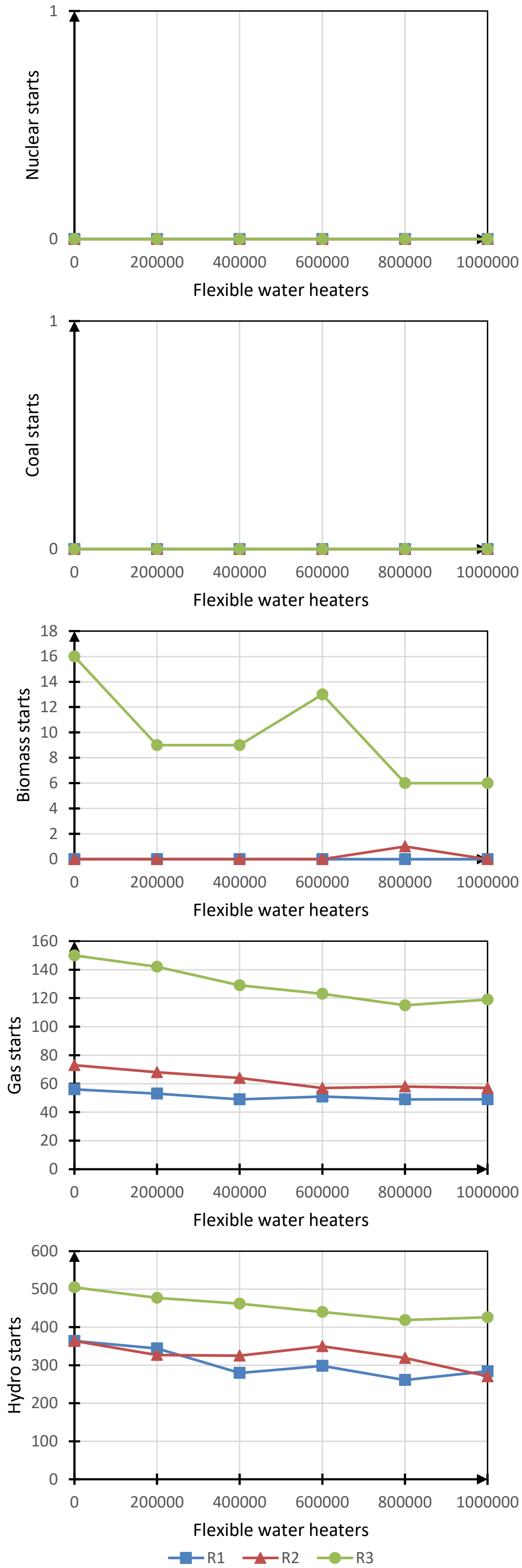


Figure A.2: Parametric analysis: power plants start-ups per fuel (water heaters)

(a) Non-flexible



(b) Non-flexible



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