École polytechnique de Louvain

The Walloon residential sector : Which energy system for today and tomorrow's low carbon future ?

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Abstract

At a time when the residential sector is in full swing following the new pact announced by the EU (the Green Deal), it seems appropriate to analyse the different energy possibilities of today and tomorrow residential sector. By 2050, the household segment will have to achieve carbon neutrality in terms of net CO2 emissions. An hour-based model is used to optimise the total cost of each energy system per dwelling on an annual basis. Throughout these results, we have investigated the various energy system possibilities, including renovation, the integration of renewable energy and different storage solutions. The further approach is focused on the cost-effective competitiveness of energy districts compared to the single house, both today and in a low carbon future. Large-scale thermal storage units combined by heat electrification appears to be a key player in the energy transition.

Acknowledgements

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Finally, we would not thank the Corona-virus, which our Skype relationship, counted in thousands of hours, could have been resolved to a simply physical interaction, without its existence.

Contents

Abbreviations

A2A	Air-to-Air
A2W	Air-to-Water
CHP	Combined Heat and Power
COP	Coefficient Of Performance
DHN	District Heating Network
DNI	Direct Normal Irradiance
ES	EnergyScope TD
EUD	End Use Demand
EUTs	End-use types
FC	Fuel Cells
FEC	Final Energy Consumption
FIT	Feed-in Tariff
G2W	Ground-to-Water
GHI	Global Horizontal Radiation
GHP	Gas Heat Pump
GWP	Global Warming Potential
HP	Heat Pump
HP$_{elec}$	Electrical Heat Pump
HW	Hot Water
KPI	Key Performance Indicators
kWth	thermal-Kilowatt
LCoE	Levelized Cost Of Energy
LCSE	Levelized Cost Of Saved Energy
LP	Linear Programming
MILP	Mixed Integer Linear Programming
OPEX	Operational expenditures
PT	Prosumer Tariff
PV	Photovoltaic
RE	Renewable Energy
ROI	Return On Investment
SC	Solar Collectors
SH	Space Heating
TD	Typical Day
TS	Thermal Storage

Chapter 1

Introduction

The European Green Deal aims at reaching carbon neutrality in 2050. Achieving these energy and climate goals in time represent a major challenge. The residential sector accounting for 25% of the final energy demand will be a key player in the energy transition.

It is a complex problem that can be handled in three different ways : by increasing the energy efficiency of the existing building stock (renovations), by supplying it with renewable energy through a decentralised organisation (single house) or a centralised system (integrated neighbourhood).

Either way, it will require a complete transformation of the existing energy system. The supply and management of these new systems will take place through a mix of various technological solutions in order to deal with the intermittent nature of Renewable Energy (RE) production.

This study first focuses on the optimisation of these energy systems and encompasses both the decentralized and centralized residential organisations. This is done for today (2020) and tomorrow (2050) respectively following economical and ecological criteria.

It then compares these solutions and suggests the optimal low-carbon energy strategy, according to the neighbourhood type.

Assuming the future Walloon political framework, we investigate the potential of such energy systems measures and to what extent these can influence the low carbon requirements.

Chapter 2

Context

The residential energy demand is twofold. It comprises of a heat demand and an electricity demand. Although heat is the main energy demand with 75 % of the total demand (electricity the remaining), carbon neutrality of the residential sector concerns both energy layers (electricity and heat supplies).

However, several studies found in today's scientific literature concentrate their scope solely on different heating solutions at a residential level for a low-carbon society. O. Gudmundsson and co. [14] focus on the competitiveness between district and individual heating whilst H. Vandevyvere, G. Reynders and co. from EnergyVille [35] examine the trade-off between retrofit, decentralized energy production and the use of district heating networks.

In both cases, they only focus once again on the heating side of the residential demand. To achieve this, they base their studies on standard predetermined heat systems and do not optimise them as a whole.
However, this global problem needs to be solved in a global way. A more holistic energy system will be necessary to solve this complex situation, by considering a multi-energy system (electricity and heat) into the residential centralised energy management.

Our study follows a bottom-up approach. The focus is first set on optimizing the energy system design by integrating both energy layers and confronting the different energy solutions.
Up to now, no hour-based multi-energy model has been adapted yet at both scales. With this in mind, the following in-depth study will focus not only on financial aspect, but also on multiple possible technology synergies at both scale level.

The model

To complete this study, we have used a model called EnergyScope TD (ES) which is an academic and open-source model developed by EPFL in collaboration with UCLouvain and Imperial College. ES is multi-energy, allowing the modelling of heat, electricity and mobility. It is then possible to plan a future energy system that can benefit from the synergies of these different layers. This model has been used so far for national energy planning purposes and has already been applied to

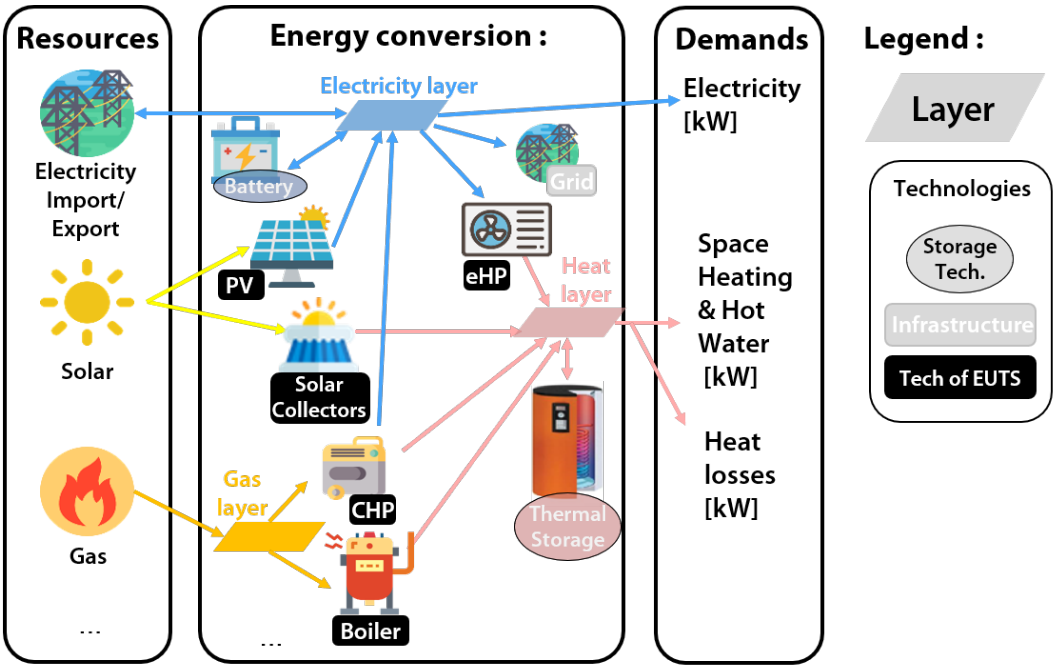

Figure 2.1: Example of an energy system modelling in the case of a household/neighbourhood. 3 resources, 8 technologies (which involve 2 storage technologies and 1 infrastructure) and 3 EUDs (of which 1 losses) are hereby considered. Abbreviations : Electrical Heat Pump (HP_{elec}), Photovoltaic (PV), Combined Heat and Power (CHP). This very similar graph was inspired by the Belgian national case [19].

the cases of Switzerland and Belgium. Its aim is simple: to satisfy the (known) energy demand at any time of the year (according to its also known profile), while minimising the total energy cost. In practice and for the purpose of this research, we will mainly use the End Use Demand (EUD) and not Final Energy Consumption (FEC). To illustrate, the FEC is the quantity of gas consumed by the boiler while the EUD is the quantity of heat produced by this boiler to satisfy the consumer needs.
The inputs of the model therefore correspond to the EUD of each component, i.e. heat and electricity and heat is itself subdivided into 2 End-use types (EUTs) : Space Heating (SH) and Hot Water (HW). A conceptual example of the energy system modelling structure has been illustrated on the Figure 2.1.

The description comes straight from the national scale EnergyScope model [19] and has slightly been adapted to the single house/neighbourhood case.

So, the system is divided into three parts: resources, energy conversion (production and storage) and demand.

- 3 resources are here presented : electricity, solar energy and natural gas (NG).
- The energy system uses all the energy conversion technologies to link resources with the EUD. In fact, solar energy or natural gas can't directly supply the heat demand. They need to be converted using technologies such as a boiler

or thermal solar to satisfy their EUT layer (e.g the heat layer).

- The EUDs are electricity, space heating and hot water (combined in a single heat demand).

Layers are defined as all the input and output elements in the system that need must be balanced at each time period (hour of the year). They include Resources and EUTs.

As an example, the electricity layer must be always balanced at any time, meaning that the production and storage must equal the consumption and losses. These layers are connected to each other by different technologies. There are three categories of technologies : EUTs, storage and infrastructure:

- A technology of End-Use Type (EUT) can convert the energy (e.g. a fuel resource) from one layer to a EUT layer, such as a unit that converts NG into heat and electricity.
- A storage technology converts energy from a layer to the same one, such as Thermal Storage (TS) that stores and provides heat. In the Figure 2.1, there are two storage technologies: TS for heat and lithium battery for electricity.
- An infrastructure technology regroups the remaining technologies in particular grids, such as the power grid and district heating networks (DHNs). In this ES version (residential sector), other infrastructure technologies (linking non end-use layers) have been considered but never been observed in the results, (e.g. methane production from wood gasification or hydrogen production from methane reforming). They are therefore not included in the last illustration (Figure 2.1).

Finally, this model could be developed and run using the AMPL™ solver. The latest version of the ES model (residential sector only) is available on the GitHub repository[1].

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[1] `https://github.com/brieucboonen/Urban_EnergyScope_2020`

Structure

The document is structured as follows.

Chapter 3, Methodology : details the hypothesis, modifications and improvements brought to the EnergyScope model in order to provide the most realistic picture as possible, these for both schemes (single house and integrated neighbourhoods).

The next two chapters look at the different optimal energy system designs in an environmental and economical point of view. Through hourly approach, they will highlight the promising technologies in the future energy systems.

Chapter 4, Case study : Single house : analyses the most optimal energy system and verifies its solution with various types of houses.

Chapter 5, Case study : Integrated neighbourhoods, analyses the most optimal energy system at the scope of a multi-energy community and compares the latter with multiple neighbourhoods in various environments on the optimal design.

Chapter 6, Energy Transition : compares the two schemes and observes their different synergy and interaction between technologies and infrastructures established today. We will end our analysis with an additional comparison in 2050 of the two entities, considering the constraint of 0 net CO2 emissions.

To conclude, we will summarise and discuss the multiple solutions presented in regards to the various trends and assumptions expressed throughout this report.

Chapter 3

Methodology

3.1 Adapting to a house

The model has been modified and improved to reach a higher level of complexity. The annual energy demand has been reviewed and modified to fit perfectly the one of a house. In addition, the hourly demand profiles (time series) are rougher with more heterogeneous peaks. In terms of sets of technologies, a household has also limited access to and obey to specific energy related and political laws.

To study the case of a household, certain assumptions and constraints need to be adapted to make the model representative of a house energy system. These adjustments have been made both in terms of input data and in the programming of the model itself, explained below.

3.1.1 Overview of a house energy system

The house model considers new technologies which are listed in the Table 3.1 in next subsection. A short description of each technology is given below in order to deepen the knowledge of each technology.

RE Technologies

PV

Photovoltaic panels, by using solar energy (especially Global Horizontal Radiation (GHI), which combines direct and indirect irradiance), produce direct current electricity. So far, photovoltaics is getting more and more attractive. Considering the current political context, the ES model considers a PV installation to be profitable over 6.3 years. This result is validated and discussed in the Appendix **??**.

$\mathbf{HP}_{elec}$

A Heat Pump (HP) is a device that transfers heat energy from a source of heat to a so called heat sink [29]. They be air-sourced or ground-sourced and can provide heat in the form of water or air. Three types of technologies are considered in the model: the **Air-to-Air (A2A)**, **Air-to-Water (A2W)** and the **Ground-to-Water (G2W)** heat pumps. The first one heats the outside air. As a consequence, the air flow

goes directly from the cold source (outside air) to the warm source (rooms of the household). This technology is only available for electrical heat pump.
The second one, acts like through an inverse refrigerator thermodynamic cycle that can be either powered by electricity **or natural gas** . The thermal energy is moved in the opposite direction of spontaneous heat transfer, absorbing heat from a cold space and releasing it to a warmer one, through heat exchanger. The water heated up at 55° at the output, will satisfy the needs for heating as well as sanitary facilities.
The G2W technology uses the same principle as above except that the heat sink comes from the ground instead of the outside air (A2W).

Solar Collectors (SC)

Thermal solar panels are composed of small tubes carrying a heat transfer fluid. This is heated by solar energy (exclusively Direct Normal Irradiance (DNI)), and its purpose is to transfer its heat to a unit in a storage water tank.

Fossil-based Technologies

Gas Heat Pump (GHP)

The Air-to-Water principle of the technology has been explained in the section HP_{elec} above. Gas adsorption as absorption heat pumps are part of the so-called “thermally driven heat pumps”, which use gas both for source of heat to be upgraded and energy source to drive the heat pump process. The heat from gas is typically produced with a full premix burner. Nevertheless, here’s the adsorption/absorption split.
The only difference resides in the fact that one concerns solid-sorption (adsorption) such as active charcoal, silical gel or zeolite (such as the Viessmann and Vaillant appliances) and the other applies liquid-sorption (ammonia).
On the small gas heat pump market, absorption technology is more available and accessible.

CHP

Combined heat and power (CHP) is a unit that produces both electricity and useful heat simultaneously. Different technologies exist : heat engines, power stations both gas engines. The valorisation of the otherwise-wasted heat leads to a very efficient technology at the neighbourhood level. Micro-CHPs now exist at a decentralized scale and are therefore considered in our simulation tool.

Fuel Cells (FC)

A fuel cell allows the direct conversion of chemical combustion energy (oxidation-reduction) into electrical and heat energy. Its yield is more interesting than a co-generation unit but its cost is much more expensive.

Boiler

The purpose of the boiler is to directly heat (thanks to its fuel) the water that circulates in the hydraulic network . It has a relatively low price, which makes it particularly attractive. Its yield today is close to 92%. Hydrogen fuel cells are also available on the market, but they are even more expensive and therefore will not be included in any of our further analyses.

Storage Technologies

Lithium Battery

Unit which ables to store electricity. Although its interest with pv production, the pricing per kWh remains very expensive in 2020. This one will therefore be interesting as a shot term storage solution in the years to come, but not yet at the moment.

Thermal Storage

Thermal storage allows to store heat in hot water heated at 55°. Different storage technologies exist. The water can either be stored in water drums/tanks for a daily use. It can also, be for larger solutions that allow the storage of heat for longer periods of time.
Seasonal storage is mainly intended for large-scale use where water heated is stored in large pits dug into the ground.
Daily storage are destined to be daily used. Smaller scale storages rather exist in metal canisters, simply larger versions of the typical home solutions.

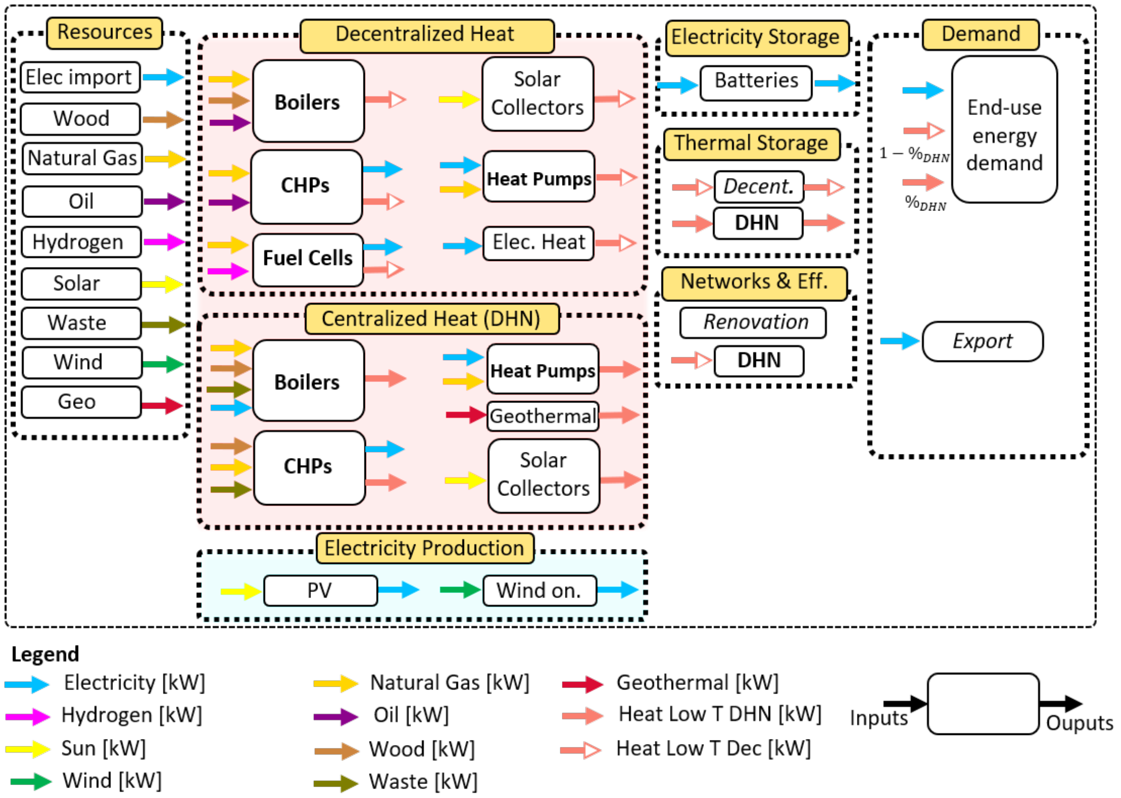

Figure 3.1: The table is divided into four categories. From left to right we have : resources, production, storage infrastructure and Demand. **Bold technology** is a group of multiple technologies with various inputs. (e.g. **Boilers**, encompasses gas boiler, wood boiler, oil boiler). *Decent.* represents the thermal storage unit provided for each household. *Renovation* is considered as an infrastructure which allows the household to reduce its heat demand. **DHN infrastructure** encompasses all components of a DHN network. *Electricity Export* to the grid, is available for households and integrated neighbourhoods when production is higher than the demand.

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[1] electrical HP

[2] gas HP

[3] gas CHP

[4] oil CHP

Table 3.1: **Year 2020** - Belgian Housescale ES data

	investment	**maintenance**	**gwp$_{constr}$**	**lifetime**	**minimum size**
Production :	$[€_{2015}/kW_{th}]$	$[€_{2015}/kW_{th}/y]$	$[kgCO_2 - eq/kW_{th}]$	$[y]$	$[kW]$
PV	1130	13	2081	25	0.25
eHP$_{A2A}$[1]	425	27	165	12	2
eHP$_{A2W}$	848	28	165	20	8
eHP$_{G2W}$	1300	28	165	20	10
gHP$_{A2W}$[2]	600	13	382	20	18
gHP$_{G2W}$	867	13	382	20	18
gCHP[3]	1408	93	1024	20	5
oCHP[4]	1305	82	1024	20	5
gFC	1408	667	2193	20	1.2
h$_2$FC	15714	1000	2193	20	0.7
gBoiler	310	20.5	21	20	11
wBoiler	680	50	21	20	10
oBoiler	393	16	21	20	15
SC	809	16	221	25	0.7
Elec. Heat	967	8	1.47	30	3
Storage :	$[e_{2015}/kWh_{th}]$	$[e_{2015}/kWh_{th}/y]$	$[kgCO_2 - eq/kWh_{th}]$	$[y]$	$[kWh]$
Lithium Battery	730	0.6	61	15	2.2
Thermal Storage	130	2	0	30	0.5

All cost and lifetime data were taken from the Danish Energy Agency public database [6]. To be noted, the investment cost includes the technology itself, its installation, and its auxiliary instruments cost. We consider the capacity factor (*The annual real energy output to the maximum possible energy output over the same period*) values do not vary, as most of the technologies being approximately at a mature stage. The minimum and maximum capacity installed (f_{min} and f_{max}) and respectively their f_{perc} values (the share of the energy demand, a technology can cover) were chosen given the size availability on today's market. The global warming potential values taken remain unchanged from the EnergyScope TD (ES) previous version;

3.1.2 Time-series

Time-series are normalised hourly profiles of the parameters that can vary during the year. The ones from our model have been in the most part adapted to a Belgian house and a new thermal method has been developed to better approximate the heating demand.
These time-series are of two types : meteorological parameters and energy demands.

All the meteorological time-series correspond to the same time and place : Uccle Brussels, year 2005. They are mostly based on the same data-set provided by the Royal Observatory of Belgium. This provides a high level of consistency between energy production and consumption. The only exception made is the electricity profile that is typically less climate sensible and as a consequence, less of an issue.

Irradiation profiles

The solar resource is described with irradiance. In fact, PV depends on the GHI parameter on Figure 3.2, while Solar Collectors (SC) rely exclusively on DNI[9].

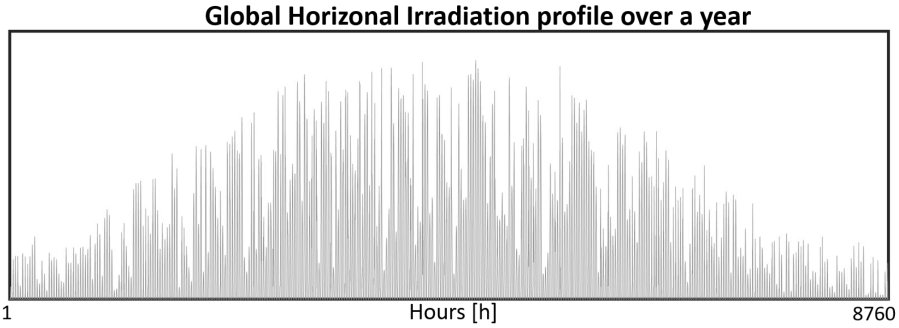

Figure 3.2: Global Horizontal Irradiance (GHI) time series over the year

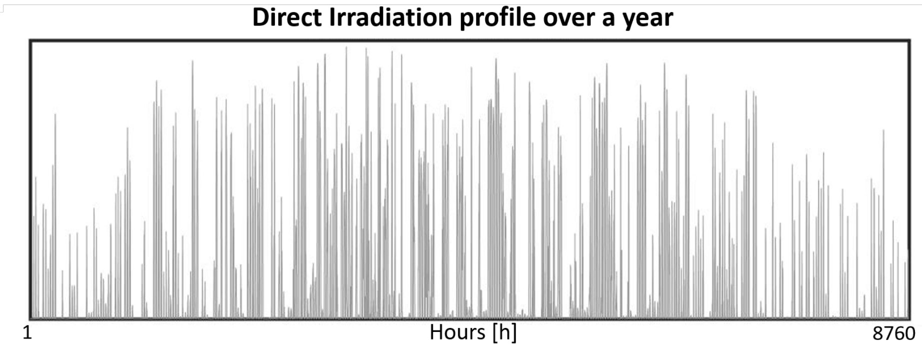

Figure 3.3: Direct Normal Irradiance (DNI) time series over the year.

Temperature profiles

As we can see on Figure 3.4, temperature profiles are also of interest for some technology efficiencies, in order to constantly be able to supply the heating EUD. Once again, both profiles come from this same Uccle data-set.
The first, the exterior air temperature profile directly corresponds to the bulk temperature.
The other profile represents the ground temperature at four meters deep. This profile was extracted from the first one by accounting for the soil's thermal inertia and resulting in a much more constant temperature. This approach is commented in the Appendix A.3.

Electricity demand

The electricity demand of a Belgian household comes from the Flemish Regulator for Electricity and Gas (VREG) [34]. This profile from year 2019 is a generic profile based on average historical, residential measurement data. They have been displayed on the Figure 3.5. In order to observe the household electricity profile over the year,

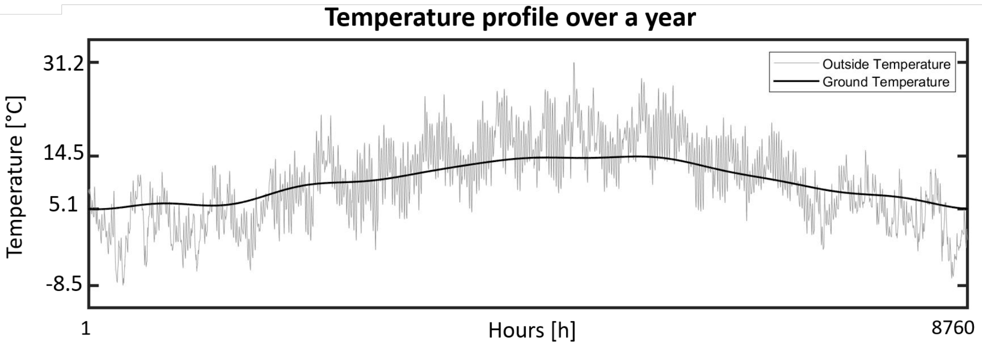

Figure 3.4: Exterior temperatures over the year. The light grey time-series corresponds to the outside air temperature and the black one to the ground temperature 4m deep.

the total electricity demand needs to be multiplied by the electricity demand time-serie. As a consequence, the integral of the plot will return back the total electricity demand.

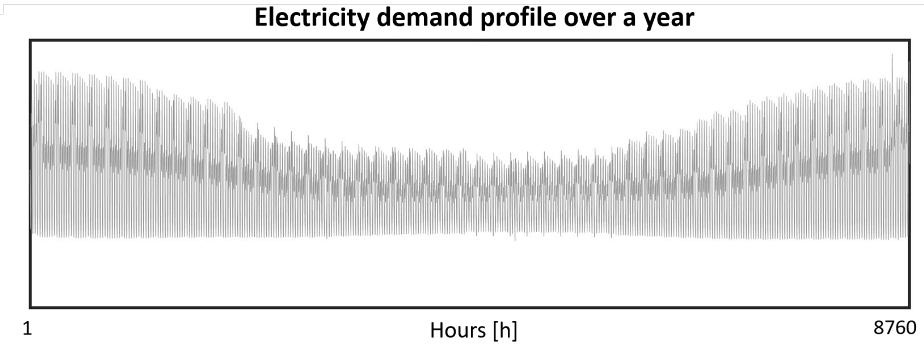

Figure 3.5: Residential electricity end use demand over the year

Heating demand

The heat demand of a household is twofold and is therefore treated separately ; the Hot Water (HW) demand and the space heating Space Heating (SH) demand.

Hot water is the heat demand for the water used for domestic applications. Most commonly in the kitchen and in the bathroom, this water is typically heated up to 55°C. In our model this demand is considered constant. No time-series is thus required. Although not completely true, this assumption has little to no impact on the total heating demand and it has even less impact on the end solution.
This for two reasons : firstly the yearly HW demand is much smaller (11.4 % of the final energy consumption) than the SH (75.5 % of the final energy consumption) [13] and secondly the system is designed for the worst case (winter) where the HW share in the heat demand will be negligible in contrast to the SH share.

Space heating (as its name suggests) is the heat demand used to heat the house and maintain the interior temperature at a constant temperature, (considered at 19.5°C).

Heating degree hours (HDH) was the method previously used to determine the SH time-series [2]. Within this model, the demand was considered proportional to the difference between the fluctuating hourly temperature and a constant base temperature - the outside temperature above which a building needs no heating. The heat demand profile thus had the same form as the one from the outside temperature.

HDH made different assumptions, no more valid for the house. At first, heat requirements are not linear with temperature. Moreover, it should be dependent on several other factors (previously neglected) such as the thermal mass of a building or the radiation it receives from the sun. As a result the heating demand profile does not resemble the characteristic residential demand with a morning peak and a daytime lump.

To better approach the space heating requirements of a household, a new simplified model based on heat exchange has been developed. More precisely, heat convection physical principles is applied to the model [8].

Adopting the electrical analogy, we have represented the one-dimensional conduction through the exterior walls whilst taking into account their thermal capacities through resistances and lumped capacitors. Those represent respectively the heat dissipation and the temperature storage, show in the Figure **??**.

The modelled house consists of a simple square room without windows where the only thermal mass are exterior walls. Thermal exchanges through sun, people or appliances in the building are not integrated into this approach.
Every building component (wall, heating zone, etc.) is represented as a node in which the energy conservation law is applied. The transient energy balance at the central node in the wall that takes the thermal mass into account is written as following :

$$C_w \frac{dT_w}{dt} = \dot{q_w}$$

The exterior temperature, presented above, is known and the interior one is fixed at a temperature of 19.5°C. In order to resemble true space heating habits, the heat flux brought into the system, has been forced to be equal to zero between the hours h=11pm and 4am. Although not considered in the model, the same methodology could have been applied to a building's cooling demand.

The result with this thermal model seems like real space heating profiles and hence preferred to simulate heating energy consumption in buildings. The annual space heating demand is displayed on the Figure 3.7.

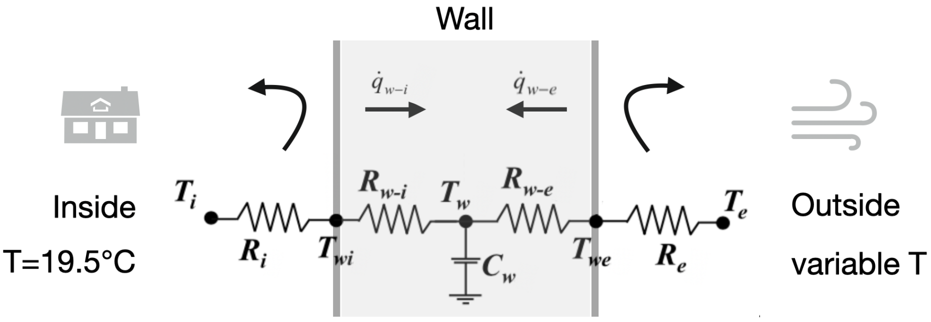

Figure 3.6: Simplified illustration of the one dimensional heat flow q across the outside wall of a building. The thermal mass represented by the lumped capacitor C_w is considered at the center of the wall and is at the temperature T_w. The conduction resistances R_{w-e} and R_{w-i} are equal and situated on either side. The resistances at either end are related to the convection heat transfer.

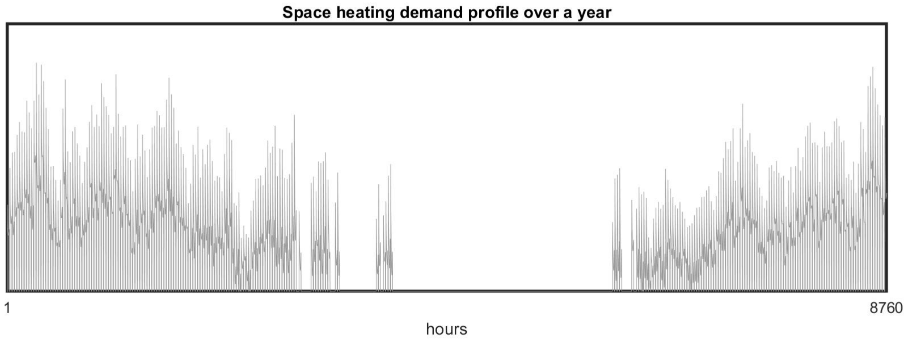

Figure 3.7: Residential space heating end use demand over the year

A Typical Day (TD) approach

For ease and fast calculations of the processor, a typical day has been assigned to each day. A whole year can be resumed by approximately 12 different typical days (with low margin of error). [19, 20]. In fact, 12 days of the year will be designated as typical reference days. The others will be assigned to one of them according to their similarities. In this case, three different time series criteria (such as the electricity and the heat end use demand and the GHI) have been defined with the same weighting on the pattern of typical days.

1 typical day

The 3 profiles represented on the Figure 3.8 fit perfectly the notion of TD. As observed, each day plotted refers to the selected TD . Of course, the same days are linked to the identical typical day for each time-serie considered in the generation process. An important remark to consider is the divergence of the TD of the electricity, compared to all the other days.
In fact, a profile can drift apart from its TD curve in a particular daily profile. But in compensation, in the two other time-series criteria, its profile will closely match with the proper TD. As intended, the sun doesn't show up during the night, and its value equals 0. For all households, the heating system is considered to be turned off during the night (from 12pm until 4pm), and will switch on from 5, to supply the

morning heat peak demand.

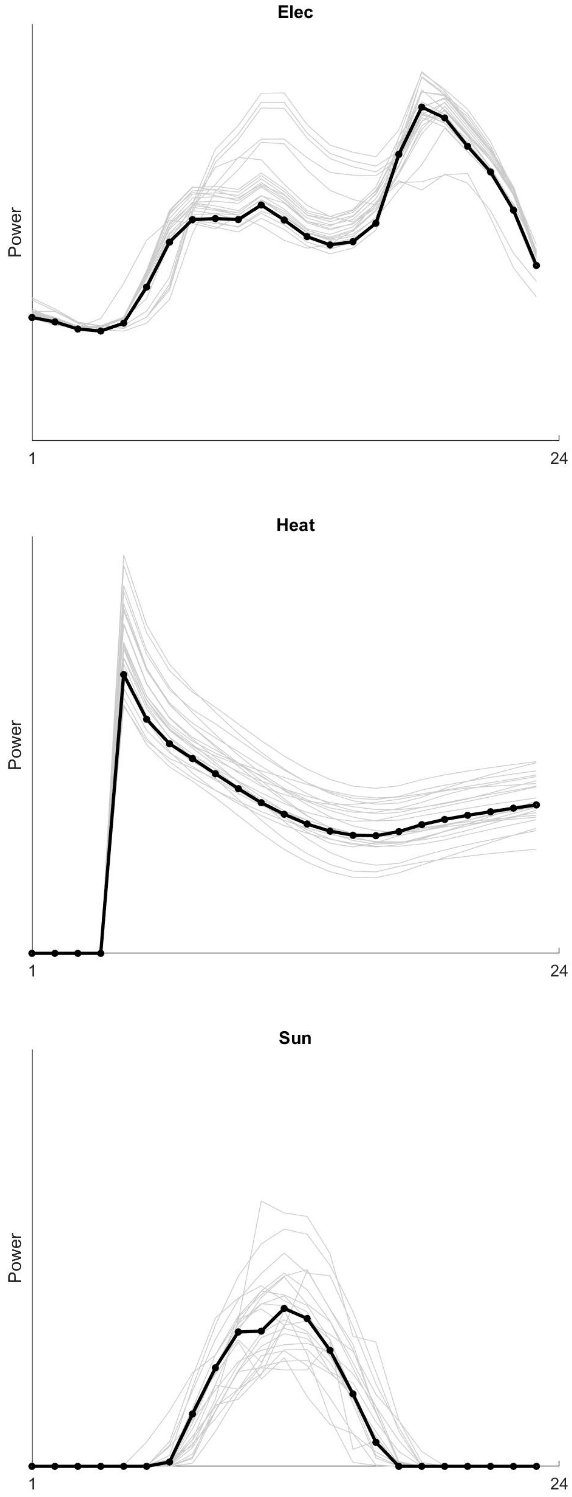

Figure 3.8: A cluster of 11 days (light grey line), represented by 1 TD (black dotted line). The x axis represents the hour of the day.

Application with 12 typical days

While the previous section explain the application of a typical day, an overview of the 12 typical days on a yearly basis is illustrated on the figure 3.9.
The 12 TDs can be gathered as such :

- 3 cold winter days (TDs 10, 11 and 12). with very high heat electricity demand. Nevertheless, TD-10 is distinguished by its weather with a few clear skies, but cloudy.
- 5 warm summer days (TDs 4, 5, 6, 7 and 8). with no space heating demand (only hot water). TD-4 and TD-6 are very sunny, with lower electricity demand where TD-5 and TD-8 are partially cloudy. TD-7 is nearly entirely cloudy, but both with medium electricity demand.
- 2 hot intra-season days (TDs 2 and 3). TD-2 is partially clouded and TD-3 is a sunny day but both with mild temperature.
- 2 cold intra-season days (TDs 1 and 9). TD-1 and TD-9 are both cold but TD-1 is clouded while TD-9 is partially sunny.

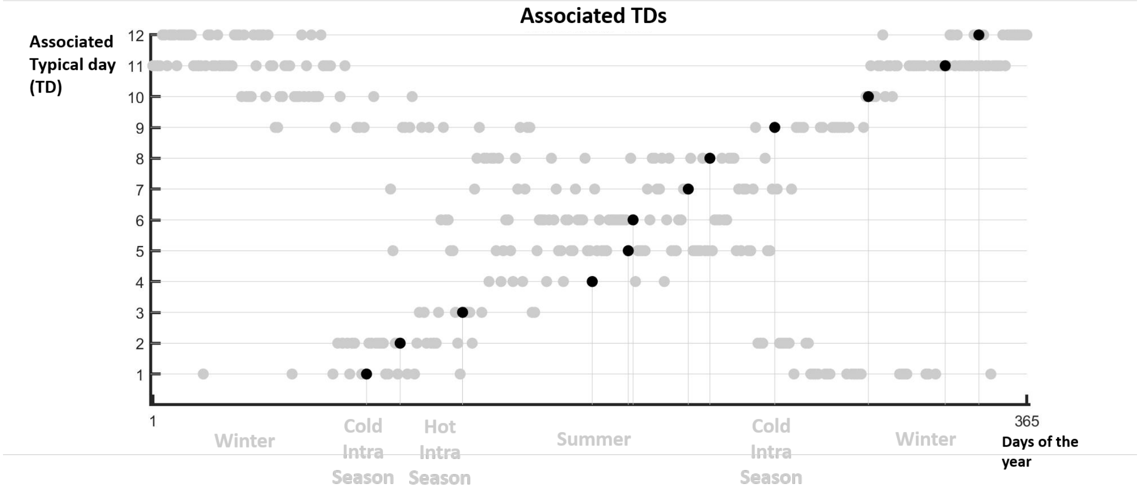

Figure 3.9: Associations between the days of the year and their referenced typical day. Black points represent the selected typical days for each cluster. Grey points represent the day of the year.

3.1.3 Wallonia Context

Auto-consumption rate

Part of the prosumer[5]'s production can directly be consumed to fulfill its own energy-needs, and the rest can be either stored or injected into the grid for future use. This is called auto-consumption. In others words, it is the ratio between the energy production minus the electricity export over the entire production. On a yearly basis, the mean auto-consumption rate of prosumers is typically around 30%.

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[5] Physical or moral entity able to produce and consume electricity (e.g. having pv at home)

This means that 30% of the electricity produced through PV is directly consumed by the household itself.

Auto-sufficiency rate

This indicator shows the percentage of independence of the prosumer from the grid. This is 100% achieved when no energy resource is imported from the grid. By definition, it represents the ratio of the total energetic demand minus the energy import over the total energy demand.

Grid policies

The pricing applied to the power exchanged between the individual and the utility grid, in a now bi-directional manner, can be done in different ways. Two methods exists and named net-metering and feed-in tariff.

Net-Metering

Until May 2020[6], the prosumer is able to inject his electricity into the network and use it as a free infinite lossless battery. Indeed, no injection tariff is applied whilst its cost is non negligible for the grid operator. In practice, the existing electricity meters count forward when electricity is imported from the grid and change direction when it is exported out of the household. The annual cost charged to the prosumer is the positive difference between its annual consumption and its annual production.[7].

As a consequence, prosumers don't contribute entirely to the financing of the network and the maintenance to the extent of the use they make of it. This policy profits tremendously to the prosumer, but is, with time, unfortunately, no longer viable to the supplier.

Feed-in Tariff

On the government's measures, a new approach has been established in order to rebalance the energy-market for each consumer to be on an equal footing. From May 2020[8], prosumers in Wallonia (when using the grid for "storage") will be compelled to contribute to the cost of transmission and distribution losses on the grid and thus to the maintenance and development of the electricity grid. This charge will depend on the type of the electricity meter a household dispose of :

1. **Dual electric meters - Smart meters**
   It records separately the electricity withdraw and the injection. In fact, with this new charge policy and meter, it spurs the prosumer to directly consume the energy they produce at the same time, and reduce their reliance on grid. The replacing cost for this type of meter is invoiced at 150€ at the prosumer's expense[9].

---

[6] Planned to be postponed but in the context of the Covid-19, no exact deferral date has been given.

[7] No capital gains can be granted, if production is larger than consumption

[8] see footnote n°6

[9] This substantial cost has not been considered in the current ES model

2. **Mono electric meters**
   A basic meter that measures only the net amount of electricity withdrawn from the grid.

Prosumer tariff

This new political framework (illustrated on the Figure 3.10) is not very advantageous for those who don't auto consume during the day. In these circumstances, Wallonia decided to introduce a prosumer tariff based on the net developable electric power from the production facility (essentially PV). In that context, the mono electric meters can still be installed and the principle of the counter turning backwards is maintained but this time, at a fixed annual fee.

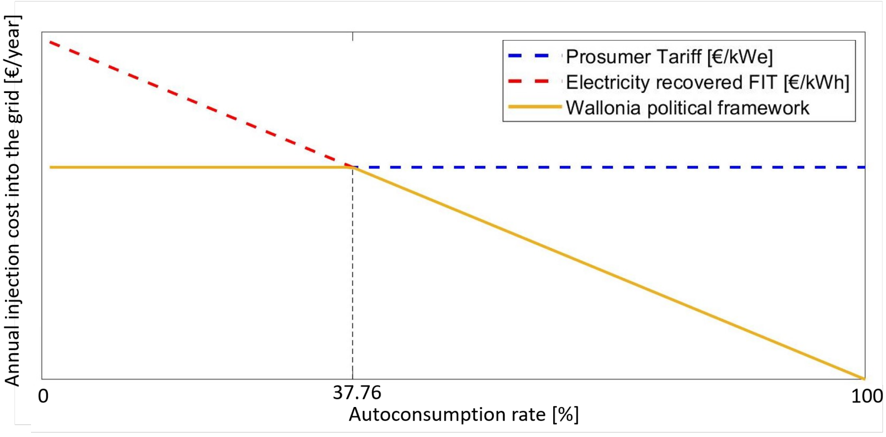

Figure 3.10: Annual cost charged to the prosumer for export and later recover from grid electricity in the Wallonia grid policies. The x axis shows the autoconsumption rate, while the y axis represents the total injection cost. Below an autoconsumption rate of 37.76 %, the prosumer tariff would be favored for the prosumer (the least expensive solution). Otherwise, the Feed in Tariff is opted for.

Depending on the auto-consumption rate of a household, one solution is more economically favorable than the other. The prosumer tariff has been calculated by the CWaPE which supposed an auto-consumption rate of 37,76% [28].
At this auto-consumption rate, the amount charged is identical between the fixed fee per power unit and the injection tariff per energy re-imported.

In contrast, if the auto-consumption rate of a household is lower, the prosumer tariff is favored. In the opposite case, the transport and distribution cost per kWh is the most attractive. This has been established in order to always minimize the prosumer's cost, following the new regulation.

The pricing for both methods [28], evaluated in 2020 available in the Table 3.2 :

- The distribution tariff of withdrawn is equal to 0,091597 €/kWh and the rebilling rate for transport costs to 0,04588 €/kWh. As a total each kWh cost 0.13747 [€] to be recovered from the grid.

- A fix prosumer tariff of 77.86 €/kWe (per net developpable electric power)

Table 3.2: **Political Framework Year 2020** - Belgian Housescale ES data

	Injection costs	**Fixed annual fee**
	[$€_{2020}$ /kWh]	[$€/kWe/y$]
Prosumer fee :		
Electricity recovered FIT	0.137	0
Prosumer Tariff	0	77.86

Constraints

As explained above, some constraints had to be adjusted, depending on the specific household energy policy context.

$\mathbf{C_{tot}}$ represents the total costs, which is the objective function to be minimised. It relies on τ the investment cost annualization factor (calculated based on the interest rate ($\mathbf{i_{rate}}$) and the technology lifetime (**lifetime**)), $\mathbf{C_{inv}}$, the total investment cost, $\mathbf{C_{maint}}$, the total annual maintenance cost, for all technologies, and $\mathbf{C_{op}}$, the operation cost of all resources. $\mathbf{F}$ represents the power capacity of each installed technology. A $\mathbf{Prosumer_{tariff}}$ is also involved, in case the auto-consumption rate is lower than the threshold defined by the CWaPE (37.76%).

$$\min \; \mathbf{C_{tot}} = \sum_{j \in TECH} \Big(\tau(j)(\mathbf{C_{inv}}(j) + \mathbf{C_{maint}}(j) \Big) + \sum_{i \in RES} \mathbf{C_{op}}(i) + \mathbf{Prosumer_{tariff}} \tag{3.1}$$

$$\text{s.t.} \;\; \tau(j) = \frac{i_{rate}(i_{rate}+1)^{lifetime(j)}}{(i_{rate}+1)^{lifetime(j)} - 1} \qquad \forall j \in TECH \tag{3.2}$$

$$\mathbf{C_{inv}}(j) = c_{inv}(j)\mathbf{F}(j) \qquad \forall j \in TECH \tag{3.3}$$

$$\mathbf{C_{maint}}(j) = c_{maint}(j)\mathbf{F}(j) \qquad \forall j \in TECH \tag{3.4}$$

$$\mathbf{C_{op}}(i) = \sum_{t \in T | \{h,td\} \in T\_H\_TD(t)} c_{op}(i)\mathbf{F_t}(i,h,td)t_{op}(h,td) \qquad \forall i \in RES \tag{3.5}$$

$$\mathbf{Prosumer_{tariff}} = \mathbf{F}(PV) * Tariff\ per\ kWe \tag{3.6}$$

The last constraint implies the possibility to re-import at a Feed-in Tariff (FIT) as long as the quantity re-imported is less than the quantity of electricity exported. This equation will always take precedence over the import of electricity at full price since its "low-cost" price.

$$\sum_{t \in T | \{h,td\} \in T\_H\_TD(t)} \Big(\mathbf{F_t}(ELECTRICITY\ REIMPORTED\ FIT, h, td) * \mathbf{t_{op}}(h, td) \Big) \tag{3.7}$$

$$<= \sum_{t \in T | \{h,td\} \in T\_H\_TD(t)} \Big(\mathbf{F_t}(ELECTRICITY\ EXPORT, h, td) * \mathbf{t_{op}}(h, td) \Big) \tag{3.8}$$

3.1.4 Incentives

Incentives play a non-negligible part in households energy related decisions and can be more often than not a decider between one technology and another. In the national version of ES they were not taken into account [19]. But given the new consumer focused approach specific to our thesis, they are now of great importance and added into the energy system's total cost minimisation.

These incentives exist in all shapes and forms and can in some cases be very complex to take into account. The focus of our work is not political nor administrative and therefore set on the main technology related ones.
Two types of incentives are considered : fixed revenue and variable revenue. The former is typically applied to the purchase of a production unit whilst the latter is mostly suitable to renovations.

Walloon incentives

The Walloon region has decided to set up incentives. This is intended to influence the choice of households and encourage them to opt for certain pricey technologies by paying less. Renovation and some production units are concerned.

Table 3.3: **Wallonia Incentives Year 2020 [37]**. The production and storage technologies are expressed per unit installed whereas renovation is per kWh$_{saved}$

	Fix Revenue	**Variable revenue**
	[€$_{2020}/unit$]	[€$/kWh_{saved}/year$]
Production :		
EHP	$n \cdot 1000$	0
GHP	$n \cdot 1000$	0
Wood boiler	$n \cdot 1000$	0
Wood stove	$n \cdot 500$	0
Storage :		
Thermal Solar	$n \cdot 750$	0
Reduction :		
Facade	0	$n \cdot 0.0075$
Roof	0	$n \cdot 0.0075$
Floor	0	$n \cdot 0.0075$
Window	0	$n \cdot 0.0075$

The amount of incentives received is function of the house's income. It is proportional according to the household's income range, between 1 and 6 (1 being the highest income and 6 the lowest) [37]. Nevertheless, no matter the incentive category, they can cover up to 70% of the total cost. The different technologies covered and their respective incentives are detailed in the Table 3.3.

Constraints

These different incentives have therefore been taken into account in the ES model and annualized.
In the case of technologies, the incentive received is multiplied by the investment cost annualization factor.

$$\min \ \mathbf{C_{tot}} = \sum_{j \in TECH} \Big(\tau(j)(\mathbf{C_{inv}}(j) - \mathbf{R_{inc}}(j)) + \mathbf{C_{maint}}(j) \Big) \tag{3.9}$$

$$- \sum_{k \in RENOV} \mathbf{R_{ren}}(k) + \sum_{i \in RES} \mathbf{C_{op}}(i) + \mathbf{Prosumer_{tariff}} \tag{3.10}$$

$$\text{s.t.} \ \ \tau(j) = \frac{i_{rate}(i_{rate}+1)^{lifetime(j)}}{(i_{rate}+1)^{lifetime(j)} - 1} \qquad \forall j \in TECH \tag{3.11}$$

$$\mathbf{R_{inc}}(j) <= \mathbf{c_{incfix}}(j) * \mathbf{X_{active}}(j) \qquad \forall j \in TECH \tag{3.12}$$

$$\mathbf{R_{inc}}(j) <= 0.7 * \mathbf{C_{inv}}(j) \qquad \forall j \in TECH \tag{3.13}$$

$$\mathbf{R_{ren}}(j) <= \mathbf{c_{incvar}}(j) * F(j) \qquad \forall j \in TECH \qquad 2005/06/28ve$$

$$\mathbf{R_{ren}}(j) <= 0.7 * \mathbf{C_{inv}}(j) \qquad \forall j \in TECH \tag{3.15}$$

3.2 Adapting to a neighbourhood

3.2.1 Adding neighbourhood technologies

The neighbourhood represents a cluster of several houses. These can include from a hundred houses up to several thousand. As a consequence, not only large-scale technologies might be installed, but also new technologies might be considered. With the economy of scale, these lead to more cost-effective technologies compared to their decentralized counterparts.

Typically three sizes of each production unit were taken into account : small (S), medium (M) and large (L).
Again, larger neighbourhoods lead to larger technologies and thus lower capacity installed production prices.
The following table summarizes the new technologies that are now considered with their key associated cost and performance parameters. The source of this dataset is the Technology Catalogue of the Danish Energy Agency [5]. When available in different sizes, only the medium sized technologies are displayed on the table 3.4.

Table 3.4: **Neighbourhood technologies** - 2020

		investment	**maintenance**	**gwp**$_{constr}$	**lifetime**	**min size**
Production :		$[€_{2015}/kW_{th}]$	$[€_{2015}/kW_{th}/y]$	$[kgCO_2-eq/kW_{th}]$	$[y]$	$[kW]$
	PV	1130	13	2081	25	0.25
	WT$_{HAWT}$	1120	14	623	30	2000
	WT$_{VAWT}$	3800	95	623	20	10
	Geothermal	1500	57	809	30	5000
e	HP$_{A2W}$	700	2	175	20	200
e	HP$_{G2W}$	800	2	175	20	200
g	HP$_{A2W\ ABS}$	213	3	382	20	80
g	HP$_{G2W\ ABS}$	388	3	382	20	80
g	HP$_{A2W\ ED}$	80	5	382	20	50
g	HP$_{G2W\ ED}$	360	5	382	20	50
g	CHP$_{TURB}$	1000	27	491	25	6250
g	CHP$_{ENG}$	950	10	30	25	1000
wo	CHP$_{TURB}$	945	42	165	25	14000
g	Boiler	60	2	12	25	500
wo	Boiler	690	33	29	25	5000
e	Boiler	70	1	2	20	5000
	SC	274	0.4	221	30	0.7
Storage :		$[e_{2015}/kWh_{th}]$	$[e_{2015}/kWh_{th}/y]$	$[kgCO_2-eq/kWh_{th}]$	$[y]$	$[kWh]$
Battery lithium		730	0.6	61	15	2.2
Daily storage		3.84	0.0086	0	40	40000
Seasonal storage		0.58	0.003	0	30	8000000

Some of these technologies are only available in certain resource-rich neighbourhoods. Namely wind turbines (WT) and geothermal can only be installed in neighbourhoods with respectively high winds and geothermal sources of 2-3 kms depth. Solar collectors (SC) can be installed at undercut price in neighbourhoods as panels are installed on the ground in long rows connected in series and no longer on roofs.

3.2.2 Time-series

A neighbourhood comes with an accessibility to more technologies and resources but also smoother EUDs.

Wind profile

The wind profile used in this model comes from the Belgian national ES model. It is a mean Belgian wind production profile (at a national scale) and now applied at the scope of a neighbourhood. It is thus a slightly optimistic assumption as wind production is a local production technology.

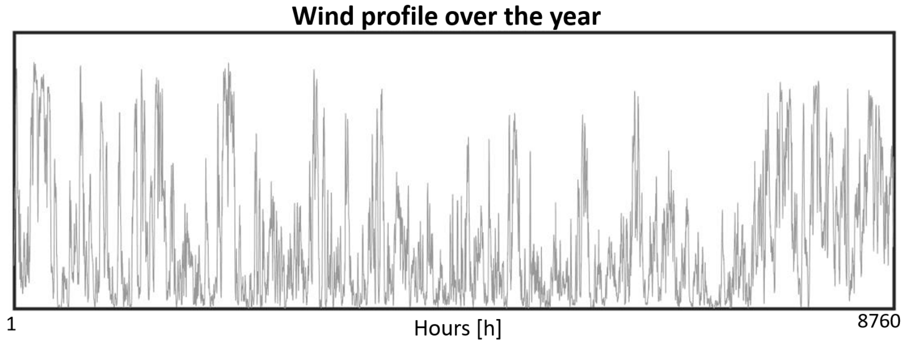

Figure 3.11: Wind power time series over the year

EUD profiles

A neighbourhood gathers multiple households, all with different lifestyles and habits. The aggregated demand profile has flatter profiles; ie. electric and space heating. These new neighbourhood EUD time-series are produced from a weighted average of different demands with the respective weights; one early (1), one average (2), one late (1). These new neighbourhood profiles are again normalised, considered independent of the number of houses and displayed in Fig 3.12.

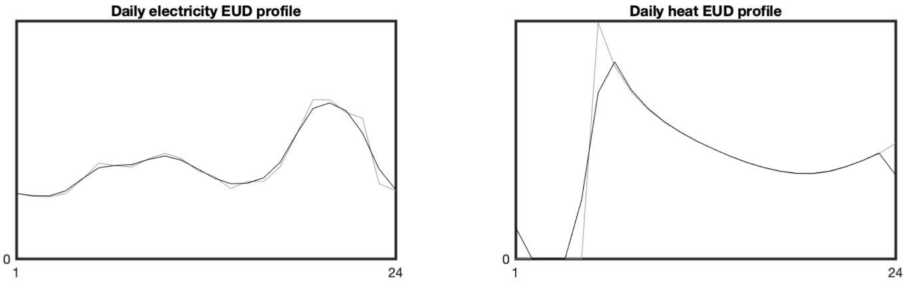

Figure 3.12: EUD profiles over 24 hours. The grey line represents the theoretical mean household demands and the black line represents the neighbourhoods profiles.

In both cases the new profile leads to lower peak demands and will thus require a lower production capacity per capita. The critical normalised maximum heat peak demand of the worst heating day is thus reduced by 15%.

Typical days

The typical days selected and used in the model remain identical. Wind being only available under certain conditions, is not considered in our reference neighbourhood, thus takes not part as a criteria in the TDs generation process. Its time-serie has thus no impact on the previously determined TDs.

3.2.3 DHN infrastructure

In order to produce in a centralised way and dispatch this energy to the household consumers, a complex network of pipes, pumping stations and installations are required. The cost of this DHN infrastructure had to be taken into account in this model. The chosen cost scheme is composed of three different components : the pipes and the multiple stations and substations.

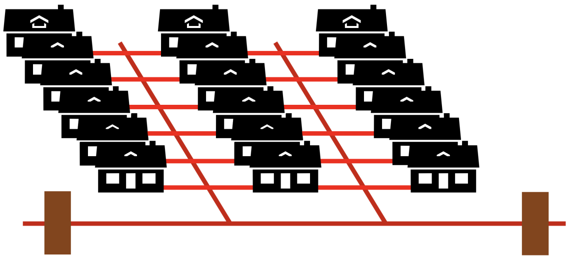

Figure 3.13: **The different components of a DHN infrastructure**
The red lines are the network lines and the connection lines are shown in orange. The stations in brown are supposed outside the neighbourhood and distribute the heat on a large scale. Finally, substations are considered to be installed in each (in black) house.

Cost

The pipes cost is split in two categories. On one hand, appears the so-called connection lines which link each household to the DHN. It is a fixed cost, only dependent on the number of houses in the neighbourhood [€/dwelling]. On the other hand, there are literally the network lines, defined by [€/m]. The stations and consumer substations are both power dependant [€/kW]. The former (stations) is used to distribute the heat through the DHN while substation is installed in each house, to withdraw the heat from the DHN for its individual needs. Both station costs rely on the maximum hourly heat demand (which occurs during the coldest day in winter).

The Table 3.5 details the different DHN components considered and their associated costs to DHNs. This data is once again provided by the Technology Catalogue of the Danish Energy Agency. These costs only concern the investment cost. The only one that has maintenance costs are substations, of about 4.5 [€/kW/year/dwelling[10]].

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[10] dwelling being the number of household in the neighbourhood, the result is therefore expressed per dwelling

Constraints

The **dwellings** encompasses the number of household concerned in the neighbourhood. **LHD** is the Linear Heat Density (expressed here in [kWh/m])[11]. The main pipes depends on two parameters (fixed for a neighbourhood), the **LHD** and the **End Uses (HW + SH)** (total heat demand)[12] The connection pipes are a fixed cost, applied to each household, which allows access to the heat produced by the DHN. The **Share Heat DHN** is the percentage of heat supplied by the district heating network. In fact, the less the household relies on centralized heat, the smaller must be sized substation. The following constraints were also added to the model to take these costs into account :

$$\mathbf{F}(p) = \mathbf{dwellings} * \Big(\text{End Uses (Heat HW+SH)}\Big)/(\text{LHD}) \qquad \forall p \in PIPES \tag{3.16}$$

$$\mathbf{F}(con) = \mathbf{dwellings} \qquad \forall con \in CONNECTION \tag{3.17}$$

$$\mathbf{F}(st) = \textbf{Share Heat DHN} * \textbf{max}\ \text{End Uses (DHN, h, td)} \qquad \forall st \in STATION,\ SUBSTATION \tag{3.18}$$

Losses

Heat losses had to be also considered. In fact, The Aalborg university [23] approximates the losses of a current generation of DHN from Danish DHNs data. Following their work, a percentage of losses can immediately be extrapolated from linear heat density (LHD). These are listed in the Table 3.5 below for a selected linear heat density.

Table 3.5: **DHN infrastructure** - varying parameters following the LHD

	urban	**peri-urban**	**suburban**	**rural**
LHD $[MWh/m]$	6	3.5	1.5	0.75
losses [%]	5	10	20	24
network lines [€/m]	750	625	500	500
connections lines [€/m]	3200	3200	3200	3200
stations [€/m]	240	240	240	240
substations [€/m]	210	210	210	210

---

[11] In fact, a common neighbourhood is characterized by its number of dwellings and its area. Considering the spaces between each household and their average heat consumption, the linear heat density can be deduced. This is an indicator for defining a DHN.

[12] However, the demand could vary in the case where renovation is applied. Therefore, the LHD would also vary. These two adjustment factors cancel each other out, therefore we consider this cost to be constant.

3.3 Upgrading the model

Further modifications are added to the existing ES model [19] to better resemble the domestic energy system and its residential sector. To reach this stage, new constraints and parameters have been defined. These are argued and detailed in this following section.

Minimum capacity installed

In a single household, multiple technologies might be required in order to meet the energy demand. The cost associated would be minimized but the technologies involved might not be available on the current market. Therefore, we have to consider a minimum power requirement boundary (in terms of kw) to be installed. [5, 6, 7]

To implement this new parameter, we have added new variables and constraints. Depending on the size of the home's energy demand, some technologies might or not be solicited. ES being defined as a Linear Programming (LP) model, will no longer be linear but Mixed Integer Linear Programming (MILP).
For example, if the amount of energy demand is greater, a wider panel of technology will be available. The non-linearity comes from the fact that, depending on the situation, the system will activate or deactivate a technology, based on the minimum installed capacity (7th column in the Table 3.4).
If a technology demonstrates therefore potential, then at least the $f_m in$ will be installed.

If a higher capacity is needed, compared to the f_{min}, then ref_{size} is taken into account. In fact, it ensures that the number of installed units is an integer, and is added to the minimum installed capacity. For instance, 1 pv panel provides 0.25 kWe. If the electrical demand is 0.3 kWe, in order to fully satisfy the demand, two panels will be installed, and will in total provide 0.5 kWe.
To enable this feature, a new constraint also had to be developed. Nevertheless, the computation time in MILP has been multiplied by 10 approximately. For reasons of speed of code processing, the ref_{size} condition has only been applied to certain technologies[13].

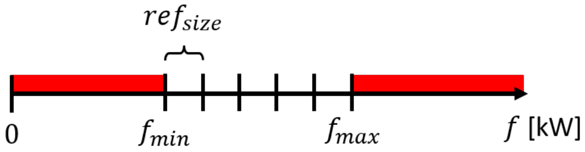

Figure 3.14: Minimum capacity installed represented by the f_{min} constraint. The ref_{size} is considered as an interval between two sizes of technologies. This has been implemented in order to always have an integer number of units. The red zone identifies the condition when the technology does not satisfy the constraint and thus, can't be installed.

---

[13] The most obvious being supposed : pv, solar thermal and air-to-air electric heat pump (small unit in each room of the household)

Constraints

In fact, three new constraints are required, the first one ($\mathbf{f_{min}}$) applies to minimum capacity, the second ($\mathbf{f_{max}}$) to maximum capacity, and the last ($\mathbf{N_{Units}}$) to integer units purposes. $\mathbf{X_{active}}$ operates as a binary variable. Its value is equal to 0, if a technology is not installed and on the contrary, 1 if so. The first two equations will always be respected, regardless the value of X_{active}.
Thanks to $\mathbf{N_{Units}}$, the capacity installed will no longer be continuous but rather discrete, considering the last constraint.

$$\mathbf{F}(j) >= \mathbf{f_{min}}(j) * \mathbf{X_{active}}(j) \qquad \forall j \in TECH \quad (3.19)$$
$$\mathbf{F}(j) <= \mathbf{f_{max}}(j) * \mathbf{X_{active}}(j) \qquad \forall j \in TECH \quad (3.20)$$
$$\mathbf{N_{Units}}(j) = \mathbf{F}(j)/\mathbf{ref\_size}(j) \qquad \forall j \in TECH \quad (3.21)$$

3.3.1 Sizing adjustment

The heat EUD profile used in the model (presented in the section 3.1.2) has a smooth nature as it based solely on a physical model. It was based on the temperatures of the year 2005. Real consumption profiles are not as perfect and usually have more fluctuating and higher peaks.

Constraints

Two factors are added in order to take these imperfections into account in the model. The first factor, **real peak factor**, takes the difference between the smooth physical profile and a real one. The second, the over-sizing factor called **worst year factor**, takes the difference between the current year and the worst year case into account. They are both added to the decentralised heating technology constraint. For the integrated neighbourhood case, only the **worst year factor** parameter has been considered[14]. $\mathbf{F_t}$ represents the operation of resources and technologies every hour.

$$\mathbf{F}(j) >= \mathbf{peak\_sh\_factor} * \mathbf{peak\_real\_factor} * \mathbf{worst\_year\_factor} * \mathbf{F_t}(j,h,td)$$
$$\forall j \in TECH, \forall h \in H, \forall td \in TD \quad (3.22)$$

3.3.2 Variable Coefficient of Performance for heat pumps

Until now all technologies efficiencies were supposed constant except for the renewable technologies (pv, solar collectors, wind turbines) which depends on the weather conditions. But in fact, the HP relies on the outside temperature and thus also related to the weather.
The performance of a heat pump is expressed via its Coefficient Of Performance (COP). A number greater than 1 expresses the amount of power extracted from the heat source compared to the power needed to use the HP. This COP is dependant on the difference in temperature between the source and the sink.
The sink temperature is here the heat operating temperature in house which is

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[14] The interest of a large sample of houses, allows to smooth the profile of demand and thus to avoid peaks osciallations for the neighborhood.

constant and equal to 55°C. On the other hand, the source temperature is climate sensible. It varies during the year and will thus have consequences on the performance of the HPs.

But, until now, in the existing ES model, the COP for a HP technology was defined as a constant value. It means that no matter the source-sink temperature difference, the efficiency of the technology would remain constant. In fact, this seems not very coherent facing the reality.

This following section is a close-up on this variable feature implemented in the model.

Energyscope Model

Basically, the maximum power input would remain constant. In other words, the same maximum amount of energy at the input will not be affected.
Nevertheless, as the COP changes with temperatures, the amount of heat produced will vary. Thus, through this new implementation, the maximum power output becomes rather variable.

In the model, the installation cost of a technology depends on its capacity which relies on the power output. In this situation, as the heat pump produces heat, the reference unit for the installed capacity is expressed in thermal-Kilowatt (kWth). As the energy output varies, the capacity installed is scaled in order to always fulfill the household needs even in winter, while temperature are the coldest.

Constraint

As a consequence, the hourly factor, $\mathbf{cop_{timeseries}}$ has been implemented in order to adjust the efficiency $\mathbf{f}$ with respect to the outside temperature, in the equation 3.23 which ensures the right balance for each layer. Indeed, all outputs from resources and technologies (storage included) match each hour the EUD and the input of other technologies.
In equation 3.23, $\mathbf{F_t}$ $\mathbf{F_t}$ represents the operation of resources and technologies every hour (storage technologies excluded). In the model, the efficiency $\mathbf{f}$ is a constant and specific parameter to each technology and resource. In fact, the output and the input are defined from the corresponding layer.

For instance, considering an electrical HP with a COP of 3, the electricity consumed to produce 1 kWh of electricity is thus 0.333 kWh. As a consequence, **f(HP,electricity)** equals to -0.333 (negative as it's a input layer), and **f(HP,Heat Low T)** equals to 1. Again, incorporating the variable COP feature, will make the efficiency **f(HP,Heat Low T)** varying. Of course, this adjustment factor matches hourly the temperature of each TDs and adjusts consistently and accordingly the COP.

$$\begin{aligned}&\sum_{i \in RES \cup TECH \setminus STO} \Big(\mathbf{f}(i,l)\mathbf{F_t}(i,h,td) / \mathbf{cop_{timeseries}}(i,l,h,td) \Big) \\ &+ \sum_{j \in STO} \Big(\mathbf{Sto_{out}}(j,l,h,td) - \mathbf{Sto_{in}}(j,l,h,td) \Big) \\ &- \mathbf{EndUses}(l,h,td) \\ &= 0 \\ &\qquad \forall l \in L, \forall h \in H, \forall td \in TD \quad (3.23)\end{aligned}$$

COP Model

To link the COP with the temperature, a hypothesis has been established and confirmed, on the linear evolution between the two variables [29]. Three types of sources can be distinguished : the air source based for a A2A and A2W heat pump and the ground source (G2W heat pump) based at 4m depth.
At the lowest temperature occured during the year, the global COP is in fact minimal and thus the default COP in the ES will be adjusted by the corresponding factor (specific COP), and inversely for the highest temperature[15].
As the reference temperature is equal to 9.9°C, the specific COP at this value equals 1 (cfr figure 3.15). The real COP is exactly the default COP defined in the ES model. Once the temperature is warmer, then the specific COP value is superior to 1. The real COP is therefore the default COP value defined for the proper technology times the specific COP value.
Therefore in this case, the COP value increases compared to the default value.
From a more overall and global point of view, the three different specific profiles have been plotted following the hour of the year on the figure 3.16. Considering the ground thermal inertia, it seems logical that the ground temperature profile varies less than the outside temperature. By natural thermal inertia, the soil during winter has a globally higher temperature than the outside (see explanations Section 3.1.2 for details). The ground has a very high thermal mass and acts as a thermal resistance due to its low conduction coefficient.

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[15] At -8.5°, considering a default COP of 3, the real COP would be, the multiplication between the default COP and the specific COP. In fact, the real COP would be : 0.47*3 = 1.41

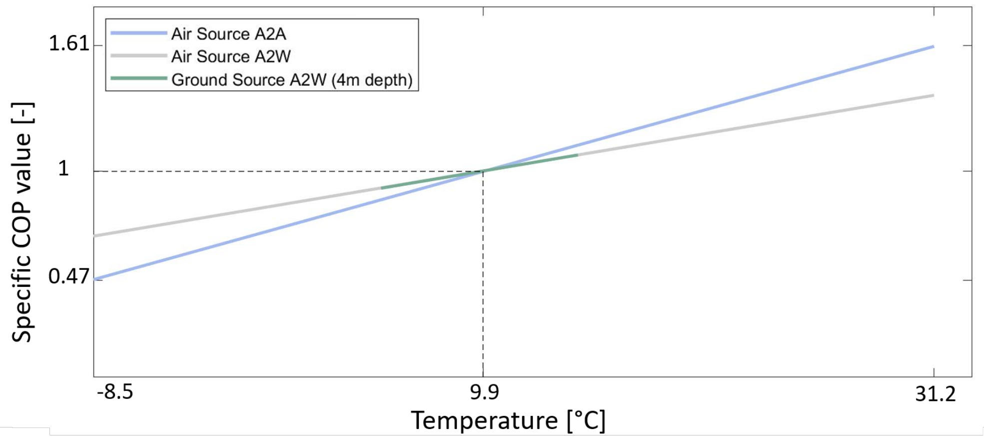

Figure 3.15: This graph shows the specific COP depending on the temperature and the type of source. The A2A heat pump has proven to behave differently in terms of efficiency facing a temperature difference compared to the A2W and G2W

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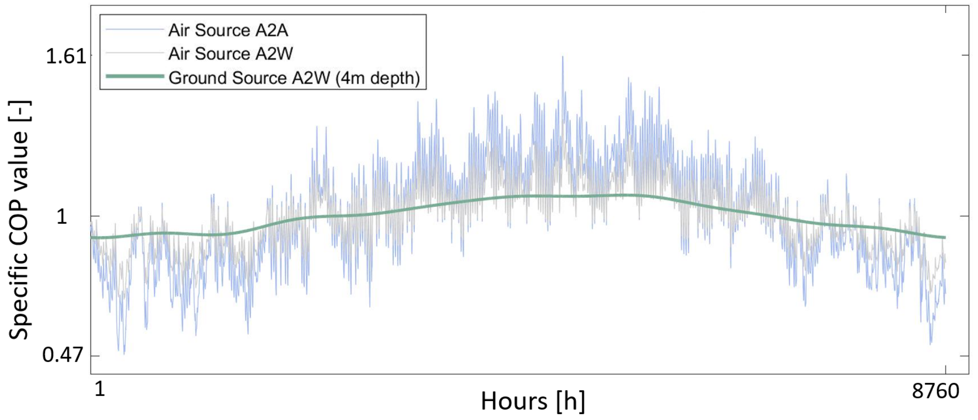

Figure 3.16: Yearly specific COP profiles for the three types of HPs. Two of them concern the air, which happens at outside temperature, and the last one about the ground temperature.

3.3.3 Retrofitting to reduce energy demand

The building stock in Belgium is one of the oldest on the continent. It is second to the UK with 40% of it being built before 1960 and 90% before 1990 [30]. These older buildings typically consume more energy and are therefore responsible for a very large portion of the country's final energy consumption.
Reducing this demand is key to a more sustainable overall energy system. Slight improvements in the average building efficiencies have the potential to significantly lower the total energy consumption.
In general, single-family houses represent the largest share of buildings (45%) and can therefore play a major role.

When considering the residential energy system optimisation it is important to also consider options that allow buildings to be refurbished next to various options of energy production.

We will first detail its implementation in the existing model through retrofitting. Then we will study its cost and potential in Belgium's residential building stock in order to better grasp its competitiveness in the energy market.

Price and potential indicators

The cost of the saved energy or cost-effectiveness of these retrofitting options are represented with the Levelized Cost Of Saved Energy (LCSE) indicator [27]. It is a defined as following :

$$LCSE = \frac{c_{inv}}{E_{saved}} \cdot \tau$$

with τ being the capital recovery factor.

This cost-effectiveness metric describes the annualized investment cost per saved energy of a certain renovation option. The lifetime of the refurbishment, in the range of 20 to 40 years and depending on the technology, is hence already taken into account.
This indicator keeps the cost-efficiency independent of the cost of primary energy and allows a direct comparison with energy supply prices. If the LCSE is lower than the current energy price, the measure is cost effective.

Constraints

The possible renovations are defined in the same way as technologies are in the model. The heat demand of a house can therefore be managed in 3 different ways, either by renovations (**Share Renovations**) or by centralized (**Share Heat DHN**) or decentralized production (**Share Heat Dec**).The last equation verifies that the sum of all the proportions equals 1, so that the heat demand can be supplied in all situations.

$$\begin{aligned}
&\mathbf{End_{Uses}}(HEAT\ LOW\ T\ DHN, h, td) = \\
&\Big(\mathbf{end\ uses}_{\ \mathbf{input}}(HEAT\ LOW\ T\ HW)/\mathbf{total\ time}+ \\
&\mathbf{end\ uses}_{\ \mathbf{input}}(HEAT\ LOW\ T\ SH) * \mathbf{time\ series_{heating}}(h, td)/\mathbf{t_{op}}(h, td)\Big) \\
&\qquad * \mathbf{Share\ Heat\ DHN}
\end{aligned} \tag{3.24}$$

$$\mathbf{End_{Uses}}(HEAT\ LOW\ T\ DECEN, h, td) = \Big(\mathbf{end\ uses}_{\ \mathbf{input}}(HEAT\ LOW\ T\ HW)/\mathbf{total\ time} + \mathbf{end\ uses}_{\ \mathbf{input}}(HEAT\ LOW\ T\ SH) * \mathbf{time\ series_{heating}}(h, td)/\mathbf{t_{op}}(h, td)\Big) * \mathbf{Share\ Heat\ Dec} \tag{3.25}$$

$$\mathbf{Share\ Renovation} = \sum_{k \in RENOV} \Big(\mathbf{F}(k)/(\mathbf{end\ uses}_{\ \mathbf{input}}(HEAT\ SH) + \mathbf{end\ uses}_{\ \mathbf{input}}(HEAT\ HW))\Big) \tag{3.26}$$

$$\mathbf{Share\ Renovation} + \mathbf{Share\ Heat\ DHN} + \mathbf{Share\ Heat\ Dec} = 1 \tag{3.27}$$

Implementing by this way, it follows a hierarchical order prioritising the installation of the most cost effective solution to its full potential before considering the next installation. This combined with the price competitiveness of our model, renovations will even have a binary behaviour (either be installed and exploited a certain renovation at full potential or disregard this option and invest into more energy supply).

Retrofitting possibilities

Four different renovation options are added in order to improve the building envelope thermal insulation.
From cheapest to most expensive these retrofitting options are : walls, roof, floor insulation and window replacements (e.g. double-glazed windows). Their cost-effectiveness and potential saving values are displayed in the following Table 3.6. These costs are allocated in such a way in the code that in order to benefit from a certain renovation, an annualized capital cost must be paid each year until the defined renovation lifetime.

Table 3.6: Retrofitting options

	$\mathbf{c}_{inv}$ $[e_{2015}/kWh_{saved}]$	$\mathbf{f}_{max,\%}$ [%]	lifetime [y]
Reduction			
Walls	0.09	0.28	40
Roof	0.14	0.14	40
Floor	0.24	0.05	40
Window	0.33	0.1	25

The cumulative cost of retrofitting in function of the share in space heating savings is displayed in the figure 3.17 below. This represents the investment costs of all renovations. Each renovation was considered over the same life span of 40 years. In fact, window insulation has a 25-year [15] lifetime. For the estimation of the renovation investment, we consider a replacement of the windows, as the defined horizon is 40 years. Finally, by installing these insulations, the household will benefit from a reduction in space heating consumption of 57% for 40 years. This initial investment is estimated at about 55.000 [€].

The average price of a house in Wallonia has a median price of 240,000 €[32], depending on the type of house (2, 3 or 4 facades).
According to the Energy Performance of Buildings Directive, the cost of deep renovations represents about 25 % of the value of the building (excluding the value of the land) [26] which is consistent with our results.

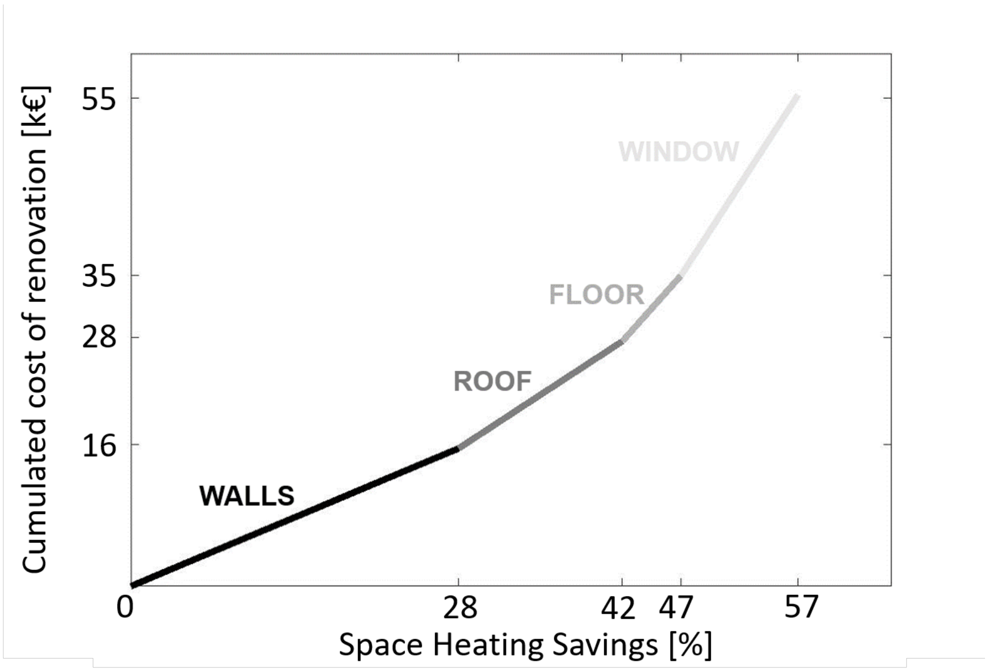

Figure 3.17: Cost of saved energy with respect to the space heating savings

Chapter 4

Case study : a single house

The most common way of supplying energy to the residential sector in Belgium is in a decentralized way, specific to each individual building. The consumer's main objective is to minimize the energy system's price; the system's CO2 emissions is secondary.

This chapter looks at the design of these single house energy systems. We focus on the interesting technology solutions and combinations that make this option of interest.

We start by studying the optimal energetic design of a typical Walloon house, called reference case. After comparing and verifying the results obtained, the focus is set on its energy transition by first looking at the actual situation and then looking at the possible changes in the years to come, aiming to achieve the carbon neutrality by 2050 in chapter 6.

4.1 Reference house

The reference case studied in this section is a household of 4 people in a $120m^2$ house [31].
This reference house has an electricity EUD of 2650 kWh and heat EUD of 17780 kWh. The heat demand is shared between hot water (HW) and space heating (SH) demands, respectively of 13.4 and 86.6%. [13].

The house studied also has different spacial constraints that limits the installable capacities of several technologies. A limited roof area of $80m^2$ restricts the installed capacity of both PV and SC technologies [1][2]. We also consider a garden with sufficient space to be able to install a ground-to-water HP.

The following resource prices are considered : [3]

- Natural gas : 0.052 [€/kWh]

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[1] When assuming PV panels alone, a maximum power of 6 kW can be installed

[2] A $80m^2$ roof has been supposed and 50% has full potential for solar panels.

[3] all resources prices are available in the Appendix A.1 and correspond to prices in early December 2019.

- Electicity from the grid : 0.286 [€/kWh]
- Electricity re-imported at Feed-in Tariff (FIT) : 0.137 [€/kWh]
- Prosumer tariff : 77.35 [€/kWe]

4.2 Household designs

The environment of the reference case has therefore been introduced and the results can now be examined. Several house designs has been set up :

1. **Classical case** that represents an average Walloon house in 2020. PV are not present, only standard imports are applied. Since there's no renovation, all the heat is generated by a gas boiler, coupled with a thermal storage. For more details, a validation has been carried out in the Appendix B.1.
2. **Cost-effective solution** that is comprises of a gas boiler and PV, which appears to be the most cost-effective solution.
3. A similar case with a **GHP** has been assumed but more pricey.
4. **Full electrification of the heat** thanks to the use of a PV and eHP.

The 4 cases are displayed on the Figure 4.1, followed by an overview of the Key Performance Indicators (KPI) on the Table 5.4, and the details of the technologies installed 4.2

For the classical case, the auto-consumption rate is set to zero, as no electricity is produced locally. In contrast, the 3 other situations although their energy systems diverge, have very similar auto-consumption. For all 3, it is above 37.76%, the CWaPE threshold. In fact, all our future analyses, from this point on, the FiT situation is exclusively favored. Therefore, the prosumer tariff is no longer concerned.

For the gas boiler and gas heat pump system, the two layers (heat and electricity) are treated separately. Therefore, as both rely on PV, their auto-consumption is identical.

When heat pumps operate with electricity produced from PV, the heat required is generally needed outside the hours of the day and therefore outside the hours of sunshine (morning and evening). A majority of the electricity produced during the day is directly exported to be re-imported later. The auto-consumption is hence roughly the same. However, auto-sufficiency is much more consequent (75.38%), since the only resource (electricity) is entirely produced via PV, but still remains dependent on the grid, (used as an electrical storage in exchange for a FIT).

From an economic and Global Warming Potential (GWP) point of view, the classical case is not optimal. The most cost-effective solution combines the use of a gas boiler with PVs and renovation. Although full electrification of the heat is possible but more expensive, it remains above all more affordable than the current

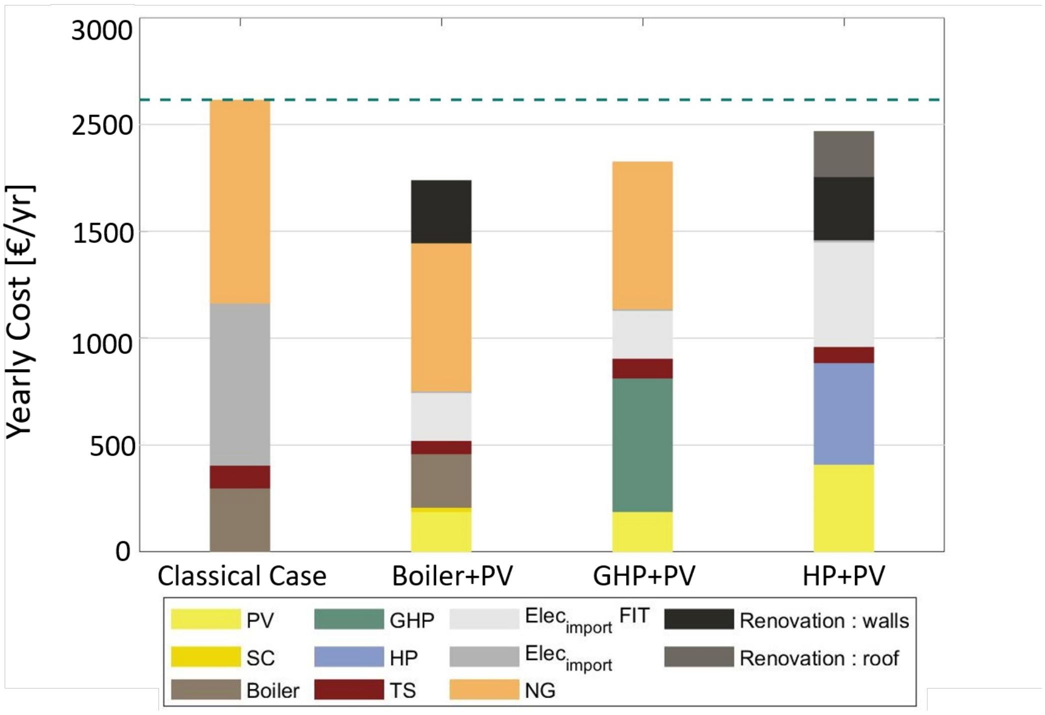

Figure 4.1: **The comparison between the 4 different house designs**. The y axis is the annualised cost. The classical case appears to be the most expensive solution compared to the 3 others solutions. In a bar, each color stands for the proportion of either a resource (Operational expenditures (OPEX)), or a technology/infrastructure (CAPEX) that it represents in the total annualized cost.

Table 4.1: **KPIs**

	Classical Case	Boiler + PV **Ref Case**	gHP + PV	eHP + PV	Units
Auto-consumption	-	37.94	37.94	37.88	[%]
Auto-sufficiency	-	6.9	6.21	75.48	[%]
Total costs	2115.4	1739.22	1826.36	1968.9	[€/yr]
Total GWP	5393.18	3606.63	3923.77	610.57	[kgCO2/yr]

classical situation and more ecological (in terms of CO2 emissions). Indeed, the CO2 reductions are diminished by 88.7 %.

4.3 Interesting technology combinations

The primary objective of EnergyScope is to observe the multiple possible synergies between technologies. Depending on various parameters (i.e. efficiency, costs, time schedules, capacity factors etc...), an energy system is designed. Therefore, in the following sections, we will better grasp through hourly profiles not only the importance and interactions of certain technologies but also their impact into the energy system cost for each household designs.

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[4] based on the classical case

[5] based on the classical case

Table 4.2: **Technology for different scenarios**

	Classical Case	Boiler + PV **Reference Case**	gHP + PV	eHP + PV	Units
Electricity					
Import (Standard)	2650	25	25	35	kWh
Re-import (FiT)	-	1629	1629	3557	kWh
PV	-	2.75	2.75	6	kW
Heat					
NG	18370	13357	12333	-	kWh
Boiler$_{NG}$	13	11	-	-	kW
gHP$_{abs}$	-	-	18	-	kW
eHP$_{a2a}$	-	-	-	2	kW
eHP$_{a2w}$	-	-	-	8	kW
SC	-	0.7	-	-	kW
Storage					
Seasonal TS	14.42	8.375	12.45	10.20	kWh
Reduction					
Walls	-	28	-	28	% of SH saved
Roof	-	-	-	12	% of SH saved
Cost variation[4]	-	-17	-13.6	-7	[%]
Gwp variation[5]	-	-33.1	-27.2	-88.7	[%]

Fuel powered production unit

In any situation other than full electrification, the use of fossil fuel-based heat generation technology, such as gas, is essential. It provides the base load of the single house energy demand and operates almost constantly.

With the use of a thermal storage

Especially on winter days, when the heat demand is at the highest, the boiler/ghp plays its role even better, and appears to be relatively complementary to thermal storage.

Indeed, without thermal storage, the gas boiler must be able to directly supply the power needed to meet the morning heat demand. Such a large-sized power would only be necessary for the rare worst (very cold) days of the year. In terms of , the solution is less interesting.

On an annual basis, the use of the thermal storage is insignificant. About 0.5 % of the heat generated is first stored, before use. However, thermal storage is actively used in the morning. To prepare the morning peak, it will produce extra heat at night. This heat will then be stored and delivered as an "extra" to cover the remaining peak. In fact, it acts like a real booster, which enables to add the few last kWh necessary to cover the heat demand especially in the morning.

In conclusion, the only use of thermal storage helps to size a smaller gas boiler by 35[6]%. This energy optimization offers an economy of 13% on the gas and boiler cost [7].

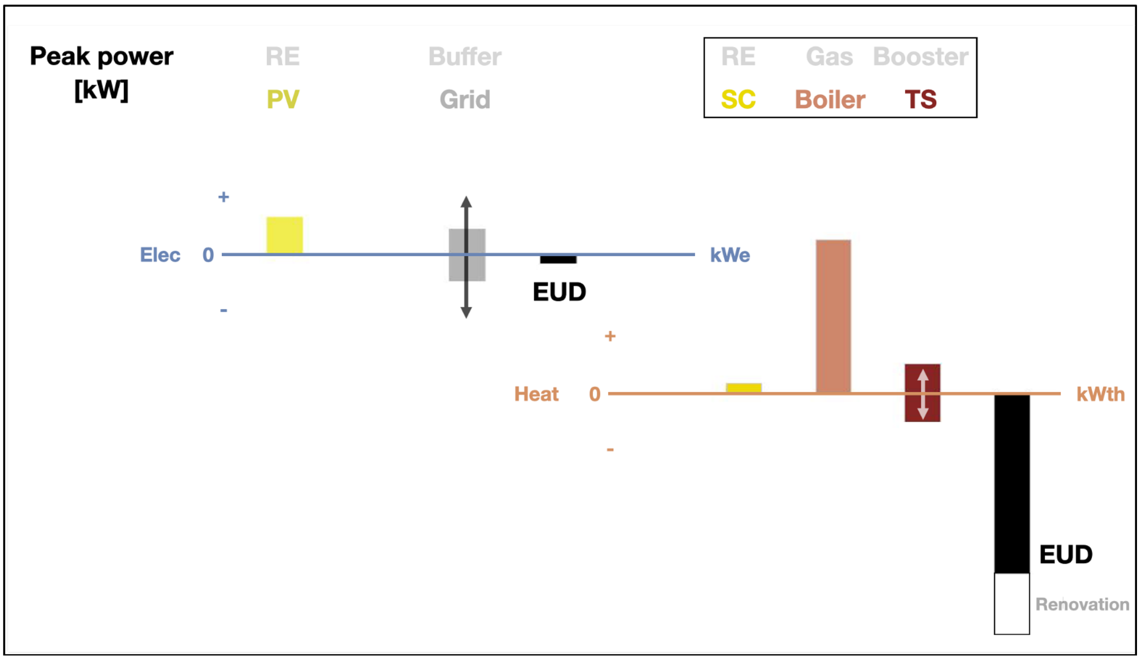

Figure 4.2: **General energy system solution expressed in peak power, in the cost-effective case** In positive axis, is shown the production and the negative axis is the demand. The demand can be split in two categories (the EUD and the Storage unit when unloads). The double arrow shows the limit of the storage technology. The grid potential use is unlimited (standard import always possible) while the thermal storage is limited in its maximum power delivery. The RE encompasses the PV and SC. At any time, from the electricity point of view, the sum of the buffer and RE can supply the electricity EUD. On the heat side, the heat EUD is constantly ensured by the combination of SC, gas boiler and TS. Adding renovation reduces the peak demand.

The impact of renovations

The impact of renovations is quite significant : it allows to reduce the annual heat consumption of the household.

The reference case (gas boiler + PV) shows the positive impact of renovation and is even more attractive when incentives are taken into account. [8]. As we can observe on the Figure 4.3, the LCoE of heat produced is higher than the price of the walls renovation. This impliesa reduction of 28% of the end-use demand.

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[6] The ratio between the highest power peak in the year and the power from the gas boiler at the same time (1 - 3.909/6.002 = 35%).

[7] CAPEX and OPEX included

[8] The income perceived by the household in this case, is equal 0.0015 (€/kWh$_saved$) times 3 (the household category). In total, the first renovation (outside walls will be equal to 0.09-0.0215 = 0.0675)

The renovation of the exterior walls makes a yearly reduction of about 1.6% (nearly 29 €). A deep comparison study (between the reference case with and without renovation) has been conducted and is available in the Appendix B.2

Renovation is of even greater interest when it comes to full electrification. When the entire roof potential is covered by PV, the electricity produced is not sufficient to cover all the needs of the household. Through renovation the total demand in heating is reduced.

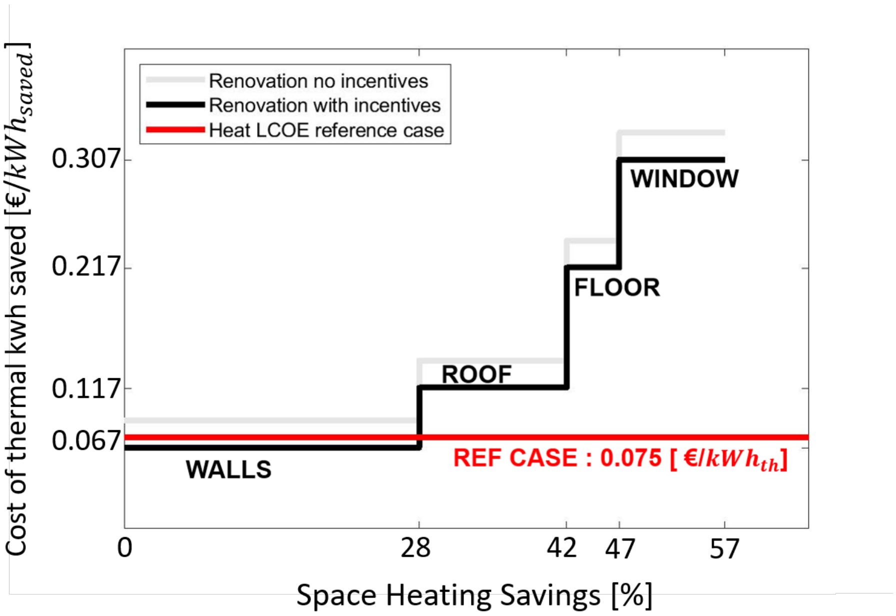

Figure 4.3: **Renovation in the reference case**. The light grey line represents the cost of renovation without incentives, in €/kWh saved. The black line shows the renovation cost for the reference case (category 3 eligible to incentives). The straight red line is the LCoE of the rest of the heat generated to cover the heat demand.

Other promising gas based technology

The gas boiler is not the only technology which can ensure the base load. The gHP can also supply the heat demand at higher efficiency.
Today this technology is only available in high capacities and is only relevant in high consumption homes[9][25] (further explanations on its implementation and limitation are available in the Appendix A.2). In the future, it should become available in lower capacities. [6].

Larger thermal storage units are installed when using a gHP. By taking advantage of the better COP during the warmer hours by storing it the thermal storage during the day and using it for the evening needs.

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[9] The Robur power installed is relatively significant (at least 18 kW). Therefore, it is able to reach higher peaks and renovations don't show interest.

Gas boiler and Solar Collectors

During the summer, SC and gas boilers are complementary. In absence of SH only HW needs to be supplied. This heat can be provided by solar collectors.

Heat produced during the day is stored for later use in the evening, as shown in the Figure 4.4 below. This reduces the gas consumption.
Globally, we observe in the reference case a price reduction of 8 €per year. Heat requirements for HW in summer are best provided by solar energy versus fossil fuels, which have a significant operational cost. The LCoE of the solar collectors is relatively low (3.7 c€/kWh)[10].

In the case of a gHP, solar collectors are not part of the solution. The COP of a gHP depends on the outside air temperature. Taking the average weighted efficiency of the heat pump (1.45[11]) we obtain a price per thermal kWh therefore of 0.0358[12] [c€/kWh].

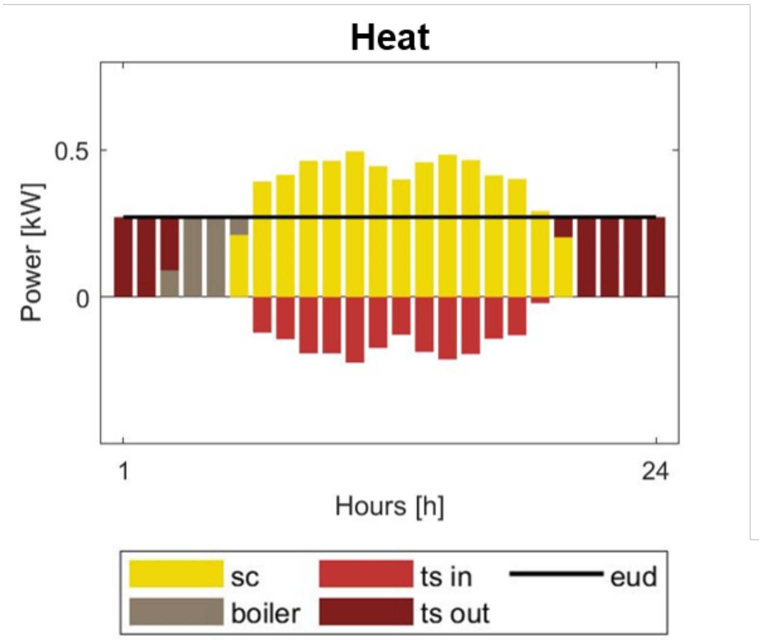

Figure 4.4: **Overview of a daily heat management though SCs**. The positive axis shows the production while the negative axis displays the storage loading. The black horizontal line represents the HW EUD (no space heating considered as this TD is in summer). As we may observe, solar collectors supply almost the entire HW demand and store part of their production for later use (morning and evening). The rest of the EUD is covered by the gas boiler in "back-up".

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[10] without considering the dimensioning of the thermal storage because this one does not change.

[11] (the heat produced over the gas consumption over a year : 17884.15/12332.91 = 1.45)

[12] 0.0519 / 1.45 = 3.58

PV panels

Electricity today in Wallonia is expensive compared to other Western European countries, and is traded at a price close to 28 c€/kWh [3] . Therefore, the installation of photovoltaic panels allows a single house to produce and consume electricity at a lower price. For a Feed-in Tariff (FiT) price, produced PV power can be exported to the grid at one moment (when production is high) and used at another.

A PV installation of 2.75 kW is installed for an electricity EUD purpose only. When electricity and heat generation are treated seperately (via gas boiler or gHP). , which It produces 2625 kWh over a year and has an auto-consumption of 37.94%[13]. The FIT is very appealing. Each re-imported kWh then costs 0.13747 [€/kWh]. The amount of PV installed in this case is just not enough to cover the entire electricity demand.

An extra 25 kWh must be re-imported at standard tariff during the year. In total, in this situation, producing its own electricity has a of 15.77 [c€/kWh][14]. The LCoE of the electricity is in fact about 45% less expensive than electricity standard import price.

eHPs with PV

Today, Engie does not promote the use of domestic electric heat pumps. The import cost of electricity is too high (28c€/kWh), so the investment is not profitable. Therefore, they recommend the use of a gas boiler [10].

However, PVs allows to produce more affordable electricity. The maximum capacity of PV panels being limited to 6 kW per roof and considering the auto-consumption of 37.88 [%], the LCoE of electricity is of 0.1574 [€/kWhe]. This remains expensive for heating, except, if it is operated by a heat pump. With an annual COP of 3.78, the electricity resource for space heating becomes more competitive than gas solutions.

Taking into account the electricity cost, the COP, CAPEX and OPEX of the eHPs, the LCoE of heat is about 0.082 [€/kWh$_{th}$].[15]

The varying COP of the eHP, function of the outside temperature, is shown by Figure 4.5. We observe a strong heat production occurs in the afternoon. This can be explained by two combined factors :
First, low-cost and off-grid electricity is produced through PV panels and directly auto-consumed.

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[13] The ratio between the quantity produced and immediately exported. (1-1629/2625 = 37.94%

[14] It takes into account the investment and maintenance cost of the PV panels and the electricity price at both tariff.

[15] The LCoE of heat is equal to the ratio between the LCoE of electricity and the COP of the HP : 0.1574 / 3.78 = 0.0416 [€/kWh].
Then, considering the CAPEX : The two eHPs have an annualized cost of 475.31 [€] in order to produce 11776 kWh. The final LCoE of heat is thus obtained by summing the 2 ratios (0.0416 + 475.31/11776 = 0.0.82 [€/kWh$_{th}$].

Also, COP is higher as the temperatures are at their warmest, part of the heat will be stored for 4 hours and useful to ensure the evening and morning demand (when the COP would be less interesting).
Thermal storage plays the role of buffer between the production and the demand. About 22.42% of the heat produced, is stored for later use.

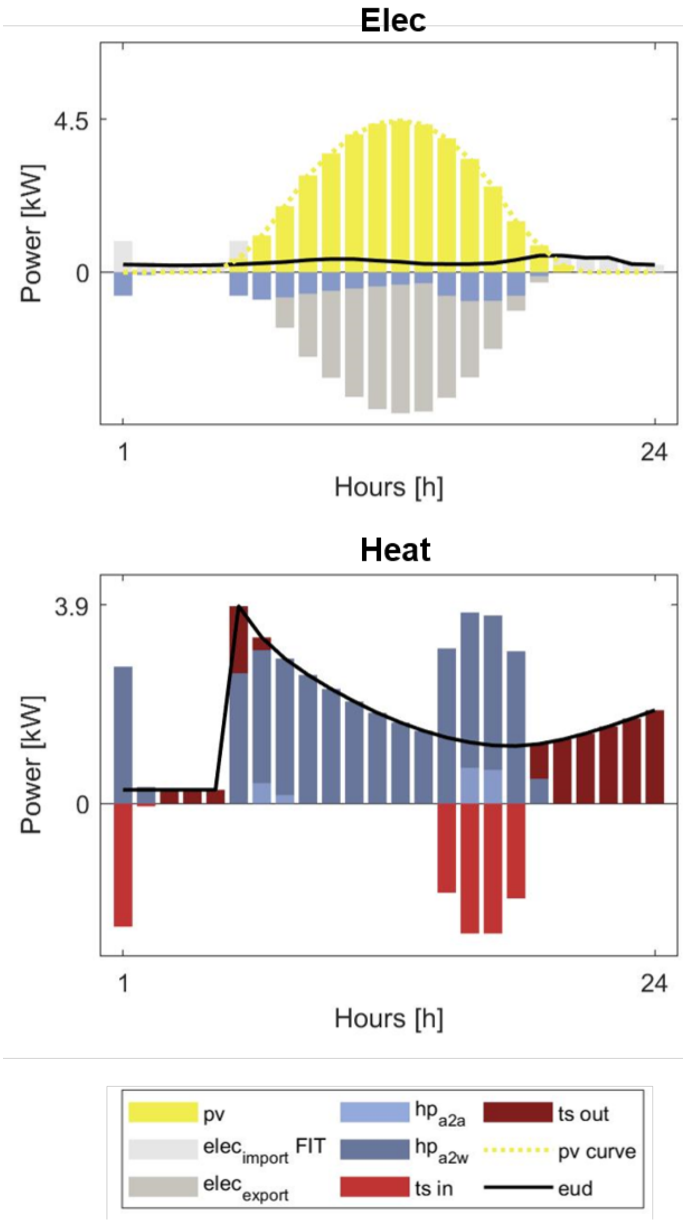

Figure 4.5: **Overview of a daily energy management though HPs**. 2 layers are represented (the electricity and heat). The negative axis shows the demand and positive axis, the production. In yellow bars, is shown the hourly PV production during spring TD. During the day, massive electricity production occurs though PV. Part of it, is stored into the grid, to cover the electricity EUD outside the day. The rest, is used to produce heat (light blue), and cover the heat EUD. The variable COP takes advantage of the hour, to produce excessively amount of heat during the afternoon, aiming to store and later supply the evening heat EUD.

If no area restriction is applied to the roof 6.5 kW of PV (26 panels) is needed, to fulfill the entire demand. In this particular situation, less roof renovation would be required (see Appendix B.3 for full comparison).
To conclude with eHPs, they have shown benefits when coupled with PVs. Due its variable performance they are dimmensionned on the coldest day of winter to be still able to satisfy the heat demand. The COP is therefore drastically lower than the theoretical COP of the heat pump. The installed capacity of the heat pump is therefore larger. Thermal storage demonstrated strong value, by storing the timely produced heat for later use.
However, this combination appears to be restrained. In fact, the price and the daily constraint of a thermal storage is not sufficiently attractive to take full advantage of the variable output of the heat pump.

However, this solution, although interesting, is not the optimal solution. Its heat LCoE of 0.082 $€/kWh_{th}$ remains higher than the one of the gas boiler (close to 0.06 $€/kWh_{th}$).

4.4 Type of household

The reference house studied in the previous section represents a typical Walloon house. But this specific case is not universal to all houses in Wallonia. Households will have different energetic demands and will have different spatial constraints. Some are young families, some others are retirees. Some live in the city, others in the countryside.
To achieve a better understanding of the situation, we will focus on the main influence factors which might vary the optimal energetic design. The idea behind this study is to verify the robustness of the reference solution and to observe alternative energy system for other house designs.

These different parameters can be placed in two distinct categories : dwelling characteristics and external factors (such as incentives).

Annual EUD variation

Two separate factors describe the EUD of a household : the yearly demand and the hourly demand, more commonly called time-series. The second parameter hasbeen considered, and discussed in the Appendix B.1. In fact, it has been shown that time-series variation does not influence the energy system of the house.

The scope of the following analysis is on the influence of different yearly EUD. In this analysis, the same proportions of electricity, SH and HW EUDs are maintained. We only vary the yearly total energy consumption value, illustrated by 4 different types of household in the Table 4.3.

Table 4.3: **EUD variation**

	DINK[16]	Retired	Family **Ref Case**	Flat-share	Unit
Area	70	70	**120**	150	m^2
Number of people living	2	2	**4**	6	-
Electricity Demand	1550	1900	**2650**	3560	kWh
Space Heating Demand	9009	11043	**15402**	20691	kWh
Hot Water Demand	1391	1706	**2379**	3196	kWh

The DINK and the retired couple have been considered to live in the same space area. What differs between the two is the greater energy demand for a retired couple, who are more inclined to stay at home than the young working couple. The family house is presented as the reference case of our analysis. The energy demand of the flat-share, made up with 6 students, is very close to the CREG data presented in the validation of the house scale in the Appendix B.1. As a result, we find an increasing EUD, where the lowest comes from the DINK, up to the flat-share.

At first sight, the ES model suggests the same energy system for each demand (Table 4.4). A gas boiler is considered to be the cheapest option and is installed at its

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[16] Double Income No Kids

lowest capacity. Systematically, the gas boiler is used to cover heat peak demand. As a consequence, the more the technology needed, the lowest its Levelized Cost Of Energy (LCoE) would be, as expressed in [€/kWh]. Thus, appears a dilemma between solar collectors and renovations for lowering the system cost.

On one hand, solar collectors are generally used for sanitary purposes (HW). Globally, they satisfy the heat demand in the summer when DNI occurs.
On the other hand, renovations reduce the space heating demand all year round. The winter (highest) peak is then lowered due to renovation. Therefore, there is a perfect balance between using the gas boiler, reducing heating consumption and providing Hot Water via Solar Collectors in the summer.

Table 4.4: **EUD influence**

	DINK	Retired	Family **Ref Case**	Flat-share	Unit
Production					
Elec Import[17]	-	-	**25**	-	kWh
Elec Re-import (Fit)	956.68	1183.6	**1629**	2444.6	kWh
PV	1.75	2	**2.75**	4.25	kW
$\text{HP}_{elecA2A}$	-	-	-	2	kW
NG	10263	9471.06	**13357**	15933	kWh
Gas Boiler	11	11	**11**	11.41	kW
Solar Collectors	0.7	0.7	**0.7**	1.4	kW
Storage					
TS unit	3.623	2	**8.375**	14.13	kWh
Renovation					
Walls	-	28	**28**	28	[% of SH saved]
Total Cost	1080.37	1287.29	**1739**	2318.5	€/yr
Total GWP	2739.42	2561.54	**3607**	4405	kg-CO2/yr

The DINK household has a preference for solar collectors and gas boiler. Applying renovation would increase the LCoE of heat, as a gas boiler is automatically installed.
In the other house designs, as the heat demand increases renovations become more interesting. The combination of solar collectors and gas boiler remain valid.

Incentives

In Wallonia, support mechanisms have been introduced to promote the installation of certain technologies or infrastructures such as renovations. These energy subsidies are hugely dependent on the household income. There are 6 different categories defining the amount of incentives eligible (n=1 being the household with highest

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[17] For almost each case, excessive amount of PV panels has been installed, in order to be sure to fulfill the electricity demand. As a consequence, part of the electricity produced along the year and exported to the grid, is never reimported. This solution is prefered as importing at standard cost, is very expensive.

income and n=6 the one with lowest income). In our case study, we consider being part of the third group (n=3). We study here the influence of being in a different group and therefore receiving more or less energy related subsidies. As a reminder, for each investment, the incentives will cover maximum 70% of the costs.

As shown in Table 4.5, above a n value of 2, wall renovations are considered attractive. In fact, renovations are very much incentivised. The greater n is, the more renovation would be applied at lower cost. Once renovation is considered, the gas boiler size is reduced. Only the biggest incentives - associated with the lowest income - can afford to consider a new technology to minimize the domestic energy system. Therefore, the gHP from Robur® only available in 2020 in 18 kW is optimal.

Table 4.5: **Incentive group influence**

n	1	2	**3** **Ref Case**	4	5	6	Units
Production							
PV	2.75	2.75	**2.75**	2.75	2.75	2.75	kW
Elec Import	*25*	*25*	***25***	*25*	*25*	*25*	kWh
Solar Collectors	0.7	0.7	**0.7**	0.7	0.7	-	kW
gHP$_{abs}$	-	-	**-**	-	-	18	kW
Boiler$_{NG}$	13	13	**11**	11	11	-	kW
NG	*17858*	*17858*	***13357***	*13357*	*13357*	*9314*	kWh
Storage							
Grid FiT	1629	1629	**1629**	1629	1629	1629	kWh
Thermal Storage	14.458	14.458	**8.375**	8.375	8.375	3.53	kWh
Reduction							
Walls	-	-	**28**	28	28	28	% of SH saved
Cost	1767.93	1767.93	**1739**	1706	1674	1613	€/yr
GWP	4738	4738	**3607**	3607	3607	3106	kg-CO2/yr

Incentives promote in particular renovations and gHPs. On the figure 4.6, the impact of incentives towards a low-carbon solution (low gwp) is observed. The reduction of emissions is driven by incentives. Higher incentives bring the price of low CO2 solutions to lower values.The solution optimizes the cost, and is independent of the others. Globally, we observe an increasing slope without support mechanism. This means it is not financially interesting to reduce its CO2 emission. However, taking incentives into account, they objectively not only enable to reduce CO2 emissions, but also to optimize the cost of the energy system.

Therefore, globally, looking at the reference case, with incentives of n=3, we find full electrification which remains more affordable than the classical case (based only on import of electricity at standard price). This proves that the incentives set up by the Walloon Region are well worthwhile in the sense of an energy transition. At present, it is already more interesting to opt even for a 100% heat electrification solution with low CO2 emissions, compared to the classical solution.

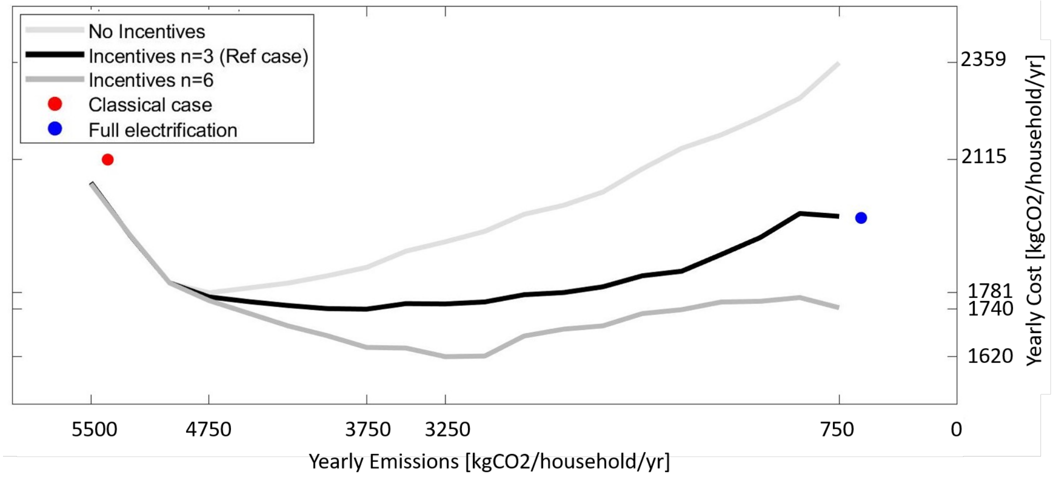

Figure 4.6: **The total energy system cost following its CO2 emissions (in terms of operational and technology construction)**. The light grey curve shows the the energy system without incentives while the darker curves concern the incentive policy (n equals 3 and 6). Considering the reference case study, it is clear that the support mechanisms guide houses to reduce their CO2 emissions, minimising their cost. This is all the more confirmed, in comparison, the situation of low-emission heat electrification, and the classic case, in contrast extremely polluting. Detailed graphs (illustrating each energy systems for each CO2 emissions situation) are available in the Appendix B.5

Chapter 5

Case study : an integrated neighbourhood

Another way to supply energy to the residential sector consumers is through integrated neighbourhoods. Also known as energy communities, these are systems that produce energy in a centralised way and distribute it to the household consumers through networks - both electric and heating networks.

This chapter concerns primarily the energy system design of such integrated neighbourhoods. We focus on the overall design and the interesting technology solutions and combinations that make this option of interest. We also look at the influence of different parameters that will make these integrated neighbourhoods more or less attractive in the residential sector.

The neighbourhood is composed of multiple houses. It is considered within the model as a single large energy system. Its demand[1] is a global one and the production is also common. The energy distribution dispatch within the system from one unit to the individual houses is not modeled. We consider the distribution losses[2] but not the hourly electricity operational demands from the pumps.

5.1 Reference neighbourhood

The case study focuses on a specific type of district called reference neighbourhood. It is a middle-class peri-urban district consisting of 3000 single-family homes [3]. It considers only the most accessible technologies, those that could be installed in most single-family houses in Wallonia. The only renewable source considered in this case is the solar radiation. The other renewable resources that are only suitable to specific neighbourhoods, ie. wind and geothermal, are not considered in this base case and are studied in a separate section.

Examples of different real neighbourhoods are provided in the Appendix **??** in order to better visualise the types of neighbourhoods talked about.

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[1] Both electricity and heat. Moreover, heat is also considered as a whole. This hypothesis is discussed in the Appendix C.2

[2] Depend on the neighbourhood characteristics

[3] The reference single-family homes defined in the previous chapter (3rd incentives group).

5.2 Neighbourhood designs

5.2.1 Classical case

The classical neighbourhood energy system consists of a gas powered production units : a CHP in combination with a boiler.
This system design applied to the reference neighbourhood yields a gas CHP that provides for 14% of the heat and a gas boiler for the remaining 86%. The annualized cost of the system is 4.7 million €, amounting to 1566 €/household.
It already provides neighbourhoods with a competitive energy supply but might no longer be the optimal cost-effective solution due to the rise of new technologies.

Before examining the various technology possibilities, here is first a merit order that highlights the importance and usefulness of specific technologies.

5.2.2 Merit order

The different technologies are classified in function of their order of appearance as cost-effective solutions in the model (see Table 5.1 and 5.2). This was done through a Levelized Cost of Energy (LCoE) analysis. The technologies on top are the cheapest solutions and therefore the first to appear in the model optimization .

As explained in the methodology section, most of these technologies were modeled through piece-wise linear optimisation to take the varying prices into account in accordance with the LP model. There is thus different sizes for each technology but these have few to no impact on the classification.

Table 5.1: **Merit order** - production units

	Elec	**Heat**
1	PV	eHP
2	gCHP	gCHP
3	woodCHP	gHP
4	wasteCHP	woodCHP
5		wasteCHP
6		gBoiler
7		woodBoiler
8		wasteBoiler

We observe that the appearance and development of very competitive renewable production technologies has changed the game. The renewable technologies, ie. PV panels, SCs and eHPs, are in operation the cheapest technologies. They are very appealing in an energy system but their stochastic and uncontrollable nature implies the incorporation of a flexible energy system.

This flexibility can be achieved by various ways throughout the energy chain : through controllable production, buffer storage units or an adapting end-use demand (renovation).

CHPs are a reliable and controllable production solution. Moreover, from its high efficiency in electricity and heat production, it becomes the most competitive technology. Gas is the cheapest option even though wood and waste can be sourced locally and produced at a lower cost. Wood and particularly waste furnaces operate at higher temperatures and are dirtier fuels and therefore cost more at purchase and to maintain.

Flexibility from the infrastructure can either come from storage and conversion solutions or from energy exchanges with the exterior.

Table 5.2: **Merit order** - storage and exchange solutions

	Elec	**Heat**
1		Seasonal storage
2		Daily storage
3	FiT reimport	
4	Battery Lithium	

In brief, heat storage solutions are by far the cheapest options with the seasonal storage being the optimal solution when a large enough capacity can be installed.

Upcoming neighbourhood designs will be based on the most efficient solutions of the merit order to optimize their cost.

From this point, the waste resource will not be involved in the optimization of an energy community. As our model is based solely on energy system optimisation, waste appears to demonstrate no economic interest in finding its way through. Besides from a societal and environmental point of view, waste is thus not profitable compared to the other technologies it faces.

5.2.3 Different designs

Four different designs arise for the standard neighbourhoods.

- **Classical case** that represents the conventional neighbourhood energy system.
- **Cost-effective** solution case with seasonal thermal storage as main storage asset.
- **Case with daily thermal storage** as main storage asset.
- **Low-carbon case** with lithium battery and seasonal storage.

The 4 cases are displayed on the Figure 5.1.

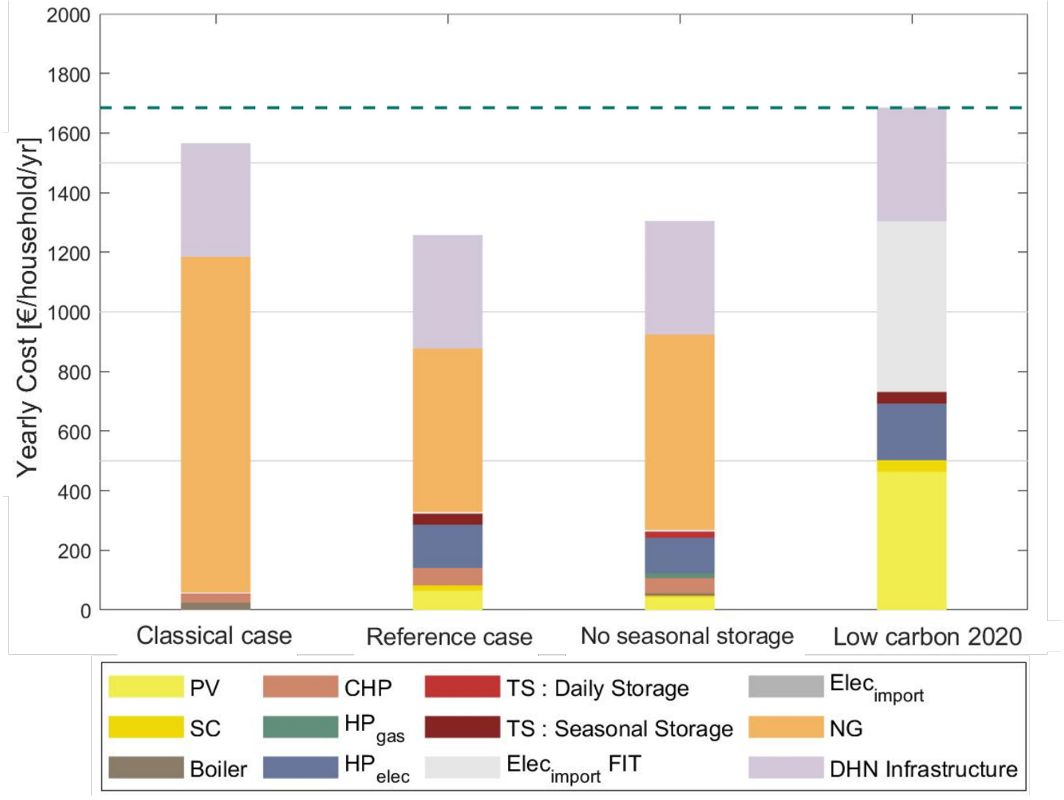

Figure 5.1: **The total cost comparison between the 4 different neighbourhood designs**

The different neighbourhood energy system assets and resource imports with their associated total costs and total emission levels are presented below (see Table 5.3. They are expressed in terms of the specific values to one dwelling.

Table 5.3: **Technology for different scenarios**

	Classical case	**Reference Case**	No seasonal storage	Low carbon	Units
Electricity					
Re-import (FiT)	34.3	40.3	45	4168	kWh/dwelling
PV	-	0.93	0.63	6.8	kW/dwelling
Heat					
NG	21.6	10.66	12.51	-	MWh/dwelling
CHP	0.5	1.03	0.9	-	kW/dwelling
Boiler$_{NG}$	15	-	5.2	-	kW/dwelling
gHP$_{abs}$	-	-	1.06	-	kW/dwelling
eHP$_{g2w}$	-	2.96	2.43	3.9	kW/dwelling
SC	-	1.5	0.43	3.26	kW/dwelling
Storage					
Daily Storage	7.33	-	5	-	kWh/dwelling
Sasonal Storage	-	606	-	633	kWh/dwelling
Infrastructure					
DHN infrastructure	381	381	381	381	€/dwelling
Total costs	1565.75	1257.88	1305.07	1685.44	[€/dwelling]
Total GWP	5450.59	2770.45	3267.16	625.93	[kg$_{CO2}$/yr/dwelling]

Table 5.4: **KPIs**

	Classical case	**Reference case**	No seasonal storage	Low-carbon 2050	Units
Auto-consumption	-	96	92	81	[%]
Auto-sufficiency	-	52	42	36	[%]
Cost variation	-	-19.7	-16.6	+7.6	[%]
Gwp variation	-	-49.2	-40	-88.5	[%]

Main design principles

Optimal neighbourhood energy systems are based on four design principles :

1. Integration of **RE** technologies, ie. PVs
2. **Heat electrification**
3. Use of **buffer storage** solutions, preferably seasonal thermal storage solutions
4. **Controllable production units**

In fact, Figure 5.2 allows to better grasp at different times and in different conditions the various system solution possibilities in terms of technology usage.
During the day, PVs (the yellow bar top-left) will produce enough power to provide for the majority of the electricity demand. But, when this RE production is not available (the yellow bar set at zero), complementary solutions, such as the gas CHP and grid combination in this case, will take over to provide the necessary power.

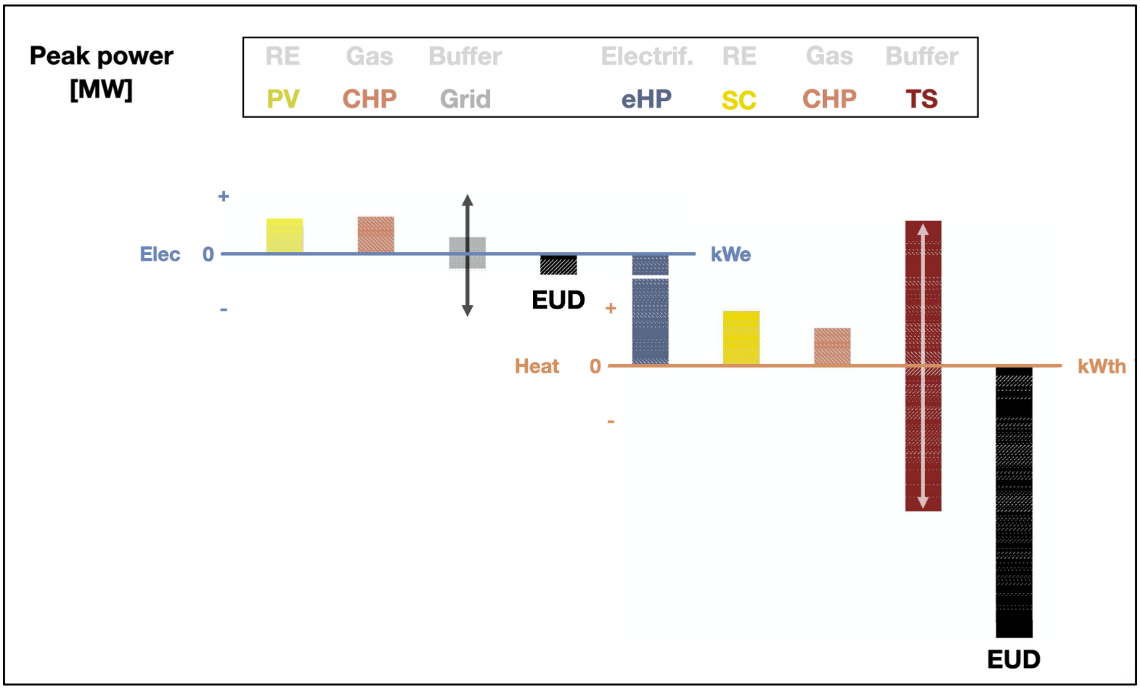

Figure 5.2: **General energy system solution, in the cost-effective case**. Are displayed on the positive y axis, the peak production power (positive bars). On the negative y axis, the peak demand is shown (negative bars). The double arrow shows the limit of the storage technology. In this situation, both energy layers are connected thanks to heat electrification. Part of the electricity produced is especially dedicated to produce considerable amount of heat with the help of the COP from the eHP.

High RE integration

Renewables and in particular PV panels produce electricity at very competitive rates (see merit order Table 5.1). Electricity is a noble form of energy [4] that brings more flexibility in the energy system management. It can be directly consumed, exchanged with the grid for later use or be downgraded to heat (i.e. via heat pumps), to be once again, either consumed or stored. This flexibility is of great importance when designing a renewable based energy system.

Optimal integrated neighbourhood solutions are therefore based on these RE production units but, whilst low-cost in operation and producing a high flexibility type of energy, they are intermittent and cannot be fully relied upon. Other solutions are also necessary to deal with the intermittency challenge and the delay between the RE production and EUDs.

The production of electricity is therefore provided by PV panels but also a gas CHP. The PV panels provide 16% of the electricity production for an LCoE of 0.07€$/kWh$. The CHP comes into action when the PV production is not sufficient.

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[4] Electricity can be converted to almost any other form of energy: mechanical, chemical, heat, etc.

Electrification of the heat

In the cost-effective case in particular, only 45% of the electricity produced is allocated for the electric EUD. The remaining 55% is at some point downgraded to heat and assigned for the heat EUD.
This has an impact on the total electricity demand profile as it will approach the heat demand profile for better consumption and approach the PV production profile for a cheaper production.
We observe on Figure 5.3 that the morning heating peak induces an increase in the electric demand and the use of the CHP (salmon). The PV (yellow) production increases through the morning while the heat demand decreases. In the early afternoon the entire energy demand, both electric and in heat, is fully provided by the renewable solar technologies.
PVs provide the full electrical EUD and also part of the heat through the eHP (green). The remaining heat comes from the solar collectors (orange).

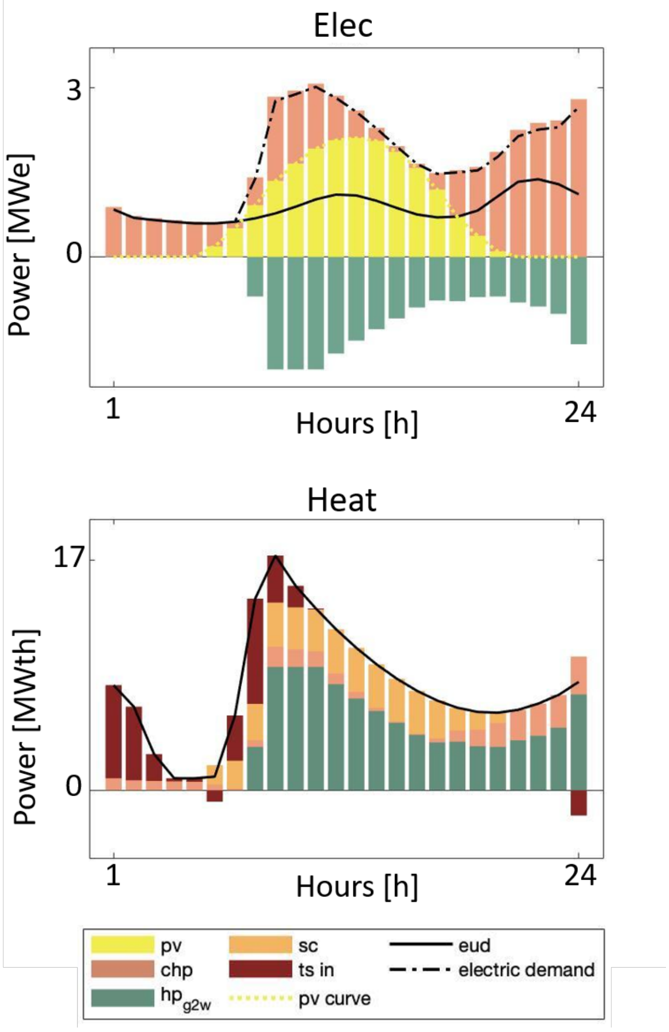

Figure 5.3: **Overview of a daily heat management though Heat electrification from PV production**. 2 electrical demands appear on this graph, namely the EUD (continuous black line) and the heat pump's electricity demand (discontinuous black line).

The electrification of this heat is supplied through the electric heat pumps.
The ground heat pump is preferred as for the reasons detailed in the previous section. It accounts for 70% of the heat produced and is, with the auxiliary CHP heat (25%), responsible for the base load of the heat supply. The other neighbourhood designs have similar electrification rates.

The nature of the controllable and buffer units diverges according to different neighbourhood designs.They are managed with different sets of technologies.

Buffer units : thermal storage, FiT exchange, battery

Different buffer units are used to delay the production in order to match with the fixed demand of the system. These units are available both in the electrical and heat layers. These technologies are listed in the storage and exchanges merit order (Table 5.2). Whilst the thermal storage solutions are cheaper than the electric alternative options, they do not fulfill the same functions and will appear at different moments.

As previously explained, electricity is a "higher quality" energy that can be used to provide electricity, directly, or heat, via electrification. Even though it is a more cost-intensive solution it provides more flexibility compared to heat solutions. Two solutions exist.

Firstly, the Walloon grid policy allows a prosumer to export and later re-import this electricity via the utility grid for a FiT cost, all of this without any losses. This solution is used for the long term storage as it induces no losses and no other buffer solution can compete in such a time-frame. Electricity is usually exported during the summer when the high PV production has no demand and is imported back into the system in the coldest winter days when the electricity and heat demand are at their highest.
It is a trade-off between investing in larger production units and larger electricity net-imports.

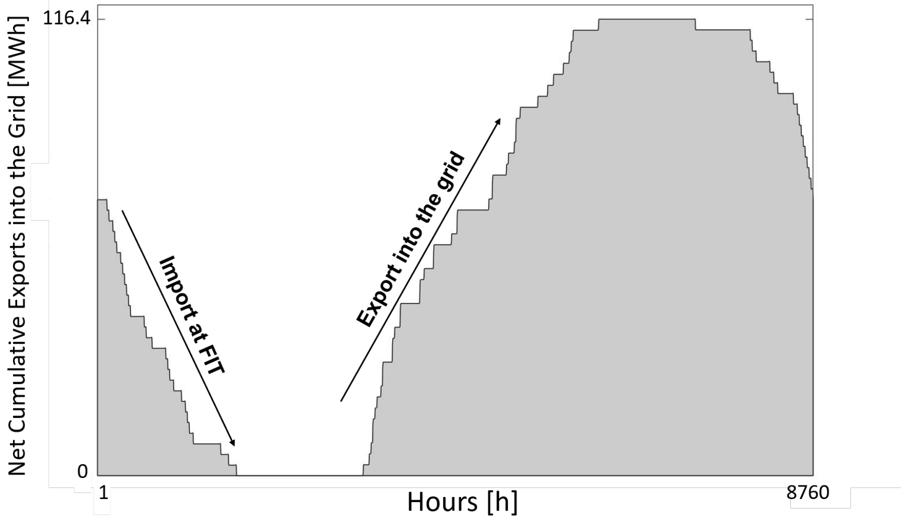

Figure 5.4: **Yearly profile of net cumulative grid exports into the grid**.

The other electricity buffer is the lithium-ion battery. Ranked last in the storage merit-order, it is today not a competitive technology.[5] Its high losses mean even at a lower price in 2050, this technology will only be a short term daily buffer solution.

Heat storage is done through the storage of hot water. Its low energy density ($40kWh/m^3$, discussed in the Appendix C.3) means that large storage units are very voluminous (50 000 m^3 in order of magnitude for neighborhoods of 3 000 dwellings.) and not always feasible in all neighbourhoods.
These large quantities of water are usually stored in large pits of waters dug into the ground. Smaller scale storages rather exist in metal canisters, larger versions of the typical home solutions.

The cost-effective and the low-carbon solutions both depend on the seasonal storage. It plays an important double role in the heat management, shown in Figure 5.5.
Firstly, it acts as a "booster" in its daily use. As in the case of a decentralized system, it fills up, typically with the CHP energy (both electric through the heat pump and the auxiliary heat), in the early hours of the coldest days to fulfill the morning peak in demand.
But the thermal storage also, and more importantly, takes up a seasonal role. It fills up during the high resource months with any excess solar energy PV through a PV-eHP combination or directly via SCs. This heat is then retrieved for later use during the coldest winter days.
We observe the use of both these roles in the following Figure 5.6 where the degree of filling the reference case seasonal storage is displayed in terms of the energy transiting through the buffer solutions.

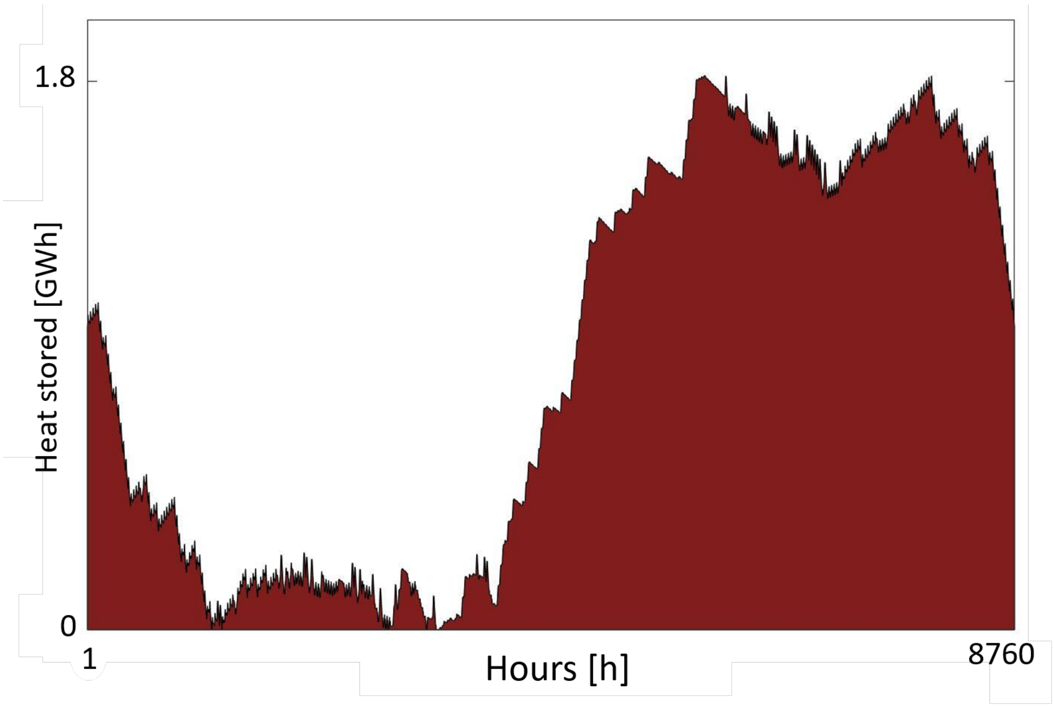

Figure 5.5: **Yearly profile of stored thermal energy in large storage unit**.

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[5] Importing through the FiT remains cheaper even for very short term buffers

The absence of a large thermal storage [6] (third system design) is overcome with additional controllable production units and a smaller thermal storage.

The overall buffer solution usage is represented on figure 5.6.

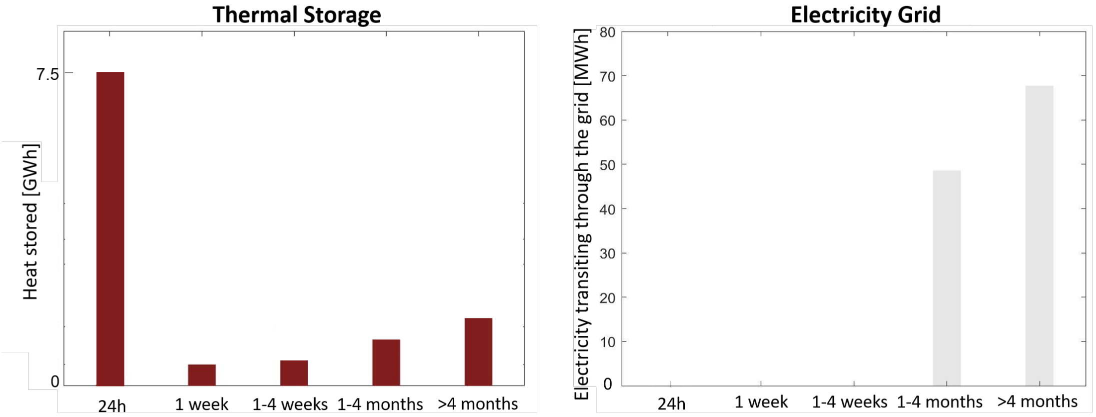

Figure 5.6: **Buffer solution residence times**. The grid (grey) and the thermal storage (red) solutions play key roles in different time frames.

Controllable units : Gas boiler vs gHP vs CHP

Gas powered units are integral to a renewable heavy system. They are controllable technologies that can be used at any time to produce energy. CHPs, gHPs and boilers are all gas technologies that have been used in the systems above.

The CHP produces both heat and electricity and is the main controllable electricity provider. It is dimensioned to supply the electricity demand and is predominantly used in this highly electrified system.
In the cost-effective solution the CHP plays a large role in the electricity production. 84% of the annual electricity production is provided by the CHP. In this case, it mostly plays the role of a base load. It is only turned off when the PV starts producing.
In a low-carbon solution the CHP gives way to a higher PV integration (Appendix C.4). It then plays more of a back-up role, only producing when the PV production is not sufficient.

Gas heat pumps (gHPs) and boilers are both controllable heat only production units. These technologies are used to supply for the heat demand when a large, low loss thermal storage cannot be implemented (see Figure 5.7. With different prices and efficiencies both technologies are installed to cover different roles.
In this case, the eHP is smaller and will receive a first boost via the gas powered heat pump. When not sufficient, during the winter days, the boiler is activated for a further boost.

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[6] Due to a lack of space or simply by design.

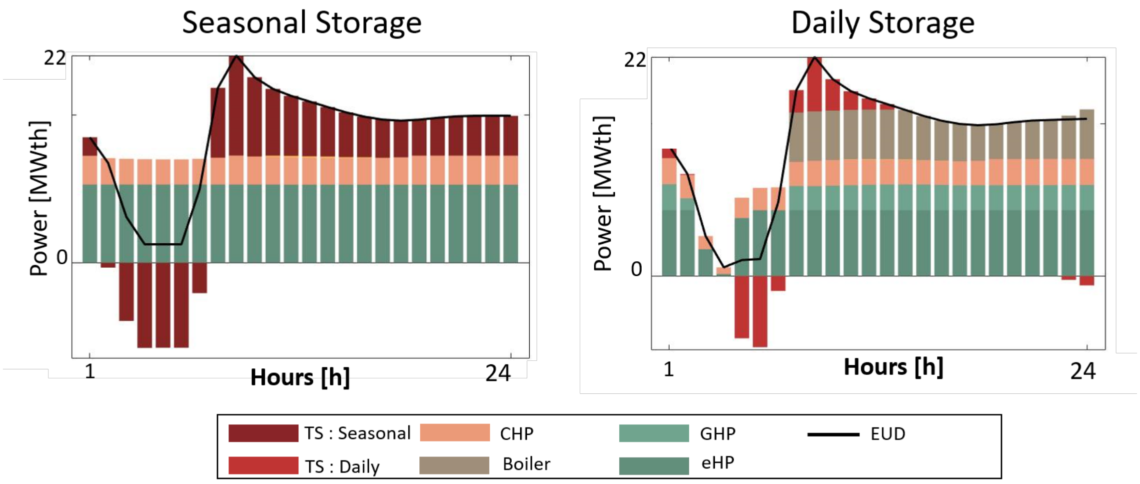

Figure 5.7: **The different energy systems depending on the type of thermal storage**

5.3 Influencing parameters

This section studies the different parameters that affect the designs and consequently the total cost of a neighbourhoods energy system. The available resources in the set neighbourhood will have a great influence on the energy production price whilst other intrinsic neighbourhood characteristics will have an impact on the infrastructure and its performances.

5.3.1 Different resources

Until now we have considered a standard set of technologies, those that could easily be installed in Wallonia. The only renewable source considered was the solar radiation. Depending on the location of a neighbourhood, other natural resources could be accessible. We will analyse the influence of these other potential RE resources could have on the energy design of a neighbourhood.[7]

Three neighbourhood scenarios have been defined. Each one considering the availability of a new type of RE resource :

1. **Wood** - We assume a neighbourhood at proximity of an exploitable forest. This local resource production gives access to a biomass at a price of 0.028 [€/kWh].[8]. In this case only, we consider a neighbourhood of 10.000 dwellings[9]
2. **Geothermal** - We assume a neighbourhood with a geothermal potential. Geothermal wells allow to reach at a depth of a few kilometers heat sources around a constant crust temperature of 80°. We do not take the electric demand of the pumps into account.

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[7] The neighbourhood reference size (3000 dwellings) remains valid unless mentioned otherwise.

[8] Price of locally produced wood for small- to medium-sized units.[4]

[9] Biomass technologies (especially, CHPs) are mostly available in larger capacities (than gas).

3. **Wind** - We assume a neighbourhood with sufficient wind potential. Utility-grade onshore wind turbine technology is considered.[10]. The wind time-series is based on the national Belgian wind speed.

All three scenarios enable the development of lower-priced energy systems. Their prices are displayed on Figure 5.8. [11]

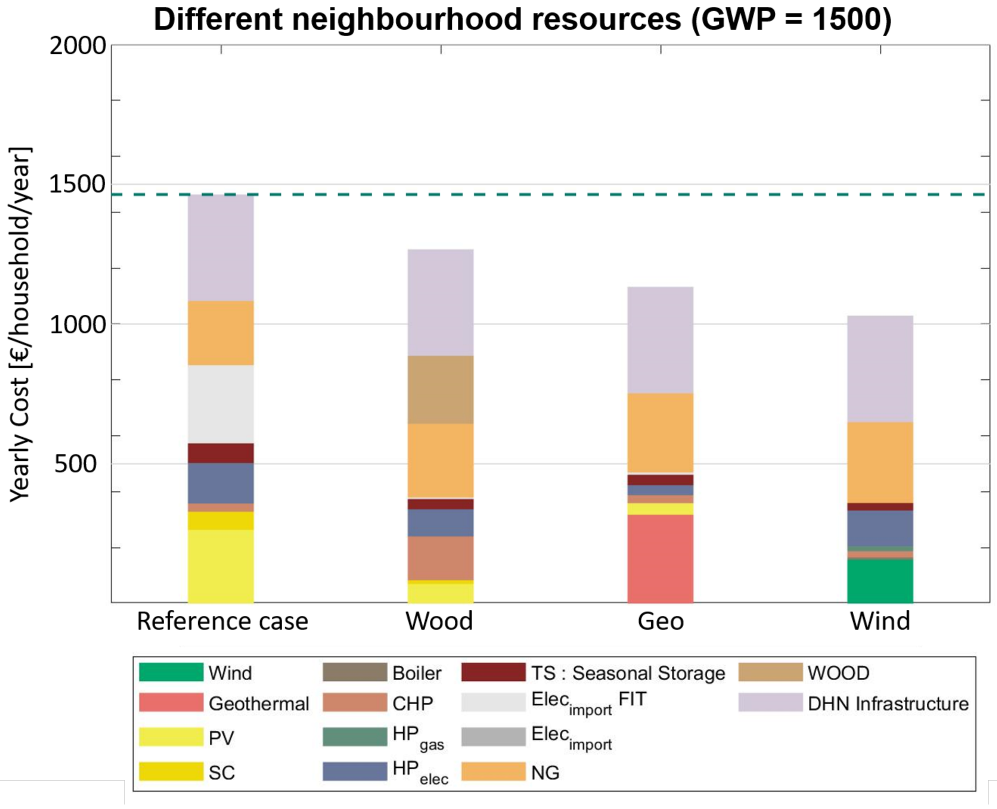

Figure 5.8: **Comparison of total costs between the reference case and 3 other neighbourhoods with access to renewable energy (wind, wood or geothermal)**

The local biomass based system offers prices 16% lower than the reference case. Here, wood fills in the same controllable role as the gas in the reference case. Its far lower global warming potential (21 times smaller than gas) means that it can be much more solicited for a same GWP. The CHP technology shows again great interest, being able to provide with a high global efficiency for electricity and heat. But this technology only exists in high capacities, the minimum installed capacity found is of 14 MW leading to a minimum district size close to 10.000 dwellings.
In this situation, for 10.000 dwellings and a gwp of 1500, the demand in biomass resource is of 86.85 [GWh] annually. This represents in a sustainable biomass exploitation of 1447 [ha] [12], one fourth the size of the Sonian Forest in Brussels.

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[10] Nominal power of 3 MW and capacity factor of 22.41 %.

[11] For the sake of comparison they were all taken at a GWP of 1500 kgCO2-eq/yr/household.

[12] Considering therefore a yield of 6 GWh/km² [38]

The geothermal based energy system is 25% cheaper. Geothermal wells provide a very competitive heat production price all year round. It supplies the majority of the heat production as the heating base load. The peaks are covered either by CHP, thermal storage or electrification.

The most interesting solution is the integration of wind turbines. It yields a decrease in price of 31%. When in operation, they are a very competitive electricity production solution; even more competitive that the PV panels considered until now.
In fact a wind turbine reaches a LCoE of 0.029 [€/kWh] [13] Wind resource availability and operation hours are also superior to PV panels. They have an annual capacity factor of 23.4% compared to the PV (11%).
In this situation, electricity is produced in abundance. More electricity is produced than necessary. Therefore there is no import at FIT and in addition there is a net export towards the grid (nearly 2.6 % of its total production). The neighbourhood becomes a power provider to the grid.
Even though the wind production is high, it remains intermittent.
Like in the reference case, the CHP is used as a backup to the wind production and together form the base load of electricity. The surplus electricity produced leads to the electrification of the heat, mostly through a large electrical heat pump and supplemented with a small electrical boiler.

In short, these renewable energy sources not only provide cheaper production solutions but also yield greener energy systems with higher auto-sufficiency rates as well. The wind system offers the most low-carbon solution as shown in Figure 5.9.

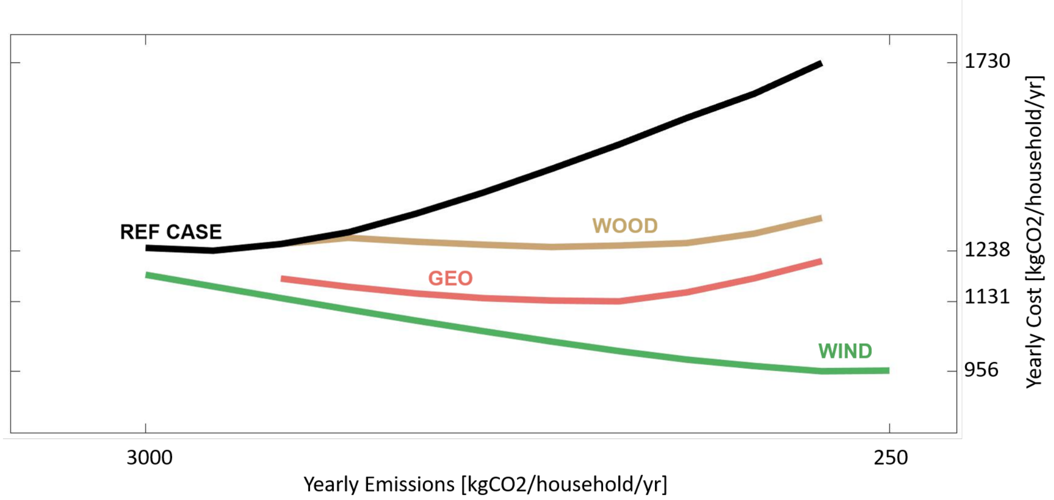

Figure 5.9: **Pareto fronts of total costs following the GWP variation for the different types of neighbourhoods**

5.3.2 Intrinsic neighbourhood characteristics

Neighbourhoods exist in many sizes, types and densities. They are certainly not equal and will definitely not have the same ideal energy system design.

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[13] Similar to the 0.030 [€/kWh] stated in a study done by the Danish Energy Agency, that states a LCoE of onshore wind, at 30 [€/MWh]. [1]

Two parameters, the neighbourhood size and the linear heat density (LHD) [14], allow to characterise the different types of existing districts (see Figure 5.10). These parameters mainly have an influence on the DHN design, even though it ripples down on the global design due the inter-linkage through heat electrification.

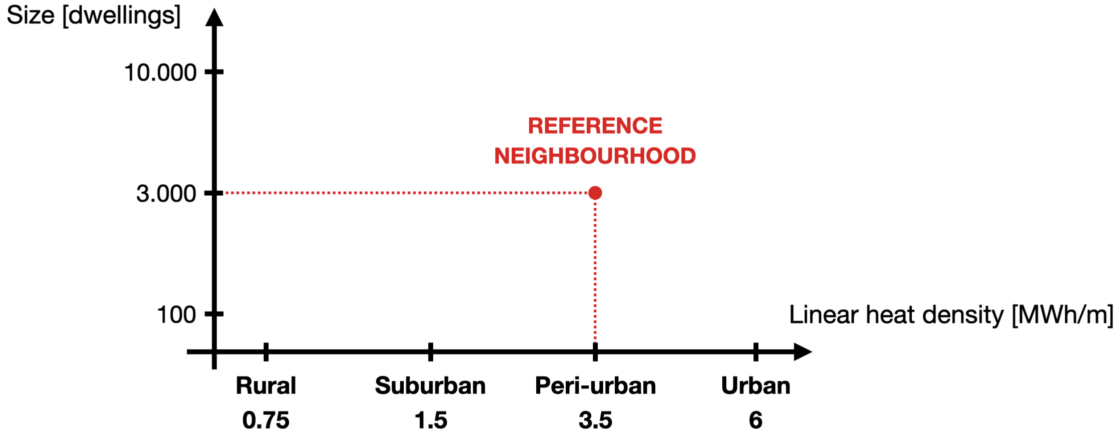

Figure 5.10: Neighbourhood characterisation in function of its size and its linear heat density (LHD). The reference neighbourhood is displayed in red.

The reference neighbourhood, studied up-to now, was a medium-sized 3000 dwelling peri-urban neighbourhood with a LHD of $3.5[MWh/m]$. We now study neighbourhood with different characteristics.

Size of neighbourhood

The size of the neighbourhood will influence the production cost as larger neighbourhood systems will have access to larger and cheaper technology solutions.

The optimal system design, in terms of technology choices and overall energy management, remains the same whatever the size of the system. Only the size of units and prices of technologies installed, change.
In smaller neighbourhoods, under 300 dwellings, smaller boilers and CHPs have to be installed. The thermal storage volume becomes so low that its use as large-scale storage solution becomes too expensive. Only daily (small-scale) storage solution technologies can be installed.

As a result, smaller neighbourhoods (regroupings of several houses) cost more per household compared to larger ones that approach sizes of entire towns or cities.

Linear heat density

The linear heat density (LHD), expressed in [MWh/m], influences the price of heat in two ways. A lower heat density means that the heat in the network will have to

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[14] Linear heat density is the annual heat demand per metre of grid length expressed in [MWh/m]. It is commonly used to estimate the financial viability of potential heat networks.

cover longer distances and leads to an increased relative and absolute heat loss in the system. In turn, this means more heat needs to be produced to cover the same district heating demand.
Therefore, the infrastructure installation costs of the network pipes will be higher in these rural neighbourhoods as the distances between the production and the consumers is larger (see Figure 5.11.

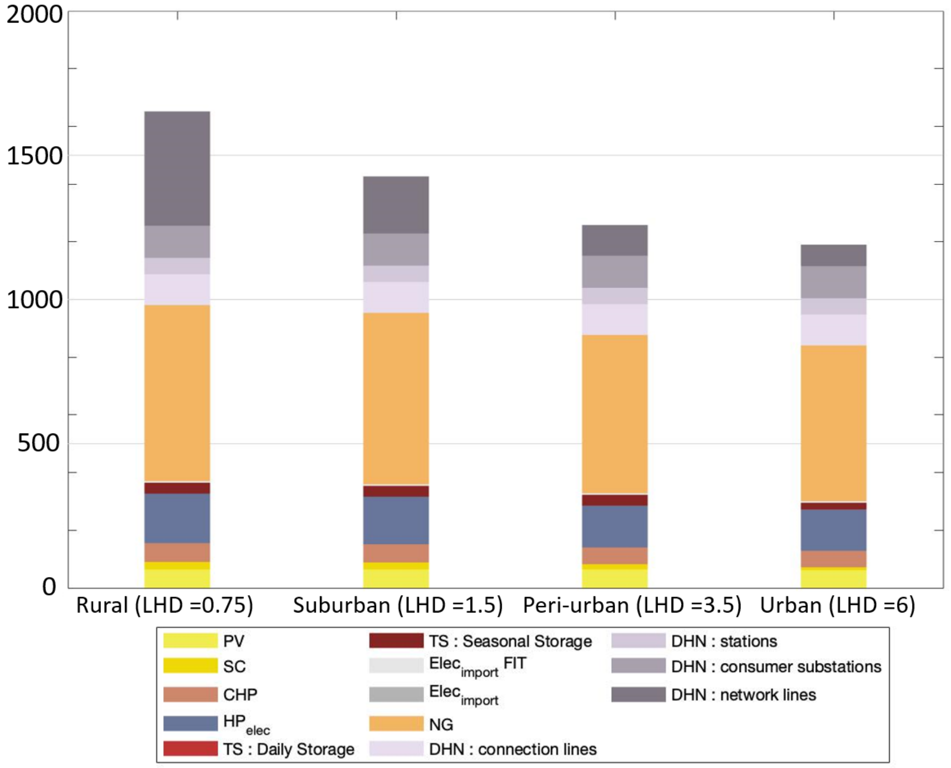


Figure 5.11: **The total cost comparison between the 4 different neighbourhood designs**

We observe an increase in the production costs, both the CAPEX and OPEX components, that is due to the increase in losses in the DHN system. It accounts for a change of 16% between the urban and rural cases.
The other and more significant change in price comes from the higher DHN infrastructure costs and in particular the higher network lines cost. The rural network lines cost is 533% the cost in an urban environment because houses are farther apart from each other as the is becomes much larger.

The following figure 5.12 summarizes the influence of both characteristics (size and LHD) on the consumers price.

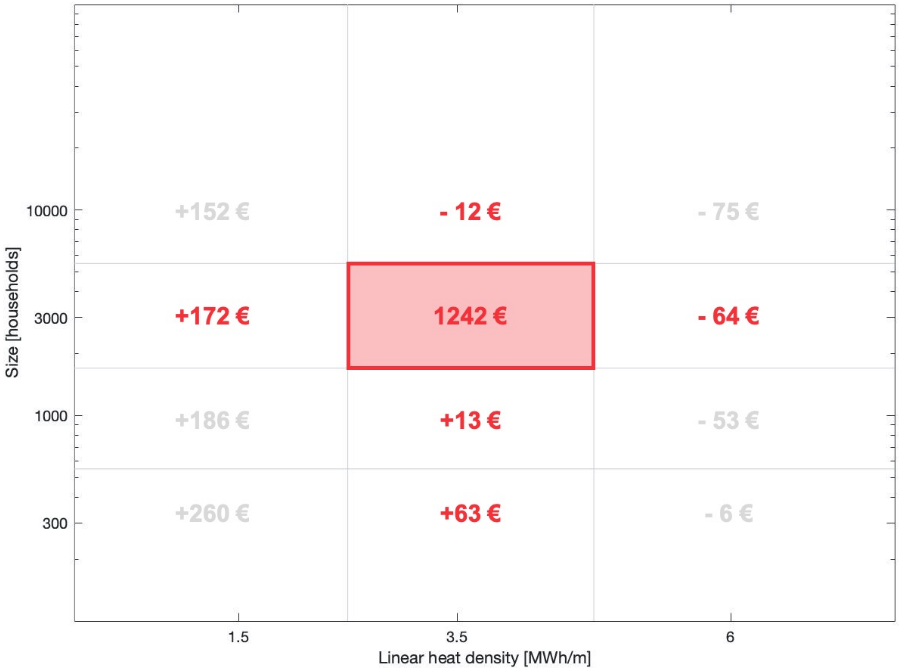


Figure 5.12: Specific household price variations depending on the characteristics of neighbourhood : size and LHD. Price differences expressed in yearly €/household in comparison to the reference neighbourhood (red rectangle).

Chapter 6

Energy Transition

The EU has the grand ambition of making Europe the first climate-neutral continent by 2050. This deadline is only 30 years away. And to achieve this low-carbon scheme and reach a zero-emissions state, big changes are needed at the residential sector level.

Most of the decisions made today, in 2020, are likely to be part of the low-carbon future. The average lifetime of production technologies and of a DHN are respectively 25 years and 50+ years.
The choices of today's energy system is a trade-off, drawn out between short-term cost minimisation and long-term low-carbon perspectives.

Domestic energy decisions are typically short-sided with the sole objective of minimizing the energetic cost. As detailed in the case studies, two residential energy system organisations are possible : separated in single houses or united in integrated neighbourhoods. Both optimal systems are compared for the different types of neighbourhoods. In a first part we will look at these optimal cost-effective solutions today in 2020. Then we will do the same for the low-carbon systems of 2050.

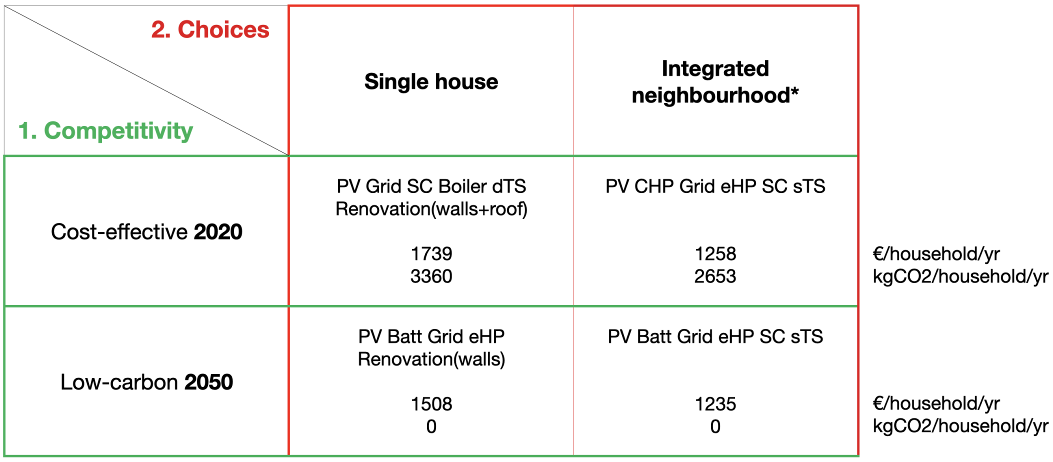
Once the economical comparison is done for both cost-effective 2020 and low-carbon 2050 (see Figure 6.1), we will then look one by one at the choices that should be taken today for the different types of neighbourhoods. The objective is to understand which investments today (2020) would be the most interesting for tomorrow's (2050) energy systems.

6.1 Today's situation : Cost-effective energy system

6.1.1 Energy system design comparison

The single house energy system treats electricity and heat separately whilst, on the other hand, the integrated neighbourhood system takes advantage of the additional flexibility that both the electrification and the seasonal storage provide.

The single house, due to the size limitations, can only install a few technologies at the same time. The integrated neighbourhoods do not have any of these limitations



2. Choices 1. Competitivity	Single house	Integrated neighbourhood*	
Cost-effective **2020**	PV Grid SC Boiler dTS Renovation(walls+roof) 1739 3360	PV CHP Grid eHP SC sTS 1258 2653	€/household/yr kgCO2/household/yr
Low-carbon **2050**	PV Batt Grid eHP Renovation(walls) 1508 0	PV Batt Grid eHP SC sTS 1235 0	€/household/yr kgCO2/household/yr

Figure 6.1: The 2 reference cases are represented on this figure, each time, in the 2 contexts studied, i.e. 2020 and 2050. Abbreviations : Daily Thermal Storage (dTs), Seasonal Thermal Storage (sTS), Electrical Heat Pump (eHP), SC, Lithium Battery (Batt).

and may benefit much more from the many flexibility options.

Electricity management is quite straightforward. In both schemes, it is mainly provided by PV panels and supplemented either through a CHP unit in the case of a neighbourhood or, in the case of the house, through electric exchanges with the grid through the FiT grid policy.

Heat management on the other hand is dealt with in different ways. The single house classically treats it mainly through a gas boiler and decides to lightly renovate with wall renovations. The neighbourhood does it through electrification and the CHP combined with the large seasonal storage.
Solar collectors in both cases are used in order to limit the use of gas boilers during sunny days but do not play a vital role in the system.

6.1.2 Competitiveness of different systems in 2020

The optimal solution depends on the type of neighbourhood. Whilst the single house energy system and cost is constant within the assumptions of this work, the neighbourhood costs will depend on the intrinsic characteristics of the case study. The LHD is the main parameter that influences the result. The size of the neighbourhood has limited influence on the cost of the energy system. In fact, larger units leads to cheaper LCOE of heat.

We observe this trend on the reduced neighbourhood domain Figure 6.2. The LHD axis is now focused especially between a null and peri-urban (3.5) density neighbourhoods. Above these values the integrated neighbourhood organisation remains the most interesting solution.

The limit at which an integrated neighbourhood stops being the optimal solution and where a single house becomes the more interesting option appears, at a linear

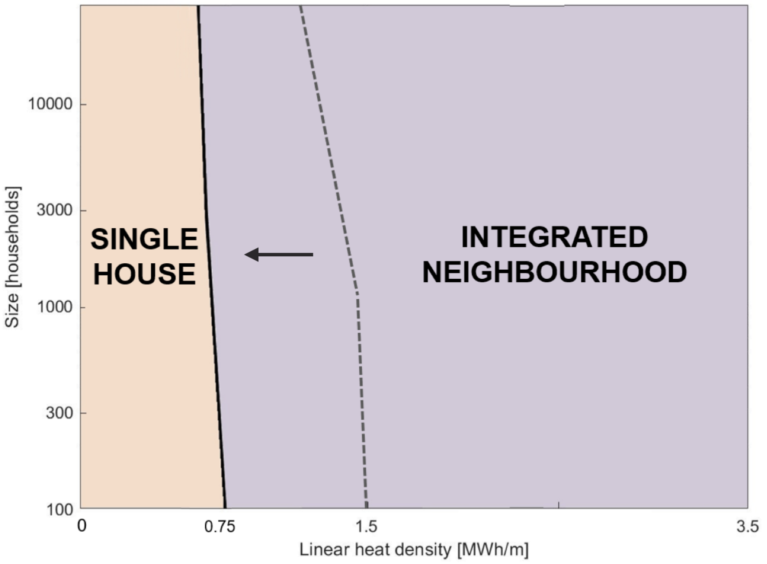


Figure 6.2: Optimal cost-effective 2020 scheme depending on the type of neighbourhood

heat density of 0.75 MWh/m. In more classical DHN neighbourhoods (only focus on the heat supply and where the electricity is treated apart) the limit is at a higher density value of 1.5 MWh/m : values equivalent to those found in the literature [36, 12]. This shows once again the positive impact of managing both heat and electricity together within a same integrated neighbourhood.

The transition from integrated neighbourhood to a decentralised solution is an abrupt switch-over.
At no point, it is interesting to have a energy demand split between DHN and decentralised house system.
The steep fixed DHN infrastructure price implies the use of district production technologies which offers low-cost energy. If decentralized energy takes part of the energy demand, the DHN will not be fully used despite the massive investment. The total cost will then be much higher. Decentralized and DHN technologies will thus not coexist, from a financial point of view. The switch in system will only occur when a fully decentralized solution becomes more competitive than the entire DHN system itself.

The influence of the neighbourhood size is negligible and we will consequently only focus, for the later analysis, on the LHD variation to describe the different neighbourhoods. The size of the neighbourhood is supposed at 3000 dwellings.

In order to understand the main reasons behind the two total costs, a further investigation based on the different components differentiates the single house solution from the integrated neighbourhood prices, displayed on the Figure 6.3.

In this example, we maintain the reference neighbourhood environment valid (LHD of 3.5 MWh/m and pop of 3000 dwellings). Therefore, the integrated neighbourhood shows a more cost-effective solution by 18%.

From left to right we observe respectively the variations in total yearly cost related to multiple factors : the difference in price for neighbourhood technologies, the new technologies (only available in the integrated neighbourhood), the heating network losses and finally the network infrastructure costs.
These economic changes are expressed in percentages related to the same base cost, the single house.

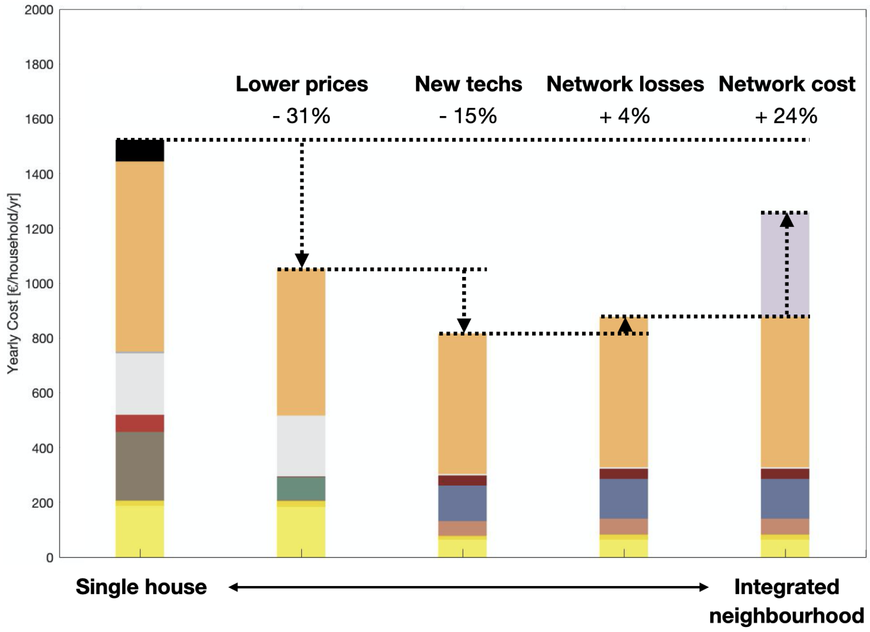


Figure 6.3: Cost components between single house to integrated neighbourhood.

The cost of centralised production induces the biggest cost (-31%). Bigger units mean lower prices. In return the increase in cost related to the network losses and infrastructure accounts for a similar +28%.
The net reduction in price thus comes from the additional DHN technologies and the flexibility associated. In particular the CHP and the larger seasonal thermal storage solution play huge roles in the flexibility increase and are the main reasons for this reduction in total costs, and this accounts for -15%.

6.1.3 Competitiveness of renovation in the different systems

This section looks at the competitiveness of the renovation in both schemes (single house and integrated neighbourhoods). It has been processed from a whole-system perspective by looking at the attractiveness of each proposition when a house has the choice to be linked to an existing system or to function by itself in a decentralized manner (see Figure 6.4).

As we have seen in the house section, decentralized heat production and walls renovation match well together. In fact, light renovation takes part of the optimal solution at the house scale.

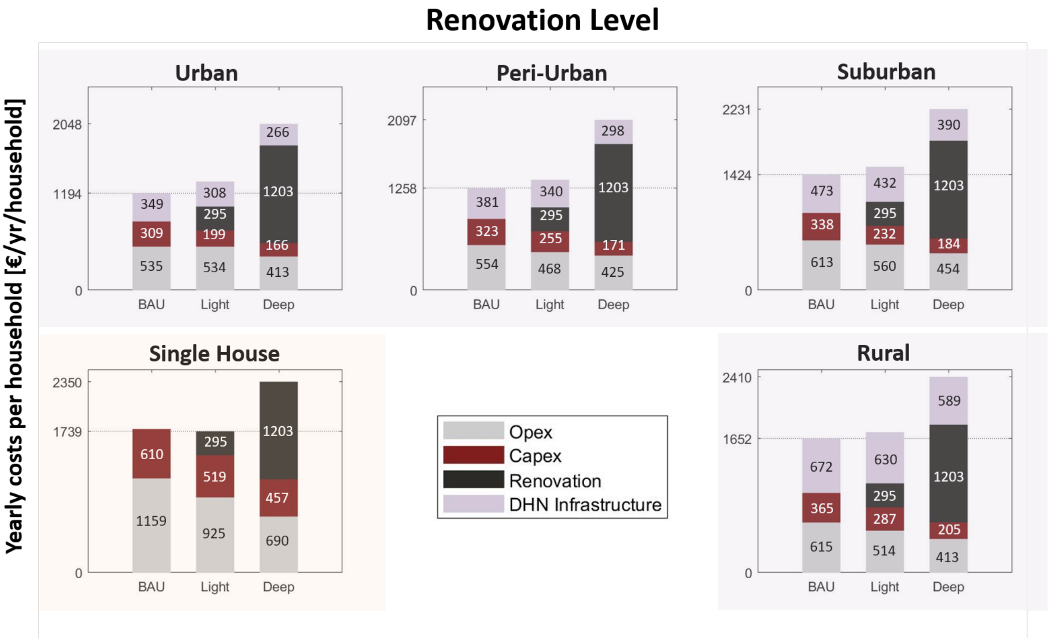


Figure 6.4: Yearly costs in function of for the different types of neighbourhoods

But district heating networks and renovations are not compatible. The confrontation between the DHN and renovation is the same as the one between DHN and decentralized technologies. The cost of infrastructure represents a significant investment, but it provides access at the same time to relatively low-cost energy and wider range of centralized production units.
As the renovation will never cover the whole heat demand, a DHN connection remains necessary. Considering its actual mandatory fixed costs (approx. 60% of the infrastructure costs), the energy demand reduction actually competes with the low-cost energy production. In fact, it will typically not be installed. The Business As Usual (BAU) (no renovation installed) remains the optimal solution regardless of the neighbourhood environment.
The light renovation costs at minimum 100 €per household and therefore additional heat production with losses through the DHN is favored. This unfortunately leads to more carbon-intensive neighbourhoods (i.e for the rural case, the CO2 emissions increase by 19% from the Light to the BAU case).

However, we note that the price of infrastructure still decreases[1] when the share of renovation increases. This is because the DHN has to cover less in terms of demand due to the energy reduction of renovation. Unfortunately, this is not enough to make the renovation attractive due to the high fixed costs[2] of the infrastructure.

It should also be noted that when we examine the situation of a completely renovated rural neighbourhood, the situation of a house in the integrated neighbourhood becomes more costly than an isolated house in the same configuration (and this by 3%).

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[1] Smaller stations and substations need to be sized. Their price depends on the heat demand to supply.

[2] Assuming the LHD and the total EUD vary at the same rate, their variation is cancelled. Connection lines and main pipes costs remain thus constant.

Finally, renovation and integrated neighbourhoods do not match together. At least, renovations would only become competitive in very low heat density neighbourhoods (<0.75), when heat losses would become extremely high. Huge amount of heat would have to be produced to cover the same demand. At this condition, DHN would surely no longer be of interest.

6.2 The objective : Low-carbon energy system

6.2.1 Energy system design comparison

Low-carbon energy systems are based on the same combination of technologies for both the integrated neighbourhood and the single house.

Both systems convert electricity (the most affordable low carbon resource considered in the model) to heat.
Electricity production is solely provided by PV panels whilst heat production is provided by an electric heat pump and solar collectors. These solutions diverge from one to another in the buffer options available.

The integrated neighbourhood relies deeply on the seasonal thermal storage to value the excess PV production by storing it in the form of heat.
The single house will still depend on the electricity grid exchanges via FiT (assuming this grid policy still valid in 2050).

By 2050, and according to predictions, the price of lithium-ion batteries will approach prices of 200 [€/kWh] and thus become interesting for a daily storage of electricity. Both the house and neighbourhood will use batteries for this purpose.

6.2.2 Competitiveness of different systems in 2050

The low-carbon 2050 solution re-evaluates the limit between the optimum of an integrated neighbourhood and a single house, in Figure 6.5.
The reduced prices due to the technology maturation, the accessibility of low-power technologies in decentralized and the arrival of the lithium battery in the energy system, lead to have a more attractive and competitive proposition for the house. We observe this on Figure 6.5 and 6.6, where the limit reaches a higher LHD of 1.3 [MWh/m]. The single house scheme becomes now more interesting for a larger spectrum of neighbourhoods such as rural environment.
For the same reasons as previously[3], the switch from one optimal solution to the other is an abrupt switch-over.

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[3] The high fixed DHN infrastructure price means that the decentralised production is solely and directly compared to the centralised low cost production solution.

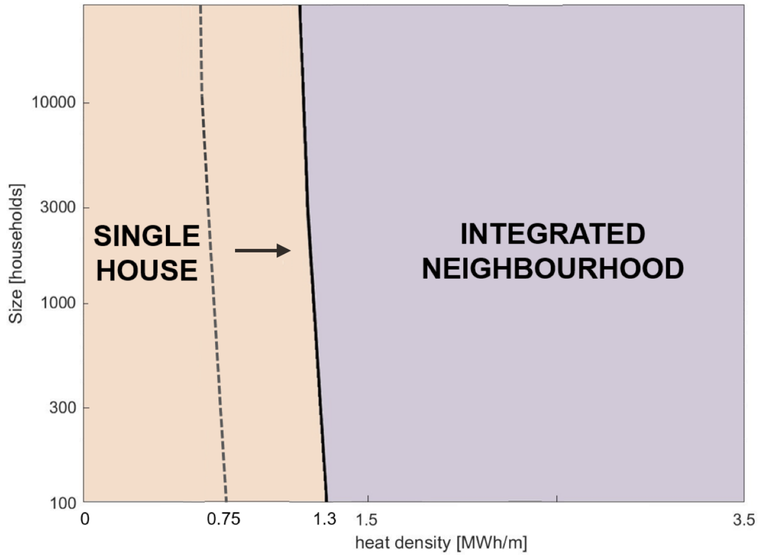

Figure 6.5: Optimal low-carbon 2050 scheme depending on the type of neighbourhood

6.3 Energy system choices

We now have an understanding of the optimal energy systems both in the 2020 cost-effective case and in the 2050 low-carbon case. The main critical question remains : which affordable energy system should we invest in today and tomorrow's low-carbon future ? And what are the associated costs in such a future-proof approach ?
Answers will of course depend on the type of neighbourhood.

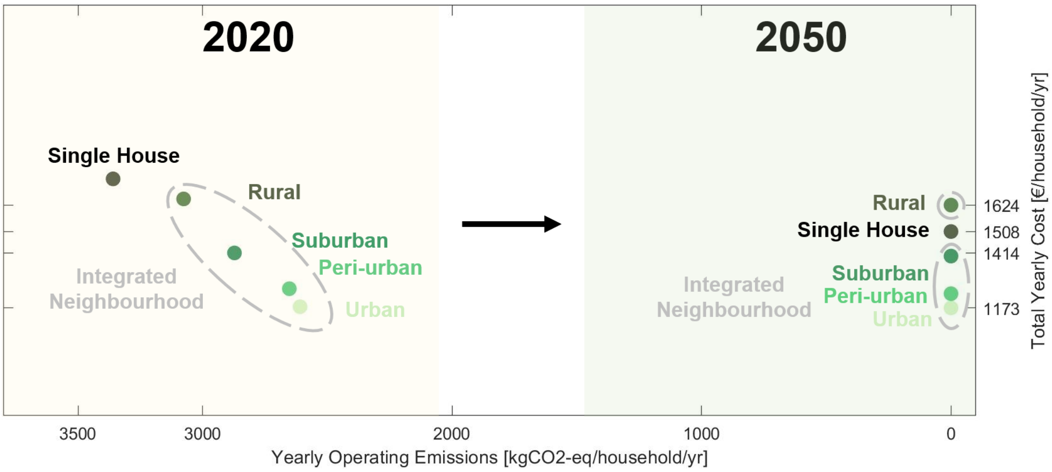

Figure 6.6: Comparison of the cost-effective 2020 and low-carbon 2050 solutions in function their yearly costs (x-axis) and emissions (y-axis)

Low density neighbourhoods (below 0.75)

In rural scenarios, areas with a LHD below 0.75, the optimal residential design consists of individual single house energy systems. The 2020 cost-effective system today differs from the full-electrification low-carbon one in 2050.

The ideal solution for the decentralized consumer seeking exclusively to minimize his total costs is the following :
The first stage is to review the condition of the energy system. If it is outdated, it is encouraged to use a cutting-edge gas boiler, coupling with a thermal storage for the best performance, and apply light renovation to the building. This will drastically reduce the building energy performance (PEB classification).
For the electrical needs of the home, photovoltaic panels are the optimal if not the best alternative to import electricity at standard prices.
In a second stage, once the gas based technology will reach its technical lifetime, it will have to be replaced by an electrical heat pump in order to reach the 0 carbon emission operational goal of 2050. A lithium battery is also strongly encouraged, to bring more flexibility and limit the load on the electricity grid at FIT. This will then allow an auto-sufficiency of around 83%.

Higher density neighbourhoods (above 1.3 MWh/m)

Above a linear heat density of 1.3 MWh/m, the integrated neighbourhood remains the optimal residential solution; both in the cost-effective 2020 case and in the low-carbon 2050 scenario.
The energy systems are based on the same technologies, ie. PV panels, eHPs and a large seasonal thermal storage, but differ in the technologies available for the flexibility management of the system. In 2020 the electrical controllability comes from the gas CHP whilst in 2050 the daily flexibility is solely provided by batteries as higher amounts of PV are planned to be set.

According to our results, the optimal choice for these neighbourhoods is to invest in a DHN network with a CHP and to slowly phase it out through the installation of batteries once these are available at competitive prices.

Neighbourhoods between 0.75 and 1.3 MWh/m

In this case, the optimal design in 2020 is to install an integrated neighbourhood but by 2050 the single house design seems to become a more interesting proposition. As the investment in a DHN infrastructure is high and the lifetime of such a system is of 50 years+, the proposed solution is to invest in a decentralised single house energy system as for the low density neighbourhoods.

Chapter 7

Discussion

First of all, ES model is a planning tool which aims to observe major technological trends. An extended study will have to be undertaken to observe the reliability of the technology interactions in their daily operation.

We supposed there is no existing heat supply in any case studies (single house or neighbourhood). Our assumption is therefore based on the fact that the actual installation has reached its technical lifetime and needs to be replaced by a new energy system. The analysis of the incremental cost and return on investment by switching from a single house to an integrated neighbourhood was not considered in this thesis. Thus, our case study only focuses on the dimensioning of new energy systems.

The model developed does not include mobility. Vehicle2Grid (V2G) is therefore not taken into account, and could potentially provide an energy flexibility solution. Renewable fuels are also excluded from the simulation. At low emissions, they could potentially compete with the solution of electrification of all energy.

In the 2020 scenario, the Feed-in Tariff (FIT) policy is considered to be already in place. The identical political framework has been supposed, for both schemes and allows to "store" their electricity production on the grid at a Feed-In Tariff. In order to reach the 2050 objectives (which impose carbon neutrality from an operational point of view), the electricity (at FIT), is considered at zero net CO2 emissions. This hypothesis is quite serious at a national scale, especially if this solution is replicated for a large number of neighbourhoods. This macro analysis is therefore not included in our case study.

A parametric study in Figure 7.1 shows the evolution of a single house and neighbourhood auto-sufficiency as a function of total cost. From a practical point of view, it is impossible for the house to become completely autosufficient. A mathematical solution exist but it is far from being consistent with reality. Therefore, it is limited to 90% autosufficiency. For the neighbourhood case, it can however reach a higher autosufficiency (99%) provided that solar collectors and photovoltaic panels are installed in very large quantities in order to meet the winter energy needs.

Since it is difficult to project future resource prices, they remain unchanged from 2020 in the 2050 scenario. Also, the Feed-in Tariff, initially aiming to cover losses

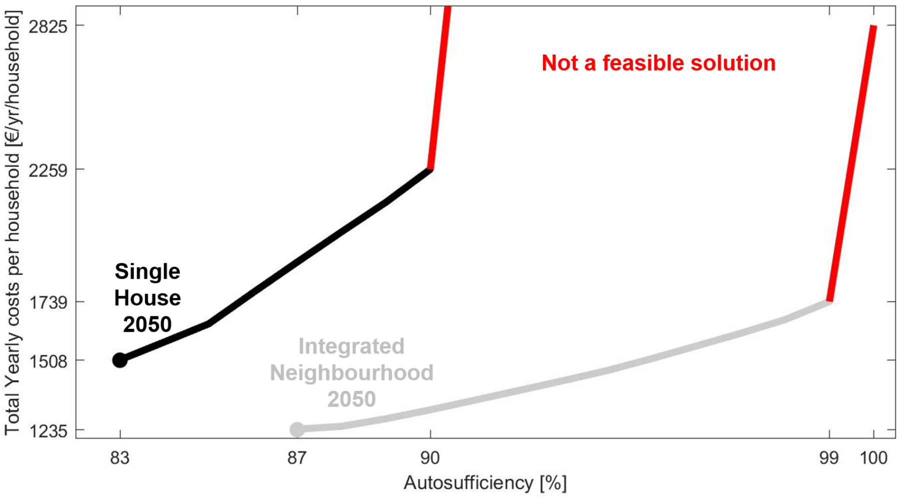

Figure 7.1: The graph shows the influence of the auto-sufficiency on the total energy system cost. When the energy system becomes more auto-sufficiency, closer to 100%, its total cost increases de facto. The red line on the graph, shows a solution for both cases, provided by the model, but not feasible in reality.

and maintenance of the power grid, has been considered as constant, and therefore identical to 2050.

Chapter 8

Conclusion

Our study reviewed the various technological solutions in order to reach a low-carbon residential sector by 2050. Optimal energy systems were identified both in decentralized and centralised schemes.

Today the cost-optimal design today still highly relies on gas resources with a boiler in the single house and a in the integrated neighbourhood.

Future low-carbon requirements imply in both cases fully-electrified energy systems. Heat is provided through electrical Heat Pumps (eHP) whilst electricity is entirely supplied by PV panels.

But this high intermittent Renewable Energy (RE) will be integrated through flexible solutions. In fact, they have to be included in the energy system to manage the produced energy by decoupling the energy demand from its production. In 2050, batteries will supplement thermal storage solutions to provide flexibility in daily applications, each in their respective layers.Nevertheless, the actual main challenge remains in the longer term storage solutions. Indeed, only integrated neighbourhoods have access to large-scale heat storage solutions, through seasonal application.This long-term buffer solution enables to optimize both the financial and environmental aspects.

Neighbourhoods provide more flexibility solutions and are much more interesting in the energy management. But their high fixed infrastructure costs do not promote renovations.
On the opposite, single houses lean more towards energy reduction, due to their low alternative options.

Two pathways are therefore foreseeable. One with renovation in a decentralized system and an other in an integrated neighbourhood without renovation.
The upcoming future will more likely be a combination of these different solutions. Indeed, integrated neighbourhoods have a great potential in more dense area whereas single houses with renovation will remain the optimal solution in more rural situations.

The further development of the integrated neighbourhood energy systems is quite promising. The coming generations of District Heating Networks (DHNs) focus on low temperature networks while offering both lower losses and reduced infrastructure costs. Higher DHN performances would allow the integrated neighbourhood design to be installed in an even broader range of districts. Additionally, the decrease of fixed cost could make the renovations more competitive to centralised heat production.It would bring the best of both schemes in one residential energy system.The DHN will therefore become even more affordable in the future and accessible in lower density region.

Finally, under our electricity exchange assumptions, the high reliance on PV panels implies a greater dependency on the electrical grid.
By observing the auto-sufficiency of the different solutions, the integrated neighbourhood reaches, for limited costs, a higher rate than in a single house scheme in the current political context.

On a national level, given the current trade-off between increasing the auto-sufficiency of the integrated neighbourhood, at the expense of the neighbourhood's prices and, relying heavily on the grid at the detriment of the grid balance, what compromise will be optimal for both the national electricity supply and the integrated neighbourhoods ?

Appendices

Appendix A

Methodology appendix

A.1 Photovoltaic ROI

In EnergyScope, for the Walloon case (no more green certificates considered) in 2020 the ROI of a PV installation is of 6.3 years. The auto-consumption identified is 37.96%. This implies a net Fedd-in Tariff (FIT) very close to the Prosumer Tariff (PT) (below 37.76%).
Comparing this result to the one provided by Engie [11], this one seems similar. Indeed, Engie confirms that the return on investment of a pv installation is about 7 years (also without green certificates), in Wallonia, in 2020, by applying exclusively the prosumer tariff.

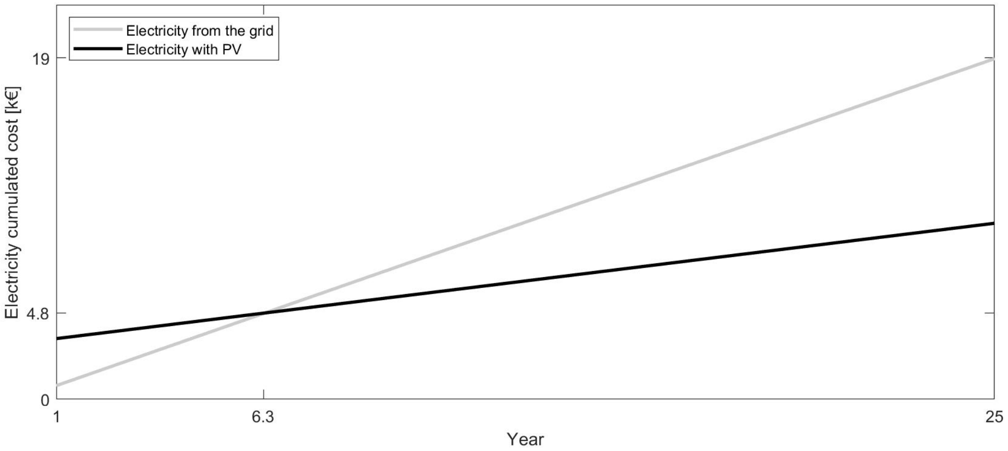

Figure A.1: This graph represents the cumulative annual electricity cost as a function of time. The electricity system provided by PVs (black line) is initially more expensive due to its investment, then after 6.3 years, it becomes much less expensive than simply taking electricity from the grid at standard rates (grey line).

A.2 Technology over-sizing

A GHP (Gas Heat Pump) of 18 kW is installed, but can only supply (in our simulation) a maximum 6 kW in an hour. The reason is simple; the model in question is written in linear programming. As explained above, over-sizing factors have been considered in order to be as close as possible to the existing installations of the market and to meet the energy demand of the last 10 years in Belgium. For the hourly approach, this model supplies energy according to the theoretical heat demand, without considering this over-dimensioning, although it is taken into account in the global solution. Overall, the proposed solution is approximately correct[1], but the hour-by-hour approach is not optimal since EnergyScope is not dedicated to daily energy system operation.

A.3 Ground temperature profiles

The profile of the ground temperature was developed from the air temperature profile provided by the meteorological data of Uccle, 2005. This was imperative as all time series have to come from the database; same location and same year. It had to be modeled.

No single soil temperature models were found in the literature. Hence, we developed our own simplified model articulated around the following characteristics of the researched ground temperature characteristics. These are :

- Lower frequency temperature profile in comparison to the air temperature.
- The shallow soil still follow the same daily temperature trends but with a delay that increases with the depth.
- The deeper, the more the profile approaches a yearly constant temperature, the mean yearly temperature of the air (9.92°C in Uccle).
- The ground temperature is warmer than the air in the winter and cooler in the summer.

Our simple model thus takes the thermal mass and inertia of the ground into account. This has been done by evaluating the temperature at a set time by taking the temperature of the previous hours/days into account. And the frequency is reduced through a filter to approach the data found in the literature.

We have modelled the ground temperature at Uccle in 2005 for four different depths: 10cm, 50cm, 2m and 4m.

One representative week in the winter (left) and in the summer (right) weekly zooms are visible to show the daily variations in ground temperatures, on the Figure A.2.

The two shallower profiles (under 1m) retain some high frequency (daily) variation. They follow a dampened version of the profile and have a delay of a couple of hours.

In the deeper time series, the high frequency variations have completely disappeared. At 4m the temperature really starts to approach daily constant values. Seasonal

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[1] The use of a thermal storage is questionable, during the morning peak, as enough power should be installed to supply the heat demand. But its share is relatively low in proportion to the total costs.

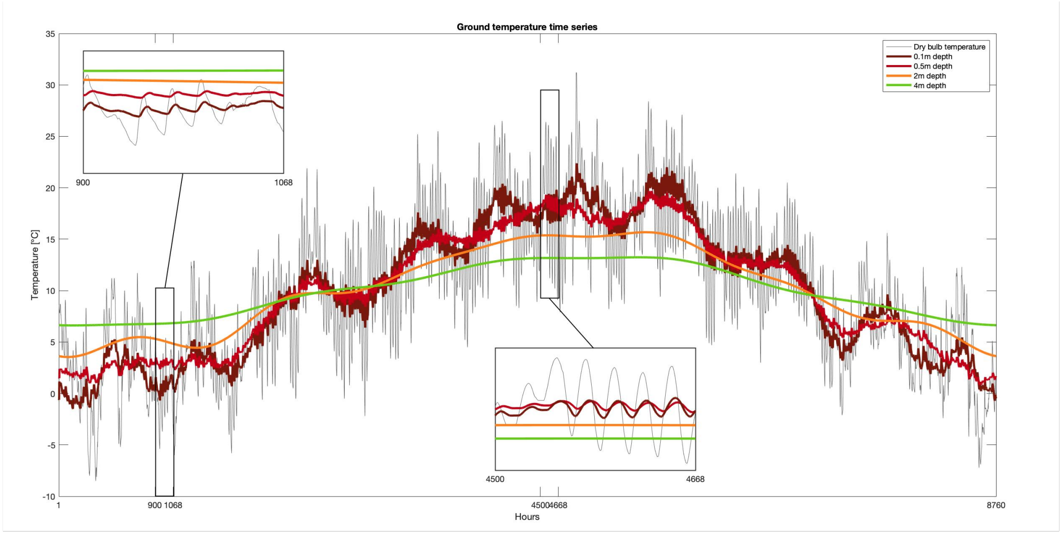

Figure A.2: Temperature profiles. The dry-bulb temperature (air temperature) provided by the Uccle data is displayed in grey. The modeled ground temperatures at different temperatures are displayed in different colors.

variations remain with a higher temperature soil in the summer and a lower temp in the winter.

All the detailed characteristics are hereby present.

A.4 Typical days (TD) - single house case

Figure A.3 gives a complete view of the TD selection from the three distinct time-series profiles that are taken into account, ie. electricity, space heating demands, and the global horizontal irradiation resource.

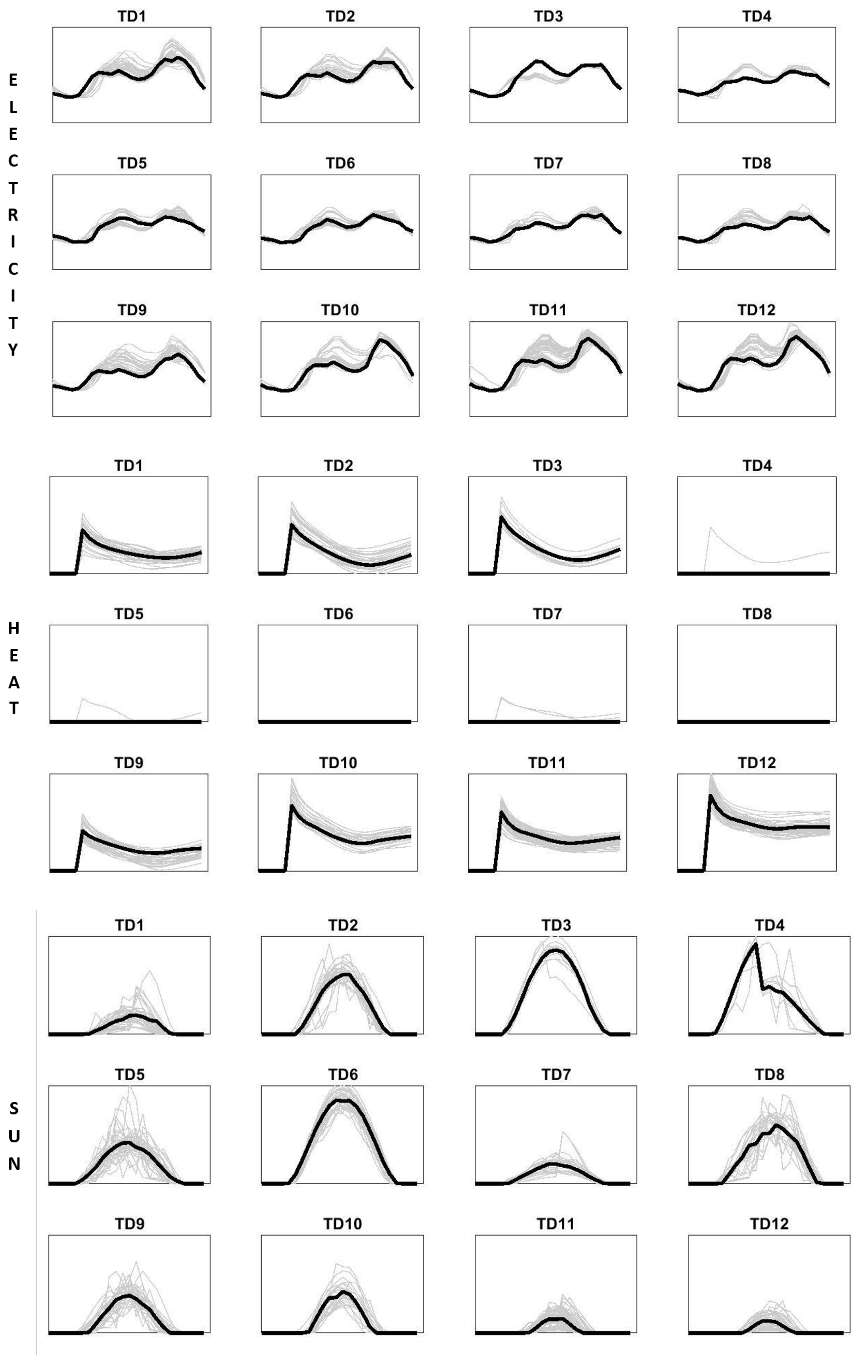

Figure A.3: The 12 TDs corresponding to the Elec (1) and Heat (2) production profiles and the GHI irradiation profile (3). Daily power profiles with the x-axis and y-axis expressed respectively in hours and kW.

We observe the impact of the TD approach on the reconstructed yearly demand profiles of figure A.4.

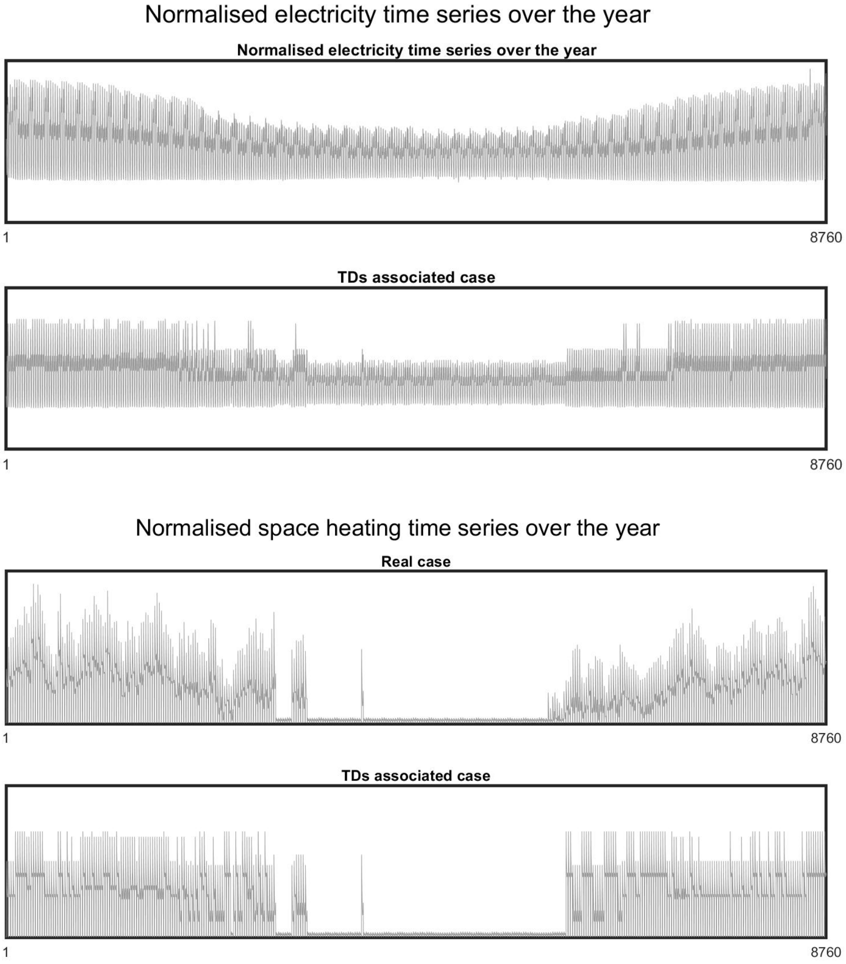

Figure A.4: These 2 comparisons of graphs between the real time-serie and the one provided by the TDs, on a year basis. show graphically how the ES model perceives it.

A.5 Cost of heat reduction through renovations

Energy renovations are an option to reduce space heating consumption within a building. Different renovations are possible within a house. Each one has its own price and its own heat reduction capacity.
The four most common types of renovations are considered in the model, ie. wall renovation, roof renovation, floor renovation and the replacement of windows.

The relationship between a set renovation and its energy reduction impact is less tangible. In comparison, to a production unit where power and production capacity is known at purchase, the price and potential savings associated with a renovation is thus less straightforward. Therefore, we reviewed the scientific literature on this subject to understand how to best represent these different renovations. [22, 24, 27, 30]

Renovation incentives

The support mechanisms were considered to be spread over 20 years (defined in an arbitrary way), given that the cost of the infrastructure, as a parameter in ES, is already annualized.

A.6 Resources prices 2020

Table A.1: **Resources Year 2020** - Belgian Housescale ES data

	$\mathbf{c}_{op}$ $[€_{2020}/kWh]$	$\mathbf{gwp}_{op}$ $[kgCO_2 - eq/kWh]$
Resources :		
Electricity	0.286	0.29
Oil	0.0.64	0.311
NG	0.0.52	0.251
Wood	0.051	0.012
Waste	0.027	0.15
Solar	0	0

Appendix B

Single house appendix

B.1 House validation

Verification of the ES model

The CREG[1] has provided the cost of the annual energy bill in Wallonia for 2019 for a representative electricity and gas consumption. This energy demand is above our defined threshold. In Wallonia, the gas bill for a consumption of 23260 [kWh/year] amounts to 1187 [€/year], while electricity for a consumption of 3500 [kWh/year] costs 979 [€/year].

This specific energy demand will be considered only for the validation case. In fact, this section aims to validate the EnergyScope model at a household level, and will ensure that our following analysis and assumptions hold up. However, as those costs were given by the CREG, this analysis excludes prosumers and only focuses on the case of a classical house, i.e. a gas boiler, electricity import and thermal storage. As a result, auto-sufficiency and auto-consumption are neglected in this study, only the OPEX and CAPEX are compared according to the installed technology.

Table B.1: **Comparison between the ES model and a Real Case**

	2020 ES no RE	2020 REAL no RE	Unit
Opex			
Electricity Imports	1001.35	979	€
NG Costs	1271	1187	€
Capex[2]			
Heat Tech	Gas Boiler	Gas Boiler	
Power	17.4	24	kW
Annualized CAPEX	314.5	310.8	€
Annualized Maint. Costs	82.73	40-70	€
Thermal Storage capacity	483	496	Liters
Annualized CAPEX with Maint.	143.39	203.8	€
Total annualized cost	2813	2755.6	€/year

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[1] (Commission de Régulation de l'électricité et du gaz)

The data between the case (ES and the real case) is displayed on the Table B.1. From an OPEX point of view, the differences are explained by the price variation. The real case is based on the gas and electricity price in end of December 2019 in Wallonia. At this time, the prices were slightly lower than the price identified by ES (considered constant along the optimization). Therefore, as the gas price is volatile, a gap can be observed but still valid.

From heat appliances perspectives, when comparing technologies and efficiencies, the Vaillant EcoTec Pro [33] 24 kW boiler (available in the 2020 market), matches quite accurately with the boiler defined in ES. ES defines its investment cost following the output power whereas actually, there is no linear variation. A 24 kW boiler does not cost twice more than a 12 kW [6]. Therefore, the CAPEX analogy between a 17.4 kW boiler from ES can be made with a real boiler of 24 [kW]. Regarding the maintenance costs, it is compulsory especially in Wallonia to review the heat installation every 3 years [18]. Its cost is between 110 and 200 €per revision. The ES model supposes a maintenance cost of 82.73 [€] a year. Following Lampiris, a gas boiler review recommended every 2 years[3], is estimated at 160 €[17]. This leads to the conclusion that the results obtained from ES are quite realistic.

From the thermal storage side, the UniStor VIH R 500 from Vaillant [33] with a 500 liters tank capacity, is used. Although a small pricing difference (around EUR 60) is observed between the two situations (see Table B.1, it is assumed to be of approximately the same order of magnitude.

Therefore, in conclusion, our ES model finally represents a reliable picture of the reality of 2020. Indeed, the price difference between the two situations is only about 60 euros. The error percentage is 2%.

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[2] Considering investment and maintenance cost

[3] Evaluating the cost of maintenance, over 3 years, is even more variable.

B.2 Parametric study on the reference case

Table B.2: **Reference case comparison**

	Ref Case No renovation	Ref case No SC	Ref Case No TS	Ref case	Units
Electricity					
Import (Standard)	25	25	-	25	kWh
Re-import (FiT)	1629	1629	1635	1629	kWh
PV	2.75	2.75	3	2.75	kW
Heat					
NG	17858	13890	13435	13357	kWh
Boiler_{NG}	13	11	16.89	11	kW
SC	0.7	-	0.7	0.7	kW
Storage					
Thermal Storage	14.45	8.37	-	8.37	kWh
Reduction					
Walls	-	28	28	28	% of SH saved
Total costs	1767.91	1747.37	1826.24	1739.22	€/yr
Total GWP	4738.57	3734.38	3645.95	3606.63	kgCO2/yr

Table B.3: **Full electrification comparison (no pv restriction)**

	Full electrification No pv limit	Full electrification With pv limit	Units
Electricity			
Import (Standard)	-	35	kWh
Re-import (FiT)	3882.3	3557.3	kWh
PV	6.5	6	kW
Heat			
HP_{A2A}	4	2	kW
HP_{A2W}	8.01	8	kW
Storage			
Thermal Storage	10.5	10.2	kWh
Reduction			
Walls	28	28	[% of SH saved]
Roof	2	12	[% of SH saved]
Total costs	1924.8	1968.9	€/yr
Total GWP	669.6	610.6	kg-CO2/yr

B.3 Sensibility studies : Influence of different heat demand profiles

Four different types of households are introduced in the single house case study. They were described as having different annual EUDs values (see Table 4.3) assuming the same demand profile. We looked at its influence on the optimal decentralised energy system.

In this section, it is the opposite that we aim to study. We consider a constant yearly EUD value and rather focus on the influence of the electricity demand profile.[4] Four different profiles are thus investigated (Figure B.1).

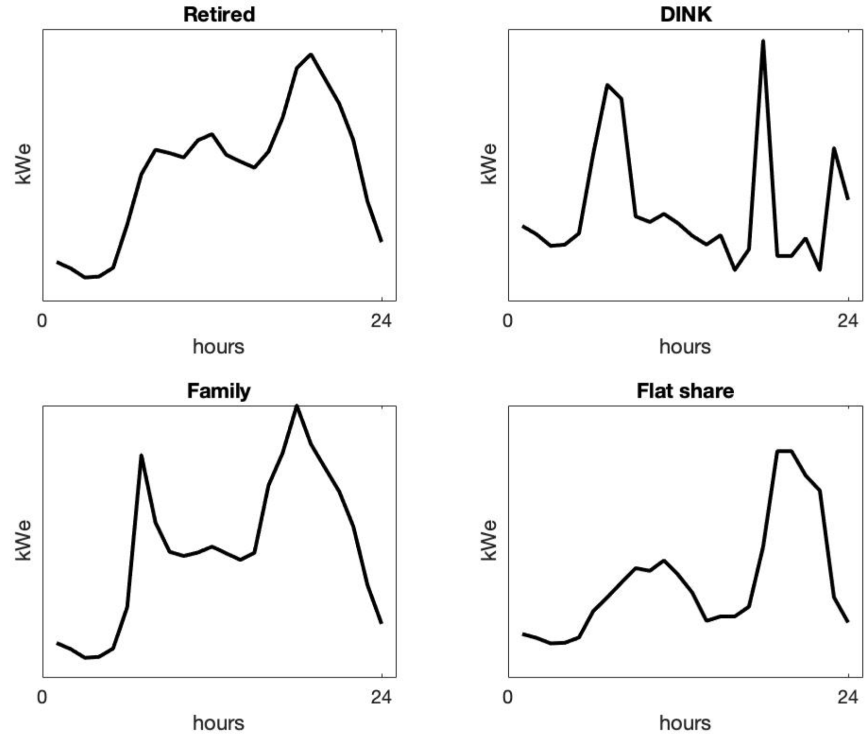

Figure B.1: Electricity EUD for the 4 different household types

The optimal decentralised energy system remains the same in all cases. The results show that whatever the profile, their impact have been considered minimal and thus negligible, in the energy system designing. In fact, only the daily operation varies between each scenario, but this does not enter in the scope of ES.

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[4] We consider the heat profiles identical in all households as it mainly varies in function of the exterior temperature and not according to the habits of the residents.

B.4 Low-carbon 2020 single house design

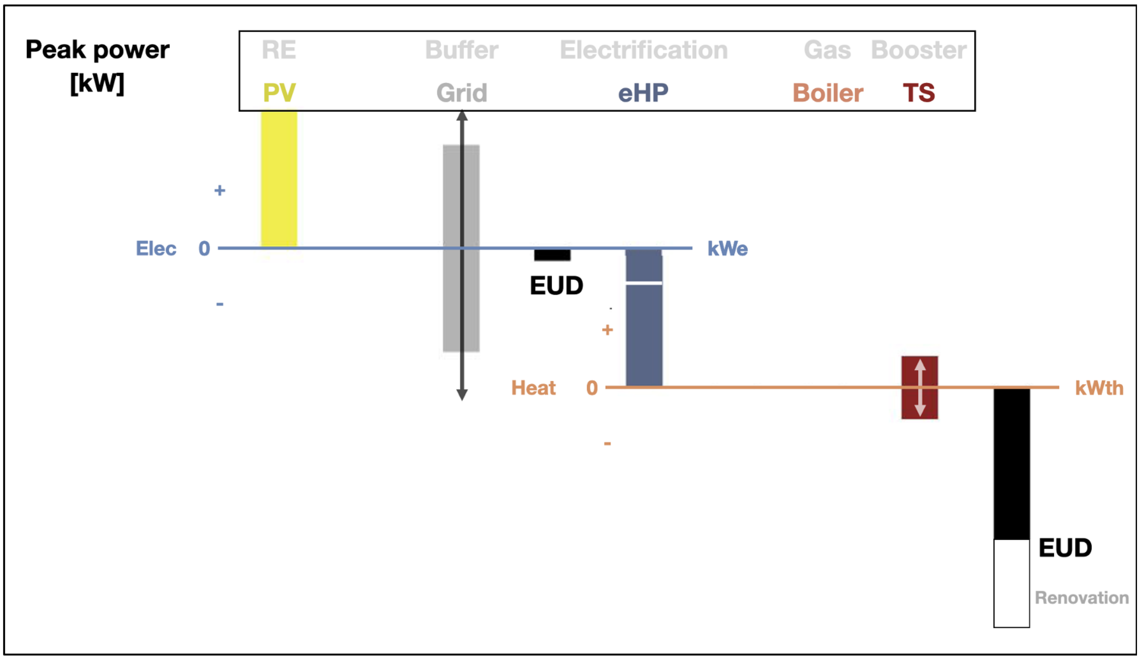


Figure B.2: **General energy system solution expressed in peak power, in the single house low-carbon case 2020.** In positive axis, is shown the production and the negative axis is the demand. Both are expressed in terms of peak power.

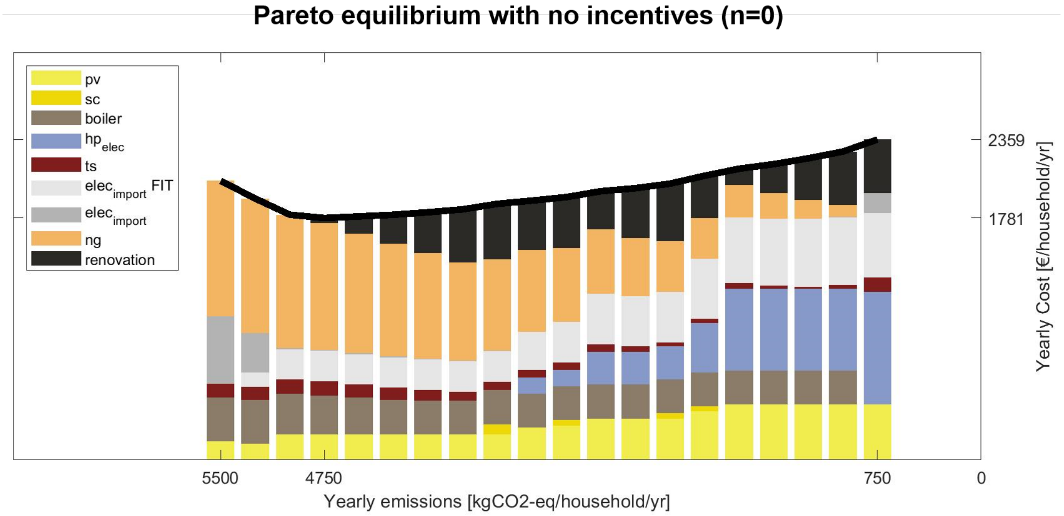
$Generalenergysystemsolutionexpressedinpeakpower, inthecost-effectivecase.Inpositiveaxis,$

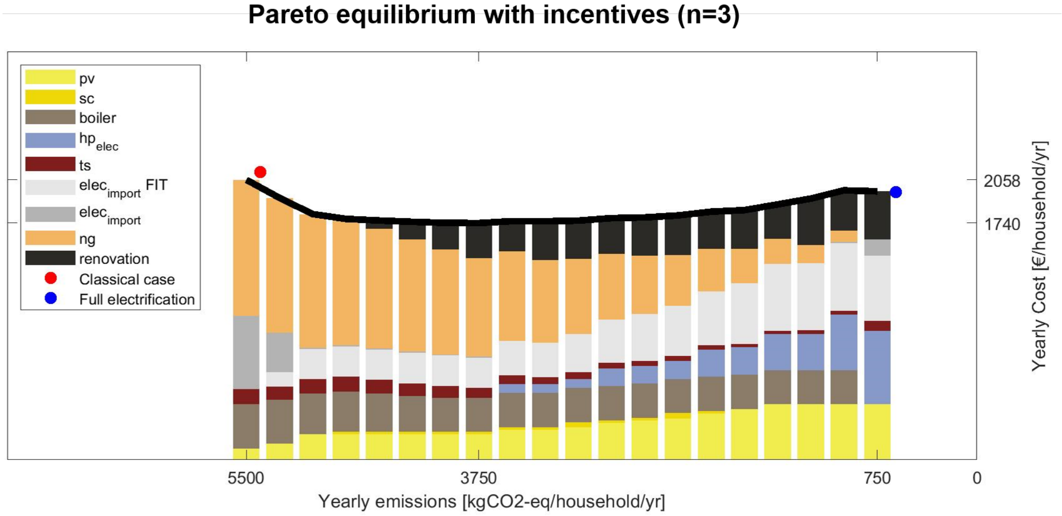
B.5 Influence of incentives

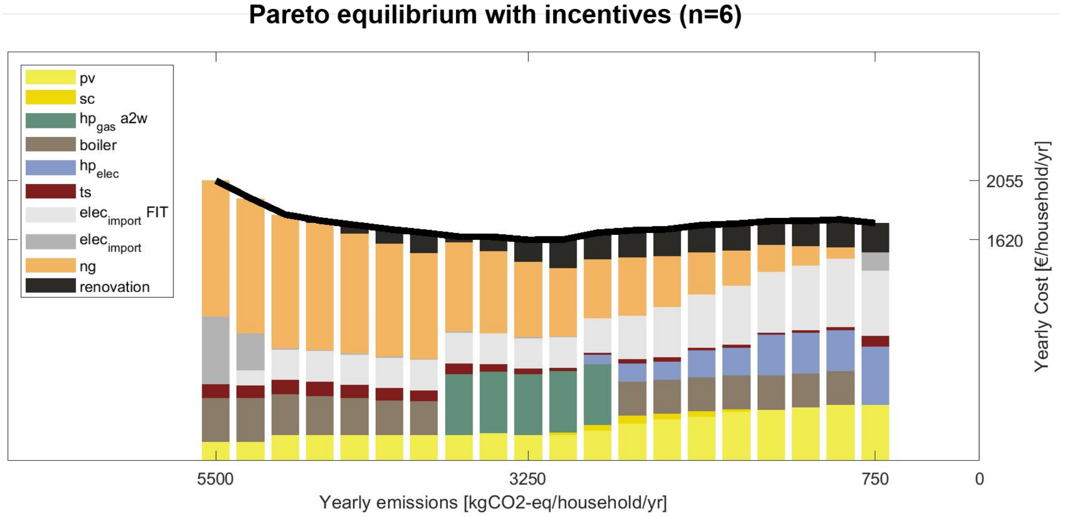
Fully detailed pareto equilibrium can be viewed on the next page in Figure **??** . The pareto front is illustrated by the black curve, and therefore represents the minimum total cost for a certain amount of CO2 emissions per year.

Globally, renovation in the most cost effective solution appears when incentives are considered as well as solar collectors. Otherwise, technology trends remain very similar between situations with and without incentives (n=3).
Once again, it is obvious that the cost gap widens as we move towards a reduction in CO2 emissions.

On the opposite, where higher incentives (such as n=6) are considered, the optimal solution relies on the Gas Heat Pump. However, this solution is only shown to be short-lived, as the electrification of the heat takes precedence over it when the global warming potential is minimised.


Pareto equilibrium with no incentives (n=0)
pv
sc
boiler
hp elec
ts
elec import FIT
elec import
ng
renovation
5500
4750
750
0
Yearly emissions [kgCO2-eq/household/yr]
2359
1781
Yearly Cost [€/household/yr]


Pareto equilibrium with incentives (n=3)
pv
sc
boiler
hp elec
ts
elec import FIT
elec import
ng
renovation
Classical case
Full electrification
5500
3750
750
0
Yearly emissions [kgCO2-eq/household/yr]
2058
1740
Yearly Cost [€/household/yr]


Pareto equilibrium with incentives (n=6)
pv
sc
hp gas a2w
boiler
hp elec
ts
elec import FIT
elec import
ng
renovation
5500
3250
750
0
Yearly emissions [kgCO2-eq/household/yr]
2055
1620
Yearly Cost [€/household/yr]

Appendix C

Integrated neighbourhood appendix

C.1 Brussels neighbourhoods as reference to the domaine

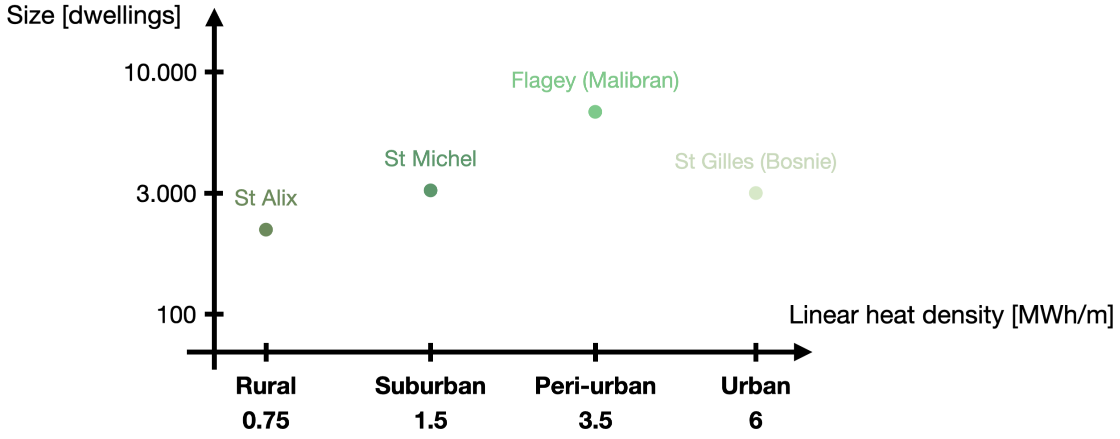


Figure C.1: Neighbourhood characterisation in function of its size and its linear heat density (LHD). Real case Brussels neighbourhoods are displayed in green to grasp the types of neighbourhoods considered.

Various districts and neighbourhoods of Brussels are presented in Figure C.1 to better grasp the types of neighbourhoods identified[1].
The reference neighbourhood presented in the integrated neighbourhood case study can be associated closest to the Flagey neighbourhood in Ixelles.

It should be noted that the linear heat density values attributed to these Brussels reference neighbourhoods should be taken with a grain of salt. They are based on multiple hypothesis : the European conversion from MWh/m to kWh/m^2 [21] and the average number of people per dwelling in Brussels [16]. The values and the computation steps are displayed below.

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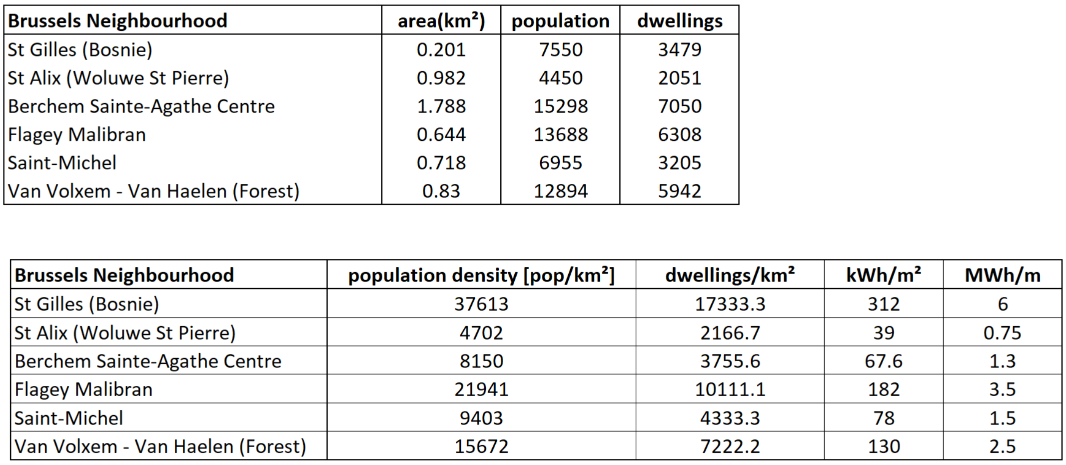
[1] Brussels being the only Belgian city to give exact population densities for very small districts.



Brussels Neighbourhood	area(km²)	population	dwellings
St Gilles (Bosnie)	0.201	7550	3479
St Alix (Woluwe St Pierre)	0.982	4450	2051
Berchem Sainte-Agathe Centre	1.788	15298	7050
Flagey Malibran	0.644	13688	6308
Saint-Michel	0.718	6955	3205
Van Volxem - Van Haelen (Forest)	0.83	12894	5942

Brussels Neighbourhood	population density [pop/km²]	dwellings/km²	kWh/m²	MWh/m
St Gilles (Bosnie)	37613	17333.3	312	6
St Alix (Woluwe St Pierre)	4702	2166.7	39	0.75
Berchem Sainte-Agathe Centre	8150	3755.6	67.6	1.3
Flagey Malibran	21941	10111.1	182	3.5
Saint-Michel	9403	4333.3	78	1.5
Van Volxem - Van Haelen (Forest)	15672	7222.2	130	2.5

Figure C.2: Details from the different Brussels neighbourhoods considered

C.2 HW in the integrated neighbourhoods

We assume in our modeling that Hot Water (HW) demand can be fully supplied by the District Heating Network. However, in practice, it is strongly recommended to apply a small hot water installation in each house to cover the sanitary needs. As the HW demand is relatively small compared to the demand for space heating, the heat demand was considered to be global.

C.3 Energy density thermal storage

To obtain energy density in the thermal storage, several hypothesis have been made :

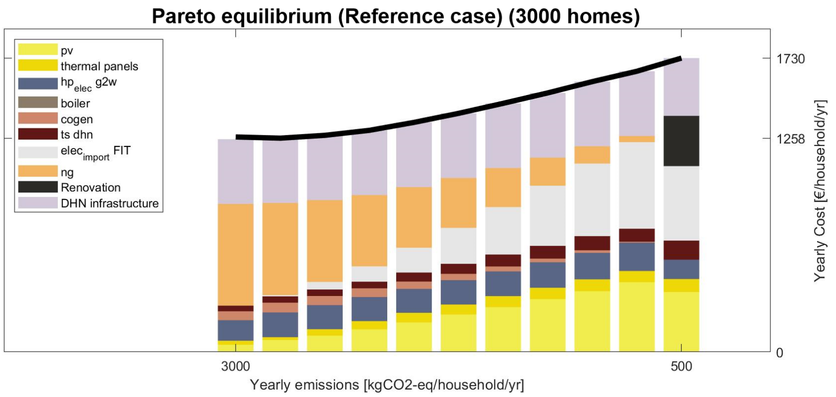
- The temperature at the entry is equal to 20°. And the final close to 55°C.
- The heat capacity is as we know for water, 4.185 [kJ/kg*K].
- 1 water m^3 leads to 985 kg.

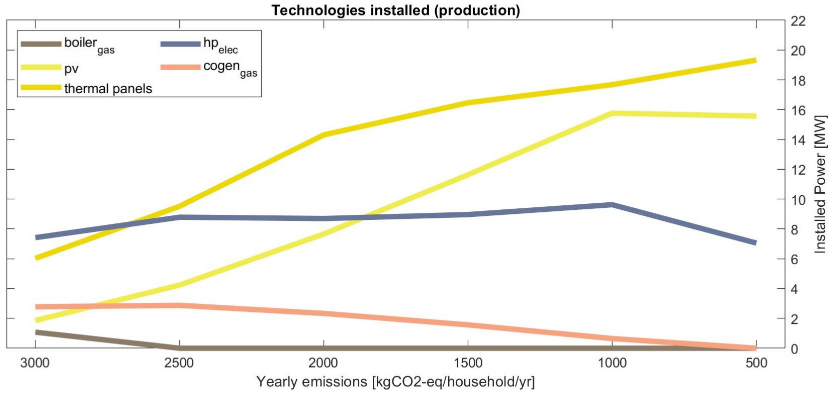
As a result, we can evaluate the energy in one cubic meter :
$E = m * c_p * (\delta T) = 985 * 4185 * 35/3600/1000 = 40.077[kWh/m^3]$

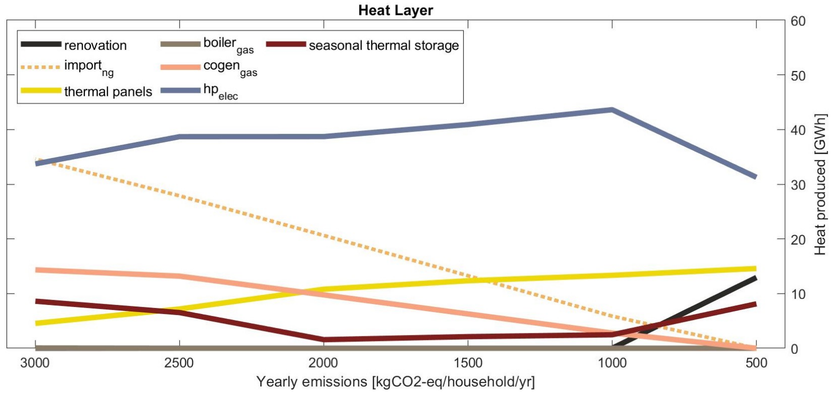
In conclusion, the energy density in a thermal storage unit is equal to approximately 40 [kWh/m^3]

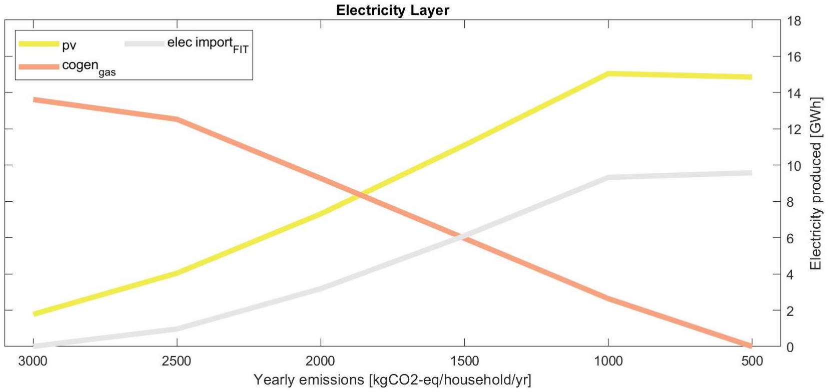
C.4 Reference integrated neighbourhood

When we decrease CO2 emissions, from the baseline case of the neighbourhood, we see not only an increase in cost but also a change in technology. In fact, we notice that the CHP gas is decreasing proportionally to already make way for the electrification of heat, via PVs and heat pumps.









C.5 Resource rich neighbourhoods

Table C.1: **Technology for different resources scenarios**

	Reference case	with Wood	with Geo	with Wind	Units
	3 000	10 000	3 000	3 000	homes
Electricity					
Re-import (FiT)	6.1	0.402	0.173	-	GWh
PV	11.63	10.33	1.82	-	MW
WIND	-	-	-	7.78	MW
Heat					
Boiler$_{elec}$	-	-	-	1.35	MW
eHP$_{g2w}$	8.96	19.97	2.22	9.8	MW
NG	13.26	50.82	16.38	16.7	GWh
gCHP	1.56	5.92	1.543	1.18	MW
Boiler$_{NG}$	-	-	-	2.21	MW
gHP$_{abs}$	-	-	-	3.64	MW
WOOD	-	86.85	-	-	GWh
wCHP	-	14.08	-	-	MW
SC	16.46	11.18	-	-	MW
GEO	-	-	7.979	-	MW
Storage					
Seasonal Storage	3440	6021	1821	1310	MWh
Total costs	1463.42	1267.56	1133.06	1030.28	€/household/yr
Total GWP	1500	1500	1500	1500	kg-CO2/household/yr

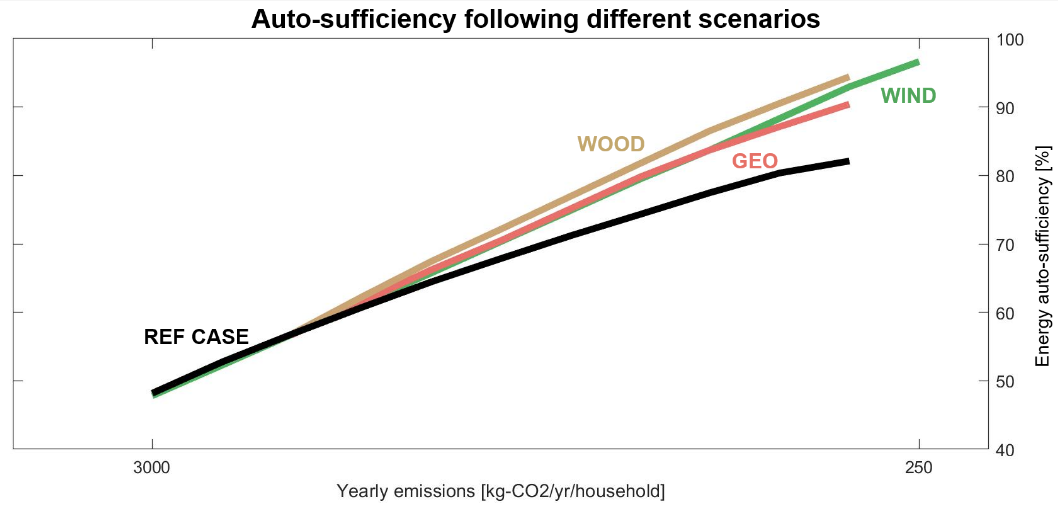
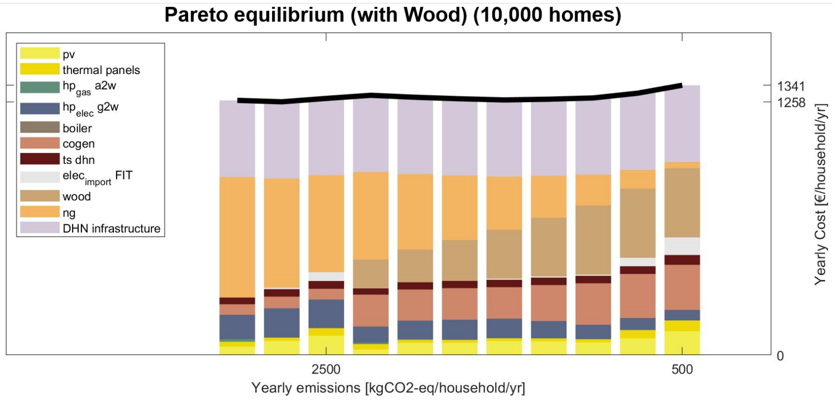
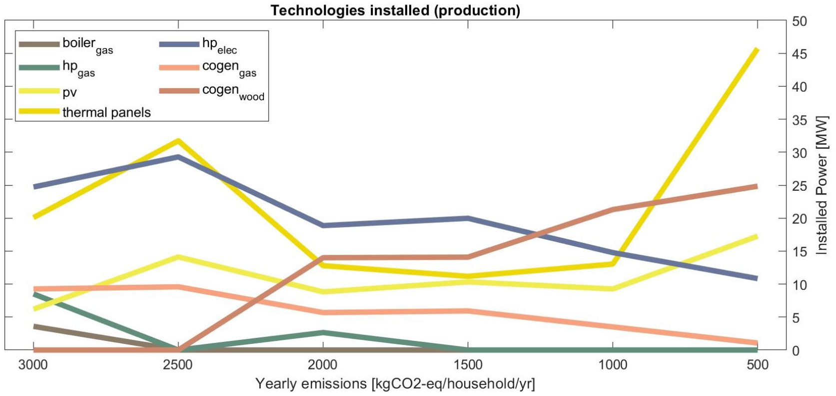
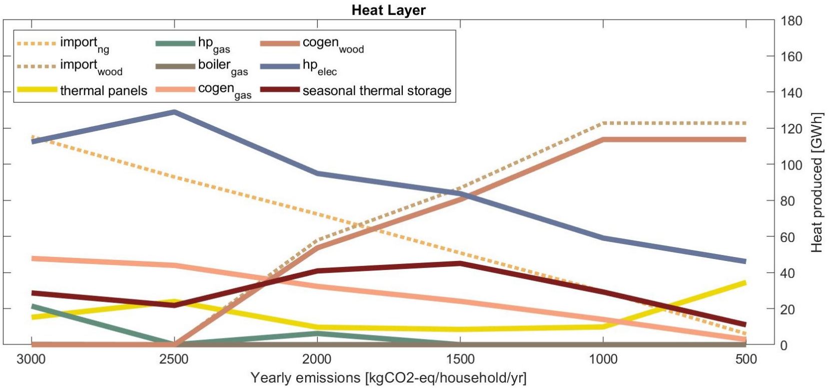


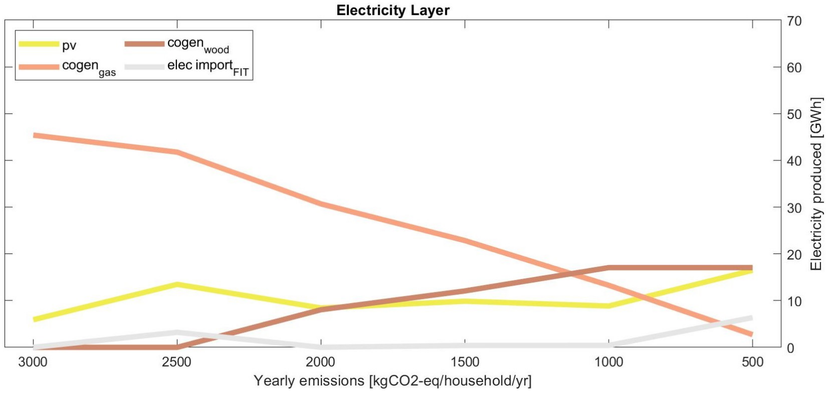
Figure C.3: Pareto of GWP and auto-sufficiency for the different types of neighbourhoods

C.5.1 Wood case

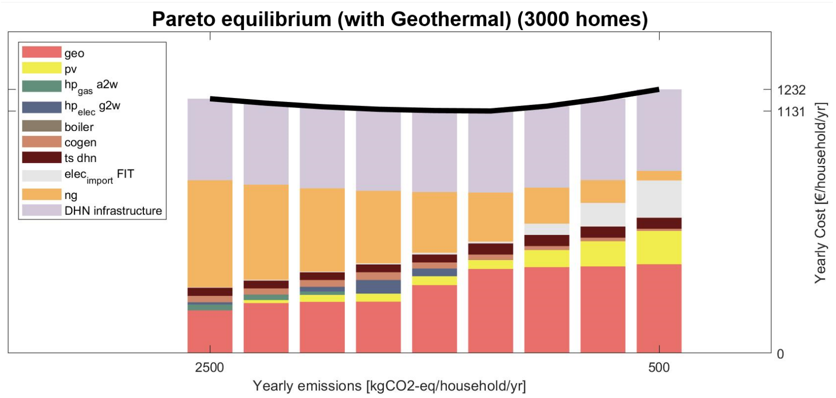


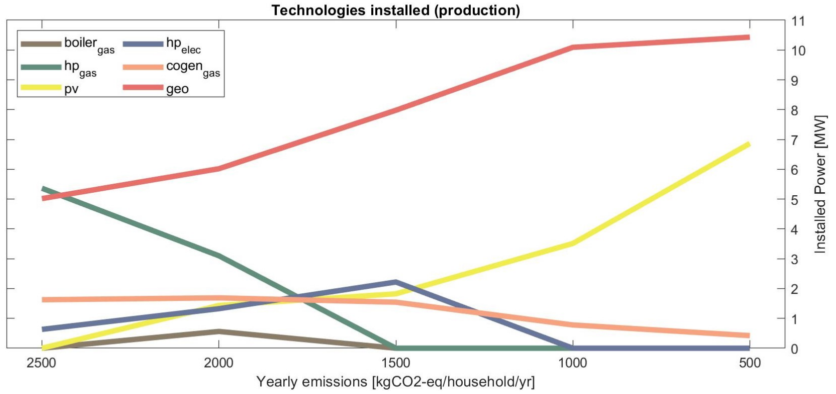


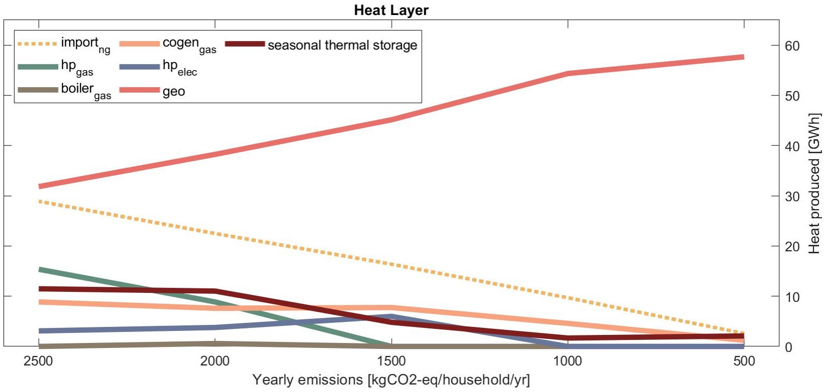


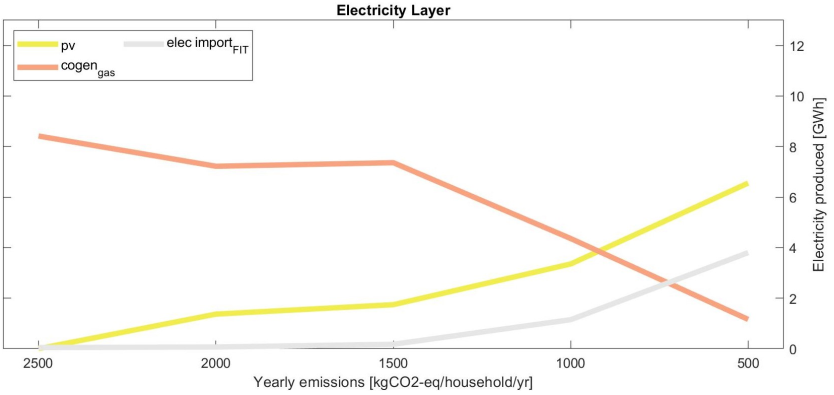


C.5.2 Geothermal case









C.5.3 Wind case

One of the system's limitations is shown in the Figure **??**. The solution depends greatly on wind production. When it drops thermal storage is the only technology that can provide the base load of heat in place of the HP. If the thermal storage cannot meet the district's heat demand, the electricity must be taken from the grid at the standard tariff (0.2861 €/kWh) or at FiT if electricity export occured during the year. At the standard price, the LCOE of heat would climb to 0.086 [2] [€/Kwh], i.e. 4 times more expensive (LCOEs comparison) compared to the directly consumed electricity wind resource, which offers a LCOE of heat of 0.02[3] [€/kWh].

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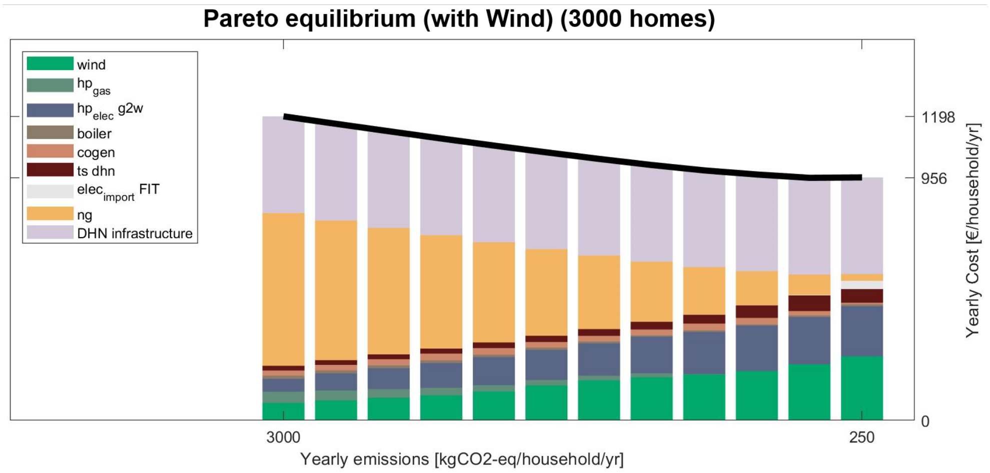
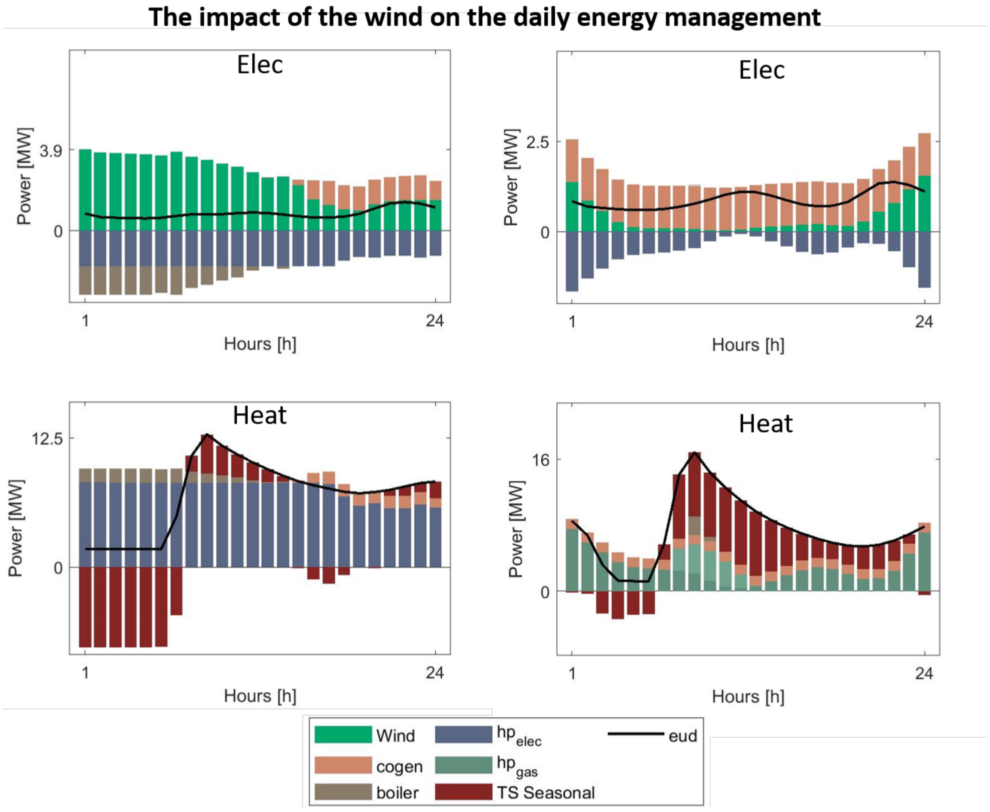
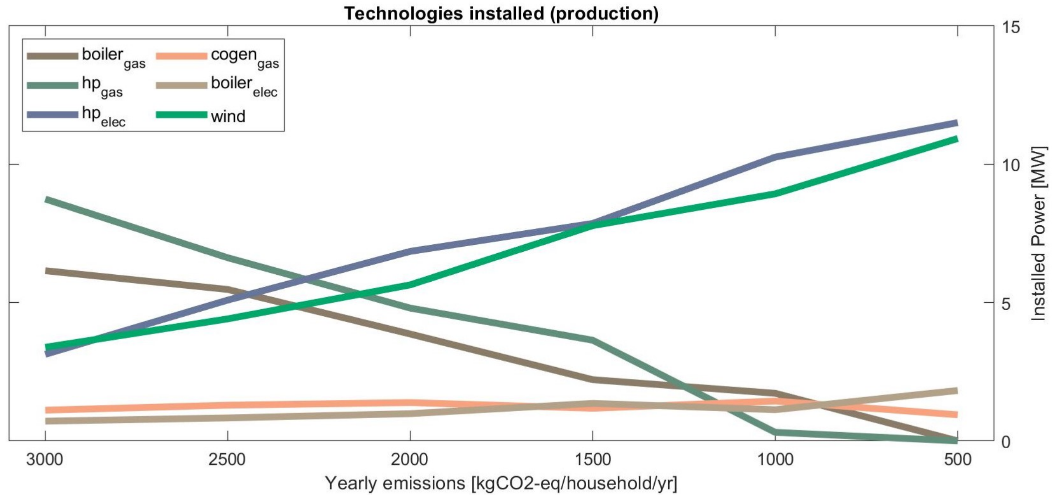
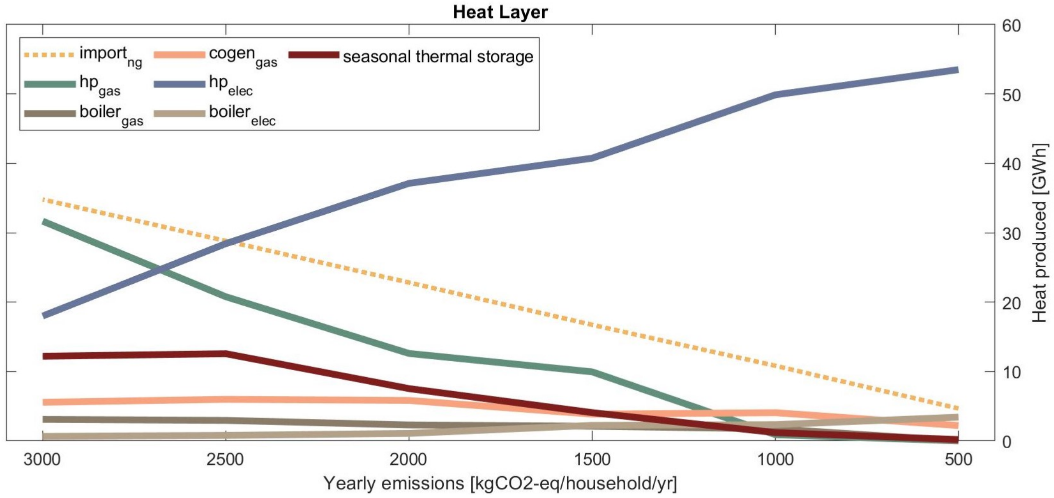
[2] The total amount of electricity needed over the year times the standard price plus the CAPEX and maintenance cost of the heat pump and electricity boiler, divided by the total amount of heat generated.

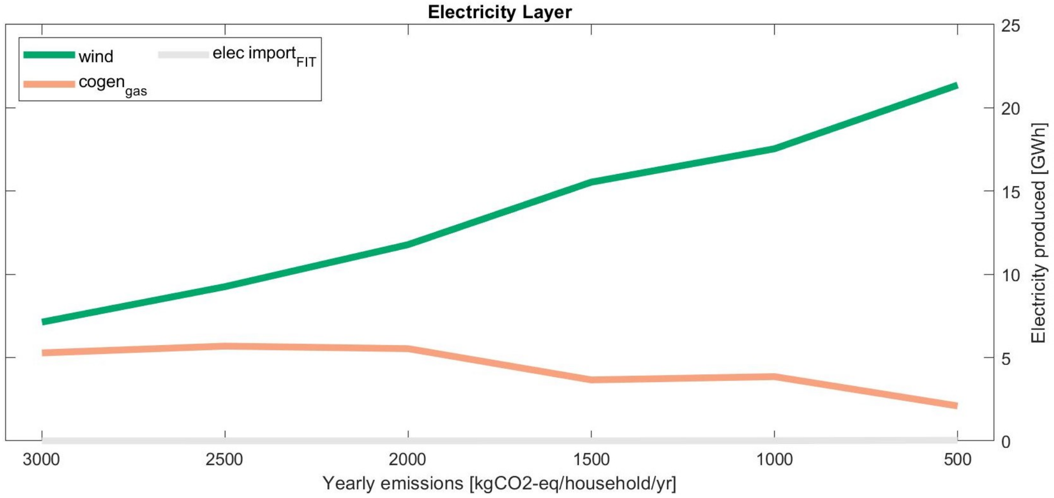
[3] Having a LCOE of electricity of 0.03 [€/kWe] and thanks to the use of eHP with high COP, such as small LCOE of heat can be reached


Pareto equilibrium (with Wind) (3000 homes)
wind
hp gas
hp elec g2w
boiler
cogen
ts dhn
elec import FIT
ng
DHN infrastructure
1198
956
0
Yearly Cost [€/household/yr]
3000
250
Yearly emissions [kgCO2-eq/household/yr]


The impact of the wind on the daily energy management
Elec
Power [MW]
3.9
0
1
24
Hours [h]
Elec
Power [MW]
2.5
0
1
24
Hours [h]
Heat
Power [MW]
12.5
0
1
24
Hours [h]
Heat
Power [MW]
16
0
1
24
Hours [h]
Wind
hp elec
eud
cogen
hp gas
boiler
TS Seasonal


Technologies installed (production)
boiler$_{gas}$
cogen$_{gas}$
hp$_{gas}$
boiler$_{elec}$
hp$_{elec}$
wind
Installed Power [MW]
15
10
5
0
3000
2500
2000
1500
1000
500
Yearly emissions [kgCO2-eq/household/yr]


Heat Layer
import$_{ng}$
cogen$_{gas}$
seasonal thermal storage
hp$_{gas}$
hp$_{elec}$
boiler$_{gas}$
boiler$_{elec}$
Heat produced [GWh]
60
50
40
30
20
10
0
3000
2500
2000
1500
1000
500
Yearly emissions [kgCO2-eq/household/yr]


Electricity Layer
wind
elec import$_{FIT}$
cogen$_{gas}$
Electricity produced [GWh]
25
20
15
10
5
0
3000
2500
2000
1500
1000
500
Yearly emissions [kgCO2-eq/household/yr]

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