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Micro energy communities: collective residential heating system retrofits for carbon emission abatement

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Preface

09/06/2022 - The culmination of a chapter

Five years ago, Leuven was not much more than a city near Brussels to me. The very first time I came here will probably have been for the open days of the faculty from which I will graduate now, if all goes well. Five years have flown by with countless memories on campus *Arenberg* in all its facets to every pub on the *oude markt*, not to mention all the wonderful people I have had the privilege to meet here. Leuven, you are in my heart.

This thesis is the culmination of five years of study which I could not have achieved without the people around me, for whom I would like to take this opportunity to express my gratitude. I firmly and foremost want to thank my mentors, Wouter and Lucas, for the many discussions we had in the past year and the advice and insights you gave me. I enjoyed our weekly meetings which were guaranteed to last longer than planned, perhaps because of the amusing off-topic conversations that often took place. Without you, this work would not be where it is right now. In addition to my mentors, I would also like to thank my supervisors, prof. Helsen and prof. Boydens, for their enthusiasm and the trust they placed in me during our, unfortunately, limited meetings. I took many courses in the past five years among which *Thermal systems* is ranked high on the list of courses I really enjoyed and it undoubtedly influenced me in choosing this thesis topic.

Five years of Leuven wouldn't however have been possible without my parents for whom I would also like to say a very heartfelt thank you. Without your support I would not be where I am right now, I would not be the mechanical engineer I (almost) am today. I would like to say thanks for more than supporting my academic choices, for being there in general, for driving me to Leiden as I want to run a marathon or for providing me with small bowls of fruit during the often long sessions of modelling. Not to forget my brother, I really appreciate the late night talks and beers we share when we go home at the weekends. Finally but not lastly, I would like to thank my friends, from Antwerp and Leuven, and my girlfriend for being around me in general and providing the regularly needed distractions from the thesis work. These might have caused a few less productive days, but in the long run they were certainly worth it. Going to *de Wipschutter* is like coming home and it is you who will let me remember Leuven as the great city I think it is right now.

Arno Meessens

Contents

Abstract

Global warming is the most prominent problem of the last decade with its consequences being observed in every facet of life. In order to stabilise the yet increasing global temperature, fewer greenhouse gases have to be emitted with an emphasis on CO_2 emissions as they represent three quarters of the total greenhouse gas emissions. Many different ways exist to decarbonise society with one of them being renovating residential buildings. This thesis will investigate the carbon abatement that can be achieved by collectively renovating the existing heating systems of three houses to create a micro energy community. The objective is to create a graph with a large number of possible retrofits, which can be used as a tool to choose the most cost-effective retrofit for a given desired carbon reduction.

To construct this graph, a base case heating system will be defined based on the residential market today and a component selection will define which relevant technologies will make up the retrofits. A total of 12 retrofits will be evaluated for their ability to reduce carbon emissions by simulating each one in a dynamic simulation environment. For these models, a rule based control strategy will be developed with the aim of reducing carbon emissions and costs while providing comfort in each case. The simulations of these models will use demand profiles for an average Flemish household which are assumed to be known in advance. At the final stage, the remaining independent parameters in the models are correlated to avoid an elaborate optimisation.

The graph that will be presented at the end shows many interesting results, for example the importance of the emission side which can contain radiators or floor emission systems. It was concluded that a micro energy community with only radiators barely reaches the 2030 emission standard, whereas a micro energy community with only floor emission systems can almost reach the 2050 emission standard. Also, the importance of how the excess electricity from photovoltaic panels is used proved to be significant as the 2050 emission standard could only be reached if the excess electricity could be delivered to the electricity grid. Besides, it turned out that the combination of a ground source heat pump and solar thermal collector panels is able to abate most carbon emissions for any emission side. In addition to these conclusions, the graph can effectively be used as a tool to select the preferred retrofit based on a cost budget or to achieve a desired carbon abatement.

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Abbreviations

ASHP	Air source heat pump
CAPEX	Capital expenditures
COP	Coefficient of performance
DHW	Domestic hot water
GSHP	Ground source heat pump
HEX	Heat exchanger
HP	Heat pump
MEC	Micro energy community
OPEX	Operating expenses
PV	Photovoltaic
PVT	Photovoltaic thermal collector
SH	Space heating
STC	Solar thermal collector
WSHP	Water source heat pump

Symbols

A	Annual occurring cost [€]
A_{PV}	Area of photovoltaic panels [m^2]
A_{STC}	Area of solar thermal collector panels [m^2]
c_p	Specific heat capacity [J/kgK]
E	Energy [J]
EP	Electricity price divided by coefficient of performance [€/kWh]
$EP_{set-point}$	Electricity price divided by coefficient of performance set-point [€/kWh]
F	Future cost [€]
i	Net discount rate [/]
$\dot{m}$	Mass flow rate [kg/s]
n	Time horizon [years]
N	Year in which cost occurs [/]
P_{PV}	Power generated by photovoltaic panels [W]
$P_{threshold}$	Power threshold for photovoltaic panels [W]
$\dot{Q}$	Heat flow rate [W]
$\dot{Q}_a$	Capacity of air source heat pump [W]
$\dot{Q}_{a,therm}$	Thermal capacity of air source heat pump [W]
$\dot{Q}_b$	Capacity of condensing gas boiler [W]
$\dot{Q}_c$	Capacity of air-cooler [W]
$\dot{Q}_g$	Capacity of ground source heat pump [W]
$\dot{Q}_h$	Capacity of heat exchanger [W]
$\dot{Q}_{peak,heat}$	Peak heating demand [W]
$\dot{Q}_{peak,cool}$	Peak cooling demand [W]
T	Temperature, many different are defined but clear by their subscripts [K]
UA	UA-value [W/K]
V_{tank}	Tank volume [m^3]
ρ	Density [kg/m^3]
ΔT	Temperature difference [K]

Chapter 1

Introduction

Climate change and global warming. Presumably the most prominent problem of the last decade. From the world's most influential politicians debating on multi-day congresses to high school students skipping classes to fill capital city streets in so-called "climate-protests". The world is on an unprecedented mission to cease the yet increasing global temperature. Many nations and organisations have been reporting several actions, with all member states of the European Union aiming to reduce their greenhouse gas emissions to net-zero by 2050 [19]. CO_2 emission reduction will be of major importance in this story due to its large contribution. They account for 76% of total greenhouse gas emissions [6] in particular. To achieve this thorough reduction, efforts must be made across all sectors. One of these sectors is the building sector which accounts for more than one third of the CO_2 emitted in Europe, more precisely 36% [21].

The building sector is multi-faceted with this thesis focusing on the residential facet and in more detail micro energy communities (MECs) which are small clusters of residential buildings that often consist of no more than a handful of households. The Flemish climate strategy for 2050 specifies how much the building sector is allowed to emit by 2030 and 2050. From these numbers, it can be deduced that in 2030 and 2050, a household may emit 2.4 and 0.53 tonnes of CO_2 per year respectively [74, 75, 58], which is considerably lower than the 3.78 tonnes of CO_2 an average Flemish household emits today [54]. CO_2 emissions can be reduced by intervening in two parts of a residential building: the building envelope and the heating system. The latter provides heating - and sometimes cooling - and has two sides, the heat emission and the heat generation side. The emission side often consists of a floor emission system, radiators, convectors or a combination of them. The focus of this thesis is on the heating system, whereby the heat emission side is considered immutable.

A typical way to reduce CO_2 emissions through the heating system is to lower - or even replace - the heat delivered by a gas consuming boiler which is nowadays the main source of heating in residential buildings [33]. However, replacing the gas consumption in order to reduce CO_2 emissions often involves costs that form a threshold for these types of renovations. By performing the retrofit in a collective fashion and as such creating a MEC, the threshold can be lowered significantly while enhancing the thermal efficiency of the heating system [12]. This thesis examines various collective heating system retrofits for a micro energy community consisting of three households based on their ability to reduce CO_2 emissions.

In other words, the aim of this thesis is to find the collective heating system retrofit that has the lowest cost to reduce CO_2 emissions. The answer to this will not be a simple yes or no, but rather a graph of when which heating system retrofit will have the lowest cost. Although it may seem that cost is the most important criterion, it is in fact the third, with comfort - heating and cooling - and CO_2 emissions in first and second place respectively. This means that comfort should always be guaranteed after which the CO_2 emission reduction will be prior to the cost. The results which will be visualised in this graph will be obtained by simulating every collective heating system retrofit in a dynamic simulation environment.

This thesis will be divided into seven chapters of which this is the first. The four subsequent chapters - chapters two to five - each unravel a different part of the path to the final graph with each answering a central question.

- **Retrofit foundations** On which existing heating system will the renovations be carried out and which components will be used in these retrofits?
- **Methodology** Which collective heating system retrofits will be examined and how will they be translated into this final graph?
- **Implementation in simulation environment** How are the immutable heat emission side and fully known demand profiles modelled?
- **Rule based control strategy** How are the components of the heat generation side controlled and how do the retrofits work in their entirety?

To avoid a lengthy optimization in the final stage, the remaining independent parameters in the models are correlated via results in the sixth chapter, which is followed by the presentation of the final cost - CO_2 abatement graph. The final chapter will summarise the main conclusions at the end of this text.

In a less chapter-by-chapter explanation: First, the existing heating system and components needed for the retrofits are defined, followed by the selection of the feasible retrofits. These retrofits will be modelled in a dynamic simulation environment with a rule based control strategy providing the necessary control. These models will then be simulated with their results being visualised in the final graph to find out which retrofit is preferred for a certain CO_2 reduction.

Chapter 2

Retrofit foundations

The word retrofit was often used in the introduction and when using this word a certain heating system - on which the retrofit is performed - is implicitly assumed. This chapter will identify this heating system and the components used in the retrofits. The first part of this chapter will shortly discuss the used criteria which were already mentioned in the introduction. The second section will define a heating system based on the most common heating system in residential buildings today which will serve as the starting point for the retrofits. This section will start with the heat emission side after which it will examine the heat generation side. This is followed by the third section which contains a component selection analysis used to decide which components will be used in the retrofits. The fourth section will be the last section of this chapter and will explain some problems with the cooling provision for which appropriate solutions will be proposed immediately. The combination of these four chapters lays the foundation for the following chapter, Chapter 3, in which the retrofits will be designed.

2.1 Criteria

As mentioned in the introduction, Chapter 1, three criteria will be used throughout this text as an objective ground for when decisions have to be made in regards to the retrofits. The criteria, named *the three C's*, are in descending order of importance:

1. The comfort criterion - heating and cooling demands should always be fulfilled
2. The CO_2 criterion - the lower the CO_2 emission the better
3. The cost criterion - the lower the cost the better

Ranking the comfort criterion under the CO_2 criterion would lead to not heating or cooling at all since this would result in the lowest emitted CO_2. It is obvious that this kind of solution is not preferred and therefore the comfort criterion should be in first place. After the comfort requirement, reducing the CO_2 will be most important meaning that every decision - even if it comes with a cost increase - that lowers the CO_2 emissions will be made. The last criterion makes sure that every reduction in

CO_2 will be at the lowest possible cost. Now that the criteria are clear, the existing heating system on which the retrofits are carried out will be discussed.

2.2 Retrofit starting point

This section will select the heating system on which the retrofits will be carried out based on the current state of the residential market. This heating system will be referred to as the base case heating system or in short the base case. The first part of this section will discuss the emission side which is followed by the discussion on the generation side.

2.2.1 Heat emission side

The heat emission side of a residential heating system often consists of either radiators, a floor emission system or convectors with each representing 63%, 15% and 10% of the Flemish households respectively [41]. Other technologies being used are directly heating the air (3%) or a wall heating system (2%) [41]. As mentioned in the introduction, Chapter 1, this thesis will focus on the heating system with the emission side considered to be immutable. This means that a retrofit cannot change the emission side and only affects the generation side. Consequently, each retrofit works on the same emission side. Nevertheless, it is possible to change the emission side prior to a retrofit which would allow to compare the same retrofit for different emission sides. This does not change the working principles of the components in the retrofits since changing the emission side would be equal to changing a boundary condition and as such it only influences the results.

This thesis will consider two different combinations of emission sides or differently said two different boundary conditions. The two different boundary conditions that will be considered consist of emission sides of either radiators or floor emission systems. In other words, the three houses will either only have radiators or a floor emission system. Note that a house with a floor emission system often has this type of system only on the ground floor while the upper floor(s) use radiators. However, because heat rises naturally and the upper floor(s) are typically smaller than the ground floor, the heating load(s) for the upper floor(s) will be lower, implying that the floor emission system will be the most important system. This allows to describe a house with a floor emission system as if it is the only system present.
Because radiators have the highest temperature regime and floor emission systems have the lowest, the all radiator boundary condition is likely to produce the largest amount of CO_2 emissions making it the worst case boundary condition. The floor emission systems will cause the lowest emissions making it a best case boundary condition. Other combinations, for example two dwellings with only radiators and one with a floor emission system, are also possible and will obtain results in between the results of the best and worst case.

2.2.2 Heat generation side

The Flemish energy and climate agency publishes a two-year survey which studies the attitude, knowledge and intentions of Flemish households concerning their energy usage and the Flemish energy policy. It also gives insights into the current state of heating systems used in residential buildings. The latest survey dates back to November 2019 [33] and will be used to determine the base case. A list which contains all useful conclusions can be found in Appendix A with the main conclusions summarised here:

- 84% of the Flemish households have a central heating system
- 68% of the Flemish households use natural gas as main energy source for heating
- 73% of the installed residential gas boilers are condensing boilers
- 69% of the Flemish households have their domestic hot water (DHW) generation for bathrooms coupled to the central heating system, 63% for kitchens
- 31% of the Flemish households suffers from overheating in summer whereas only 9% has a technology to provide cooling

From these numbers it can therefore be concluded that most households use natural gas in a central heating setup with their domestic hot water production coupled to this circuit. Furthermore, almost one third of the households experience overheating in summer which indicates a demand for cooling in summer. It is worth noting that 19% and 24% [33] of households experienced overheating in 2015 and 2017, respectively, indicating that the demand for active cooling is likely to rise further in the coming years. This confirms the need to take cooling into account by including it in the comfort criterion. The DHW provision will also use a small storage tank which is standard in today's central heating systems. A last important point which will later on become clear why is that the average central heating system is around 10 years old, Appendix A.

Besides the survey used to determine the base case, two regulations are also of great interest. The first one has been mandatory since 26 September 2015 under the European Ecodesign Regulation. It states that heating devices with an energy efficiency below a certain level may no longer be marketed in EU countries or manufactured for use in the EU. Since only condensing boilers can reach this level, this rule implicitly bans all non-condensing boilers [22]. The second stipulates that from 1 January 2022 and onward, no oil-fired boilers may be installed apart from the specific case where a household replaces its oil-fired condensing boiler with a new boiler if there is no natural gas pipeline in the street and if it is not part of a so called radical energetic renovation [73]. (For completeness: A radical energetic

renovation is a renovation where cumulatively at least 75% of the outer walls, roof, floor, windows or doors get (re)isolated and where at least one source for heating or cooling gets replaced [72].)
With these two laws taken into account, a renovation of the heating system should at least result in a system where the heat is provided by a condensing gas boiler. Therefore, a renovation starting from a system with oil-fired or non-condensing boilers will at least achieve a situation that is conform with the most commonly occurring heating setup. This proves the relevance of the base case.

2.2.3 Conclusions

In conclusion, the base case consists of three houses with each a central heating system that uses a condensing gas boiler as their main heating source with the DHW generation coupled to this central heating system with a small storage tank. There is no system for cooling provision in place in residential buildings today, but a cooling demand will be taken into account. Cooling will be more elaborately discussed in the last section of this chapter but first the component selection analysis will follow.

2.3 Selection of components

Previous section defined the base case heating system from which possible renovations can start. A retrofit can be seen as adding an extra component to the base case which then can lower - or completely replace - the heat delivered by the gas boiler and as such lower the CO_2 emissions. Many technologies that have this potential exist but not all are relevant within the scope of this thesis. An analysis will follow which will determine the technologies that will be taken into account. The analysis will start with thermal storage - short term and long term - followed by electrical storage and photovoltaic (PV) panels. These three are passive components meaning that they are not able to reduce the emitted CO_2 on their own, they need the presence of other components to benefit the system. After the passive components, the active components will be analysed which are characterised by the ability to reduce the emitted CO_2 on their own. Solar thermal collector (STC) panels, three types of heat pumps, a biomass stove and photovoltaic thermal collector (PVT) panels are the active components considered in this selection analysis.

2.3.1 Thermal storage

Thermal storage by itself will not be able to reduce CO_2 emission, in fact it will only increase them due to the extra thermal losses that have to be compensated for. Storage in combination with other components can however lower the emissions if for example solar thermal collector panels are present since their excess energy can be stored reducing the CO_2 embedded fuel usage at a future time instance. Storage is also able to lower the overall system cost if varying electricity and/or gas prices are taken into account by heating the tank at times where the prices are lower and hence avoiding heating at more expensive future instances. Note that this only makes sense if the saved costs outweigh the investment cost of the thermal storage itself and the extra cost for compensating the thermal losses. A constant gas price and an hourly varying electricity price are considered within the scope of this thesis. Thermal storage can be on a short timescale - hours and days - or on a large timescale - seasons. First, short-term storage will be discussed, followed by long-term storage.

Short term thermal storage

On the short term timescale the building thermal mass, phase change materials and water storage tanks are possible technologies [70]. As mentioned in the introduction, Chapter 1, the building envelope will not be considered within the scope of this thesis, nor will the emission side be changeable throughout a retrofit. Therefore the thermal mass will not be considered as a possible short timescale storage option. A phase change system is a rather expensive technology more often used for larger systems, for example the solar cooling and solar power plant industry or waste heat recovery systems [47]. Due to its relevance being minor for the application of three residential houses, it will not be examined either.
The only option remaining is a simple storage tank filled with water. It does however perfectly fit inside the scope of the thesis and has many advantages: it is relatively cheap and robust, it uses the same fluid as the thermal system itself and it is easily scalable. Besides this a tank can be stratified which enhances the heat transfer and heat storing capacity [23]. In conclusion, a water storage tank will be the only short timescale storage component taken into account. Next, long-term thermal storage will be examined.

Long term thermal storage

Long term thermal storage with a seasonal timescale very often includes one of the following technologies: a solar pond, tank thermal storage or pit thermal storage which use artificial made environments and an aquifer, a rock bed storage system or ground based storage systems which use naturally occurring environments.

The first category of long term storage uses artificially made systems such as tanks or pits. A solar pond is an artificial small lake with a salt solution inside on which the sun irradiates causing the fluid inside to heat up. A heat exchanger is placed at the bottom facilitating the heat to be extracted [1]. Tank thermal storage consists of a tank which can be buried, bermed or placed above ground with a fluid - often water - inside allowing for sensible heat storage [14]. Pit thermal storage is similar to tank storage except for the fact that it doesn't use a static structure. It uses an artificial pit with a lid over the top to reduce the heat losses to the atmosphere [49]. The scales on which these technologies become beneficial are however too large for the three residential dwellings considered and as such are excluded in this work. Both technologies are schematically represented on Figure 2.1.

Another category of technologies makes use of naturally occurring structures as an aquifer or porous rock formations. Aquifer storage uses naturally occurring water which can be found in underground layers of permeable rock or unconsolidated materials [78]. Two wells are made - a cold and hot well - which enable the heat storage and transfer. This technology can also be seen on Figure 2.1. Rock bed thermal storage uses porous rock in which water or air is circulated to transfer its thermal energy to the rock which functions as storage medium. The stored energy can be extracted by circulating cold water or air through the rock which will then heat this water [49]. Storage in aquifers and porous rocks are both too site-specific meaning that they can only be used in very few cases. They are also not beneficial on the scale of three houses wherefore they are excluded in this text.

This leaves only one technology still available, a ground based thermal storage system. This however fits perfectly in the stated context as it is a technology that is beneficial on a smaller scale. Besides this it even becomes more cost-effective for a micro energy community when compared to a single household because the extra cost for three houses is minor in comparison with the cost for one house and as such the cost per house will decrease significantly [12]. The heat storage medium is the ground which avoids the site-specific bottleneck previous technologies experienced. Very often this technology will be used in combination with a ground source heat pump facilitating heating and cooling besides the seasonal storage. Finally, of all previous long term thermal storage options, this is the only one that will be considered.

This concludes thermal storage, next is electrical storage.

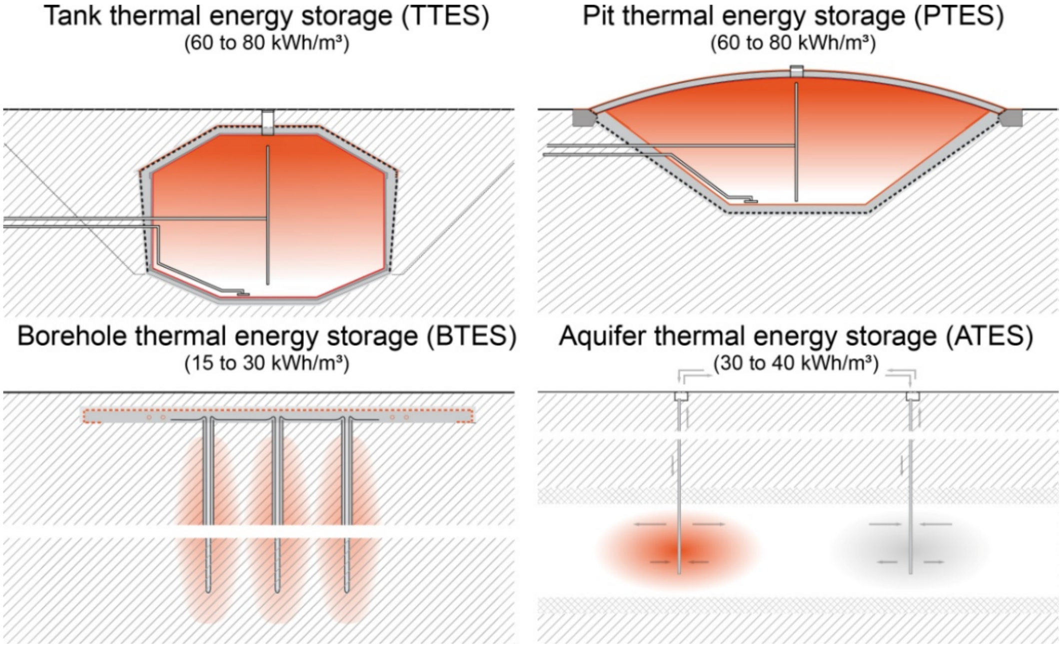


FIGURE 2.1: Different seasonal thermal energy storage technologies [14]

2.3.2 Electrical storage

Besides thermal storage, electrical storage could also be an option if an electricity producing component is present. The main advantage of electrical storage is the possible reduction of future CO_2 emissions by storing green electricity when there is excess electricity production. Since this electricity needs to be converted to heat at a certain point, the presence of an electricity producing component would only make sense if an electricity consuming heat generation component is present. Therefore the electricity could be directly stored in the form of thermal energy instead of electrical energy. Thermal storage will be more suitable since the active components directly produce heat and the scope of this thesis focuses on the heating system. Therefore only thermal storage will be considered. This concludes the discussions on the possible storage technologies. Next, photovoltaic panels will be discussed.

2.3.3 Photovoltaic panels

Photovoltaic (PV) panels are passive components because they convert incident solar energy to electrical energy which cannot directly be used in the heating system. They need an electricity consuming heat generation component to be of relevance for the thermal system. They do however allow to lower the CO_2 emissions by replacing electricity from the grid - which has a certain amount of embedded CO_2 - with their green electricity if for example a heat pump would be present. They can be used in small scale applications and are often placed on rooftops of residential buildings. They as such perfectly suit the context of this thesis and will be taken into account. This concludes the discussion on the last passive component. From here on active components will be discussed, starting with solar thermal collector panels.

2.3.4 Solar thermal collector panels

Solar thermal collector (STC) panels are the first active components being discussed. STC panels can - in contrast to PV panels - reduce the emitted CO_2 emissions by themselves by delivering their green thermal energy to the thermal network and as such reduce the CO_2 embedded fuel usage. STC panels for residential use are almost always non-tracking collectors meaning that they have a fixed position in time [56]. Two main technologies exist in this category namely flat plate solar collectors and evacuated tube solar collectors [56]. Although their specific working mechanisms differ, their purpose remains the same, transferring irradiated solar energy towards a working fluid which transfers its energy to the thermal circuit. Since they are the cheaper option [60] and the dynamic simulation environment libraries only contain flat plate STC panels [46], they will be used throughout this thesis. The next discussion presents the possible heat pumps that can be used.

2.3.5 Heat pumps

The first heat pump was built and demonstrated around 1856 however only in the last decade they have seen a rise in usage and efficiency [11]. The most common types of heat pumps are air source-, water source- and ground source heat pumps for which schematic representations can be seen on Figure 2.2. As their names suggest, each type uses another heat source from which they extract heat that will be upgraded using electricity. Heat pumps can lower the CO_2 emissions under certain circumstances but very often due to their working principle, less CO_2 embedded energy is needed to provide the same amount of thermal energy.

A water source heat pump (WSHP) is often used with the primary side being the space heating (SH) circuit and the secondary side being the domestic hot water (DHW) circuit. A heat pump in this setup is called a booster heat pump [50]. A WSHP supplying the SH circuit is less common due to the geographical dependence on a natural water source, often a river or a lake. Therefore a WSHP will not be considered within the scope of this thesis.

An air source heat pump (ASHP) on average needs three times less electrical energy than a gas boiler would need energy from gas to provide the same amount of thermal energy [65]. For a ground source heat pump (GSHP) the reduction is even greater equalling four times [65]. This means that an ASHP and GSHP would produce three and four times less CO_2 to generate a same amount of thermal energy as a gas boiler would, assuming the same CO_2 intensity for both fuels. Besides this, the ASHP and GSHP are very convenient technologies in a residential context due to their source - air and ground respectively - being omnipresent and the ability to always provide heating or cooling when needed. The GSHP is more expensive mainly due to the high drilling costs of the borefield [29] but as was explained in Section 2.3.1 this is a less important problem for a micro energy community. Both the ASHP and GSHP will be considered within the scope of this work. Next on the list is the biomass stove.

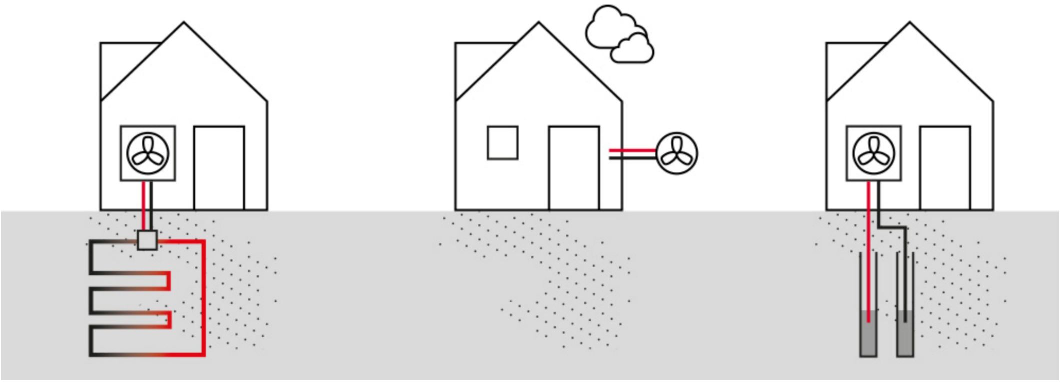


Figure 2.2: Different types of heat pumps, from left to right: ground source-, air source-, water source heat pump [13]

2.3.6 Biomass stove

The one before last component which will be discussed is a biomass stove which is a rather dubious renewable energy source due to the sustainability issues surrounding biomass [20]. Technically speaking it is CO_2 neutral since the combustion of biomass releases the same amount of CO_2 as was absorbed when the biomass source was growing. However very often the demand for biomass is bigger than the sustainable supply which then contributes to deforestation, land degradation and desertification [40]. Besides this the particulate matter emitted by for example a pellet stove - this is a stove using compressed sawdust as its fuel - is around 30 times higher than for a heating oil-fired boiler and up to 50 times higher than for a natural gas boiler [17].

Apart from the issues around biomass, a biomass stove's working principle is actually very similar to that of a gas boiler causing the heat production to also be controllable which avoids the need for backup heat generation systems or storage. Based on the equivalence between the already present natural gas boiler and the issues still present around biomass, a biomass stove in particular will not be considered. Note that biomass outperforms any fossil fuel boiler since it will have net zero CO_2 emissions making it nevertheless an interesting fuel source for the future. The last component to be discussed is photovoltaic thermal collector panels.

2.3.7 Photovoltaic thermal collector panels

PVT panels are a relatively new and promising technology with the first research only dating back to 1998 [43]. The idea is that both electricity and heat are produced using the surface of the PVT panel as a PV panel with on the backside tubes which represent the STC part. PVT panels reduce a major problem that normal PV panels face, namely a decreasing efficiency with increasing temperature. In PVT panels however, the STC part cools the PV part increasing the efficiency of the PV cells thereby heating the STC fluid [53]. This component seems to have a lot of potential in the future but due to it not being a very mature technology yet, PVT panels are not considered in the scope of this thesis.

2.3.8 Conclusions

This finalises the discussion of the selection of components. Many different technologies were examined but only five possible components will be used in the retrofits: a thermal storage tank providing short term storage, solar thermal collector panels, photovoltaic panels, an air source heat pump and a ground source heat pump with a borefield yielding long term thermal storage. The only remaining section in this chapter is the one which will discuss the cooling provision in more depth.

2.4 The appearance of the cooling provision

A careful reading of the previous sections may have revealed some problems related to the base case and the emission side in regards to the first criterion - comfort. The first problem is encountered when the base case should provide cooling in which it will fail as it does not have any technology to do so. This absence of a technology capable of cooling is in fact equal to the absence of a heat pump since this is the only component capable of cooling which will be taken into account in the retrofits, Section 2.3. In other words, if a heating system does not contain a heat pump, cooling cannot be provided. If for the sake of argument the presence of a heat pump is assumed - solving this first problem, yet another problem arises when one of the houses has a cooling demand while the others have a heating demand, as a heat pump cannot inject and extract heat in or from the same source at the same time. If again for the sake of argument is assumed that a technology is present which can provide cooling and heating at the same time, a last problem occurs if a house does not have a floor emission system as normal radiators do not allow for proper cooling [32]. Since the emission side may not be changed throughout this thesis, the only way to provide cooling in this case is by installing a separate device which directly cools the air in the house, namely an air-cooler. This air-cooler in essence is an air-to-air heat pump and will only serve cooling purposes within the scope of this thesis. Consequently, when the boundary condition states that all houses use radiators, each house requires the installation of an air-cooler in every retrofit to fulfil the cooling demand. This however directly solves the last problem as radiator systems will not be found in the other boundary condition which states that every house has a floor emission system.

Although the last problem is solved, the two other problems still remain with their answers depending on the components present in a heating system. Therefore, these problems will be discussed in three sections, each with their focus on a certain component that characterises that solution. The first section will discuss cooling when no heat pump is present, the second one when a ground source heat pump (GSHP) is present and the last one when an air source heat pump (ASHP) is present. For all clarity, the emission side in these sections will consist of three floor emission systems as the presence of radiators requires air-coolers in any case as was discussed above.

2.4.1 No heat pump and cooling

A first category of heating systems are the ones where no kind of heat pump is present - the base case falls into this category. In these types of heating systems the only option to fulfil the cooling demand is via air-coolers, which immediately solves both problems.

2.4.2 Ground source heat pump and cooling

If a heating system contains a ground source heat pump (GSHP), the accompanying borefield allows for passive cooling which in essence is cooling without using electricity. Cooling as well as heating inside the same borefield can be achieved by splitting the borefield and using a part passively via a heat exchanger (HEX) [36]. When passive cooling is no longer possible due to the ground temperature being too high, active cooling will be used to fulfil the demand. This however means that the GSHP can not be used for heating purposes. It is therefore assumed that at the moment the ground temperature becomes too high for passive cooling, the season has come thus far that no more heating for any house will be present. There is still the domestic hot water (DHW) provision but due to the DHW tank, the demand can be decoupled from the provision, allowing the GSHP to charge the DHW tank when not cooling. This solution will therefore always be able to satisfy all demands and do this at lower CO_2 emissions meaning that this solution will always be chosen above the air-coolers based on the second criterion. Even if only one house would have a floor emission system - which will not occur in the scope of this thesis - installing two air-coolers and a HEX - instead of of three air-coolers - will result in lower CO_2 emissions due to the ability to cool passively.

2.4.3 Air source heat pump and cooling

The last solution is identified by the presence of an air source heat pump (ASHP) in the thermal system. An ASHP can be used for both heating and cooling due to the ability to reverse its working principle however it cannot do both at the same time. A solution to this is placing two heat pumps, a small and big one. The small one will be designed to cope with the peak cooling demand while the big one would be designed so that both together can cope with the peak heating demand. In winter, both can work together to meet the heating demand, while at times when there is a cooling and heating demand, they each fulfil their designated demand. It is assumed that both the ASHP and air-coolers work at comparable COPs and so no real CO_2 emission reductions are possible. Since no CO_2 reductions are possible, the cost is the next highest criterion to decide on which solution is preferred. The question therefore deduces to a cost analysis which will determine which solution is the cheaper one. The complete cost analysis for this purpose can be found in Appendix B. The main conclusion is that the dual ASHP solution is cheaper than placing three air-coolers. The dual ASHP solution costs 25.809 euros whereas the air-cooler solution costs 35.182 euros.

2.4.4 Conclusions

Previous discussion showed that several heating system retrofits will not be able to provide cooling and if they can provide cooling they will not be able to provide cooling and heating at the same time. The solutions provided for these problems can be summarised as:

- When no heat pumps or floor emission systems are present, three air-coolers will be placed
- If a retrofit considers an ASHP, the solution will be placing two if at least two floor emission systems are present
- When a GSHP is considered in a retrofit, placing an additional HEX which provides passive cooling and is supplemented by active cooling via the GSHP is always preferred

The last option is even preferred if both the ASHP and GSHP are considered in one retrofit due to the decrease in CO_2 emissions it can achieve via passive cooling. This concludes this section and thereby also this chapter. Only the chapter's conclusion remains.

2.5 Conclusion

The first section of this chapter discussed the criteria which will be used throughout this text, in descending order of importance: comfort, CO_2 emissions and cost. The second part discussed the base case heating system on which the retrofits are carried out. The base case consists of three houses each with a central heating system that uses a condensing gas boiler as its main heating source with the DHW generation coupled to this central heating system with a small storage tank. No component able to provide cooling is yet in place. After this base case definition, the relevant components for the retrofits were selected which resulted in five possible components: a thermal storage tank, solar thermal collector panels, photovoltaic panels, an air source heat pump and a ground source heat pump with an accompanying borefield.

The last part of this chapter discussed the problems related to the cooling provision and also presented the solutions to these problems. The first conclusion was that when only radiators are present, placing three air-coolers in every retrofit would be the only possible solution. The second conclusion was that if three floor systems are considered, the solution will depend on the components present in the retrofit: no heat pumps means that three air-coolers are needed, the presence of an ASHP means that the dual ASHP solution will be preferred and if a GSHP or both types of heat pumps are present, the solution with the heat exchanger and passive cooling will be employed. This concludes the foundations of the thermal system which leads to the next chapter, methodology. This chapter will build further on the retrofits by selecting which retrofits will be of relevance to this thesis. The chapter will also explain the final graph on which the results will be visualised.

Chapter 3

Methodology

The previous chapter explained the existing heating system on which renovations are carried out, which components will be in these retrofits and how cooling will be provided given the retrofits. This chapter will further build on the foundations, starting with designing the retrofits based on all possible combinations of the selected components. From all these combinations, only the relevant ones to this thesis will be retained whereas the others will be ruled out based on several insights. This will all be handled in the first section of this chapter. The second section introduces the graph that will contain the results at the end, albeit in a simplified version. This graph will be of great importance and therefore more than half of this chapter will be dedicated to how it is constructed and how it should be read. As a reminder, this graph will make it possible to select the retrofit with the lowest cost for a given CO_2 reduction, therefore also showing which retrofit will be able to reduce CO_2 emissions the furthest.

3.1 Retrofit design

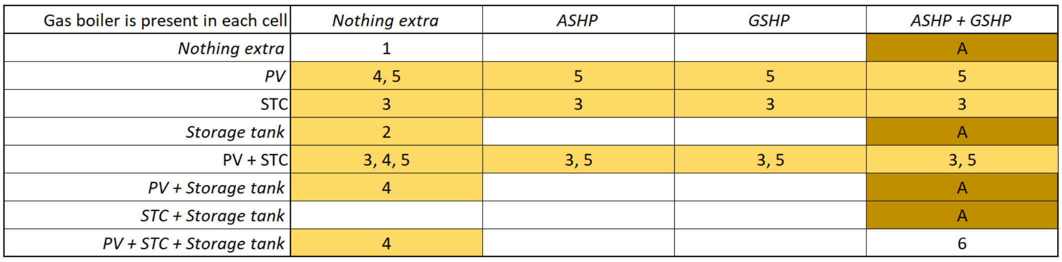
Section 2.3 explained that five components will be used in the retrofits: a thermal storage tank, solar thermal collector panels, photovoltaic panels, an air source heat pump and a ground source heat pump with an accompanying borefield. This section will discuss the actual retrofits which can be formed starting with the base case and these additional components. In a first part, a discussion on which retrofits can be formed will be presented which will be followed by a second part narrowing down the number of feasible retrofits by imposing rules based on insights.

3.1.1 Possible retrofits

A renovated heating system is equal to the basic case with the addition of one to five of the various components, leading to a total of 325 possible retrofits - 5 retrofits in which one component is used, 20 retrofits in which two components are used, 60 retrofits in which three components are used etc. In this number many possibilities are however redundant because if, for example, component A is placed first and component B second, exactly the same result would be obtained if the placement order were reversed, and thus both retrofits are equivalent. By this manner 294 retrofits can be ruled out which leaves a total of 31 possible different retrofits to further look into. All of these 31 retrofits plus the base case are presented in a matrix structure which can be found in Figure 3.1.

A possible heating system in this matrix is represented by a cell with the heating system containing the components indicated by the respective row and column. The columns contain the two different heat pumps and their combination while the rows contain all three remaining components with their respective combinations. The first row and column are a bit different in the way that they do not represent a component, they represent the absence of a component which allows to represent the retrofits consisting of only one component. For example, the cell in the first row and second column represents the retrofit in which only an air source heat pump is added to the base case. The top left corner mentions that a gas boiler is present in each cell. This is true since all retrofits build on the base case which contains a gas boiler as was explained in Section 2.2. This means that the cell in the first row and first column in fact represents the base case itself as no components are added to the gas boiler. This cell is indicated by number 1 in the matrix.

Apart from the fact that this cell contains a number, the yellow colour of some of the cells is even more striking. These cells in addition also contain one or multiple numbers ranging from 2 to 5, or even the letter A. The yellow colour of a cell indicates that the retrofit it represents does not make much sense based on several insights. Next section, Section 3.1.2, will discuss the insights which make several retrofits non-relevant with each insight being given a number or letter. It is this number or letter that can be seen in the yellow cells. This allows to see which retrofit or cell is being ruled out on which insight(s). A final note for extra clarity is that *storage tank* in the rows represents the water tank which allows for short term thermal storage and that *GSHP* is the ground source heat pump which is accompanied by a borefield that allows for seasonal thermal storage.



Gas boiler is present in each cell	*Nothing extra*	*ASHP*	*GSHP*	*ASHP + GSHP*
Nothing extra	1			A
PV	4, 5	5	5	5
STC	3	3	3	3
Storage tank	2			A
PV + STC	3, 4, 5	3, 5	3, 5	3, 5
PV + Storage tank	4			A
STC + Storage tank				A
PV + STC + Storage tank	4			6

Figure 3.1: Remaining 31 retrofits and the base case in a matrix structure

3.1.2 Ruling out retrofits

This section will defines five rules - each based on domain knowledge in the problem - which will lead to a reduction of the feasible retrofits. The yellow coloured cells in Figure 3.1 correspond to retrofits that have been excluded, with the number indicating the insight on which this was decided.

Storage tank and the base case

The first rule reviews the use of a storage tank if only gas boilers are present. When a storage tank is added, the system will have more thermal losses meaning that more gas will be needed to provide the necessary heating demand. This means that both CO_2 emissions and costs - in case of a constant gas price - will increase meaning that this retrofit will be excluded. This rule is indicated by number 2.

Solar thermal collector panels and a storage tank

The second rule states that solar thermal collectors (STC) panels always need a thermal storage tank. If no storage tank would be used, the supply by the collectors is directly connected to the heat demand which in most cases only slightly overlaps as can be seen on Figure 3.2. The blue line shows the demand for domestic hot water (DHW) and the orange line the thermal power that could be supplied by the STC panels. As can be seen, the DHW demand only overlaps in the afternoon and a small part of the morning and evening peak, meaning that a large portion of the heat produced by the STC would not be used. If however a storage tank would be used, the excess heat could be stored in the tank which could then be used to cover the evening peak and even a part of the morning peak in summer - since the STC could generate more heat in summer. This would greatly increase the STC potential and therefore it is concluded that STC always requires a storage tank. This also complies with what is done in practice [69, 23]. This rule makes all retrofits involving STC panels without a tank otiose and hence the corresponding rows in the matrix are marked in yellow and contain the number 3 which indicates this rule.

Photovoltaic panels and heat pumps

Photovoltaic (PV) panels are passive components meaning that they can't produce heat by themselves. However, they can reduce CO_2 emissions by replacing electricity from the grid - which has some embedded CO_2 emissions - with their green electricity. Since a heat pump is the only component in the context of this thesis that uses electricity to generate heat, this rule implies that if there is no heat pump in a retrofit, the application of PV is useless because in that case they will only increase costs. All retrofits with PV panels without a heat pump can therefore be excluded which is indicated by number 4 in the matrix.

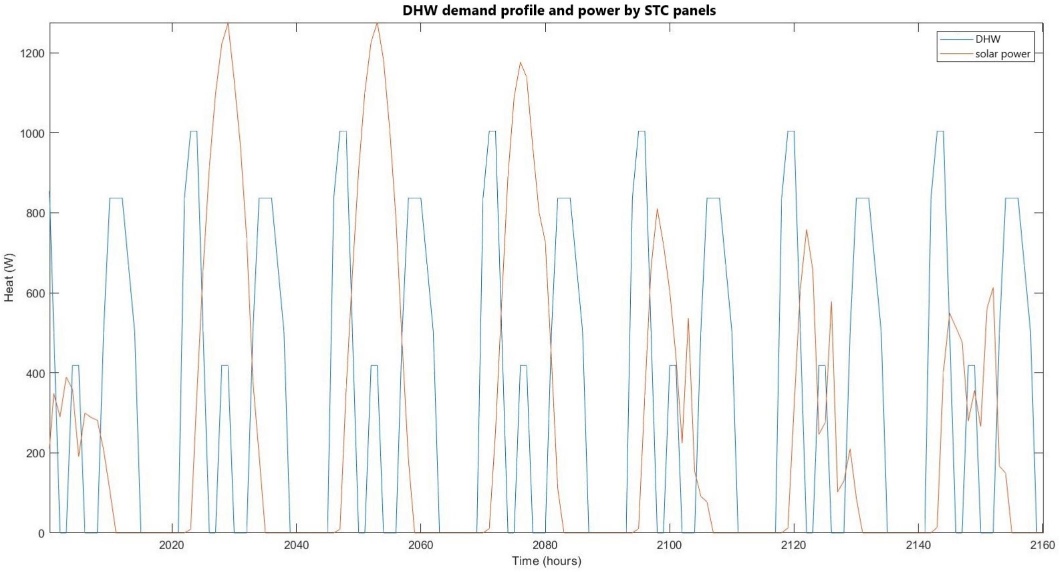


Figure 3.2: Domestic hot water demand (blue) and the deliverable thermal power by the solar thermal collectors (orange)

Photovoltaic panels and a storage tank

This rule will be the fourth one of the five and is identical to the rule concerning storage and STC. Since PV panels are also dependent on the incident solar power, the same problem occurs when the heating demand most of the time doesn't overlap with the generated electricity. Therefore the same analogy can be drawn meaning that, if PV is present, a storage tank is required for the retrofit to be relevant. This is indicated by number 5 in the matrix. Note that since PV also requires a heat pump - mentioned by previous rule - a retrofit with only PV and a storage tank is not a valid retrofit.

Ground source heat pump and air source heat pump

A last rule concerns the use of an air source heat pump (ASHP) and a ground source heat pump (GSHP) together in one retrofit. The presence of both heat pumps in one retrofit allows to reduce more CO_2 emissions compared to a retrofit where only one type would be present. This is because the most efficient heat pump changes throughout the year, and by being able to switch to the most efficient HP, fewer electricity usage would be required to meet the demands, resulting in lower emissions.

However the benefit in CO_2 reduction is expected to be very minor since the COP difference will also be rather minor. Besides this the ASHP is likely to work only a very small part of the time due to the GSHP being more efficient most of the time. Placing both heat pumps together will also increase the complexity and cost quite a bit. Strictly speaking, since a reduction of CO_2 is possible, each retrofit with both

types of heat pumps should be preserved based on the second criterion. However based on previous arguments, the retrofits containing both heat pumps will be ruled out after all which is indicated by letter A in the matrix. This rule is indicated with a letter since it is based on expected results.
Nevertheless, these expected results will in fact be proven in Section 6.1.4, Chapter 6, which discusses the results from the simulations. To maintain the structure of the text it was not directly included in this section. Note that the retrofit which contains all different technologies - also the two heat pumps - will not be ruled out as it has the potential to reduce the CO_2 emissions the furthest and thus has a very important theoretical value. This retrofit is indicated by number 6 in the matrix. However, in practice this retrofit will almost never be used since the costs usually don't outweigh the little extra reduction in CO_2.

3.1.3 Conclusions

To conclude, this section started by discussing how many different retrofits could be made using the components from the component selection, which is 31. Some of these retrofits however did not make much sense as was proven using five different rules, each one ruling out certain retrofits. Cumulatively, these five rules ruled out 19 retrofits meaning only 12 remain which will effectively be simulated and of which their results will be displayed in the graph. This graph has now been mentioned many times and next section will finally address how it will look, work, should be read and how the results will be visualised on it.

3.2 Cost - CO_2 abatement graph

Previous section defined which 12 retrofits will be considered in the scope of this thesis. These 12 will be simulated in order to obtain their costs and CO_2 emissions which will be presented in a graph containing each retrofit and therefore allowing to select the retrofit which has the lowest cost for a certain CO_2 emission reduction. Two of these graphs will be made, one for each boundary condition - the emission side being only radiators or only floor emission systems. In this section this final graph will be discussed using a simplified version which can be seen on Figure 3.3. This simplified version was drawn at the start of this work before any retrofits were selected let alone simulated, as such it is based on simple insights. Each curve in the final graph corresponds to one retrofit meaning that in the end this graph will contain 12 curves but only 3 are represented in the simplified version. This section will start by explaining the two axes of this graph each in a separate part. The vertical cost axis will be handled first followed by the horizontal CO_2 abatement axis. The discussion on the cost axis will also explain how the cost of a retrofit is calculated. The third and last part of this section will explain how the retrofits will be translated onto this graph via three examples and how the graph can be interpreted.

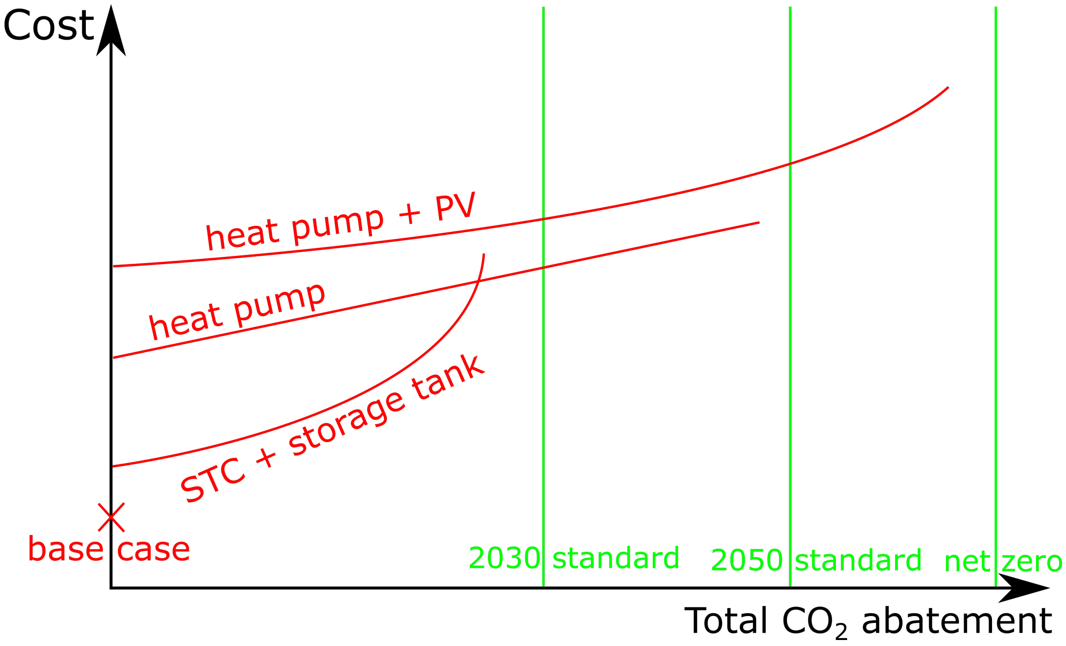


FIGURE 3.3: The simplified cost - CO_2 abatement graph

3.2.1 Cost axis

The cost axis represents the total cost for the next 30 years for a retrofit. This total cost consists of four parts: the installation costs, the capital expenditures (CAPEX) for the initial- and reinvestments, the operating expenses (OPEX) - gas and electricity costs and the maintenance costs. This cost will be calculated for the next 30 years, but why 30 years? Well, if solar thermal collector (STC) panels or photovoltaic (PV) panels are installed, a certain investment and installation cost will occur at the moment of their installation. Every following year they have the opportunity to reduce costs by reducing the gas usage or electricity taken from the grid. If only one year would be analysed, STC and PV panels would seem much less interesting since these saved costs would be neglected. A time horizon will therefore be used to make a proper comparison between the retrofits. This time horizon is chosen at 30 years since this is at least one time the average expected lifetime of the STC and PV panels - 30 years and 20 years respectively [57, 34] - which means that their potential is fully taken into account. Besides this, a time horizon of 30 years reaches the year 2050 which is a very important year due to the deadlines of many environmental targets [19]. This time horizon introduces future costs which will be brought back to the present resulting in one value for all costs which can be red on the cost axis. In other words, the value on the cost axis is the net present value for a retrofit over the time horizon where four different cost aspects are taken into account.

To ease the interpretation of the costs, a 30 year time axis with all partial costs will be used. An example of such a time axis can be seen on Figure 3.4 with this figure representing the costs for a gas boiler. As was mentioned in Section 2.2, the average lifetime of the condensing gas boiler in the base case is 10 years, which means that - knowing that the average expected lifetime for a condensing gas boiler is 15 years [45] - the first reinvestment in a gasboiler should be made after five years. Then again after 15 years (so in year 20) a new reinvestment would be needed. The red arrows represent these investment costs. At the end of the 30 years, the gas boiler would be 10 years old however it could still work for an extra five years. This is taken into account via a salvage value and using linear depreciation over the life time of the boiler. For example, if a gas boiler costs € 3000, its value after 10 years would be equal to 3000 - $10 \cdot \frac{3000}{15}$. This salvage value is given by the grey arrow at the end. The orange and blue arrows represent the yearly maintenance cost and OPEX for the gas respectively. Finally the green arrow represents the net present value for the gas boiler. Each component which will be used in a retrofit has such a time axis meaning that the cost of a retrofit can be found by superimposing the cost axes of its components. This allows to visualise and calculate the net present value for each retrofit rather easily. All the cost axes for each component - besides the gas boiler - can be found in Appendix C. All partial cost values represented by the arrows and the average expected lifetimes for each component can be found in Table 3.1.

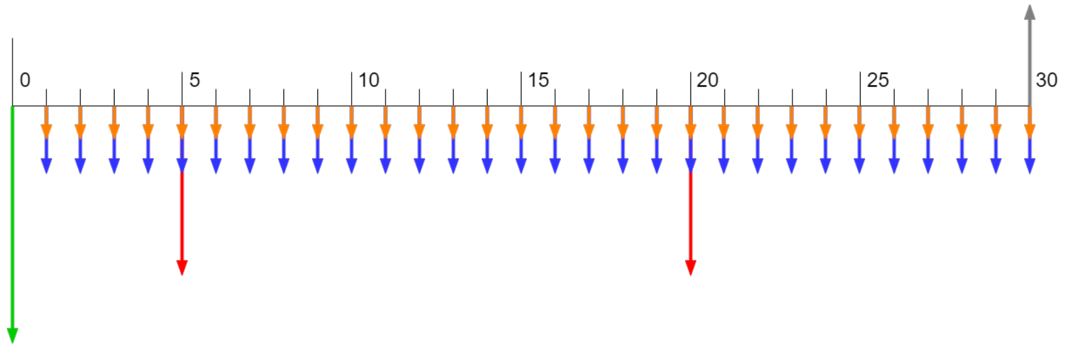


Figure 3.4: Cost - time axis for the gas boiler

Once all costs are known and placed on the axis, the net present value can be found using two equations. Equation 3.1 brings a future cost - like a reinvestment - to the present with F being equal to the future cost. Equation 3.2 is used to bring an annual reoccurring cost - e.g. a yearly maintenance cost - to the present with A being equal to the yearly amount. In these equations, N is equal to the year in which the cost occurs and i is the used net discount rate, 2.2% in this thesis [4].
To summarise, the value which can be read on the vertical axis for e.g. the base case heating system is equal to the net present value of this system for the next 30 years which is calculated via the superimposed time axis consisting of the time axes of the gas boiler and three air-coolers as these are the only components present in this heating system. This concludes the discussion on the cost axis. Next part will discuss the CO_2 axis for which much less explanation is needed.

$$F \cdot \frac{1}{(1+i)^N} \tag{3.1}$$

$$A \cdot \frac{(1+i)^N - 1}{i \cdot (1+i)^N} \tag{3.2}$$

3.2.2 CO_2 axis

The CO_2 axis represents the amount of CO_2 emissions a retrofit abates in the next 30 years compared to the base case. This means that the zero point on this axis corresponds with no abatement or in other words, a retrofit emits an equal amount of CO_2 emissions as the base case does. The other extreme is the green vertical line on the right hand side of Figure 3.3 which represents zero CO_2 emissions emitted or in other words, all CO_2 emissions are abated. Two other green lines can be seen which represent the abatement needed to reach the 2030 and 2050 standards for residential CO_2 emissions respectively. For example, in 2030 a household will only be allowed to emit 2.4 tonnes of CO_2 annually [74, 75, 58] and since an average Flemish household emits 3.7 tonnes of CO_2 today [54], an abatement of 1.3 tonnes per year is needed to reach the 2030 standard. This is where the green line corresponding to the 2030 standard is located. In 2050 houses are only allowed to emit 0.53 tonnes of CO_2 [74, 75, 58] resulting in a yearly needed abatement of 3.17 tonnes of CO_2 to reach this standard. This axis also uses the time horizon of 30 years but since there is no time dependency these yearly amounts can be multiplied by 30 to obtain the amounts for 30 years which can then be read from the axis.
Now that the reasoning behind each axis has been explained, the discussion of how the retrofits will be translated onto this graph follows.

3.2.3 Translation of the retrofits onto the cost - CO_2 abatement graph

The explanations in previous parts clarified what the axes mean and which concepts are used. The graph itself can be used to compare retrofits to one another based on their cost and CO_2 emissions. This section will explain how the curves for a retrofit are constructed via three examples. Three examples are chosen since there are three different methods on how a curve will be constructed with the components inside a retrofit determining which method is used. The components which determine the used method are photovoltaic (PV) panels, solar thermal collector (STC) panels and heat pumps. A first example considers how a curve is built if only STC panels are present. A second example explains the used method if only a heat pump is present. And the third and last example will explain how a curve is constructed if STC or PV panels and a heat pump are present. The base case is an exception since it does not have any of these components causing it to be a single point and not a curve as can be seen on Figure 3.3. The base case will have the lowest cost of all heating systems ending up in this graph since no extra components are installed and only gas is used which is the cheaper fuel today when compared to electricity.

Solar thermal collector panels and the cost - CO_2 abatement graph

This first example will be used to explain how the curve for a retrofit which only contains STC panels will be constructed. This example corresponds to the curve on Figure 3.3 with the subscript *STC + storage tank*. For all clarity, this curve corresponds to the retrofit where a gas boiler, STC panels and a storage tank are present. As can be seen, this curve intersects the vertical axis at a higher point than the base case. This is because in this retrofit STC panels are present which come with a certain CAPEX, installation and maintenance cost which weren't present in the base case. This intersection is of course on the zero point of the horizontal axis which can be seen as if the panels are placed without using their potential - hence the entire demand is still provided via the gas boiler and so no CO_2 abatement is achieved.
The final graph will not be a smooth curve as drawn here but will consist of several points each resulting from a simulation. Each point will correspond with a certain area of STC panels and only the first two points of this graph will have the same area. The left-most point will be this theoretical point in which the panels are placed but not used. The first point to the right of this theoretical point will have the same STC area but now the potential will be used causing less gas usage resulting in CO_2 abatement. The following point to the right corresponds with another area etc. In other words, this curve is essentially a parameter sweep of the STC range. This means that when moving to the right on the curve, the area of STC panels increases causing more energy normally generated by gas to be replaced by energy generated by the panels, hence reducing the CO_2 emissions. Placing extra panels does come with a certain cost which can also be seen, as moving to the right on this curve also means moving up. The rightmost point corresponds with the roof of the houses being completely filled with panels reaching the maximal CO_2 abatement for this retrofit.

For the final curve this area corresponds to 90 m^2 - three times 30m^2 - as the average roof area for a house is 60 m^2 where only one side of the roof will have potential for STC panels [44]. This curve will contain 15 points and the theoretical point, meaning that every non-theoretical point is equal to an area increase of 6 m^2. To conclude, this method will only be used in one retrofit as the STC panels only occur once by themselves in a retrofit.

Heat pump and the cost - CO_2 abatement graph

This second example will be used to explain how the curve for a retrofit which only contains a heat pump (HP) will be constructed. This example corresponds to the curve on Figure 3.3 with the subscript *heat pump*. This curve refers to a retrofit where a gas boiler and a HP are present. In this retrofit, two types of heat producing components are present, each using another fuel. If both components would produce a same amount of thermal energy, the HP will produce fewer CO_2 emissions but at a higher cost. This in essence means that the more the HP is used, the lower the emission will be but the higher the cost. This is exactly what the curve represents.

At the intersection with the vertical axis, no emissions are abated meaning that still all thermal energy is provided by the gas boiler. The intersection is at a higher point than the base case since in this retrofit also a HP is present which has its own four partial costs. The OPEX however would be zero since the HP is not used at this intersection. If a point on this curve to the right of this intersection is taken, it can be seen that the cost as well as the abated emissions increase. Hence, moving to the right on this curve means that more of the thermal energy - needed to provide the houses - will be delivered by the HP. The most right point on this curve corresponds with the HP delivering as much thermal energy as possible. Note that this point does not guarantee no gas usage since if the temperature regimes at which the heat should be delivered are higher than the HP can provide, the gas boiler will always be needed.

The final curves will consist of 11 points - so called usage levels - 0% HP usage, 10% HP usage until 100% HP usage which will be the point at the right end of the curve. Hence this curve is essentially a parameter sweep of the HP usage level. On the final graph this curve will not be a linear curve due to the varying electricity price. Due to the third criterion, if the HP is only allowed to work 20% of the time, it will work at the 20% cheapest moments. This means that the more the HP is allowed to work, the higher the cost per unit abatement will get and therefore the final curve will not be linear. This analogy applies to both the ASHP and the GSHP. To conclude, this method will be used four times as four retrofits will be studied where only a heat pump is present.

Heat pump and solar thermal collector or photovoltaic panels and the cost - CO_2 abatement graph

This last example will be used to explain how the curve for a retrofit which contains both a HP and STC or PV panels will be constructed. This example corresponds to the curve on Figure 3.3 with the subscript *heat pump + PV*. This curve applies to a retrofit that includes a gas boiler, a HP and photovoltaic (PV) panels. PV panels are treated in exactly the same way as STC panels, hence only the main conclusions will be repeated here. Placing PV panels comes with a certain cost however they also allow to reduce the CO_2 emissions by upgrading heat via the HP. The more panels are placed, the higher the CO_2 abatement and cost. A maximum of 90 m^2 can be installed, which would fill the feasible sides of the three roofs. Again 15 points each corresponding to an area increase of 6 m^2 and a theoretical point will be used. If however both PV panels as STC panels are present in one retrofit, it is not possible to increase both areas to 90 m^2 as the combined roof area of the three houses is only 90 m^2. Therefore, their areas will increase from 3 m^2 to 45 m^2 in steps of 3 m^2.
The HP can also be used in exactly the same way as was explained before, therefore the only difference for this type of retrofit is that the method now combines both previous methods. Hence this curve is essentially a combined parameter sweep of the STC and/or PV area and the HP usage level. This curve will be constructed by always applying the next cheapest option to reduce a same amount of CO_2, be

it installing an extra 6 square meter PV panels, be it using the HP for another 10 extra percent. This could lead to for example using the HP up to 20% followed by three consecutive additions of 6 m^2. The final curves will therefore contain 26 points, 11 points for a HP usage increase and 16 points for the PV area increase. The first point of both methods reduces to one point in this method so that there are 26 points and not 27 points. To conclude, this method will be used in the remaining seven different retrofits.

3.2.4 Conclusions

To finalise this section on the cost - CO_2 graph, a practical example of how this graph can be used will be explained. Imagine a setting where an architect or engineer gathers at a table with the people of three neighbouring households who want to renovate their houses in a collective fashion. The architect or engineer asks the people if they want to reach a certain CO_2 target or if they have a certain budget for the renovation, which will be the case most of the time. Based on this budget the engineer can then choose the retrofit or thus components which will reduce the emissions the most using this graph. On the other hand also the retrofit which has the lowest cost for a certain CO_2 reduction can be found. Note that this is a simplified setting of what will really happen but it pictures the idea quite nicely.

3.3 Conclusion

This chapter started by discussing how many different retrofits could be made using the components from the component selection after which many of these retrofits were ruled out based on five different rules. From all the 325 possible retrofits only 12 are remaining which will be simulated and whose results will be displayed in the graph. The second half of this chapter was dedicated to this cost - CO_2 abatement graph. It started by elaborately explaining how the axes of the graph must be read and which concepts determine their appearance. This was followed by three examples each explaining how different types of retrofits - determined by their components - will be translated on this graph.

Chapter 2 determined the foundations for the retrofits by discussing the base case, the components used in the retrofits and how cooling will be provided. This chapter further built on that by narrowing down the retrofits which will be simulated and by explaining how the results of these simulations will be presented. The next chapter will take this a step further by discussing which simulation environment will be used and how the immutable emission side will be modelled inside this environment. Besides this, the demand profiles used in these simulations will also be clarified.

	Lifetime	CAPEX	OPEX	Installation cost	Maintenance cost[a]
Condensing gasboiler	15 year [45]	150 €/kW [45]	Gas price[b] [77]	2000 € [27]	100 € [7]
Air-cooler	15 year [5]	2400 € [64]	124.83 €/y App. B	2000 € [64]	130 € [28]
ASHP	15 year [24]	$5+\frac{8}{15}(Q_a$-3) 10^3€[c] [37]	Electricity price[d] [16]	5000 € [4]	3% of installation [4]
GSHP	25 year [25]	$7+\frac{13}{9}(Q_g$-3) 10^3€[e] [37]	Electricity price[d][16]	5000 € [4]	3% of installation [4]
Borefield	50 year [4]	26000 €[f] [39]	0	0	0.5% of CAPEX [52]
Heat exchanger	15 year [51]	50 €/kW [4]	0	1000 € [4]	3% of installation [4]
Storage tank	30 year [55]	1 €/L [4]	0	800 € [2]	0.5% of CAPEX [52]
STC	30 year [57]	600 €/m² [4]	0	2500 € [79]	35 € [3]
PV	20 year [4]	240 €/m² [80]	0	4500 € [61]	2% of installation [48]

TABLE 3.1: Overview of the average expected lifetime and partial costs for all components

---

[a] all values expressed per year

[b] 0.07 €/kWh

[c] Q_a is the capacity of the air source heat pump in kW

[d] hourly varying value with a yearly average of 0.3964 €/kWh

[e] Q_g is the capacity of the ground source heat pump in kW

[f] Due to the fixed building envelope and all houses either having floor heating systems or not, the size of the field is predetermined. The installation cost is also included in this value.

Chapter 4

Implementation in simulation environment

The aim of this thesis is to find the collective heating system retrofit which has the lowest cost to reduce CO_2 emissions. Each feasible retrofit defined in the previous chapter, Chapter 3, will be modelled in a dynamic simulation environment to determine its costs and CO_2 emissions. This chapter will start by discussing which dynamic simulation environment is used, why it is needed and which libraries are used. Each component of the heating system will directly come out of a library. The rooms and building structure of a house will not be modelled within the scope of this thesis, resulting in a different approach to how the emission side is represented, as will be explained in the second section. The last section of this chapter will discuss the demand profiles which are used in the simulations and the temperature regimes as the mass flow rates needed to comply with these profiles. This chapter builds the foundations for the next chapter, Chapter 5, which will discuss the generation side and which rule based control strategy will be used.

4.1 Dynamic simulation environment

The first section of this chapter discusses the simulation environment that is being used. Dymola - developed by Dassault Systems [9] - is the dynamic simulation environment in which the models will be made and allows for external libraries to be imported to enlarge the list of components. A dynamic simulation environment - in contrast with a static environment - does have a time aspect which is needed in the simulations as the phenomena which are present vary in time and by using a static program distorted results would be obtained. Using a dynamic environment increases the complexity quite a bit but it is necessary for accurate results.

The language used in Dymola is the Modelica modelling language on which the main focus will be as all the models will be built through this language using the Modelica Buildings Library [63]. This Modelica modelling language is object-oriented allowing for a very convenient modular approach and uses multiphysics modelling

for its models which allows for non-sequential programming that consequently makes debugging however quite the challenge. Three extensively used libraries are the IDEAS, Modelica-buildings and Modelica StateGraph2 libraries. IDEAS is short for Integrated District Energy Assessment Simulations library. This library was developed by the KU Leuven and 3E and holds many components which facilitate simultaneous transient simulations of thermal and electrical systems at both building and feeder level [35]. Especially the thermal systems are extensively used. The buildings library contains dynamic simulation models for building energy and control systems. The library contains models for air-based HVAC systems, water-based heating systems, controls, heat transfer among rooms and the outside, multi-zone airflow, including natural ventilation and contaminant transport, and electrical systems [46]. From this library the air-based and water-based heating systems are mainly used. Finally the Modelica StateGraph2 library provides components to model discrete event, reactive and hybrid systems in a convenient way with deterministic hierarchical state diagrams [26]. This library was used to model the rule based control strategy as the state diagrams are very convenient for this control implementation. These three libraries are chosen to build the heating system models using ready-to-use reliable models of each components since the goal is not to compare nor build a component model but to simulate the retrofits.
This section explained which simulation environment is used and why. Next section, Section 4.2, will explain how the heating system emission side will be modelled in this environment.

4.2 Heating system emission side modelling

As was explained in Section 2.2.1, Chapter 2, the emission side is considered to be immutable in the heating system retrofits. This makes the emission side a boundary condition to the problem. In the same section it was also explained that each retrofit will be simulated with two different boundary conditions - an emission side consisting of only radiators and an emission side consisting of only floor emission systems. In order to simulate the heating system retrofits the emission side will have to be modelled and preferably in such a way that without any extra modelling the boundary conditions can easily be changed. This section will discuss how this will be achieved starting with a first subsection which will explain how the emission side will be modelled without the need to model the whole house with all its rooms. A second subsection will explain how the pumps in the emission side are controlled.

4.2.1 Emission side model

The emission side will not be modelled as a radiator or a floor emission system placed inside a room since this would require to also model the room and building structure which is out of the scope of this thesis. The way the radiators and floor emission systems are modelled is via their thermal mass. The water present inside of them will be modelled as one lumped volume from which heat will be extracted. Modelling the emission side in this way is sufficient for the purposes of this work as the same mass flows and temperature regimes will be present, which is all that matters for the generation side. Modelling the situation in this way however requires the amount of extracted heat to be known up front, which is the case in the scope of this work as was mentioned in the introduction, Chapter 1.

The discussion on the base case from Section 2.2 explained that each house has its own domestic hot water (DHW) tank and radiator or floor emission system. All three DHW tanks will be modelled as one big DHW tank with its volume equal to the cumulative volume of the three separate tanks. The radiators and floor emission systems are modelled as two lumped volumes whose respective volumes are equal to the cumulative amount of water present in the radiators and floor emission systems in the three houses. For example, if each house has a 70 litre DHW tank, two houses have radiators with each 100 litres of water in the system and one house has a floor emission system with 120 litres of water in the system. Then these systems are modelled as one large DHW tank with a volume of 210 litres, one lumped volume representing the radiators with a volume of 200 litres and one lumped volume representing the floor emission system with a volume of 120 litres. Modelling the emission side in this way allows to easily change the boundary conditions as it only requires to change the volume of the lumped volumes which is just a parameter in the models. Due to the emission systems of different houses being lumped together, the respective demand profiles for each house will also be superimposed onto one demand profile.

Figure 4.1 shows a simplified visual representation of the emission side in the Modelica language. Modelling the emission side as presented above allows to connect different generation sides without the need to change the emission side as can be seen on this figure. The lumped volumes for the floor emission system and radiators can be seen at the sides and the DHW water tank can be seen in the middle. At the bottom, a table is observed which contains the fully known demand profile and is connected to the lumped volumes and DHW tank - be it via a DHW tap in this case. The connection to the volumes is made via a converter which receives the demand profile at its input causing it to extract heat equal to that amount from the volume. The DHW tap receives the mass flow rate of the DHW as input from the demand profile causing it to pump water out of the tank while providing water to the tank at 10°C which is the temperature for DHW when it enters a house [71].

There is however one problem with this model. Namely, if at least two of the three houses have a floor emission system and if at least one of these houses has a cooling demand while another one of these has a heating demand, then the model will not be able to represent the physics correctly. This will be the case because if a heating demand profile from one house and a cooling demand profile from another house will be superimposed, a distorted demand profile will be obtained as the demand profiles partly cancel each other out.
However, the chances for this to occur are awfully low. According to the information

in Section 2.2.1, the chance that at least two houses have a floor emission system is equal to 7.0875% and according to Section 2.2, the chance that a single house even has a cooling demand is equal to 31%. This means that the chance for a heating and cooling demand to occur at the same time each in a different house with a floor emission system is extremely low. A possible way to solve this problem nonetheless would be to model separate lumped volumes for each floor emission system however this would mean that the number of lumped volumes would increase from two to four hence complicate the model and increase the simulation time significantly. Based on these insights, it was decided that the additional complexity and simulation time - in each retrofit - do not outweigh the very small chance of distorted results.

Despite the fact that the distorted results in general would most likely never be obtained, Section 4.3 will even prove that due to the used demand profiles this problem can never occur in the performed simulations in the scope of this thesis, assuring that the models will represent the physics correctly.

This concludes the actual model itself, next subsection will explain how the pumps, also visible in Figure 4.1, are controlled.

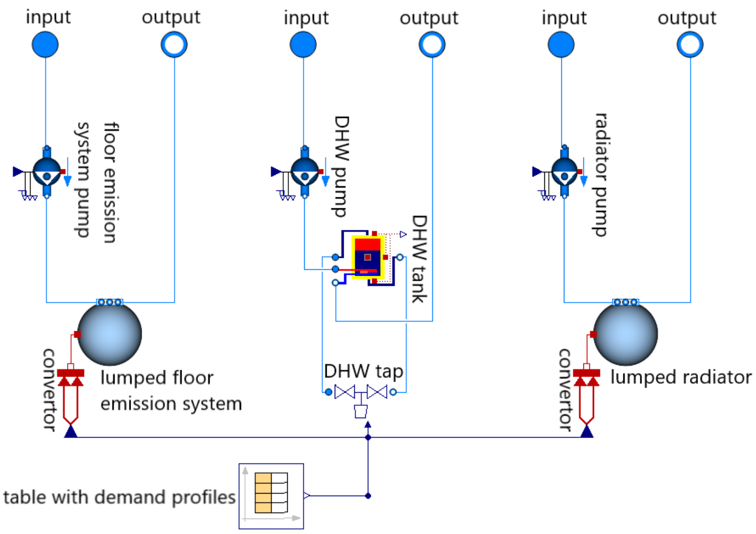


FIGURE 4.1: Simplified visual representation of the emission side model in the Modelica language

4.2.2 Emission side pump control

As can be understood, the water temperature in the lumped volumes/DHW tank must be the same as in the actual emission systems/DHW tank in order to represent them correctly. If heat is extracted from the lumped volumes/DHW tank, the temperature of this water will decrease. Since this temperature must be kept within limits to provide comfort - as is the case with the actual system -, the lumped volumes/DHW tank have to be reheated if the water temperature decreases below a

certain margin under the temperature needed to fulfil the demands. Therefore the pump coupled to the lumped volumes/DHW tank will turn on to reheat this water. The pump will however only turn on if the temperature is too low and that heat is being extracted out of the system at that moment. For example due to tank losses the DHW tank temperature could decrease below the margin of the temperature needed to fulfil the demand. As a consequence the generation side would reheat the tank while it is strictly speaking not needed since there is no demand.
The elegance of this control is that the generation side will do all the work and as such as little importance as possible is put on the emission side. The pump turning on will cause the water to circulate through the generation side which will act accordingly as will be elaborately explained in next Chapter 5.

4.2.3 Conclusions

The first subsection of this section discussed the implementation of the emission side in the dynamic simulation environment which can be summarised as each type of emission system and DHW tank being modelled by their thermal mass resulting in two volumes and a single DHW tank. A short subsection followed which discussed how the pump coupled to the lumped volumes and DHW tank is controlled. This concludes the section on the emission side modelling. Next section will discuss how the demand profiles are designed.

4.3 Standardised demand profile

Previous section already mentioned that certain fully known demand profiles will be used in the simulations. This section will discuss the shape and magnitude of these demand profiles, for which many options are possible. A best case demand profile could correspond with very well insulated buildings and evenly spread demands. A worst case demand profile could correspond with very poorly insulated buildings and large demand peaks. For this thesis one standardised heating, cooling and domestic hot water (DHW) demand profile will be designed for all houses. As was mentioned in Section 4.2.1, the demand profile in the models will be a superposition of the demand profiles for each house. This section will be split up into four parts: the first part will discuss the demand profile for space heating, the second one discusses the demand profile for space cooling, the third part discusses the demand profile concerning domestic hot water (DHW) and the last section will elaborate on the temperature regimes and mass flow rates needed in the heating system to fulfil these demands.

4.3.1 Space heating demand profile

The first profile which will be discussed is the space heating (SH) demand profile and has a time step of one hour. This profile - and in fact each profile - will be designed in two steps, the first step determines a normalised profile based on literature which will be scaled to Flemish averages in a second step. The normalised profile for the

SH demand is based on a profile which varies in magnitude throughout the day and year which can be seen on Figures 4.2 and 4.3 respectively. These day and year profiles are divided into blocks of comparable magnitude which are indicated in red on the figures. Also the respective magnitude is indicated in red on these figures. The unit of the numbers on the figures is kW whereas the unit for the numbers at the bottom of the figures is hours and days respectively. The values on the figures are normalised per figure after which they are multiplied with each other so that a day and year time dependant normalised SH profile is obtained.

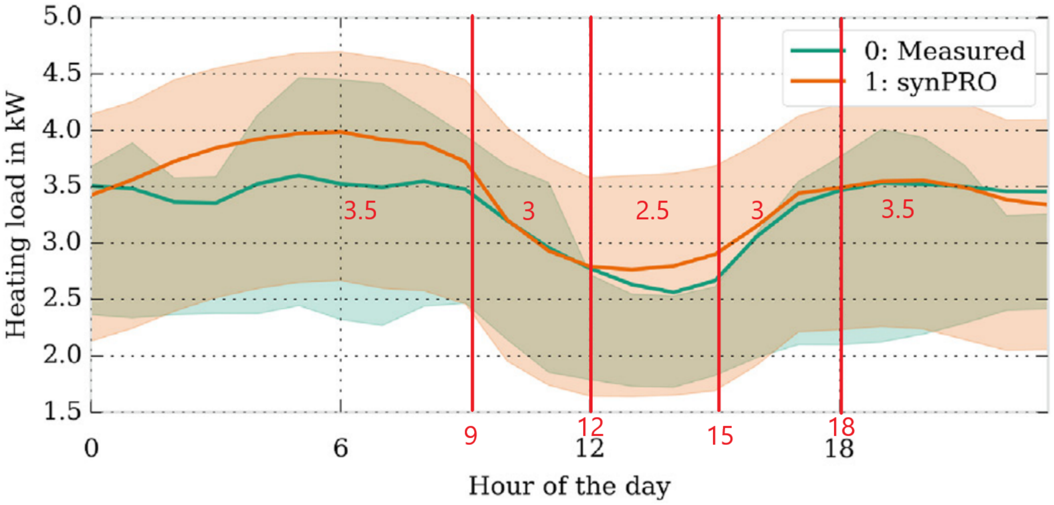


FIGURE 4.2: Heating demand for a residential building over the day, used for variations throughout the day [10]

The next step is to appropriately scale this profile to an average Flemish demand. For this purpose, the heating report of Flanders from 2020 is used [42]. This report states that all households together use 47712 GWh for SH yearly. Via the total number of households in Flanders - which equals 2835604 households [59] - it can be found that one household on average uses 16.8 MWh for SH applications annually. This nicely corresponds with 17 MWh which is the energy usage stated by the Flemish regulator for electricity and gas [76]. This number is now multiplied with the normalised profile and results in the SH demand profile for one house. This final SH profile for one household can be seen on figure 4.4, taking the integral of this profile equals 16.8 MWh as it should. The SH peak demand for one household is just below 4.5 kW. Note that the SH input profile used in the simulations is the superposition of three of these profiles - one for each house.

4.3.2 Space cooling demand profile

The next profile that will be discussed is the space cooling demand profile. As mentioned in the SH profile discussion, each profile uses the same methodology where in a first step a normalised demand profile will be made which will be scaled to the

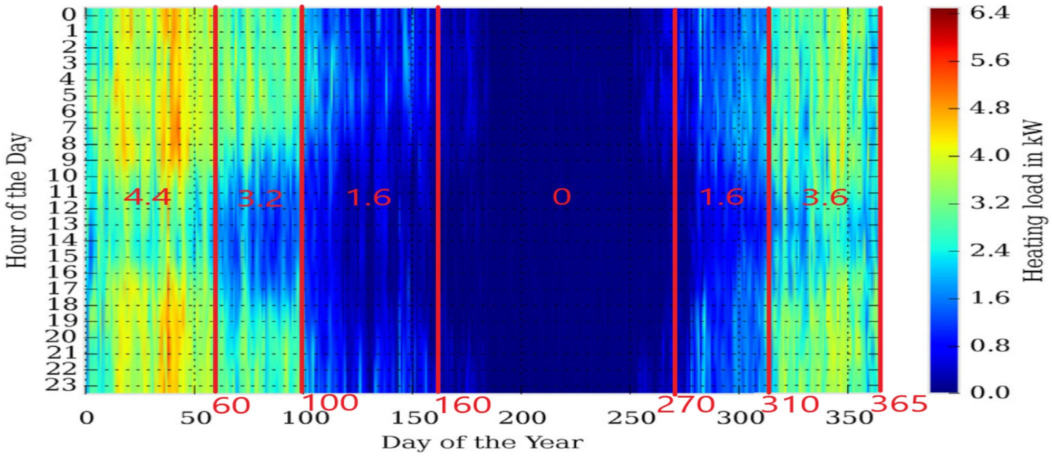


FIGURE 4.3: Heating demand for a residential building over one year, used for variations throughout the year [10]

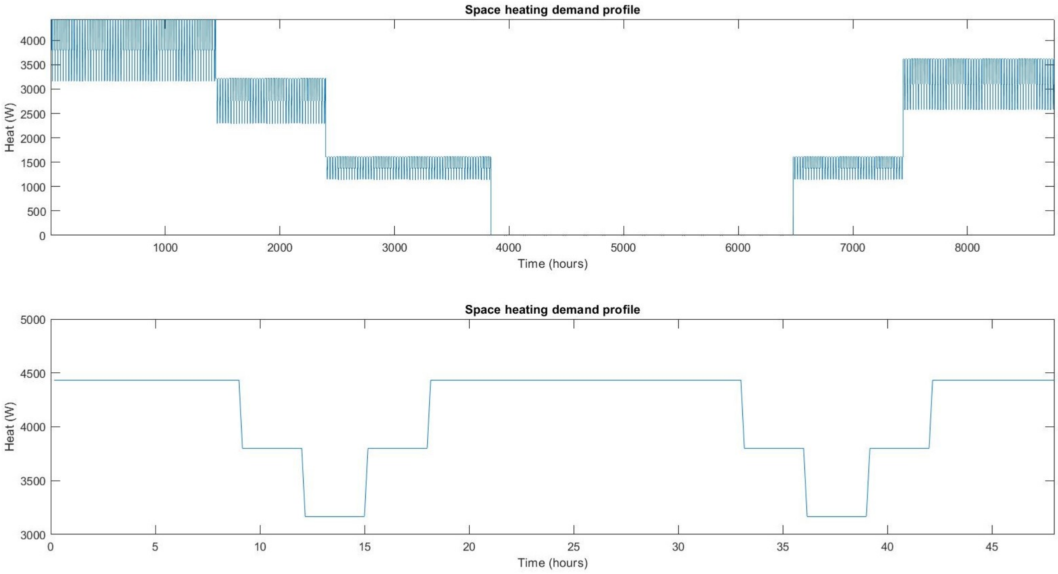


FIGURE 4.4: Top figure: the space heating demand for the whole year, Bottom figure: zoomed in picture of the space heating demand showing two days at the beginning of the year

Flemish average demand in a second step. The space cooling demand also varies throughout the day and year. The cooling demand is only present in the summer months and was based on Figure 4.3 where the summer months are characterised by the SH demand being equal to zero. More precisely, the space cooling is only non-zero from day 160 until day 270. The daily variations in the cooling profile were based on the inverse of daily variations of the SH profile - hence the inverse of Figure

4.2 - and slightly adapted based on domain knowledge.

The second step in the methodology is scaling this normalised profile to an average Flemish demand. Using the average cooling demand and average floor area for a Flemish household of 23 $\frac{kWh}{m^2}$ [68] and 60 m^2 [44] respectively, a value of 1.38 MWh can be found. This value corresponds to the average energy usage of a Flemish household to provide space cooling. This value can be used to scale the normalised profile to the final space cooling demand profile which can be seen on Figure 4.5. This figure shows that the peak demand for space cooling for a single household is just under 2.1 kW. Again note that the space cooling input profile used in the simulations is the superposition of three of these profiles.

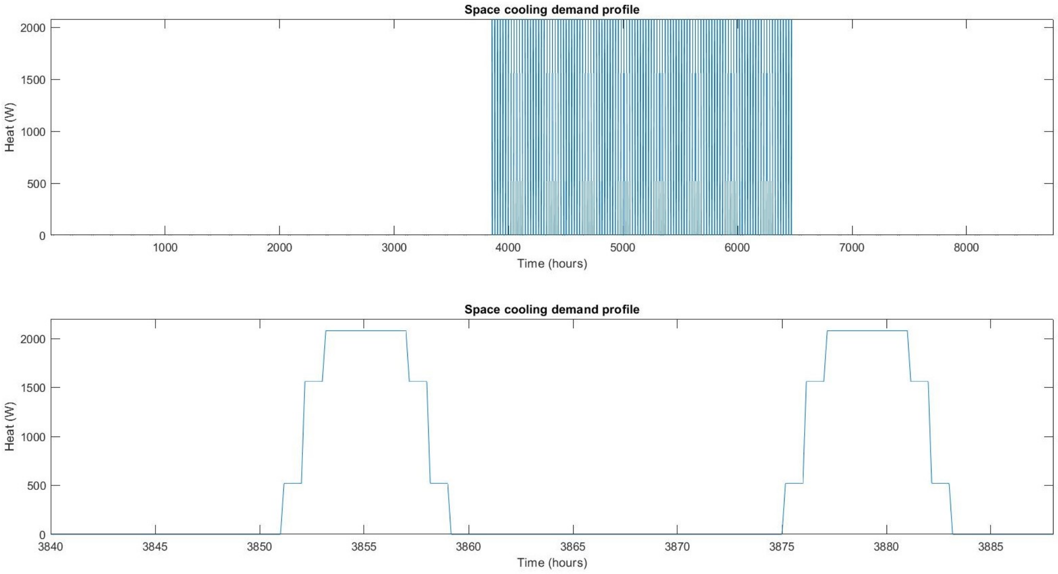


FIGURE 4.5: Top figure: the space cooling demand for the whole year, Bottom figure: zoomed in picture of the space cooling demand showing two days in mid summer

4.3.3 Domestic hot water demand profile

The domestic hot water (DHW) demand profile is the last profile which will be discussed. Again the same methodology as used previously is applied. This profile also uses a time step of 10 minutes which allows to properly model the DHW demand. It is assumed that the water usage does not vary throughout the year but only on a daily basis [38]. The daily variations take showering and general water usage - like cooking and washing - into account. A normalised DHW profile for one day - constant over the year - which consists of three showers of 10 minutes each and some general water usage in the midday and evening [66] is used.

The second step will be scaling this profile to the average DHW demand for a Flemish household which will be equal to 3 MWh yearly [75]. When DHW enters a house it has an average temperature of 10°C [71] and as will be shown in Section 4.3.4 it should be heated to 50°C. This means that - according to Equation 4.1 - on average a household uses 175 litres per day which is a realistic value [4]. The final DHW demand profile can be seen on Figure 4.6 with the peak demand for one house being just below 14 kW. This concludes the discussions on all three demand profiles. Next subsection discusses how the temperature regimes and mass flow rates which can be deducted from these profiles are calculated.

$$\frac{E_{av,DHW}}{c_p \cdot \rho_{water} \cdot \Delta T_{DHW}} = \frac{3 \cdot 10^6 \cdot 3600}{4186 \cdot 1 \cdot (50 - 10) \cdot 365} = 176.71 \tag{4.1}$$

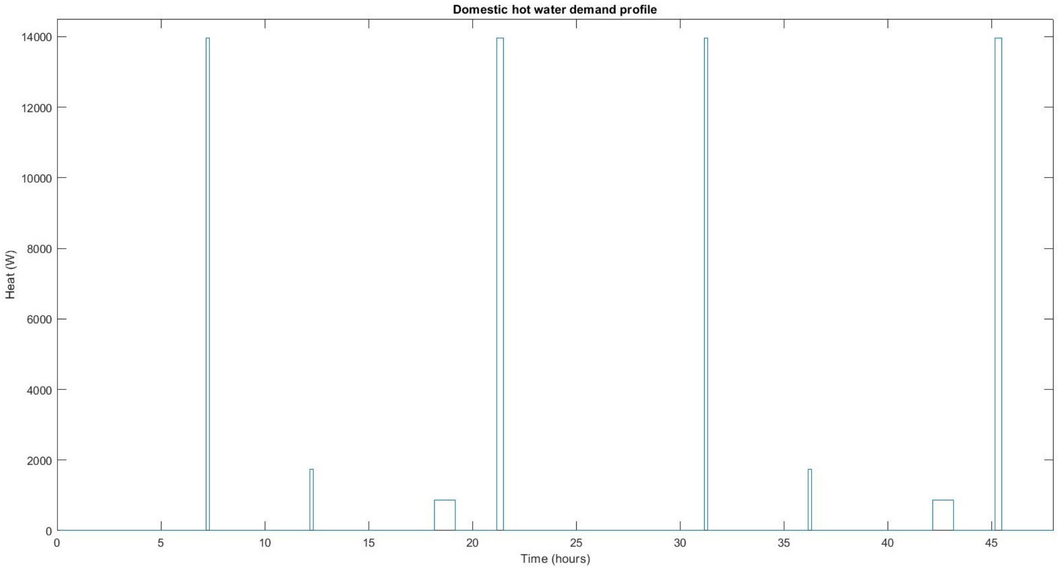


FIGURE 4.6: Zoomed in picture of the domestic hot water demand for two days

4.3.4 Temperature regimes and mass flow rates

The fully known demand profiles discussed in previous three subsections will determine how much heat is extracted from each lumped volume and DHW tank. Besides the heat, also the temperature at which this heat is extracted and at which mass flow rate the lumped volume/DHW tank should be reheated are important. This section will be dedicated to both the temperature regimes and mass flow rates.

Radiator and floor emission systems can both deliver the same amount of heat but do this at different temperatures. Floor emission systems in heating mode typically work around 40°C [67] whereas in cooling mode typically water of around 18°C is flowing through the system [4]. Radiators typically work at around 60-70°C [18]. The DHW tank temperature will be maintained at 45°C [4] with periodic temperature increases to 60°C to avoid legionella bacteria formation inside the tank [30]. From the known heating and cooling demand profiles the needed temperature and mass flow rates to fulfil this demand can be distilled via two formulas.

$$\dot{Q} = UA \cdot (T_{water} - T_{room}) \tag{4.2}$$

$$\dot{Q} = \dot{m} \cdot c_p \cdot (T_{emi,out} - T_{emi,in}) \tag{4.3}$$

Equation 4.2 expresses the heat $\dot{Q}$ in function of the difference between the water temperature T_{water} and the room temperature T_{room} multiplied by the thermal transmittance and area of the emission side, UA-value. This equation allows to calculate the water temperature as every other parameter is known. The room temperature is equal to 21°C, the UA-value for a radiator is around 100 $\frac{W}{K}$ [4] and the UA-value for a floor emission system is around 230 $\frac{W}{K}$ [4]. This water temperature represents the temperature the water should have in the emission system to fulfil the demand and will be called the set-point temperature.
This set-point temperature can be used to calculate the required output temperature for the generation side which will be called the functional temperature. If a linear temperature decrease as the water flows through the emission systems is assumed - which is a reasonable assumption in this context - and knowing that the total decrease in water temperature over an emission system is around 10-12°C [31, 15], the water should be heated 5-6°C above the set-point temperature to on average be the set-point temperature in the emission system. For cooling, the total temperature increase over the emission side will be around 4°C [4], meaning that the water should be cooled 2°C below the needed set-point temperature. And finally for DHW, the functional temperature will be equal to 50°C in order to maintain the tank at 45°C via the internal heat exchanger.

Equation 4.3 can be used to find the mass flow rate through the emission side in order to fulfil the demand at the set-point temperature. This equation expresses the heat $\dot{Q}$ in function of the difference between the outlet temperature of the emission side $T_{emi,out}$ and the inlet temperature of the emission side $T_{emi,in}$ multiplied with the specific heat capacity c_p (= 4187 $\frac{J}{kgK}$ at 15°C for water) and mass flow rate through the emission side $\dot{m}$.
As an example: A certain heat demand is present ($\dot{Q}$ in Eq. 4.2 and Eq. 4.3) which corresponds with a set-point temperature of 60°C (T_{water} in Eq. 4.2). This means that if the water enters a radiator at 65°C (T_{in} in Eq. 4.3) and leaves the radiator at around 55°C (T_{out} in Eq. 4.3), the water temperature was 60°C on average when passing through the radiator. The generation side therefore has to heat the water to 65°C which is the functional temperature. From Eq. 4.3 the required mass flow rate through the heating system to provide this $\dot{Q}$ can then be found.

4.3.5 Conclusions

This section discussed the demand profiles and the temperature regimes as mass flow rates needed to provide these demands. The demands were designed via a two-step approach: first the shape of the profiles was designed based on literature which was then normalised to scale to Flemish averages in the second step. These demands can then be used to determine the temperature regimes and mass flow rates via two equations allowing to fulfil the same demand with different emission systems.

4.4 Conclusion

This chapter started by discussing the Dymola simulation environment, the Modelica modeling language and which libraries are used. The following section explains how the emission side is modelled without modelling all rooms or entire building structure. This requires the demand profiles to be known up front which is the case in the scope of this work. In summary, each type of emission system and DHW tank are modelled by their thermal mass resulting in two lumped volumes and a single DHW tank. The last and third section discussed how each demand profile was made with the general rule that first a normalised profile is made which is then scaled to average Flemish values. Also, more explanations of the temperature regimes and mass flow rates were provided in this section.

This chapter has provided the final pieces of information needed to understand the heating system layout and rule based control strategies which will be elaborately explained in the next chapter.

Chapter 5

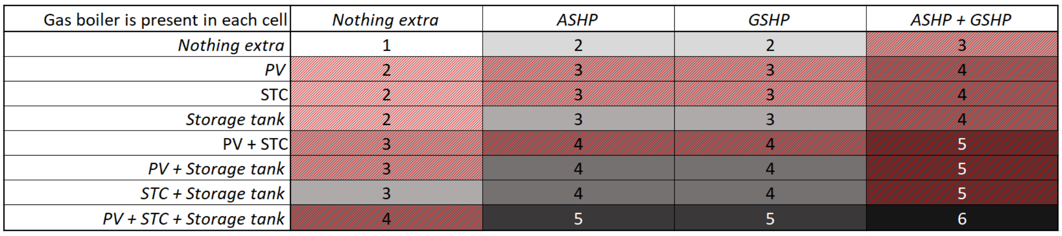
Rule based control strategy

Previous chapters all together defined the base case heating system on which the 12 renovations will be performed, how the emission side of this heating system is modelled, which demand profiles will be used in the simulations and how the final results will be presented. This chapter discusses the control of the generation side and the operation of the retrofits as a whole, which is the last part needed to simulate all retrofits for each of the two boundary conditions. The control strategy will be rule-based meaning that the behaviour of the system is fully defined by *if-this-than-that* behaviour. This chapter will be split up into three parts, the first one will discuss the rules for heating purposes, the second one will discuss the rules for cooling purposes and the last one will touch upon interesting control concepts for future work.

5.1 Control for heating purposes

This first section will be the biggest section of this chapter claiming almost three quarters of it. Figure 5.1 shows the same matrix as presented in Section 3.1, Chapter 3, only now the cells contain a number equal to the number of components present in that heating system while being colour coded in shades of grey to enhance the visual representation of the numbers. The cells shaded in red are the retrofits which were ruled out based on the five rules discussed in that same section. The number of components in a heating system determines the order in which they are discussed starting with the base case and ending with the most complex retrofit in which all five possible components are added. Furthermore, if two retrofits have the same number of components, their order is determined by reading the table from top to bottom and left to right.

This section will contain eight subsections, each one discussing one type of heating system. Although the matrix contains 13 different feasible heating systems, two retrofits where only the type of heat pump is different are identical from a control point of view meaning that they will be discussed in one subsection. Each heating system requires certain rules which will be explained in the subsection - or thus retrofit - where they are needed for the first time. A total of 10 different rules



Gas boiler is present in each cell	*Nothing extra*	*ASHP*	*GSHP*	*ASHP + GSHP*
Nothing extra	1	2	2	3
PV	2	3	3	4
STC	2	3	3	4
Storage tank	2	3	3	4
PV + STC	3	4	4	5
PV + Storage tank	3	4	4	5
STC + Storage tank	3	4	4	5
PV + STC + Storage tank	4	5	5	6

FIGURE 5.1: The heating system matrix representation with the number of components indicated

will be discussed throughout these eight subsections each receiving a letter. In each subsection, a simplified scheme of the heating system will also be presented on which the letters are indicated. It should be noted that these schemes are not hydraulic drawings but simplified sketches of the actual heating systems to ease the understanding of the concepts. Table 5.1 given an overview of which heating system contains which rules. The order of the heating systems in the first column is also the order in which the heating systems will be discussed. A letter in bold means that the rule is explained in that subsection. For all clearness: in this table every row which contains *HP* refers to two refits, one with an air source heat pump and one with a ground source heat pump, but due to their control being identical, they are discussed under the general term heat pump.

Heating system	Control rules by letter
Base case, Section 5.1.1	**A**
Base case + HP, Section 5.1.2	A, **B**, **C**, **D**
Base case + STCs + storage tank, Section 5.1.3	A, **E**
Base case + HP + storage tank, Section 5.1.4	A, B, **F**
Base case + HP + PVs + storage tank, Section 5.1.5	A, **G**, **H**
Base case + HP + STCs + storage tank, Section 5.1.6	A, B, E, F
Base case + HP + STCs + PVs + storage tank, Section 5.1.7	A, E, G, H
Base case + HP + STCs + PVs + storage tank, Section 5.1.8	A, E, G, **I**, **J**

TABLE 5.1: Control rules per heating system - heat pump (HP), solar thermal collectors (STCs), photovoltaics (PVs)

5.1.1 Base case heating system

The first heating system for which the control rules will be discussed is of course the base case heating system. Before the only rule for this heating system is explained, a short comment on the sizing of the gas boiler. As was mentioned in Section 4.3, the space heating peak demand is just short of 4.5 kW and the domestic hot water peak demand is just below 14 kW. This means that for the three houses combined, a heating peak demand of 55.5 kW can be present if all demands happen to occur at the same time. Since the comfort criterion should be met, the gas boiler should be able to cope with this peak demand. When using a gas boiler with an efficiency of 90% [46], the gas boiler should have a capacity of at least 61.6 kW. Therefore a gas boiler with a capacity of 65 kW will be used throughout the simulations to also account for a small safety margin. This gas boiler represents the combined capacity of the three separate gas boilers, one in each house, Section 2.2.

Figure 5.2 shows the simplified scheme for the base case on which the gas boiler and three houses - with each a domestic hot water (DHW) tank and emission system - can be seen. No pumps are shown as they are included in the emission side - as was discussed in Section 4.2 - which is represented by the houses to avoid an overloaded figure. The only rule applied here is rule A and provides control for the gas boiler. The gas boiler should turn on if the water temperature at its input is below the highest functional temperature - the temperature the generation side should deliver to fulfil demand - and at the same time heat must be extracted from the emission side. In a more schematic manner:

Rule A

```
If $T_{inlet\ gas\ boiler} < T_{max\ functional}$ and demand = true
  gas boiler on
else
  gas boiler off
```

In this rule the concept of demand is used by which the Boolean version of the instantaneous value of the demand profiles is meant. In other words, if heat is being extracted from the emission side, the demand is true as long as this is the case. This is to make sure the gas boiler doesn't turn on due to leakages in the system or natural convection which could cause water to pass through the gas boiler.

An elaborate example of how the base case works: If e.g. the floor emission system lumped volume has demand and its temperature decreases below a certain margin under its set-point temperature, the pump connected to this volume will start pumping. This causes colder water flow through the boiler which knows demand is true and that the water temperature at its inlet is below the maximal functional temperature at that point - which is the set-point temperature of the floor emission system plus 5-6°C, see Section 4.3.4. The boiler will therefore turn on and heat the passing water to this functional temperature. It will keep doing this until either the demand turns false or the inlet temperature reaches the functional temperature - which will happen if the pump stops meaning that the volume is back at its set-point temperature plus the margin. This starts all over again if the temperature of the volume decreases again below a certain margin under the set-point temperature.

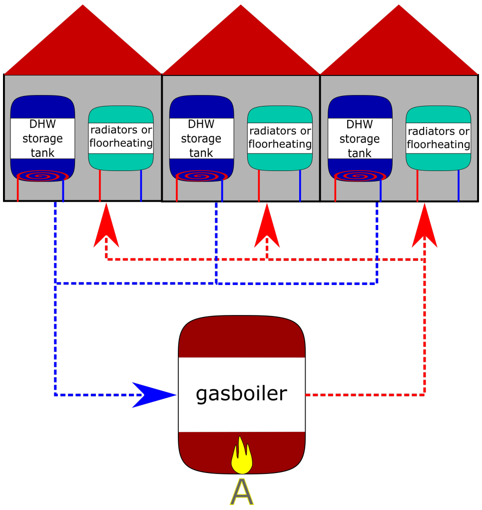


FIGURE 5.2: The simplified scheme of the base case heating system

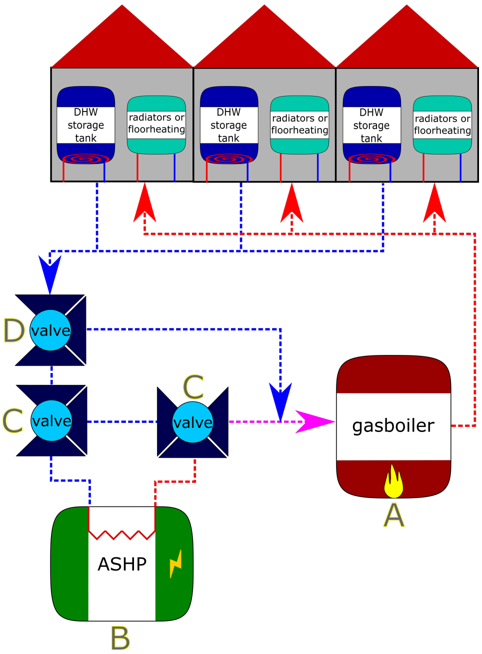


FIGURE 5.3: The simplified scheme of the retrofit base case + heat pump - air source heat pump in particular

5.1.2 Retrofit with heat pump

The first actual retrofit that will be discussed is the one where one type of heat pump is added to the base case. In practice, when a heat pump is installed, storage is always used to prevent heat pump cycling which is essentially turning the heat pump rapidly on and off. Therefore these retrofits will never be used in practice but serve as theoretical limit for what is possible if no storage would be used. It will be a theoretical limit since the introduction of storage also means inevitable thermal losses which will increase the total energy usage, hence CO_2 emissions. Before the control rules will be explained, a discussion on the characteristics of the heat pump will be presented first.

CO_2 emissions should be eliminated as much as possible meaning that as much gas as possible should be removed in the heat provision. Therefore, the HPs will be designed to cope with the peak demand such that the gas boiler should never be used - apart from when the HPs cannot reach the functional temperature. From the results, which will be discussed in Chapter 6, is was concluded that the air source heat pump (ASHP) and ground source heat pump (GSHP) have a coefficient of performance (COP) of at least 2.1 and 3.19 respectively. This means that, using the peak demand of 55.5 kW, Section 4.3 and the worst COP of the HPs, the ASHP and GSHP have to be 26.5 kW and 17.5 kW respectively. Although it might be quite a bit cheaper to size the HPs to provide e.g. 90% of the peak demand - because their capital expenditures will be lower - since the CO_2 criterion is more important than the cost criterion, it is justified to size them to cope with the full peak demand. Besides their capacity, their temperature limit is also of importance since it determines when the gas boiler should upgrade the heat further. Inside the scope of this thesis, a maximal output temperature of 50°C was chosen since this allows to provide domestic hot water, Section 4.3.4, without the need for the gas boiler while maintaining an acceptable COP [4]. The heat pumps both work with a temperature set-point as input which they will try to maintain at their outlet. The temperature they receive as set-point is defined by rule B.

Rule B will ensure that the HP works as efficiently as possible while also reducing the gas usage to its minimum. This is done by giving the HP a set-point temperature which is equal to the highest functional temperature as long as it is below the maximal temperature. This ensures that the HP uses the lowest possible temperature while providing comfort. Knowing that a lower temperature difference across a HP means that the COP will be higher and therefore its electricity usage lower, this rule ensure the lowest electricity and gas usage. In a more schematic manner:

Rule B

$$\boxed{T_{input\ HP} = \text{minimum}(T_{max\ functional}, T_{max\ HP})}$$

Figure 5.3 shows the simplified scheme for the base case + ASHP retrofit. An identical scheme for the base case + GSHP retrofit can be seen on Figure D.1 in Appendix D. On these figures, the gas boiler and ASHP can be seen which are controlled by rule A and B respectively. Besides these two, three valves are also depicted with the two valves around the ASHP being controlled by rule C and the valve closest to the emission side by rule D. Rule C will be discussed first which will be followed by rule D.

As was explained in Section 3.2.3, Chapter 3, to obtain the curve from a retrofit in which a HP is present, multiple simulations have to be performed each with another usage level for the HP. Since the HPs don't have an on-off input but receive a set-point temperature, the valves around the heat pump will be used to accomplish this behaviour. If a HP is not allowed to work the entire year, it is preferred that the HP will always work on the cheapest moments first. Rule C takes this into account by checking whether the current electricity price divided by the instantaneous COP of the HP is smaller than a set-point that corresponds with a certain usage level. The price is divided by the COP since it influences the cost/kWh thermal energy. The set-point mentioned in rule C is based on Figure 5.4 which shows the instantaneous and load duration curve of the electricity price divided by the COP. If for example the value on the left axis where the horizontal line with subscript *mean* intersects this axis is taken as the set-point, the HP would work 50% of the year. The valves would open and allow water passage through the HP when the instantaneous value of the electricity price divided by the COP would be below this set-point. Note that this 50% usage level does not mean that 50% of the total thermal energy delivered to the system comes from the HP. Besides this, the Boolean demand should also be true to avoid that water would pass though the HP when it is not needed. In a more schematic way the electricity price divided by the COP is written as *EP*:

Rule C

```
If EP $< EP_{set-point}$ and demand = true
  valve open
else
  valve closed
```

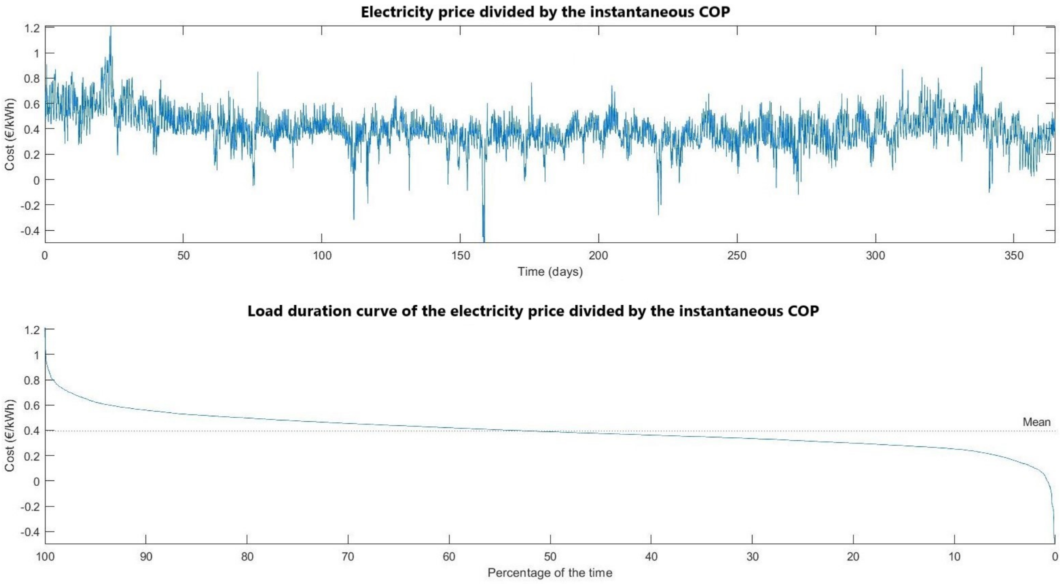


FIGURE 5.4: Top figure: electricity price divided by the COP, Bottom figure: the load duration curve of electricity price divided by the COP

The final rule regarding this retrofit is rule D which controls the valve closest to the emission side. In some cases the temperature which comes out of the emission side might be larger than the maximal temperature the HP can provide. It would be useless to pass the water through the heat pump at that point, as the heat cannot be upgraded. It could even lead to heat flowing out of the heating system if the temperature were higher than the temperature of the working fluid at the condenser side of the HP. Rule D makes sure that this will not happen by bypassing the HP if the water out of the emission side would be higher than the maximal HP temperature. In practice, the water temperature of a floor emission system or DHW tank will never exceed the maximal temperature since their respective functional temperatures will always be below the maximal temperature. Only returning water from radiators might need to by-pass the HP. In a more schematic way:

Rule D

```
If $T_{emission\ side\ out} < T_{max\ HP}$
  valve open
else
  valve closed
```

The boiler does not need any valves as the control strategy behind it does not turn the boiler on if the temperature is already high enough. If only floor emission systems are present, the boiler will not turn on because the functional temperature is already reached by the HP. If radiators are present the boiler measures a temperature lower than the functional one and will upgrade the heat further to the desired level.

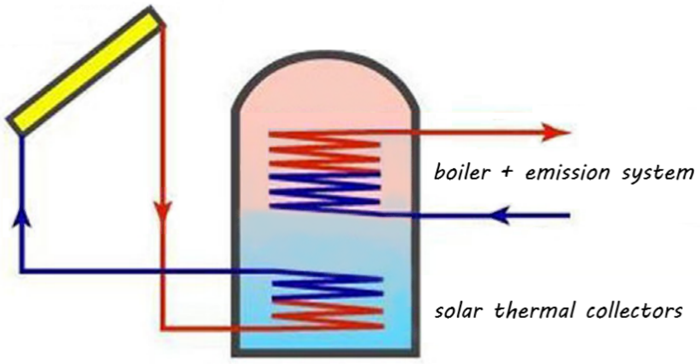


FIGURE 5.5: Storage tank with two internal heat exchangers, inspired on [23]

5.1.3 Retrofit with solar thermal collectors and storage tank

This part will discuss the first retrofit which adds two components to the base case, namely solar thermal collector (STC) panels and a storage tank with an internal heat exchanger. Only one extra rule - rule E - will be needed for this retrofit which will control the pump coupled to the STC panels as can be seen on Figure 5.6. This simplified scheme inter alia shows the tank which has a red spiral at the bottom representing the internal heat exchanger to which the STC panels are connected. This internal heat exchanger is needed since propylene glycol water - with a mass fraction of 40% - flows through the collectors [46]. The water returning from the emission system enters the tank at the top which prohibits circulation in the tank. If the water would enter at the bottom, the STC panels need to get their fluid temperature higher which consequently means that the STC panels sometimes will not be able to deliver to the tank if for example the sun only irradiates the panels with low intensity. If the water enters at the top however, the temperature around the heat exchanger will be lower meaning that more heat can be dissipated which will then travel to the top of the tank. This idea can be seen on Figure 5.5 in a more realistic drawing. Rule E now makes sure that the STC panels will deliver their heat to the tank only if the temperature of the fluid inside the panels is greater than the temperature at the bottom of the tank plus a certain margin to ensure proper heat transfer via the heat exchanger. This is achieved by turning the pump coupled to the STC panels on once the described condition is fulfilled. In a more schematic manner:

Rule E

```
If $T_{STC} > T_{tank\ bottom}$ + margin
  pump on
else
  pump off
```

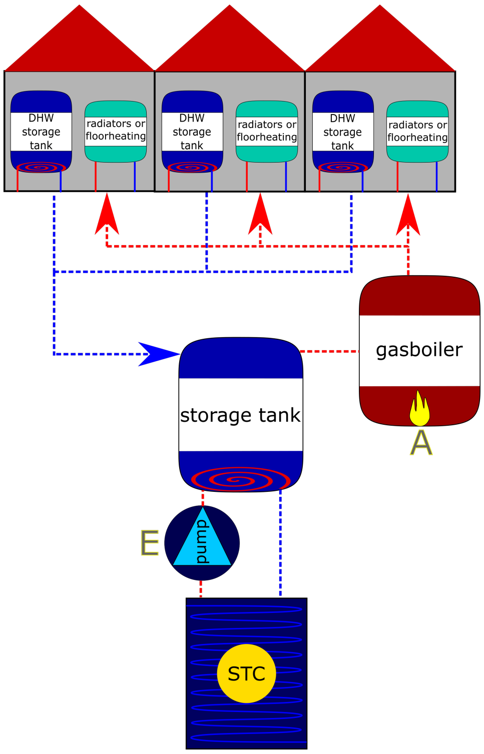


FIGURE 5.6: The simplified scheme of the retrofit base case + solar thermal collectors + storage tank

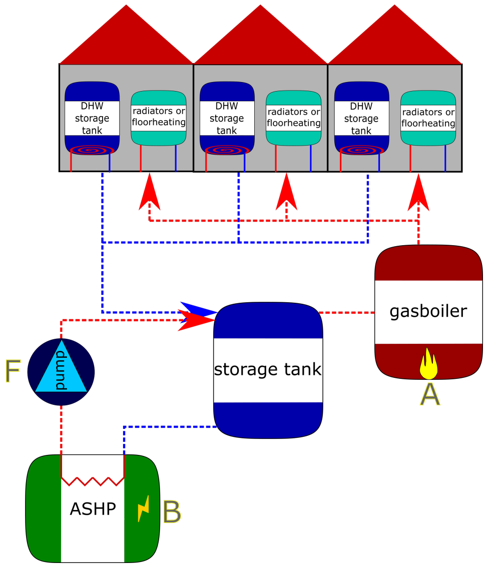


FIGURE 5.7: The simplified scheme of the retrofit base case + heat pump + storage tank - air source heat pump in particular

5.1.4 Retrofit with heat pump and storage tank

This part will discuss the second retrofit which adds two components to the base case, namely a heat pump (HP) and a storage tank. Figure 5.7 shows the simplified scheme for this retrofit, in particular for the air source heat pump variant. The same scheme for the ground source heat pump variant can again be found in Appendix D, Figure D.2. As can be seen, the returning water from the emission side is again connected at the top of the tank. If the connection was made at the bottom of the tank, it could occur that water with a temperature higher than the maximal temperature passes through the HP which should be avoided. Figure 5.7 also shows that no more valves around the HP are needed as the pump coupled to the HP takes over their functionality. This also means that the control rule used to control this pump - rule F - will extend on rule C which controlled these valves.

Rule F will in fact have two parts, a so called functional and opportunistic part. The functional part makes sure that the heat demand is provided and it is this part that extends on rule C. Rule C stated that if the electricity price divided by the COP is below a certain set-point and the demand is true, then the water may pass through the HP. This functional part adds to this that the temperature of the tank at the top should be below the maximal functional temperature meaning that the tank should only be heated if the heat which is already stored in the tank cannot fulfil the demand. The Boolean demand should again be true since otherwise the tank would be kept on temperature when not needed.

The opportunistic part is able to lower the costs for the retrofit by fully heating the tank at a moment when the price will be the lowest for a certain future time interval which will be called *n*. By preheating the tank at a cheaper moment, more expensive future costs are saved. Of course the tank should not already be entirely heated and the price divided by the COP must still be smaller than the set-point for this opportunistic part to turn the pump on. Finally, the Boolean demand doesn't have to be true at the moment of heating but it should become true in this time interval so that the tank is not heated without the heat being used in the near future. In a more schematic representation:

Rule F

```
If EP $< EP_{set-point}$ and demand = true and $T_{tank\ top} < T_{max\ functional}$
  pump on
if EP $< EP_{set-point}$ and EP = minimum(EP,...., $EP_n$) and
      $T_{tank\ bottom} < T_{max\ functional}$ and OR(demand,...., $demand_n$) = true
  pump on
else
  pump off
```

5.1.5 Retrofit with heat pump, photovoltaics and storage tank

The retrofit discussed here will be the first one that adds three different components while it is also the first one that adds photovoltaic (PV) panels to the base case. The addition of PV panels will cause both the rule which determined the input temperature for the HP as well as the rule for the pump coupled to the HP to change. The new rule for the temperature input will be discussed first.

The rule which determined the input temperature for the HP before was rule B which in essence stated that the temperature should be as low as possible while providing comfort. The new rule - rule G - will extend on this rule B by adding a part which will utilise the potential of the PV panels. By introducing PV panels in a retrofit, the HP can upgrade heat without producing CO_2 emissions. This means that the tank can be charged without CO_2 emissions if the sun is irradiating the panels. To fully use this potential, the HP will upgrade the heat to its maximal temperature. The lower COP is not relevant in this case because the electricity does not have embedded CO_2 emissions anyway. However, this does not mean that when the sun irradiates the panels, the input temperature must always be the maximal temperature. For example, if the heat pump were to meet the demand while the power supplied by the panels could only cover part of this demand, this would mean that more electricity would be needed from the grid if the HP were to supply this heat at the maximal temperature. Therefore the Boolean demand must be false for the input temperature to be equal to the maximal temperature. Also a threshold value for the power supplied by the PV panels is used to avoid that the HP would be used if only very little solar power is available - 150 W is used in the scope of this thesis. This power is represented as P. In a more schematic way:

Rule G

```
If demand = false and $P_{PV} > P_{threshold}$
  $T_{input\ HP} = T_{max\ HP}$
else
  $T_{input\ HP} = \text{minimum}(T_{max\ functional}, T_{max\ HP})$
```

The second rule which will see a change is the control for the pump coupled to the HP. This new rule - rule H - adds a part to rule F since the pump should now also turn on when the PV panels deliver power greater than the threshold while the tank is not already fully charged. Rule F - the rule with the functional and opportunistic part - will however slightly be adapted in this new rule as fully heating the tank via the opportunistic part might not be the preferred action if the tank could be heated via the power from the PV panels in the same future time interval. This would mean that CO_2 free electricity would be unused while the tank was heated with CO_2 embedded electricity. To avoid this from happening, the opportunistic part will only be used when there will be no solar irradiation in the time interval. Since the solar irradiation for the whole year is known up front in the scope of this thesis, this is a valid approach. In a real situation, weather predictions will provide this information, be it with a lower accuracy. In a more schematic way:

Rule H

```
If EP $< EP_{set-point}$ and demand = true and $T_{tank\ top} < T_{max\ functional}$
  pump on
elseif EP $< EP_{set-point}$ and EP = minimum(EP,...., $EP_n$) and
        $T_{tank\ bottom} < T_{max\ functional}$ and OR(demand,...., $demand_n$) = true and
        $P_{PV}$,...., $P_{PV,n} < P_{threshold}$
  pump on
elseif $P_{PV} > P_{threshold}$ and $T_{tank\ bottom} < T_{max\ HP}$
  pump on
else
  pump off
```

There is one more thing that has to be explained with regard to this rule. Previously, the pump connected to the HPs always had its mass flow rate defined according to Equation 4.3 from Chapter 4. This equation determined the mass flow rate such that the demand would be met with the temperature difference over the emissions side being 10-12°C, Section 4.3.4. However due to the addition of PV panels, the pump could receive the signal to turn on while this equation might say that the mass flow rate should be zero if there is no demand at that point. Therefore the mass flow rate in this case would be defined according to Equation 5.1. This equation in essence says that, if this mass flow rate flows through the HP, it will use exactly the amount of electricity provided by the PV panels.

$$\dot{m}_{PV} = \frac{COP_{HP} \cdot P_{PV}}{c_p \cdot (T_{defined\ by\ rule\ G} - T_{HP\ in})} \tag{5.1}$$

Now it could be that both equations define a mass flow rate - demand is present while the PV panels deliver power - and therefore the maximal mass flow rate of the two will be chosen as this guarantees that the heat demand is fulfilled and that the PV potential is fully used.

Rule G and rule H together try to utilise the full potential of the PV panels without compromising the comfort criterion or using more CO_2 embedded fuels than strictly needed. The simplified scheme of this retrofit can be seen on Figure 5.8, which is for the air source heat pump in particular. As can be seen, it does not differ much from the retrofit seen in Figure 5.7 apart from the extra PV panels. The scheme for the ground source heat pump variant can again be found in Appendix D, Figure D.3.

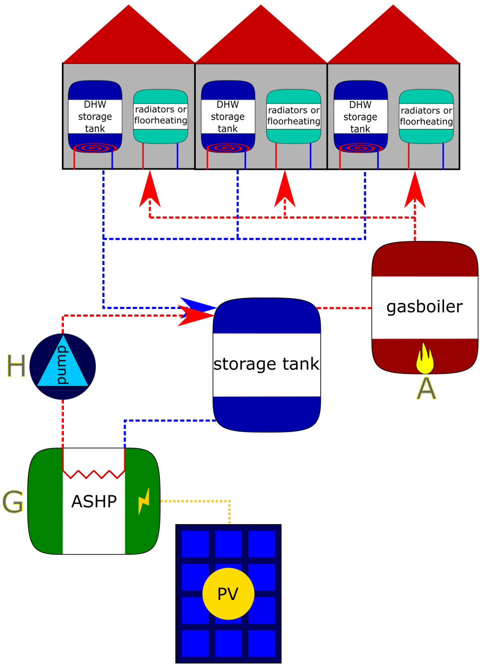


FIGURE 5.8: The simplified scheme of the retrofit base case + heat pump + photovoltaics + storage tank - air source heat pump in particular

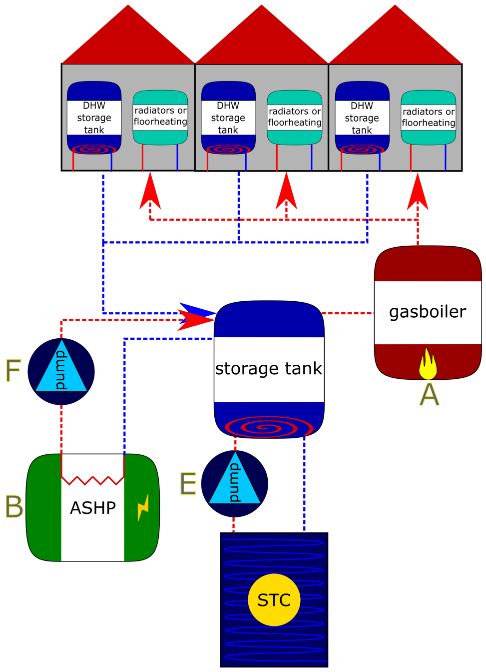


FIGURE 5.9: The simplified scheme of the retrofit base case + heat pump + solar thermal collectors + storage tank - air source heat pump in particular

5.1.6 Retrofit with heat pump, solar thermal collectors and storage tank

Figure 5.9 shows the simplified scheme of this retrofit where a HP - in this case an air source heat pump, solar thermal collector panels and a storage tank are added. The ground source heat pump variant can again be found in Appendix D, Figure D.4. This will be the first retrofit in the discussion which will see no new rules. This is because the HP and STC panels can operate in parallel without interference. Worth mentioning are the connections to the tank as the HP is not connected to the bottom of the tank anymore. The inlet of the HP is no longer connected to the bottom of the tank to avoid circulation as much as possible. This is done so that the STC panels can use as much of their potential as possible, which is preferable because their heat comes without emissions while the HP consumes electricity. This can also be confirmed by the criteria as prevented CO_2 emissions are more import than saved costs which can be obtained via the opportunistic part in rule F. However, the inlet of the HP cannot be connected entirely to the top of the tank as it needs a certain volume to prevent cycling as was explained before. The water which flows out of the emission side was previously always connected to the top of the tank as was discussed in Section 5.1.4 and Section 5.1.3. As the HP and STC panels are now combined into one scheme, it can again be connected to the top of the tank for the same reasons. The way in which the connections are made corresponds again to the tank now seen on Figure 5.10. Note that in the models only the STC is coupled via a heat exchanger as the rest is directly connected to the tank.

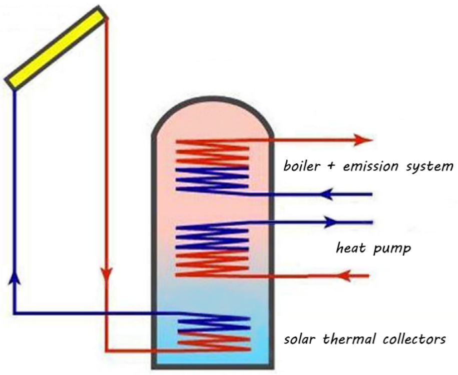


FIGURE 5.10: Storage tank with three internal heat exchangers inspired on [23]

5.1.7 Retrofit with heat pump, solar thermal collectors, photovoltaics and storage tank

This retrofit adds five different components to the base case meaning that it adds photovoltaic panels, solar thermal collectors, a storage tank and a heat pump. Figure 5.11 shows the simplified scheme for this retrofit for the air source heat pump in particular. The exact same scheme but for the ground source heat pump can again be found in Appendix D, Figure D.5. This retrofit is in fact the superposition of the two retrofits in which four components were added. Both retrofits can be combined without any adaptations to existing rules or implementations of new rules. All rules indicated on this figure and every important connection was explained in Section 5.1.6 and Section 5.1.5. One point worth mentioning is that the HP is still connected to the top with its inlet and outlet. This might seem counter-intuitive as the PV panels now cannot charge the tank completely. However the results which will be explained in the Chapter 6, Section 6.2.3 indicated that lower CO_2 emissions are obtained if the inlet is connected to the top of the tank.

5.1.8 Retrofit combining every possible component

This subsection will discuss the final retrofit which combines all possible components. This is the only retrofit where both types of heat pumps are present which therefore requires the addition of two new rules which in fact are very similar to one another. Both rules will actually be the superposition of rule H and an additional part determining which type of heat pump should work. The addition to decide which heat pump to use is based on their respective COPs. Namely, it is preferred to always use the heat pump which has the highest COP since this will result in fewer electricity usage to upgrade the same amount of heat. Each rule therefore in essence

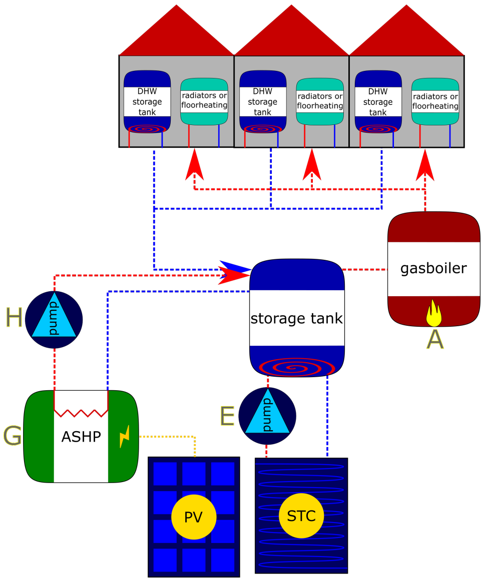


FIGURE 5.11: The simplified scheme of the retrofit base case + heat pump + solar thermal collectors + photovoltaics + storage tank - air source heat pump in particular

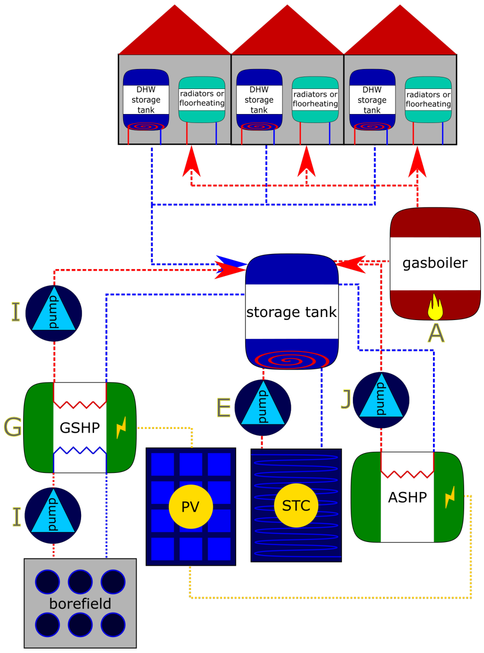


FIGURE 5.12: The simplified scheme of the final retrofits in which all six components are present

says, if this type of heat pump can work more efficiently, then apply rule H to the corresponding pump and turn the pump connected to the other heat pump off in any case. In a more schematic manner:

Rule I

```
**If** $COP_{GSHP} > COP_{ASHP}$
  pump controlled via rule H
**else**
  pump off
```

Rule J

```
**If** $COP_{ASHP} > COP_{GSHP}$
  pump controlled via rule H
**else**
  pump off
```

Figure 5.12 shows the simplified scheme for this retrofit where each component is included. An interesting observation is the difference in inlet connections between the ground source heat pump (GSHP) and the air source heat pump where this first one is connected lower on the tank. This again is caused by the requirement to avoid heat pump cycling which is different for each heat pump as their minimum run time also differs. The minimum run time is larger for a GSHP meaning it should have a larger volume to which it can dissipate its heat - if needed - meaning that it should be connected lower. More on this in next chapter, Chapter 6, Section 6.2.3.

5.1.9 Conclusions

This concludes the elaborate section which discussed all retrofit schemes and heating control rules. Throughout this section, 10 different rules were explained in eight different subsections as was mentioned in the beginning with the aid of Table 5.1. Each rule was implemented with the idea to reduce the CO_2 emissions in the first place and the cost in the second place while always providing comfort. Besides the explanation of each rule and a schematic representation of it, also important points for each retrofit were discussed using the simplified schemes. The next section in this chapter will discuss the cooling control strategy which will be much less extensive as cooling was already discussed in Section 2.4 however not from a control point of view. A third and last section of this chapter will discuss interesting control concepts for future work.

5.2 Control for cooling purposes

Previous section, Section 5.1, discussed the control of the heating system for heating purposes. This section will expand upon the control of the heating system for cooling purposes. Section 2.4 already discussed how cooling will be provided in the different retrofits which resulted in three different approaches:

- Three separate air-coolers have to be installed in case no heat pumps or floor emission systems are present.
- Placing two smaller air source heat pumps instead of one big air source heat pump is preferred if at least two houses have a floor emission system.
- Placing an additional heat exchanger - when a borefield and ground source heat pump are present - which facilitates passive cooling and is supplemented by active cooling with this ground source heat pump, is preferred above anything else.

This section will discuss each of these three options from a control point of view in three subsections. The options will be discussed in the same order as they are listed here.

5.2.1 Air-cooler control

A cooling demand is seen by the generation side as water leaving the component with a lower temperature than water which enters the component, which is due to the heat absorption by the water as it passes through the emission side. The air-coolers will work a bit differently as they don't act on the thermal network but directly cool the air inside the room and export the heat outward. Since the rooms from the houses are not modelled within the scope of this work, another approach is followed. As was explained in Section 2.4.3, the air-coolers are air-to-air heat pumps assumed to work at a comparable COP as an air source heat pump (ASHP). This allows to model the air-coolers as ASHPs acting on a lumped volume as the used electricity will be the same for a same amount of heat that should be extracted or thus a same cooling demand. The control strategy for the air-coolers will turn them on if the temperature of a room is higher than the maximal allowable temperature for such a room. The air-coolers will switch off again when the comfort temperature in the room has returned. This room temperature will be equal to the lumped volume temperature in the models. In a more schematic way:

Control air-cooler approach

```
If $T_{room} > T_{max\ room}$
  while $T_{room} > T_{comfort\ room}$
    air-cooler on
else
  air-cooler off
```

5.2.2 Dual air source heat pump control

The second subsection will discuss the control behind the dual air source heat pump (ASHP) approach. This approach was explained in Section 2.4.3 and installs two ASHPs - instead of just one - ensuring that the cooling and heating demand can always be met using only electricity - which reduces the CO_2 emissions as much as possible. Figure 5.13 shows the simplified scheme for this approach. It can be seen that two extra valves and a pump are needed for the ASHP not to be coupled to the tank. This ASHP will be the small one which will switch between cooling and heating with the pump and valves regulating this behaviour. Since the HP will only start to work when the room temperature goes above the maximal permissible temperature - and then cools the room until it returns to the comfort temperature - the HP is assumed to run for its minimum operating time meaning that it can be directly connected to the houses.

The small ASHP will be designed to cope with the peak cooling demand while the other will be designed to the peak heating demand minus the peak cooling demand. This method of design guarantees that the heating and cooling demands will always be fulfilled using only electricity as long as the peak heating demand is at least three times larger than the peak cooling demand which will practically always be the case. In the scope of this thesis the peak heating demand is 8.8 times larger than the peak cooling demand, Section 4.3.
If the peak heating demand occurs, both HPs work together to fulfil this demand and if the peak cooling demand occurs, the small ASHP can entirely fulfil this demand. The requirement for the peak heating demand to be at least three times the peak cooling demand arises when one house has a cooling demand while the other two have the peak heating demand as can be seen in Equation 5.2.

$$Q_{a,therm} - 2 \cdot Q_{peak,heat} > 0 \; with \; Q_{a,therm} = 3 \cdot Q_{peak,heat} - 3 \cdot Q_{peak,cool} \tag{5.2}$$

The control behind these heat pumps ensures that each heat pump operates in the correct mode determined by the demand profiles. The control for a HP in cooling mode can be summarised by the control for the air-coolers because they use the same principles. If the room temperature is greater than the allowed temperature, the pump coupled to the floor emission system of that house and the valves coupled to the HP will cause water to flow through this HP. This HP will observe a temperature higher than the set-point temperature causing it to extract heat out of this water to get it to the required functional temperature. For a heat pump in heating mode the control depends on the retrofit as was explained in Section 5.1. In a more schematic manner:

Control dual air source heat pump approach

```
If $demand_{cooling} = \text{false}$
  both ASHPs in heating mode according to the control in Section 5.1
if $demand_{cooling} = \text{true}$ and $demand_{heating} = \text{true}$
  big ASHP in heating mode according to the control in Section 5.1
  small ASHP in cooling mode according to the control in Section 5.2.1
else
  small ASHP in cooling mode according to the control in Section 5.2.1
```

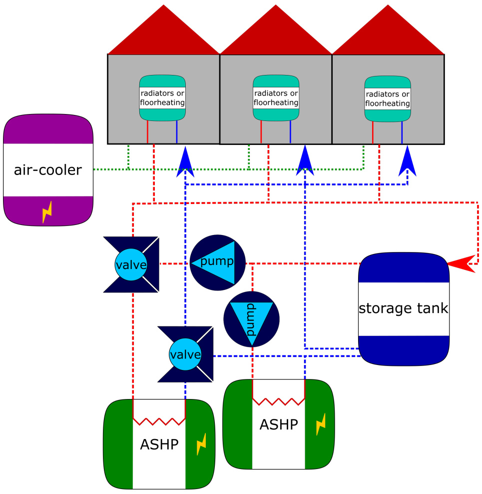


FIGURE 5.13: The simplified cooling scheme of the dual ASHP approach

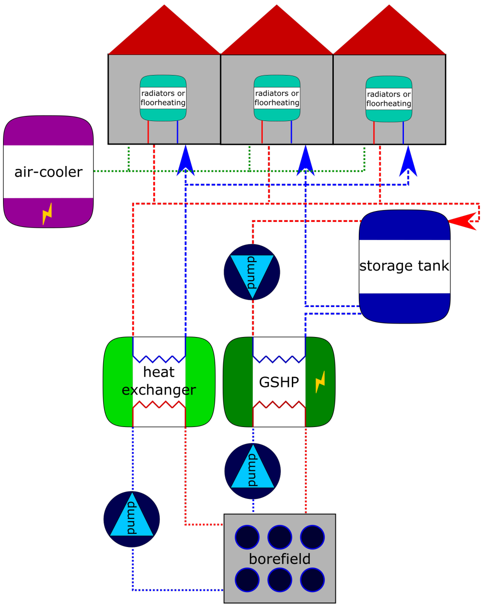


FIGURE 5.14: The simplified cooling scheme of the heat exchanger and ground source heat pump approach

5.2.3 Heat exchanger and ground source heat pump control

This last subsection will discuss the control behind the heat exchanger and ground source heat pump (GSHP) in cooling mode. The general idea was explained in Section 2.4.2 and can be summarised as placing a heat exchanger (HEX) directly between the borefield and houses to enable passive cooling. Figure 5.14 shows the simplified scheme for this idea. It can be seen that only a heat exchanger is new and - since it can only be used for cooling - does not require any valves. The control strategy becomes quite complex very fast due to the borefield. For example, if cooling and heating are present at the same time, the borefield should be split up to use one part for heating and the other for cooling which is not possible at the moment in the Modelica modelling language [46]. This however is not a problem in the scope of this thesis as the demand profile causes no overlap of heating and cooling, Section 4.3. Besides this also the temperature regimes are important since the passive cooling via the heat exchanger might not work properly if the temperature of the borefield becomes too high. To solve this also active cooling via the GSHP is needed at some moment in time as was explained in Section 2.4.2. A very detailed control strategy would be too complex for what this thesis wants to achieve and therefore a simple control strategy was used. This strategy in essence uses the heat exchanger at the beginning of summer when the borefield would allow passive cooling after which active cooling via the heat pump will be applied. In a more schematic way:

Control heat exchanger and ground source heat pump approach

```
If $demand_{cooling}$ = false
  GSHP in heating mode according to the control in Section 5.1
elseif $demand_{cooling}$ = true and $demand_{heating}$ = true
  split the borefield if needed, use a part to cool passively with the HEX
  use a part for heating with the GSHP according to the control in Section 5.1
else
  cool via the HEX or GSHP depending on the time of the year
```

The heating and cooling simplified schemes were always depicted separately to give a clear view on what is being discussed. Nevertheless, they can be combined into one scheme without any problem but were excluded in this text as they would not add much value. However, for completeness a full heating system containing both the heating and cooling components is presented for the last retrofit which can be seen on Figure D.6 in Appendix D. This scheme uses the GSHP with HEX approach as it is preferred over the ASHP one.

5.2.4 Conclusions

This concludes the discussion on the control for cooling purposes. Throughout this section the three options to provide cooling were discussed from a control point of view. In general, it can be said that the room temperature is decisive for the components that determine when to switch to cooling mode, and for the GSHP option in particular, the time of year is also decisive. The next section will be the last one of this chapter and discusses some interesting control concepts for future work.

5.3 Future work for control strategy

Although many control rules were already discussed, there are still a lot of rules which could make the heating systems perform even better. This section will discuss a few interesting concepts which could reduce the CO_2 emissions further. It was chosen to discuss this here as the future work which will be discussed in next chapter, Chapter 6, will not have its emphasis on the control strategy. This section will be divided into five subsections:

- The borefield, ground source heat pump and solar thermal collector panels
- The borefield, ground source heat pump and photovoltaic panels
- Negative electricity price
- Exchange heat in between households
- Model predictive control

The subsections will be discussed in the same order as they are listed here.

5.3.1 The borefield, ground source heat pump and solar thermal collector panels

As can be seen on figure 5.15, the solar thermal collector (STC) fluid temperature (in blue) is often below the water temperature at the bottom of the tank (in red) in the winter, which means that the STC panels cannot deliver heat to the tank. It can be seen that the STC temperature however does exceed the temperature of the borefield (black). This means that the borefield could be heated by the heat of the STC panels which is otherwise not being used. This would have the consequence that the average temperature of the borefield will be higher which means that the ground source heat pump (GSHP) will have a higher COP on average and as such fewer electricity will be used. This is however a trade-off as by heating the borefield too much, passive cooling in the summer could be used less often. Besides this, delivering the heat will cause the fluid inside the STC panels to remain at a low temperature which at a certain moment in the year might not be preferred anymore as the STC panels could increase their fluid temperature above the water temperature of the tank. Again this will be a trade-off.

Another option to use this low temperature heat of the STC panels in the winter, is to directly couple the STC panels to the GSHP instead of the tank. The heat pump could then upgrade this heat instead of the heat extracted from the borefield. The downside of this idea is that it requires a GSHP which can work with two different

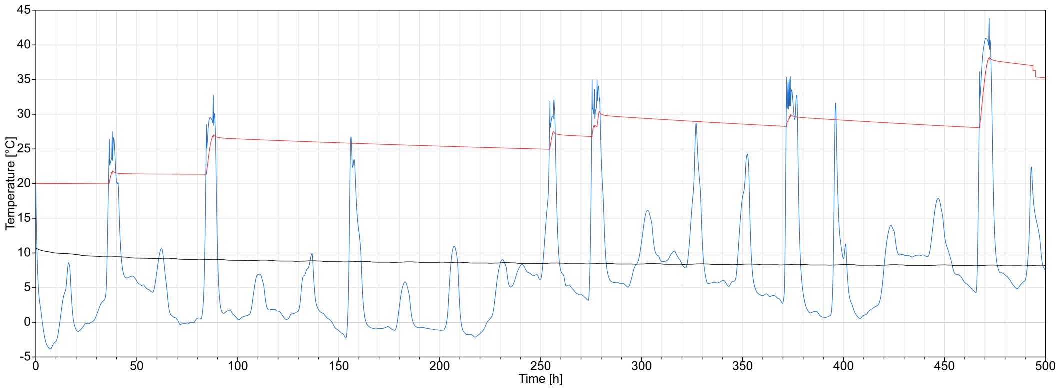


FIGURE 5.15: Temperature profile of borefield wall (black), solar thermal collector fluid (blue) and tank bottom (red) at the beginning of the year

fluids at its evaporator side which means an increased complexity and cost. Again this results in a trade-off.

5.3.2 The borefield, ground source heat pump and photovoltaic panels

Photovoltaic (PV) panels generate electricity without any CO_2 emissions nor cost. Using this electricity is therefore key in reducing the overall CO_2 emissions. The implemented rules try to do this via storing as much of this electricity as possible in the storage tank in the form of thermal energy. Nevertheless, there will still be electricity which will not be used. Expanding the tank might seem an option but as will be shown in next chapter, Chapter 6, this is not always beneficial. However if a borefield is present, the extra electricity could be stored in the borefield via the GSHP. Namely, the GSHP could reverse its working direction and heat the borefield with the remaining electricity. This again would cause a higher average borefield temperature and therefore lower CO_2 emissions due to the higher COP. It would however again result in a trade-off since heating the field too much may lead to less potential for passive cooling.

5.3.3 Negative electricity price

As could be seen on figure 5.4, a few times throughout the year the electricity price becomes negative. This figure in fact shows the price divided by the COP but as the COP is always positive, the negative values should be caused by negative electricity prices. When the assumption is made that the negative electricity prices are mainly caused by photovoltaic panel parks and/or wind turbine farms, which is a reasonable assumption [8], it can be stated that the electricity from the grid at that point does not have any embedded CO_2 emissions. If the storage tank would not be fully charged at that point, it could be charged by the electricity from the grid which would mean that the household receives money. This means that the electricity from the grid is preferred even above the electricity from own PV panels as these have a higher cost - although it being zero. Using this principle could thus benefit the third criteria, being the cost. For this to work is however also a CO_2 varying electricity price needed.

5.3.4 Exchange heat between households

This section will discuss a concept where houses can exchange heat with each other. At a few moments throughout the year it could happen that one of the houses has a heating demand while the others already have a cooling demand or vice versa. At this moment both demands are fulfilled by using electricity and/or gas. It might however be possible to exchange the heat between the houses - via a heat exchanger - or for example upgrade the extracted heat from one house via a heat pump to heat another house. However, due to the small temperature differences, exchanging the heat directly might not be feasible and also upgrading the heat via the heat pump might not be worth the extra complexity. This however does not mean that it couldn't potentially improve the performances for which reason it is explained here.

5.3.5 Model predictive control

This last part briefly touches on model predictive control. In contrast with the previous parts discussed in this section, this one does concern a certain rule. Model predictive control is a whole other approach to a control strategy. Instead of the rule based approach used in the scope of this work, model predictive control could also be used. In short: model predictive control solves an optimisation algorithm which tries to find the most optimal control action for a certain desired output while using a model to predict the system's future behaviour [62]. Where rule based control is a rigid method based on predefined rules, model predictive control allows to really minimise for example the CO_2 emissions. Model predictive control therefore seems a very promising technology which might be used in future work.

5.4 Conclusion

This chapter was entirely dedicated to the control strategy on which it elaborately expanded. Three sections filled this chapter with the first and second one discussing the control for heating and cooling purposes respectively. The heating control strategy was explained in eight different subsections each discussing a retrofit and the control rules that were introduced in that retrofit. A total of 10 different rules were explained always starting with a general explanation of the insights and ending with a more schematic representation. The cooling control strategy was explained using three subsections each discussing how one of the three options is controlled. Also here a more general discussion of the concept preceded a more schematic representation. The final section of this chapter presented some interesting concepts which can be used in the control strategy in future work.

Remember that the aim of this thesis is to find the collective heating system retrofit which has the lowest cost to reduce CO_2 emissions. Everything discussed so far has helped building the path to reach this goal. From the design of the base case to the rule based control strategy, all individual parts are needed to obtain the results which will be presented in next chapter, Chapter 6. Chapter 6 will also answer the question of which retrofit has the lowest cost to reduce the CO_2 emissions presented in the final graph which was already explained in Section 3.2.3, Chapter 3.

Chapter 6

Results

As repeated many times throughout this text, the aim of this thesis is to find the collective heating system retrofit which has the lowest cost to reduce CO_2 emissions. This chapter will finally answer this question. It will, as the name suggests, present the results which were obtained by simulating all the retrofits for both boundary conditions. The first part of this chapter will illustrate a handful of interesting results which will show how the models react to the control strategy. This section will be followed by a discussion of preliminary simulations which have to be performed to simulate the models for the final cost - CO_2 abatement graph. This second section is based on results which is why it is included in this chapter. The third section will then finally present the cost - CO_2 abatement graphs. In any case, two graphs will be present, namely one for each boundary condition. However more graphs than these two are made because, as will be shown in this section, the way in which the excess electricity generated by the photovoltaic panels is treated has a big impact on the graph. A fourth and final section will discuss interesting points that emerged during this work but are not treated in the scope of this thesis.

Two very important parameters used throughout all results are the CO_2 intensities for gas and electricity being 0.161 $\frac{kg\ CO_2}{kWh}$ [46] and 0.168 $\frac{kg\ CO_2}{kWh}$ [**?**] respectively. Besides these, Appendix E contains all the parameter values which were used in the models.

6.1 Results in relation to the control strategy

This first section will show four interesting results which visualise how the models react on the control strategy. This section will be divided into four parts, each presenting one result. The first subsection shows a result from the base case, the second subsection shows a result from the base case + air source heat pump (ASHP) + storage tank retrofit, the third one does this for the base case + ground source heat pump (GSHP) + storage tank retrofit and the final one presents a result from the final retrofit.

6.1.1 Saw-tooth profile of lumped volume temperature

The top plot of Figure 6.1 shows the temperature of the domestic hot water (DHW) which comes out of the tap as a function of time. The blocks which can be seen correspond with the DHW profile as was defined in Section 4.3.3 while the temperature at which the DHW is delivered can be seen to be equal to the 45°C as was defined in Section 4.3.4.

The bottom figure shows the temperature inside the lumped volumes of the radiators and floor emission systems in blue and green respectively. Their set-point temperatures are represented by the red and pink curves. It can be observed that the shape of the set-point temperature is the same as the shape of the space heating profile as defined in Section 4.3.1. However, more importantly is the saw-tooth behaviour of the water temperature inside the lumped volumes. As was explained in Section 4.2.2, the pump coupled to each lumped volume will start pumping water through the generation side as its temperature decreases under the set-point temperature minus the margin. From the moment the pump turns on, the gas boiler in this case will see water at its outlet at a temperature below the functional temperature which causes it to turn on. This will heat the water which then flows back to the lumped volume again increasing its temperature. At a certain moment the temperature of the lumped volume will exceed the set-point temperature plus the margin causing the pump to turn off again. Nevertheless, the demand is still causing heat to be extracted from the volume which again causes the temperature of the water inside the lumped volume to decrease. This explains the observed saw-tooth behaviour.

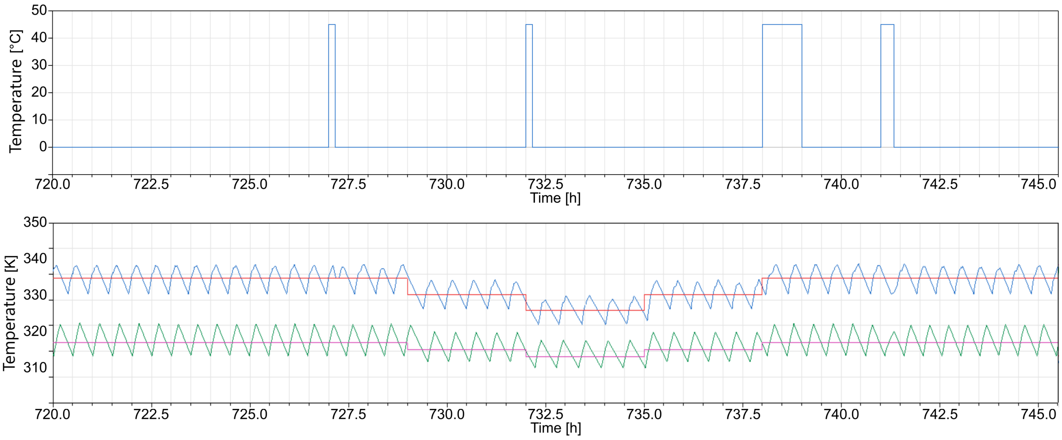


Figure 6.1: Top figure: temperature of domestic hot water out of the tap, Bottom figure: saw-tooth temperature profile inside the lumped volumes

6.1.2 Electricity price influence on the heat pump behaviour

Figure 6.2 shows the influence of the electricity price divided by the COP on the behaviour of the air source heat pump (ASHP) - which was explained in Section 5.1.2 - for the boundary condition of only floor emission systems. This figure shows

many things with on the top figure the hourly varying electricity price divided by the COP in red and the set-point for this in blue. The bottom figure shows the input signal for the gas boiler in red, the input signal for the pump coupled to the ASHP in blue and the highest functional temperature in black.
The first thing to notice is that from the moment the price divided by the COP becomes bigger than the set-point, the ASHP will not turn on anymore and the demand has to be fulfilled by the gas boiler. Secondly, since the functional temperature stays below 50°C - which is the maximal temperature of the ASHP, Section 5.1.2 - the gas boiler never has to turn on when the ASHP is allowed to work as it can provide the needed temperature. A third and final point is that in the functional temperature shape, the superposition of the DHW and floor emission system demand profiles can be observed which were defined in Section 4.3.3 and Section 4.3.1 respectively. The functional temperature and the demand profiles depend on each other according to Equation 4.2, Chapter 4.

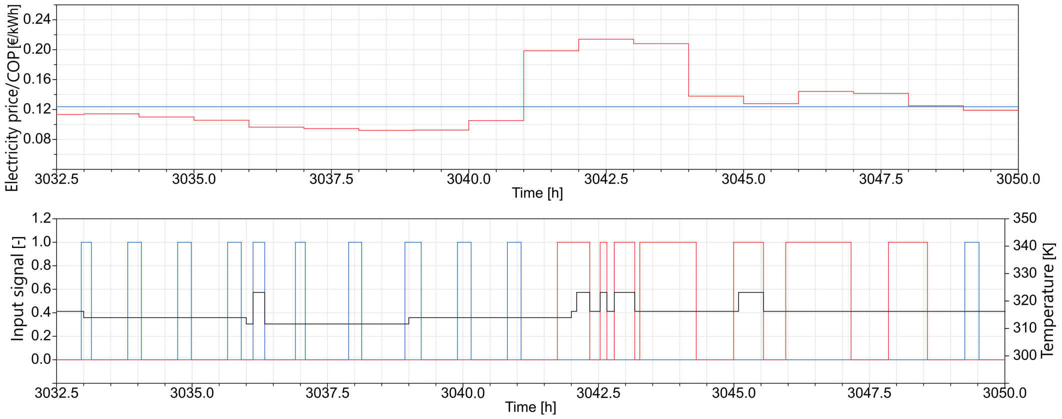


Figure 6.2: Top figure: electricity price divided by the COP and its set-point, Bottom figure: input signal of the gas boiler and pump coupled to the air source heat pump and the highest functional temperature

6.1.3 Boundary condition influence on the required energy

Figure 6.3 shows the influence of the boundary condition on the energy the gas boiler and ground source heat pump (GSHP) use to fulfil the demand. The top plot shows the energy usage by the gas boiler whereas the bottom plot shows the energy use of the GSHP - note the different scales of the vertical axis of the plots. The black curve corresponds to the base case, the red curves correspond to the base case + GSHP + storage tank retrofit if only radiators are present in the emission side and the blue curves correspond to the same retrofit but now if only floor emission systems are present in the emission side. This figure shows that without any doubt the base case consumes most energy. But more importantly what this figure shows is that if the emission side consists of radiators, the gas boiler still consumes gas whereas no gas is used if only floor emission systems are present. This is because - as could be seen on Figure 6.2 - the functional temperature always remains below 50°C if no radiators are present allowing the HP to fully fulfil the demand. If however radiators are present, the heat pump will not be able to upgrade the heat all the way to the functional temperature required for the radiators. A second interesting point which can be seen is that if radiators are present, the energy consumed by gas remains constant for quite a long time throughout the year. This is because the space heating demand has a varying magnitude throughout the year - Section 4.3.1 - which means that at a certain point even the functional temperature for the radiators becomes low enough allowing the heat pump to entirely fulfil the demand.

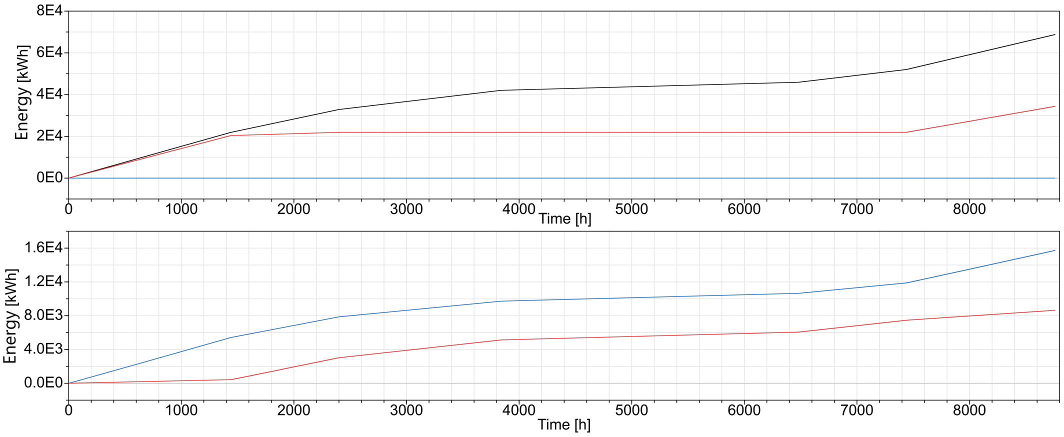


FIGURE 6.3: Top figure: energy usage by gas boiler, Bottom figure: energy usage by ground source heat pump

6.1.4 Ground source heat pump versus air source heat pump

This last section will prove the expected results as was promised in Section 3.1.2, Chapter 3. This section said that it is very likely that the benefit in CO_2 reduction - by placing two types of heat pumps in one retrofit - is very minor and that it is expected that the ASHP will only work a very small part of the time compared to the GSHP. To prove the expected result that both heat pumps together will have little benefit will be done using Figure 6.4 which was obtained after simulating the final retrofit. The top figure shows the subtraction between the COP of the GSHP and ASHP throughout one year with a horizontal line at zero. The bottom figure shows the space heating demand throughout one year as defined in Section 4.3.1. From the top figure it can be deduced that the difference between the COPs is almost always greater than zero meaning that the COP of the GSHP is almost always greater than the COP of the ASHP. Besides this, when the difference goes below zero - meaning that the ASHP can work more efficiently at that point - the difference is rather minor indicating that the COP of the ASHP is only slightly greater than the COP of the GSHP. To be more specific, the ASHP only works more efficiently 5.17% of the time. When the magnitude of the space heating demand is taken into account - in winter the heating demand is much greater - the domination of the GSHP becomes even more severe with the ASHP only delivering 3.20% of the total delivered energy. When as a final point the CO_2 is taken into account, the final retrofit abates 40 kg CO_2 more than the same retrofit without the ASHP, this is 0.38% of the total abated CO_2 yearly. This proves that the benefit in CO_2 reduction is very minor due to the COP difference being minor and the little usage of the ASHP in comparison to the GSHP. From a cooling point of view, the GSHP would also always be preferred since it allows for passive cooling which reduces CO_2 emissions and costs. Since the DHW demand does not vary over the year it would have no impact and is therefore excluded in this analysis.

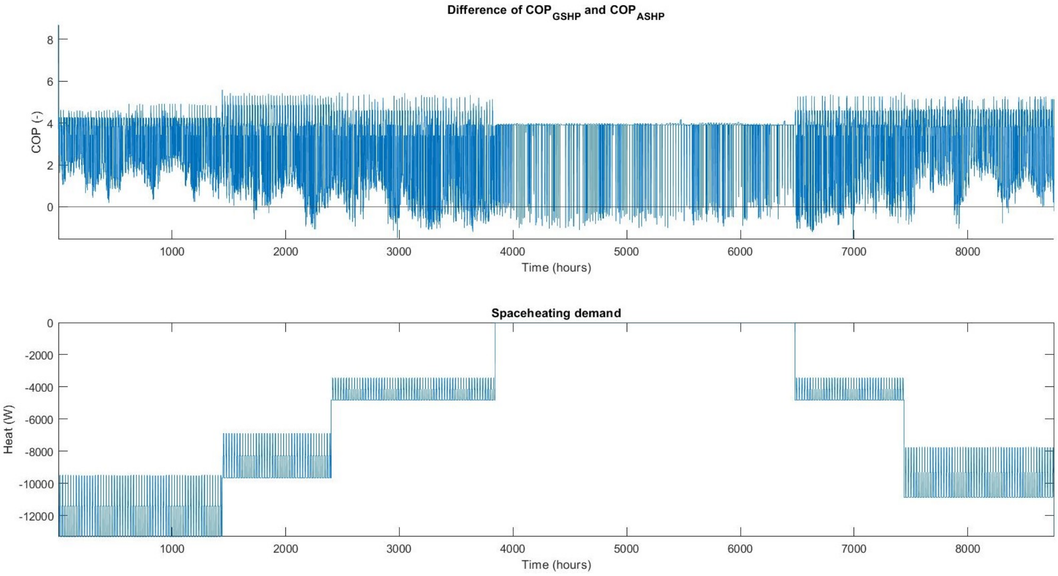


FIGURE 6.4: Top figure: difference of the COP of the heat pumps, bottom figure: the space heating demand

6.1.5 Conclusions

This concludes the section on the results in relation to the control strategy. Many more results could be presented as the simulation of the final retrofit alone contains more than 1200 different parameters. Taken into account that 13 models are simulated twice - once for each boundary condition - a tremendous amount of figures could be made. This section only presented the tip of the iceberg - although this might even be exaggerated - of all the data obtained via the simulations. Next section will present the results from the preliminary simulations needed for the cost - CO_2 abatement graph.

6.2 Preliminary simulations

As can be understood, each component has a certain number of independent parameters which can take many different values e.g. a capacity or area. This section will discuss the results of the simulations which were performed to define these parameters in order to run the simulations for the cost - CO_2 abatement graph. It will be split up into three parts of which the first one will be a general discussion on the independent parameters and how their number has in fact already been reduced throughout this entire text. The second subsection will explain how the number of parameters can be reduced by how the final graph is constructed. The third and last subsection will discuss how the remaining independent parameters can be correlated to each other.

6.2.1 Reduction by assigning a value

An independent parameter is a parameter which does not have a value a priori nor a relationship with other parameters. Table 6.1 gives an overview of which component has which independent parameters and in total 13 different parameters can be counted. If no single value was chosen, but instead all parameters were determined through an optimisation that minimised CO_2 emissions, it becomes clear that this would be an immense task. Therefore the values of some parameters will be fixed which was in fact already done throughout this entire text. Each parameter which is already fixed has its value also written in the table with a reference to the section where it was defined. By this manner already eight parameters are fixed: the capacities of the boiler, heat pumps, air-coolers and heat exchanger, the maximal temperature for the HPs and the threshold for the photovoltaic (PV) power. With all these parameters defined, five independent parameters remain. The reduction is significant although still a lot of iterations would have to be performed if these parameters were to be determined via an optimisation.

6.2.2 Reduction by the nature of the curves

A second reduction of independent parameters follows simply from the way the curves on the cost - CO_2 abatement graph are constructed. As was discussed in Section 3.2.3 of Chapter 3, three different ways exist in which a curve for a retrofit will be constructed depending on the components that are present in the retrofit. The first option occurs if only solar thermal collector (STC) panels are present in which the curve would in essence be a parameter sweep of the STC area. The second option is used when only heat pumps are present in a retrofit which results in the curve in essence being a parameter sweep of the set-point for the electricity price divided by the COP. The final option is the one where both a heat pump and STC panels or PV panels are present in which case the curve in essence is be a combined parameter sweep of the respective area and the price divided by the COP set-point. This means that four of the remaining five parameters should remain independent as they must

Component	Parameters
Condensing gasboiler	capacity Q_b = 65 kW, Section 5.1.1
Air-cooler	capacity Q_c = 2.1 kW, Section 2.4.1
ASHP	capacity Q_a = 26.5 kW, Section 5.1.2 maximal temperature $T_{max\ ASHP}$ = 50°C, Section 5.1.2 electricity price divided by COP set-point $P_{set-point}$
GSHP	capacity Q_g = 17.5 kW, Section 5.1.2 maximal temperature $T_{max\ GSHP}$ =50°C, Section 5.1.2 electricity price divided by COP set-point $P_{set-point}$
Heat exchanger	capacity Q_h = 2.1-6.3 kW, Section 2.4.2
Storage tank	tank volume V_{tank}
STC	area A_{stc}
PV	area A_{pv} threshold power $V_{threshold}$ = 150 W, Section 5.1.5

TABLE 6.1: Independent parameters per components

vary to obtain the curves. The only parameter remaining which has no value nor use in the construction of the curves, is the volume of the storage tank.

An option would be to optimise the tank volume for each simulation that will be performed. However, a small calculation shows that this would still mean an incredible amount of simulations and time. As was also explained in Section 3.2.3, a curve can either consist of 16, 11 or 26 points depending on which option is used to construct the curve. For one single cost - CO_2 abatement graph, this means that 243 simulations need to be performed: seven curves with 26 points, four curves with 11 points, one curve with 16 points and the base case which is just one simulation. When the simulation time for each model is multiplied with the respective number of simulations that need to be performed for the curve corresponding to that retrofit, a single cost - CO_2 abatement graph takes 54 hours of simulation time on a standard laptop. The average simulation time to simulate one year for the base case is 2.5 minutes where on average a model with a GSHP or ASHP takes 25 minutes and 7 minutes respectively - this as reference of the order of magnitude of the simulation times. Now at least two of these graphs are made meaning that the total simulation time is already around 4.5 days. This substantiates that adding an optimisation for the tank volume in each simulation would simply take too much time. Next section will discuss how this was solved.

6.2.3 Reduction by correlating parameters

This last subsection will show how the tank volume was determined to avoid an optimisation for each simulation while also assuring that the chosen tank volume allows to use as much potential of the STC and PV panels as possible. This subsection will be split up into four parts of which the first one discusses the tank volume if only a heat pump is connected to it. The second part will discuss the tank volume if again only a heat pump is connect to it but this time also PV panels are present in the retrofit. The third one will again discuss the tank volume but now if only STC panels are present in a retrofit and finally the fourth and final part will discuss what happens if combinations of these three are present in one retrofit.

Tank volume and heat pumps

The first part will talk about the tank volume if heat pumps are present. In fact, the volume can be defined based on insights into the problem. Since a heat pump (HP) uses a CO_2 embedded fuel and a tank increases the thermal losses, increasing the tank volume means more losses which have to be compensated and therefore the smaller the tank the better - note that this argument only holds if the CO_2 is considered more important than the cost. Nevertheless it was argued in Section 5.1.2 that a heat pump needs a tank to prevent it from cycling - which is essentially turning the heat pump rapidly on and off. Using Equation 6.1, the minimal tank volume needed to prevent the heat pump from cycling can be calculated. From left to right in this equation: the peak thermal capacity of the heat pump which is 55.5 kW - as it should provide peak demand, the minimum modulation percentage of the heat pump which equals 0.2 [35], the minimal run time which is 6 minutes for an ASHP and 10 minutes for a GSHP [4], the volumetric heat capacity for water and the temperature increase over the heat pump which is equal to the temperature decrease over the emission side, Section 4.3.4. This results in a volume of 78.8 litres for the ASHP and 131.4 litres for the GSHP. To provide a small safety margin, the tank volume associated with the ASHP is chosen at 100 litres, while for the GSHP 150 litres is chosen. These insights were also proven by simulations, but since the graph showing CO_2 emissions as a function of tank volume only shows a strictly rising curve, it is not included in the text but can be found in Appendix F.

$$\dot{Q}_{peak} \cdot m_{min} \cdot t_{min} = c_{vol} \cdot \Delta T \cdot V_{tank} \tag{6.1}$$

Tank volume, heat pumps and photovoltaic panels

This part will address the tank volume when photovoltaic (PV) panels and a heat pump are present in a retrofit. Section 5.3.2 mentioned that expanding the storage tank to store more electricity from the PV panels in the form of thermal energy seems an option but that the results however showed the opposite. It does indeed make sense to say that the tank volume which results in the lowest CO_2 emissions for a given PV area increases as the area of the PV panels increases. Because as the area increases, more electricity is generated and can potentially be stored. This seemingly ideal volume corresponds to the volume at which increasing the size of the tank would mean more additional energy use to counteract the losses than the benefit of storing more electricity from the PVs. This is because at that point the extra storable energy in the summer does not outweigh the extra absolute losses that also occur in the winter and have to be fulfilled by CO_2 embedded fuels.

However, the results show otherwise which can be understood if a second thought is given to the question. Figure 6.5 shows the electricity from 90 m^2 PV panels used by the ASHP in function of the tank volume on the top left, the tank losses in function of the tank volume on the top right and the losses divided by the energy from panels used by the ASHP on the bottom. Three things can be noticed: the electricity being used from the PV panels increases and seems to slow down with the tank volume, the tank losses increase linearly with the tank volume and the losses of the tank increase faster in magnitude than the extra electricity that is being used. Therefore it can be concluded that also for a retrofit with heat pumps and photovoltaics the tank volume is chosen as small as possible. This again results in the tank being sized to the volume needed to prevent heat pump cycling as was defined in Section 6.2.3 by Equation 6.1.

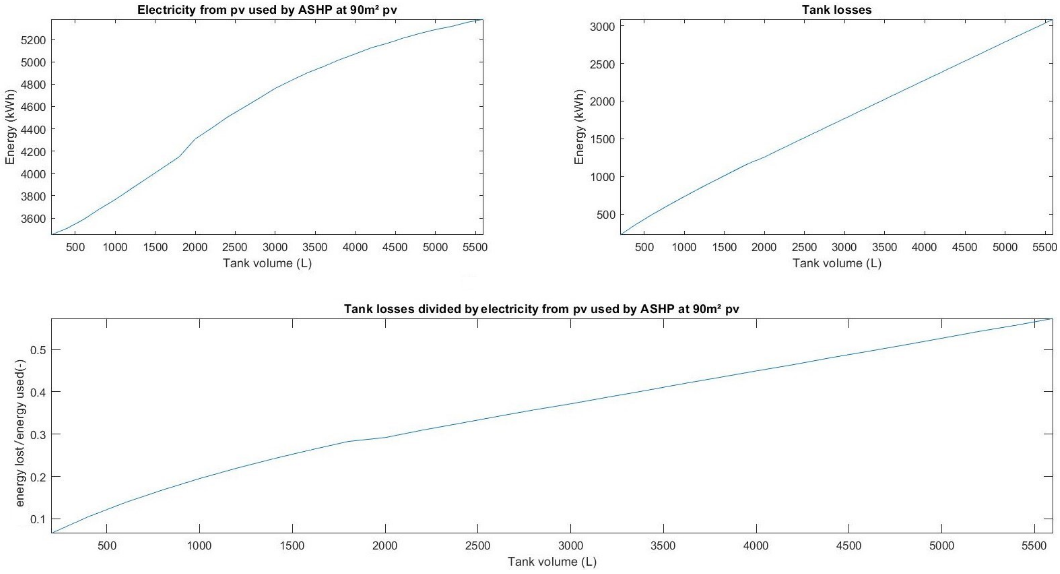


Figure 6.5: Top left figure: electricity from 90 m^2 PV panels used by the ASHP, top right figure: tank thermal losses, bottom figure: the tank thermal losses divided by the electricity from 90 m^2 PV panels used by the ASHP

Its one thing to draw conclusions from the results but another thing to understand why it is that way. Sure that the losses might increase faster than the extra electricity which can be stored, as is shown on Figure 6.5, but the argument which was constructed in the first part of this subsection does also makes sense meaning that a trade off should be present. And in fact Figure 6.6 indeed shows this trade-off. The top figure shows the CO_2 emissions for the ASHP and PV panels retrofit - again 90 m^2 PV panels - if the excess electricity would not be used whereas on the bottom figure the excess electricity can be sent to the grid. In the top figure the trade-off can effectively be observed: there is a tank volume at which increasing the volume would result in more losses than additional stored electricity which means that CO_2 embedded fuels have to compensate for these extra losses, hence the CO_2 emissions increase. The bottom figure now shows the CO_2 emissions as the excess electricity can be sent to the grid in which the CO_2 emissions can be reduced further - note the magnitude of both vertical axes. But more importantly, increasing the tank now only means that more energy from the PV panels will be used to compensate for these extra losses which means that fewer emissions are abated. Therefore the CO_2 emissions are again a strictly rising curve which confirms the conclusions drawn on Figure 6.6.

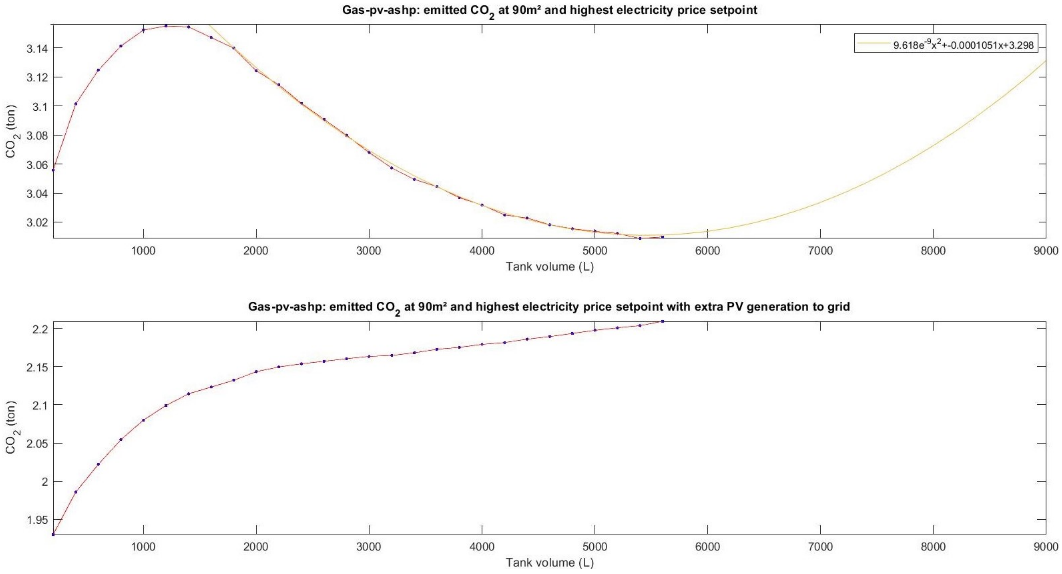


FIGURE 6.6: Top figure: CO_2 emissions for the ASHP + PV panels retrofit, excess electricity not used, bottom figure:CO_2 emissions for the ASHP + PV panels retrofit, excess electricity send to the grid - both at 90 m^2 PV area

Tank volume and solar thermal collector panels

This part discusses the tank volume if only solar thermal collector (STC) panels are present in a retrofit. As was explained in Section 6.2.3, each area of PV panels has a certain tank volume that has the lowest CO_2 emissions for that specific area. The same is true for STC panels as the same arguments still hold: increasing the tank means that more of the thermal energy generated by the STC panels can be stored until a certain volume at which the extra storable energy does not exceed the extra thermal losses of the tank. However, since the excess energy could not be delivered to an external grid - apart from when a district heating network would be present, but for all clearness this is not the case - there will effectively be a certain volume corresponding with each area. Figure 6.7 shows the CO_2 emissions in function of the tank volume for an area of 5 m² STC panels if only floor emission systems are present. In this figure a clear minimum of the emissions can be observed at 600 liters.

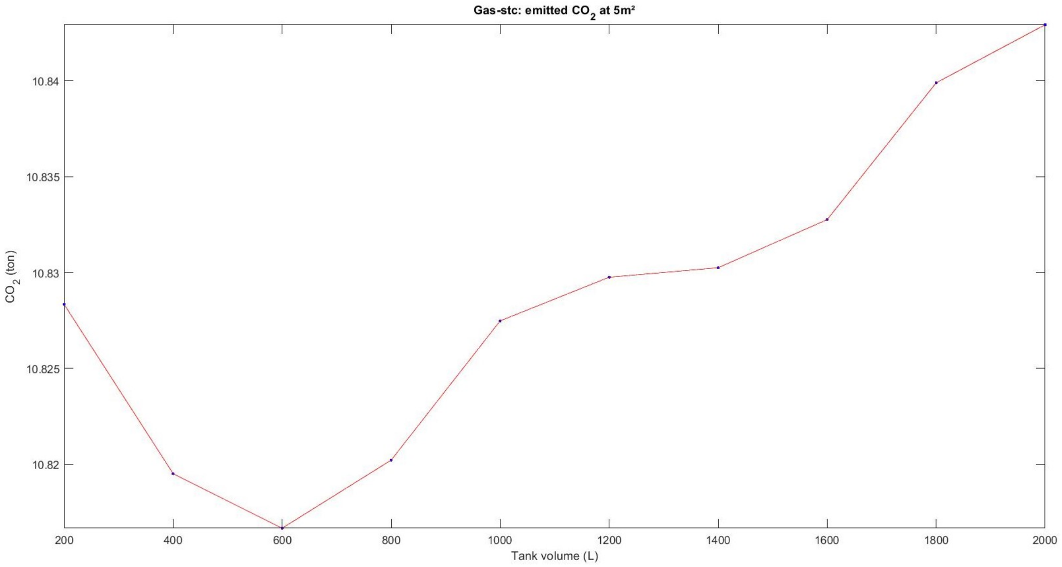


FIGURE 6.7: CO_2 emissions in function of the tank volume at 5 m² STC area, all floor emissions systems

Such a curve was obtained for many different areas for both the boundary conditions as they also influence the volume at which the CO_2 emissions are minimal. The results are summarised in Figure 6.8 which shows two fits on several points. Each point represents the tank volume at which the CO_2 emissions are the lowest for that certain STC area. For example, the previous result of 600 litres at 5 m² can be observed on the red curve as this curve represents the boundary condition of all floor emissions systems. The blue curve therefore represents the other boundary condition where only radiators are present. These fits correlate the tank volume to the STC area using a second order polynomial which nicely fits the points. This makes sense based on following reasoning: if the STC area increases, the STC will provide more and more thermal energy reducing the gas usage and hence the emissions. However at a certain moment they will generate so much that they are able to fulfil the demand in the summer months by themselves. Further adding panels therefore means that a smaller amount of gas will be reduced as the reduction is not longer taking place over the whole year. Nevertheless, the tank losses do however still increase at the same rate because the tank still loses energy over the whole year. This consequently means that the importance of the tank losses increases, as increasing the tank size leads to relatively adding more losses than the additional gas that can be avoided. As a result, increasing the tank at a smaller rate counters this effect which is observed in the results as the curves flatten with increasing STC area. The equations for the fitted curves can be seen in Equation 6.2 and Equation 6.3:

$$Radiators: \ V_{tank} = -0.6781 \cdot A_{STC}^2 + 181.4 \cdot A_{STC} - 691.3 \tag{6.2}$$

$$Floor\ emission\ systems: \ V_{tank} = -0.3455 \cdot A_{STC}^2 + 200.4 \cdot A_{STC} - 435.8 \tag{6.3}$$

A second interesting point which can be deduced from Figure 6.8 is that the tank volumes for an emission side of only radiators are smaller than the volumes for an emission side of only floor emission systems. This makes sense because radiators require a higher temperature regime, Section 4.3.4, which means that it is beneficial to have less water at a higher temperature, as then the gas boiler needs to upgrade the water less. By reducing the tank volume, the STC panels will be able to upgrade the water in the tank to a higher temperature for the same amount of solar irradiation. The curve for radiators also flattens faster since a higher temperature regime leads to more losses which can be reduced by a smaller tank. This explains why the tank volume at which the CO_2 emissions are the lowest for radiators.

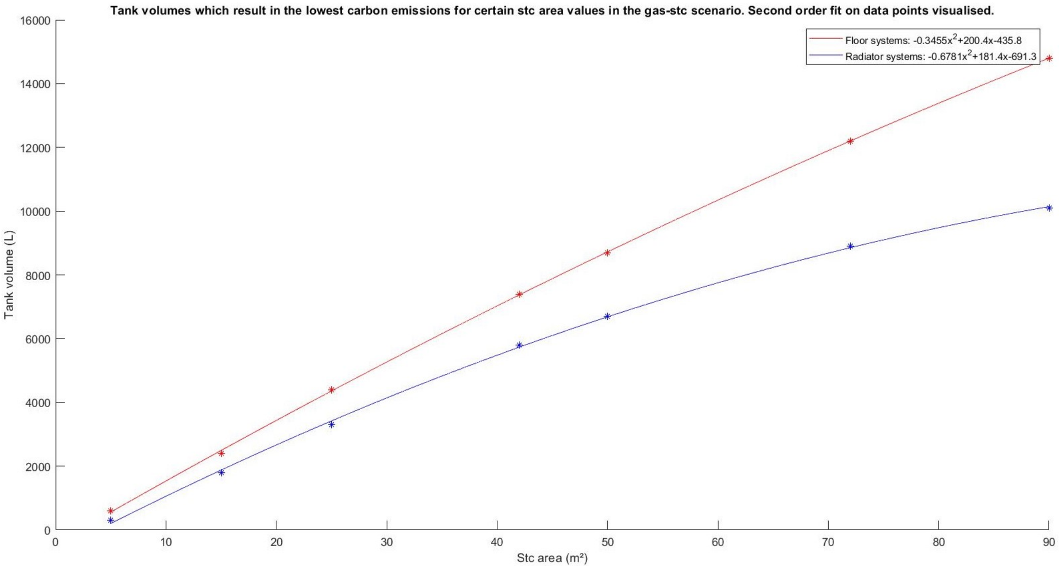


Figure 6.8: Tank volumes at which CO_2 emissions are minimal for several solar thermal collector areas with a second order polynomial fit

Combining different tank volumes

Previous three sections each discussed which tank volume is most beneficial for the CO_2 emissions. One explanation is still needed to clarify what happens if a retrofit for example contains both STC panels and a heat pump. In fact this was already subtly explained in Section 5.1.6. Since the STC panels generate CO_2 free thermal energy, their potential should be utilised as much as possible. Besides this, the heat pumps - with or without PV panels - require a tank as small as possible. Combining these therefore means utilising the STC potential as much as possible while also providing a minimal tank volume for the heat pumps. This is done by placing the heat pumps at the top of the tank - as was seen in all the simplified schemes of Chapter 5. Consequently, the STCs see the tank as one big volume without inference on which they can act. The heat pumps will be placed on the tank top so that they have their minimal volume available which explains why the GSHP was always connected just a bit lower on the tank than the ASHP, Section 5.1.8.

6.2.4 Conclusions

The first subsection discussed the 13 independent parameters for the models and summarised which eight of them had already gotten a value throughout the entire text. The second subsection further explained that four of the remaining five need to remain independent as they are used to construct the curves of the final cost - CO_2 abatement graph. The third subsection then correlated the last remaining independent parameter - being the tank volume - to the four parameters which are used to construct the curves. The conclusions here were that heat pumps - with or without - photovoltaic panels need a tank volume as small as possible while still assuring that no heat pump cycling would occur. This means that in this case the tank volume is fixed at 100 litres for an air source heat pump and 150 litres for a ground source heat pump. When solar thermal collectors are present, the volume was correlated to the STC area via a second order polynomial fit. The final subsection then concluded that connecting the STC panels to the bottom and the heat pumps to the top of the tank results in using the potential of the CO_2 free technologies as much as possible while preventing heat pump cycling. Now everything is in place to run the 243 simulations for one cost - CO_2 abatement graph which is presented in next section.

6.3 Cost - CO_2 abatement graph

This section will finally answer the research question of this thesis: which collective heating system retrofit has the lowest cost to reduce CO_2 emissions? In total four Cost - CO_2 abatement graph will be shown in this text: one for each boundary condition at which the excess photovoltaic (PV) electricity will not be used, one for the floor emission systems where the excess PV electricity is put on the grid at 30% of the prevailing electricity price and one where this is done at 100% of the prevailing electricity price. These figures can be found at the end of this chapter. As was explained in Section 3.2.3, the cost and CO_2 axes present the cost and CO_2 for the next 30 years however this will result in high costs and CO_2 emissions at which the feeling of magnitude is lost. Therefore, the scale of the axes will be *per year* such that they represent the cost per year and the abated CO_2 emissions per year. Besides this, the graphs will be vertically scaled such that the base case cost will be at zero cost per year which means that all the other costs will be interpreted as the extra cost per year for this retrofit compared to what is already installed. This allows for the easiest understanding and feeling of magnitude. These four figures without the adaptions can however be found in Appendix F for completeness.

6.3.1 Cost - CO_2 abatement graph, influence of the emission side

This section will discuss and compare the cost - CO_2 abatement graphs of an all floor emission system emission side versus an all radiator emission side. Figure 6.10 shows the graph for the floor emission systems and Figure 6.11 does this for the radiators. On both graphs the excess electricity from the photovoltaic (PV) panels is not utilised. The dashed lines represent the retrofits which contain an air source heat pump (ASHP), the full lines represent the retrofits which contain a ground source heat pump (GSHP) and the dotted-dashed line is either the retrofit which only adds solar thermal collector (STC) panels and a storage tank (in orange) or the final retrofit in which each component is present (light blue). All the other colour codes can be found in the legend of the graph.

The first thing to notice about these graphs is that the STC retrofit is the cheapest of them all, but it only allows for a minor reduction in CO_2. A parabolic shape is seen as the amount of gas that can be reduced decreases with increasing the area of the STC panels. This is caused by the saturation of the potential of the STC panels: Increasing the STC area will cause the demand at certain points throughout the year to be fulfilled by only the STCs. Meaning that an extra square meter will reduce less gas usage than the previous square meter could as the STCs can only reduce extra gas usage where the demand is not yet fully supplied by STCs. Hence the availability of demand not being fully supplied by the STCs decreases as the STC area increases. Due to the same square meter reducing less and less gas usage, the CO_2 abated per square meter decreases and cost per square meter increases causing this hyperbolic shape. This phenomenon can be seen on Figure F.1 in Appendix F. This phenomenon is very important as it is observed for PV panels as well and therefore will be present in a lot of curves.
Another interesting point that can be seen on this curve on Figure 6.10 is that it has a minimum whereas the same curve on Figure 6.11 strictly increases. This means that for only floor emission systems placing a small number of STC panels results in a lower cost while for only radiators the saved costs by using less gas don't outweigh the CAPEX and installation cost of the panels for the first few square meters. A final point on this curve is the total CO_2 abatement that can be achieved in both graphs. It can be seen that the all floor emission system can reduce the emissions much further because less of the heat is needed to upgrade the temperature and so more water can be heated meaning that fewer gas is needed.

A second observation on Figure 6.10 is that every retrofit - apart from the one just discussed - reaches the 2030 standard while none of them reaches the 2050 standard. If however Figure 6.11 is taken all the retrofits barely make the 2030 standard. This clearly shows that an all radiator system is harder to decarbonise due to the higher temperature regimes. Besides that, the average cost for a retrofit is higher for all radiators for several reasons:

- The cooling has to be provided by all air-coolers which is more expensive as was explained in Section 2.4 or as more elaborately shown in Appendix B.
- The COP of the heat pumps will be lower due to the higher temperature regimes meaning that they need more electricity for the same amount of thermal energy.
- This one only holds for when PV or STC is present but due to the higher temperature regimes, fewer energy will be delivered by these technologies which means that either more gas or electricity from the grid is needed.
- This one will have a minor impact but due to the higher temperature regimes the tank losses will be a bit larger meaning that more energy is needed to compensate for this.

It can also be observed that the GSHP retrofits are clearly more expensive than the ASHP retrofits as all the solid lines start above the striped lines. The cost difference between the ASHP and GSHP changes however rather significant on both graphs which is due to the way cooling is provided. In the all floor emission systems, the heat exchanger option to cool can be used which is way cheaper than the three air-cooler installation which is used in the all radiator case. The difference is less pronounced for the ASHP as the dual ASHP option for cooling is just more expensive causing the contrast with the air-coolers to be smaller.

The shape of some curves also directly stands out due to their almost step-wise shape. Such a step-wise shape is only observed in the curves where a heat pump and either STC or PV panels are present due to the way the double parameter sweep is performed. As was explained in Section 3.2.3, the curves are constructed by always applying the next cheapest option to reduce a same amount of CO_2. Figure 6.9 (next page) shows the actual order in which the parameter sweep was performed for the all floor system for a retrofit with both STC panels and a heat pump. These two figures were based on the results of the only STC retrofit and the only HP retrofit - both with a tank for all clarity. They represent what the next cheapest option is to reduce a same amount of CO_2. This can clearly be seen on the curves in the graph. For example: the full blue curve on Figure 6.10 has at its end a steep increase preceded by a less steep increase preceded by a steep but smaller increase. This corresponds with what can be seen on the left figure of Figure 6.9 as the last increases are all STC area increases preceded by a GSHP usage increase preceded by fewer STC area increases than at the end. If this was not done in this way, the curves would not be strictly increasing of which an example in Figure 6.13 but more on that one in Section 6.3.2. Figure F.4 in Appendix F shows the same figure as was discussed here but for the all radiator emission side boundary condition.

It is becoming clear that a huge amount of conclusions can be drawn just from these two graphs alone. To conclude this subsection, a final discussion will be presented

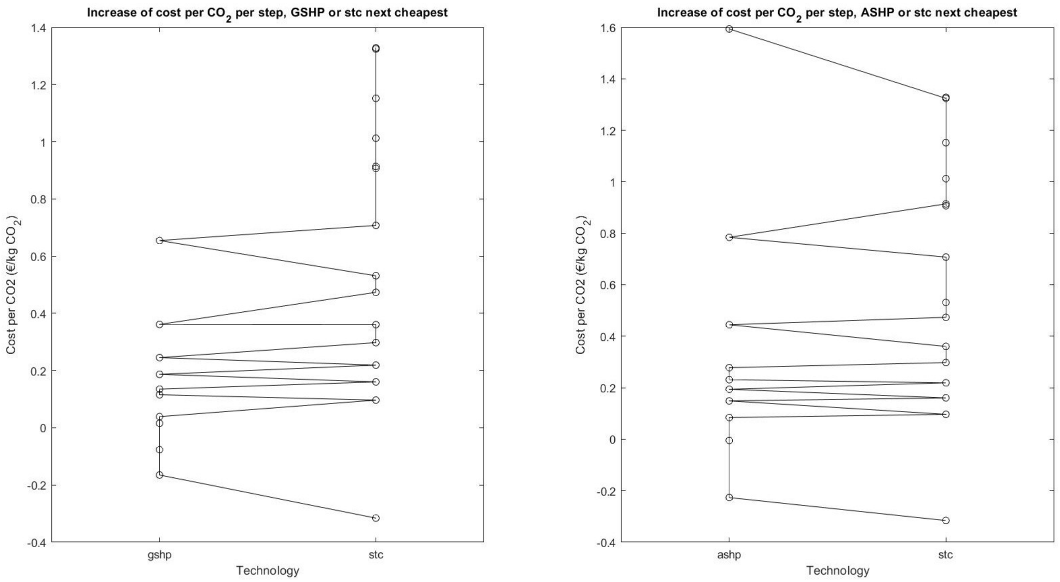


FIGURE 6.9: Comparison of additional costs per unit CO_2 for adding STC panels or using the HP more frequently, only floor emission systems

concerning which retrofit is now in fact preferred for each emission side. For both emission sides, the cheapest retrofit is installing STC panels. If the three households want to reduce the emissions further, placing an ASHP is the way to go for both emission sides. However if the 2030 standard is the goal, the ASHP is sufficient if only floor emission systems are present, however if only radiators are present also PV panels need to be installed. Reducing the emissions even further means that a retrofit which uses a GSHP is preferred in both cases although the radiators directly also require STC panels whereas for the floor emission system the GSHP by itself does the job. For the radiators this is also the retrofit which can reduce the emissions the furthest. For the floor emission systems however, first adding PV panels to the GSHP can reduce the emissions further but also here the retrofit which reduces the CO_2 the furthest is the GSHP with STC panels.
Next section will now investigate how these graphs will look if the way the excess electricity from the PV panels is handled, changes.

6.3.2 Cost - CO_2 abatement graph, influence of excess photovoltaic electricity

This section will discuss the importance of how the excess electricity from the photovoltaic (PV) panels is used. The figures used in this section are Figure 6.12 in which the electricity is put on the grid at 30% of the prevailing electricity price and Figure 6.13 in which this is done at 100% of the prevailing electricity price. Both figures use the boundary condition where only floor emission systems are present and in both figures the full CO_2 intensity of the electricity is taken when this electricity is put on the grid. Electricity generated by PV has zero embedded CO_2 and by adding it to the grid, the generation of CO_2 embedded electricity can be prevented. This is the reason that adding the PV generated electricity to the grid prevents an amount of CO_2 per kWh equal to the carbon intensity of the grid. Note that on these graphs the curves for the retrofits where only a heat pump is added are excluded since these retrofits are not feasible in reality and they are not relevant for this discussion therefore only complicate the graph.

The first thing that stands out is that the 2050 standard can be reached. Using the excess electricity in essence stretches each curve that contains PV panels to the right as the full potential of the PV is now used which reduces the emissions further. Based on this figure, it is key to use the excess electricity to reach the 2050 standard. Also the preferred retrofits change as can be seen on Figure 6.12: the retrofit which adds a GSHP and PV panels is now the preferred one from the moment it becomes the cheapest option meaning that the GSHP + STC loses its spot on the throne to reduce the emissions the furthest the cheapest. If however 100% of the prevailing electricity price is used as payment for the electricity put on the grid, the ASHP + PV retrofit seems to be preferred after the only STC retrofit until almost the point where the GSHP + PV takes over.

Probably more striking at Figure 6.13 is the somewhat saw-tooth shape of the curves which contain PV. This relates again to how the multi parameter sweep is performed. Again for these curves the order on Figure 6.9 was used which led to this distorted graph. Because of the PV receiving 100% of the price as its electricity is put on the grid, the cost to abate CO_2 in fact is negative meaning that installing an extra 6 m^2 PV would always be the first choice to make, even until 90 m^2 as there is no saturation in potential due to the usage of the grid. Since the order is alternating and not first all the PV area additions are performed, a saw-tooth profile is obtained. This also means that using these curves to select which retrofit is the best one for that amount of CO_2 reduction is dangerous. The end point will be the same and the ASHP + PV will be preferred almost everywhere but by first placing all PV panels, the curve will intersect with the only STC retrofit earlier. Note that for Figure 6.12 the strict increasing curves are still maintained although the area increases of PV almost become horizontal.

6.3.3 Conclusions

In this section the long-awaited cost - CO_2 abatement graphs were shown with a discussion on the most interesting conclusions which can be drawn. They can be used to select the retrofit which reduces a certain amount of CO_2 emissions the cheapest or can be used to select the retrofit which will reduce the CO_2 emissions the furthest based on a certain budget. In general the conclusion can be drawn that STC panels are the cheapest retrofit, followed by an ASHP followed by a GSHP, possibly with PV or STC added. Also the way in which the electricity from the PV is treated has a major impact on the results. Next and final section of this chapter will discuss the recommendations and future work in regards to this thesis.

6.4 Recommendations and future work

This final section of this chapter will briefly touch upon some interesting recommendations that might be used in future work. This chapter is divided into four parts, each of which highlights a different aspect of this work that can be built on in the future. The first part concerns the components taken into account in the scope of this thesis, the second one the modelling and what is considered fixed a priori, the third one discusses what might be interesting with regards to the results and the final one highlights interesting sensitivity analyses which can be conducted.

6.4.1 Additional components

Throughout this work five components were taken into account as part of the retrofits. However as Section 2.3 from Chapter 2 already showed, many more components exist which might seem interesting for micro energy communities. A possible way to solve the issue of which price is taken for electricity that is put on the grid would be installing an electric battery. Via this battery the excess electricity from the photovoltaics can be stored which will presumably be more cost efficient as the prevailing electricity price will be rather low due to many houses providing the grid at the same moment. This would add a whole new dimension to the work however a very analogous control now being used on the storage tank would probably already work quite well.

Another interesting option would be the addition of photovoltaic thermal collector panels which generate heat and electricity at the same time. Due to the technology being rather new, as was discussed in Section 2.3, it was not used in the scope of this thesis but as technology does not pause, it might mature faster than expected. Also due to the high expected potential, they seem a very interesting component to look deeper into.

A last component which seems interesting is a biomass stove. This biomass stove could potentially fully replace the gas boiler as it can also reach the higher temperature regimes but as long as biomass does not guarantee its sustainability, this component will remain doubtful nevertheless interesting.

6.4.2 Boundary conditions and models

In the scope of this work, the building envelope and emission side of the heating system were considered immutable in a retrofit. However it might be interesting to also be able to change one of these during a retrofit. For example the cheapest way to reduce CO_2 emissions might be placing an air source heat pump, insulating the windows and placing low temperature radiators. Allowing the building envelope and whole heating system to change inside one retrofit would result in a very complex problem which however more closely resembles reality. By adapting the emission side during a retrofit the temperature regimes at which the heat should be provided change and by changing the building envelope the whole demand profile changes in magnitude.

The models as they are built right now could cope with a changing temperature regime as the parameters defining the emission side can be changed throughout the simulations and only the demand is used as an input to the simulations. Changing the building envelope would however not be possible with the models as they are right now. The models are nevertheless built in such a way that the emission side can be connected to the generation side meaning that any emission side could be coupled. It might therefore be interesting to model the rooms and whole building envelope inside the Modelica language and directly couple the radiators and floor emission systems to the generation side where now the lumped volumes are connected. Also modelling each house separately will allow to take changes per house into account. Such an elaborate model could provide results which might be used in reality.

6.4.3 Extra cost - CO_2 abatement graphs

Four different cost - CO_2 abatement graphs were presented in this work. However many more could also provide interesting results. The first and most obvious extra graphs are the ones for combinations of radiator and floor emission system of which the results would be in between the results presented here. A graph could in fact be made for every possible combination of emission systems which would only take time as the models and control strategy can simulate any combination right now.

A very clear conclusion was that the influence of the excess photovoltaic electricity is very large which immediately rings a bell, what about those STCs? It might therefore be interesting to further look into options to utilise the full STCs potential because the STCs do also have excess heat which cannot be stored in the tank. Options could be generating electricity from this heat to then sell on the grid or supplying other nearby buildings creating a larger micro energy community or even a district heating network.

A last interesting point could be to inverse the question and instead of asking which retrofit can reach the 2050 norm, for example, ask how much the demand profile should decrease in magnitude to reach the 2050 norm with a certain retrofit. This could presumably already be found based on the data generated via the models and might provide further interesting insights - for example a house needs at least an EPC-label B or higher for the ASHP retrofit to reach the 2050 norm.

6.4.4 Extra sensitivity analyses

The results discussed one sensitivity analysis, namely the impact of the price at which the excess electricity from the photovoltaic panels is being put on the grid, Section 6.3.2. However, more interesting parameters could be investigated, with presumably the two most interesting being the price of electricity and the carbon intensity of electricity. These sensitivity analyses could show the impact on the curves of electricity becoming cheaper than gas, they could reveal which carbon intensity is needed for a retrofit to reach the 2050 standard without the need for electricity from PV being put on the grid, they could show whether solar thermal collector panels will remain the cheapest retrofit if the electricity price varies and to what carbon reduction. In conclusion, sensitivity analyses could show interesting results to even more interesting questions for which they are suggested as future work.

6.5 Conclusion

The chapter started with a discussion of results which showed how the models react to the control strategy defined in Chapter 5. This was followed by a discussion on how the independent parameters were selected: some received a value already before that section, some needed to remain independent as they are swept to obtain the curves on the cost - CO_2 abatement graph and one was correlated to these parameters. The one being correlated was the tank volume and the main conclusions were that if a heat pump is present, then the tank should have a volume of 100 litres or 150 litres depending on the type of heat pump and that a second order polynomial fit correlates the tank volume to the solar thermal collector area.
This was followed by the presentation of the cost - CO_2 abatement graphs which contained a large number of conclusions of which the most interesting ones were discussed. In short: the emission side influences the maximal abated CO_2 largely and the way in which the excess energy of the PV is used has a big impact on which retrofit is preferred for certain CO_2 reductions. This chapter ended by presenting some interesting points for future work as for example adding more components to the retrofits, making the building envelope and emission side immutable, reversing the question and searching for which demand profile is needed to obtain a certain emission norm for a certain retrofit or performing extra sensitivity analyses. Only one final chapter now remains, Chapter 7, which contains the final conclusions of this thesis.

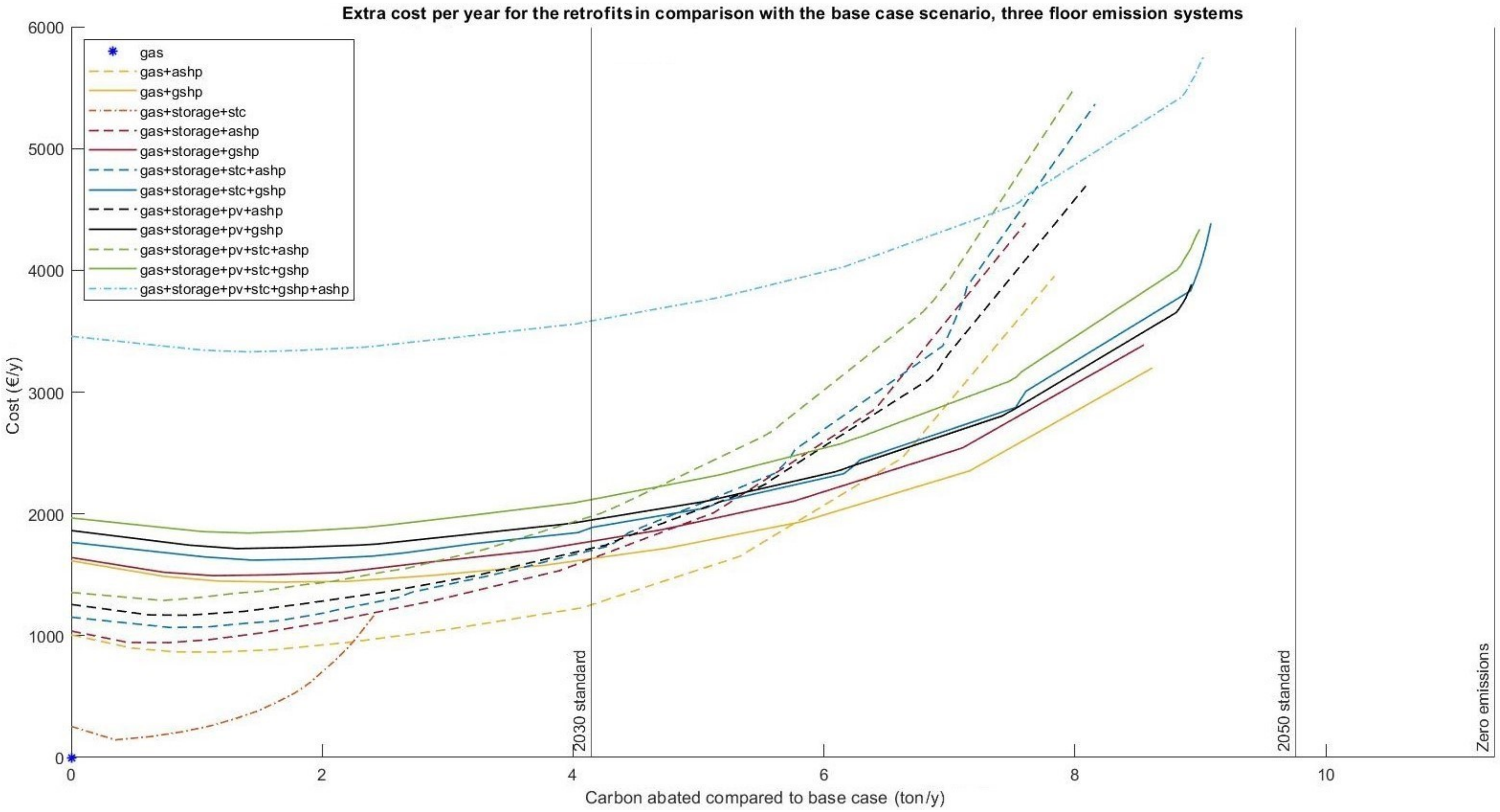


FIGURE 6.10: Cost - CO_2 abatement per year graph for all floor emission systems without excess photovoltaic electricity usage

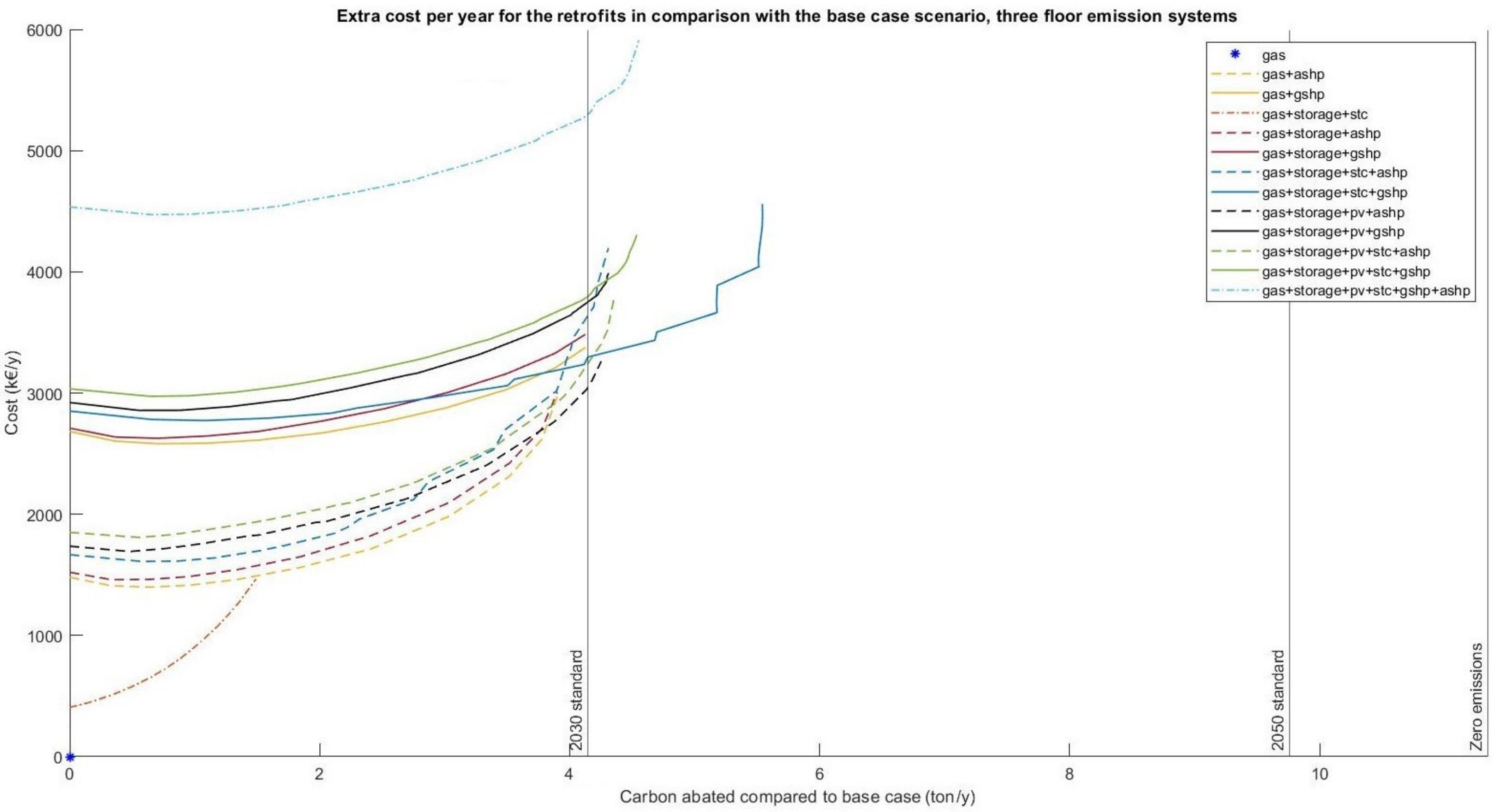


FIGURE 6.11: Cost - CO_2 abatement per year graph for all radiators without excess photovoltaic electricity usage

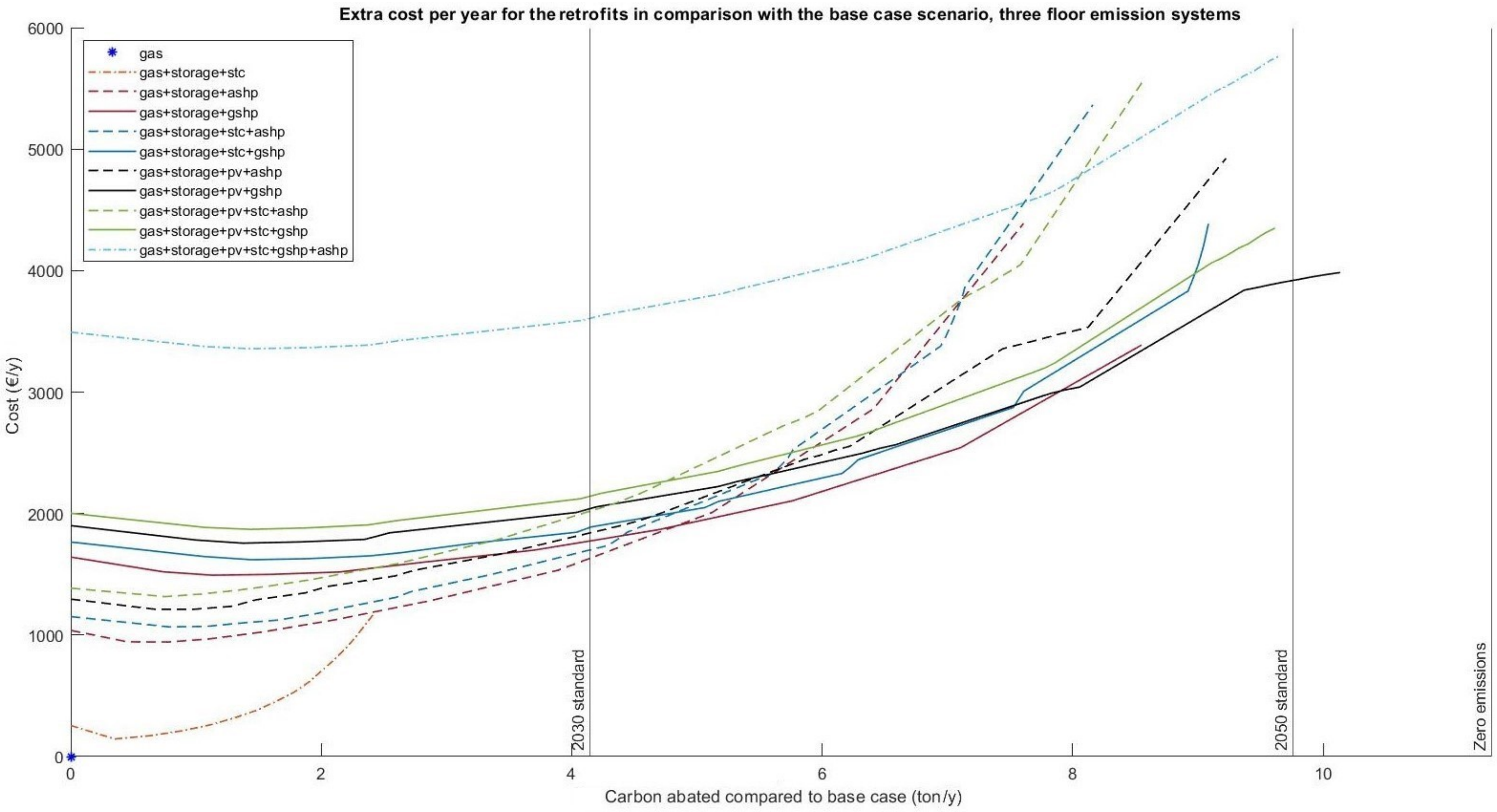


FIGURE 6.12: Cost - CO_2 abatement per year graph for all floor emission systems with full excess electricity put on the grid at 30% of electricity price

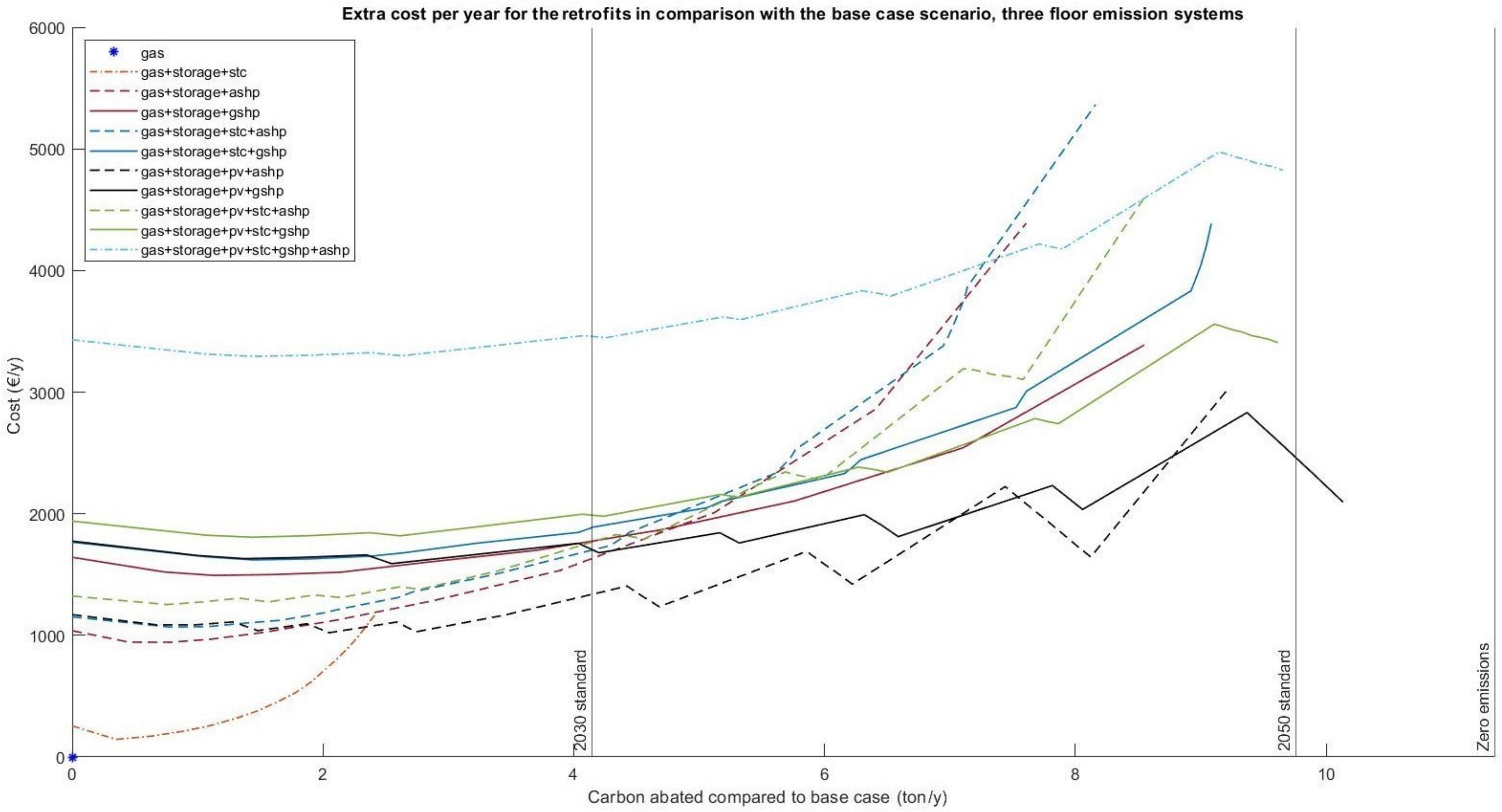


FIGURE 6.13: Cost - CO_2 abatement per year graph for all floor emission systems with full excess electricity put on the grid at full electricity price

Chapter 7

Conclusion

This thesis tried to answer the question of which collective heating system retrofit has the lowest cost to reduce CO_2 emissions, in particular for a micro energy community of three households. This text was divided into five main chapters with the first four chapters each answering a central question to arrive at the fifth main chapter in which the results are presented.

The first main chapter started with the search for a generalised Flemish average heating system on which the retrofits are performed and what components are relevant for use inside the retrofits. It was concluded that a typical Flemish household has a central heating system with a condensing gas boiler as the main heating source with no provision for cooling yet. Therefore, a small analysis was conducted to determine how cooling can be provided which led to the conclusion that installing a heat exchanger if a borefield is present is always preferred if at least one house has a floor emission system based on CO_2 emissions and cost. If no borefield is present but an air source heat pump is, it is then preferred to install two air source heat pumps if at least two dwellings have a floor emission system. If both are not an option, external air-to-air heat pumps are installed to fulfil the cooling demands. Besides, five components were selected which have the potential to lower the emissions without being too location dependent or too extensive for the scale of three households. These components include a ground source heat pump, an air source heat pump, solar thermal collector panels, photovoltaic panels and a storage tank.

Then followed a selection process to determine which retrofits are interesting to perform. Based on a few rules, a large number of retrofits were considered irrelevant. For example, solar thermal collector panels and photovoltaic panels always require a storage tank with the latter also requiring an electricity consuming heat generation component. It was also concluded that placing storage when only a gas boiler is present would solely increase the cost and emissions for the system. A final conclusion was that the combination of two types of heat pumps in one retrofit is in fact equal to using the ground source heat pump for 96.8% of all the energy provided and that the extra emissions which can be abated are very minor, 0.38 % to be exact.

All results were obtained by simulating each retrofit in a dynamic simulation environment, Dymola, using the Modelica modelling language. This language is object-oriented which allows for a very convenient modular approach. In these models the emission side was defined by lumped volumes representing the thermal masses of the emission systems present in the micro energy community. The used demand profiles were inspired by previous work for their shape and scaled to the averages for a Flemish household. The control strategy for these models is rule based, and it aims to reduce CO_2 emissions and costs as much as possible while providing comfort in any case.

In a final step, the correlation between the tank volume and the usage levels of the heat pump was determined. It was concluded that heat pumps - with or without photovoltaic panels - require a tank as small as possible while being large enough to prevent heat pump cycling. Also, the correlation between the tank volume and the area of the solar thermal collector panels was determined, which resulted in a second order correlation which depends on the emissions systems of the emission side.

Returning to the question at the start of this chapter: which collective heating system retrofit can reduce CO_2 emissions in the cheapest way? The answer is: it depends on how much CO_2 has to be abated. For a minor amount, solar thermal collectors are clearly the winners regardless of the emission side. However, if the goal is to reach the 2030 emission standard, the cheapest option would be to install an air source heat pump and photovoltaic panels if only radiators are present. If only floor emission systems are present, solely installing an air source heat pump is the cheapest option. It was concluded that the retrofit which adds a ground source heat pump and solar thermal collector panels can abate most emissions for every possible emission side. The 2050 standard could not be reached as long as the excess electricity from the photovoltaic panels is not utilised. This also signifies the importance of how surplus green electricity is managed. Other interesting conclusions indicated the importance of how cooling will be provided or that little benefit in CO_2 emissions can be achieved by installing both an air source heat pump and a ground source heat pump.

The cost - CO_2 abatement graphs hold an incredible amount of interesting information and the way in which they are constructed allows them to be used in a practical environment. By modelling the emission side and building envelope in its entirety and connecting those to the models of the generation side built in this work, the graphs would resemble reality with more accuracy. This might lead to them being used as a tool when a few families - for example three - want to perform a collective retrofit on their households, as such creating a micro energy community.

Appendices

Appendix A

Main conclusions from the market study done by VEKA

This appendix shows all the interesting results obtained from the market study on the Flemish households which was performed by VEKA [33]. Only the most essential results were mentioned in the text.

1. Main type of fuel used for space heating:
    - 68% natural gas
    - 16% heating oil
    - 9% electricity
    - 7% other fuels
2. Type of heating system:
    - 84% has a central heating system
    - 15% has a separate heating device
    - 1% doesn't know
3. DHW production in the bathroom and kitchen provided by:
    - Boiler or instantaneous water heater connected to the central heating system: 69% and 63%
    - Separate boiler on electricity: 15% and 21%
    - Separate boiler on natural gas: 7% and 6%
    - Other: 8% and 6%
4. Presence of condensing gas boilers:
    - 73% has one
    - 17% doesn't have one

    - 10% doesn't know

5. Presence of condensing heating oil boiler:
    - 34% has one
    - 58% doesn't have one
    - 8% doesn't know
6. Concerning cooling in the households:
    - 31% suffers overheating in summer
    - 9% has some sort of cooling system
7. Presence of renewable energy systems:
    - 14% has solar panels
    - 3% has a solar boiler
    - 3% uses pellets
    - 1% has a heat pump
    - 1% has a heat pump boiler
8. The average central heating system is 10 years old.

Appendix B

Cooling cost analysis

This appendix contains the elaborate cost analysis which was performed to choose the preferable solution between the dual ASHP and three air-coolers solution. This cost analysis only takes the extra costs compared to the normal heating layout into account as will become more clear throughout the analysis. All specific costs used in following analysis are summarised in Table 3.1 which can be found at the end of Chapter 3. To shorten the notations in the cost analysis, a CAPEX will be shortened to C, an OPEX to O, maintenance costs to M and installation costs to I. The subscript c refers to air-cooler, the subscript a to ASHP, g to GSHP and h to heat exchanger. The values to get a cost from 15 years in the future to now and to get the present value of a yearly returning cost for the next 30 years as defined in Section 3.2.1, Chapter 3 will be shorted to F and A respectively.

Before the cost analysis is performed, a little intermezzo on the OPEX for the air-coolers as it is the only OPEX in Table 3.1 which has a value. This is because the air-coolers will have the same OPEX in every retrofit in contrast to the other components. This intermezzo shortly explains how this value was found. By multiplying the electricity price with the hourly electrical power consumed by the air-coolers, the operational costs can be found. This power consumption was obtained after performing the simulation of the base case, the electricity price is known up front [16]. These calculations resulted in the operational costs being equal to 124.83 euros for one household. A back of the envelope calculation confirms this. As was mentioned in Section 4.3 1380 kWh thermal energy is needed to fulfil the cooling demand. Figure B.1 shows both the average COP and electricity price in the period when cooling is present. When this 1380 kWh is divided by this average COP of 3.82 and multiplied with this average electricity price of 0.3509, the result equals 126.76 euros, which closely resembles the value from the calculations. This already concludes the intermezzo on the OPEX. Now the real cost analysis will be performed starting with the three air-coolers.

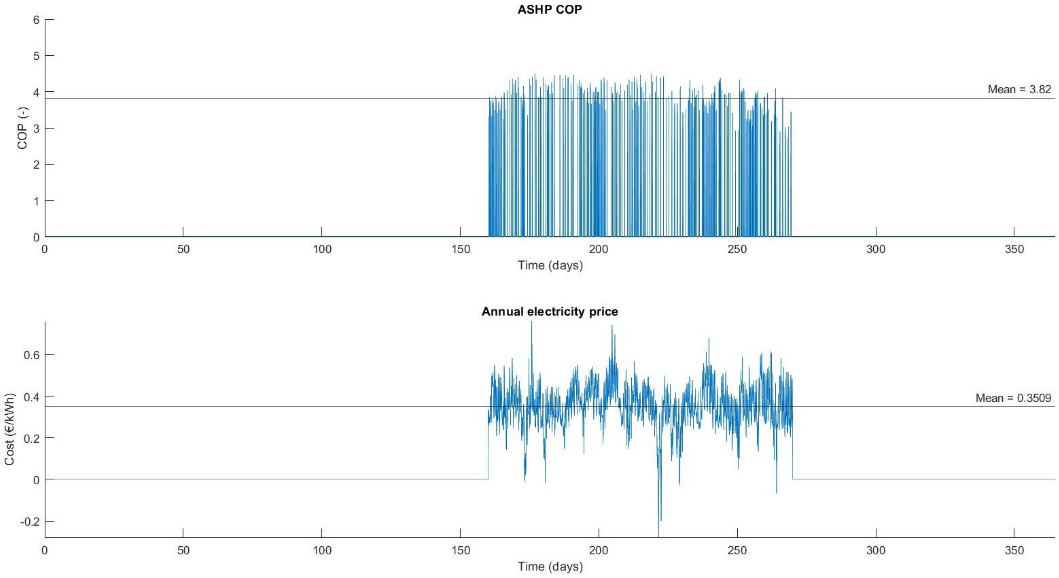


FIGURE B.1: The COP and electricity price with their averages when the cooling demand is present

B.1 Three air-coolers

For the three air-coolers the cost analysis becomes:

$$cost = 3 \cdot C_c \cdot (1 + F) + 3 \cdot O_c \cdot A + 3 \cdot M_c \cdot A + 3 \cdot I_c = 35.182 \ euros \tag{B.1}$$

Three air-coolers need to be bought now and 15 years in the future because their average lifetime is 15 years. They have a one time installation cost each and will consume electricity when being used which is taken into account via the OPEX. Also yearly maintenance costs are present. The cost calculated here is for three houses for 30 years which would be equivalent to 412 euros per household per year to not suffer from overheating.

B.2 ASHP

The dual ASHP solution needs to be compared to what would normally be installed, which is just one big ASHP with the cumulative capacity of both combined. The CAPEX for the two ASHPs is therefore equal to the extra cost for two ASHPs compared to the single one. Also only one extra installation cost for an ASHP is taken into account since one would be installed anyway. The OPEX for the air-coolers and the ASHP are the same (as they are assumed to work between the same two temperature regimes at a comparable COP) but are written as two terms for clarity. The cost analysis for when this dual ASHP solution would be used if only one house has a floor emission system looks as:

$$cost = (2 \cdot C_c + C_a) \cdot (1 + F) + (2 \cdot O_c + O_a) \cdot A + (2 \cdot M_c + M_a) \cdot A + 2 \cdot I_c + I_a = 39.293\ euros \tag{B.2}$$

It can be concluded that the situation with three air-coolers and one big ASHP only used for heating is cheaper than the situation with two air-coolers and the dual ASHP solution. However when the boundary conditions state that two houses have a floor emission system, the dual ASHP solution does become cheaper than the three air-cooler solution as can be seen in following equation.

$$cost = (C_c + C_a) \cdot (1 + F) + (O_c + 2 \cdot O_a) \cdot A + (M_c + 2 \cdot M_a) \cdot A + I_c + I_a = 32.551\ euros \tag{B.3}$$

The cost when three floor emission systems are present equals 25.809 euros according to following equation:

$$cost = C_a \cdot (1 + F) + 3 \cdot O_a \cdot A + 3 \cdot M_a \cdot A + I_a = 25.809\ euros \tag{B.4}$$

B.3 GSHP

For completeness, the cost analysis for a system with a GSHP and one house with a floor emission system is also given:

$$cost = (2 \cdot C_c + C_h) \cdot (1 + F) + (2 \cdot O_c + O_g) \cdot A + (2 \cdot M_c + M_h) \cdot A + 2 \cdot I_c + I_h = 26.052\ euros \tag{B.5}$$

The CAPEX now contains two air-coolers and a heat exchanger with the capacity of the peak cooling demand for one house. The OPEX reduced to two times the OPEX for the air-coolers plus the electricity used for the active cooling via the GSHP. It was already concluded that this option would be the better one but now it can be seen that it also comes at a lower cost than the three air-coolers. The more floor emission systems that are present, the lower the carbon emissions and costs. Analogous calculations were completed for two and three floor emission systems which resulted in 16.053 euros and 6.185 euros respectively.

Appendix C

Cost - time axis for each component

This appendix contains all the time axes on which the partial costs are visualised for each component. Red arrows correspond to CAPEX, blue arrows correspond to OPEX, orange arrows correspond to maintenance costs, purple arrows correspond to installation costs, grey arrows correspond to the salvage value which can be found using linear depreciation over the life time of the component and finally green arrows represent the present worth. By superimposing these time axes, the time axes for the retrofits can be found. The value for each partial cost and the average expected lifetime - determining the reinvestments - can be found in Table 3.1 in Chapter 3.

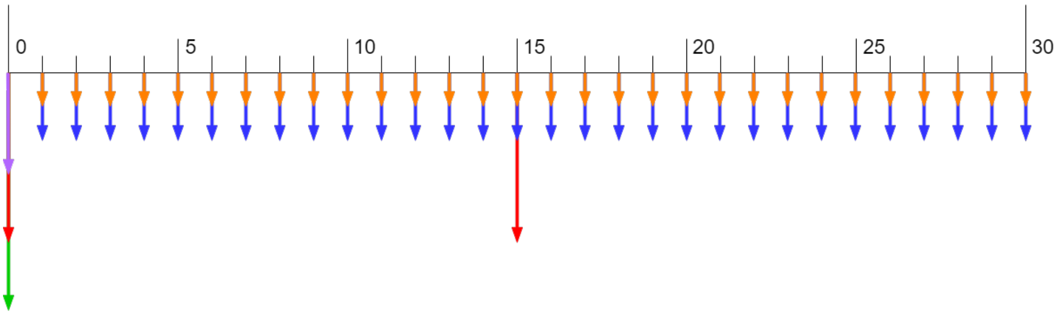


FIGURE C.1: Cost - time axis for an air-cooler or air-to-air heat pump

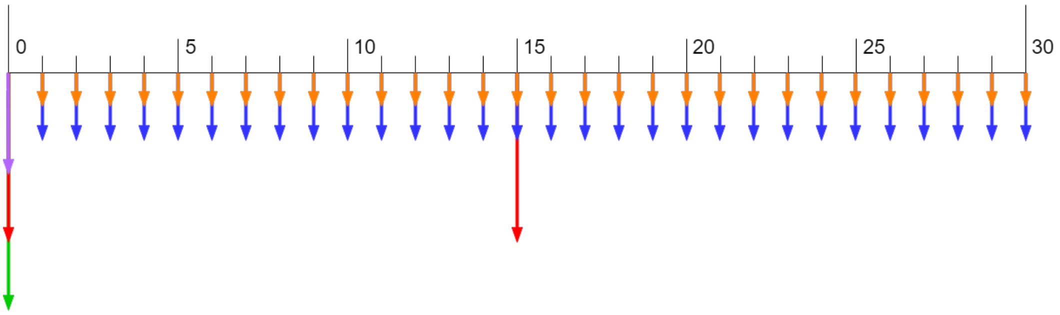


Figure C.2: Cost - time axis for an air source heat pump

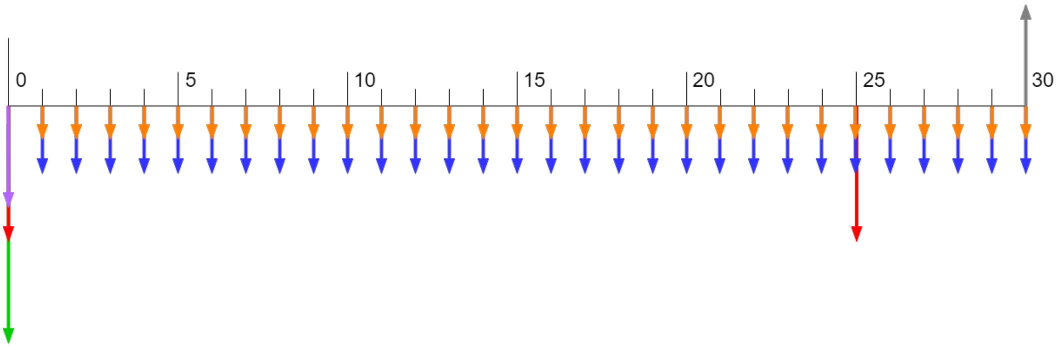


Figure C.3: Cost - time axis for a ground source heat pump

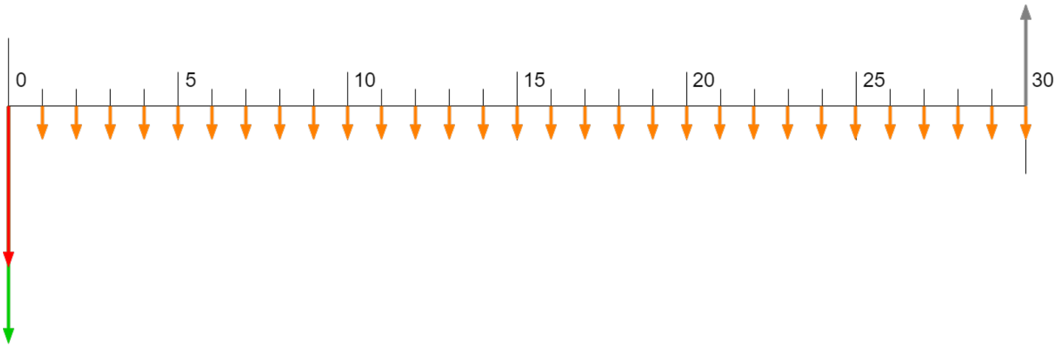


Figure C.4: Cost - time axis for a borefield

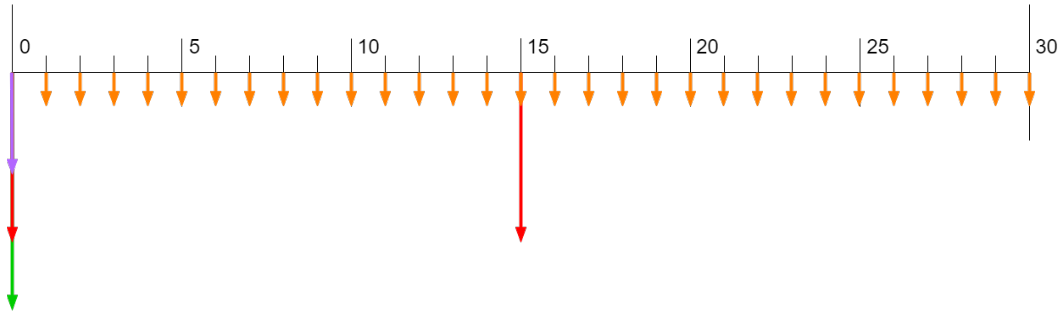


Figure C.5: Cost - time axis for a heat exchanger

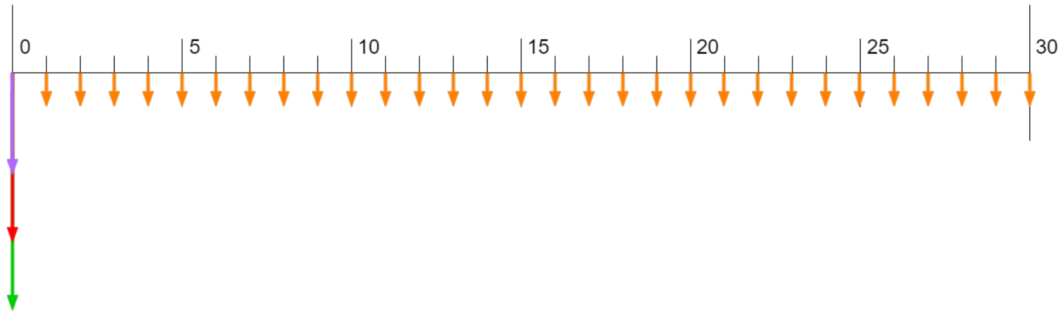


Figure C.6: Cost - time axis for a storage tank

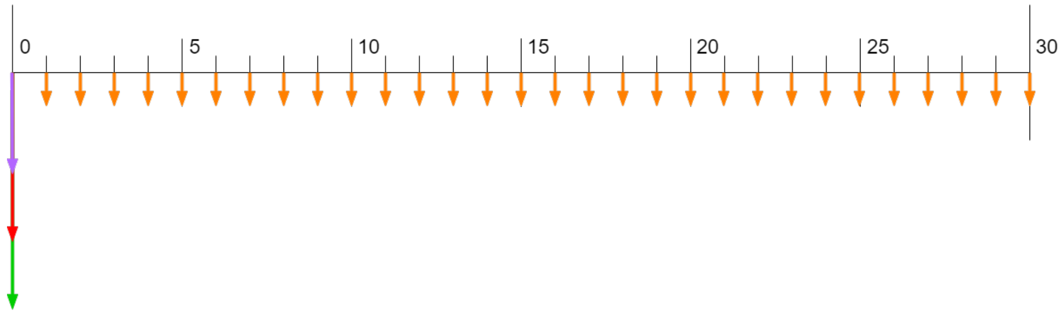


Figure C.7: Cost - time axis for solar thermal collector panels

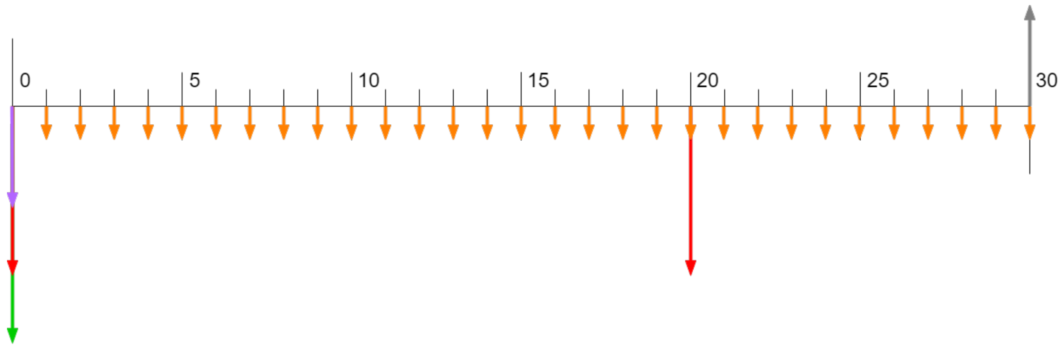


FIGURE C.8: Cost - time axis for photovoltaic panels

Appendix D

Simplified schemes

In this appendix all the remaining schemes for the heating systems can be found. All schemes are identical in control to the ones discussed in the text apart from the extra pump coupled to the borefield at the evaporator side of the GSHP. This pump works with another mass flow rate which is defined by the borefield itself. The same control rule as the pump coupled to the GSHP is used because it works at the same moments but at a different mass flow rate. The final figure in this appendix is the only figure in this text which combines a heating and cooling scheme. As can be seen does this figure in essence combines Figure 5.12 and Figure 5.14. Since every heating scheme can be combined with its respective cooling scheme based on the components present, not much extra value would be in presenting all these figures. Therefore only the last retrofit is added in this fashion (figures start on next page).

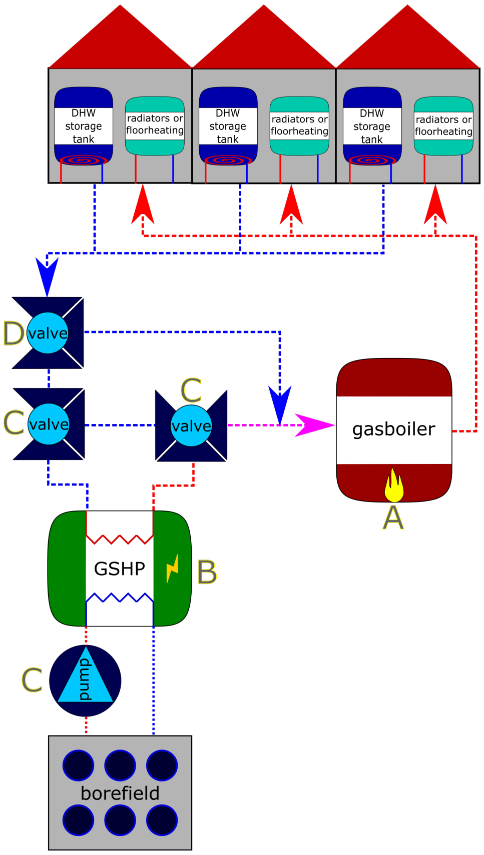


Figure D.1: The simplified scheme of the retrofit base case + heat pump - ground source heat pump in particular

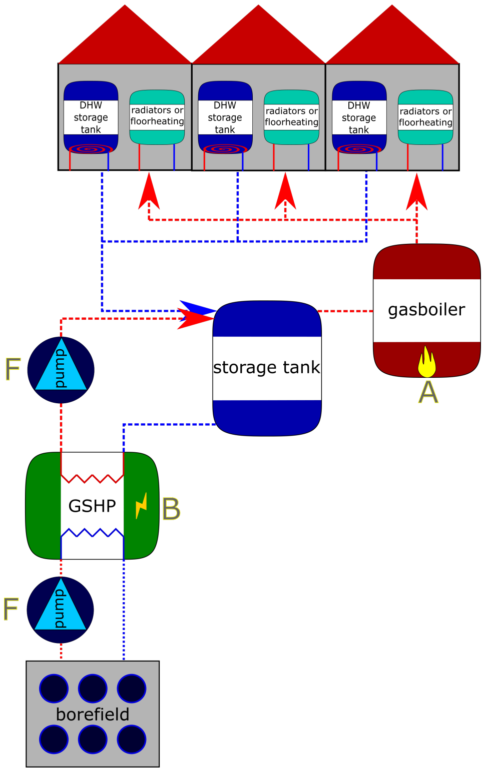


Figure D.2: The simplified scheme of the retrofit base case + heat pump + storage tank - ground source heat pump in particular

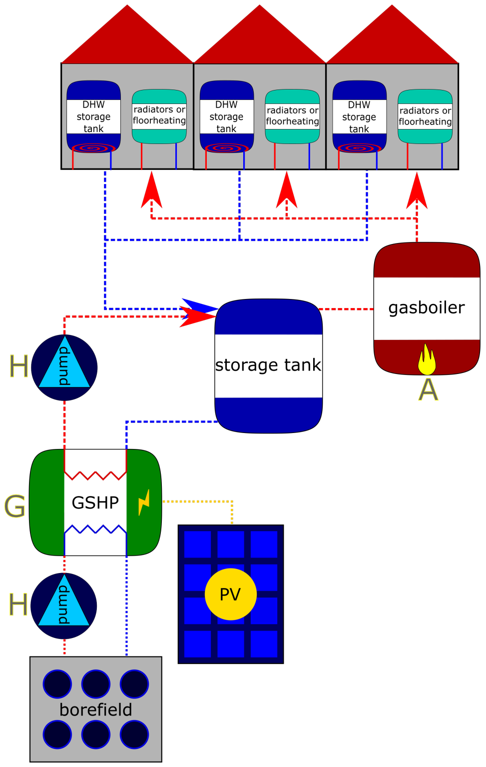


FIGURE D.3: The simplified scheme of the retrofit base case + heat pump + photovoltaics + storage tank - ground source heat pump in particular

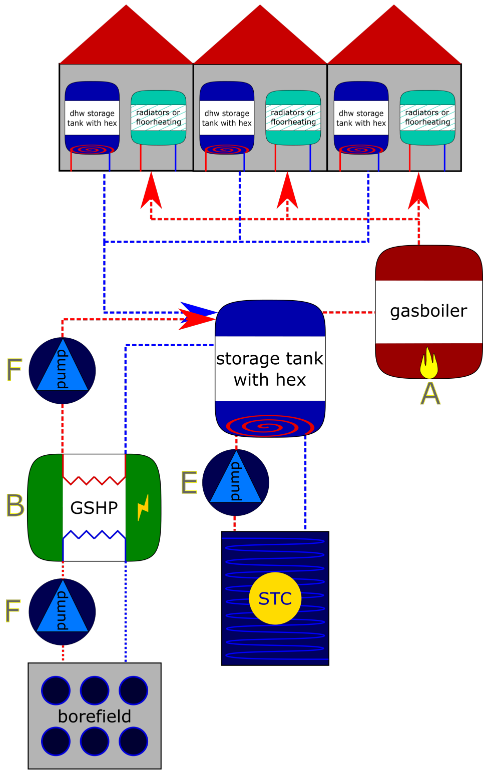


FIGURE D.4: The simplified scheme of the retrofit base case + heat pump + solar thermal collectors + storage tank - ground source heat pump in particular

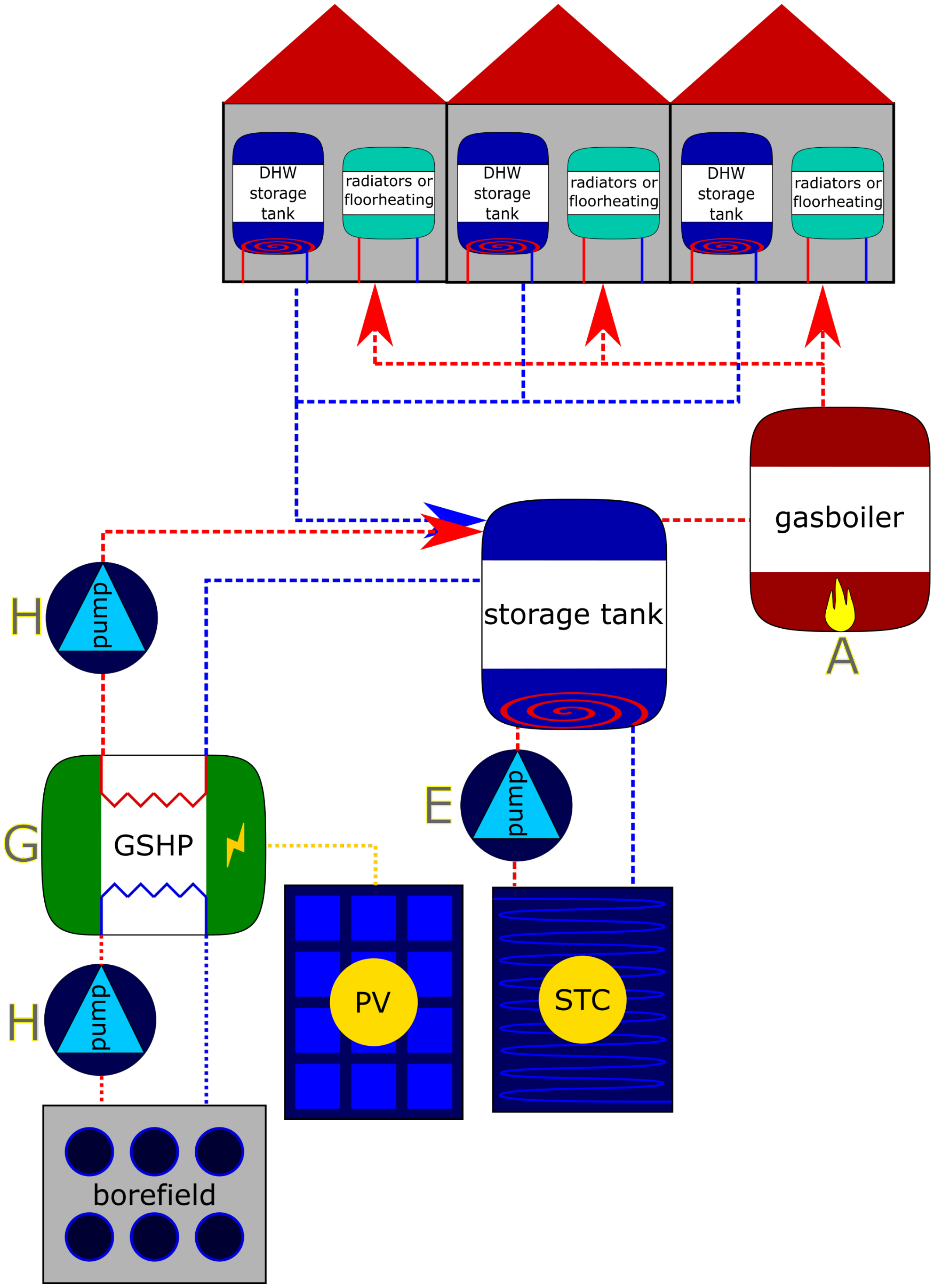


Figure D.5: The simplified scheme of the retrofit base case + heat pump + solar thermal collectors + photovoltaics + storage tank - ground source heat pump in particular

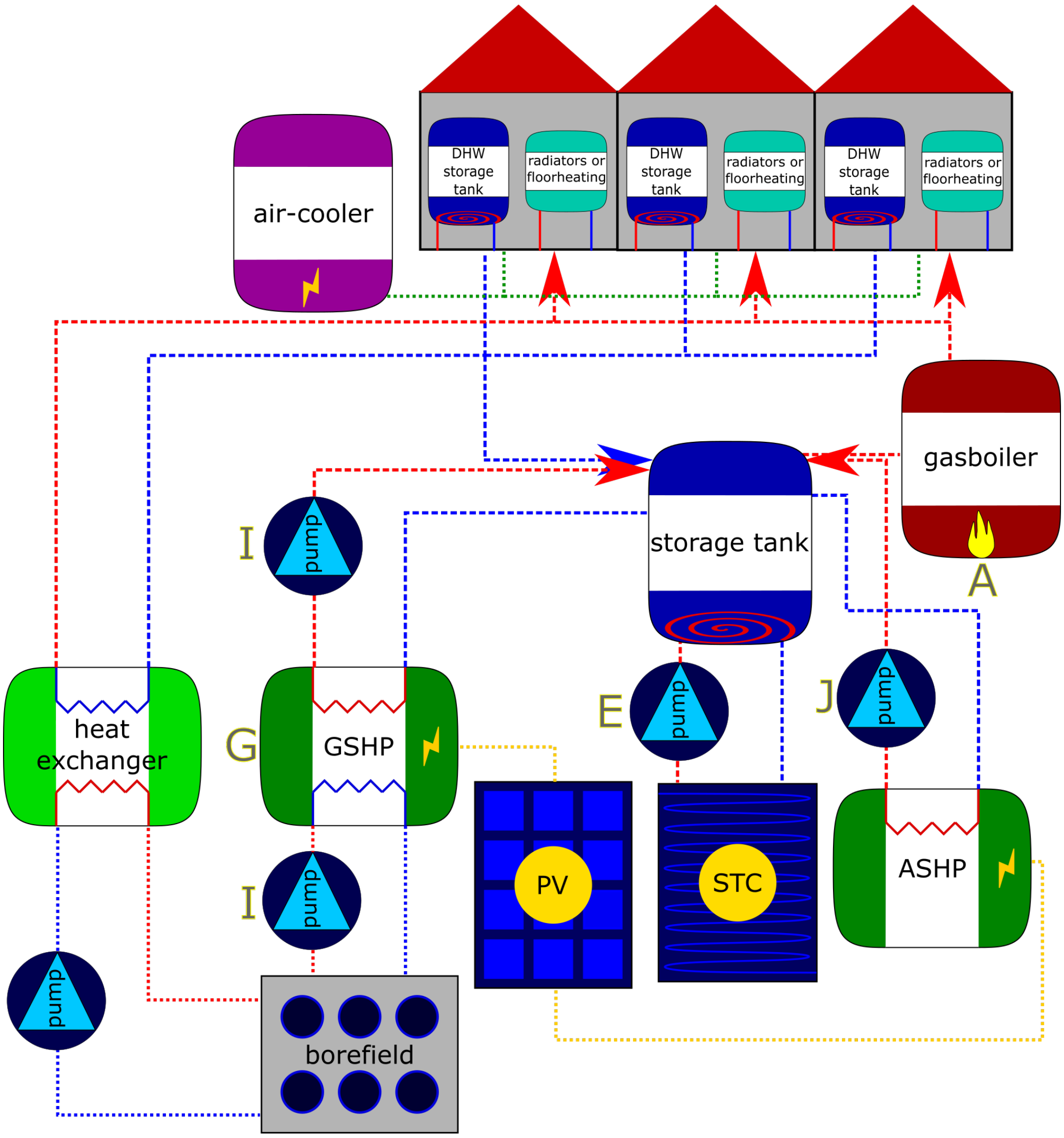


FIGURE D.6: The simplified scheme of the final retrofits in which all components are present for both heating and cooling

Appendix E

Simulation parameters

This appendix contains all parameter values used in the models which were built via the Modelica modelling language. As many parameters as possible use the standard values defined in the libraries and therefore only the values of the parameters which were chosen are given here. They were based on insights and from direct contact with the company Boydens Engineering [4]. All mass flow rates were defined via Equation 4.3. Previously defined parameters are also not repeated as for example tank volumes, capacities of heat pumps, specific heat capacity of water, etc. The time constant used for the control strategy is 120 seconds which is 1/5 of the shortest variations in the demand profiles.

Domestic hot water tank parameters	Value
Component	IDEAS.Fluid.Storage .StratifiedEnhancedInternalHex
Medium	water
Volume	210 liter
Height	0.9 meter
Thickness of insulation	0.05 meter
Time constant for mixing	600 seconds
Height of input internal heat exchanger	0.7 meter
Height of output internal heat exchanger	0.05 meter
Heat exchange at nominal conditions	45 kW
Nominal temperature inside the tank	45°C
Nominal temperature of the fluid inside the heat exchanger	50°C

Table E.1: Domestic hot water tank parameter values used in the Modelica models

Storage tank without internal heat exchanger parameters	Value
Component	IDEAS.Fluid.Storage .StratifiedEnhanced
Medium	water
Height	0.4 meter
Thickness of insulation	0.05 meter
Time constant for mixing	600 seconds

Table E.2: Storage tank without internal heat exchanger parameter values used in the Modelica models

Lumped volume parameters	Value
Component	IDEAS.Fluid .MixingVolumes.MixingVolume
Medium	water
Volume	100 liter per emission system

Table E.3: Lumped volume parameter values used in the Modelica models

Pump parameters	Value
Component	IDEAS.Fluid.Movers .FlowControlled_m_flow
Medium	water
Nominal values define default pressure curve	true
Energy dynamics	steady state initial
use input filter	false

Table E.4: Pump parameter values used in the Modelica models

Photovoltaic panel parameters	Value
Component	Buildings.Electrical.DC .Sources.PVSimpleOriented
Fraction of surface area with active solar cells	0.95
Surface tilt	45°
Surface Azimuth	0°
Nominal voltage	12 volt

Table E.5: Ground source heat pump parameter values used in the Modelica models

Solar thermal collector panel parameters	Value
Component	Buildings.Fluid .SolarCollectors.ASHRAE93
Medium	propylene glycol water 40%
Number of segments	9
Surface azimuth	90°
Surface tilt	45°
Ground reflectance	0.2
Performance data	FP - Solahart Kf

Table E.6: Solar thermal collector panel parameter values used in the Modelica models

Air source heat pump parameters	Value
Component	IDEAS.Fluid.HeatPumps .HP_AirWater_TSet
Medium	water
Design power	Nominal power
Minimal modulation percentage to start heat pump	20%
Pressure difference	3000 pascal

Table E.7: Air source heat pump parameter values used in the Modelica models

Storage tank with internal heat exchanger parameters	Value
Component	IDEAS.Fluid.Storage .StratifiedEnhancedInternalHex
Medium	water
Height	0.4-2 meter depending on the volume
Thickness of insulation	0.05 meter
Time constant for mixing	600 seconds
Height of input internal heat exchanger	0.3-1.6 meter depending on the height
Height of output internal heat exchanger	0.05 meter
Heat exchange at nominal conditions	20 kW
Nominal temperature inside the tank	40°C
Nominal temperature of the fluid inside the heat exchanger	50°C

Table E.8: Storage tank with internal heat exchanger parameter values used in the Modelica models

Rectangular borefield	Value
Component	IDEAS.Fluid.Geothermal .Borefields.OneUTube
Medium	propylene glycol water
Height of the boreholes	150 meter
Borefield width	10 meter
Borefield length	10 meter
Distance between two boreholes	10 meter

Table E.9: Rectangular borefield parameter values used in the Modelica models

Three way valve parameters	Value
Component	IDEAS.Fluid.Actuators .Valves.ThreeWayLinear
Medium	water
Nominal pressure drop of fully open valve	0.1 pascal

Table E.10: Three way valve parameter values used in the Modelica models

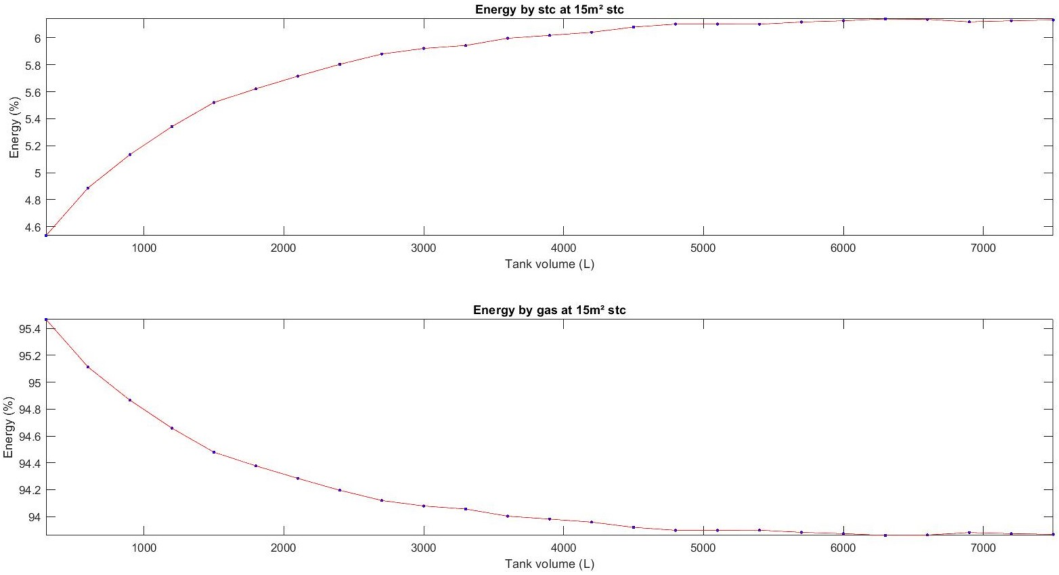
Ground source heat pump	Value
Component	IDEAS.Fluid.HeatPumps .HP_WaterWater_TSet
Medium evaporator	propylene glycol water
Medium condenser	water
Heat pump data	Viessmann VitoCal 300G, type BW 301.A45
Use on-off signal	false
Use scaling	true
Use modulation signal	true
Use modulation security	true
Pressure difference evaporator	3000 pascal
Pressure difference condenser	3000 pascal

Table E.11: Ground source heat pump parameter values used in the Modelica models

Appendix F

Extra results

This appendix contains some extra results and the same four cost - CO_2 abatement graphs as were discussed in Section 6.3 but now with the cost and CO_2 axis for 30 years.


Energy by stc at 15m² stc

Energy by gas at 15m² stc

Figure F.1: Top figure: the energy delivered by the solar thermal collector panels, bottom figure: the energy delivered by the gas boiler - both for the retrofit solar thermal collectors + storage tank

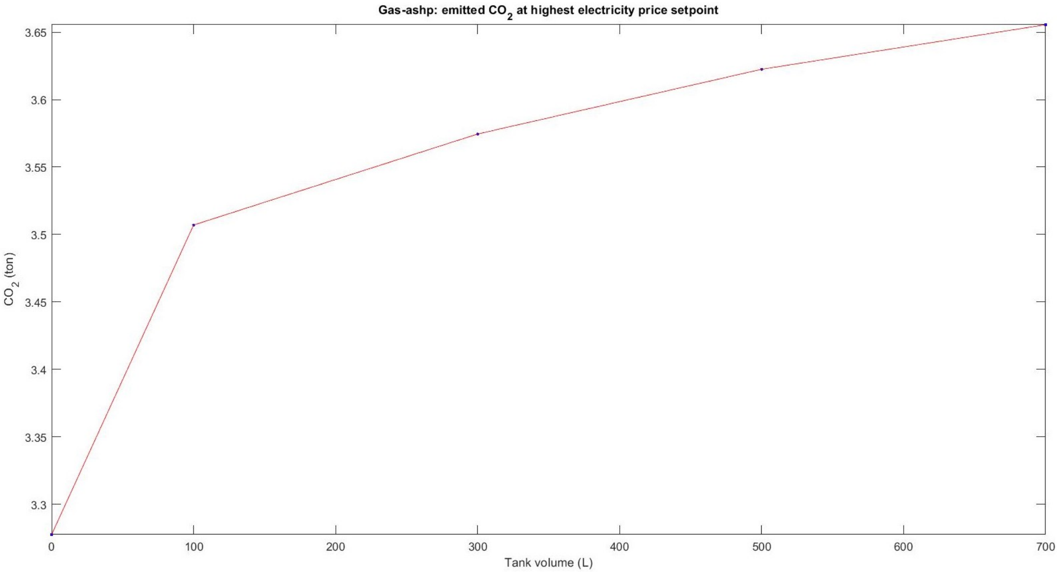


FIGURE F.2: CO_2 emissions in function of the tank volume for the air source heat pump retrofit

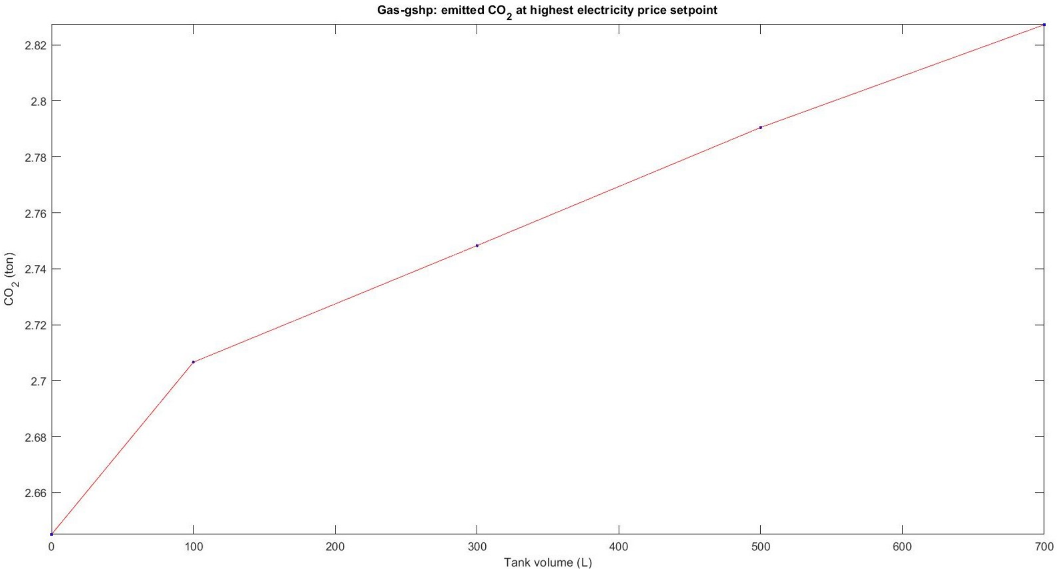


FIGURE F.3: CO_2 emissions in function of the tank volume for the ground source heat pump retrofit

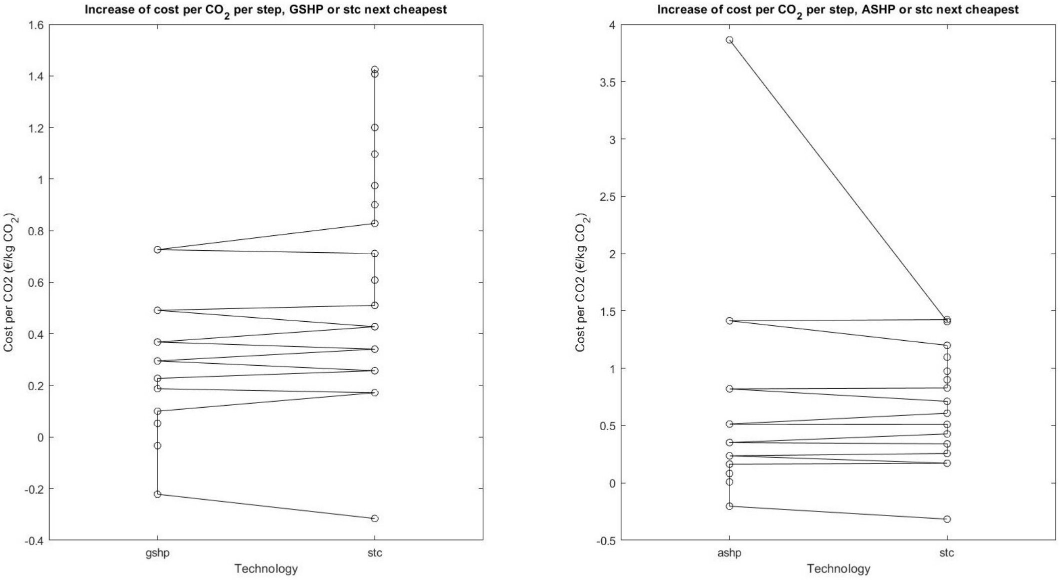


FIGURE F.4: Comparison of additional costs per unit CO_2 for adding STC panels or using the HP more frequently, only radiators

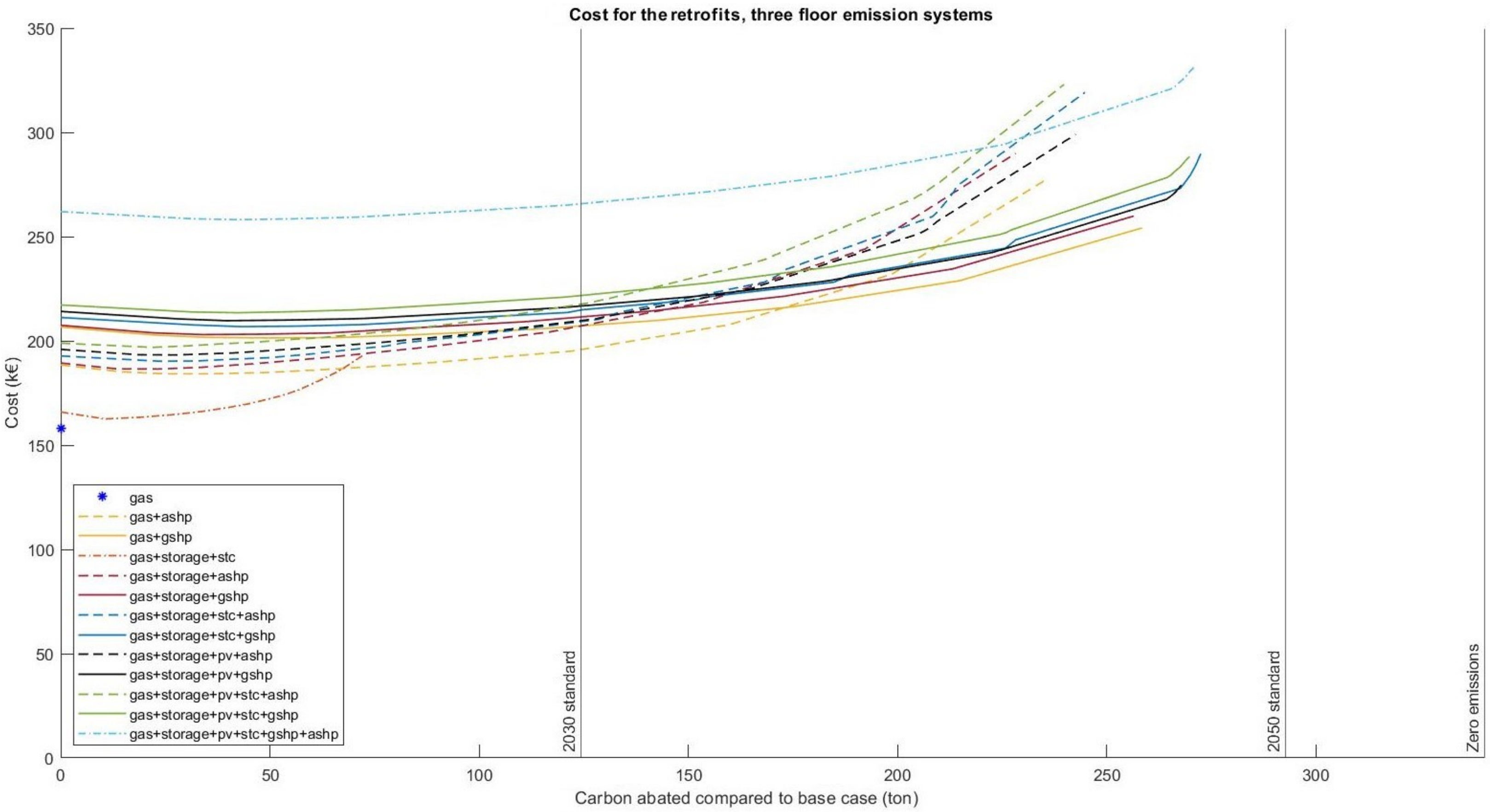


FIGURE F.5: Cost - CO_2 abatement for 30 years graph for all floor emission systems without excess photovoltaic electricity usage

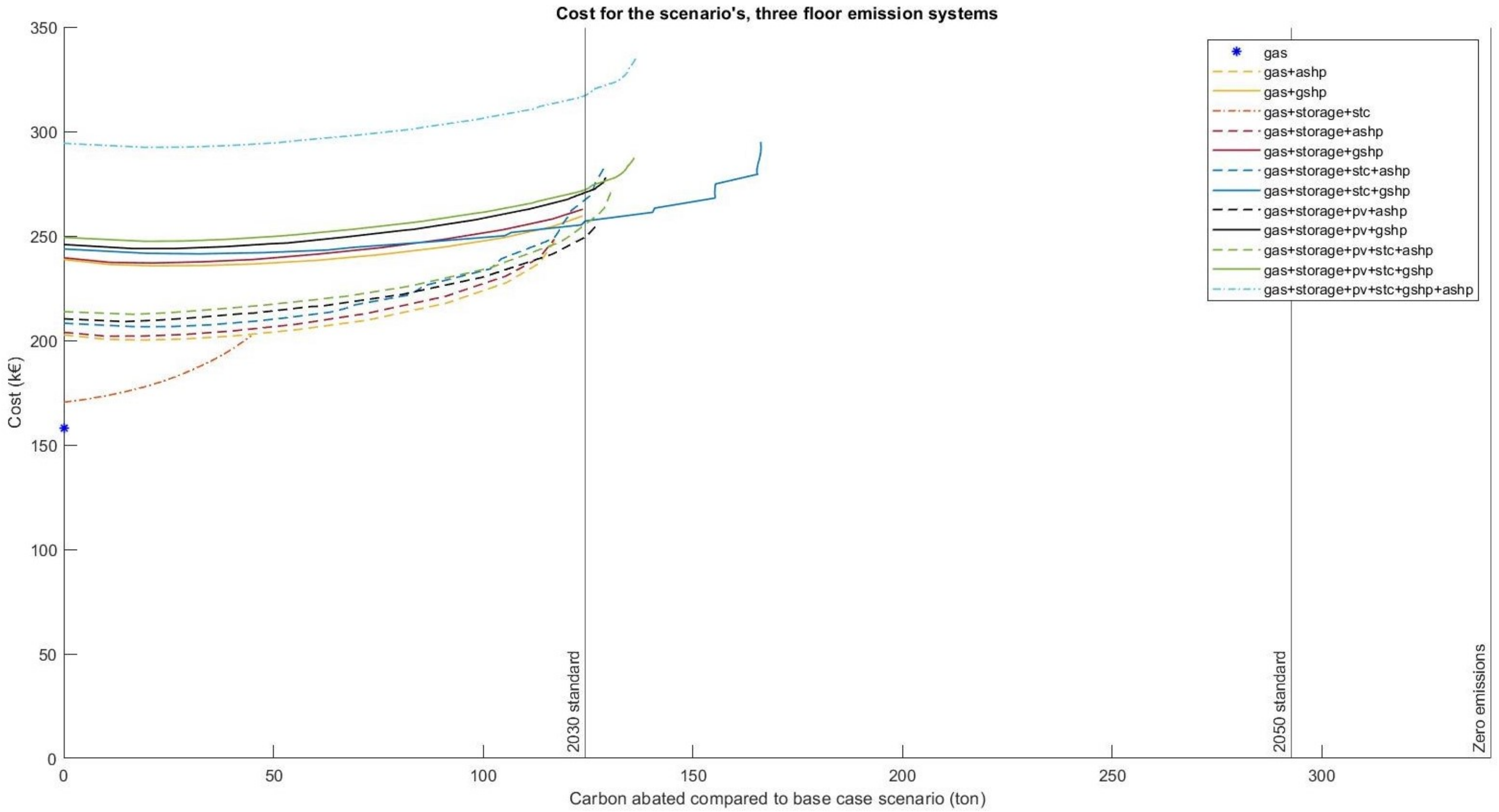


FIGURE F.6: Cost - CO_2 abatement for 30 years graph for all radiators without excess photovoltaic electricity usage

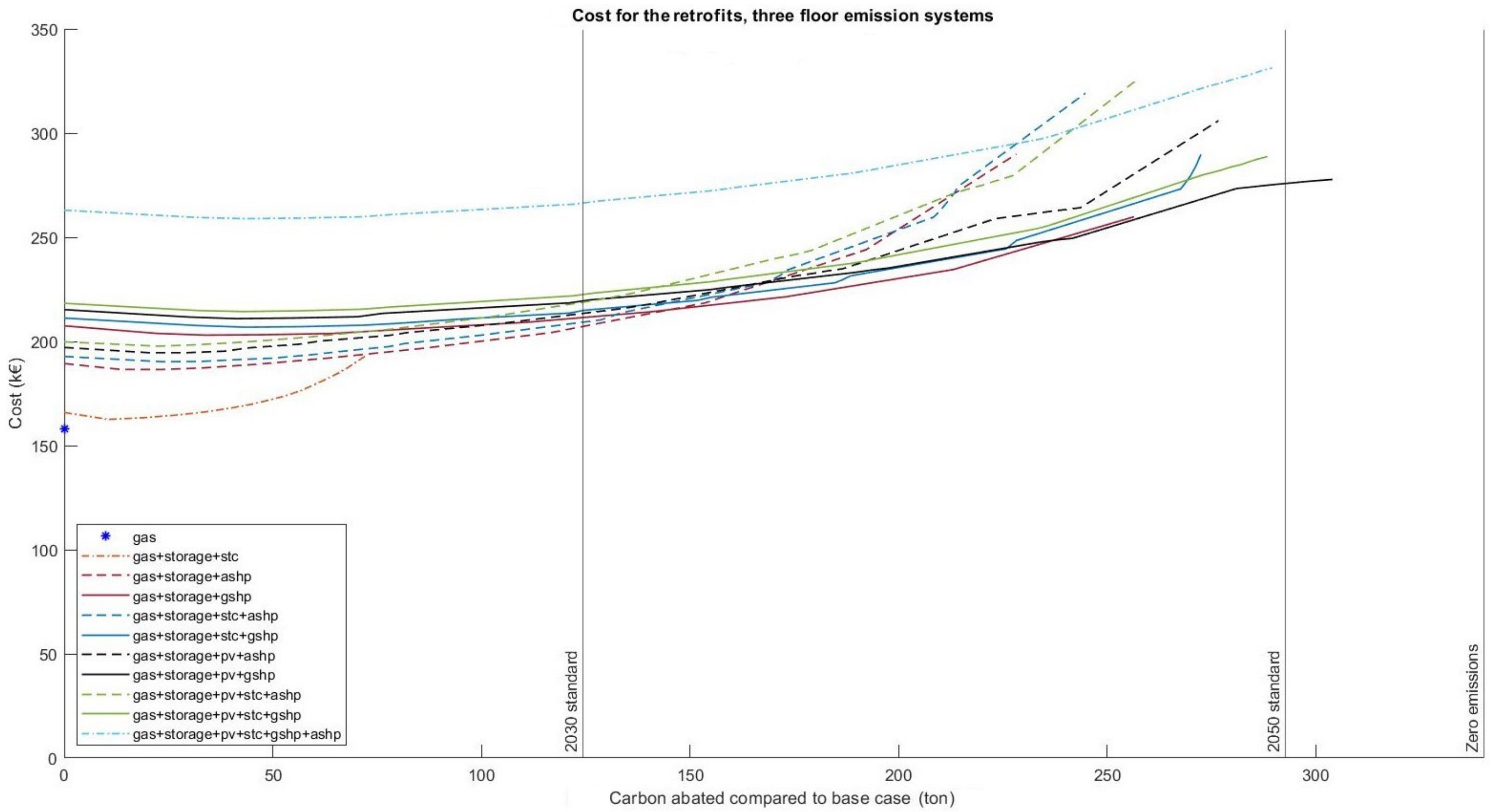


FIGURE F.7: Cost - CO_2 abatement for 30 years graph for all floor emission systems with full excess electricity put on the grid at 30% of electricity price

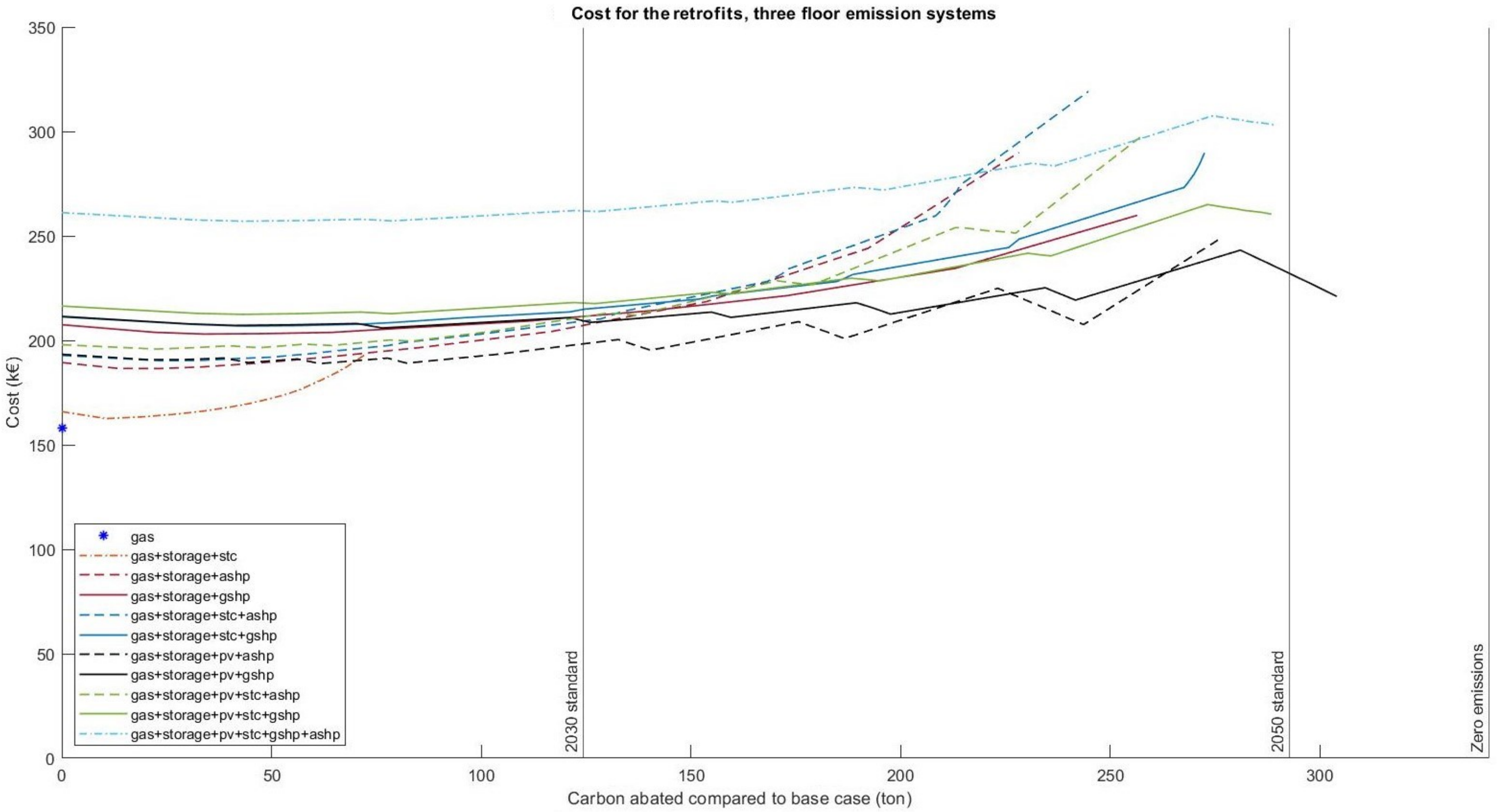


FIGURE F.8: Cost - CO_2 abatement for 30 years graph for all floor emission systems with full excess electricity put on the grid at full electricity price

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