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Fossil Free Heating in Private Households for Germany and The Netherlands

Vattenfall, Sweden

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Abstract

Heating currently corresponds to almost half of the total global energy consumption in buildings (Francois Briens, 2023), and is being one of the main sectors affected by global warming as we are currently experiencing record breaking temperatures during the winter. At the same time the heating industry in buildings is responsible for more than 4000 mega-tons of CO_2 equivalent emissions every year (IEA, 2023), and from this total around 44% correspond to residential heating (IEA, 2022).

For Germany the current main sources for residential heating are natural gas (46%) and heating oil (25%), while for The Netherlands the panorama is similar with natural gas (85%), which correspond to fossil fuels. On the other hand fossil free technologies only account for less than 16% of the demand in these countries (IEA, 2023). Hence the need to look for ways to decarbonize the heating sector urgently as most of the efforts are focused on power generation (electricity), but heat tends to be left out of the focus in most cases.

This study was aimed to answer a broad question on what the future of heating would be, then several approaches were studied, reviewing heat generation technologies mostly related to electrification, but also investigating on heat communities, heat as a service, storage technologies and also having a more complex system approach combining power and heat generation with heat and electricity storage based on computational simulations.

The way to approach the research was divided in different steps, first a general overview of the heat industry and current situation in both countries is presented and also compared to the Swedish case, then a techno economic analysis was performed using an excel model based on a 20-year cashflow (and operation of the devices), to evaluate different economical, performance and environmental key performance indicators. This was done taking specific study cases for buildings in Germany and The Netherlands (2 single-family housing (SFH) and 2 multi-family housing (MFH) for each country) and also based on weather data from Berlin and Amsterdam between September and May. For the selected buildings the average energy need for Germany is 137.9 kWh for SFH and 115.7 kWh for MFH, while for The Netherlands case the average for SFH is 112.2 kWh and for MFH is 85.6 kWh (Tabula WebTool, 2017).

A total of 22 innovative ideas or technologies were evaluated, and, in most cases, the natural refrigerant heat pumps showed high potential as well as cold-climate air source heat pumps and specially the combination of heat pumps with solar power (PV and solar thermal), from these results the next step was to further analyze the systems combinations. For Germany the first ranked technologies in reference to NPV were natural refrigerant HP, solar PV and HP, and flat plate collector and HP, while for the Netherlands the top 3 was hydrogen enriched natural gas heat pump, solar PV and HP and natural refrigerant HP. Results clearly influenced by the electricity and gas markets on each country. On the other hand for performance KPIs (efficiency and annual energy consumption) for both countries the top was natural refrigerant HP, cold climate air-source HP and flat plate collector and HP, while in relation to operational carbon footprint the top technologies where the ones based on hydrogen (hydrogen boiler, PEM FC and SOFC) due to the assumption of using green hydrogen.

Based on these results and the high potential of combining HP with solar energy sources, the system approach was further analyzed using *Polysun*, a heat system simulation software based on templates to evaluate the use of different power and heat sources and devices as well as the combination with different types of storage based on specific demand parameters.

From the simulations results in Germany the NPV showed that the best economical option are still the most simple systems (only a heat generation technology with a water tank) mostly due to high investment costs in this country when compared to the Netherlands (between 1.5 and 3 times more for a HP), but nevertheless, in both countries the inclusion of PV and lithium ion batteries showed the best

lowest energy consumption and carbon emissions. Now for the Netherlands also the economic parameters show the inclusion of PV and Li-ion batteries as the best economic alternative, mostly due to high electricity prices (0.44 €/kWh in The Netherlands versus 0.30 €/kWh in Germany in 2023 (Eurostat, 2024)), showing the system approach as a good way to go even more considering current and future subsidies and government aids to foster the use of clean technologies.

As this was intended as a high-level study, then the future steps are also discussed and should be focused on the prove of concept of the results obtained here and the application in specific sites and cases within field testing for different technologies and system combinations.

1. Introduction

Decarbonizing the heating sector is one of the main concerns when it comes to achieve the United Nations net zero 2050 goal, nevertheless is also a sector where there is currently not enough focus to fulfill the fossil free scenario on time according to the business as usual projections and even with the enhanced projections (IEA, 2023) as can be seen in the following graph (figure 1) taken from (IEA, 2023) where the green line represents the IPCC 1.5 scenario and the orange line represents the Gt of CO_2 equivalent based on the announced pledges scenario.

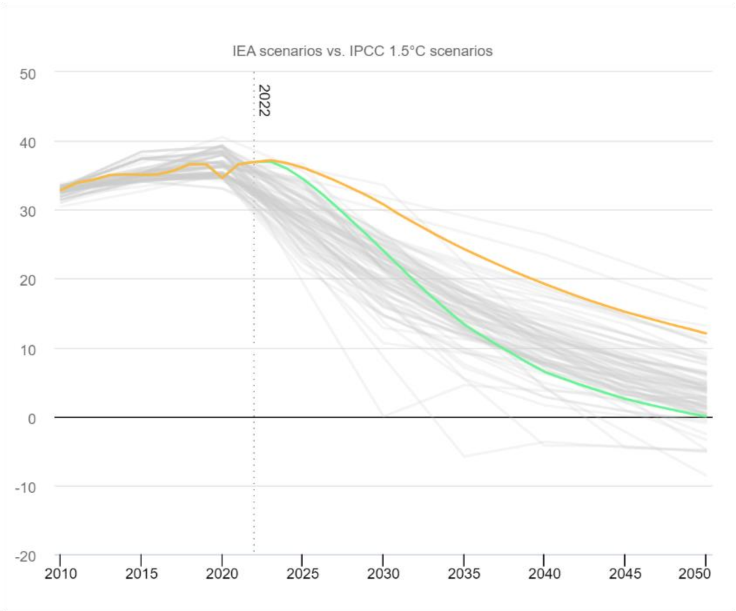

Figure 1, CO2 from energy combustion and industrial processes, Global Energy and Climate Model scenarios compared to IPCC scenarios (IEA, 2023)

The heating sector is currently responsible for the 39% of the total global emissions (World Wildlife Fund, 2021), and from this the residential sector only is responsible for 21.6% of them, this represents more than 4000 mega-tons of CO2 equivalent per year that are released into the atmosphere as a result of having our homes warm during the winter (Francois Briens, 2023).

Now if we look into the specific case for Europe, the residential sector consumes 25.1% of the total energy requirement in the continent (IEA, 2023), while space and water heating represents 63% of this share (Eurostat, 2025). With this in mind it is clear that the heating sector needs to be in the top list of priorities to fight global warming and become a sustainable species.

So far the main strategy for heating decarbonization has been and still be heating electrification, fostered by the growing use of heat pumps. In recent years the trend for heat pump sales has been growing steadily, especially in Europe (with the exception of last year as can be seen in figure 2).

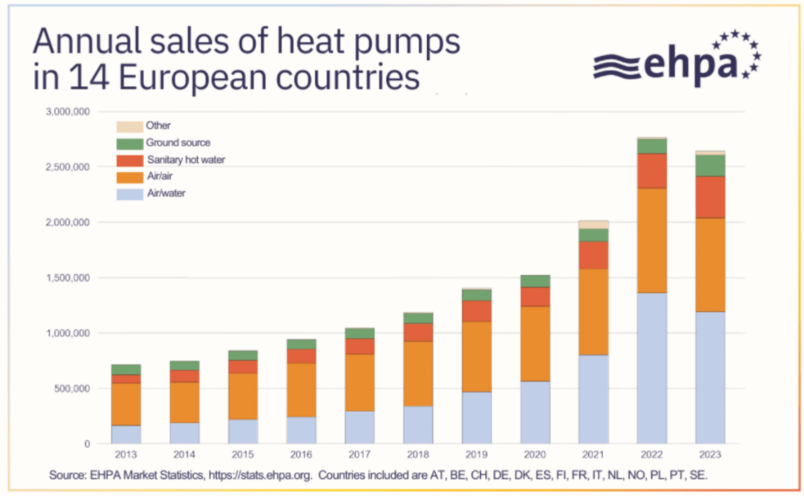

Figure 2, Annual sales of heat pumps in Europe 2013-2023 (Azau, 2024)

Nevertheless, by reviewing the main heating sources used in the continent there is still a majority ruled by fossil fuels (mainly gas), this is also exemplified by the data on figure 3.

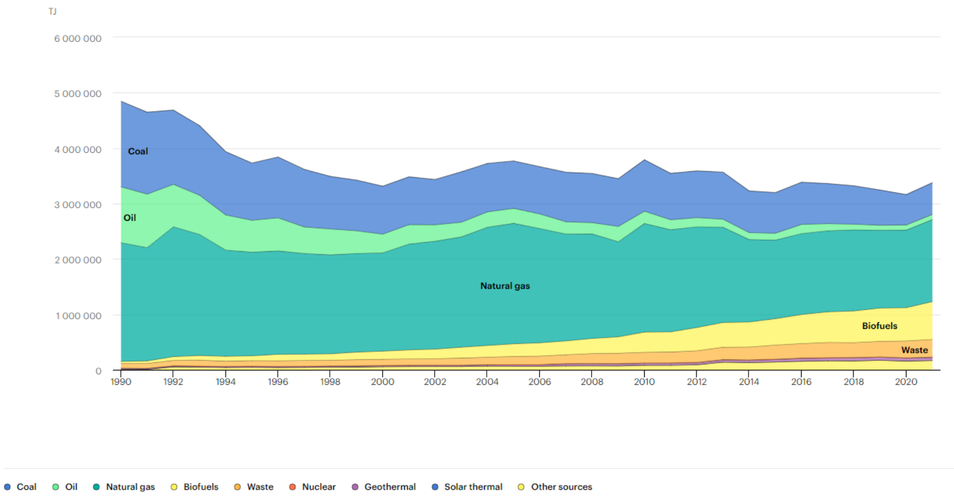

Figure 3, Heat generation by source in Europe (IEA, 2023)

Now the question will be what is the path to follow in order to reduce the emissions generated by the heating sector, and also select a focus case study in order to further scope the thesis, in this case the reference scenario taken as a success case will be Sweden, a country where 93% of the heating is renewable (IEA, 2023), and also considering the electricity sources (figure 4) we can confidently say that by electrifying the heating sector we are also reducing the carbon emissions. The path that led Sweden to implement heat pumps in a massive scale in the heating sector will be discussed in the *State-of-the-Art* section for the *Current Situation in Sweden*.

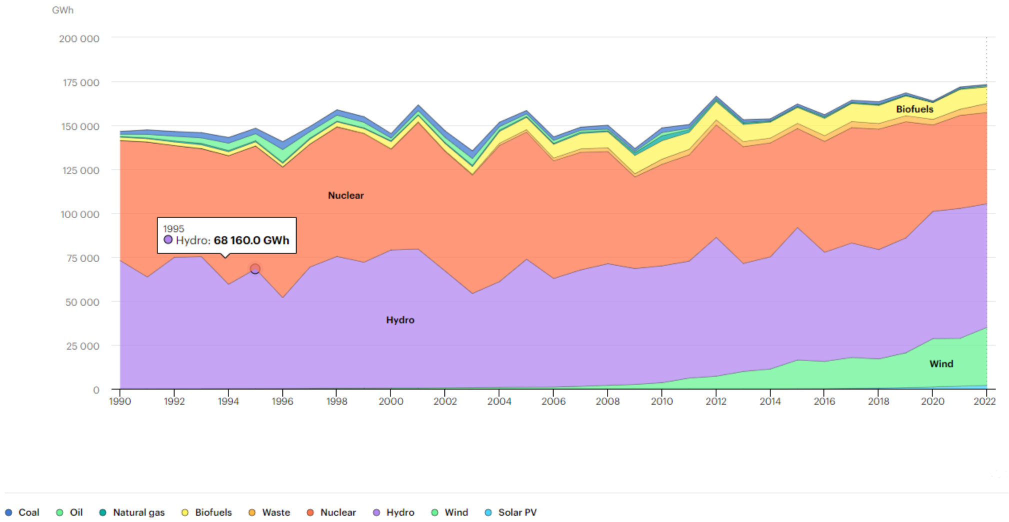

Figure 4, Electricity generation by source in Sweden (IEA, 2023)

By analyzing the Swedish case we can have an understanding on which could be the main drivers to electrify the heating sector, and it also becomes important to analyze and compare this to the background from Germany and The Netherlands, and also to look into the key parameters that should be considered to follow a similar trend in these countries, this will be analyzed in the *State of the Art* section, specifically in *Current Situation in Germany* and *Current Situation in The Netherlands*.

In a nutshell the development of the heating sector depends on many variables, as for example the expertise for proper installations in the country, the government subsidies and policies, the availability of free competence in the appliances market, but also one of the main parameters is always the market for electricity and fossil fuels and the cost that they represent for the final consumer. This market is permanently changing and also has many different aspects to consider, making its behavior very difficult to predict in the medium and long term, the influence of energy prices is also considered in this study in section *State of the Art, Market and Prices Dependency* and will be one of the core considerations during the report.

Nevertheless the value of the thesis is found in an extensive review of the different innovative technologies for heat generation, as well as for storage and even an analysis of how a complete system approach might be the future of heating for private household in Germany and The Netherlands, based on 2 case studies (Berlin and Amsterdam), also considering different representative building types based on the specific heat demand (directly related to the year of construction) and in their condition as single-family housing or multi-family housing, and also dividing each of this scenarios into two different considerations being including or excluding domestic hot water demand on top of the ambient heating demand.

A techno-economic analysis is performed for 22 different heating technologies based on economic, performance and environmental key performance indicators described in *Results, Techno-Economic Analysis, Assumptions*, and also presenting a review of how coupling these technologies and including also electricity generation will represent the base scenario for the consumers.

In order to be able to provide concrete numbers for the analysis several assumptions were made, these assumptions will also be presented in detail in the same section, and they will also define the limitations of the obtained results, nevertheless the obtained ranking is a good indicator of the potential for new technologies and on what might be the future for the sector. Finally, keeping an open scope, the future of heating as a general case will be discussed and the main technologies, strategies and tendencies will be presented and analyzed as a way to keep an eye on what might be beyond a quantitative analysis and with the aim to serve as a teaser for future studies.

2. Scope of the Research

This research aims to understand and analyze what could be the future of fossil free heating in private households in Germany and The Netherlands, this was done by reviewing the reasons behind the current situation for the heating sector in Germany and the Netherlands, also using Sweden as a reference success case.

The thesis also analyzed several innovative technologies with high potential for heat generation and storage and performed a techno-economic analysis to provide a ranking of the best cases for each country, building type and heat demand, and also reviewed a system approach considering electricity generation, heat generation and storage, and examine how this might represent additional savings for the consumers and how it could represent a better economy, higher performance and/or lower carbon emissions.

To better understand the scope the research question was defined, as well as the general objective and specific objectives.

2.1 Research Question

What could be the potential future approach for heating systems in private household in Germany and The Netherlands to achieve fossil freedom?

2.2 General Objective

Examine the heating sector in Germany and The Netherlands and analyze in a qualitative and quantitative way (techno-economic analysis) what could be the future of heating considering heat generation, storage and the combination of both including electricity generation as a system approach.

2.3 Specific Objectives

- Understand the current situation of the heating sector in Sweden, Germany and The Netherlands and the key parameters that led to said situation.
- Remark the main differences between the development for the heating sector in the 3 countries and analyze how the market prices can affect this.
- Define specific criteria and select representative building types for each country as an input for the techno-economic analysis.
- Research on heating generation and storage innovative technologies and determine the main economic parameters as well as performance and environmental indicators in a quantitative way.
- Define the KPIs to evaluate the technologies found.
- Perform a techno-economic analysis bases on 2 specific locations (Berlin in Germany and Amsterdam in The Netherlands) considering all the innovative technologies as well as reference scenarios with conventional technologies, this for each building type and including and excluding domestic hot water demand on top of ambient heating demand.
- Estimate possible approaches that could define the future of heating in Germany and The Netherlands and describe their potential.
- Analyze the conjunction of electricity generation, heat generation and heat storage as a system approach and quantify the economical, performance and environmental advantages of this case.
- Give recommendations for future studies on this topic and specific cases with high potential according to the obtained results.

3. Work Structure

In order to perform this study a series of milestones were defined and an structured path was followed also considering the time available for the research, analysis and presentation of the results, the scope was also defined and refined as the research finding were constantly showing different opportunities and possible developments always keeping in mind looking into the future of heating, while trying to provide a tangible result that could work as a hint of where the market is currently going and where could it point in the medium and long term future.

3.1. Milestones

Country Heating

The first step was to research and consciously understand the current scenario for heating on each country, what was the total heat demand, which were the heat sources, how was the specific panorama for the residential sector and what were the main methods and appliances for heating and also how were they distributed. Also, a glance review about the policies, subsidies and regulations for heating in private households was performed. The goal of this milestone was to get a general overview on what is the context at the time of this study (first semester 2024) and what were the typical cases for each country (Sweden, Germany and The Netherlands).

Fossil Free Heating in Sweden

Then, as it was mentioned before, the research looked for the Swedish case as it is a country with a large share of the residential heating sector electrified and with low or null carbon emissions, the main approach of this milestone was to understand what were the specific conditions that led to the extensive use of heat pumps (and also district heating) in the country in terms of social, political, economic and technical context.

Fossil Free Heating in Germany and The Netherlands

After having the context of the current development of the heating sector in Germany and The Netherlands it is also important to review what are the two countries doing to become fossil free, what are the aids offered by the government, what is the social expectancy about the subject and what success cases and trends had developed towards carbon freedom.

Market Dependency Analysis

One of the main realizations of the study was the heavy influence that market prices for electricity and fossil fuels can have in the development of fossil free technologies for the heating sector, then based on a previous study a series of graph were developed showing how different economic behaviors can favor an specific technology making it the most attractive solution in economic terms.

Building Types

One of the main parameters to quantify the potential of the technologies is to define specific buildings as a case study where the technologies can be implemented. For this milestone a research on the different characteristics and distribution of residential buildings and houses in each country was considered, then the key parameters were defined in order to have specific and clear divisions and from this data 4 cases were extracted for each country.

Fossil Free Heating Technologies and Innovations

An extensive review of several innovative technologies related to heating was done for this milestone, the main source of information was the IEA Clean Tech Guide (IEA, 2023), but the study was not limited to this only source but also to additional projects and trends. An inspection of the working principle, characteristics, advantages, disadvantages and technical and economic data was performed and standardized as much as possible to have even and comparable variables.

Metrics System (KPIs)

Various key performance indicators were selected and defined as a way to have specific numbers for each technology and be able to evaluate them in an even bases so that an objective ranking could be obtained, the KPIs cover 3 main aspects: economics, performance and operational carbon footprint.

Techno-Economic Analysis

A model based on the parameters for each technology was developed considering a cash flow for 20 years (based on the average life expectancy of the technologies). Also the performance was researched and recalculated considering the weather parameters for Berlin and Amsterdam during the winter period and the behavior and related costs for the technologies were estimated and totalized based on the KIPs to finally extract an objective ranking. This was done for the heat generation technologies and also for the storage technologies separately and finally a cross examination between both parts was analyzed to suggest the best probable combinations, the specific assumptions and calculations for the analysis will be presented in the section *Results, Techno-Economic Analysis, Techno-Economic Analysis Technologies for Heat Generation.*

The Future of Heating

Another important outcome and motivation for this study was to give a glance on what could potentially be the future of heating in general terms, then three different approaches were considered, one based solely on the possible technologies, one presenting a system as a combination of several technologies and one as a community approach. As an extra the HaaS (Heat as a Service) approach was also reviewed and briefly described as a promising business strategy for the future.

System Combination Assessment and Simulation

As mentioned in the previous milestone the system approach was the final outcome of the thesis, then a matrix with the key parameters to define a set of system combinations for each case was developed and then these systems were simulated using the software Polysun. This is intended to serve as a guide to understand the specific conditions that could stir the best scenario towards one specific combination or another, the combinations were evaluated in a 20 years timespan and considering the different market values for gas and electricity in each country as well as the investment cost for the required appliances, the detailed methodology and explanation for the simulation process will be presents in the section *Results, System Approach, Simulations*.

Conclusions and Recommendations

Finally the conclusions of the study were redacted and presented, here it is important to highlight that this thesis is intended to be kept as a high level guide, and as a reference to identify future and more specific study cases.

4. State of the Art

4.1. Current Situation in Sweden

The following graph (figure 5) shows how in Sweden electricity (heat pumps) represent the second largest energy source for heating in buildings of the total heat generation for residential buildings, which can be accounted as a success for fossil freedom, despite still having some fossil fuels involved. Also it is notable that the main source is district heating with more than half of the supply.

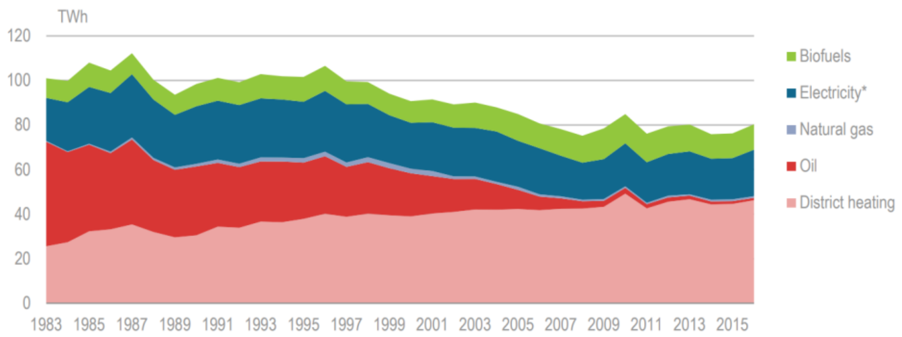

Figure 5, Energy consumption for heating in buildings by fuel in Sweden, 1983-2016 (IEA, 2019)

Also, when looking at the distribution for energy sources in different types of houses (see figure 6) it is clear that for detached houses, electric heating plays the most important role, showing the penetration of heat pumps in the Swedish market (when district heating is not available).

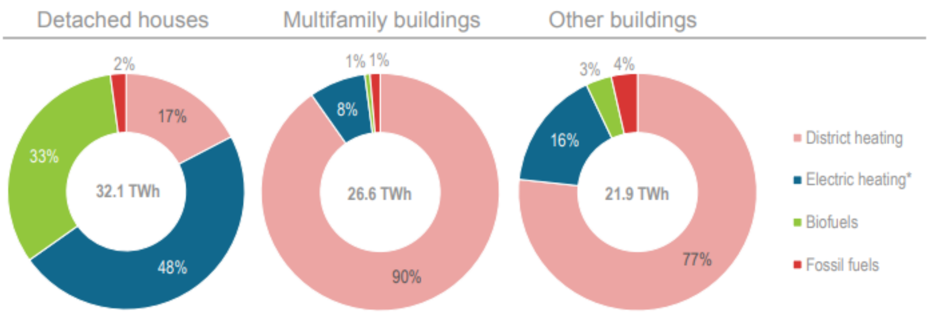

Figure 6, Energy consumption for heating by fuel and building type in Sweden, 2016 (IEA, 2019)

Now as explained by Johansson in his paper (Johansson, 2021) the Swedish case is the product of many historical factors that aligned to create a behavioral change, but as expected is was mainly driven by economic factors.

The current context is that more than half of the Swedish population lives in small buildings of one or two stores and even more private ownership is the most common. This are conditions that promote the capacity of consumers to decide how they want to heat their homes, and also gives a lot of freedom and simplicity to implement new technologies as the decision will basically only depend on the property owner.

Also, as a consequence of the geographical location of the country, the heating demand is quite large, between 8 and 10 months per year, according to the paper (Johansson, 2021) the energy consumption in Sweden due to heating is around 50% higher than the average in EU. This causes that heating expenses becomes also one of the main concerns for home owners, also making system performance much more significant when evaluating which technology to use, with high efficiency come bigger savings for the consumers.

Now it is also important to highlight the sequence of events that conducted the steering in the heating system, starting in the early 70´s when around 75% of all new houses used electric heating due to pressure from the nuclear industry (Johansson, 2021). Electricity prices dropped and heat electrification peaked accordingly.

Also, certain regulations enforced the use of a recovery system in new built houses, promoting the installation of exhaust air heat pumps, the reason for this was that a single system could fulfill all the required criteria and it seemed like the way to go for many as it was in most cases the cheapest and safe option. Around 80% of the market share for new built one dwelling houses implemented this method (Johansson, 2021).

Now, in reference to the energy system context the author present the influence of the electricity and district heating market and what was their influence on the heat pump market development. Once again it is highlighted that the expansion of nuclear energy, also combined with hydro power, generated large amounts of electricity, pushing prices down.

Then from the 70´s until the 2000´s the electricity prices remained stable, even despite the shift from oil to nuclear and hydro. In 1973 the oil prices increased drastically due to the Yum Kippur War, causing an increase of around 350% (Johansson, 2021). This situation changed during the 80´s when oil prices dropped again back to pre-war rates, but due to taxation and additional fees, it was still highly expensive as a heat source. Then, the oil prices increased again during the 90´s crisis, helping to make more sense into investing in more efficient devices (such as heat pumps).

It was only after the 2000´s that electricity prices started to increase, but mostly due to taxes, by then the heat pump market was already stablished enough to continue growing.

Also, the policy and institutional context was addressed. The rapid economic growth after WWII (mostly fueled by oil imports) caused an oil crisis in Sweden during 1973, and energy became a priority, mainly tackled by nuclear, but also wind, solar, and heat pumps, that represented a significant reduction in the demand (after a few years), promoting the creation of various subsidies schemes.

On top of this, there was a general opposition against nuclear energy, product of the geopolitical context of that time, putting pressure in the government to reduce electricity consumption for heating.

Also, the EU policies demanding energy efficiency and emissions reduction were taking place and fostered the heat pumps market mainly by the Ecodesing Directives and the Energy Labeling Directive (Johansson, 2021).

The subsidies started from 1978 where a direct 10% to 15% was approved, this lasted until 1984 where the focus changed from homeowners to residential multi-family buildings. Then subsidies were re-introduced during 1998 to 1999, followed by another in 2001 to 2003, and another in 2006 to 2007, after that it has been possible to get tax deduction for the cost of labor for certain installations since an approval in 2009 (Johansson, 2021).

Also, the ban of CFC refrigerants from 1995 until 2000 also affected negatively the heat pump market as new more expensive alternatives had to be found and this cost was directly transferred to the consumers.

Even social awareness played an important role as well, Mäklarsamfundet (Johansson, 2021) found that the most popular heating system among people looking to buy a house was vertical ground source heat pump, while the least popular was a boiler.

There is also a technical aspect to be considered in the story, as the need for alternative ways of heating generated a lot of venture projects with entrepreneurs trying to create rudimental heat pumps from inverted refrigeration units, which opened the market to several quality ranges.

Luckily Sweden had a strong refrigeration industry before the popularization of heat pumps, then many technicians were already trained in similar devices and installations, causing heat pumps installations to be easier to implement and avoiding technical issues and lack of performance. This has been a main barrier in other countries where there is not enough expertise, ending in poorly designed systems and a generalized disappointment feeling from the customers.

Nevertheless, it is also important to mention that actually the biggest impact in the heating system from heat pumps was made on district heating, where big size and capacity heat pumps were installed, and are still running and providing fossil free heating to the grid.

4.2. Current Situation in Germany

Germany has a considerable amount of natural gas consumption and also relays on coal as can be seen in the figure 7. Also, for the residential sector, heating oil represents an important share (around 25%) (IEA, 2023). This outcome has been driven by high investment prices for new technologies and also low taxation in heating oil and natural gas compared to the electricity prices.

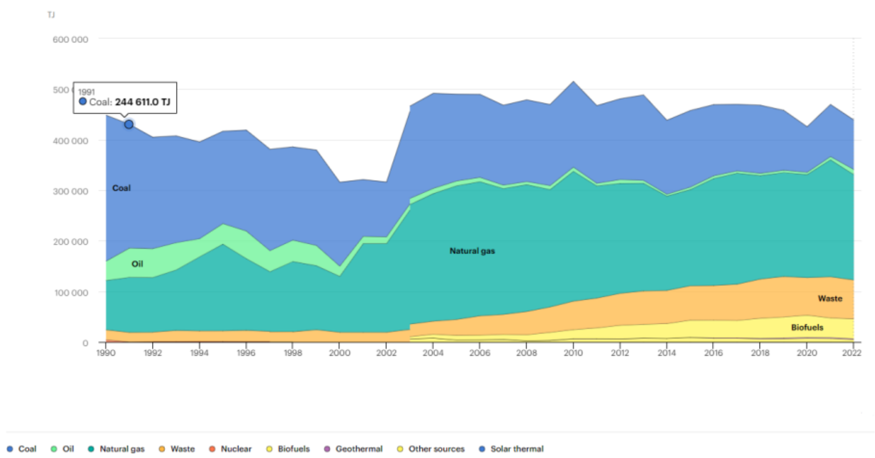

Figure 7, Heat generation by source in Germany (IEA, 2023)

Heating oil represents around 25% of the consumption in the residential sector being fostered by low prices due to taxation schemes, 1000 liters of diesel can cost around 470.4 euros, while 1000 liters of heating oil will only be around 60.6 euros (Sorge, 2023) (European Comission, 2015).

Nevertheless, according to the IEA report from 2020, based on the climate cabinet´s proposal, the government adopted the climate action program 2030 sin the 9th of October 2020, which includes a phased carbon pricing system for certain sectors not covered by the EU ETS, heating and transport among others.

The pricing system is a cap-and-trade scheme as follows (Clean Energy Wire, 2024):

- Fixed price in 2021: 25 euros per allowance (ton of CO_2 equivalent) (means around 7 cents price increase per liter of petrol, 8 ct/l of diesel), then an increase in 2022 and 2023 to 30 euros.
- Also a fixed price in 2024: 45 euros (around 8.4 cents price increase per liter of petrol, 9.5 ct/l of diesel), and a further increase in 2025: 55 euros.
- In 2026 the price will be defined in auctions, with a price corridor of 55-65 euros.
- From 2027: market price, with option for price corridors (to be decided in 2025)

Also, the revenues from this pricing system will go into the Climate and Transformation Fund (KTF), which is used, between others, for energy-efficient building renovation and boiler replacements. Despite these efforts the market is still ruled by fossil fuels, this is showing a decreasing trend but is still the case nowadays.

It is also important to understand the clients perspective, that mention that the main challenge when implementing energy saving measures is always the investment cost (52%), followed by the constructional conditions (39%) (Statista / Vattenfall, 2023), this is backed up in the techno-economic parameters for the technologies where the investment cost in Germany is always higher than in other countries.

Also according to the Statista report (Statista / Vattenfall, 2023), the German consumers are mostly hesitative and reliant to heat pumps, despite the promise of saving in expenses and a generalized conscience for saving natural resources, also fostered by the government grants, the German population still consider the implementation costs too high, not presenting an attractive investment for around 58% of the house owners (Statista / Vattenfall, 2023).

As can be seen in the following graph (figure 8) from the IEA report from 2019 (IEA, 2019), in the residential sector around 60% of the energy consumption is provided by fossil fuels, nevertheless it is important to notice that the residential sector also shows the highest potential for bioenergy and waste, which could be also a possible path for heating with biogas in the future.

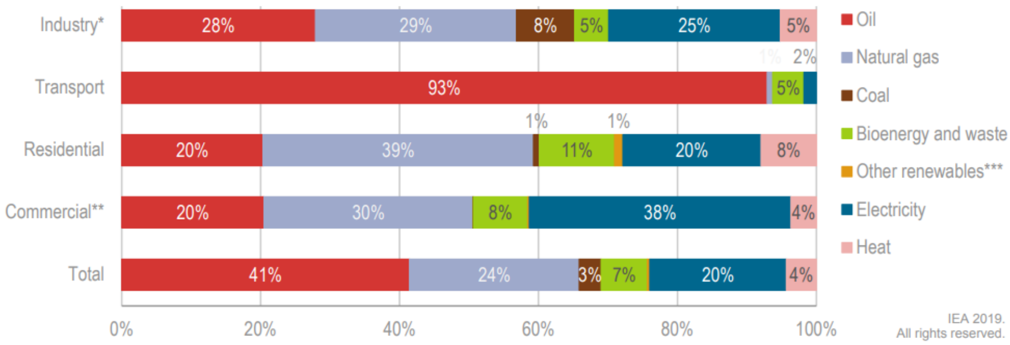

Figure 8, Total final consumption by source and sector in Germany, 2017 (IEA, 2019)

The share of district heating is also as low as 20% for new apartment buildings, and the heating networks are usually located in big cities. More than 2/3 of the district heating supply is produced in cogeneration plants.

Now by looking at figure 9 we can identify that the biggest share of consumption comes from space heating (65%), while water heating is the following 19%.

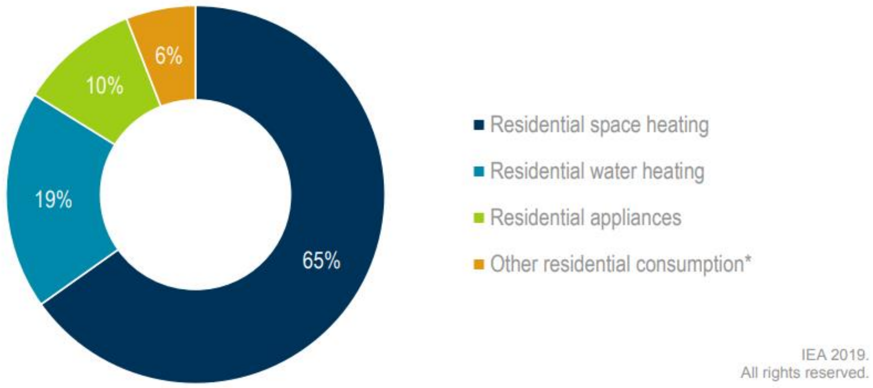

Figure 9, Breakdown of TFC in the residential sector in Germany, 2017 (IEA, 2019)

The IEA report (IEA, 2019) also presents the energy concept diagram from the German government (figure 10), where they mention the steering targets for climate mitigation where heat from renewable energy sources is mentioned. In general terms heating and cooling represent 50% of the energy consumption and 40% of the emissions (IEA, 2019).

Around 10 million heating systems in the country are older than 15 years, and 25% of the heating systems are based on oil, while the use of heat pumps is as low as 2% (IEA, 2019).

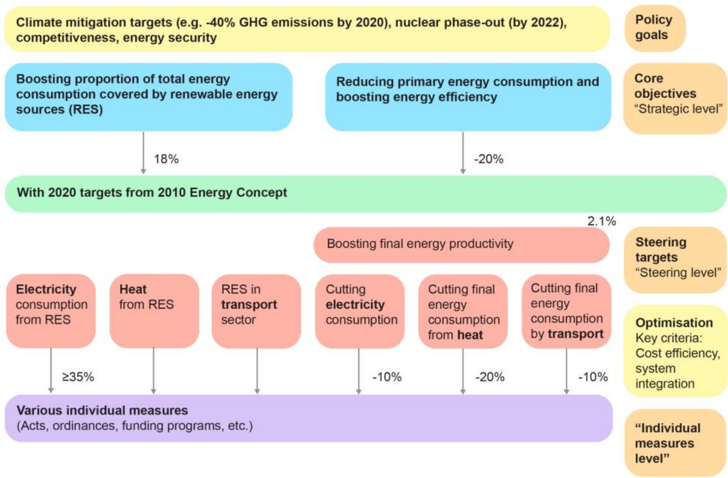

Figure 10, Structure and targets of the energy concept for Germany (IEA, 2019)

This optimization is proposed from cost efficiency and system integration, as Germany accounts heavy industry presence in the south, there is a possibility to use waste heat in this area, covering a large demand and providing grid balance and flexibility as one of the main current issues with renewables in Germany is the high concentration of wind farm in the North, while the demand comes from the south. There had been also incentives from the government, facilities that co-generate heat and power in non-mobile plants with a monthly or annual capacity utilization of at least 70% are fully exempt from the energy tax on fuel inputs (IEA, 2019).

One of the main drivers for the current situation is the high electricity cost, preventing indirect use of renewables. Also, low taxation for fossil fuels promotes this situation. This is likely to change in the near future as NAPE 2.0 and NECP set a goal to increase the share of renewables for heating to 27% by 2030. Even more, the Climate Action Program for 2030 includes a CO2 pricing and ban the use of oil-based boilers from 2026 (IEA, 2019).

Indeed, the Climate Action Program seems to be the main strategy from the government to achieve the emissions mitigation goals. The strategy is based on energy efficiency and an increased share of renewables.

Tax relief has been available since January 2020 for energy-efficient renovation measures such as replacing heating systems, fitting new windows, insulating roofs and external walls, and will continue until the end of 2029: the tax payable can be reduced by 20 percent of the renovation costs – spread over three years. This tax relief applies to owner-occupied residential property (Bundesregierung, 2020). On top of this the heating optimization program aims to subsidize 30% of the costs of heat pump and to increase expertise in the market.

By the Federal Funding for Energy-Efficient Buildings (Bundesamt für Wirtschaft und Ausfuhrkontrolle, 2020) since the beginning of 2020, a grant of up to 45 percent has been available to property owners who replace their old oil heating system with a more energy-efficient heating system under the market incentive programme (Federal Ministry for Economic Affairs and Climate Action, 2024).

4.3. Current Situation in The Netherlands

According to the IEA report for The Netherlands released in 2020 (IEA, 2020), natural gas has a major role as an energy source for domestic energy production and building heating. This is also due to the Groningen gas field located in the northeast of the country being also one of the biggest fields in the world.

Groningen has been an important energy source in the Netherlands since it was discovered in 1959, nevertheless it has also been the driver of many protests and claims to shut it down as it has been related to several earthquakes around the territory (Global Energy Monitor Wiki, 2024). During January 2018 and May 2019, the field activity was blamed of causing earthquakes that damaged around 10000 buildings, resulting in strong opposition to the operations and an urgent claim to stop production (IEA, 2020).

Production was set to end by mid-2022, increasing energy import dependency until becoming a net importer in 2018. This momentum was stopped when the Russian gas crisis arrived pushing the phase out until 2025/2026. This situation caused the residential heating market in the country to be highly dominated by gas boilers (around 90%), also fostered by elevated electricity prices a heavy chemical industry and high-level natural gas heating (Global Energy Monitor Wiki, 2024).

Even more, by having the second largest agricultural exports in the world, causes that greenhouses also create a considerable heating demand, also raising the question about the use of bioenergy in the country.

The government of The Netherlands has been working on strategies to decarbonize the heating sector, the introduction of a carbon levy in 2021 is mentioned, as well as strategies based on low carbon gases (biomethane) and CCS. Also, an initiative called Gas Act bans new gas connections for new buildings since 2018.

On the other hand, district heating has seen a slow decline, from 3.7% demand in 2000 to 2.9% in 2018. The Netherlands is aiming to increase the use of both renewables and districting heating

Looking specifically at the residential sector (Figure 11), district heating is included in the development plan to supply low carbon heating to 1.5 million buildings by 2030, the expectation from the Environmental Assessment Agency (PBL) is that 20% to 30% of homes will be connected to district heating by 2050.

Space and water heating accounted for 81% of total energy demand in 2017, followed by appliances (15%), cooking (3%), and lighting (2%). Electricity is used mainly for appliances, but electric heating has been growing.

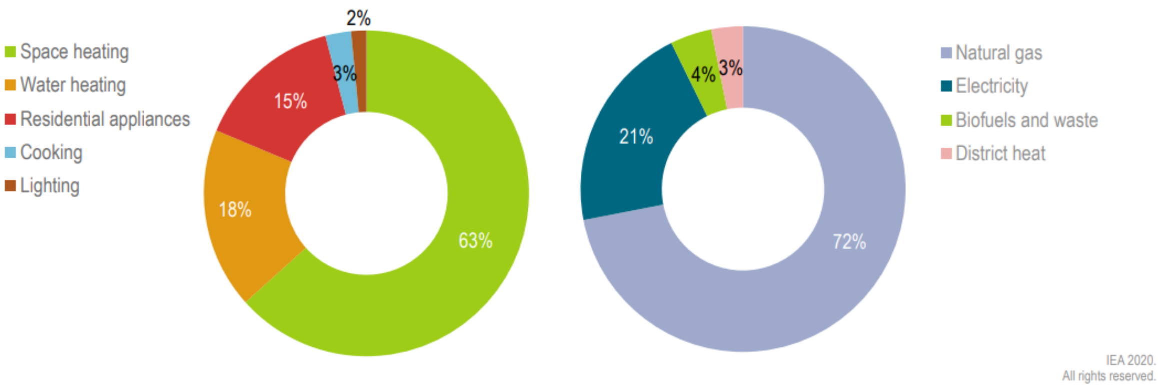

Figure 11, Residential energy consumption by use and by fuel in The Netherlands, 2017 (IEA, 2020)

In 2017, approximately 68% of district heat production came from combined heat and power (CHP) plants, mainly fueled by natural gas and some waste incineration. The remaining share of district heating came from biomass boilers, natural gas boilers or other heat sources (e.g. industrial waste heat). This is expected to decline by the Climate Agreement to move towards electricity for heating and direct use of renewable energy.

Energy efficiency has also made an important impact in the demand reduction.

The Netherlands is carrying a project called Natural Gas Free Districts Program (PAW program) (Programma Aardgasvrije Wijken, 2020) where 19 communities volunteered as pilot projects to investigate the possibilities of a district-oriented approach for heating systems. Some of the projects were reviewed in general terms as a good reference source for a real-life community approach, a brief description of the projects is presented below (Programma Aardgasvrije Wijken, 2024).

- Proeftuin Hilversumse Meent: Renovation project for private homes with encouragement for open house at the end of the project to create trust in other neighbors and show how the final result looks like and what are the benefits.
- Testing ground Overwhere-Zuid: This is an example for government financial support and subsidies for replacing devices and investing in efficiency, they also offer drop-in sessions to answer questions about the system and the possible advantages.
- Experimental garden Van der Pekbuurt & Gentiaanbuurt: The valuable lesson from this project is that the renovations are made by small groups of houses at a time, it is also highlighted that an all at once approach is not sustainable because they will not have enough place to accommodate the habitants while the houses are being renovated.
- Zandweerd in Deventer: This case is mostly based on a financing model. They use water source heat pumps using a nearby lake as a reservoir to increase the temperature and deliver hot water at 60°C to 70°C. It is not a fully technical solution as they mention that from an efficiency point of view it will not make so much sense as the performance will drop due to the high temperature increase, but when analyzing the levelized cost of heating it becomes a good business case for the residents, then they do not focus on the technical perspective, but in the affordability.
  They also promote a more stable price as they only deal with electricity prices instead of gas prices, then they can keep the investment cost lower. Besides, the investment is not new money as it comes from the district current investing funds according to the specific investment budget. Despite this, it is important to mention that the initial investment will be higher but based on long-term calculations the savings will be more significant in a 20+ years timeframe. They have an approach based on how to use the district money more efficiently for the greater good (doing more with the same money), offering subsidies and low-rate loans.
- Testing grounds Eemsdelta: Based on utility solar PV to provide affordable electricity, the goal is to become an autonomous energy community. It is planned as a complete system, as they have experts to guide people on subsidies and technical decisions, while also focusing on a complete assessment for each particular case, first checking and improving the insulation levels and only after (and if necessary), looking into the replacement of the heating system (usually with a heat pump).
- Rozendaal Testing Garden: Project mostly focused on investing in insulation. Guided step by step (or more like stage by stage) on how to improve energy efficiency, also doing open house events for people to see and understand the benefits and methods.
- Experimental garden Ramplaankwartier: Use of solar panels to generate heat and electricity plus a geothermal storage system. It is planned as a community approach, so all the houses are prosumers, keeping prices down and ensuring flexibility.
- Proeftuin Heeg: Aqua-thermal energy storage project, involving also a heat exchanger and a heat pump, still in development, and focused on 1 to 1 interactions and open spaces for conversations and Q&A, really concerned about the community approval and support to the project.

- Testing ground Garyp: Already own a PV farm, offering private energy scan and assessment. Community consisting of old houses, causing the first approach to be on insultation in combination with a hybrid heat pump.
- Experimental garden De Wijert, Paddenpoel and Selwerd: very similar approach to Haryp, also focused on insulation improvement and participation from the community.
- Nagele Testing Garden: Development of a heating network running over the roof of the houses as heat is removed into an underground buffer to use during the winter (seasonal storage).
- Ramplaankwartier in Haarlem: Solar heat network, it is a collective initiative, expecting to have enough early adopters living close by so that the project can have at least 90% of the required financing to begin construction, they also expect the addition of new customers afterwards.
  Use of flat plate collectors to produce heat during summer combined with the use of TES and reuse the heat during winter, the plan is using a heat pump to increase the temperature to the desired level at the final step of the process. The project also offers the possibility to participate using an online form to provide useful data about the house.
  It´s a low temperature system, then old houses with poor insulation need to couple this with a hybrid form of PVT and a hybrid heat pump.
- Experimental garden Drimmelen: Not many details about the project can be found except that they mention that the ownership of the network and the earnings will be for the community.
- De Glind in Barneveld: Also, a solar thermal heat network combined with underground storage and heat pumps for back up temperature increase. The project includes an storage system with high visibility to create conscience and affinity, the storage tank is planned to be located close to a park and a playground, also the school has visible solar panels in the rooftop.
- Testing grounds Pendrecht and Bospolder-Tussendijken: Once again not just technical perspective, but also social. Introducing the idea of a “financial coach” as a help for the users to better understand their system and optimize their investment. Project developed in a neighborhood where most habitants are unemployed, therefore the need to consider the economic capacity of the people becomes crucial.
- Experimental garden Opsterland: A case involving the use of green gas (biogas), while also focusing on improving insulation, the plan is to use local cow manure as fuel for the digestor and foster biogas production.

Besides the study cases (Programma Aardgasvrije Wijken, 2024) the project also presents the point of view of a few stakeholders involve, for example Maarten Schurink (secretary general of the ministry of defense) said “don't make integral work the domain of a few, but of everyone”. He mentions that with this project now they know what the people want and what they are concerned about, so they can better understand how to get people involved.

Another example is Peter Derk Wekx (municipal secretary and general manager at the municipality of Alphen aan den Rijn): The more assignments linked, the greater the added value on all fronts, he also shares the perspective of not just focus on the technical aspects, but also on social issues and plan in an open table with representatives from all the parties. Also, he acknowledges that sometimes this can shift the focus of the conversation to discuss even something very “basic” that seems like the main concern for a specific community.

Eelke de Jong (municipal secretary of Leeuwarden) says “It's not coupling opportunities but coupling necessity” as a clear statement in favor of heat communities. Eelke highlights that biogas, aqua thermal energy and geothermal heating had been on the table for a long time, and in the future could be a game changer, while he also recognizes a tight community feeling in the project, improving the adaptability for a community approach. He also mentions that they are always looking for any opportunity to expand the heating network, as they seem to get great benefits out of it, to achieve this they keep track on any other excavation work that can be used for the project. On top of this they train the citizens to be “heat coaches”, getting everyone involved.

4.4. Sweden, Germany and The Netherlands in Numbers

Now using data from the International Energy Agency (IEA, 2023), the main parameters to understand and define the situation for residential heating on each country were analyzed. The approach was starting from a broad perspective to a more specific one. The first step was to review the energy sources for each country (total and domestic), then check the energy consumption by sector and then define the specific sources for the residential energy demand.

Then the use of said energy was determined and for the specific case of heating also the proportion of district heating and independent heating was checked. This was also a parameter to further scope the thesis as the use of district heating as well as ambient heating, hot water supply or heat for cooking were also part of the initial research.

The total energy supply for each country is presented in figure 12 below, the graph presents the relative percentages for each source per country, nevertheless it is important to notice that the energy supplied for Germany is more than 4 times higher than for the other cases. The total energy supply for Sweden is 562.3 TWh, for the Netherlands is 741.4 TWh, while for Germany it rises to 3151.2 TWh (data from 2022) (IEA, 2023).

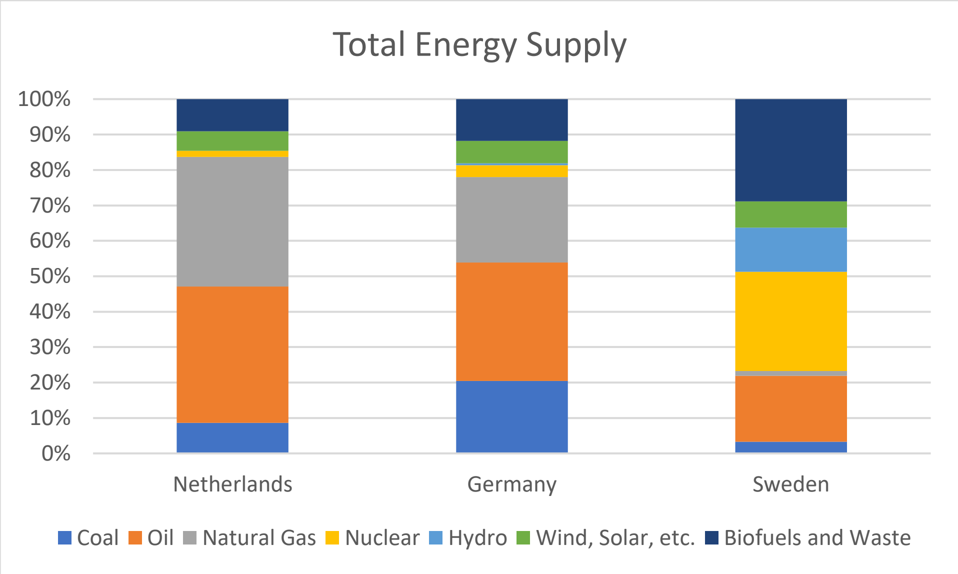

Figure 12, Total energy supply for The Netherlands, Germany and Sweden (IEA, 2023)

As can be seen in the graph, Germany and the Netherlands have a high share for oil and natural gas, while Sweden has more renewable energy sources, this is also why the goal of this project is highly justified as a manner to cope with this issue and reduce the orange and grey bars. Nevertheless, it should be kept in mind that this is the total energy supply including the transport and industrial sectors, among others, the specific case for the residential sector will be presented further down in the report. Another interesting data is the to better understand the population energy use intensity is the annual energy supply per capita, this was calculated using the previous data and the population from 2022 (CBS, 2024) (Destitas Statistisches Bundesamt, 2024) (Statistikmyndigheten, 2024), as presented in the following table (table 1), the data for GDP is also presented in the chart just for as an additional data. Sweden turns out to be the most energy intensive per capita, despite having the lowest GDP and population.

Country	*Population 2022 (millions)*	*GDP (Billion USD)*	***Energy Supply per Capita (MWh/person)***
The Netherlands	17.59	1009.40	**42.15**
Germany	84.60	4082.47	**37.25**

Sweden	10.52	591.72	**53.35**

Table 1, Population, GDP and Energy Supply per Capita per country (CBS, 2024) (Destitas Statistisches Bundesamt, 2024) (Statistikmyndigheten, 2024)

Now the domestic energy production per country is presented in figure 13, this data also gives a glance at energy imports. From the graph we can conclude that Germany and The Netherlands are high energy importers, noting that oil and natural gas are the most representative imports. In The Netherlands the domestic energy production represents only 37.3% (276.9 TWh) of the total energy supply, for Germany this is even lower (35.0% (1102.3 TWh)), while for Sweden it represents the 74.0% (415.6 TWh) (IEA, 2023). Also, it can be observed that basically all renewable energy id produced locally in all countries.

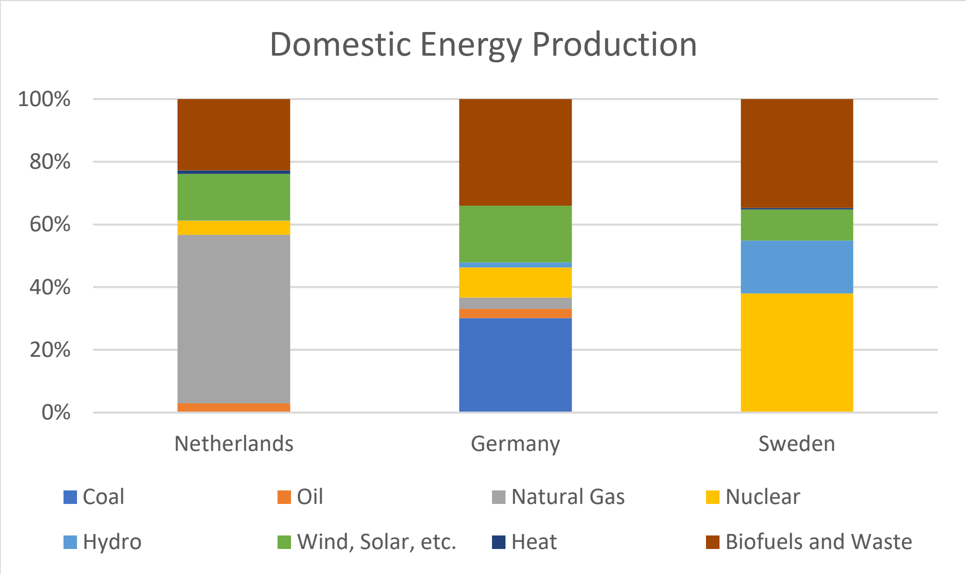

Figure 13, Domestic energy production per country, 2022 (IEA, 2023)

The next step was to analyze the energy consumption per country (data from 2021), the data is presented in figure 14 below again in relative percentages. The total values for energy consumption are 651.0 TWh for The Netherlands, 2610.59 TWh for Germany and 383.5 TWh for Sweden.

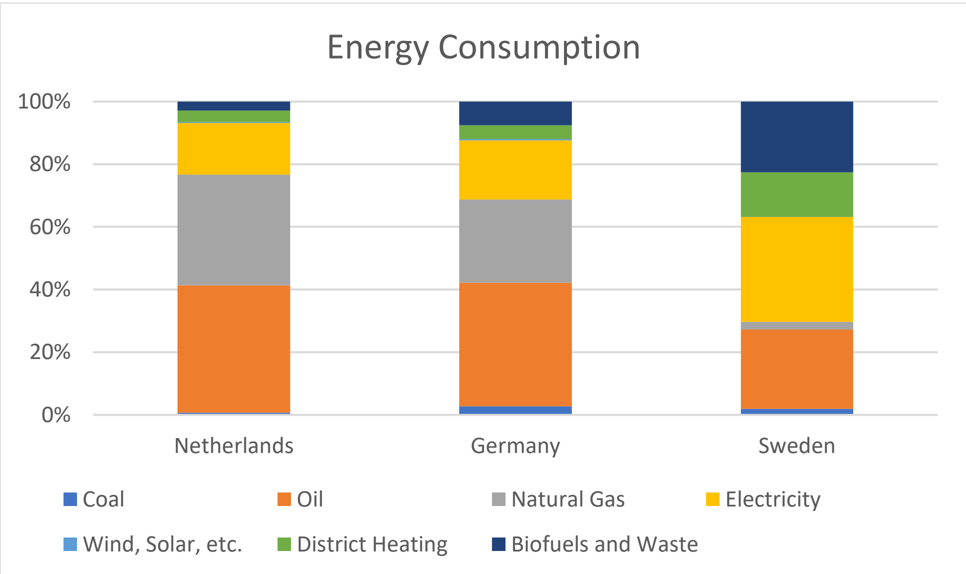

Figure 14, Energy consumption by source for each country, 2021 (IEA, 2023)

Now from this data we can calculate the percentage of consumption in relation to the energy supply, for The Netherlands this number is 87.8%, for Germany it is 82.9% and for Sweden it is 68.3%. It is interesting to notice the lower percentage for Sweden as they could be interpreted as system losses, this can be justified due to the significant share of nuclear energy in Sweden compared to the other two cases, as the losses related to this type of energy are around 18% of the energy supply in Sweden, hence the difference (Swedish Energy Agency, 2024).

The net exports can also partially be a reason for this difference as for The Netherlands and Germany they represent 0.58% (4.29 TWh) and 0.86% (27.3 TWh) respectively, while for Sweden they represent 5.92% (33.2 TWh) of the total energy supply.

Now it becomes important to understand the energy consumption for the residential sector by first reviewing the general consumption by sector (see figure 15). From the graph it is obtained that the percentage of residential consumption compared to the total energy consumption for The Netherlands corresponds to 17.7%, 25.6% for Germany and 23.9% for Sweden.

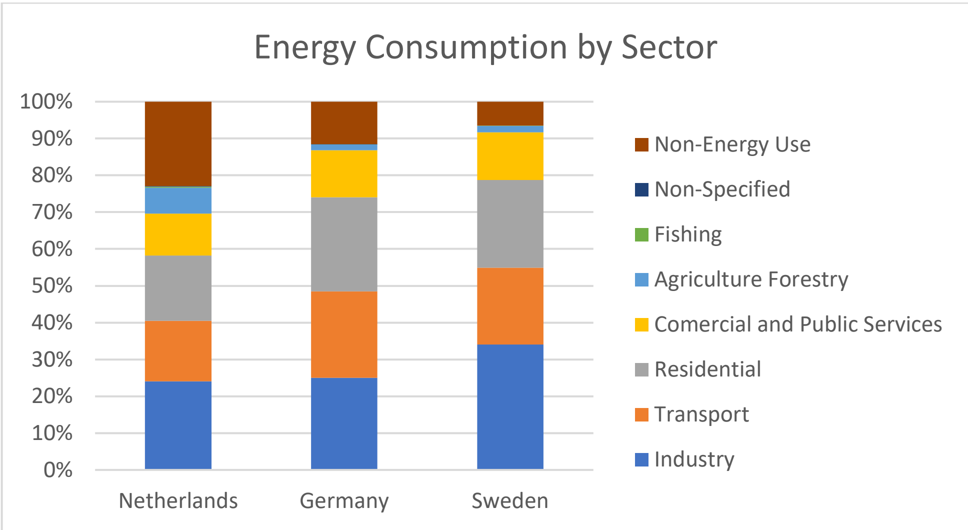

Figure 15, Energy consumption by sector for each country, 2021 (IEA, 2023)

Also the energy sources for the residential energy supply are presented in figure 16, this data is quite relevant for the project as by assuming that the shares of electricity and heat are renewable in order to define the use of coal, oil and natural gas as fossil fuel sources, then we can say that the residential sector in The Netherlands is 27.0% fossil free, in Germany it rises to 41.8%, while in Sweden it goes up to 97.1% (IEA, 2023).

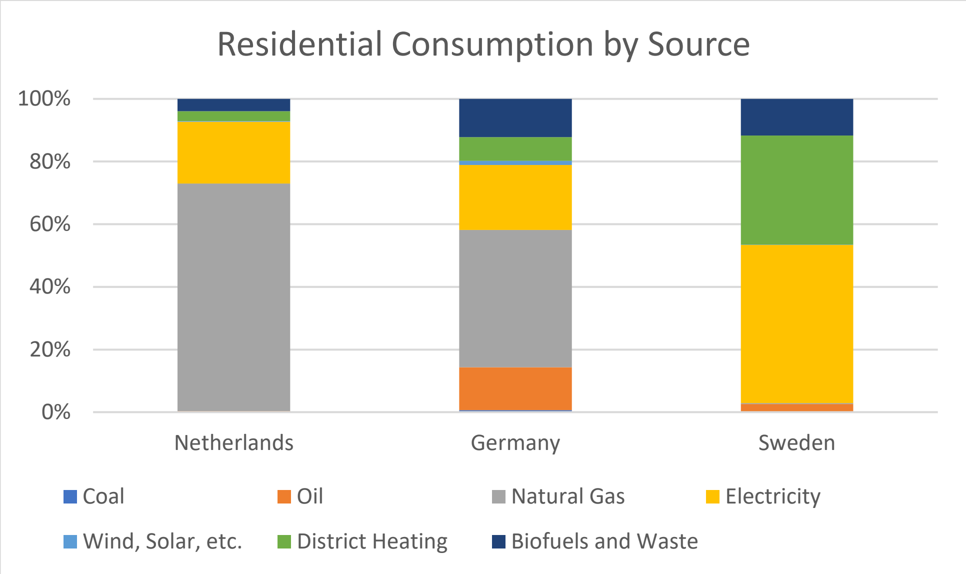

Figure 16, Residential energy consumption by source for each country, 2021 (IEA, 2023)

Inside the residential sector the energy consumption by end use is presented in the following graph (figure 17). From this data it becomes clear that space heating is the main consumer of energy in the residential sector, complemented with water heating. Also, it becomes clear that the energy use for cooling is almost negligible in all countries as it represents less than 0.3% in all countries.

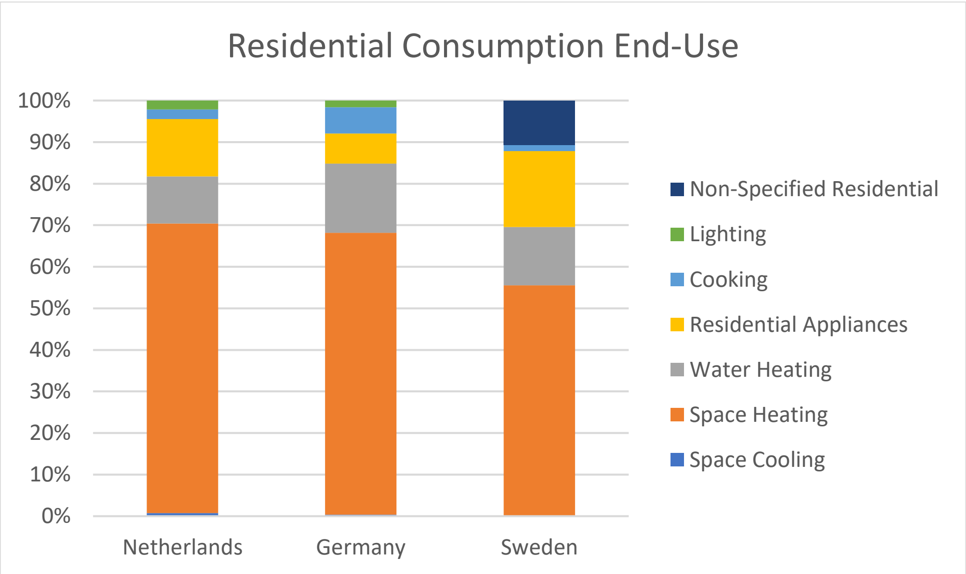

Figure 17, Residential energy consumption by end-use for each country, 2021 (IEA, 2023)

Also, the heating sources are presented in figure 18, this numbers were updated to 2022 with the consolidate data from IEA, statistics for heating demand in private households and sources. Note that the total energy consumption for residential space heating for The Netherlands is 83.8 TWh, 441.0 TWh for Germany and 49.9 TWh for Sweden.

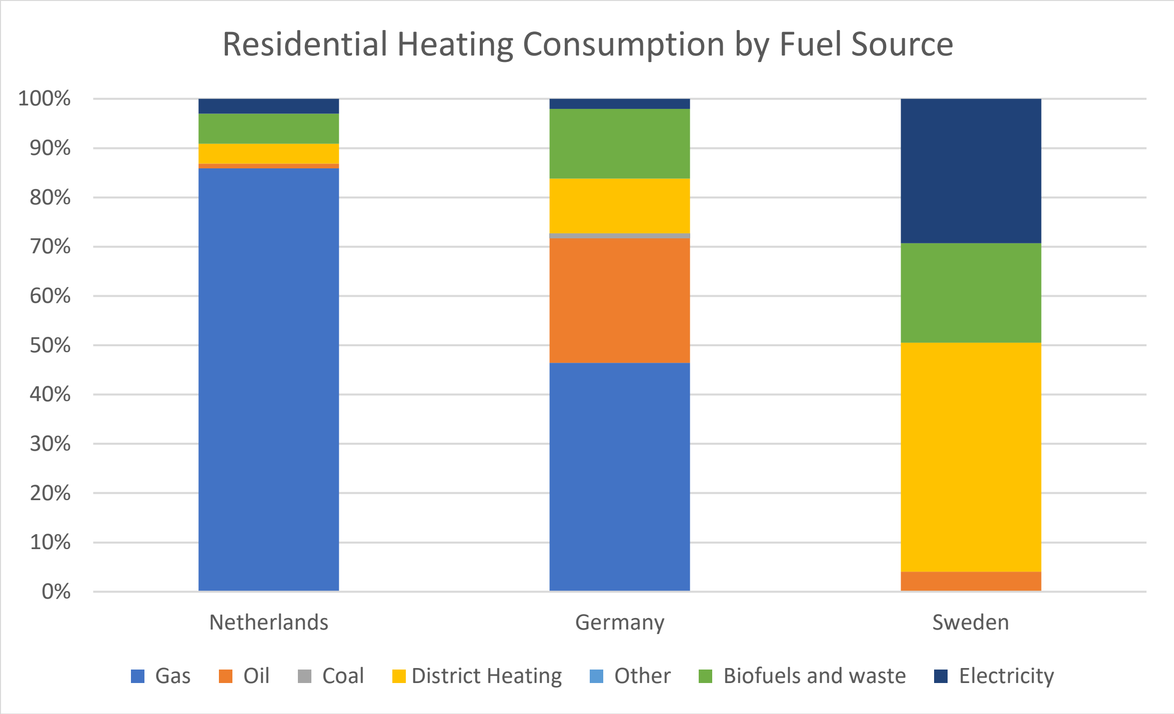

Figure 18, Residential heating consumption by fuel source for each country, 2022 (IEA, 2023)

In comparison to the total country energy consumption, it is important to highlight that in the Netherlands there is almost no oil use for heating, despite in the general country overview oil represents a big share (mostly for transport). Also, once again it becomes clear that The Netherlands and Germany are highly dependent on fossil fuels, while Sweden is mostly relying on renewable sources for residential heating.

Finally, the use of district heating was reviewed and is shown in the following graph (figure 19). The Netherlands presents the lowest share of district heating with only 6.4% (IEA, 2023), for Germany the share is 14.0% (W.E. District Heating and Cooling Solutions, 2020), while for Sweden it rises up to 58.3% (W.E. District Heating and Cooling Solutions, 2020).

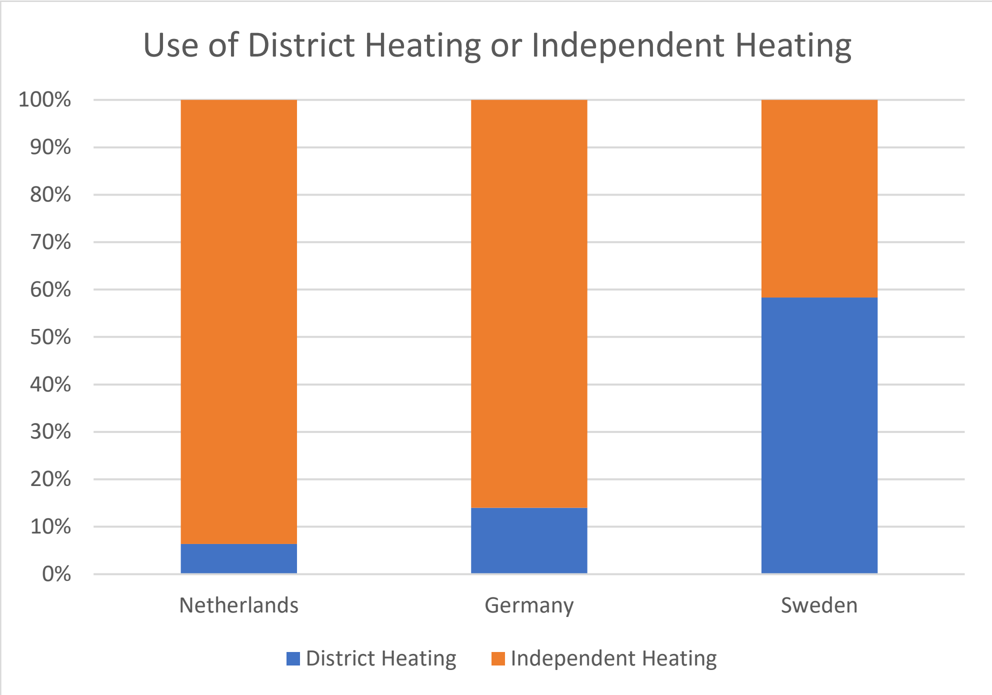

Figure 19, Use of district heating and independent heating for each country (IEA, 2023) (W.E. District Heating and Cooling Solutions, 2020)

In Sweden most cities and town have a district heating system, while in Germany and The Netherlands it is mostly related to big cities like Berlin and Amsterdam, despite this in both countries the share of district heating is expected to increase (Vattenfall, 2023) (Gessel, 2020), also including residual heat from the industry and improving system efficiency and flexibility.

4.5. Market and Prices Dependency

After reviewing the general heating scenario for each country, it is clear that the market behavior plays a key role in how the industry develops and what the users will actually adopt and what can be a popular solution, as for Sweden a lot of factors caused the wide use of heat pumps around the country, while in Germany and The Netherlands this hasn´t been the case.

To tackle this issue and have a broader overview of how the market can influence the industry towards one technology or the other the best approach found was based on (Johansson, 2021), by presenting a graph divided in 3 areas where depending on the electricity, gas and oil prices there can be a better economy with a gas boiler, an oil boiler or a heat pump.

To generate these graphs MATLAB was used and the full code can be checked in annex *Market Dependency (MatLab Code)*, nevertheless the logic behind the programing and the graphs will be presented in this section.

First the main factors for the system are define, meaning the heating capacity (set at 10kW), the efficiency for the 4 devices considered, being electric boiler (100%), gas boiler (90%), solid fuel boiler (85%) and also oil boiler for the Berlin case (85%) the COP of the selected heat pump is selected based on field data (presented in table 2), and calculated based on a linear regression .

Temp (°C)	*-20*	*-7*	*2*	*7*	*15*	*25*
COP	1.13	2.29	3.07	3.5	4.21	5.25

Table 2, heat pump COP for different ambient temperatures (ehpa, 2024)

Also, the CAPEX and OPEX for each case is defined based on data from the International Energy Agency (IEA, 2021) and presented in the table below (table 3).

Technology	*OPEX (USD/year)*			*CAPEX (USD/year)*		
	Stck	Berl	Amst	Stck	Berl	Amst
Heat Pump	270	210	270	359	750	441
Electric Boiler	150	150	150	176	176	176
Gas Boiler	190	195	190	360	340	300
Solid Fuel/ Oil Boiler	300	250	300	155	290	375

Table 3, annual CAPEX and OPEX for different heating technologies in Stockholm, Amsterdam and Berlin (IEA, 2021)

Now after defining all the characteristics for the selected devices then the heat demand was defined for each study case (Stockholm, Berlin and Amsterdam) based on data from September to May according to (ehpa, 2024), as well as the average COP.

Then the cost calculation is performed based on an assumed price variation for each energy source for a reasonable range, it will be 0 to 2 euros per kWh for electricity, the same scale per cubic meter for gas and also the same scale for solid fuel per kilogram and for heating oil per liter.

Then the cost function for each heating device is calculated based on the CAPEX, OPEX and fuel consumption multiplied by the fuel price to finally evaluate a linear regression on this data and obtain a specific cost function. It is important to mention that the cost equations are also presented in a separate graph to check the behavior for each country.

As this process is repeated for each case and each technology then it is possible to evaluate in which values two equations have the same value, which is how the limit lines are traced as well as how the intercept points are found.

Finally, the lines are plotted and the different areas are labeled, also in the graph the historical data for average price of electricity is presented per year from 2018 until 2023 to better understand the industry behavior on each country.

First the energy carrier cost graphs will be presented for Sweden (figure 20), this graph shows the cost per year for each technology as a function of the fuel price.

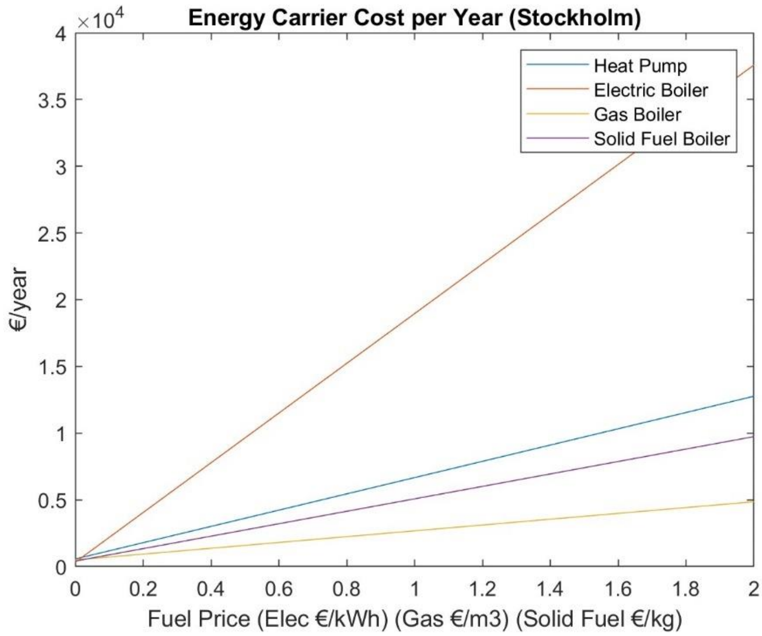

Figure 20, Energy Carrier Cost per year for different heating technologies in Stockholm

This graph should be interpreted as how the price increase for each type of fuel will influence the total annual cost of the operation of any technology.

Then, the graph representing the best economic viability based on electric boiler, gas boiler and heat pump for the Stockholm case is presented below (figure 21).

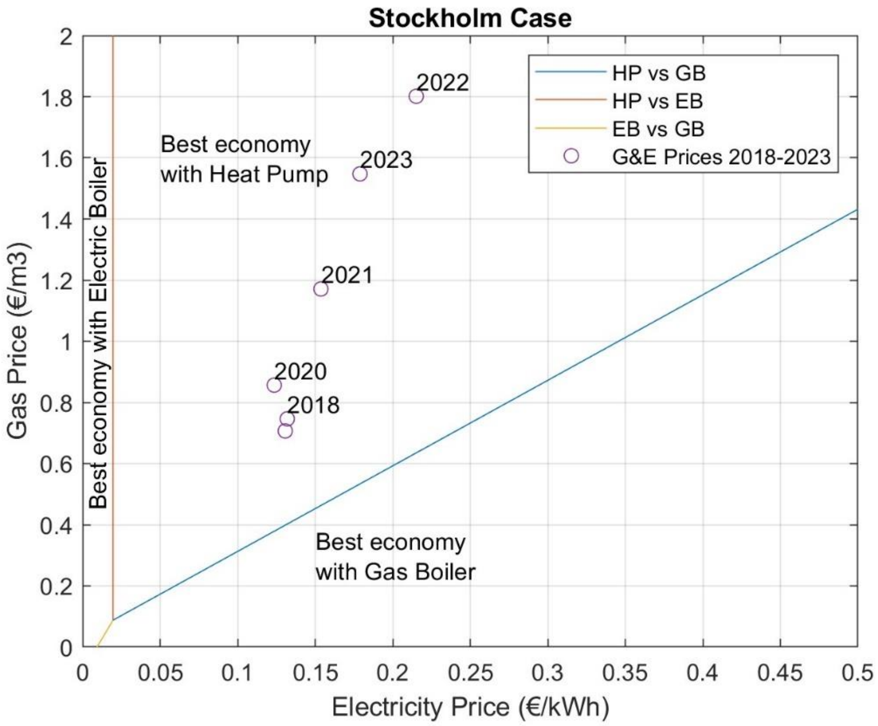

Figure 21, Economic analysis based on electricity and gas prices for Stockholm comparing electric boilers, heat pumps and gas boilers

Here we can see that for all the dots displayed the best economy is achieved with a heat pump, this behavior is promoted by low electricity prices compared to gas prices and also a reasonable capex for heat pump devices. It is important to mention that the prices for gas and electricity for all countries were taken from the Eurostat data browser according to the gas prices for household consumers data set (Eurostat, 2024) and the electricity prices for household consumers data set (Eurostat, 2024).

Now for Berlin the energy carrier cost functions are also presented, including this time the heating oil, as it has some presence in the share of residential heating in the country (figure 22).

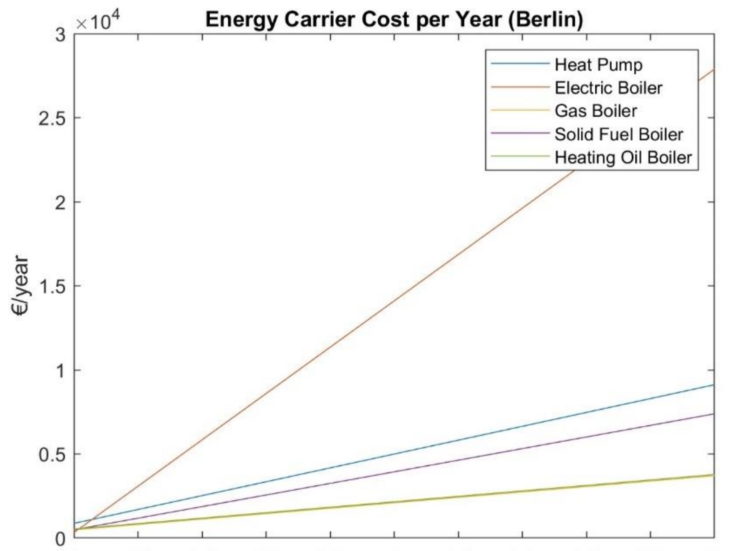

Figure 22, Energy Carrier Cost per Year for different heating technologies in Berlin

Now for the graph based on electricity and heating oil we obtain figure 23, showing that when we compare the use of an oil boiler with an electric boiler and a heat pump, considering the oil and electricity prices from 2020, 2021, 2022 and 2023, it is clear that the best economy is achieved with a heat pump.

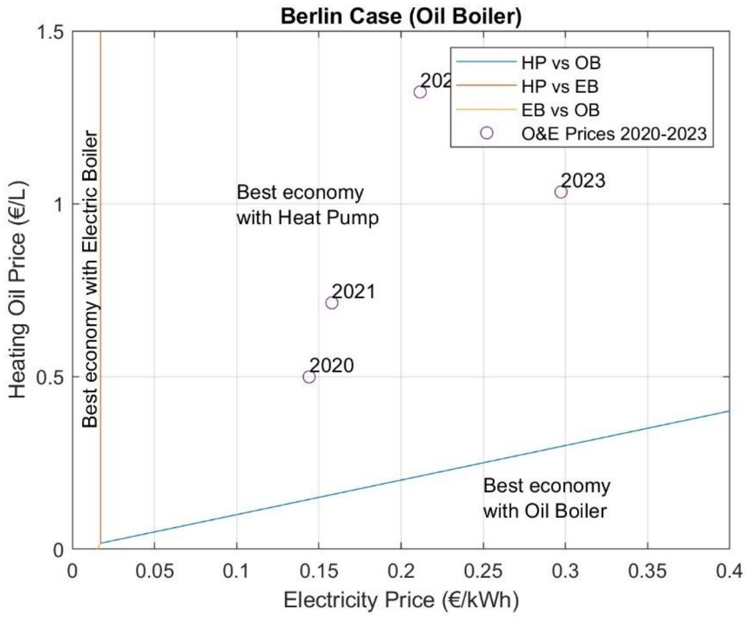

Figure 23, Economic analysis based on electricity and heating oil prices for Berlin comparing electric boilers, heat pumps and oil boilers

Nevertheless, when we evaluate the graph for the electricity and gas market the scenario is not so clear as we can see in figure 24.

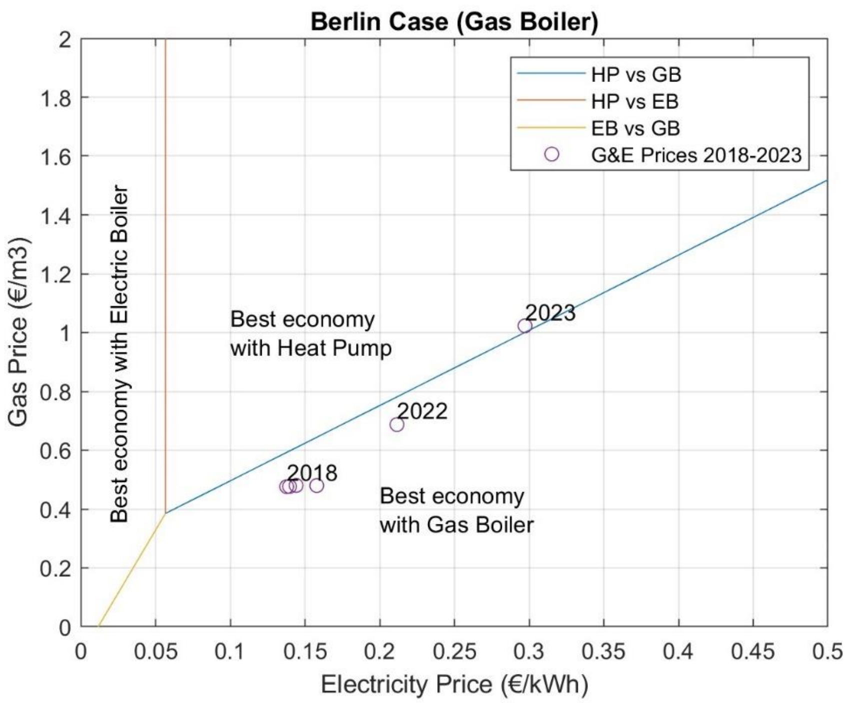

Figure 24, Economic analysis based on electricity and gas prices for Berlin comparing electric boilers, heat pumps and gas boilers

As all the dots before 2023 land below the blue line, then it means that the best economy was achieved with a gas boiler, which also partially explains why heat pumps haven't become the popular choice in the country yet. On the other hand, it is also important to note that for 2023 the dot lands above the blue line and the best economy is with a heat pump, despite the high capex, and mainly driven by high electricity prices but higher gas prices. This trend is expected to continue in the future so the balance can be shifted towards electrification and the users can make a more confident decision to change their heating systems.

Finally for Amsterdam the energy carrier cost graph is presented below (figure 25).

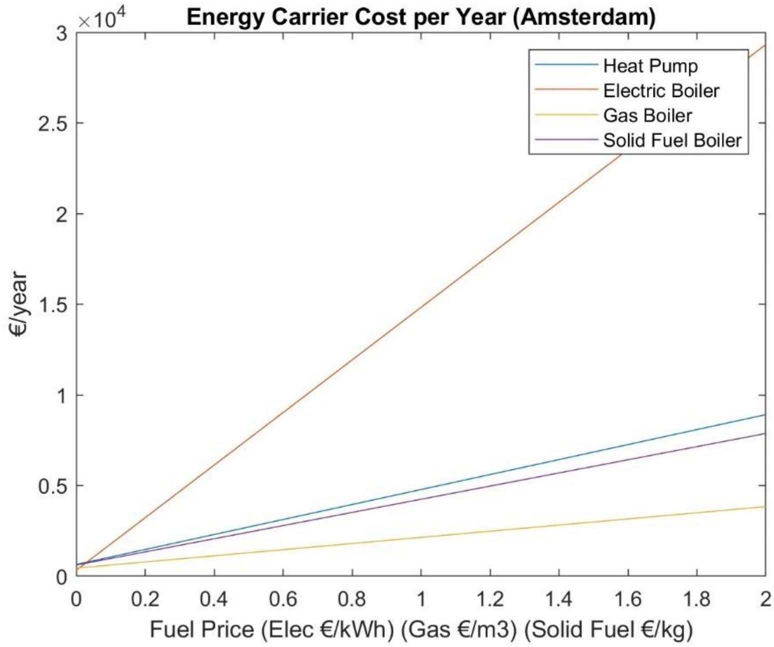

Figure 25, Energy Carrier Cost per Year for different heating technologies in Amsterdam

And for the graph considering electricity prices and gas prices we can see a similar behavior as for the Berlin case but this time with a further step to the northeast corner of the graph and getting further away from the limit defined by the blue line, then having a more promising approach to heating electrification with heat pumps. Also, it is important to note that in the Netherlands the current prices of electricity and also gas are much higher than in the other two case studies, making it more important to consider energy savings in general terms for the users (figure 26).

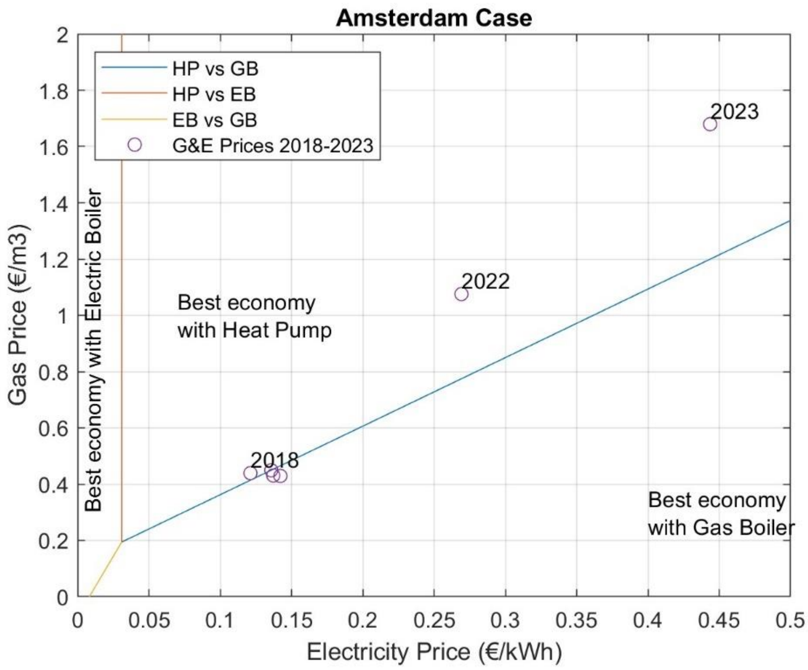

Figure 26, Economic analysis based on electricity and gas prices for Amsterdam comparing electric boilers, heat pumps and gas boilers

4.6. Representative Buildings Selection

In order to define the best representative type of buildings for each country as week as specific demand and energy consumption data the web page Tabula Web Tool was used (Tabula WebTool, 2017).

From the data base presented in the webpage the first step was to select the countries separately and review all the cases presented, in the database each building is distinguished with an specific code referring to the country, type of building (single family housing or multi-family housing) among other characteristics less relevant for this study.

The database also presents the year of construction of each building, one representative building for each timeframe was selected for each country (also separating data for SFH and MFH) and based on the number of buildings distribution for each time frame the first distinction was defined.

For Germany the distribution is presented in figure 27 (Destatis, 2021).

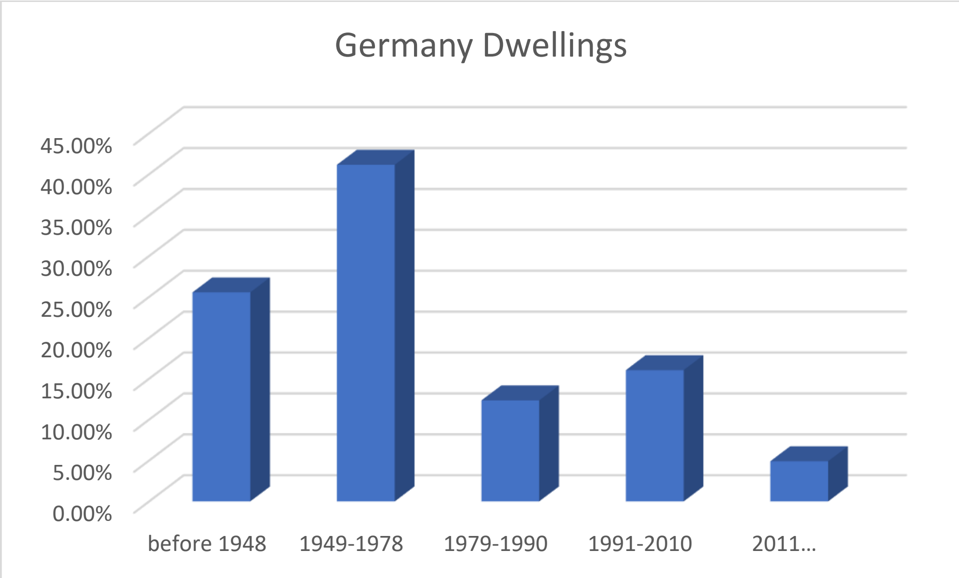

Figure 27, Dwellings year of construction distribution for Germany (Destatis, 2021)

Then for Germany the breakpoint year was 1978, then a case before 1978 (66.7% of the buildings) was selected for SFH and MFH and a case after 1979 for SFH and MFH were also selected.

For The Netherlands the distribution is presented in figure 28 (Society, 2015)

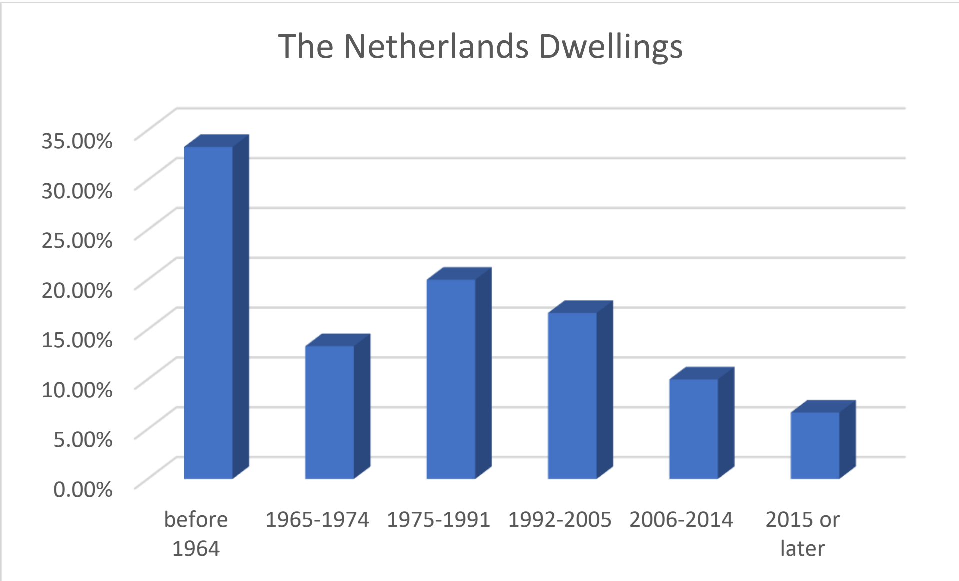

Figure 28, Dwellings year of construction distribution for The Netherlands (Society, 2015)

Then in this case the break point year was 1974 so that a distribution as close to 50-50 is achieved. The buildings before 1974 represent 46.67% of the total number of buildings in the Netherlands.

Finally, the same analysis was also made for Sweden and the numbers are presented in figure 29 (SCB, 2023).

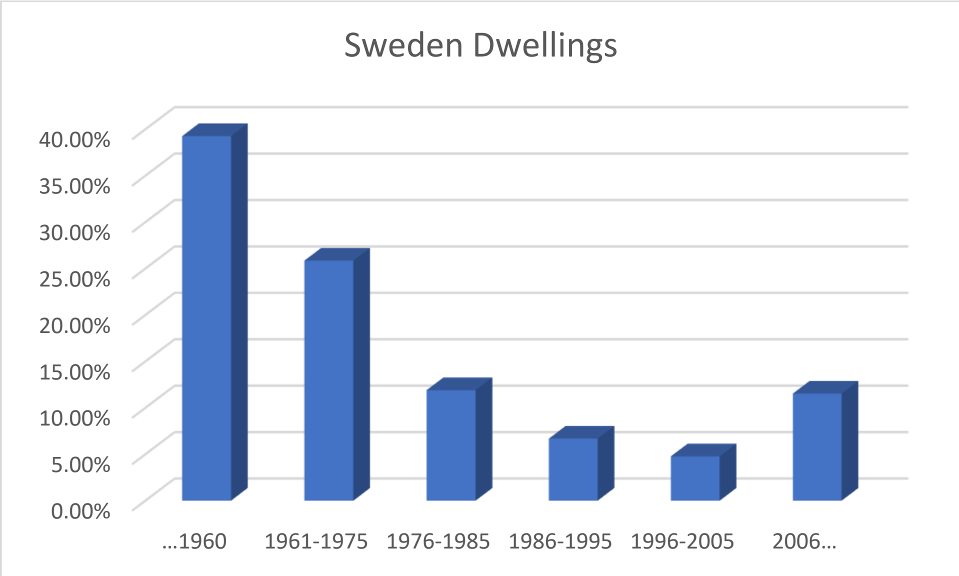

Figure 29, Dwellings year of construction distribution for Sweden (SCB, 2023)

For the Swedish case the breakpoint year is then 1975, as the buildings erected before that year represent the 65.12% of the total.

Also, additional information was used in the analysis, such as the area, volume, number of apartments, number of storeys, heat supply system and energy need are presented. Table 4 and 5 present the buildings data for Germany for SFH and MFH respectively, also the average energy need was calculated, and one specific building was selected as the base for the calculations (highlighted in bold letters).

Germany					*SFH*		
Building	Year	Area (m2)	Volume (m3)	Apartments	Storeys	Energy need (kWh/m2)	Heat Supply System
DE.N.SFH.01.GEN	...1859	219	767.58	1	2	167.3	gas central heating, poor efficiency
DE.N.SFH.02.GEN	1860-1918	142	595	1	2	164.5	gas central heating, poor efficiency
DE.N.SFH.03.GEN	1919-1948	303	1052.5	2	2	148.9	gas central heating, poor efficiency
DE.N.SFH.04.GEN	**1949-1957**	**111**	**380**	**1**	**1**	**165.3**	**gas central heating, poor efficiency**
DE.N.SFH.05.GEN	1958-1968	121	502.9	1	1	163.4	gas central heating, poor efficiency
DE.N.SFH.06.GEN	1969-1978	173	606	1	1	139.5	gas central heating, poor efficiency
DE.N.SFH.07.GEN	1979-1983	216	647	1	2	108.9	gas central heating, poor efficiency
DE.N.SFH.08.GEN	1984-1994	150	514	1	1	120.4	gas central heating, poor efficiency
DE.N.SFH.09.GEN	**1995-2001**	**122**	**427.3**	**1**	**1**	**110.5**	**gas central heating, medium efficiency**
DE.N.SFH.10.GEN	2002-2009	147	478.92	1	2	78.7	gas central heating, medium efficiency
DE.N.SFH.11.GEN	2010-2015	187	827.1	1	2	82.7	gas central heating, rather high efficiency
DE.N.SFH.12.GEN	2016…	187	827.1	1	1	70.8	gas central heating, rather high efficiency

Table 4, List of buildings and characteristics for single-family housing in Germany (Tabula WebTool, 2017)

Germany					*MFH*		
Building	Year	Area (m2)	Volume (m3)	Apartments	Storeys	Energy need (kWh/m2)	Heat Supply System
DE.N.MFH.01.GEN	...1859	677	2488	5	4	172	gas central heating, poor efficiency
DE.N.MFH.02.GEN	1860-1918	312	1360	4	4	131.5	gas central heating, poor efficiency

DE.N.MFH.03.GEN	1919-1948	385	1171	2	3	151.3	gas central heating, poor efficiency
DE.N.MFH.04.GEN	**1949-1957**	**632**	**1919.2**	**9**	**3**	**140.3**	**gas central heating, poor efficiency**
DE.N.MFH.05.GEN	1958-1968	3129	10397	32	4	115.5	gas central heating, poor efficiency
DE.N.MFH.06.GEN	1969-1978	469	1435	8	4	119.4	gas central heating, poor efficiency
DE.N.MFH.07.GEN	1979-1983	654	2040	9	3	104.8	gas central heating, poor efficiency
DE.N.MFH.08.GEN	1984-1994	778	2413	10	3	108.1	gas central heating, poor efficiency
DE.N.MFH.09.GEN	**1995-2001**	**835**	**2971.88**	**12**	**4**	**91.1**	**gas central heating, medium efficiency**
DE.N.MFH.10.GEN	2002-2009	2190	7687	19	3	58	gas central heating, medium efficiency
DE.N.MFH.11.GEN	2010-2015	1305	5371.1	17	5	73.5	gas central heating, high efficiency
DE.N.MFH.12.GEN	2016…	1305	5371.1	17	5	74.3	gas central heating, high efficiency

Table 5, List of buildings and characteristics for multi-family housing in Germany (Tabula WebTool, 2017)

The same data is presented in table 6 and 7 for the Netherlands and in table 8 and 9 for Sweden.

The Netherlands			*SFH*				
Building	Year	Area (m2)	Volume (m3)	Apartments	Storeys	Energy need (kWh/m2)	Heat Supply System
NL.N.SFH.01.GEN	…1964	143	-	1	2	166.1	Individual gas-fired boiler, condensing, for heating and DHW, mechanical ventilation with alternating current
NL.N.SFH.02.GEN	**1965-1974**	**135**	**-**	**1**	**2**	**141.1**	**Individual gas-fired boiler, condensing, for heating and DHW, mechanical ventilation with alternating current**
NL.N.SFH.03.GEN	1975-1991	135	-	1	2	103.8	Individual gas-fired boiler, condensing, for heating and DHW, mechanical ventilation with alternating current
NL.N.SFH.04.GEN	**1992-2005**	**189**	**-**	**1**	**2**	**83.2**	**Individual gas-fired boiler, condensing, for heating and DHW, mechanical ventilation with alternating current**
NL.N.SFH.05.GEN	2006-2014	186	-	1	2	68.5	Individual gas-fired boiler, condensing, for heating and DHW, mechanical ventilation with alternating current
NL.N.SFH.06.GEN	2015…	186	-	1	2	68.8	individual gas-fired low-temperature boiler, condensing, for heating and DHW, balanced ventilation with direct current

Table 6, List of buildings and characteristics for single-family housing in The Netherlands (Tabula WebTool, 2017)

The Netherlands			*MFH*				
Building	Year	Area (m2)	Volume (m3)	Apartments	Storeys	Energy need (kWh/m2)	Heat Supply System
NL.N.MFH.01.GEN	…1964	2064	-	28	4	127.8	Individual gas-fired boiler, condensing, for heating and DHW, mechanical ventilation with alternating current
NL.N.MFH.02.GEN	**1965-1974**	**4235**	**-**	**50**	**10**	**104.2**	**Individual gas-fired boiler, condensing, for heating and DHW, mechanical ventilation with alternating current**
NL.N.MFH.03.GEN	1975-1991	1540	-	20	4	91.7	Individual gas-fired boiler, condensing, for heating and DHW, mechanical ventilation with alternating current
NL.N.MFH.04.GEN	**1992-2005**	**1804**	**-**	**20**	**5**	**67**	**Individual gas-fired boiler, condensing, for heating and DHW, mechanical ventilation with alternating current**
NL.N.MFH.05.GEN	2006-2014	3032	-	27	4	56.5	Individual gas-fired boiler, condensing, for heating and DHW, mechanical ventilation with alternating current

NL.N.MFH.06.GEN	2015 …	3032	-	27	4	58.2	individual gas-fired low-temperature boiler, condensing, for heating and DHW, balanced ventilation with direct current

Table 7, List of buildings and characteristics for multi-family housing in The Netherlands (Tabula WebTool, 2017)

Sweden						*SFH*	
Building	Year	Area (m2)	Volume (m3)	Apartments	Storeys	Energy need (kWh/m2)	Heat Supply System
SE.N.SFH.01.GEN	…1960	106	380	1	1	198.6	Single family house 125m2/heating system with oil/no ventilation system
SE.N.SFH.02.GEN	**1961-1975**	**106**	**380**	**1**	**1**	**188.7**	**Single family house 125m2/heating system with oil/no ventilation system**
SE.N.SFH.03.GEN	1976-1985	106	380	1	1	165.2	Single family house 125m2/heating system with oil/no ventilation system
SE.N.SFH.04.GEN	**1986-1995**	**106**	**380**	**1**	**1**	**160.1**	**Single family house 125m2/heating system with oil/no ventilation system**
SE.N.SFH.05.GEN	1996-2005	106	380	1	1	156.1	Single family house 125m2/heating system with oil/no ventilation system
SE.N.SFH.06.GEN	2006 …	106	380	1	1	156.1	Single family house 125m2/heating system with oil/no ventilation system

Table 8, List of buildings and characteristics for single-family housing in Sweden (Tabula WebTool, 2017)

Sweden						*MFH*	
Building	Year	Area (m2)	Volume (m3)	Apartments	Storeys	Energy need (kWh/m2)	Heat Supply System
SE.N.SFH.01.GEN	…1960	1207	3500	14	3	184.6	Multi family house 1499 m2/heating system with oil/exhaust air ventilation system
SE.N.SFH.02.GEN	**1961-1975**	**1207**	**3500**	**14**	**3**	**173.8**	**Multi family house 1499 m2/heating system with oil/exhaust air ventilation system**
SE.N.SFH.03.GEN	1976-1985	1207	3500	14	3	144.5	Multi family house 1499 m2/heating system with oil/exhaust air ventilation system
SE.N.SFH.04.GEN	**1986-1995**	**1207**	**3500**	**14**	**3**	**135**	**Multi family house 1499 m2/heating system with oil/exhaust air ventilation system**
SE.N.SFH.05.GEN	1996-2005	1207	3500	14	3	134	Multi family house 1499 m2/heating system with oil/exhaust air ventilation system
SE.N.SFH.06.GEN	2006 …	1207	3500	14	3	134	Multi family house 1499 m2/heating system with oil/exhaust air ventilation system

Table 9, List of buildings and characteristics for multi-family housing in Sweden (Tabula WebTool, 2017)

From the selection then the data used for each case is presented in tables 16 and 17 presented in the results section for the techno-economic analysis.

5. Innovative Technologies for Heat Generation

Several technologies related to heating were reviewed at the beginning of the project, not just for heat generation but also for storage, control systems, heat distribution among other trying to answer the one of the initial questions of the study "what would be the next big thing in heating?".

In the following chapter the investigated technologies will be described, and a selection process will be explained on how the final 22 final systems were selected.

The main source of information was the ETP clean energy technology guide developed by the international energy agency (IEA, 2023) which consists of a list of 550 innovative technologies, classified by sector (buildings, industry, transport, CO2 management and energy transformation) and also by technology readiness level. By using the category buildings and then filtering by heating and cooling technologies we obtain a total of 64 technologies that can be relevant for the study. The complete list is presented in table 10.

Technology	*TRL (2023)*	*Nature*
Wood-burning stove	11	Heat generation
Hot water tank	11	Heat storage
Heat exchanger	10	Heat transport
Air-source heat pump using heat recovery	10	Heat generation

State-of-the-art air-to-air heat pump	10	Heat generation
Vapor compression packaged air conditioners	10	Heat generation
Vapor compression split air conditioners	10	Heat generation
State-of-the-art air-to-water heat pump	10	Heat generation
Shallow ground-source heat pump	10	Heat generation
Pellet burning stove and boiler	10	Heat generation
Programmable thermostat	9	Heat infrastructure
Hydrogen boiler	9	Heat generation,H2 use
Fuel cell micro-CHP using polymer electrolyte membrane	9	Heat generation,H2 use
Fuel cell micro-CHP using solid oxide materials	9	Heat generation,H2 use
State-of-the-art evaporative technology	9	Heat generation
Central inverter heat pump	9	Heat generation
Central heat pump water heaters	9	Heat generation
Natural refrigerant heat pump water heaters	9	Heat generation
Hybrid heat pump	9	Heat generation
Synthetic methane heat pump	9	Heat generation,H2 use
High vacuum flat plate collectors heat pump	9	Heat generation
Absorption heat pump (thermally driven)	9	Heat generation
Adsorption heat pump (thermally driven)	9	Heat generation
Standalone liquid or solid desiccant cooling	9	Heat generation
Trigeneration	9	Heat generation
Solid-liquid aqueous salt solutions thermal storage	9	Heat storage
Solid-liquid ice storage	9	Heat storage
Chilled water storage	9	Heat storage
Aquifer thermal energy storage (ATES)	9	Heat storage
Borehole thermal energy storage (BTES)	9	Heat storage
Proportional hydraulic control	8	Heat transport
Water heating heat pump booster	8	Heat generation
Cold climate air-source heat pump	8	Heat generation
Combined solar PV and heat pump	8	Heat generation
Inclined or deep horizontal wells heat pump	8	Heat generation
Flat panels solar thermal heat pump	8	Heat generation
Combined latent and sensible storage system	8	Heat storage
Liquid-gaseous thermal storage	8	Heat storage
Solid-liquid fatty acids thermal storage	8	Heat storage
Solid-liquid low temperature heat	8	Heat storage
Solid-liquid salt thermal storage	8	Heat storage
Solid-liquid salt hydrates and paraffins thermal storage	8	Heat storage
Solid-liquid sugar alcohols thermal storage	8	Heat storage
Solid-solid thermal storage	8	Heat storage
Vacuum-insulated high-temperature water tank	8	Heat storage
Active control systems for heating and cooling	7	Heat infrastructure
Membrane heat pump	7	Heat generation
High-temperature heat pump	7	Heat generation
Hydrogen-enriched natural gas heat pump	7	Heat generation,H2 use
Metal hydride heat pump	7	Heat generation,H2 use

Vuilleumier heat pump	7	Heat generation
Thermo-acoustic heat pump	6	Heat generation
Magnetocaloric cooling	5	Heat generation
Evaporative cooling coupled with permeable membrane	4	Heat generation
Liquid or solid desiccant evaporative cooling system	4	Heat generation
Integrated heat pump with storage for heating and cooling	4	Heat generation
Barocaloric cooling	4	Heat generation
Elastocaloric cooling	4	Heat generation
Electrocaloric cooling	4	Heat generation
Active latent heat storage	4	Heat storage
Shape-stabilized phase change material (ss-PCM)	4	Heat storage
Thermo-chemical storage	4	Heat storage
Integrated heat pump with storage for cooling	3	Heat generation
Quad-generation	3	Heat generation

Table 10, Initial list of innovative Technologies according to (IEA, 2023)

From this list, the technologies related to cooling were removed as well as the storage technologies, the control technologies, and the heat distribution technologies, so that only the heat generation devices were left, leaving a total of 22 presented in table 11, this technologies are also classified based on their TRL, considering that the first 5 have a TRL of 10 meaning that they are mature technologies and they have reached proof of stability then this technologies will be used as reference and comparison point.

Technology	*TRL 2023*
Gas boiler	10
Oil boiler	10
Electric boiler	10
Air to air heat pump	10
Ground source heat pump	10
Hydrogen boiler	9
Fuel cell micro-CHP using polymer electrolyte membrane	9
Fuel cell micro-CHP using solid oxide materials	9
Central inverter heat pump	9
Natural refrigerant heat pump water heaters	9
Hybrid heat pump	9
Synthetic methane heat pump	9
High vacuum flat plate collectors heat pump	9
Absorption heat pump (thermally driven)	9
Adsorption heat pump (thermally driven)	9
Cold climate air-source heat pump	8
Combined solar PV and heat pump	8
High-temperature heat pump	7
Hydrogen-enriched natural gas heat pump	7
Metal hydride heat pump	7
Vuilleumier heat pump	7
Thermo-acoustic heat pump	6

Table 11, Final list of the technologies included in the analysis

5.1. Infrared Heating

An infrared heater as it names suggest works based on the principle of infrared radiation to deliver heat directly to the objects or users without heating the surrounding air, it is the same type of heat as the sun generates. It works as a heat generator and also as a radiator, then the cost should be compared with the complete system (not just the heat source, but source plus radiator) (Industrial Quick Search, 2024).

There are 3 types of infrared heaters, quartz infrared heaters which have short wave lengths to provide higher temperatures, ceramic infrared heaters which are the cheapest option, usually used to heat work areas (this will be the technology used in residential heating as well), and metal sheathed infrared heaters which are the most durable with temperatures up to 1093 °C, can also be used for submersible heating applications.

This technology presents a series of advantages like high efficiency because of no heating for the surroundings, instant heat capacity and silent operation. But on the other hand it also presents some disadvantages as having a hot core that can be dangerous if touched and in some cases also when standing at close distances for a prolongated exposition, also exposition to vision for too long can cause sight problems and the maintenance to the core and reflector can also be an issue.

The efficiency of these devices depends highly on the reflector, they must have high reflectivity and absorb as low radiation as possible. Nevertheless, it is difficult to quantify and compare this parameter with other technologies as the theoretical efficiency for turning electricity into heat will be 100% (just like an electric boiler), but the energy requirement should be lower as in theory there is no energy wasted into heating the air. This is exactly the reason why this technology was not considered in the analysis as the comparison point was not easy to quantify unless applied on a specified building and with the possibility to do more complex measures.

One way to consider and quantify this factor is as presented in (Brown, 2015), as they measured the radiant heat flux emulating a spherical surface and a vertical 50 cm x 50 cm panel using a robotic arm and a radiant heat flux sensor. Also this in conjunction with other measurement methodologies can be translated into thermal comfort, that is more related to the temperature difference between the indoor temperature and the ambient temperature as well as the temperature variation during the whole day and how the user perceives it (Corsten, 2021).

This technology uses infrared waves to transfer heat, with a wave frequency between 780 nm and 10 microns. Shorter wavelengths and higher frequencies are associated with high energy. The heat source usually goes from hundreds of Celsius degrees to up to 3600 °C (Industrial Quick Search, 2024).

By using infrared heaters there is an extra capability of rapidly raise temperature of objects or materials using a minimal amount of energy at lower cost, making it useful for industrial purposes as it can heat a surface rapidly, evenly and homogeneously, plus is a flameless heating method.

5.2. Active Control Systems for Heating and Cooling

Regarding control systems, two different approaches were researched. The first one being the use of private heat pumps and heat storage as virtual power plants to improve grid flexibility, while the second one is based on smart thermostats for a more efficient operation and energy use.

Regarding the second type of approach, Google nest thermostat seem to be the best one in the market so far. This device can learn from habits and it´s able to tweak the temperature based on daily routines and phone location, also can monitor the energy quality and probably work with variable tariff (Google Store, 2024).

A case study presents a RC systems (resistance / capacitor) to simulate thermal systems using a MatLab-Trnsys simulation where the optimization parameter was regulated based on electricity prices, solar radiation and room occupancy (Duman, 2021).

Specifically, they use and optimization model based on branch and bound intlinprog in MatLab to define the day ahead algorithm. The objective is to minimize the daily electricity cost of the house.

As a side note they considered as well the battery degradation cost associated to its use and it is a decision parameter for the model (¨V2G and B2G are considered if only the benefit of selling energy to the grid is higher than the battery degradation cost¨) (Duman, 2021).

This technology is shortly assessed in this section as a background review but will not be considered in the analysis as it does not represent a heat generation technology, but a control strategy that can be coupled with several heat generation technologies.

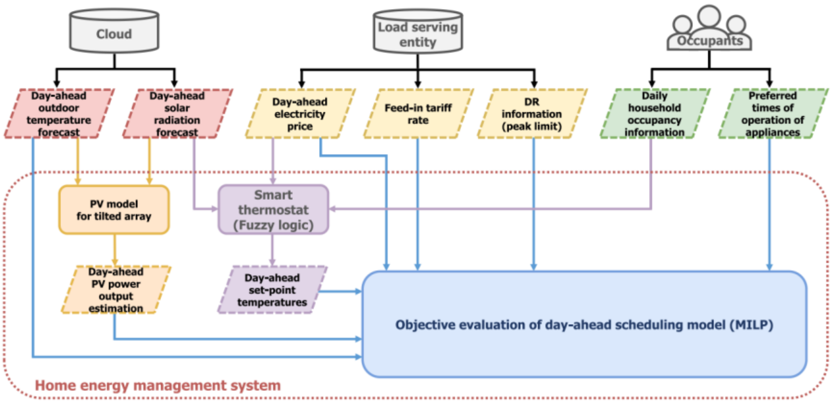

Figure 30, Workflow diagram for the home energy management system (Duman, 2021)

5.3. Evaporative Technologies

This type of devices are typically used for cooling, as they use water evaporation to cool the air, hence they need to work in areas with low humidity. It is based on a principle that has been used for ages and is a fairly simple and low energy intensive device.

Basically, the device removes the humidity from the air to cool it down, by circulating external ambient (hot) air through a wet membrane and extracting heat energy from the air resulting in water evaporation (Seeley International, 2023).

Nevertheless, as it is a technology for cooling it will not be considered in the technoeconomic analysis.

5.4. Hydrogen Boiler

This technology works by burning pure hydrogen to obtain heat, it is very similar to a gas boiler, and even most modern natural gas boilers can have a "hydrogen ready" label meaning that they can work with a blend of up to 20% hydrogen and 80% natural gas (Boilerguide, 2023). Nevertheless pure hydrogen boilers are not fully developed yet as hydrogen is not highly available in most places, and when it is available is usually too expensive to be competitive.

Sometimes hydrogen boilers can also refer to a technology using natural gas as the main fuel, and then through a steam reformer remove the carbon and immediately use the hydrogen to generate electricity in a fuel cell and heat as a product of the reaction as well as water (hot water). This case is supposed to be more efficient because of the implementation of a combined heat and power approach, but still is not fully economically viable due to hydrogen prices.

For the analysis this technology was assumed as a boiler burning hydrogen to obtain heat, having an average efficiency of 82% considering hydrogen production and combustion (Mitterrutzner, 2023), and assuming a hydrogen LHV of 33.3 kWh/kg (The Engineering ToolBox, 2003). There are a few companies trying to commercialize this technology, but due to the high investment cost and the operational cost for the fuel price it is not economically viable, also there is the problem of hydrogen storage in case it is needed.

5.5. Fuel Cell Micro-CHP Using Proton Exchange Membrane (PEM)

A proton exchange membrane is a type of electrolyzer that uses a solid polymeric material as the electrolyte layer, usually Nafion. The working principle is using the Nafion membrane containing an ionic side with hydrogen positive ions with good mobility.

The main reaction happening inside the cell is presented in equation 1, as hydrogen enters through the anode and oxygen through the cathode, then a hydrogen molecule releases 2 electrons generating electricity and moving the hydrogen through the electrolyte membrane, arriving at the cathode and mixing with oxygen to generate water as a waste product (Santarelli, 2023).

$$H_2 + \frac{1}{2}\,O_2 = H_2O \quad eq.1$$

This reaction presents an exothermic process having the need for a cooling system, then is this additional heat generated that is considered as a heat source for the micro-CHP.

For the analysis then two type of efficiencies will be considered, a thermal efficiency for heat recovery corresponding to 16% and an electric efficiency assumed as 80% (Roest, 2023). It is important to consider that the low heat recovery efficiency related to the PEM fuel cell is also partially given by the low operation temperatures for the cell, which is limited by the need to permanently permeate the membrane, then avoiding evaporation is advised.

5.6. Fuel Cell Micro-CHP Using Solid Oxide Materials (SOFC)

Solid oxide fuel cells are based on a different type of principle, but still is based on the moving of electrons and ions, in this case the electrolyte is a ceramic material, nowadays usually Ytria-Stabilized Zirconia (YSZ). The membrane possesses oxygen holes or vacancies where O^{2-} ions are conducted moving from cathode to anode. The same as for the PEM fuel cell hydrogen enters at the anode and air is present in the cathode. The hydrogen molecules are dissociated releasing 2 electrons and flowing from anode to cathode, then the electrons combined to the oxygen molecules form O^{2-} ions that move through the membrane arriving at the anode and mixing with hydrogen to once again form water as a biproduct.

In this case the process generates a heat sink, but as the total system requires heat management to stay inside the optimal operation temperature and due to the high temperatures used in the cycle it is possible to have heat recovery. The typical operation temperatures inside the cell are around 700 °C, the whole process can be also coupled with an after burner for heat generation (Santarelli, Polygeneration Class Notes 06/11/23, 2023). For this case the assumed heat recovery efficiency is 32% and the electric efficiency is 60% (Dodds, 2015).

5.7. Central Inverter Heat Pump

Different type of compressor able to manage the capacity based on control systems to have a bit more efficient operation as well as energy savings (in most cases), nevertheless it is more focused on improving thermal comfort as it can handle subtle temperature changes and constant adjustments. This also causes this device to be more expensive than two stage devices (ABID, 2021).

For the techno-economic analysis the data assumed was based on the case study (ABID, 2021), where the COP presented was estimated based on experimental data for a 3kW capacity heat pump according to the ambient temperature between -2°C and 15°C.

5.8. Natural Refrigerant Heat Pump Water Heaters

Very similar to the traditional heat pumps with the key difference being the use of natural refrigerants that can decrease the price and improve COP (Zendehboudi, 2021). In the case study 3 heat pumps were analyzed R744-ice, R290-ice and E-290 dual source that correspond to propane ice, CO_2 ice and propane dual source.

It is important to mention that for this study the inclusion of domestic hot water was included, then the inlet and outlet temperature were measured as well as the mass flow rates for each case, as well as the electrical power of the compressor. Once again, the values for COP were taken in relation to the ambient temperature to estimate the behavior of the devices in field conditions using a linear regression.

5.9. Hybrid Heat Pump

Using different fuels or electricity for a resistance in order to fill the heating demand in high peak situations where the heat pump is not working at peak efficiency. The two systems are coupled hydraulically to supply heat to the central system (ECN, TNO, 2019). There is also a variation using district heating hot water as heat source. The most common example is the combination of a traditional heat pump with a natural gas boiler (that will be the case assumed in the analysis).

They also increase system flexibility and provide a softer transition before full heat electrification, nevertheless a good control algorithm is required to ensure smoother operation and cost reduction (IEA, 2022). For the analysis the main assumption is based on the use of natural gas heating when the heat pump COP is below the acceptable value, in this case it can between 10% and 20% of the heating hours according to average daily temperatures corresponding to the colder winter days, this percentages were also backed up by (ECN, TNO, 2019), where the proportion of energy supplied is around 25% gas boiler and 75% from the heat pump itself.

5.10. Synthetic Methane Heat Pump

Is a specific type of adsorption heat pump, an adsorption heat pump uses the heat of combustion from any fuel to drive the heat pump cycle, this type of devices are usually coupled with an activated carbon filter to avoid any pollutants.

Fuel consumption is expected to decrease from 30% to 40% compared to traditional natural gas boilers, as also efficiency increases with higher methane content, according to (Europian Comission, 2017), natural gas with high content of methane will enable better rates of hydrogen to carbon in the fuel allowing for higher efficiencies.

In the analysis the data used was also based on this same report (Europian Comission, 2017), presenting an efficiency of between 107-109% based on lower heating value.

5.11. High Vacuum Flat Plate Collectors Heat Pump / Flat Pannel Solar Thermal

This approach consist on combining heat pumps with solar collectors, usually the higher benefits can be achieved when using the solar collector for hot water supply, as it is where the heat pump will have the lowest performance due to the temperature gap. The solar thermal collector can also be connected to the heat pump inlet in order to have higher input temperatures and be able to also deliver higher output temperatures.

There are several possible configurations for the system and depending on the defined control strategy and the weather conditions better performance can be achieved, mostly including the use of a buffer tank or even combined with ground source heat pumps to regenerate the heat storage (Europian Comission, 2017).

In the report by the European commission a study is mentioned where 87 heat pump systems were evaluated, with 14 of them being assisted by solar thermal collectors, leading to an increase in the SPF of between 10% and 20%, hence in the analysis a factor of additional 15% will be considered with reference to a traditional heat pump (Europian Comission, 2017).

5.12. Absorption Heat Pump (Thermally Driven)

Direct fired absorption heat pumps are thermally driven heat pumps that use gas or other fuels as the drive energy for the absorption process, the gas can also be used as a heat source input for the device using a burner, meaning that the process can be direct and in-direct fired (Europian Comission, 2017).

The advantages of this type of heat pumps is that they can easily achieve higher temperatures being able to deliver water at above 55°C, but it is important to consider that as expected the higher the output temperature the lower the efficiency of the device. Absorption heat pumps can also work with different fuels from natural gas to biogas among other and several mixture combinations of them.

The main working principle is presented in figure 31 (Europian Comission, 2017), where “ammonia is evaporated by the free energy flowing to the absorber, and mixing with water, then heat is generated and transferred from the absorber to the heating system. The ammonia-water solution is pumped at increased pressure to the generator where heat is added through for example a gas burner, finally the ammonia vapor formed in the generator flows to the condenser, where it is condensed, and energy is transferred to the heating system.” (Europian Comission, 2017).

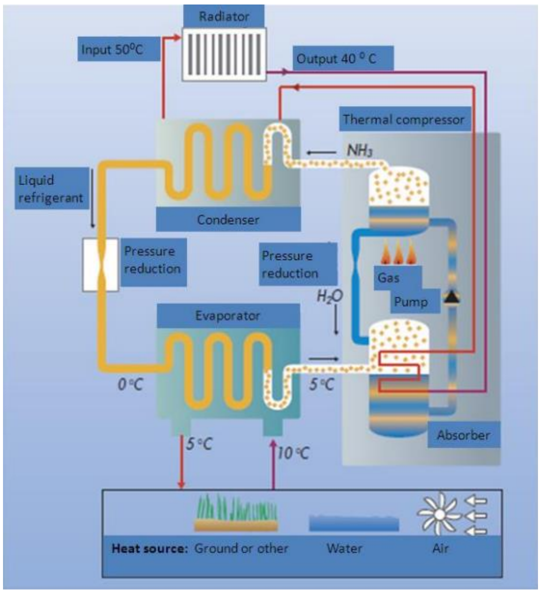

Figure 31, Absorption heat pump components and flows diagram (Europian Comission, 2017)

For the techno-economic analysis and also according to (Europian Comission, 2017), a typical efficiency for the device will be of approximately 170% which can be considered as a low value for a heat pump, but it is important to consider that the this efficiency is considered as fuel efficiency based on the primary energy consumption factor, then it seems like a better alternative than a gas boiler in terms of performance.

5.13. Adsorption Heat Pump (Thermally Driven)

Another type of thermally driven heat pumps using natural gas or other fuels depending on availability to produce heat. The adsorption process is mostly based on using water as refrigerant and absorbing ambient heat in form of vapor which is adsorbed on the surface of a solid material like active carbon or silica gel (Europian Comission, 2017). The process is complete by the condensation of the water vapor in the heat exchanger releasing heat to the system.

A considerable limitation for these devices is that the current adsorption heat pumps only can work with energy sources higher than 2°C, then coupling this technology with a ground source borehole or a flat plate collector can be beneficial and sometimes even necessary.

For the techno-economic analysis a constant COP of 1.45 will be assumed for the energy consumption calculations (Europian Comission, 2017).

5.14. Cold Climate Air-Source Heat Pump

These devices are a variation of regular heat pumps but implementing certain improvements in the compressor technologies to be able to provide adequate heating in very cold weather, optimizing the energy consumption and improving thermal comfort. They implement improvements in operation using an inverter and flash injection as a boost. Also, the inclusion of new types of coolant, presenting fluids with lower boiling point to cope with the weather conditions as well as reducing ambient air flow rates (Wu, 2022).

The main withdraw for this technology is that they are more expensive than traditional heat pumps as they need better performance, and also the installation requires additional measurements to ensure the optimal operation, this combined with a lack of expertise in this type of installations causes the popularity and adoption of cold climate air source heat pumps to decrease, then they should also be correctly sized in order to present a better economic scenario than a traditional heat pump and justify the additional investment with the performance improvement in low temperature conditions (Wu, 2022).

The estimated COP is based on the case study (Ramaraj, 2023), where in field performance of variable capacity air source heat pumps was assessed in cold climates by in field testing. A total of 13 central heat pump systems for single residential buildings were studied and located in cold climate for a full winter season. All the cases are presented separately, then the data was selected for a representative case based on the system capacity (20kW) and the design temperature (around -10°C) (Ramaraj, 2023).

The COP values were taken from figure 32.

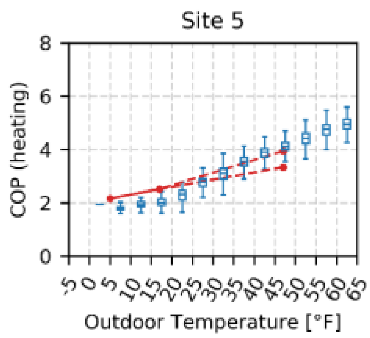

Figure 32, COP values as a function of ambient temperature for site 5 validated on (Ramaraj, 2023)

5.15. Combined Solar PV and Heat Pump

Using photovoltaic panels to harvest electricity and heat at the same time and coupling that with a heat pump shows better system performance and economic advantages for the user (depending on the market prices).

A report by Mitterrutzner (Mitterrutzner, Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, 2023), highlights the market and potential of uncovered PVT and ground source heat pumps. Also, integration of undersized horizontal ground heat exchangers and PVT, while also mentioning how the estimated COP of PV driven heat pumps is considerably high in most case scenarios as can be seen in figure 33.

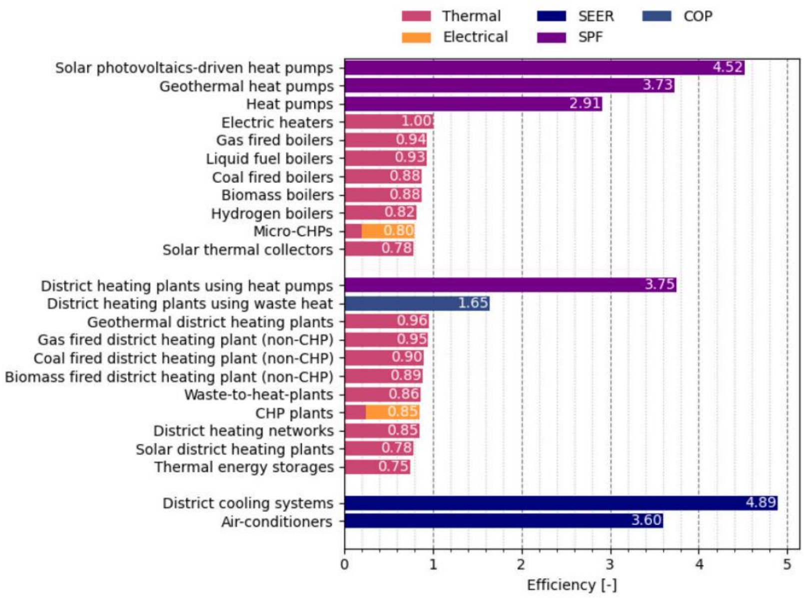

Figure 33, Average efficiency of different heating technologies (Mitterrutzner, Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, 2023)

Another report on a techno-economic analysis for an Austrian case study presents specific numbers and results for a combined system in residential buildings. The methodology used was to analyze the system performance based on energy-related and environmental KPIs. The main indicators were the seasonal performance factor and the CO2 emissions.

The analysis was based on simulations using TRNSYS, two different systems were assessed, one with a ground source heat pump and one with an air to water heat pump system as can be seen in figure 34 (Schreurs, 2021).

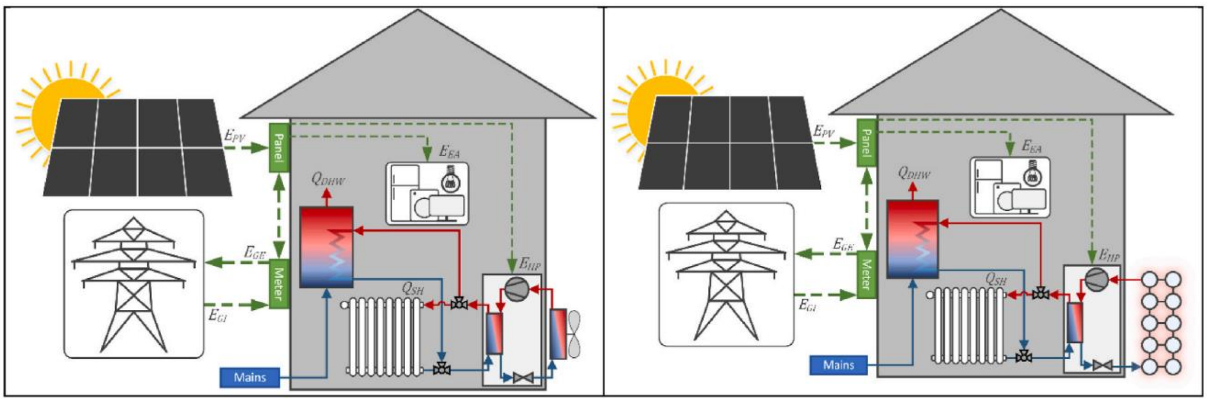

Figure 34, System diagram for AWHP (left) + PV and GSHP + PV (right) (Schreurs, 2021)

The study showed that compared to a gas boiler the implementation of a combined system can reduce the carbon emissions by almost half, and the NPV evaluated, taking into account the current subsidies, using a GSHP and PV can present an IRR of around 9%, while for the combination of AWHP and PV the IRR will be around 7.64%.

For this system it becomes relevant to consider the subsidies and regulations based on PV. Historically the EU and in general European countries had found ways to promote the use of solar panels, for example the EU Solar Energy Strategy mentions “legally binding EU solar rooftop obligation to ensure accelerated installation of solar panels on buildings" (Widuto, 2024). This initiative also aims to create expertise and jobs around the residential solar panel industry, and according to the same source is expected to be compulsory for all new public and commercial buildings with useful floor area larger than 250 m^2 by 2026, all existing public and commercial buildings with useful floor area larger than 250 m2 by 2027, and all new residential buildings by 2029 (Widuto, 2024)**.**

5.16. High Temperature Heat Pump

High temperature heat pumps are based on similar technology as a traditional heat pump but depending on the model some of them use a "cascade" cycle to increase the output temperature (around 60°C to 80°C) based on two or three different thermodynamic cycles with different types of working fluids or just adopting more efficient compressors and superior refrigerants (R290 or R32). They are attractive for some users as they can be a direct replacement for a gas boiler without the need to change the radiators or implement ground heating (as can be the case with other types of heat pumps). (Jackman, 2024).

Nevertheless, the main withdraw for this technology is that is more expensive than traditional heat pumps, the difference can be between 2 or even 4 times more. Also depending on the electricity price and due to the high energy requirements, it have a high operational expenditure value, despite having similar efficiencies as traditional heat pumps but being more energy intensive as the temperature delta is broader. They are also heavier than regular heat pumps which can increase installation costs (Jackman, 2024).

A field research based on high temperature heat pumps in combination with thermal energy storage studied the alternative to replace a gas boiler directly without any modifications to controllers or radiators in the house and including a 600L thermal storage water tank (Shah, 2018). Four modes of operation were analyzed as shown in figure 35, direct mode, storage mode, charging and discharging.

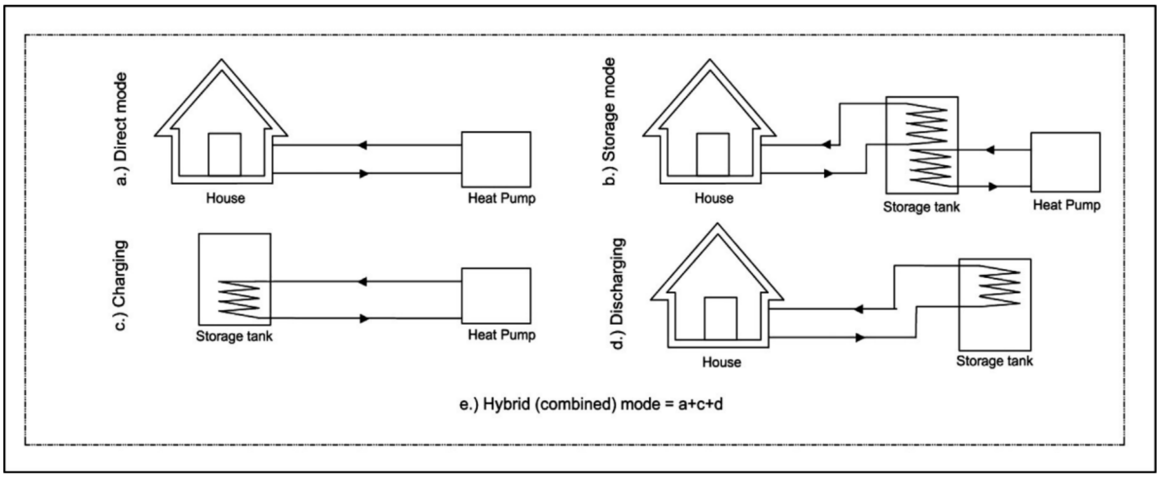

Figure 35, HTHP and TES operation mode for the field trial considered on (Shah, 2018)

The COP was evaluated in terms of the ambient temperature as can be seen in figure 36, showing an average COP of around 2.2 during the whole year variating from around 1.6 up to 2.6.

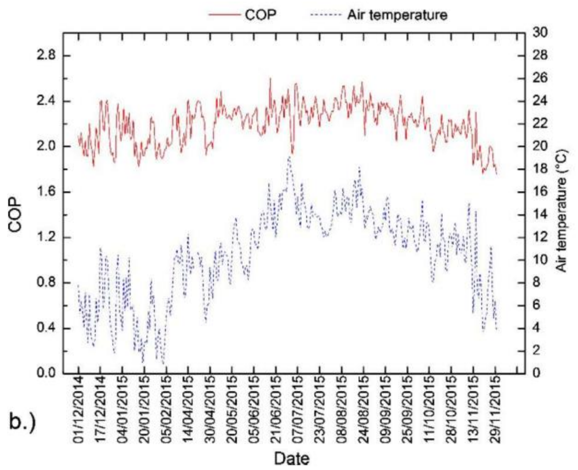

Figure 36, HTHP performance in direct mode as a COP variation in relation to ambient temperature (Shah, 2018)

Now the cost of operation can be high depending on the case, but for this particular study it was obtained that only for a COP of around 3 there will be representative savings when compared to a gas boiler, then, according to the device and the conditions used in the case study it will not be profitable to install a high temperature heat pump. Nevertheless, we should consider that the study is from 2018, then by expected technology improvement, the performance of the device as should increase and then it might be more economically viable (Shah, 2018).

5.17. Hydrogen Enriched Natural Gas Heat Pump

It is based also on thermally driven heat pumps, in this case specifically and based on the study (Sforzini, 2020), an adsorption heat pump was analyzed when using a blend of natura gas and hydrogen as fuel. This study was based on a MatLab Simulink model.

The characteristics of the technology are identical as the explained before for adsorption heat pumps, nevertheless the innovative part is about the hydrogen enriched gas. The conclusion of the study is that from an energy point of view the hydrogen blending doesn't represent a huge difference in the machine performance also due to the heat recovery architecture of the tested device not being able to use the latent heat by condensing out the exhaust gas water content (Sforzini, 2020).

For the analysis the same efficiency is assumed as for an adsorption heat pump with the difference of considering the blend of hydrogen into the natural gas changing the price as well as the low heating value (Europian Comission, 2017). Also, according to (Sforzini, 2020) a blend of 10% hydrogen is a reasonable assumption, then it was the taken value for the analysis.

This kind of device makes sense as a transition step between a gas boiler and a fully electric heat pump, also considering that including a hydrogen blend in the current natural gas network is being studied as a possibility in several countries.

5.18. Metal Hydrate Heat Pump

The technology is still very new and therefore it presents a series of assumptions related to perform the analysis, as it is not fully commercial yet. Also, it is important to mention that there are two ways to have a metal hydride heat pump, one is by using the metal hydrate cycle to provide heat to the heat pump itself and the other is by using a compressor to generate heat from the cycle (the study of the techno-economic analysis uses metal hydride as a storage material, then the values should be handled with care as the new technology is supposed to be for a non-mechanical heat pump).

According to (Krane, 2022), where the use of metal hydrate storage materials was analyzed in conjunction with a heat pump, the savings were not representative enough to justify the additional investment, as the payback time was around 35 years for a typical residential building. Also the prices of the materials were corroborated using (Krane, 2022), as well as the storage capacity and the specific energy density were corroborated by the information presented on (Malleswararao, 2022).

Nowadays the main issue with this approach is the high cost of the materials and also the range of operation, as it is difficult to find materials that perform well in a broad range of temperatures suitable for residential heating.

5.19. Vuilleumier Heat Pump

This kind of technology is also very new and has a TRL of 7, meaning that is in a prototype stage, able to operate at expected conditions, it is based on the concept of thermally driven heat pumps. The study (Luo, 2022) uses a simulation software called SAGE to validate the COP of the device and the heating capacity, also for cold weather environments.

This type of heat pump, as its name suggests, is based on the Vuilleumier cycle, that is essentially a Stirling engine with coupling of working fluid as shown in figure 37 (Luo, 2022).

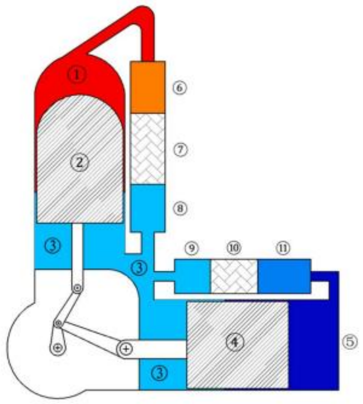

Figure 37, Schematic diagram of Vuilleumier heat pump (Luo, 2022)

The numbered components on the diagram correspond to two expansion chambers ((1) Hot and (5) Cold), one compression chamber (3), separated by two displacer (2 and 4), a hot heat exchanger (6), a cold heat exchanger (11), two regenerators (7 and 10) and two warm heat exchangers (8 and 9). The working principle is also described in the paper as “when the hot and cold displacers move, the working fluid is moved by the displacers among the three chambers. Then, heat is absorbed from the heat exchangers adjacent to expansion chamber and rejected to the heat exchangers adjacent to compression chambers.” (Luo, 2022).

This type of cycle provides and advantage as the absorbed heat in the cold heat exchanger comes from the ambient, then the heat rejected is more than the driven heat absorbed, providing potential energy savings when compared to traditional boilers.

The study is mostly focused on specific design variations to increase the device performance, nevertheless as a final note they mention that the COP and heating capacity of Vuilleumier heat pumps doesn’t really change depending on the operating temperature, presenting an advantage in residential use, also SPF is around 1.53 at -0.26°C as average cold temperature which is not as high as a traditional heat pump, nevertheless the emission reduction and the energy savings will be significant compared to a traditional boiler (Luo, 2022).

5.20. Thermo-Acoustic Heat Pump

Also, a new technology with a TRL of 6 (prototype working at scale in condition to be deployed). It is mostly based on a different type of compressor, one of the most promising companies working on this technology is *blue heart* who already have a working prototype and are planning to release a commercial device for 2024-2025, nevertheless as the device is still in development and all the testing is internal for the company, there are no real numbers available (only for performance in high temperature applications, but no economic parameters).

The device uses sound waves to exploit the natural frequency of the cavity using helium as working fluid, this increases pressure and then heat in the high-pressure region. When compared to traditional compressors the company (Blue Heart, 2024) argues that the developed device will be smaller, cheaper, less noisy and will not require any coolant. Also, an "easy to install" methodology is mentioned but not further explained. From a technical more specific perspective, this device is basically a replacement for the cold circuit of the heat pump, by expanding and pressurizing helium to create a temperature difference based on two pistons vibrating at the same frequency.

According to the study on thermoacoustic heat pumps for domestic buildings (Hu, 2023), it is a promising technology as it can use medium to low grade heat reducing the reliance on electricity. Nevertheless, for this specific case a heating capacity of 5.7 kW was achieved with a COP average of 1.4, then it is still not fully competitive with traditional heat pumps in terms of efficiency but is in the same range of operation of other thermally driven heat pumps. They also mention a case study conducted in Finland showing promising results over an annual cycle, the obtained energy savings were around 20 MWh per year with CO_2 emissions reduction of about 4 tons and a total saving of 1629 euros per year when compared to a gas boiler, nevertheless this is considering the use of waste heat as main heat source for the device (Hu, 2023). The model diagram is presented in figure 38, including domestic hot water.

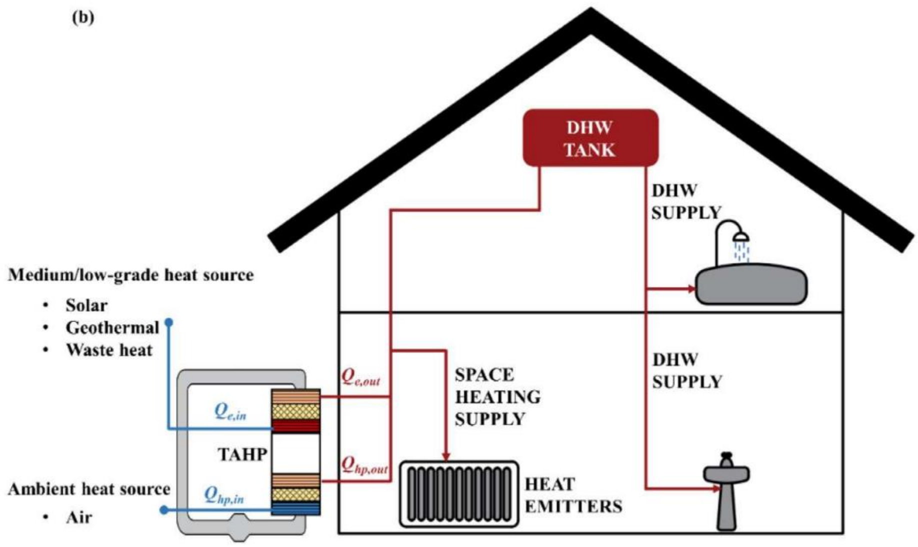

Figure 38, theoretical configuration of a heat driven thermo-acoustic heat pump system for domestic applications (Hu, 2023)

Now as a final result the study presents a comparison between different types of absorption heat pumps and the thermos-acoustic heat pump as presented in figure 39, studying the behavior of the COP in relation to the temperature delta.

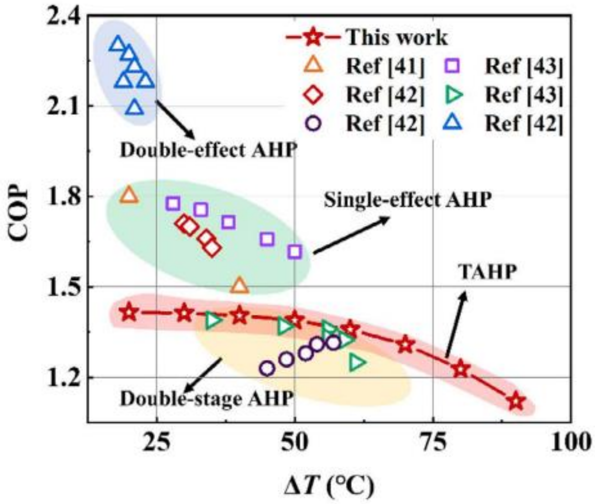

Figure 39, Comparison of the thermo-acoustic heat pump and absorption heat pump system performance (COP) in different temperature lifts (Hu, 2023)

As the COP is not as high as other type of absorption heat pumps, still the system shows great stability over a wide range of temperature increases, which can be advantageous in certain cases and applications.

6. Innovative Technologies for Storage

6.1. Batteries (Lithium Based and Flow Based)

According to the paper by Khan (Khan, 2022) the combination of PV and lithium cobalt oxide batteries show the lowest LCOE with a value of 3.4 cents per kWh, then it shows a promising economical proposition for many users. This study aims to review the combination of PV with several battery types as lithium cobalt oxide, lithium titanate, vanadium flow batteries and iron flow batteries.

The study is based on a case with 600 kW storage capacity (which is a high value for residential applications) for commercial applications. Assumptions for the system are made as the efficiencies of the modules and the inverter as also the sizing of the system, nevertheless flow batteries can also be a god option when high capacity storage is needed, nevertheless for this study both lithium based batteries achieved a lower levelized cost of electricity. The use of iron flow batteries seems to represent a profit compared to only PV and other battery storage technologies, but we should keep in mind that the study is made for a case in Saudi Arabia, then several parameters can vary drastically for an application in Europe.

6.2. Thermo-Mechanical Energy Storage

This type of storage includes several methods as for example compressed air, thermal energy storage, liquid air and pumped thermal, the diagram presented in figure 40 shows the different types and the specific classifications among each one of them.

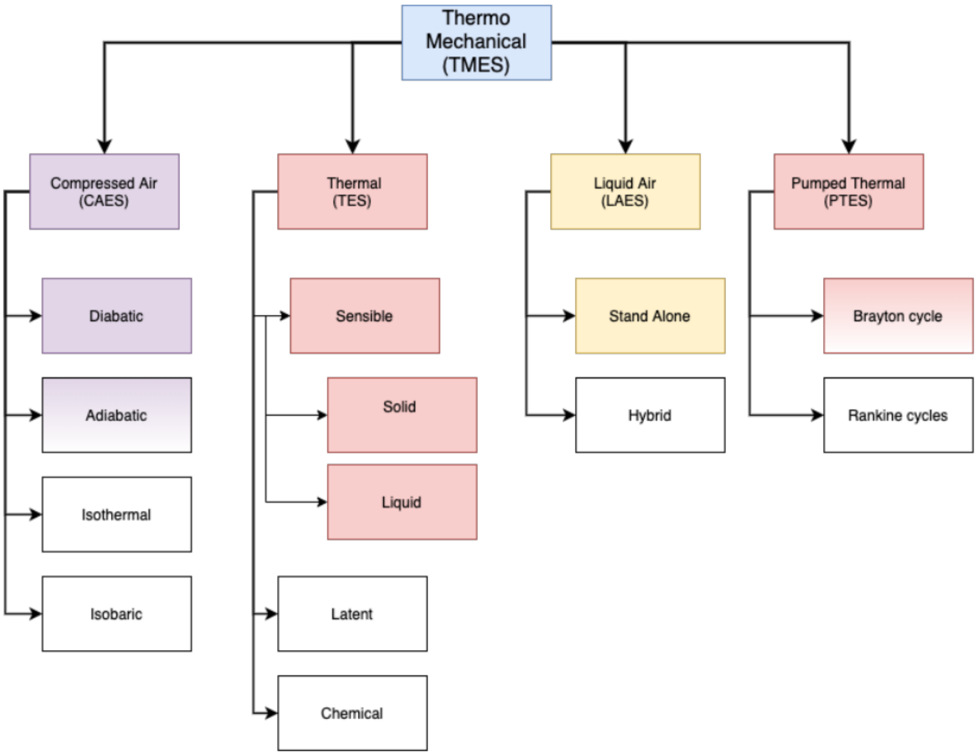

Figure 40, General classification of thermos-mechanical energy storage concepts (Gautam, 2022)

The study shows that for medium-term energy storage the current prices are not feasible as the power of components should first decrease to more competitive levels (one fifth of the current costs). This can also be explained for each specific technology as for TES it can be either sensible heat, latent heat or thermos-chemical heat. Nevertheless, for thermochemical applications the technologies are not yet developed enough for high temperature applications or to produce electricity with the available heat (Gautam, 2022).

Also, for the concept of pumped thermal energy storage as the use of heat pumps as a charging cycle to crease a temperature difference between two heat reservoirs is still not yet competitive or beneficial enough in relation to current electricity prices and thermal efficiency in full cycle mode. Also for compressed air where the air is compressed using electricity to further use this potential energy as a source the scenario is similar, it depends a in a high grade on the electricity market and on the high conditions to be viable.

For liquid air energy storage is not the accumulation of pressure but the cryogenization of air to store it in a liquid form but with the issue of keeping a very low temperature at all times, also consuming energy, mostly for the initial stage of the storage process. The efficiency of said process depends on the plant size and usually varies between 11% and 50% (Gautam, 2022).

Table 12 taken from (Gautam, 2022) summarizes in a clear way how the costs are distributed for all the different types of thermos-mechanical energy storage solutions.

Name	Unit	TES (Molten Salt)	PTES (Rock)	CAES (Adiabatic)	LAES (Standalone)
Investment cost—power #	$/kW	1341	1300	1200	1700 a
Investment cost—energy	$/kWh	18.30 a	20	27	32
Operation cost—power	$/kW-yr	10	5	4	6
Operation cost—energy ##	$/MWh	3.5	5	5	4
Cost ratio—power *	-	0.1	0.5	0.5	1
Round-trip efficiency **	-	0.42	0.55	0.6	0.5
Discharge efficiency	-	0.43	0.25	0.65	0.65
Efficiency ratio ***	-	2.3	8.8	1.42	1.18
Self-discharge	/day	0.01	0.01	0.01	0.005 x
Lifetime	cycles	30,000	16,250 y	16,250	16,250 y
Shelf life	years	30	30 y	30	25
Energy density	$kWhm^{-3}$	200	250	15	177

Table 12, Techno-economic data estimated for the different thermo-mechanical storage technologies analyzed (Gautam, 2022)

6.3. Water Tanks and Batteries

On the study (Parra, 2016) they compare hot water tanks, lead-acid batteries and lithium-ion batteries to define which one is best to be coupled with a PV system for residential use. The optimum battery capacity is defined as the one that maximizes the ratio between the self-consumption and the battery capacity, or the one with higher profitability. Also two sizes are defined, batteries with 5 kWh/2.6 kW for low electricity homes and 22 kWh/5.2 kW for high electricity homes.

This study took a building with both annual energy demands of 3.0 MWh (3.0 MWh electricity and 3.0 MWh hot water), also the PV array is assumed with a peak capacity of 3 kWp (average PV installation in the UK). The study tested several battery and tank capacities as can be seen in figure 41 (see figure 4 of research papers, storage, "water tank and batteries").

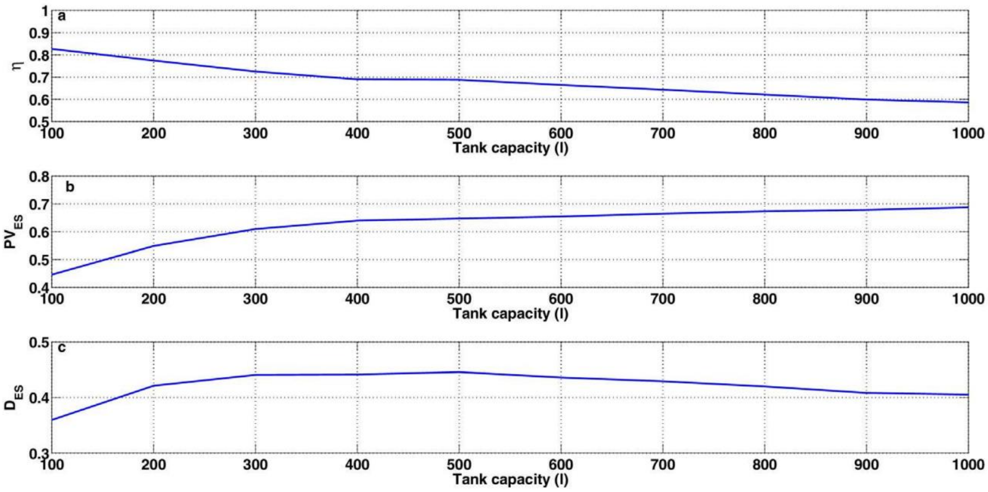

Figure 41, Performance results of hot water tanks with PV depending on the capacity (efficiency, PV ratio and self-consumption) (Parra, 2016)

The comparison between PbA batteries (most developed type of battery), Li-ion Batteries (most attractive for short term TES) and water tanks (most used TES) is very interesting and provide the results presented in table 13.

Technology	EFC	η	PV_{ES}	SC_{ES}
PbA	932 (4 kWh)	0.85 (20 kWh)	0.45 (20 kWh)	0.26 (20 kWh)
Li-ion	2511 (4 kWh)	0.89 (20 kWh)	0.36 (20 kWh)	0.36 (20 kWh)
Hot water tank	n.a.	0.83 (100 l)	0.69 (1000 kWh)	0.45 (500 l)

Table 13, Performance indicators optimized for PbA, Li-ion and hot water tank (Parra, 2016)

It is important to consider that the battery efficiency is quantified as the roundtrip efficiency (ratio between the energy used for charging and the energy obtained at discharging). Also they assume that the lifetime of the battery is up to the point when the capacity drops to 70%. Regarding water tanks they assumed no degradation (with proper maintenance) and a lifetime of 20 years.

Based on the economical results the batteries capacity that minimized the LCOE was 12 kWh for PbA and 8 kWh for Li-ion batteries. For the tank a good capacity value (and representative) seems to be 200L. The assumed storage cost for Li-ion was 350 £/kWh, and for PbA was 140 £/kWh.

6.4. Phase Change Materials (PCM)

The paper (Jayathunga, 2024) presents a classification of PCM materials as well as a series of advantages and disadvantages for each case, as can be seen in table 14 below.

PCM		Advantages	Disadvantages
Organic PCM	Paraffin	❖ High melting enthalpy ❖ Availability in a large temperature range ❖ Safe and non-corrosive ❖ Little or no super-cooling ❖ Low vapor pressure ❖ Less expensive ❖ Reliable and predictable behavior ❖ Congruent melting with good nucleation properties ❖ Chemically inert and stable below 500 °C ❖ Good thermal stability ❖ Compatible with all metal containers	❖ Low thermal conductivity. ❖ Non-compatible with plastic containers (Infiltrate and soften some plastics). ❖ Moderately flammable. ❖ High volume change upon melting. ❖ Generally, they do not have sharp, well-defined melting points.
	Non-paraffin	❖ High latent heat of fusion ❖ Inflammable ❖ Safe and non-corrosive ❖ Congruent melting and good nucleation properties ❖ little or no super-cooling	❖ Low thermal conductivity ❖ Low flashpoint ❖ Instability at higher temperatures ❖ Expensive (Fatty acids are about three times the cost of paraffin)
Inorganic PCM	Salts and Salt hydrates	❖ High melting enthalpy per unit volume ❖ Relatively higher thermal conductivity (almost twice as paraffin) ❖ Small volume changes during phase change ❖ Inexpensive ❖ Easy availability ❖ Compatible with plastics and only slightly toxic ❖ Sharp melting points (Maximizes the efficiency of TES)	❖ Phase separation ❖ Poor nucleation properties and incongruent melting that cause for super-cooling ❖ High tendency to cause corrosion ❖ Low specific heat capacity ❖ Low thermal conductivity of salt hydrates
	Metallics	❖ High thermal conductivity ❖ High latent heat of fusion per unit volume ❖ Low vapor pressure	❖ Higher weight ❖ Low latent heat of fusion per unit weight ❖ Low specific heat ❖ Tendency to cause corrosion
Eutectics		❖ Sharp melting temperatures ❖ Higher volumetric thermal storage density ❖ Congruent melt ❖ No phase separation	❖ Low latent heat of fusion per unit weight ❖ Expensive ❖ Low thermal conductivity ❖ Low thermal cycle stability

Table 14, PCM classification with advantages and disadvantages (Jayathunga, 2024)

Also, a classification based on different temperature applications is presented where low temperature region means a melting point lower than 220°C, medium temperature is a region between 220°C and 420°C, and high temperature is more than 420°C. For residential heating applications the low temperature materials are more than enough.

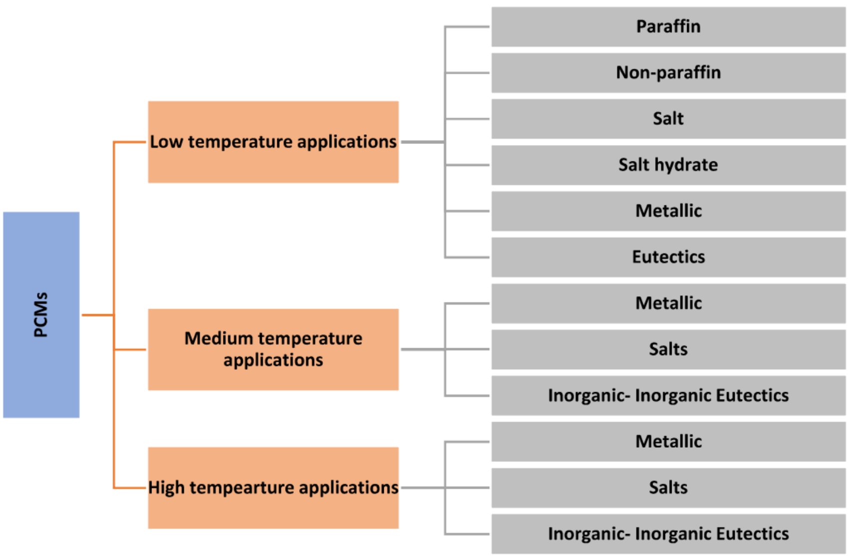

Figure 42, Potential PCM candidates for low, medium and high temperature applications (Jayathunga, 2024)

This concludes that a good PCM selection should be based on operating temperature range to be of the given application, and of course also on price and economic viability.

This study also presents an extensive table with characteristics (including cost data) for several PCM which will not be shown in this report but is still worth mentioning and will be used for the techno-economic analysis.

Also as mentioned in the paper (Mehling, 2022), ideally a PCM should undergo the phase change at a single-phase change temperature meaning that the heat should be store as pure latent heat. Then the relevant data to characterize an ideal PCM are then phase change temperature T_{pc} and phase change enthalpy variation $\Delta_{pc}h$.

The study (Mehling, 2022) classifies the use of PCM in buildings in two categories, passive and active. Passive is including the PCM in any part of the building to increment the storage capacity of the structure itself and is only driven by the temperature in the surrounding of the application place, while active classification is more related to the storage or release of heat actively affected by additional equipment, this is the section of interest for the thesis.

It is also mentioned that for heating applications the most common and usually the best economy is achieved with a hot water tank, as the PCM are still not price competitive enough, nevertheless, the PCM main advantage will be a high energy density.

A study (Belmonte, 2022) presents a field test in Madrid including a solar-assisted heat pump in combination with a PCM storage tank for residential heating applications. According to the study there is currently no standard for the size or design of any thermal energy storage (TES) using PCM, as the material can be used in different ways as for example encapsulated, used as a slurry, combined with a submerged internal heat exchanger, etc.

For this particular case, the specification for the single-family housing is a two stories building with a total volume of 444.5 m^3. Also, the PV system is defined and consists of 9 flat-plate collectors in parallel with a total area of 18 m^2, and it uses a water to water heat pump (Belmonte, 2022).

The characteristics of the PCM can be seen in table 15:

Commercial PCM: Salt hydrate S27	
Capsules dimensions	0.25 m wide × 0.5 m long × 0.032 m thick
Total number of capsules in the tank	32
Capsules arrangement	4 stacks of 8 capsules (two columns and two rows)
PCM phase-change temperature	27 °C
PCM density	1530 kg/m^3
PCM latent heat	183 kJ/kg
PCM specific heat capacity	2.2 kJ/(kg · K)
PCM thermal conductivity	0.54 W/(m · K)
Capsule mass	5.81 kg/capsule

Table 15, PCM tank details and Salt hydrate S27 thermal and physical properties (Belmonte, 2022)

Also, the demand is measured and define for 7 months of heating (from October to April) and consists of a total demand of 4278 kWh (thermal) or 30.56 kWh/m^2 (thermal).

The results seem to show that in general the integration of the latent storage tank does not improve energy performance of the analyzed system for practically any month, even degrading the system behavior for the months with higher demand and lower PV production (December, January and February).

There are 2 main reasons for this, the PCM considered has only one inlet/outlet port, then it does not permit simultaneous heat supply and recovery, resulting in loss of flexibility compared to systems that only include water tanks. And the short mismatch between peak periods of solar radiation and the heating demand in the range between a few hours and one or two days do not fully exploit the greater energy storage capacity provided by the PCM tank. Also due to the longer charging and discharging time required by the LHS compared to water tanks (Belmonte, 2022). This results can be seen in figure 43 as the monthly average heat pump COP is always lower for the 1000L tank combined with the PCM.

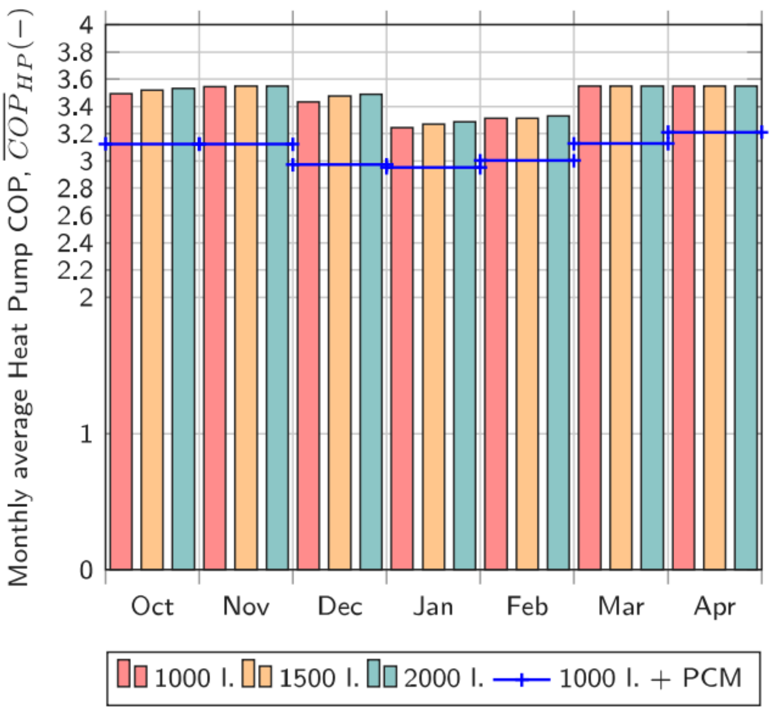

Figure 43, Heat pump performance (COP) per month for the different systems analyzed (Belmonte, 2022)

Another real life example for a company selling PCM thermal batteries is Sunamp, a heat battery with a cost between £1500 to $2300, they mention some projects where they changed a gas boiler and a water tank for a heat pump a PCM battery, causing energy and cost savings, nevertheless most of this savings are related to the heat pump more than the storage technology (Sunamp, 2024), the projects shown in the company web page are summarized below.

Replace old storage heaters in 273 social housing apartments.

They used a combination of a ground source circuit with heat pumps on each flat and thermion heat batteries. The benefits are supposed to be 67% reduction in energy bills. One resident reported a reduction from £75 to £21 per month.

Replacing a Gas Fired Water Tank for a Sunamp Thermino NYSERDA house

Replacing a 150L water tank for a thermion battery and reduced the temperature requirement from 70°C to 60°C as it was the required temperature to melt the PCM. Gas savings of around 50% were reported.

Zero Carbon Hot Water for an Outdoor Kitchen and Off-grid Home in the US

With a storage size of around 3.5 kWh, they estimate a carbon footprint reduction of 2.5 tons CO_2 equivalent per year.

Newbuild Rural Homes in Scotland

They used air source heat pumps, rooftop solar panels and Sunamp batteries reporting estimated savings in cost of 40% to 60% when compared with the original liquified petroleum gas system. Carbon dioxide emissions will be reduced by 85 tons per year (also estimated).

Replacing gas Boilers in UK High Rise Tower Blocks

Reported reduction of 70% carbon footprint every year, with a heating capacity 1.26 MW and a storage capacity 3.28 MWh.

College Campus in Liverpool

A project using thermal storage coupled with gas turbines and lithium-ion batteries (CHP). It is supposed to provide 65% of the electricity need and almost 100% of the heating and hot water demand. Energy costs reductions are estimated on around 40%. Also, a reduction of carbon emissions by 18% is expected. The system has two 65 kW gas turbines, two 64 kWh Sunamp thermal storage batteries and 134 kWh Li-ion batteries. Also, the new batteries are 70% smaller than the equivalent traditional hot water cylinders.

Tackling Fuel Poverty in 625 homes across Scotland

For this project a high solar PV consumption is reported, as between 55% and 63% of the total got water consumption was supplied with solar energy. They also present a cost of energy stored comparison for different technologies (Sunamp Ltd, 2016).

7. The Future of Heating

To answer the question on what the future of is heating several approaches were consider at the beginning of the project, after reviewing the current heat industry in Germany and The Netherlands and comparing it to the Swedish case we can have a better understanding on how the heating system could develop.

At the end 4 different paths were identified as can be seen in figure 44, electrification, heat communities, heat as a service and a system approach, these 4 paths will be further described in this section.

7.1. Electrification

Electrification refers to the use of electricity as the main source to generate heat instead of any type of fuel, it means moving from gas, coal or oil boilers into electric devices, these devices are typically either an electric boiler or a heat pump.

Electrification has been the main followed path to decarbonize heat in the recent years, pushed by the adoption and inclusion of heat pumps in the heating market, this is mainly driven for the high coefficients of performance presented by these devices, nevertheless the high initial investment in comparison to traditional technologies as coal, gas and oil boilers is the main barrier for its adoption. The heat electrification topic is transversal throughout the whole report as it is present in the techno-economic analysis for the heating technologies where the characteristics, performance and cost of the devices are presented.

The downside of electrification is that is not necessarily fossil free as it depends on how is the used electricity produced, if the main source is still a gas turbine, then the heat generation will have related emissions, nevertheless in this study it will be assumed that in the future electricity will come from renewables in a high share, and even today for Germany and The Netherlands still represents 50.79% and 45.09% of fossil free electricity respectively (IEA, 2023). Nevertheless, the share of carbon emissions related to each country's national grid was considered to assess the carbon emissions related to electrical devices. Also it should be considered that the energy demand for space and water heating corresponds to 53.4% and 15.9% of the total energy demand worldwide (IEA, 2023), then it would represent a huge load for the grid and the current system that should be addressed on time.

7.2. Community Approach

A community approach refers to the development of a complete heating system inside a geographical specific location, as the design, size and characteristics of the system will vary drastically depending on the available resources and parameters for each case, it can either include seasonal storage, use a lake as a heat sink or heat source, use system integration with nearby industries, etc.

The main advantage of this approach is the independence from the grid and from fuel markets, as it is usually the community that generates their own energy and has a prosumer approach for the houses involved in the system. Also as being a bigger system, the cost can be further divided among the homeowners and can possibly have a lower NPV than separate systems for each house and provide better system inertia, but still it has to be considered that as it is a system for many houses the appliances and installation costs will be proportional, hence high initial investment. Also, there is a matter of government support, financing or even regulations barriers depending on the country and location.

The main examples for this approach were studied for the PAW project in The Netherlands (Programma Aardgasvrije Wijken, 2024) that consist of 19 pilot cases for implementing a community approach with the aim to decrease the use of natural gas for heating in the country.

7.3. Heat as a Service

Heat as a Service (HaaS) approach is another type of strategy considered for the future of heating, for a company such as Vattenfall the main goal will be not just to be the electricity provider but also offer heat as well (in some cases it already does), but offering an integrated system and tariff.

A report by LCP delta (Briggs, 2023) shows different business models adopted by different companies and the main characteristics are presented in figure 44 as possible business models to decarbonize the heating sector.

Business Model Type	Description	Company example
1. Digitising the journey	Using data, analytics and digital platforms to improve the quality of the renovation experience. Includes better home assessments, providing access to installers and validating operational performance.	NET2GRID, Placeshaker, elia
2. One stop shop – service led	A single organisation leading a service on improving home energy performance. Taking accountability for the whole journey from initial assessment, getting quotes, project management and validation.	Rabobank, WOAB, woonnu, houzy
3. One stop shop – product led	A single organisation leading the sale and installation of products that will improve a home's energy performance. Includes integrating and controlling those products to maximise energy savings and other value streams.	VIESSMANN, evergreen energy, 1KOMMA5°, LichtBlick
4. Energy service contracting	Combining the delivery of home improvements with an energy service contract. Measures installed are part financed through the energy savings delivered. Contracts involve guarantees on energy performance or comfort.	Energiesprong, sero, ENGIE
5. Local approach	A local, co-ordinated approach to delivering retrofit. Involves service providers, local authorities and community groups collaborating to help fund and increase trust in the offer.	PadovaFIT Expanded, De Woonpas, FACIRÉNOV, People Powered Retrofit

Figure 44, 5 current approaches found in the market related to heat as a service (Briggs, 2023)

On the other hand, "Heat-as-a-service business models are also emerging, with France and Mexico having launched the first large systems with heat purchase agreements in 2021. The use of concentrating solar heat for industrial applications is also expanding strongly, with Spain in the lead thanks to grants available under the Thermal Energy Production scheme." (IEA, 2023). This shows that some companies are already starting to adopt this scheme, nevertheless another report by LCP Delta (Ottosson, 2022) also presents 3 steps or approaches to get closer to HaaS.

The first approach will be Project & Project which is not strictly a HaaS but a first step for it, it consists of a complete heat pump solution offered by the company as a whole project for a heat pump installation for the client, including design, installation, financing and service. At the end of the project the customer pays for the project development and also for the appliances installed, then the customer has full ownership after paying off the loan (Ottosson, 2022).

Then we have Standard HaaS that consists of a heat pump leasing strategy including service and maintenance for the customer, it can also be coupled with a guaranteed agreement where the company assumes some of the risks beyond d the manufacturer warranty. Still the customer owns all the appliances after the leasing period is over. The main benefit is that it eliminates the upfront CAPEX barrier for the customer and includes support from the company coupled with monthly payments and budgeting (Ottosson, 2022).

Finally we have Full HaaS, where the provider owns all the appliances and is responsible for the maintenance and functioning of all the system, while the customer only pays for the energy consumed (heat), it would typically include a heat meter to calculate the average heat consumption and define a good tariff, also the payments can be smoothed during the year to avoid unpleasant increases during the winter period. The main advantages of this approach is that totally removes the CAPEX barrier for the customer, and will also present a comprehensive support removing the technology risks for the client. Nevertheless, this has to be assumed by the company, then the payback time and market dependency becomes a strong factor when evaluating the whole business case and assessing if the payback time is based on confident enough data to justify the investment (Ottosson, 2022).

In general terms heat as a service is an interesting approach, but with the current prices for heat devices and with a volatile energy market is hard to tell if it is going to be the future of heating.

7.4. System Approach

System approach refers to the combination of several energy systems as a full package to benefit from integration and higher efficiencies, these systems are power generation devices, heat generation devices and electricity and thermal storage systems.

There are several parameters to consider when assessing a system approach:

- Energetical standard of the building (insulation level)
- Heat Demand
- Availability of Space (for ground source or other components)
- Number of apartments in the building for multi-family housing
- Ownership of the apartments (very relevant for multi-family housing)
- DHW demand (access to district system or independent)
- Installed heating transfer system (radiator/underfloor heating/air ventilation)
- Weather (temperatures, sun irradiance, wind availability)
- Ventilation type
- Indoor temperature
- Need for storage (heat and/or electricity)
- Complexity of installation
- Only residential or mixed building (mostly for multi-family housing)
- Location and proximities (consider noise requirements)

But still in order to give the best estimate for different cases on the community approach some of these parameters were assumed or neglected as presented in section *Results, System Approach, Assumptions*. Also, an important limit for the simulation done to assess the system approach was only considering single family housing buildings. This decision was taken due to time restrictions and complexity of the multi-family housing assessment but is also relevant to understand how the residential buildings are distributed between one category or the other in Germany and The Netherlands, figure 45 presents exactly this data for several countries.

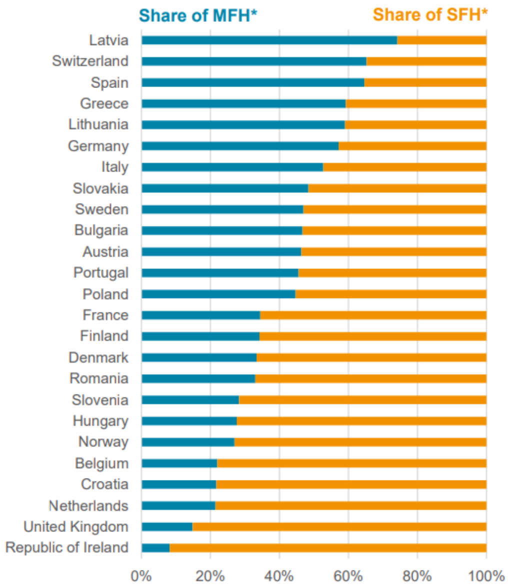

Figure 45, Share of SFH and MFH in selected European countries (Ottosson, MULTI FAMILY HOMES – THE NEXT SEGMENT FOR HEAT PUMPS TO CONQUER?, 2022)

It is interesting to see that in Germany the proportion of SFH and MFH is around 60% MFH and 40% SFH, while in the Netherlands it is around 20% MFH and 80% SFH, then both approaches are valuable in both countries, even though as mentioned before, the simulations for the system approach will be based on SFH, in the following paragraphs some remarks about a system approach for multi-family housing will be presented.

System Approach for Multi Family Buildings

There are mainly three different alternatives when assessing a system approach for a whole building, the first one is considering a decentralized system, the second one is considering one system to provide the complete building demand, and the third one is a combination of both.

A centralized system usually consists of a central heat pump that provides ambient heating and hot water for the whole building, then this heat pump needs to be of high capacity (usually high temperature). A small schematic is presented in figure 46.

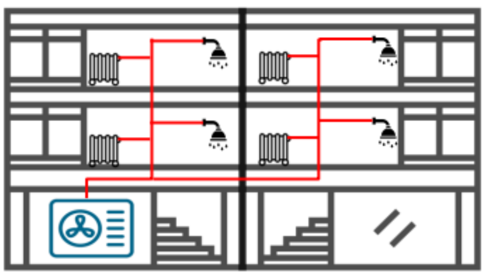

Figure 46, Centralized heat pump system schematic (Ottosson, MULTI FAMILY HOMES – THE NEXT SEGMENT FOR HEAT PUMPS TO CONQUER?, 2022)

The main benefits related to this type of system is space saving in each apartment, as it is only the pipping going to deliver hot water, also lower CAPEX as there is only one large investment for a single device divided between all the dwellers and also lower maintenance costs for the same reason. On the other hand the system requires that all the apartments (or almost all) are involved as the piping will be distributed in the whole building, also this type of system has higher losses due to the long distance that the hot water has to travel from the heat pump to the final consumption destination and also a maintenance or a problem will affect all of the customers at the same time (Ottosson, MULTI FAMILY HOMES – THE NEXT SEGMENT FOR HEAT PUMPS TO CONQUER?, 2022).

Now for decentralized systems what we have is usually each apartment having their own system to provide ambient heating and hot water as can be seen in figure 47.

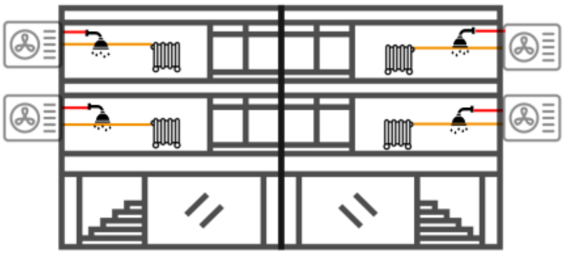

Figure 47, Decentralized heat pump system schematic (Ottosson, MULTI FAMILY HOMES – THE NEXT SEGMENT FOR HEAT PUMPS TO CONQUER?, 2022)

This type of system offers easier metering and billing as each flat pays according to their own consumption, also the acceptance is higher as everyone can choose their own solution and participation and the installation process is simplified.

Nevertheless, there are disadvantages as the space needed for the appliances inside each apartment and the total cost will be much higher compared to a centralized system because of several small separated costs for devices, installation and maintenance.

Finally, the combined system presents a collective heat pump and individual appliances on each apartment as presented in figure 48.

Figure 48, Combined heat pump system schematic (Ottosson, MULTI FAMILY HOMES – THE NEXT SEGMENT FOR HEAT PUMPS TO CONQUER?, 2022)

This type of system presents higher flexibility and higher control of the heating system for the clients, also increasing acceptance rates, as well as low heat losses as the circulating water can be low temperature and then increased in the heat pump for each apartment.

The main disadvantages of the combined system are a higher investment as it requires more hardware and increases the costs of installation, and also the maintenance becomes complicated due to logistical issues and also promoted by the system complexity.

Advantages of Using Solar Energy and Heat Pumps

Implementing a heat pump eliminates the dependency of market gas and oil prices, PV partially eliminates the dependency of electricity prices, then it can be advantageous for the client due to market volatility. Also, it is important to mention that the use of a buffer (water tank) is crucial (SolarPower Europe, 2023).

The use of PV can cover up to 1/3 of the heat pump demand in a cold year and 46% in a sunny year for Germany according to (SolarPower Europe, 2023). This is translated into a 22% saving in the energy bill if only PV is installed (€1263), and if PV is combined with a heat pump, then it will rise to a 62% savings (€3614) based in the Solar Power Heats study.

The payback time depends also on the financial scheme used, the study (SolarPower Europe, 2023) points out that the best possibility is having a interest rate below 3% with a 20 year loan, in order to have a payback time lower than the heat pump lifetime (this is for the case of Germany).

8. Methodology

8.1. Techno-Economic Analysis

For the techno-economic analysis the process was defined in different steps. The following diagram (figure 49) illustrates the inputs, calculations and outputs of the process, which will be described in detail in the following section.

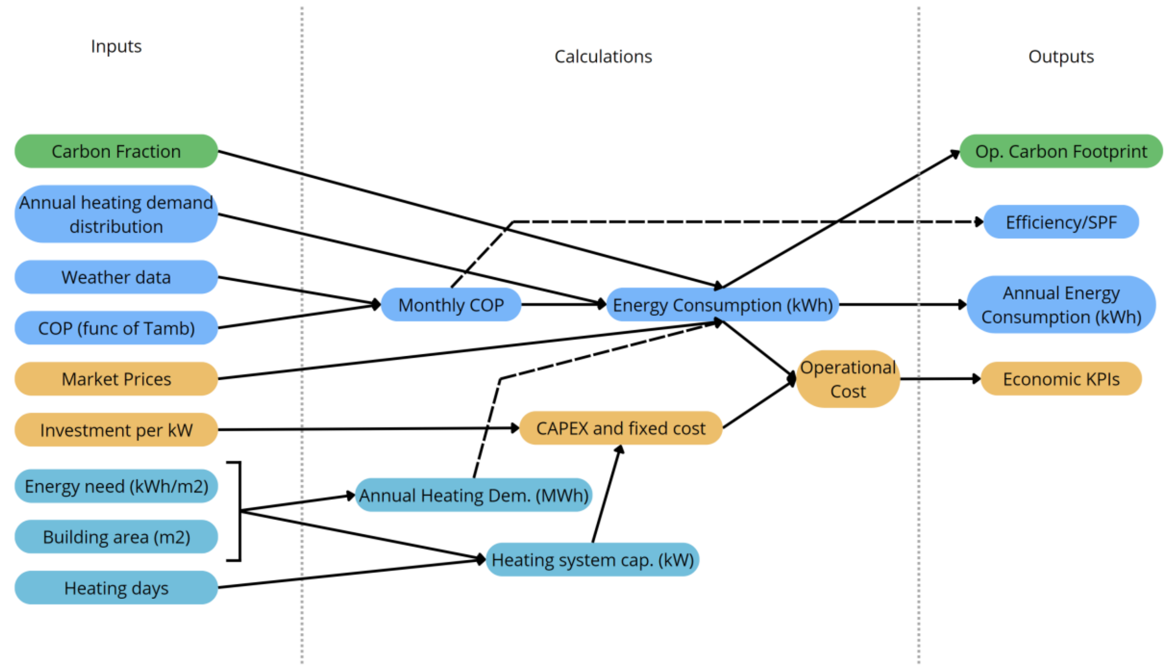

Figure 49, Block diagram with inputs, calculations and outputs for the techno-economic analysis for the heat generation technologies

Basically, the diagram is divided into 3 sections, the first one is the inputs that correspond to technical details (in blue), the economic parameters (in yellow) and the carbon fraction from the grid (in green), then the different calculations as annual heating demand, the heating system capacity as well as the monthly COP to obtain the energy consumption and also calculate the investment cost depending on the system size, finally to get the operational cost. On the right hand of the diagram the outputs are presented with the same color scheme, for operational carbon footprint, efficiency and seasonal performance facto, annual energy consumption and the economic KPIs (NPV, IRR, BCR and TCO) that will be further explained in the section *KPIs Assumptions*.

First, as mentioned in the section *Representative Building Selection*, a total of 4 buildings per country were selected based on the year of construction and on the type of housing (single-family or multi-family). Then each case was crossed with each one of the 22 heat generation technologies (including 5 reference cases) to obtain a 4 economic KPIs (NPV, IRR, BCR and TCO), 2 performance KPIs (SPF/Efficiency and Energy Consumption per Year (kWh) and 1 environmental indicator (Operational Carbon Footprint (Ton CO2 eq./Year)). Also, one city per country was selected in order to have real historical values for weather and heat demand, for Germany the selected city was Berlin and for The Netherlands it was Amsterdam.

After identifying the representative buildings, the main parameters were extracted from (Tabula WebTool, 2017), these variables are presented in table 16 for Germany and in table 17 for The Netherlands.

Code	*Type*	*Area (m2)*	*Energy Need for Heating (kWh/(m2 a) - Existing State*	*Energy Need for Heating (kWh/(m2 a) - Usual Refurbishment*	*Total Energy Need (Ambient + DHW) (kWh/m2 a) - Existing State*	*Energy Need for DHW (kWh/m2 a) - Existing State*	*Energy Need NOT for Heating (kWh/m2 a) - Existing State*	*Heating Days*
DE.N.SFH.04.Gen	SFH	111	165.3	111.5	264.9	99.6	46.284	222
DE.N.SFH.09.Gen	SFH	122	110.5	97.6	167.8	57.3	30.94	222
DE.N.MFH.04.Gen	MFH	632	140.3	79.3	225.7	85.4	39.284	222
DE.N.MFH.09.Gen	MFH	835	91.1	68.8	136.9	45.8	25.508	222

Table 16, Main building parameters for the selected buildings for Germany (Tabula WebTool, 2017)

Code	*Type*	*Area (m2)*	*Energy Need for Heating (kWh/(m2 a) - Existing State*	*Energy Need for Heating (kWh/(m2 a) - Usual Refurbishment*	*Total Energy Need (Ambient + DHW) (kWh/m2 a) - Existing State*	*Energy Need for DHW (kWh/m2 a) - Existing State*	*Energy Need NOT for Heating (kWh/m2 a) - Existing State*	*Heating Days*
NL.N.SFH.02.Gen	SFH	135	141.4	66.3	185.9	44.5	49.49	212
NL.N.SFH.04.Gen	SFH	189	83.2	62.3	127.6	44.4	29.12	212
NL.N.MFH.02.Gen	MFH	4235	104.2	55.7	153.6	49.4	36.47	212
NL.N.MFH.04.Gen	MFH	1804	67	54	116	49	23.45	212

Table 17, Main building parameters for the selected buildings for The Netherlands

The main values were the heating system capacity in kW calculated using equation 2 and the total annual heating demand in MWh using equation 3. The heating system capacity was used to determine the capacity of each one of the heat generation technologies for every case, while the total annual heating demand was coupled with the system efficiency (or COP) to calculate the energy consumption.

$$Heating\ System\ Capacity\ [kW] = \frac{Energy\ Need\left[\frac{kWh}{m2\ a}\right] * Area[m^2]}{heating\ days\ [days]} * \frac{1\ [day]}{24\ [hours]} \quad (eq. 2)$$

$$Total\ Annual\ Heating\ Demand[MWh] = \frac{Energy\ Need\left[\frac{kWh}{m2\ a}\right] * Area[m^2]}{1000\left[\frac{kW}{MW}\right]} \quad (eq. 3)$$

It should be noted that the energy need can be either only for ambient heating or for ambient heating plus domestic hot water depending on the case. The results are presented in table 18 for only ambient heating and table 19 for ambient heating and DHW.

Only Ambient Heating

Country	Code	Heating System Capacity (kW)	Total Annual Heating Demand (MWh)	Annual Energy (NOT for Heating) Demand (MWh)
Germany	DE.N.SFH.04.Gen	3.44	18.35	5.14
	DE.N.SFH.09.Gen	2.53	13.48	3.77
	DE.N.MFH.04.Gen	16.64	88.67	24.83
	DE.N.MFH.09.Gen	14.28	76.07	21.30
The Netherlands	NL.N.SFH.02.Gen	3.75	19.09	6.68
	NL.N.SFH.04.Gen	3.09	15.72	5.50
	NL.N.MFH.02.Gen	86.73	441.29	154.45
	NL.N.MFH.04.Gen	23.76	120.87	42.30

Table 18, energy need only considering ambient heating in both countries

Ambient Heating + DHW

Country	Code	Heating System Capacity (kW)	Total Annual Heating Demand (MWh)	Annual Energy (NOT for Heating) Demand (MWh)
Germany	DE.N.SFH.04.Gen	5.52	29.40	5.14
	DE.N.SFH.09.Gen	3.84	20.47	3.77
	DE.N.MFH.04.Gen	26.77	142.64	24.83
	DE.N.MFH.09.Gen	21.45	114.31	21.30
The Netherlands	NL.N.SFH.02.Gen	4.93	25.10	6.68
	NL.N.SFH.04.Gen	4.74	24.12	5.50
	NL.N.MFH.02.Gen	127.85	650.50	154.45
	NL.N.MFH.04.Gen	41.13	209.26	42.30

Table 19, energy need considering ambient heating and domestic hot water in both countries

The next step was to distribute the total annual heating demand on every month from October to May according to (ehpa, 2024) this was done by assuming a constant COP of 1 for all temperature cases and then extracting the data from the thermal performance for each month in MWh as a relative percentage. The values obtained from the European Heat Pump Association are presented in table 20 for Berlin and table 21 for Amsterdam, also note that the distribution of the demand share per month was assumed as the same with and without DHW as the difference can be assumed as a constant added value, nevertheless for future and more specific studies it should be considered as also DHW demand will be present the whole year, while the heating demand is exclusive for winter time.

Berlin	*Heating Demand (MWh)*								
Month	September	October	November	December	January	February	March	April	May	Total
HD (MWh)	0	0.67	1.71	2.72	3.16	2.64	1.96	0.76	0.16	13.78
Percentage	0.0%	4.9%	12.4%	19.7%	22.9%	19.2%	14.2%	5.5%	1.2%	100.0%

Table 20, Heating demand and heating demand distribution for Berlin from September to May (ehpa, 2024)

Amsterdam	*Heating Demand (MWh)*									
Month	September	October	November	December	January	February	March	April	May	Total
HD (MWh)	0	0.47	1.7	2.83	3.15	2.82	2.2	1.04	0.29	14.5
Percentage	0.0%	3.2%	11.7%	19.5%	21.7%	19.4%	15.2%	7.2%	2.0%	100.0%

Table 21, Heating demand and heating demand distribution for Amsterdam from September to May (ehpa, 2024)

Then the heating demand for each building type for each country and each case (with and without DHW) can be calculated using the percentages presented in the previous tables.

For the cashflow first it defined for all cases that the all the parameters will be calculated on a 20-year base, then the initial investment was done on the first year and depending on the lifetime of each technology a second investment was considered after said time.

It should be noted as well that the discount rate was assumed as the representative inflation rate for each country in 2024 and the electricity and fuel prices were taken for as updated sources as possible.

The used representative inflation rate for Germany was 2.8% (European Comission, 2024) and 2.7% for the Netherlands (Y Charts, 2024) as of March 2024. Also the values for the cost of electricity, natural gas, heating oil and hydrogen were researched in the literature and are presented in table 22 with their reference sources, the values were standardized in €/kWh using the LHV of the fuels, for natural gas the LHV used was 10 kWh/m^3, for heating oil the value is 10 kWh/L, for hydrogen the value used was 33.33 kWh/kg (The Engineering ToolBox, 2003).

Country	*Germany*		*The Netherlands*	
Fuel	Price (€/kWh)	Reference	Price (€/kWh)	Reference
Electricity	0.0661	(Trading Economics, 2024)	0.3400	(Overstappen.nl, 2024)
Natural Gas	0.0669	(Verivox, 2023)	0.1380	(Overstappen.nl, 2024)
Heating Oil	0.1074	(Statista, 2024)	0.1169	(Statista, 2023)
Hydrogen	0.1800	(Clean Hydrogen Partnership, 2024)	0.2400	(Hydrogen Insight, 2023)

Table 22, Levelized cost of energy sources for each country based on several references (presented in the table)

For the case of methane it was assumed that the price will be the same as natural gas as it usually corresponds to around 97% of the blend (MET, 2023), the low heating value taken was the one of pure methane, being 13.9 kWh/kg (The Engineering ToolBox, 2003).

It is also important to mention that for hydrogen enriched natural gas the values were assumed based on the blend composition, on this particular case a 10% fraction by volume of hydrogen was assumed (Sforzini, 2020), in that case the LHV according to the reference paper will be 14.16 kWh/kg and the price will be 0.0466 €/kWh for Germany and 0.0653 €/kWh for The Netherlands.

In relation to the income corresponding to the electricity sold back to the grid the main assumption will be that it can be sold at a price of 1/3 of the retail price as a reference value according to (Zonnefabriek, 2023). After the previous set, there will be two different scenarios where electricity will be sold back to the grid, either for the use of electrolyzers (related to hydrogen heat pump) or using PV, the details for the calculation will be described in the next section Results, Assumptions.

For this project the selected cashflow structure is as follows (figure 50):

(-) Initial investment (€)
(-) Installation Cost (€)
(-) Operational Costs (€)
(-) Maintenance (€)
(+) Electricity Generation Discount (€)
(+) Subsidies (€)
___
Total (€)

Figure 50, Cashflow structure for the techno-economic analysis

This structure was used to obtain the yearly net revenue and then the NPV was taken according to equation 4 presented below.

$$NPV_n = \frac{(Net\ Revenue)_n}{(1+i)^n} \quad eq. 4$$

The total NPV was the sum of the initial net revenue of year zero (including the initial investment of the device) plus the corresponding NPV for each year until the total of 20 years for the total techno-economic analysis.

As mentioned before, also for simplicity of the analysis 2 specific cities were selected (one for each country), and the data for the weather was obtained from visual crossing (Visual Crossing Corporation, 2024), where the dataset was from September the 1st 2022 until May the 31st 2023, the specific data will be presented in the *Annexes* section, *Weather Data*.

The weather data is relevant as for the heat pump type of devices the coefficient of performance will vary according to the temperature delta needed between the heat source (usually related to ambient temperature) and the heat sink (inside the residence), then the methodology to consider this variation was based on literature and experimental data from previous studies, as the COP varies in relation to the ambient temperature then according to the obtained data an approximation to a linear regression was assumed as COP in function of the ambient temperature. After this process for each heating day the average monthly COP was considered and coupled with the monthly heating demand to find the energy consumption of the device, this will also be further explained for each device as needed.

8.1.1. Assumptions

In the following section the specific assumptions for the analysis will be presented, as a high-level study several approximations were made and backed up with literature review to keep the results as relevant as possible while also considering the time available for the project. The assumptions are presented in separate sections in relation to the building selection, for each one of the heat generation technologies, for the KPI´s and finally a section based on the CAPEX gap between both countries.

8.1.1.1. For the Buildings

As previously mentioned, the heating days for the buildings will be from September to May, based on the heating demand per month (ehpa, 2024), while the demand and capacity data will be taken from tabula web tool (Tabula WebTool, 2017).

From this data, the yearly demand was translated into percentage of the total based on data from the European heat pump association, then with the relative demand share per month, the total demand was distributed and calculated for each building. Note that the data for each country variates as the weather conditions will be slightly different in both cities, this was also considered in the study and taken according to (ehpa, 2024).

Tow separate cases were considered, the first being exclusively for ambient heating and the second one also including domestic hot water, the variation was based on the demand presented in tabula web tool (Tabula WebTool, 2017), and then calculated as the heating capacity in kW and heating demand in MWh according to equations 2 and 3 respectively. The heating system capacity is calculated based on the total annual demand and the heating hours based on the number of heating days (it is assumed that on these days the heating is 24 hours a day).

From the total energy demand per building, it is assumed that the energy needed for any other purpose than heating is an electricity demand, this assumption is made to consider the use of electricity generation surplus as a positive saving. This means that in the techno-economic model if there is an electricity surplus first the energy demand of the residence is met and will be taken at the same price (€/kWh) as the retail price. After this demand is fulfilled then the remaining electricity surplus is sold back to the grid at 1/3 of the price as explained before.

Also, as previously mentioned, the weather data is based on the weather for Amsterdam and Berlin from September 2022 until May 2023.

When considering domestic hot water, the main changes will be based on the heating capacity needed and total annual heating demand (calculating over the total energy demand for heating and DHW). Besides that, for the heat pump type of devices the COP was reevaluated according to the literature review as the temperature delta needed will be higher, the assumed water temperature was around 60°C as it is the recommended temperature to avoid the proliferation of legionella bacteria (Lévesque, 2004).

The inner house temperature for ambient heating is variable according to the temperature in the study for an specific technology, nevertheless dur to thermal comfort it was always corresponding to a value between 16°C and 24°C.

The electricity demand was calculates as a percentage of the total energy demand according to two Odyssee reports, one for Germany (Odyssee-Mure, 2024), and one for The Netherlands (Odyssee-Mure, 2024). The calculation is based on the total energy demand per building, but the equation parameters remain constant for all the buildings in the same country, see equation 5 for Germany and equation 6 for The Netherlands.

$$Energy\ Need\ (GER)_{Not-Heating} = Energy\ Need\ for\ Heating * \frac{0.14}{0.5} \quad eq.5$$

$$Energy\ Need\ (NDL)_{Not-Heating} = Energy\ Need\ for\ Heating * \frac{0.21}{0.6} \quad eq.6$$

8.1.1.2. For the Technologies

Gas Boiler

Initial investment and installation cost are calculated as a function of the heating system capacity using equation 7 according to (Mitterrutzner, Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, 2023).

$$CAPEX_{Gas\ Boiler}\ [€] = \left(527 - \frac{Heating\ System\ Capacity\ [kW]}{Efficiency} * 1.9\right) * \frac{Heating\ System\ Capacity\ [kW]}{Efficiency} \quad eq.7$$

Also the maintenance cost is assumed as 2% of the initial CAPEX based on the previous source (Mitterrutzner, Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, 2023).

The lifetime of the device is set at 21 years, then there is only one initial investment at the first year of the analysis. The used efficiency of the device is 94% (Mitterrutzner, Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, 2023).

The yearly operational cost is a function of the fuel consumption (natural gas) and is calculated as follows (equation 8).

$$Operational\ Cost[€] = \frac{Annual\ Heating\ Demand\ [kWh] * Gas\ Price\ \left[\frac{€}{kWh}\right]}{Efficiency} \quad eq.8$$

Oil Boiler

Initial investment and installation cost are calculated as a function of the heating system capacity using equation 9 according to (Mitterrutzner, Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, 2023).

$$CAPEX_{Oil\ Boiler}\ [€] = \left(622 - \frac{Heating\ System\ Capacity\ [kW]}{Efficiency} * 2.19\right) * \frac{Heating\ System\ Capacity\ [kW]}{Efficiency} \quad eq.9$$

The maintenance cost is assumed as 4% of the initial CAPEX based on the previous source (Mitterrutzner, Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, 2023).

The lifetime of the device is set at 20 years, then there is only one initial investment at the first year of the analysis. The used efficiency of the device is 93% (Mitterrutzner, Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, 2023).

The yearly operational cost is a function of the fuel consumption (heating oil) and is calculated as follows (equation 10).

$$Operational\ Cost[€] = \frac{Annual\ Heating\ Demand\ [kWh] * Oil\ Price\ \left[\frac{€}{kWh}\right]}{Efficiency} \quad eq. 10$$

Electric Boiler

Initial investment and installation cost are calculated as a function of the heating system capacity using equation 11 according to (Mitterrutzner, Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, 2023).

$$CAPEX_{Elec\ Boiler}\ [€] = \left(100 - \frac{Heating\ System\ Capacity\ [kW]}{Efficiency} * 0.09\right) * \frac{Heating\ System\ Capacity\ [kW]}{Efficiency} \quad eq. 11$$

The maintenance cost is assumed as 1% of the initial CAPEX based on the previous source (Mitterrutzner, Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, 2023).

The lifetime of the device is set at 30 years, then there is only one initial investment at the first year of the analysis. The used efficiency of the device is 100% (Mitterrutzner, Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, 2023).

The yearly operational cost is a function of the fuel consumption (electricity) and is calculated as follows (equation 12).

$$Operational\ Cost[€] = \frac{Annual\ Heating\ Demand\ [kWh] * Elec\ Price\ \left[\frac{€}{kWh}\right]}{Efficiency} \quad eq. 12$$

Heat Pump (Air to Air)

Initial investment and installation cost are calculated as a function of the heating system capacity using equation 13 according to (Mitterrutzner, Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, 2023).

$$CAPEX_{A\ to\ A\ HP}\ [€] = 1080 * Heating\ System\ Capacity\ [kW] \quad eq. 13$$

The maintenance cost is assumed as 4% of the initial CAPEX based on the previous source (Mitterrutzner, Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, 2023).

The lifetime of the device is set at 20 years, then there is only one initial investment at the first year of the analysis.

The average COP per month was calculated using the data from (ehpa, 2024), which corresponds to the COP of an air-to-air heat pump for different ambient temperature for a LWT (leaving water temperature) of 45°C (see table 23).

Air to air	*COP*					
T amb (°C)	-20	-7	2	7	15	25
COP	1.13	2.29	3.07	3.5	4.21	5.25

Table 23, COP for air-to-air heat pump based on ambient temperature (ehpa, 2024)

These values were plotted and then a linear regression was performed as can be seen in figure 51, were also the line equation is presented together with the R^2 value.

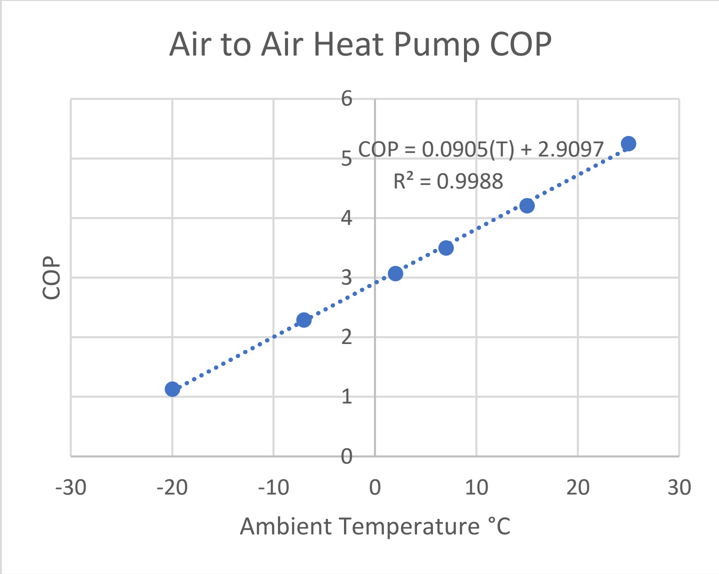

Figure 51, Variation of COP for air to air heat pump as a function of ambient temperature (ehpa, 2024)

By using the equation displayed in the graph we can calculate the daily COP of the heat pump by replacing T with the average temperature for each day (see section *Annexes, Weather Data*). Then the monthly average is taken and finally the monthly energy consumption can be calculated using equation 14.

$$Energy\ Consumption_{Month\ n}\ (kWh) = \frac{Heating\ Demand_{Month\ n}\ (kWh)}{Average\ COP_{Month\ n}} \quad eq. 14$$

The results for the air-to-air heat pump for the Germany case without domestic hot water demand are presented in table 24.

Month	*September*	*October*	*November*	*December*	*January*	*February*	*March*	*April*	*May*
COP	4.18	4.08	3.45	3.08	3.33	3.22	3.45	3.67	4.20
Elec Consumption (kWh)	0.00	0.22	0.66	1.17	1.27	1.09	0.76	0.28	0.05

Table 24, Monthly electricity consumption in kWh for the air-to-air heat pump in Germany for the first SFH building

This table is presented as an exemplification of the methodology, nevertheless the results for the other cases and technologies will be presented in *Annexes, Annual Energy Consumption for the Heat Generation Devices*.

After that the yearly energy consumption is totalized and the operational cost can be calculated using equation 15.

$$Operational\ Cost[€] = Annual\ Energy\ Consumption\ [kWh] * Elec\ Price \left[\frac{€}{kWh}\right] \quad eq. 15$$

Heat Pump (Ground Source)

The initial investment and installation cost are calculated as a function of the heating system capacity using equation 16 according to (Mitterrutzner, Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, 2023).

$$CAPEX_{GS\ HP}\ [€] = \left(\left(200 + \frac{4750}{(Heating\ System\ Capacity\ [kW])^{1.25}}\right) * Heating\ System\ Capacity\ [kW] + 800 * Heating\ System\ Capacity\ [kW]\right) * 1.3 \quad eq. 16$$

The maintenance cost is assumed as 4% of the initial CAPEX based on the previous source (Mitterrutzner, Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, 2023).

The lifetime of the device is set at 37 years, then there is only one initial investment at the first year of the analysis.

It is assumed that the COP is constant during the year due to the thermal nature of the borehole, the assumed ground temperature was between 0 and 5 degrees with a delta T of 35 degrees for the ambient heating case, giving a COP of 4.5 (Garber-Slaght, 2021), and a delta T of around 50 degrees with a COP of 3 for the case including DHW (Ruhnau, 2019).

The yearly operational cost is a function of the electricity consumption and is calculated as follows (equation 17).

$$Operational\ Cost[€] = Annual\ Energy\ Consumption\ [kWh] * Elec\ Price \left[\frac{€}{kWh}\right] \quad eq.17$$

Hydrogen Boiler

Initial investment and installation cost are calculated as a function of the heating system capacity using equation 18 according to (Mitterrutzner, Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, 2023).

$$CAPEX_{Hydrogen\ Boiler}\ [€] = 3300 * Heating\ System\ Capacity\ [kW] \quad eq.18$$

The maintenance cost is assumed as 2% of the initial CAPEX based on the previous source (Mitterrutzner, Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, 2023).

The lifetime of the device is set at 22 years, then there is only one initial investment at the first year of the analysis. The used efficiency of the device is 82% (Mitterrutzner, Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, 2023).

The yearly operational cost is a function of the fuel consumption (hydrogen) and is calculated as follows (equation 19).

$$Operational\ Cost[€] = \frac{Annual\ Heating\ Demand\ [kWh] * Hydrogen\ Price \left[\frac{€}{kWh}\right]}{Efficiency} \quad eq.19$$

The price of hydrogen is taken as the higher end from the most common price range (4-6 EUR/kg - 31.37%) according to (Clean Hydrogen Partnership, 2024).

Fuel Cell Micro-CHP (PEM)

Initial investment and installation cost are obtained from literature review and assumed as €12000 euros for a SFH size electrolyzer, while for the multifamily housing buildings the used price will be €26000 (Dodds, 2015).

The maintenance cost is assumed as 2% of the initial CAPEX based (Mitterrutzner, Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, 2023), as no specific value could be found for PEM, then the assumed value was the same as for a hydrogen boiler.

The lifetime of the device is set at 15 years, then there is an initial investment at the first year of the analysis, and a second investment at year 15. The used electric efficiency of the device is 82% and 16%

heat recovery efficiency. Also, a degradation of 1% per year for the device energy production was taken (Roest, 2023).

As this system has the capacity to generate electricity and heat as a result of the exothermic process then it was assumed that all the heat should come from the reaction, while the electricity will be used to cover the house demand, and the surplus will be sold back to the grid.

First the energy need not for heating is calculated for each building using equation 5 and 6, then the hydrogen consumption is calculated using equation 20.

$$Hydrogen\ Consumption\ [kg] = \frac{Annual\ Heating\ Demand[kWh]}{Thermal\ Efficiency * Hydrogen\ HHV\ \left[\frac{kWh}{kg}\right]} \quad eq.20$$

Where the thermal efficiency for heat recovery of the device is 16% (Roest, 2023), and the hydrogen HHV is 39.4 kWh/kg (The Engineering ToolBox, 2003).

Then from the hydrogen consumption it can be calculated the electricity generation using equation 21. The degradation percentage is used to calculate the electricity generation from the system each year.

$$Electricity\ Gen\ [kWh] = Hydrogen\ Consumption\ [kWh] * \left(Electric\ Efficiency - \left(Degradation * n_{year}\right)\right) \quad eq.21$$

Then as the electricity production is higher than the electricity demand for the residence, then to calculate the electricity generation discount equation 22 was used, also considering that the electricity sold back to the grid will have one third of the retail price (Zonnefabriek, 2023).

$$\begin{aligned} Elec\ Generation\ Discount\ [€] \\ = Energy\ Need_{Not-Heating}[kWh] * Elec\ Price\ \left[\frac{€}{kWh}\right] \\ + \left(Electricity\ Gen[kWh] - Energy\ Need_{Not-Heating}\right) * \frac{Elec\ Price\ \left[\frac{€}{kWh}\right]}{3} \quad eq.22 \end{aligned}$$

This equation describes how as the whole electricity demand is assumed to be met by the electricity production from the electrolyzer then this is taken as a saving, and then the difference between the electricity generated and the energy need not for heating will be the remaining electricity that will be sold back to the grid.

The yearly operational cost is a function of the fuel consumption (hydrogen) and is calculated as follows (equation 23).

$$Operational\ Cost[€] = Hydrogen\ Consumption[kg] * Hydrogen\ Price\ \left[\frac{€}{kg}\right] \quad eq.23$$

The hydrogen price is taken as the higher end from the most common price range (4-6 EUR/kg - 31.37%) according to (Clean Hydrogen Partnership, 2024).

Fuel Cell Micro-CHP (SOFC)

Initial investment and installation cost are obtained from literature review and assumed as €16000 euros for a SFH size electrolyzer, while for the multifamily housing buildings the used price will be €28000 (Dodds, 2015).

The maintenance cost is assumed as 2% of the initial CAPEX based (Mitterrutzner, Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, 2023), as no specific value could be found for PEM, then the assumed value was the same as for a hydrogen boiler.

The lifetime of the device is set at 15 years, then there is an initial investment at the first year of the analysis, and a second investment at year 15. The used electric efficiency of the device is 60% and 32% heat recovery. A degradation of 2% per year for the device energy production was taken (Dodds, 2015).

As this system has the capacity to generate electricity and also heat as a result of the exothermic process then it was assumed that all the heat should come from the reaction, while the electricity will be used to cover the house demand, and the surplus will be sold back to the grid.

Again using the energy need not for heating, calculated for each building using equation 5 and 6, then the hydrogen consumption is calculated using equation 20.

Where the thermal efficiency for heat recovery of the device is 32% (Dodds, 2015) and the hydrogen HHV is 39.4 kWh/kg (The Engineering ToolBox, 2003).

Then from the hydrogen consumption it can be calculated the electricity generation using equation 21. The degradation percentage is used to calculate the electricity generation from the system each year.

Then as the electricity production is higher than the electricity demand for the residence, then to calculate the electricity generation discount equation 22 was used, also considering that the electricity sold back to the grid will have one third of the retail price (Zonnefabriek, 2023).

The yearly operational cost is a function of the fuel consumption (hydrogen) and is calculated using equation 23 Also using the same hydrogen price as for PEM (Clean Hydrogen Partnership, 2024).

Central Inverter Heat Pump

Initial investment and installation cost are calculated as a function of the heating system capacity using equation 24 according to (Mitterrutzner, Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, 2023) as for a normal heat pump multiplied by a factor of 1.15 according to (Abid, 2021).

$$CAPEX_{Central\ Inverter\ HP}\ [€] = 1080 * Heating\ System\ Capacity\ [kW] * 1.15 \quad eq. 24$$

The maintenance cost is assumed as 4% of the initial CAPEX based on (Mitterrutzner, Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, 2023).

The lifetime of the device is set at 20 years, then there is only one initial investment at the first year of the analysis.

The average COP per month was calculated using the data from (Abid, 2021), this type of heat pump resents a slightly higher COP than air to air due to better control range.

These values were plotted and then a linear regression was performed as can be seen in figure 52, were also the line equation is presented together with the R^2 value.

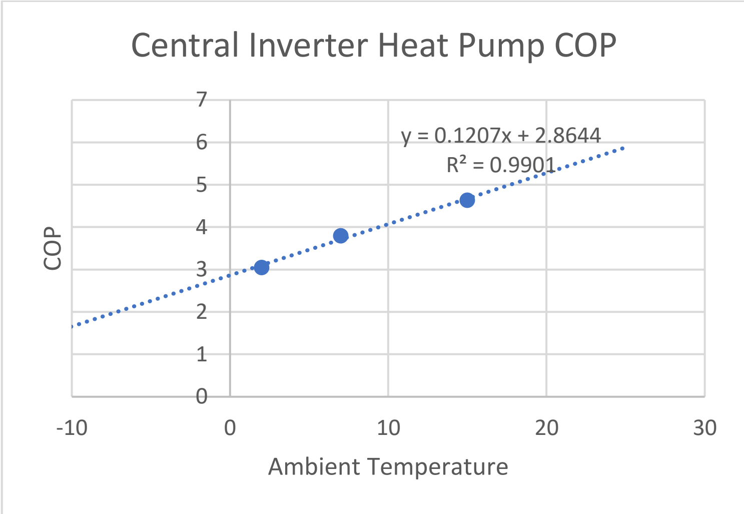

Figure 52, COP as a function of ambient temperature for a central inverter heat pump (Abid, 2021)

By using the equation displayed in the graph we can calculate the daily COP of the heat pump by replacing T with the average temperature for each day (see section *Annexes, Weather Data*). Then the monthly average is taken and finally the monthly energy consumption can be calculated using equation 14.

After that the yearly energy consumption is totalized and the operational cost can be calculated using equation 15.

Natural Refrigerant Heat Pump

Initial investment and installation cost are calculated as a function of the heating system capacity using equation 25 according to (Mitterrutzner, Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, 2023), as for a normal heat pump multiplied by a factor of 1.2 according to (Atmo Sphere, 2022), this is justified by a 20% increase in cost in the production line due to the need to introduce safety control systems as natural refrigerants are usually flammable, then it will be assumed that this 20% increase is directly proportional to the CAPEX.

$$CAPEX_{Nat\ Refr\ HP}\ [€] = 1080 * Heating\ System\ Capacity\ [kW] * 1.2 \quad eq. 25$$

The maintenance cost is assumed as 4% of the initial CAPEX based on (Mitterrutzner, Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, 2023).

The lifetime of the device is set at 20 years, then there is only one initial investment at the first year of the analysis.

The average COP per month was calculated using the data from (Zendehboudi, 2021).

These values were plotted and then a linear regression was performed as can be seen in figure 52, were also the line equation is presented together with the R^2 value.

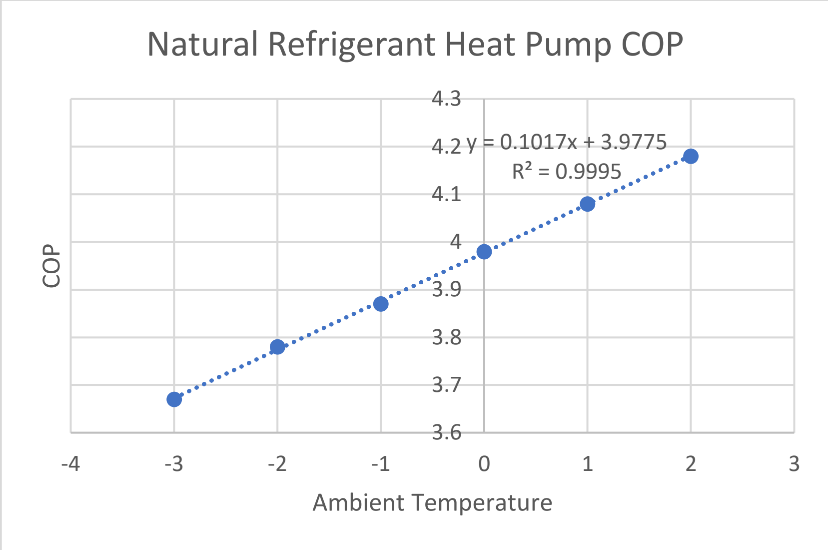

Figure 53, COP of natural refrigerant heat pump as a function of the ambient temperature (Zendehboudi, 2021)

By using the equation displayed in the graph we can calculate the daily COP of the heat pump by replacing T with the average temperature for each day (see section *Annexes, Weather Data*). Then the monthly average is taken and finally the monthly energy consumption can be calculated using equation 14.

After that the yearly energy consumption is totalized and the operational cost can be calculated using equation 15.

Hybrid Heat Pump (Air to Air HP + Gas Boiler)

Initial investment and installation cost are calculated as a function of the heating system capacity using equation 26 according to (ECN, TNO, 2019).

$$CAPEX_{Hybrid\ HP}\ [€] = \left(\frac{561 + 1044}{2}\right) * Heating\ System\ Capacity\ [kW] \quad eq.26$$

The maintenance cost is calculated as proportional to the heating system capacity being 30€ per kW based on (ECN, TNO, 2019).

The lifetime of the device is set at 20 years, then there is only one initial investment at the first year of the analysis.

The average COP per month was calculated using the data from (ehpa, 2024), which corresponds to the COP of an air-to-air heat pump for different ambient temperature for a LWT (leaving water temperature) of 45°C. This means that the linear regression equation will be the same as for the air-to-air heat pump case.

Nevertheless as a hybrid heat pump uses a gas boiler as a backup then it was assumed that the proportion of heating supplied using the HP is 75%, and 25% using gas, this was the value to cover for all days with a COP lower than 3, this behavior was corroborated also with (ECN, TNO, 2019).

Then, the electricity consumption based on the heat pump COP, and the gas consumption based on the monthly demand and the gas boiler efficiency.

To define the share of gas boiler and heat pump use the percentage of cases where the COP ranges from 2 to 5 was calculated from the weather and COP table based on 0.1 increases and then the for the lower 11% of the cases it was assumed that the gas boiler will be used which corresponds to around 75-25 distribution.

Table 25 presents the intervals considered as well as the number of days for each interval and the percentage of days represented by this same interval (data for the Berlin case).

Lower Lim	*Upper Lim*	*Days*	*Share*
2	2.1	0	0.00%
2.1	2.2	0	0.00%
2.2	2.3	0	0.00%
2.3	2.4	0	0.00%
2.4	2.5	0	0.00%
2.5	2.6	0	0.00%
2.6	2.7	0	0.00%
2.7	2.8	0	0.00%
2.8	2.9	0	0.00%
2.9	3	0	0.00%
3	3.1	12	4.40%
3.1	3.2	15	5.49%
3.2	3.3	14	5.13%
3.3	3.4	8	2.93%
3.4	3.5	16	5.86%
3.5	3.6	21	7.69%
3.6	3.7	15	5.49%
3.7	3.8	21	7.69%
3.8	3.9	22	8.06%
3.9	4	16	5.86%
4	4.1	14	5.13%
4.1	4.2	14	5.13%
4.2	4.3	19	6.96%
4.3	4.4	8	2.93%
4.4	4.5	11	4.03%
4.5	4.6	4	1.47%
4.6	4.7	1	0.37%
4.7	4.8	2	0.73%
4.8	4.9	0	0.00%
4.9	5	0	0.00%
5	5.1	0	0.00%

Table 25, Lower and upper limits for the COP evaluation for the hybrid heat pump and occurrence days

Then in table 26 the average COP per month is shown (also for the Berlin case), then also the affected days, meaning the days where the COP is lower than 3, as well as the percentage of these days for each month and the estimated demand reduction percentage for the heat pump.

Month	*Average COP*	*Affected Days*	*Percentage of days per month*	*Estimated Demand Reduction Percentage*
SEPT	4.176234	0	0.000	1.000
OCT	4.077849	0	0.000	1.000
NOV	3.581455	5	0.167	0.833
DEC	3.430004	14	0.467	0.533
JAN	3.489114	9	0.300	0.700
FEB	3.371857	7	0.233	0.767

MAR	3.549003	5	0.167	0.833
APR	3.666251	0	0.000	1.000
MAY	4.20313	0	0.000	1.000

Table 26, Average monthly COP for the Berlin Case for the hybrid heat pump

The same process is followed for the Amsterdam case and the factors are multiplied by the monthly heating demand for each building type, the results can be seen in table 27 for Germany (Berlin) and table 28 for The Netherlands (Amsterdam).

Building/Demand	*Sep*	*Oct*	*Nov*	*Dec*	*Jan*	*Feb*	*Mar*	*Apr*	*May*
DE.N.SFH.04.Gen	1.0000	1.0000	0.8333	0.5333	0.7000	0.7667	0.8333	1.0000	1.0000
HP Demand (MWh)	0.0000	0.8921	1.8974	1.9316	2.9453	2.6950	2.1748	1.0120	0.2130
GB Demand (MWh)	0.0000	0.0000	0.3795	1.6901	1.2623	0.8202	0.4350	0.0000	0.0000
DE.N.SFH.09.Gen	1.0000	1.0000	0.8333	0.5333	0.7000	0.7667	0.8333	1.0000	1.0000
HP Demand (MWh)	0.0000	0.6555	1.3941	1.4192	2.1640	1.9801	1.5979	0.7435	0.1565
GB Demand (MWh)	0.0000	0.0000	0.2788	1.2418	0.9274	0.6026	0.3196	0.0000	0.0000
DE.N.MFH.04.Gen	1.0000	1.0000	0.8333	0.5333	0.7000	0.7667	0.8333	1.0000	1.0000
HP Demand (MWh)	0.0000	4.3112	9.1694	9.3345	14.2335	13.0237	10.5099	4.8903	1.0295
GB Demand (MWh)	0.0000	0.0000	1.8339	8.1677	6.1001	3.9637	2.1020	0.0000	0.0000
DE.N.MFH.09.Gen	1.0000	1.0000	0.8333	0.5333	0.7000	0.7667	0.8333	1.0000	1.0000
HP Demand (MWh)	0.0000	3.6985	7.8663	8.0080	12.2107	11.1729	9.0163	4.1954	0.8832
GB Demand (MWh)	0.0000	0.0000	1.5733	7.0070	5.2332	3.4004	1.8033	0.0000	0.0000

Table 27, Monthly eat pump demand and gas boiler demand in MWh for the Berlin case for the hybrid heat pump

Building/Demand	*Sep*	*Oct*	*Nov*	*Dec*	*Jan*	*Feb*	*Mar*	*Apr*	*May*
NL.N.SFH.02.Gen	1.0000	1.0000	0.8333	0.5333	0.7000	0.7667	0.8333	1.0000	1.0000
HP Demand (MWh)	0.0000	0.6187	1.8650	1.9870	2.9028	2.8462	2.4136	1.3691	0.3818
GB Demand (MWh)	0.0000	0.0000	0.3730	1.7386	1.2441	0.8662	0.4827	0.0000	0.0000
NL.N.SFH.05.Gen	1.0000	1.0000	0.8333	0.5333	0.7000	0.7667	0.8333	1.0000	1.0000
HP Demand (MWh)	0.0000	0.5097	1.5363	1.6368	2.3913	2.3446	1.9882	1.1278	0.3145
GB Demand (MWh)	0.0000	0.0000	0.3073	1.4322	1.0248	0.7136	0.3976	0.0000	0.0000
NL.N.MFH.02.Gen	1.0000	1.0000	0.8333	0.5333	0.7000	0.7667	0.8333	1.0000	1.0000
HP Demand (MWh)	0.0000	14.3038	43.1142	45.9344	67.1061	65.7974	55.7949	31.6509	8.8257
GB Demand (MWh)	0.0000	0.0000	8.6228	40.1926	28.7597	20.0253	11.1590	0.0000	0.0000
NL.N.MFH.05.Gen	1.0000	1.0000	0.8333	0.5333	0.7000	0.7667	0.8333	1.0000	1.0000
HP Demand (MWh)	0.0000	3.9178	11.8089	12.5814	18.3803	18.0218	15.2822	8.6692	2.4174
GB Demand (MWh)	0.0000	0.0000	2.3618	11.0087	7.8773	5.4849	3.0564	0.0000	0.0000

Table 28, Monthly eat pump demand and gas boiler demand in MWh for the Amsterdam case for the hybrid heat pump

Then for the heat pump demand the values are divided by the monthly average COP in order to obtain the actual electricity demand, while for the gas demand the efficiency is again assumed as 94% to calculate the actual gas consumption.

Then, the total operational cost can be calculated using equation 27.

$$Operational\ Cost[€] = Annual\ Elec\ Consumption\ [kWh] * Elec\ Price\left[\frac{€}{kWh}\right] +$$

$$Annual\ Gas\ Consumption\ [kWh] * Gas\ Price\left[\frac{€}{kWh}\right] \quad eq. 27$$

Synthetic Methane Heat Pump

Initial investment and installation cost are calculated as a function of the heating system capacity using equation 28 according to (Carlsson, 2017), also considering that in this study only a 18 kW model is considered, then this price might not representative for the market.

$$CAPEX_{Synthetic\ Methane\ HP}\ [€] = 867 * Heating\ System\ Capacity\ [kW] \quad eq. 28$$

The maintenance cost is assumed as a set value of 135€ per year according to (Carlsson, 2017).

The lifetime of the device is set at 21 years, then there is only one initial investment at the first year of the analysis.

As the performance will not be as dependent on the ambient temperature as for other heat pumps due to the working principle of the device, then the COP will be assumed as constant and equal to 1.7 (Carlsson, 2017). Also, the LHV used for methane is 13.9 kWh/kg (The Engineering ToolBox, 2003).

The annual gas consumption is calculated equation 29.

$$Annual\ Gas\ Consumption\ [kg] = \frac{Annual\ heating\ Demand\ [kWh]}{Average\ COP * LHV_{Methane} \left[\frac{kWh}{kg}\right]} \quad eq. 29$$

After that, the operational cost can be calculated using equation 30.

$$Operational\ Cost[€] = Annual\ Gas\ Consumption\ [kg] * Gas\ Price \left[\frac{€}{kg}\right] \quad eq. 30$$

The price of methane is assumed as equal to natural gas price as it is the main mixture component, in reality the main issue will be the supply of pure methane (The Engineering ToolBox, 2003).

High Vacuum Flat Plate Collector Heat Pump

According to the literature review, the system achieves higher efficiency and a representative SPF increase by using solar thermal for hot tap water, then the inclusion of a 3.5kW solar thermal collector will be considered (Carlsson, 2017).

Initial investment and installation cost are calculated as a function of the heating system capacity using equation 31 according to (Carlsson, 2017), considering data for a small 20kW heat pump plus a 3.5 kW solar thermal collector.

$$CAPEX_{High\ Vacum\ FPC-\ HP}\ [€] = 808 * Heating\ System\ Capacity\ [kW] + 800 \quad eq. 31$$

The maintenance cost is assumed as a fixed value of 361€ per year also according to previous source (Carlsson, 2017). The lifetime of the device is set at 20 years, then there is only one initial investment at the first year of the analysis.

Also, according to (Carlsson, 2017), it is considered that the use of solar collectors in the system only affects by an increase in the SPF between 10% and 20%, then it is assumed the same COP as a normal air to air HP multiplied by a 1.15 factor.

Once again, the yearly energy consumption is totalized, and the operational cost can be calculated using equation 14.

Absorption Heat Pump (Thermally Driven)

Initial investment and installation cost are calculated as a function of the heating system capacity using equation 28 according to (Carlsson, 2017), considering the 18 kW model.

The maintenance cost is assumed as a set value of 135€ per year according to (Carlsson, 2017). The lifetime of the device is set at 21 years, then there is only one initial investment at the first year of the analysis.

It is a more general case for the synthetic methane heat pump, then again the performance will not be as dependent on the ambient temperature as for other heat pumps due to the working principle of the device, then the COP will be assumed as constant and equal to 1.7 (Carlsson, 2017). Also, the LHV used for natural gas is 13.1 kWh/kg (The Engineering ToolBox, 2003).

The annual gas consumption is calculated equation 32.

$$Annual\ Gas\ Consumption\ [kg] = \frac{Annual\ heating\ Demand\ [kWh]}{Average\ COP * LHV_{Natural\ Gas}\left[\frac{kWh}{kg}\right]} \quad eq.32$$

After that, the operational cost can be calculated using equation 30.

Adsorption Heat Pump (Thermally Driven)

Initial investment and installation cost are calculated as a function of the heating system capacity using equation 33 according to (Carlsson, 2017).

$$CAPEX_{Adsorption\ HP}\ [€] = 933 * Heating\ System\ Capacity\ [kW] \quad eq.33$$

The maintenance cost is assumed as a set value of 135€ per year according to (Carlsson, 2017). The lifetime of the device is set at 20 years, then there is only one initial investment at the first year of the analysis.

Also due to the working principle of the device, then the COP will be assumed as constant and equal to 1.45 (Carlsson, 2017). Also, the LHV used for natural gas is 13.1 kWh/kg (The Engineering ToolBox, 2003).

The annual gas consumption is calculated equation 34.

$$Annual\ Gas\ Consumption\ [kg] = \frac{Annual\ heating\ Demand\ [kWh]}{Average\ COP * LHV_{Natural\ Gas}\left[\frac{kWh}{kg}\right]} \quad eq.34$$

Then the yearly energy consumption is totalized, and the operational cost can be calculated using equation 35.

$$Operational\ Cost[€] = \frac{Annual\ Energy\ Consumption\ [kWh]}{Average\ COP} * Gas\ Price\left[\frac{€}{kWh}\right] \quad eq.35$$

Cold Climate Air Source Heat Pump

Initial investment and installation cost is estimated according to (Wu, 2022), where several cases are presented, then the average price for a system bellow 10000 USD (assumed small devices) for cases with SFH as the demand is below 4 kW, while for the MFH the average is considered for the values higher than 10000 USD corresponding to high heating demand. Also, the used conversion rate from USD to euros is 0.93 €/USD (Wu, 2022). It is important to mention that this study is based on the US market, then these prices can vary for the European market.

The calculated average value is €5110 for SFH size devices, and €16083 for MFH.

The maintenance cost is assumed as 4% of the initial CAPEX based on (Mitterrutzner, Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, 2023).

The lifetime of the device is set at 20 years, then there is only one initial investment at the first year of the analysis.

The average COP per month was calculated using the data from (Ramaraj, 2023).

The COP values from the literature were plotted and then a linear regression was performed as can be seen in figure 54, were also the line equation is presented together with the R^2 value.

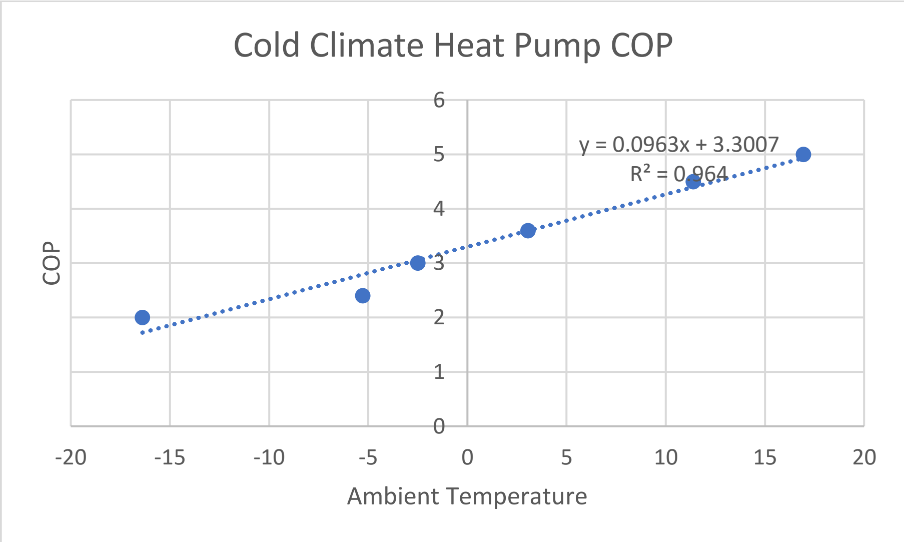

Figure 54, COP for cold climate heat pump as a function of the ambient temperature (Ramaraj, 2023)

By using the equation displayed in the graph we can calculate the daily COP of the heat pump by replacing T with the average temperature for each day (see section *Annexes, Weather Data*). Then the monthly average is taken and finally the monthly energy consumption can be calculated using equation 14.

After that the yearly energy consumption is totalized and the operational cost can be calculated using equation 15.

Combined Solar PV and Heat Pump

Initial investment and installation cost are calculated as a function of the heating system capacity using equation 36 according to (Mitterrutzner, Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, 2023), it should be considered that the CAPEX will have two different components, considering the heap pump itself plus the cost of the PV system. For the CAPEX in the given research paper (Schreurs, 2021) the HP has a capacity of 52 kW, when scaling down to 3 kW and calculating the equivalent capacity of the solar system then we can also scale down the price of the solar system with the same fraction. According to the same reference a fraction of the heating system capacity is taken to size the PV system, this fraction corresponds to 24/52. Then the cost of the PV system can be estimated by using the same case study and applying an economies of scale approach, this corresponds to the las part of equation 36.

$$CAPEX_{PV+HP}\ [€] = CAPEX_{Air\ to\ Air\ HP}[€] + \left(28053 * \frac{Heating\ System\ Capacity[kW]}{52}\right)[€] \quad eq.36$$

In the same way the electricity self-consumption for the HP, the electricity from the grid and the electricity back to the grid will be estimated based on (Schreurs, 2021). First the COP of the heat pump was defined as the same COP for a regular air to air heat pump, then the monthly heating demand was divided by the corresponding average COP obtaining the energy required by the heat pump to fulfill the heating demand.

The self-consumption was defined based on a fraction obtained from the Austrian case study (Schreurs, 2021), presented in equation 37, considering table 5 for AWHP+PV and from the values calculate the fraction of the total electricity consumption of the heat pump that is provided by the PV . The electricity from the grid was assumed as the remaining amount to fulfill the demand (equation 38). Finally, the electricity back to the grid was also calculated using a fraction obtained from the same reference (equation 39), this was done considering the total self-consumption that goes back to the total PV electricity generation according to the paper values, and then generating a fraction with the values back to the grid.

$$Elec.\ Self\ Consumption\ [kWh] = HP\ Elec. Consumption\ [kWh] * \frac{16087}{43415} \quad eq. 37$$

$$Elec. from\ the\ Grid\ [kWh] = HP\ Elec. Consumption\ [kWh] - Elec.\ Self\ Consumption\ [kWh] \quad eq. 38$$

$$Elec. back\ to\ the\ Grid\ [kWh] = \frac{Elec.\ Self\ Consumption\ [kWh]}{0.7} * \frac{6750}{22837} \quad eq. 39$$

These values were calculated for each country and each building and then totalized per year to finally obtain the

The maintenance cost is assumed as percentage of the CAPEX corresponding to 4% per year according to (Mitterrutzner, Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, 2023). The lifetime of the device is set at 20 years, then there is only one initial investment at the first year of the analysis.

The electricity sold back to the grid is calculated using equation 40, the fraction of 1/3 of the price is also applied here as was done with the hydrogen-based technologies (Zonnefabriek, 2023).

$$Elec. Sold\ Back\ to\ the\ Grid\ [€] = Elec. back\ to\ the\ Grid\ [kWh] * \frac{Elec\ Price}{3} \left[\frac{€}{kWh}\right] \quad eq. 40$$

The yearly operational cost can be calculated using equation 41 based on the electricity from the grid.

$$Operational\ Cost[€] = Elec. from\ the\ Grid\ [kWh] * Elec\ Price \left[\frac{€}{kWh}\right] \quad eq. 41$$

High Temperature Heat Pump

Initial investment and installation cost is estimated for HP bellow 100 kW capacity (for really small HP it should be higher), also considering that this technology makes sense for water heating or to avoid the need for insulation or adapting the radiators (Kosmadakis, 2020), the used equation is presented below (equation 42).

$$CAPEX_{High\ T\ HP}\ [€] = 900 * Heating\ System\ Capacity\ [kW] \quad eq. 42$$

The maintenance cost is assumed as 4% of the initial CAPEX (the same as for an air source heat pump), based on (Mitterrutzner, Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, 2023).

The lifetime of the device is set at 20 years, then there is only one initial investment at the first year of the analysis.

The average COP per month was calculated using the data from (Kosmadakis, 2020). For the researched case study, the ambient temperature and COP is presented for each day between February and April, then the COP values from the literature were plotted and then a linear regression was performed as can be seen in figure 54, were also the line equation is presented together with the R^2 value.

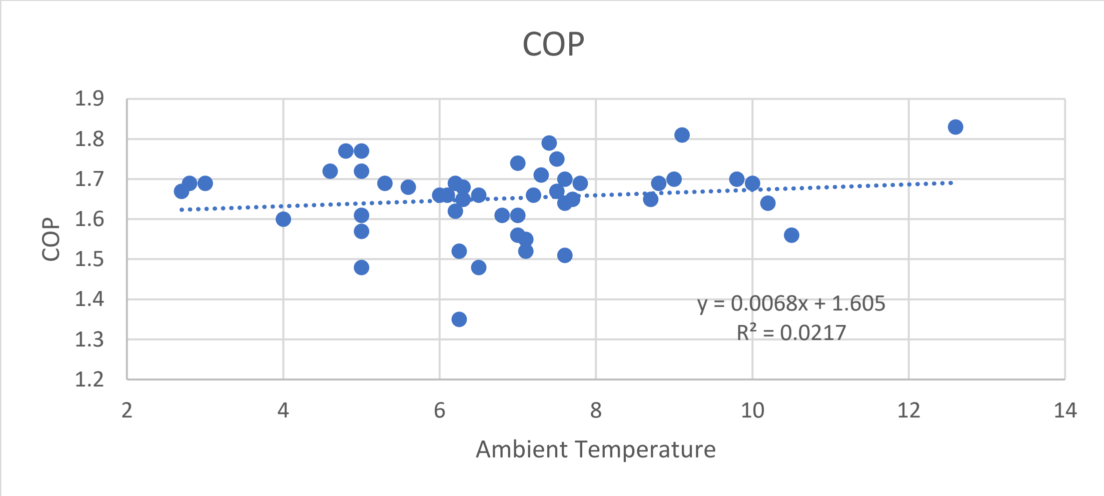

Figure 55, COP as a function of ambient temperature based on several case studies by (Kosmadakis, 2020)

By using the equation displayed in the graph we can calculate the daily COP of the heat pump by replacing T with the average temperature for each day (see section *Annexes, Weather Data*). Then the monthly average is taken and finally the monthly energy consumption can be calculated using equation 14.

After that the yearly energy consumption is totalized and the operational cost can be calculated using equation 15.

Hydrogen-Enriched Natural Gas Heat Pump

Initial investment and installation cost are calculated as a function of the heating system capacity using equation 43 according to (Carlsson, 2017), considering the 18 kW model as the closest case (absorption heat pump).

$$CAPEX_{Hydrogen\ Enriched\ HP}\ [€] = 933 * Heating\ System\ Capacity\ [kW] \quad eq. 43$$

The maintenance cost is assumed as a set value of 135€ per year according to (Carlsson, 2017).

The lifetime of the device is set at 20 years, then there is only one initial investment at the first year of the analysis. The used COP for the device is 1.45 and is considered constant along the year due to the working principle of the heat pump (Carlsson, 2017).

The fraction of pure hydrogen in the mixture is assumed as 10% fraction by volume, according to (Sforzini, 2020). This will influence the LHV value of the blend (14.16 kWh/kg (Sforzini, 2020)), and also the price according to equation 44.

$$Hydrogen\ Enriched\ Gas\ Price\left[\frac{€}{kg}\right] = \left(Natural\ Gas\ Price\ \left[\frac{€}{kg}\right] * 0.9\right) + \left(Hydrogen\ Price\ \left[\frac{€}{kg}\right] * 0.1\right) \quad eq. 44$$

The yearly operational cost is a function of the fuel consumption (hydrogen) and is calculated as follows (equation 45).

$$Operational\ Cost[€] = \frac{Annual\ Heating\ Demand\ [kWh] * Hydrogen\ Enriched\ Gas\ Price\left[\frac{€}{kg}\right]}{Efficiency * LHV_{Hydrogen\ Enriched\ Gas}\left[\frac{kWh}{kg}\right]} \quad eq. 45$$

The price of hydrogen is taken as the higher end from the most common price range (4-6 EUR/kg - 31.37%) according to (Clean Hydrogen Partnership, 2024).

Metal Hydride Heat Pump

The cost for the metal hydride is based on literature and price for each metal hydride per mass used, also as a fraction of the capacity from a case study in the research paper (Krane, 2022). The CAPEX is then based on the same source and on the amount of metal hydrides as a proportional fraction of the case study, in this case the analyzed heat pump was 10.55 kW, then for each case depending on the heating system capacity everything was scaled accordingly. The prices data can be seen in table 29.

Metal Hydrides	*Delta H absorption (MJ/kg M)*	*Delta H Desorption (MJ/kg M)*	*Average Delta H (kWh/kg M)*	*Cost (€/kg)*	*Kg used in the study*
MnNiCr	11.67	12.65	3.377778	16.74	470
LaNi	15.46	15.95	4.3625	13.95	412

Table 29, Properties and cost of MnNiCr and LaNi (Krane, 2022)

The kg needed for each case are calculated based on the average kg of metal hydride per kW which corresponds to around 44.55 kg of MnNiCr per kW and 39.05 kg of LaNi per kW. Finally, the initial investment and installation cost was calculated using equation 46.

$$CAPEX_{Metal\ Hydride\ HP}\ [€] = 4864 + 110 + 200 + 2351 + m_{MnNiCr}[kg] * Price_{MnNiCr}\left[\frac{€}{kg}\right] + m_{LaNi}[kg] * Price_{LaNi}\left[\frac{€}{kg}\right] \quad eq. 46$$

The maintenance cost is assumed as a 4% of the CAPEX according (Carlsson, 2017).

The lifetime of the device is set at 20 years, then there is only one initial investment at the first year of the analysis.

As the performance will not be as dependent on the ambient temperature as for other heat pumps due to the working principle of the device, then the COP will be assumed as constant and equal to 2.2 (Malleswararao, 2022).

Then the operational cost can be calculated using equation 47.

$$Operational\ Cost[€] = Annual\ Elec. Consumption\ [kWh] * Elec. Price\left[\frac{€}{kWh}\right] \quad eq. 47$$

Vuilleumier Heat Pump

Initial investment and installation cost Assumed the same as for an air-to-air heat pump due to lack of data as the device is not commercial yet (equation 13).

The maintenance cost is assumed as 4% of the initial CAPEX (the same as for an air source heat pump), based on (Mitterrutzner, Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, 2023).

The lifetime of the device is set at 20 years, then there is only one initial investment at the first year of the analysis.

The average COP per month was calculated using the data from (Luo, 2022).

The COP values from the literature were plotted and then a linear regression was performed as can be seen in figure 56, were also the line equation is presented together with the R^2 value, once again the device is still in development, then there is a lack of technical information.

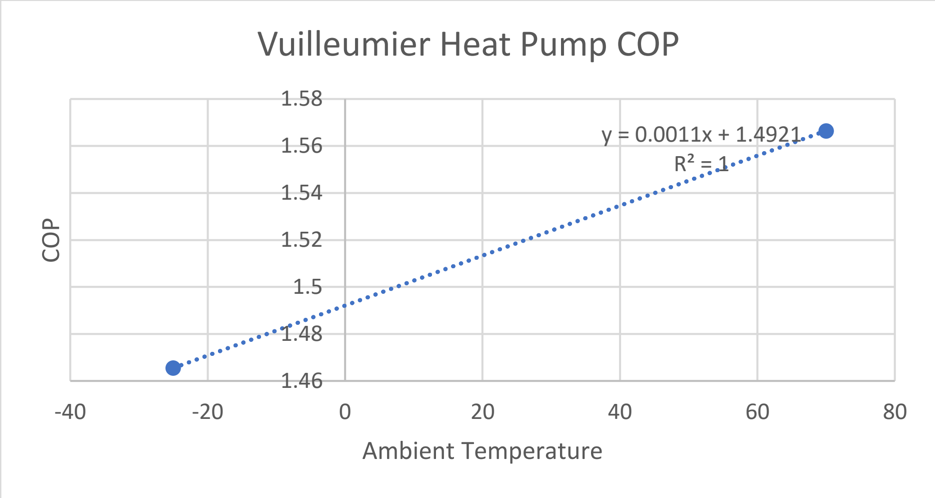

Figure 56, COP as a function of the ambient temperature for a Vuilleumier heat pump (Luo, 2022)

By using the equation displayed in the graph we can calculate the daily COP of the heat pump by replacing T with the average temperature for each day (see section *Annexes, Weather Data*). Then the monthly average is taken and finally the monthly energy consumption can be calculated using equation 14.

After that the yearly energy consumption is totalized and the operational cost can be calculated using equation 15.

Thermo-Acoustic Heat Pump

According to the literature review (Hu, 2023), the system needs a higher inlet temperature and the case study suggested the use of a flat plate collector for the heat source, then the inclusion of a 3.5kW solar thermal collector will be considered (the same as for the high vacuum system) (Carlsson, 2017).

Initial investment and installation cost are calculated as a function of the heating system capacity using equation 48 according to (Carlsson, 2017), considering data for a small 20kW heat pump plus a 3.5 kW solar thermal collector.

$$CAPEX_{High\,Vacum\,FPC-\,HP}\,[€] = 808 * Heating\ System\ Capacity\,[kW] + 800 \quad eq.48$$

The maintenance cost is assumed as a fixed value of 361€ per year also according to previous source (Carlsson, 2017). The lifetime of the device is set at 30 years, then there is only one initial investment at the first year of the analysis (Equium, 2023).

The COP is based on the high vacuum flat plate collector heat pump case, and a factor of 1.4 is assumed to multiply the average COP value as can be seen in equation 49 (Hu, 2023).

$$COP_{Thermo-Acoustic\,HP\,(Month\,n)} = \frac{COP_{High\,Vacuum\,HP\,(Month\,n)}}{Average\ COP_{High\,Vacuum\,HP}} * 1.4 \quad eq.49$$

Then from the COP values, the yearly energy consumption is totalized and the operational cost can be calculated using equation 15.

8.1.1.3. *KPIs Assumptions*

The selected KIPs to rank and evaluate the technologies from an economical perspective were NPV, IRR, BCR, TCO. To evaluate the performance of the technologies the SPF/efficiency and Energy Consumption per Year were used. Finally, from an environmental perspective the Operational Carbon Footprint was calculated.

NPV (Net Present Value) ↑

Current value of a future stream of payments using a discount rate. The timing and amount of future cash flows is needed as well as a constant discount rate equal to the minimum acceptable rate of return.

The discount rate can reflect the cost of capital or the returns available on alternative investments of comparable risk. If the NPV is positive it means that it´s rate of return is above the discount rate (Fernando, 2024).

The theoretical formula is presented below (equation 50):

$$NPV = \frac{Cash\ Flow}{(1+i)^t} - \boldsymbol{initial\ investment} \quad eq. 50$$

Where $i = required\ return\ or\ discount\ rate$

$t = number\ of\ time\ periods$

For multiple cash flows over time the formula is (equation 51):

$$NPV = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t} \quad eq. 51$$

Where $R_t = net\ cash\ inflow - outflows\ during\ a\ single\ period\ t$

$i = discount\ rate\ or\ return\ that\ could\ be\ earned\ in\ alternative\ investments$

$t = number\ of\ time\ periods$

The NPV is calculated with the inflation rate for each country as described in section *Techno-Economic Analysis*, also using equation 4.

IRR (Internal Rate of Return) ↑

The internal rate of return (IRR) was calculated assuming the savings for each technology as incomes when compared to a gas boiler (main traditional heating technology), this was done as to obtain a value for the IRR it is required to have positive values in the cash flow.

The IRR is the discount rate that causes the NPV to be equal to zero as presented in equation 52, nevertheless as the model was performed in excel the function *IRR* in excel was used, the obtained values are presented in the section *Annexes, Economic KPIs*.

$$0 = NPV = \sum_{t=1}^{T} \frac{C_t}{(1+IRR)^t} - C_0 \quad eq. 52$$

Where C_t is the net cash flow during the period t, C_0 is the total initial investment cost and t is the number of time periods (Fernando, Internal Rate of Return (IRR) Formula and Examples, 2024). It is important to notice that as certain technologies are actually more expensive than a gas boiler then there is no number for the IRR that will cause the NPV to be positive, then for those cases it cannot be calculated.

BCR (Benefit Cost Ratio) >1 ↑

Summarize the overall relationship between the relative costs and benefits of a project. Can be expressed in monetary or qualitative terms. Can not be properly representative in large projects because it uses many assumptions and uncertainties that are hard to quantify. Also does not provide any sense of how much economic value will be created.

For the benefit cost ratio (BCR) the same scheme is used as for the IRR, in order to have positive cash flow, nevertheless for the technologies that still are more expensive than a gas boiler the BCR is equal to zero, as there is no benefit (Hayes, 2024). The equation used is presented below (equation 53).

$$BCR = \frac{Income\ (savings)\ compared\ to\ Gas\ Boiler}{Initial\ Investment} \quad eq.53$$

Total Cost of Ownership (TCO) ↓

Purchase price plus the cost of operation includes the long-term costs and expenses incurred during the products useful life and disposal to assess the better value in the long run.

Usually, the cost of purchase is booked as a capital expenditure, while the cost of operation is part of operating expenditures, the TCO brings together both values to see the bigger picture of the investment.

Also, usually considers the initial purchase price, the costs associated with the operation, the maintenance, the training needed and how long the item is expected to las before a replacement is needed.

The theoretical formula is formula (equation 54):

$$TCO = Initial\ Investment + OPEX\ (NPV) \quad eq.54$$

The total cost of ownership (TCO) is calculated as the OPEX plus the initial investment (Twin, 2024).

SPF (Seasonal Performance Factor) ↑

The seasonal performance factor (SPF) is compared with efficiency for the devices that are not heat pumps, also for the heat pumps the average COP during the heating season is taken.

Could be defined as follows for a system approach (equation 55):

$$SPF = \frac{Q_{\sup tot}}{E_{el\ tot} + E_{aux} + Q_{fossil}} \quad eq.55$$

This form can change depending on the context of the system.

Energy Consumption ↓

The energy consumption is the total annual energy consumption for the device operation. In the cases where the devices use fuel instead of electricity, the values are turned into kWh by using the heating value considering the efficiency of the device (total fuel used).

Operational Carbon Footprint ↓

Carbon emissions related to the device operation (energy consumption). It is assumed that the electricity used is from the grid, then the carbon fraction is taken from the literature for each case (electricity, gas and heating oil). The values for Germany can be seen in table 30 and for The Netherlands in table 31.

Energy Source	*Carbon Fraction*	*Source*
Electricity Carbon Footprint (kg CO2eq/kWh)	0.354	(Nowtricity, 2024)
Gas Carbon Footprint (kg CO2eq/kWh)	0.20088	(Juhrich, 2022)
Oil Carbon Footprint (kg CO2eq/kWh)	0.2664	(Juhrich, 2022)

Table 30, Carbon fraction for different energy sources for Germany (references in the table)

Energy Source	*Carbon Fraction*	*Source*
Electricity Carbon Footprint (kg CO2eq/kWh)	0.145	(Nowtricity, 2024)
Gas Carbon Footprint (kg CO2eq/kWh)	0.20088	(Juhrich, 2022)
Oil Carbon Footprint (kg CO2eq/kWh)	0.2664	(Juhrich, 2022)

Table 31, Carbon fraction for different energy sources for The Netherlands (references in the table)

For the carbon footprint the carbon fraction for methane is assumed as equal to the carbon fraction of natural has, also for the hydrogen enriched gas, the carbon fraction is calculated based on the proportion of hydrogen (assumed as 10% green hydrogen).

For the carbon footprint all the hydrogen is assumed as green hydrogen, hence carbon footprint is zero.

8.1.1.4. CAPEX Variation (Germany vs. The Netherlands)

An extensive list of different technologies was found based on two sources presented below, where they mention an average price range for HP and other heating technologies for each country.

For Germany: (HP (probably W to W) €18750-€37500) (Statista, 2024)

For The Netherlands: (HP W to W €13000-€17000) (HuisAssist, 2023)

This could represent an increase in the CAPEX in Germany of around 44% to even 120%. Nevertheless, this data does not come from a study standardized enough, then it will not be directly used for the techno-economic analysis but is a good indicator.

It could be assumed as such for the system approach, as in this case the technologies are more general, as a conservative approach the increase will be taken as 50% more for Germany in respect to The Netherlands prices.

As it is shown in the graph from IEA the CAPEX for air to air HP, air to water HP and gas boilers is higher than in many countries from the EU, the graph presents selected countries (The Netherlands is not among them, but the values will be assumed as similar to Denmark as the cost of living and specifically the cost for primary services including energy and heating is similar with only 10% difference (Numbeo, 2024)).

Representative CAPEX values (without considering any subsidy) are the presented in table 32 (IEA, 2022):

CAPEX	*Germany 2022*	*Denmark 2022*	*Relative Difference*
AAHP	73	13	17.8%
AWHP	74	23	31.1%
Gas Boiler	29	15	51.7%

Table 32, Reference CAPEX values for several technologies for Germany and Denmark (IEA, 2022)

Then the base prices for the initial investment in the technoeconomic analysis will be taken as the prices for Germany, this means that in average the prices will be 33.53% for The Netherlands relative to the prices in Germany (average relative difference).

8.2. System Approach

For the system approach the software Polysun was used to simulate the different system combinations, the figure bellow (figure 57) describes the inputs, calculations and outputs for the process.

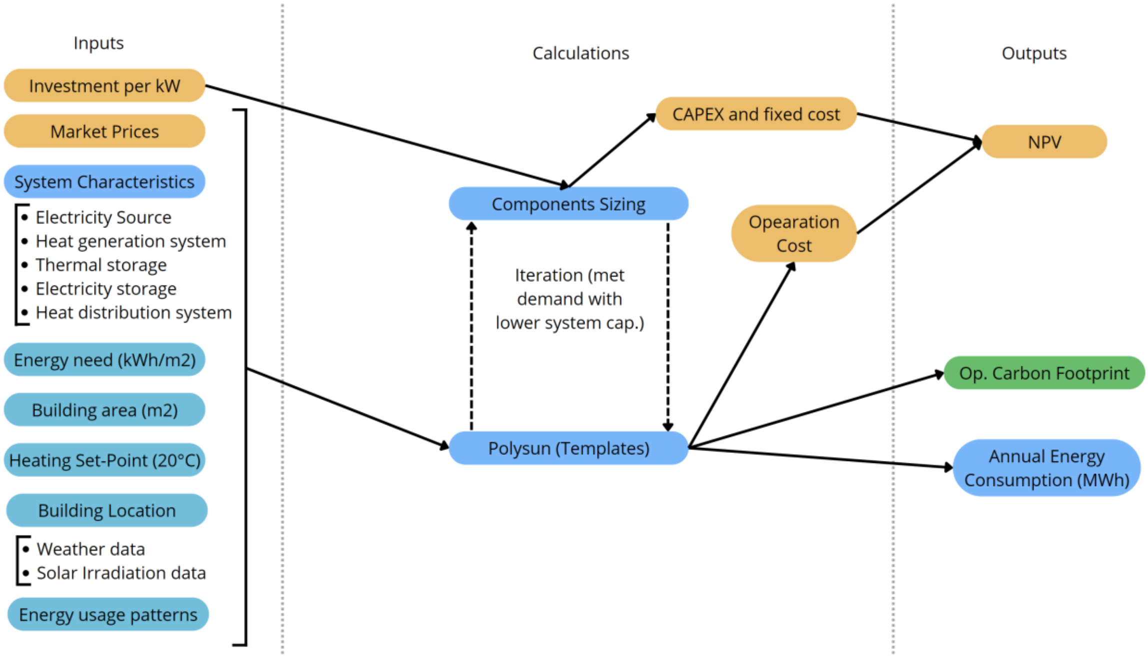

Figure 57, Block diagram with inputs, calculations and outputs for the system approach simulation using Polysun

The diagram describes the different inputs for the software based on technical and economic aspects (the weather data, solar irradiation data are based on the buildings location), and the software internally calculates the operational carbon footprint of the system. An important remark for this part of the study is that the components size was manually changed and iterated to obtain the smallest possible system capacities that will fulfill the heating demand for each case, this is also based on the data base in the software and on commercial values for the components. The system calculates the operational cost, the carbon footprint and the annual energy consumption, then the final addition to obtain the NPV was to use the different equations and values described in section *Methodology, Techno-Economic Analysis, Assumption, For the Technologies* to obtain the devices cost as a function of the system capacity.

Now, as shown in the diagram, the main variables to define the type of system were based on 6 aspects:

- Electricity Source (can be only from the grid (GR) or in combination with PV panels (PV))
- Solar Thermal (can be solar thermal (ST), photovoltaic thermal (PVT) or not in the system (NT))
- Boiler (can be a gas boiler (G) as a reference case or an electric boiler (E) as a backup device)
- Heat Pump (can be an air to water heat pump (A-W), ground source heat pump (GS) or no heat pump at all (N))
- Water Tank (a water tank was always considered, but it can be used as a buffer with an electric coil resistance (COIL) or as a potable water tank (PWT))
- Battery (can be a system without battery (No-Bt) or with a lithium-ion battery (Li-Ion))

The combinations matrix is presented in table 33 below.

Photovoltaics	*Solar Thermal*	*Boiler*	*Heat Pump*	*DHW preparation method*	*Battery*	*Code*
GR	NT	G	N	COIL	No-Bt	(GR&NT)-G-(N)COIL+No-Bt
GR	NT	E	N	PWT	No-Bt	(GR&NT)-E-(N)PWT+No-Bt
GR	NT	E	A-W	COIL	No-Bt	(GR&NT)-E-(A-W)COIL+No-Bt
GR	NT	E	GS	COIL	No-Bt	(GR&NT)-E-(GS)COIL+No-Bt
GR	ST	E	A-W	COIL	No-Bt	(GR&ST)-E-(A-W)COIL+No-Bt
GR	ST	E	GS	COIL	No-Bt	(GR&ST)-E-(GS)COIL+No-Bt
PV	NT	E	A-W	COIL	No-Bt	(PV&NT)-E-(A-W)COIL+No-Bt

PV	NT	E	GS	COIL	No-Bt	(PV&NT)-E-(GS)COIL+No-Bt
PV	ST	E	A-W	PWT	No-Bt	(PV&ST)-E-(A-W)PWT+No-Bt
PV	PVT	E	GS	PWT	No-Bt	(PV&PVT)-E-(GS)PWT+No-Bt
PV	NT	E	A-W	COIL	Li-Ion	(PV&NT)-E-(A-W)COIL+Li-Ion
PV	NT	E	GS	COIL	Li-Ion	(PV&NT)-E-(GS)COIL+Li-Ion
PV	ST	E	A-W	PWT	Li-Ion	(PV&ST)-E-(A-W)PWT+Li-Ion
PV	PVT	E	GS	PWT	Li-Ion	(PV&PVT)-E-(GS)PWT+Li-Ion

Table 33, Combinations matrix for the system approach and related codes for each combination

Once the 14 cases are defined the different templates in Polysun are selected. The diagrams based on the first case for single family housing in Germany will be presented and explained in the following section. Also, it is important to mention that in order to select the most accurate template the program requires a set of input parameters that were previously defined for each case and will be presented in the assumptions section as well.

8.2.1. Assumptions

First a specified location must be selected in order to import weather data and sun irradiation patterns. Then the system presents a series of options to include and define the photovoltaic system, solar thermal system, boiler, heat pump system and chiller.

Also, the system considers consumption patterns depending on the inclusion of domestic appliances and electricity consumption, domestic hot water, space heating and it also has the option to include a pool. Related to these parameters the electric appliances and average consumption were always considered for a typical occupancy of 2 people according to the use parameters of a couple where both persons work, also considering domestic hot water demand for all cases, as well as space heating and no pool for any case.

Finally Polysun asks to define if the system is for a residential or commercial size (residential was selected), the domestic hot water preparation method based on a potable water tank, fresh water station or immersed coil or tank, this selection was remained open for all cases in order to select the template with the highest resemblance for each case (the specific values for the appliances in each case will be presented in the next section *Results, System Approach*.

Then the number of persons also for the hot water demand and the hot water temperature are set as well, in all cases this was for 2 persons and a temperature of 60°C (as we consider the use of radiators for heat distribution), as well as the daily hot water demand and the absences.

The size of the building is also defined based on the area for each case as presented in the section State of the Art, *Representative Buildings Selection* and it's taken as a square (equal length and width), also considering the number of storeys for each building according to the data from (Tabula WebTool, 2017), also the heating setpoint temperature is set at 20°C and the convector type can be either floor heating or a radiator, for all cases a radiator was used.

Then for the systems including solar energy the type of collector can be selected as well as the orientation (for all cases due south) and the tilt angle selected as equal to the latitude for each specific city. Finally, the number of collectors was adjusted as the minimum number possible to fulfill the building demand. Also, the type and size of the water tank can be selected, but for most cases it was based on the software recommendation and increased in order to ensure the demand fulfillment.

Finally the type of boiler (heat generator) can be selected with the related capacity, in the case for heat pumps also the type of heat pump can be defined as well as the capacity, and for ground source systems also the number of boreholes and the depth can be specified, this parameters were kept according to the software recommendation for the template and slightly changed when needed to have the bare minimum while keeping the demand fulfilled.

8.2.2. System Combinations Schemes

1. (GR&NT)-G-(N)COIL+No-Bt

The first case consists of a normal scheme using a gas boiler with electricity from the grid and a hot water coil storage tank. In figure 58 we can see the system layout which will remain very similar for all cases except for the building characteristics and the heat demand.

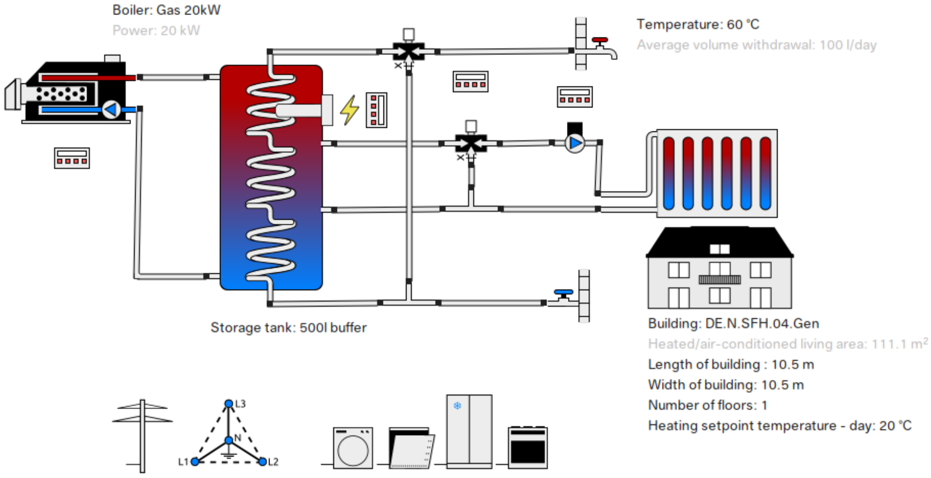

Figure 58, Diagram for the system "(GR&NT)-G-(N)COIL+No-Bt" for Germany SFH before 1978

2. (GR&NT)-E-(N)PWT+No-Bt

The second case is also a basic scheme with a electric boiler for ambient heating and an electric resistance for a potable hot water tank, this is used as a reference case to compare traditional electric boiler with heat pumps.

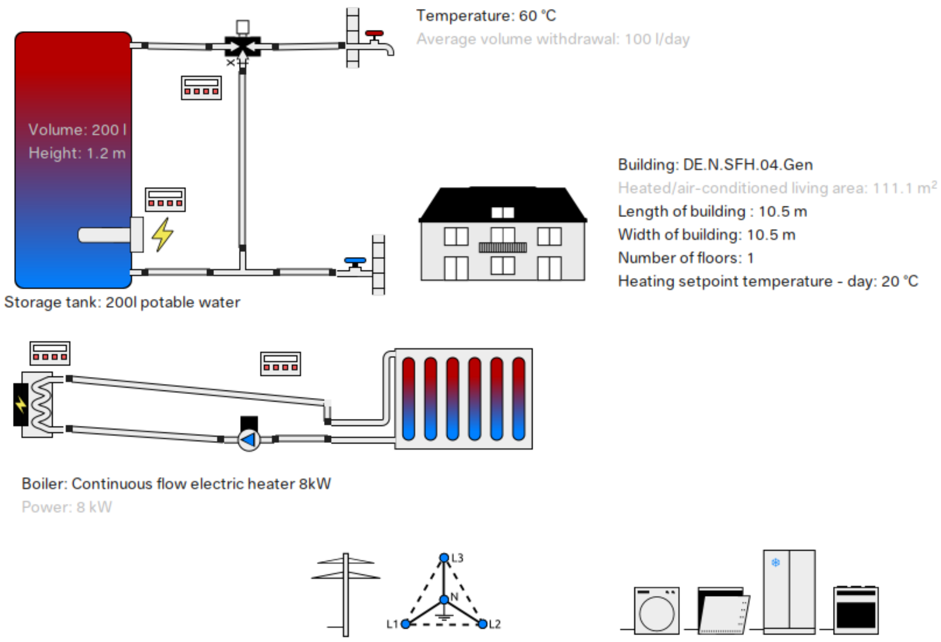

Figure 59, Diagram for the system "(GR&NT)-E-(N)PWT+No-Bt" for Germany SFH before 1978

3. (GR&NT)-E-(A-W)COIL+No-Bt

The third case is based on an air to water heat pump to provide heating and also hot water (backed up with an electric resistance when needed according to the demand behavior).

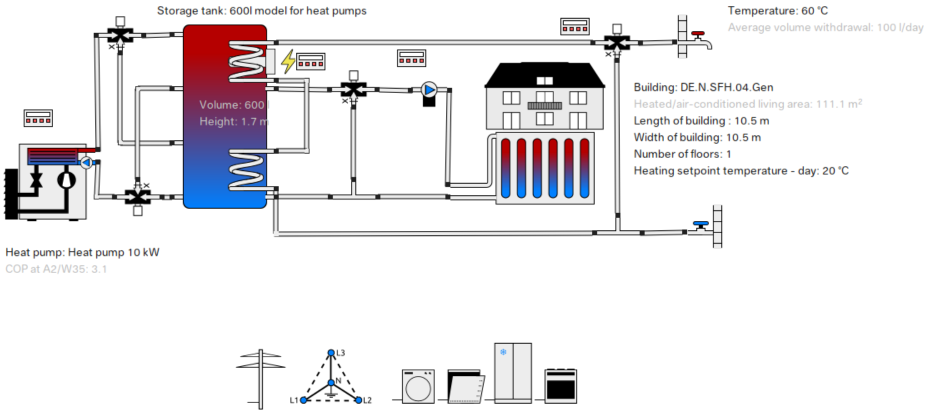

Figure 60, Diagram for the system "(GR&NT)-E-(A-W)COIL+No-Bt" for Germany SFH before 1978

4. (GR&NT)-E-(GS)COIL+No-Bt

The fourth case is also with a heat pump providing ambient heat and hot water, but this time based on a ground source loop.

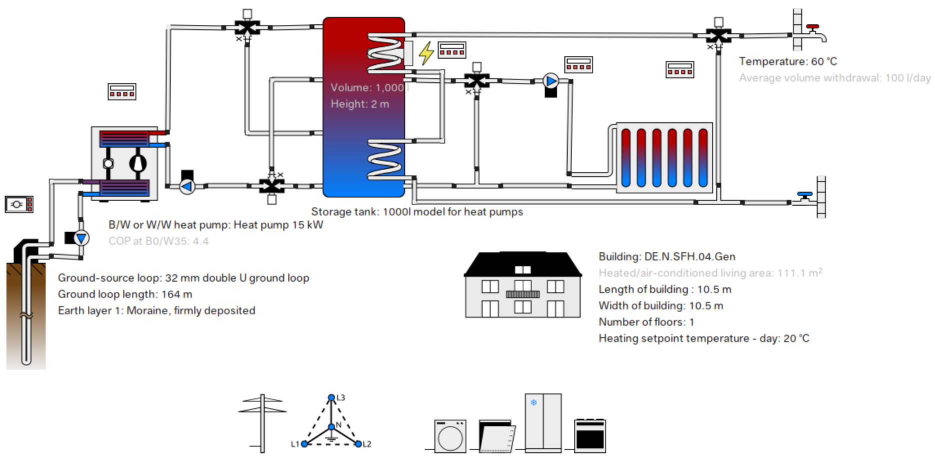

Figure 61, Diagram for the system "(GR&NT)-E-(GS)COIL+No-Bt" for Germany SFH before 1978

5. (GR&ST)-E-(A-W)COIL+No-Bt

This is the first case that includes a solar thermal device combined with an air to water heat pump and a water tank as heat storage, here the solar thermal is used to provide hot water as suggested by (Carlsson, 2017).

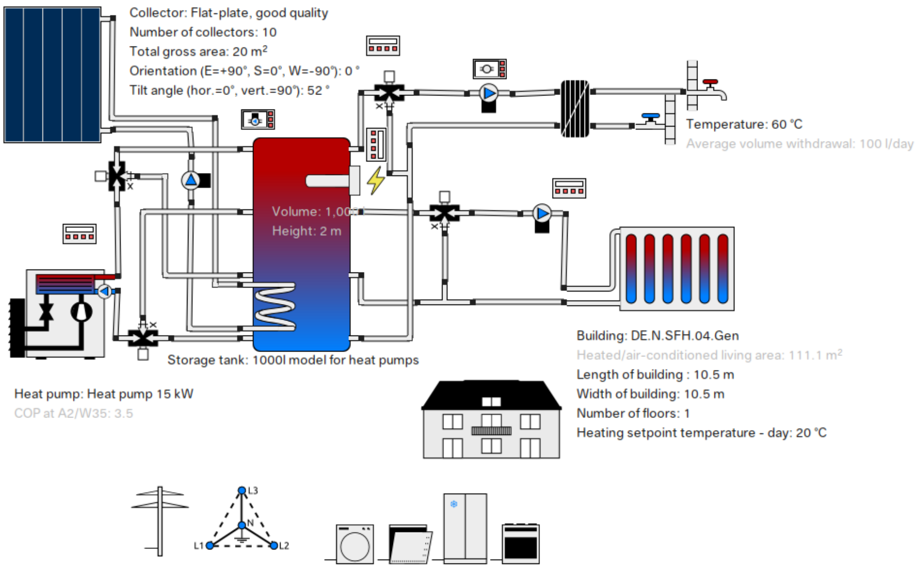

Figure 62, Diagram for the system "(GR&ST)-E-(A-W)COIL+No-Bt" for Germany SFH before 1978

6. (GR&ST)-E-(GS)COIL+No-Bt

Also including a solar thermal arrange but this time combined with a ground source heat pump, this time the flat plate collectors can either go directly to provide heat to the hot water tank or to work in combination with the underground loop to provide additional heat.

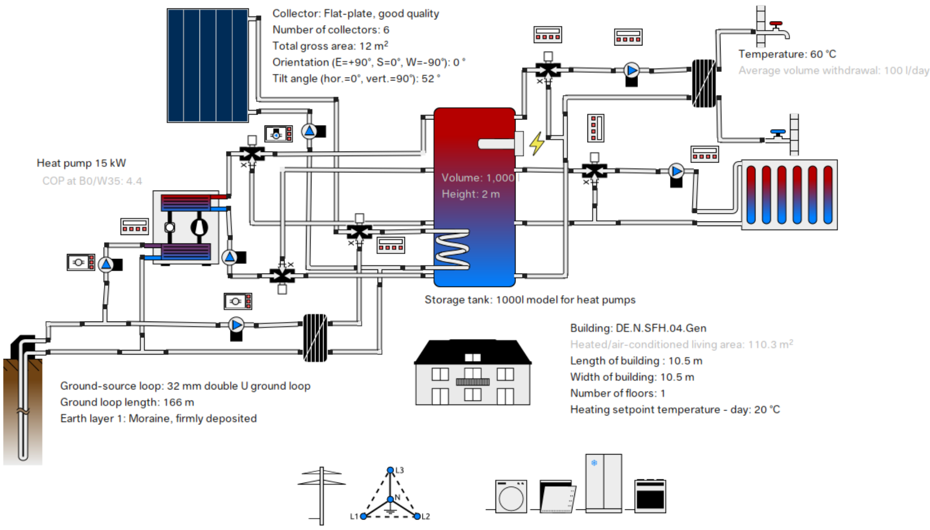

Figure 63, Diagram for the system "(GR&ST)-E-(GS)COIL+No-Bt" for Germany SFH before 1978

7. (PV&NT)-E-(A-W)COIL+No-Bt

First case including PV combined with an air to water heat pump, the PV is defined to provide electricity to the whole building, including home appliances and the heat pump. We have two different tanks, one as a heat storage for ambient heating and the other for domestic hot water. The heat provided for hot water can come from the heat pump but is also backed up by electric resistance.

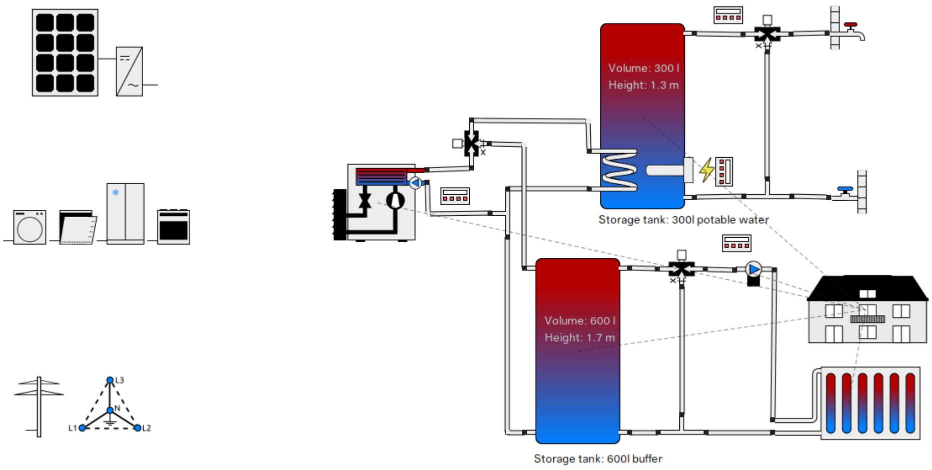

Figure 64, Diagram for the system "(PV&NT)-E-(A-W)COIL+No-Bt" for Germany SFH before 1978

8. (PV&NT)-E-(GS)COIL+No-Bt

Combined system with PV and ground source heat pump, also including a 1000L water tank for thermal storage that can be heated by the ground source heat pump or by an electric resistance.

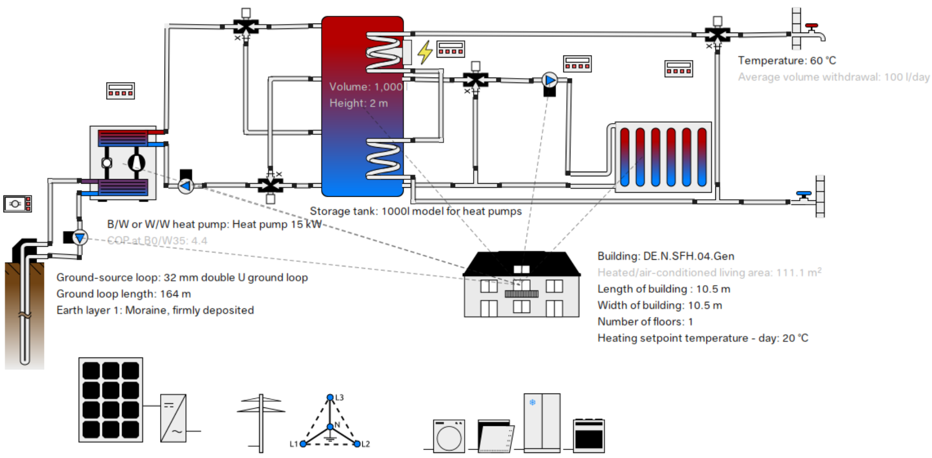

Figure 65, Diagram for the system "(PV&NT)-E-(GS)COIL+No-Bt" for Germany SFH before 1978

9. (PV&ST)-E-(A-W)PWT+No-Bt

This scheme uses both types of solar energy combining an arrangement of flat plate collectors and also a set of PV panels for electricity generation. Both systems are also working together with an air to water heat pump.

The solar thermal is used only to heat the hot water tank, while the heat pump can provide hot water directly and store it in the tank. The PV system is set to feed the whole electricity system of the building, hence home appliances and also the heat pump device.

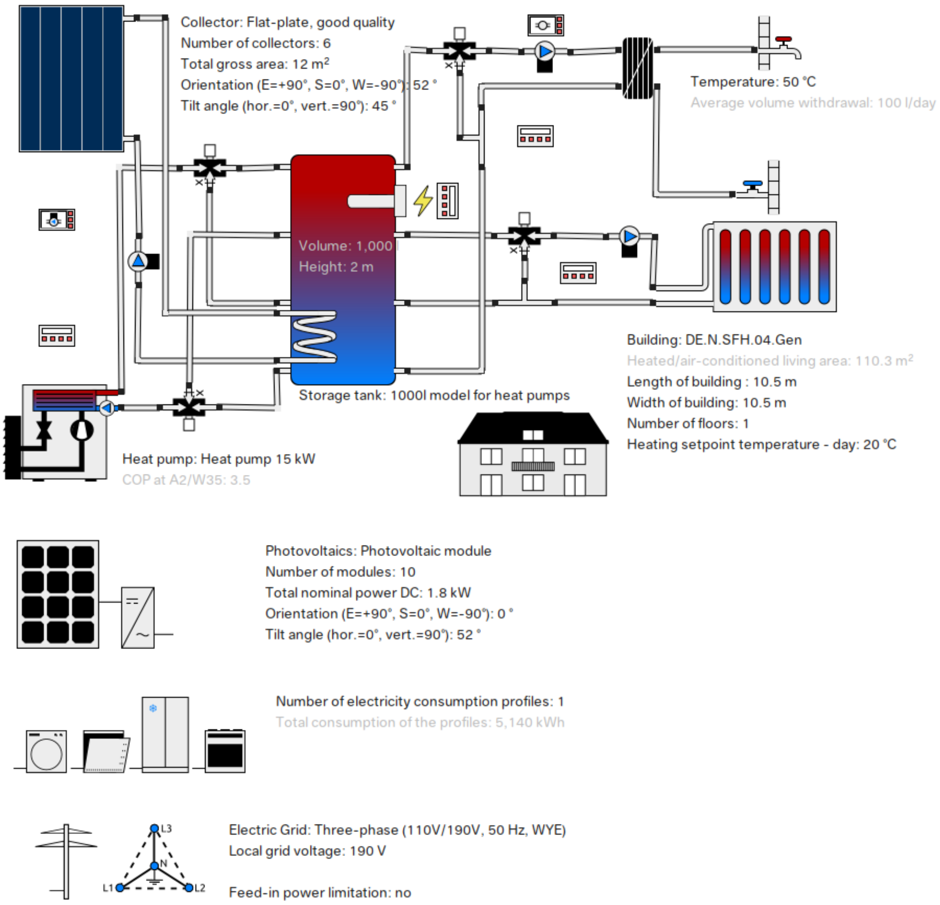

Figure 66, Diagram for the system "(PV&ST)-E-(A-W)PWT+No-Bt" for Germany SFH before 1978

10. (PV&PVT)-E-(GS)PWT+No-Bt

This system includes a PVT arrangement to use PV and also solar thermal energy, also combined with a ground source heat pump. The thermal energy generated by the PVT is used in combination with the ground source loop to be used as input for the heat pump, that will increase the temperature of the water tank for the hot water supply. Also, the electricity generated by the PV is connected to the building general circuit, then it can provide electricity to the home appliances and also to run the heat pump device.

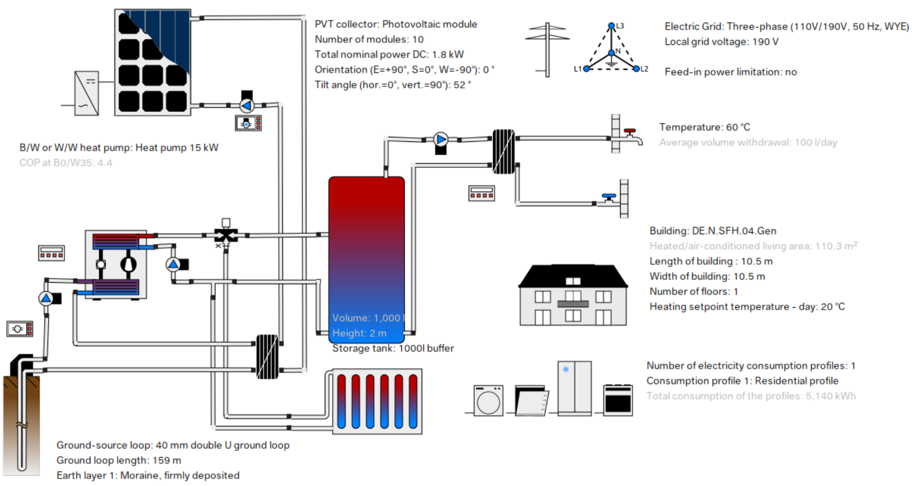

Figure 67, Diagram for the system "(PV&PVT)-E-(GS)PWT+No-Bt" for Germany SFH before 1978

11. (PV&NT)-E-(A-W)COIL+Li-Ion

This is the first case including electricity storage with a lithium-ion battery, it combines the use of PV and an air to water heat pump. The heat pump provides both ambient heating and domestic hot water (backed up with an electric resistance), and the PV and battery are part of the general electric system of the building.

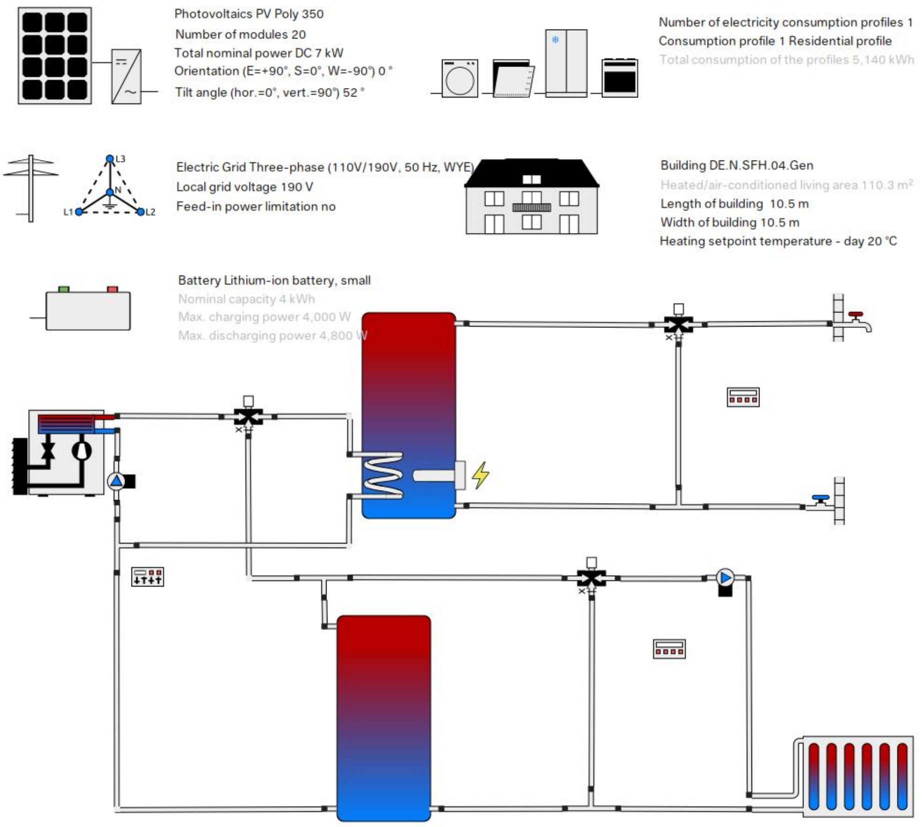

Figure 68, Diagram for the system "(PV&NT)-E-(A-W)COIL+Li-Ion" for Germany SFH before 1978

12. (PV&NT)-E-(GS)COIL+Li-Ion

Also including battery storage, PV and this time a ground source heat pump to provide ambient heat and hot water.

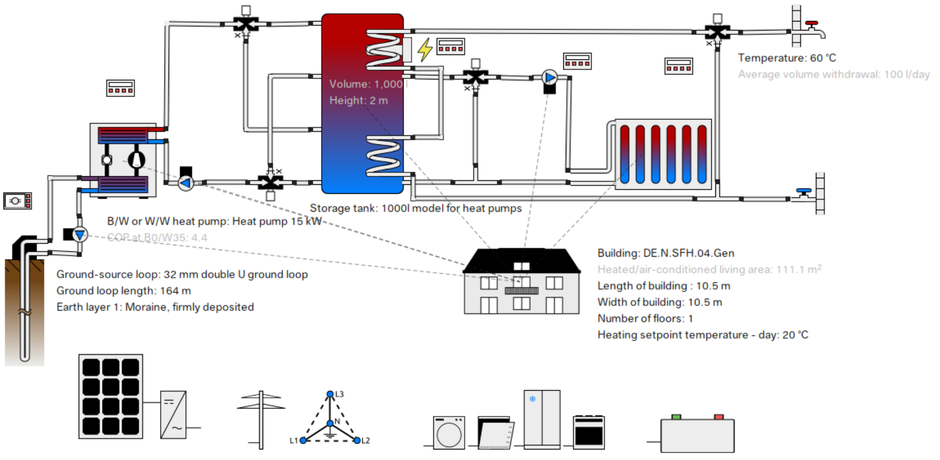

Figure 69, Diagram for the system "(PV&NT)-E-(GS)COIL+Li-Ion" for Germany SFH before 1978

13. (PV&ST)-E-(A-W)PWT+Li-Ion

System using PV and flat plate collectors to provide heat to the hot water tank. Also having electricity from the PV arrangement with the possibility of battery storage to provide for the whole house energy demand (including the heat pump energy demand).

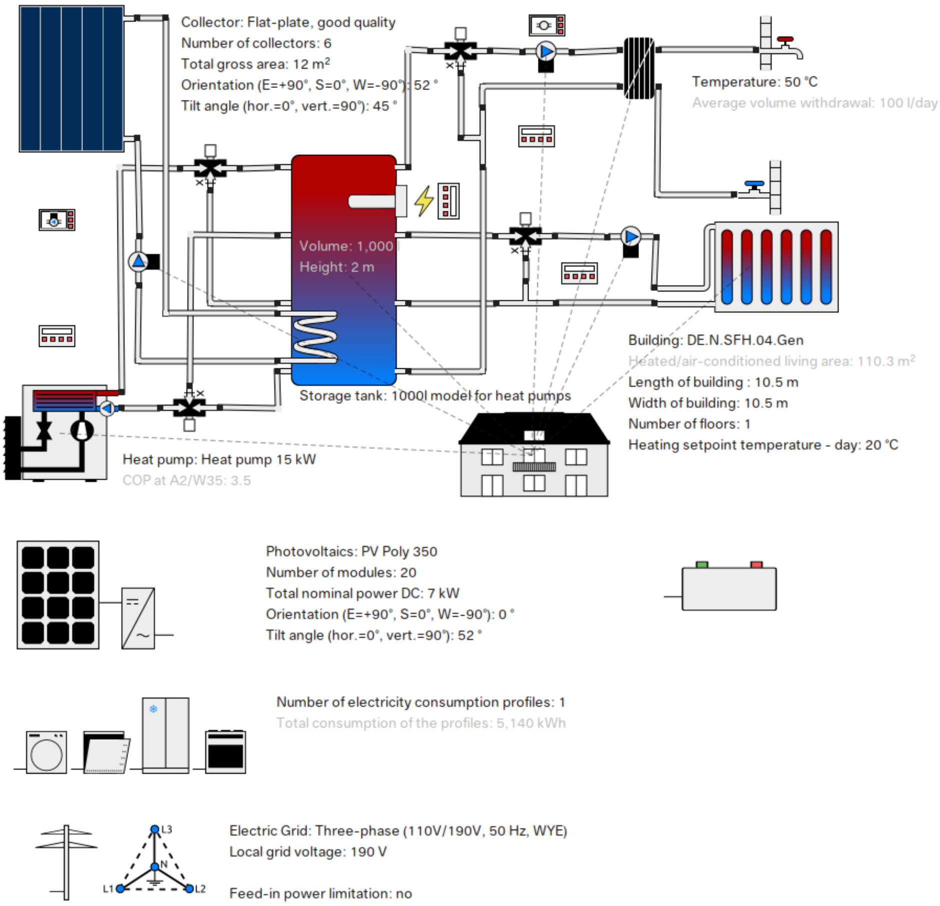

Figure 70, Diagram for the system "(PV&ST)-E-(A-W)PWT+Li-Ion" for Germany SFH before 1978

14. (PV&PVT)-E-(GS)PWT+Li-Ion

Final case including a combined PVT solar system to provide heat and electricity, also including a ground source heat pump and battery storage. Once again the heat generated by the PVT is used in combination with the ground source circuit as the input fluid for the heat pump which feds the ambient heating system and also the hot water tank.

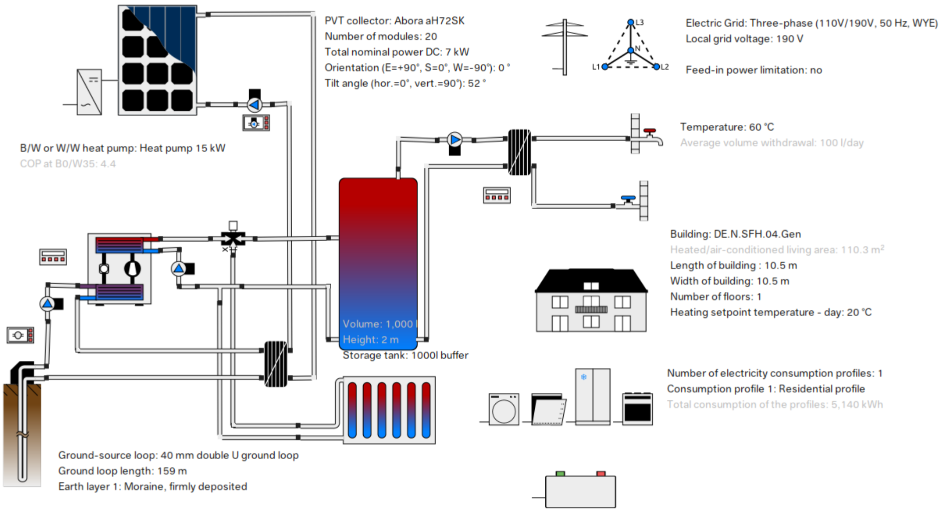

Figure 71, Diagram for the system "(PV&PVT)-E-(GS)PWT+Li-Ion" for Germany SFH before 1978

9. Results

The main results of the thesis are presented in this section, the final work consisted of a techno-economic analysis of 22 heating technologies for private households and 56 system simulations for the system approach also evaluating economical aspects as well as performance and environmental parameters.

9.1. Techno-Economic Analysis

The results presented in this section correspond to the ranking of each technology for each building and according to 4 main KPIs, the KIPs selected are NPV as it is the most representative value from an economic perspective, SPF/Efficiency and Energy Consumption per Year to assess the performance of each device for each case and Operational Carbon Footprint to evaluate the environmental impact of each technology.

In the sections *Annexes, Annual Energy Consumption for the Heat Generation Devices, Economic KPIs and Efficiency/SPF and Operational Carbon Footprint* the obtained values are presented for both countries and all cases, as well as for all the respective KPIs, nevertheless for easy presentation and analysis the following tables (table 34 for Germany and table 35 for The Netherlands) show the ranking position for each technology per case and indicator, where number 1 is the best and the evaluation starts decreasing as the number increases, this can also be graphically seen by the cells colors (green is a good indicator and red is a poor indicator). The tables previously mentioned only include ambient heating.

TRL	Technology	NPV (per year)				SPF/Efficiency				Energy Consumption per Year (kWh)				Op Carbon Footprint (Ton CO2 eq/year)			
		SFH 1955	SFH 2000	MFH 1955	MFH 2000	SFH 1955	SFH 2000	MFH 1955	MFH 2000	SFH 1955	SFH 2000	MFH 1955	MFH 2000	SFH 1955	SFH 2000	MFH 1955	MFH 2000
10	Gas Boiler [REF]	15	15	18	18	18	18	18	18	18	18	18	18	16	16	16	16
	Oil Boiler [REF]	19	19	19	19	19	19	19	19	19	19	19	19	20	20	20	20
	Electric Boiler [REF]	14	13	16	16	17	17	17	17	17	17	17	17	21	21	21	21
	HP (Air to Air) [REF]	2	3	5	5	7.5	7.5	7.5	7.5	7	7	7	7	9	9	9	9
	HP (Ground Source) [REF]	13	14	7	7	2	2	2	2	1	1	1	1	3	3	3	3
9	Hydrogen boiler	20	20	20	20	20	20	20	20	20	20	20	20	1	1	1	1
	PEM FC micro-CHP	22	22	22	22	22	22	22	22	22	22	22	22	1	1	1	1
	SOFC micro-CHP	21	21	21	21	21	21	21	21	21	21	21	21	1	1	1	1

	Central inverter heat pump	4	4	6	6	5	5	5	5	6	6	6	6	8	8	8	8
	Natural refrigerant HP	1	2	4	4	1	1	1	1	2	2	2	2	4	4	4	4
	Hybrid HP	6	5	9	9	6	6	6	6	9	9	9	9	12	12	12	12
	Synthetic methane HP	17	16	17	17	16	16	16	16	16	16	16	16	15	15	15	15
	HV Flat plate collectors HP	7	8	1	1	3	3	3	3	4	4	4	4	6	6	6	6
	Absorption HP	9	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
	Adsorption HP	11	12	11	11	13.5	13.5	13.5	13.5	13	14	14	14	13	13	13	13
8	Cold climate air-source HP	5	6	3	3	4	4	4	4	5	5	5	5	7	7	7	7
	Solar PV + HP	3	1	2	2	7.5	7.5	7.5	7.5	3	3	3	3	5	5	5	5
7	High-temperature HP	10	9	13	12	11	11	11	11	11	11	11	11	17	17	17	17
	Hydrogen-enriched NG HP	8	7	8	8	13.5	13.5	13.5	13.5	14	14	13	13	11	11	11	11
	Metal hydride HP	16	17	12	13	9	9	9	9	8	8	8	8	14	14	14	14
	Vuilleumier HP	12	11	14	14	12	12	12	12	12	12	12	12	18	18	18	18
6	Thermo-acoustic HP	18	18	15	15	15	15	15	15	15	15	15	15	19	19	19	19

Table 34, Techno-economic analysis results for Germany based only on ambient heating

TRL	Technology	NPV (per year)				SPF/Efficiency				Energy Consumption per Year (kWh)				Op Carbon Footprint (Ton CO2 eq/year)			
		SFH 1970	SFH 2000	MFH 1970	MFH 2000	SFH 1970	SFH 2000	MFH 1970	MFH 2000	SFH 1970	SFH 2000	MFH 1970	MFH 2000	SFH 1970	SFH 2000	MFH 1970	MFH 2000
10	Gas Boiler [REF]	14	14	14	14	18	18	18	18	18	18	18	18	20	20	20	20
	Oil Boiler [REF]	12	12	12	12	19	19	19	19	19	19	19	19	21	21	21	21
	Electric Boiler [REF]	20	20	20	20	17	17	17	17	17	17	17	17	18	18	18	18
	HP (Air to Air) [REF]	8	8	10	10	7	7	7	7	7	7	7	7	9	9	9	9
	HP (Ground Source) [REF]	5	5	4	4	2	2	2	2	2	2	2	2	4	4	4	4
9	Hydrogen boiler	19	19	19	19	20	20	20	20	20	20	20	20	1	1	1	1
	PEM FC micro-CHP	22	22	22	22	22	22	22	22	22	22	22	22	1	1	1	1
	SOFC micro-CHP	21	21	21	21	21	21	21	21	21	21	21	21	1	1	1	1
	Central inverter heat pump	7	7	9	9	5	5	5	5	6	6	6	6	8	8	8	8
	Natural refrigerant HP	3	3	3	3	1	1	1	1	1	1	1	1	3	3	3	3
	Hybrid HP	11	11	11	11	7	7	7	7	9	9	9	9	11	11	11	11
	Synthetic methane HP	13	13	13	13	16	16	16	16	16	16	16	16	19	19	19	19
	HV Flat plate collectors HP	10	10	6	6	3	3	3	3	4	4	4	4	6	6	6	6
	Absorption HP	4	4	5	5	10	10	10	10	10	10	10	10	15	15	15	15
	Adsorption HP	9	9	8	8	13.5	13.5	13.5	13.5	14	14	14	14	17	17	17	17
8	Cold climate air-source HP	6	6	7	7	4	4	4	4	5	5	5	5	7	7	7	7
	Solar PV + HP	1	1	2	2	7	7	7	7	3	3	3	3	5	5	5	5
7	High-temperature HP	16	16	16	16	11	11	11	11	11	11	11	11	12	12	12	12
	Hydrogen-enriched NG HP	2	2	1	1	13.5	13.5	13.5	13.5	14	13	14	13	16	16	16	16
	Metal hydride HP	15	15	15	15	9	9	9	9	8	8	8	8	10	10	10	10
	Vuilleumier HP	17	17	17	17	12	12	12	12	12	12	12	12	13	13	13	13
6	Thermo-acoustic HP	18	18	18	18	15	15	15	15	15	15	15	15	14	14	14	14

Table 35, Techno-economic analysis results for The Netherlands based only on ambient heating

Now tables 36 and 37 present the same analysis for Germany and The Netherlands respectively, but this time they are calculated based on the demand for ambient heating plus domestic hot water.

TRL	Technology	NPV (per year)				SPF/Efficiency				Energy Consumption per Year (kWh)				Op Carbon Footprint (Ton CO2 eq/year)			
		SFH 1955	SFH 2000	MFH 1955	MFH 2000	SFH 1955	SFH 2000	MFH 1955	MFH 2000	SFH 1955	SFH 2000	MFH 1955	MFH 2000	SFH 1955	SFH 2000	MFH 1955	MFH 2000
10	Gas Boiler [REF]	18	17	18	18	18	18	18	18	18	18	18	18	16	16	16	16
	Oil Boiler [REF]	19	19	19	19	19	19	19	19	19	19	19	19	20	20	20	20
	Electric Boiler [REF]	13	11	15	15	17	17	17	17	17	17	17	17	21	21	21	21
	HP (Air to Water) [REF]	4	3	5	5	6.5	6.5	6.5	6.5	6	6	6	6	9	9	9	9
	HP (Ground Source) [REF]	10	13	6	6	4	4	4	4	5	5	5	5	7	7	7	7
9	Hydrogen boiler	20	20	20	20	20	20	20	20	20	20	20	20	1	1	1	1
	PEM FC micro-CHP	22	22	22	22	22	22	22	22	22	22	22	22	1	1	1	1
	SOFC micro-CHP	21	21	21	21	21	21	21	21	21	21	21	21	1	1	1	1
	Central inverter heat pump	5	5	9	9	8	8	8	8	7	7	7	7	11	11	11	11
	Natural refrigerant HP	1	2	4	3	1	1	1	1	1	1	1	1	3	3	3	3
	Hybrid HP	11	9	12	12	5	5	5	5	11	11	11	11	13	13	13	13
	Synthetic methane HP	17	16	17	17	16	16	16	16	16	16	16	16	15	15	15	15
	HV Flat plate collectors HP	3	4	1	1	3	3	3	3	4	4	4	4	6	6	6	6
	Absorption HP	6	6	7	7	10	10	10	10	9	9	9	9	8	8	8	8
	Adsorption HP	15	14	16	16	14.5	14.5	14.5	14.5	15	15	15	15	14	14	14	14
8	Cold climate air-source HP	8	12	3	4	2	2	2	2	3	3	3	3	5	5	5	5
	Solar PV + HP	2	1	2	2	6.5	6.5	6.5	6.5	2	2	2	2	4	4	4	4
7	High-temperature HP	9	8	11	11	11	11	11	11	10	10	10	10	17	17	17	17
	Hydrogen-enriched NG HP	7	7	8	8	14.5	14.5	14.5	14.5	15	15	15	15	10	10	10	10
	Metal hydride HP	14	15	10	10	9	9	9	9	8	8	8	8	12	12	12	12
	Vuilleumier HP	12	10	14	14	12	12	12	12	12	12	12	12	18	18	18	18
6	Thermo-acoustic HP	16	18	13	13	13	13	13	13	13	13	13	13	19	19	19	19

Table 36, Techno-economic analysis results for Germany based on ambient heating plus DHW

TRL	Technology	NPV (per year)				SPF/Efficiency				Energy Consumption per Year (kWh)				Op Carbon Footprint (Ton CO2 eq/year)			
		SFH 1970	SFH 2000	MFH 1970	MFH 2000	SFH 1970	SFH 2000	MFH 1970	MFH 2000	SFH 1970	SFH 2000	MFH 1970	MFH 2000	SFH 1970	SFH 2000	MFH 1970	MFH 2000
10	Gas Boiler [REF]	14	14	14	14	18	18	18	18	18	18	18	18	20	20	20	20
	Oil Boiler [REF]	10	10	10	10	19	19	19	19	19	19	19	19	21	21	21	21
	Electric Boiler [REF]	20	20	20	20	17	17	17	17	17	17	17	17	16	16	16	16
	HP (Air to Water) [REF]	8	8	9	9	6.5	6.5	6.5	6.5	6	6	6	6	8	8	8	8
	HP (Ground Source) [REF]	9	9	8	8	5	5	5	5	5	5	5	5	7	7	7	7
9	Hydrogen boiler	19	19	19	19	20	20	20	20	20	20	20	20	1	1	1	1
	PEM FC micro-CHP	22	22	22	22	22	22	22	22	22	22	22	22	1	1	1	1

	SOFC micro-CHP	21	21	21	21	21	21	21	21	21	21	21	21	1	1	1	1
	Central inverter heat pump	13	13	13	13	8	8	8	8	7	7	7	7	9	9	9	9
	Natural refrigerant HP	3	3	3	3	1	1	1	1	1	1	1	1	3	3	3	3
	Hybrid HP	11	11	12	12	4	4	4	4	9	9	9	9	12	12	12	12
	Synthetic methane HP	12	12	11	11	16	16	16	16	16	16	16	16	19	19	19	19
	HV Flat plate collectors HP	6	6	6	6	3	3	3	3	4	4	4	4	6	6	6	6
	Absorption HP	4	4	4	4	10	10	10	10	10	10	10	10	15	15	15	15
	Adsorption HP	7	7	7	7	14.5	14.5	14.5	14.5	15	15	15	15	18	18	18	18
8	**Cold climate air-source HP**	5	5	5	5	2	2	2	2	3	3	3	3	5	5	5	5
	Solar PV + HP	2	2	2	2	6.5	6.5	6.5	6.5	2	2	2	2	4	4	4	4
7	**High-temperature HP**	16	16	16	16	11	11	11	11	11	11	11	11	11	11	11	11
	Hydrogen-enriched NG HP	1	1	1	1	14.5	14.5	14.5	14.5	15	15	15	15	17	17	17	17
	Metal hydride HP	15	15	15	15	9	9	9	9	8	8	8	8	10	10	10	10
	Vuilleumier HP	17	17	17	17	12	12	12	12	12	12	12	12	13	13	13	13
6	**Thermo-acoustic HP**	18	18	18	18	13	13	13	13	13	13	13	13	14	14	14	14

Table 37, Techno-economic analysis results for The Netherlands based on ambient heating plus DHW

For the Germany Case only for ambient heating we can see that a natural refrigerant heat pump seems to be a promising technology for SFH, while for MFH the best economical choice will be combining flat plate collector with a regular heat pump or combining solar PV with a heat pump is also advantageous for both cases.

It is also important to notice that a higher NPV is shown for The Netherlands in the MFH case as the buildings selected for the Netherlands are bigger in area, then they will have higher energy consumption.

From a technical perspective as expected the best performance is achieved by heat pump devices due to high COP (specially for natural refrigerant heat pumps), while also ground source heat pumps seem to keep high efficiency and the lowest energy consumption.

Finally, from an environmental perspective and due to the assumption of green hydrogen, the lowest carbon footprint is related to hydrogen technologies. Nevertheless, in reality this will not be exactly the case and also the availability of green hydrogen and the cost are important factors to consider when evaluating these technologies.

For The Netherlands only for ambient heating the scenario is similar to Germany, but the main differences are driven by the more uneven prices of gas and electricity. This time we see that for SFH the best economic decision will be the use of PV and a heat pump as this will promote energy savings, and a hydrogen enriched heat pump seems like a good choice also due to high electricity prices.

Nevertheless, natural refrigerant heat pumps are also a good option due to higher efficiencies than regular heat pumps and similar CAPEX, while most absorption technologies are also in the top places due again to the gas prices.

From a performance perspective, as well as for the environmental KPI the scenario is almost identical as for Germany, as the performance of the devices and the carbon footprint will not be affected by the energy market prices, but only by the weather data and demand.

By looking at the cases including domestic hot water we see a few differences due to higher consumption and demand rates. For Germany in SFH again natural refrigerant heat pumps appear as one of the top choices, also with the PV and heat pump combination. While for multi-family housing again the first technology in economic terms will be the combination of a flat plate collector with a heat pump. Once again, we see that a system approach seems like a good way to go not only in economic terms but also for energy efficiency and environmental impact. It is also interesting to see how the traditional heat pump technologies also present a good enough ranking (mostly for MFH).

In terms of performance and environmental KPIs the ranking is very similar as the case only considering ambient heating, again the natural refrigerant heat pump seems as the most efficient device closely followed by the combination of PV and a heat pump and the cold climate air source heat pump seems like a good alternative (also mostly for MFH), as well as the inclusion of flat plate collectors.

For the Netherlands once more, we see the influence of market prices in the economic KPI as technologies such as hydrogen enriched natural gas heat pump and different kinds of absorption heat pumps show high ranking, while also solar PV and heat pump and natural refrigerant heat pumps present a good business case.

From an energy efficiency point of view the ranking still shows the natural refrigerant heat pump as the best alternative, while also the combination of solar PV or flat plate collectors with a heat pump seem like good alternatives, also with cold climate air source heat pumps.

Finally, by assessing the environmental impact with the operational carbon footprint of the devices we have no further surprises as once again the hydrogen technologies seem to be the best ones, but once again this is due to the assumption of green hydrogen. But leaving this aside we have the natural refrigerant heat pump (due to high efficiency), and the combined systems.

To compare both countries for the case including the DHW demand a set of graphs was developed considering the average values for SFH and MFH in each country, first we have the economical comparison based on NVP, where the scale is inverted, then a higher bar represents a more negative NPV value. For both cases in SFH it can be seen that the technologies based on fuel cells are highly expensive, while heat pumps seem to be a better economic decision, especially for the combination of this devices with solar energy as discussed before. This can be easily seen in the graphs 72 and 73 where the obtained NPV values for SFH and MFH are presented respectively for both countries.

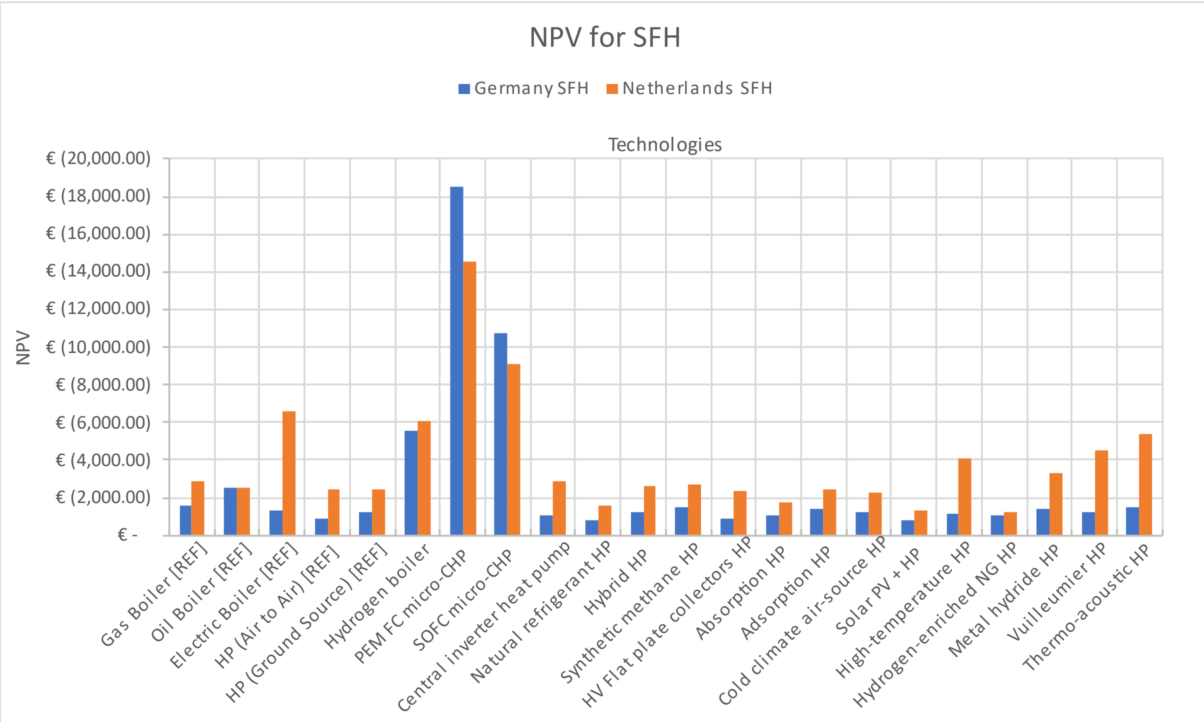

Figure 72, Obtained values for NPV for the SFH cases in both countries

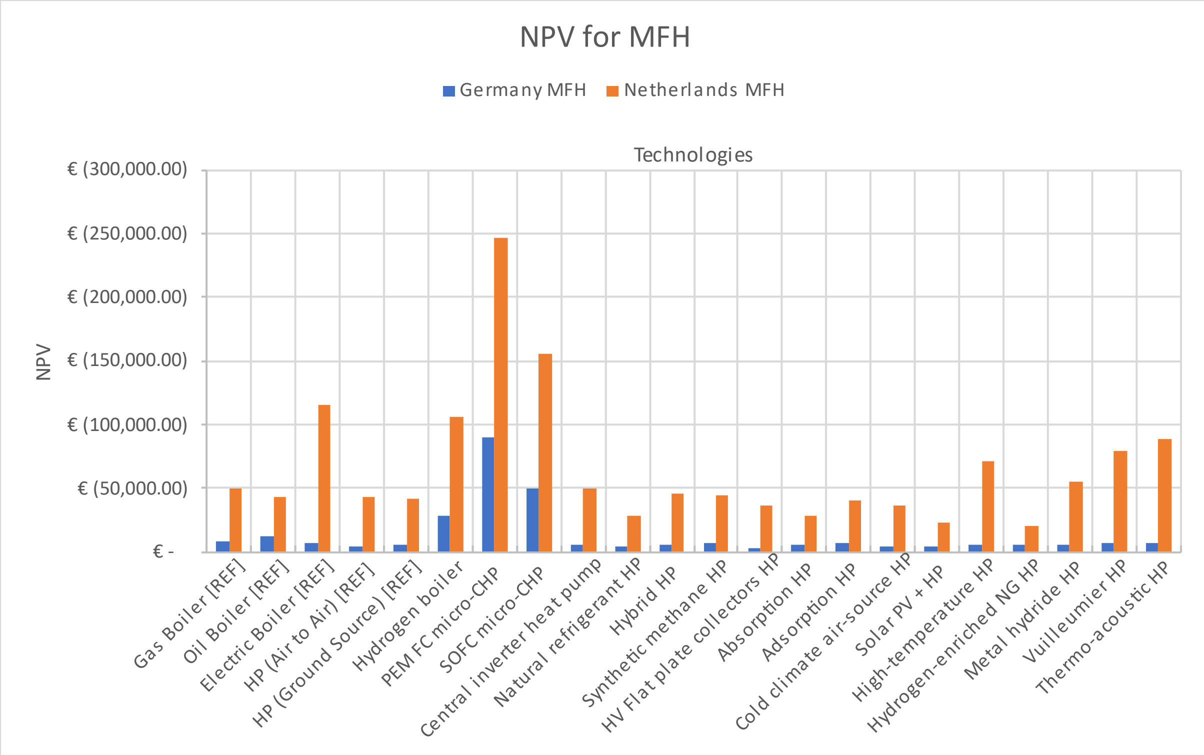

Figure 73, Obtained values for NPV for the MFH cases in both countries

Now the SPF and efficiency indicator is also compared for both countries, this time without discriminating between SFH and MFH as this will only variate due to weather conditions (as the COP is a function of the ambient temperature), the higher COPs are obtained by the natural refrigerant HP, cold climate air source heat pump and also the combination of HP with solar technologies as well as the ground source heat pump as can be seen in graph 74.

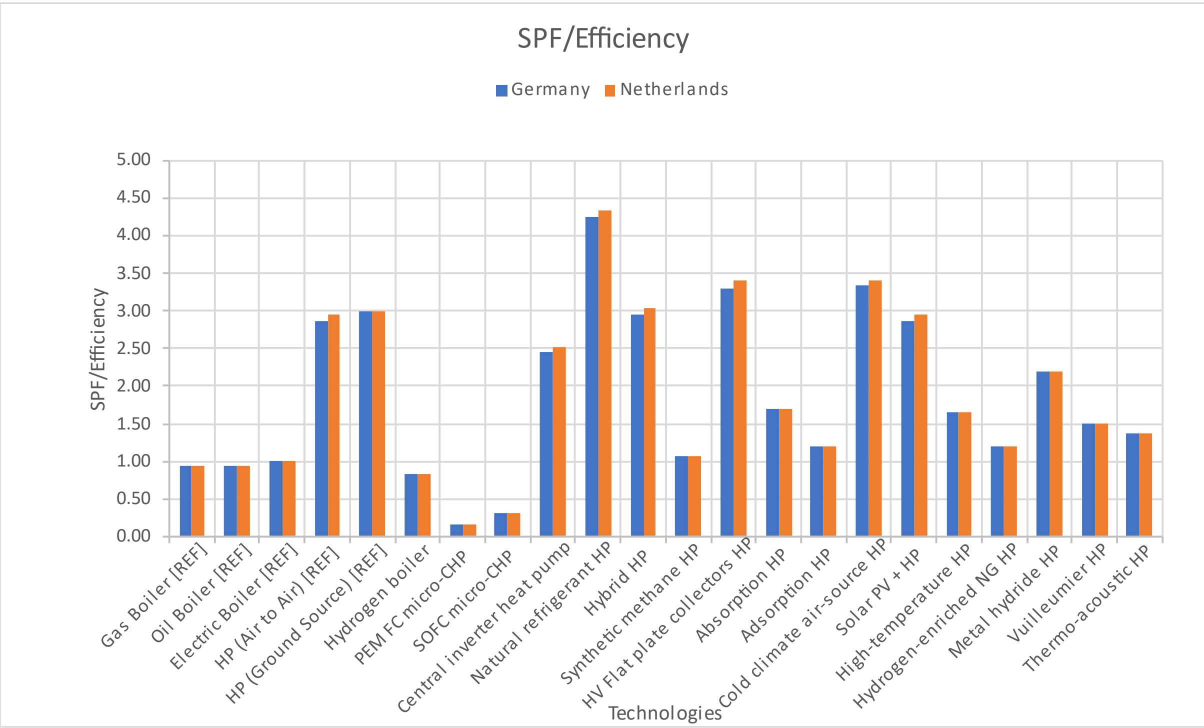

Figure 74, Seasonal performance factor or efficiency (depending on the device) for each device on each country

As expected the energy consumption represents a similar behavior as the SPF/efficiency but inverted, as with higher efficiency lower energy consumption, once again a remarkable difference is seen in graph 76 for MFH due to the larger area considered for The Netherlands cases.

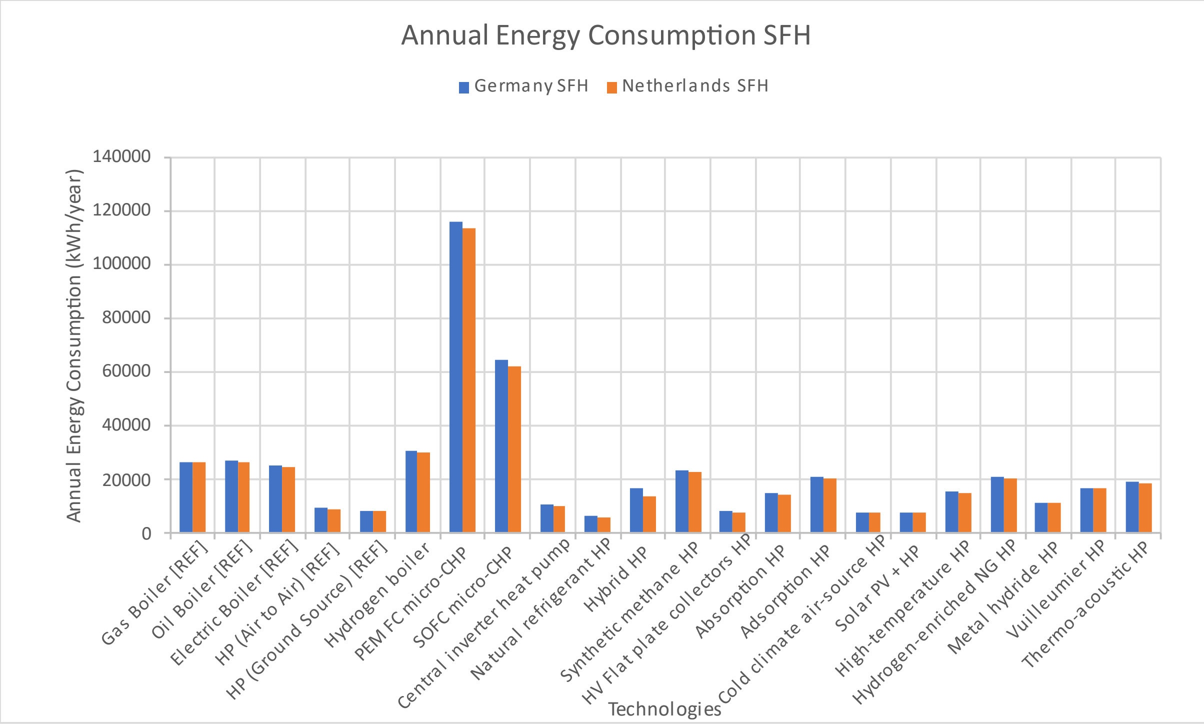

Figure 75, Annual energy consumption for SFH buildings in both countries when considering DHW

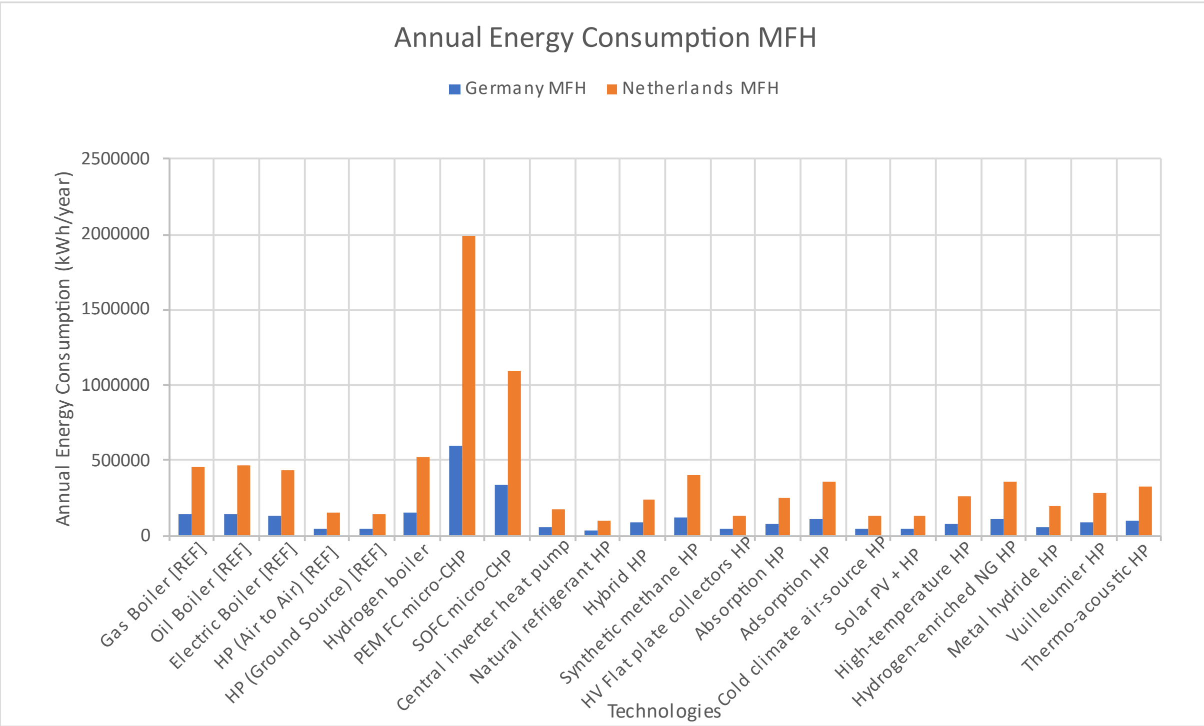

Figure 76, Annual energy consumption for MFH buildings in both countries when considering DHW

Finally when assessing the operational carbon footprint we see that the hydrogen related technologies present zero emissions, which as previously mentioned is due to the assumption of green hydrogen, but we can see that also low values are present in natural refrigerant heat pumps, cold climate air source heat pumps, and system combinations with solar energy, as expected, it is also interesting to see how for SFH (figure 77) all the values are greater for Germany due to a larger carbon fraction from the grid. Figure 78 presents the operational carbon footprint for the MFH cases in both countries, it is interesting to see how despite the area difference certain technologies present similar values in The Netherlands when compared to Germany due to a smaller carbon fraction as they are the technologies mostly relying on electricity. Nevertheless, it is also important to consider the scale as for example for a gas boiler the value for Germany is around 20 tons of CO_2 equivalent, while for the Netherlands is almost 4 times higher.

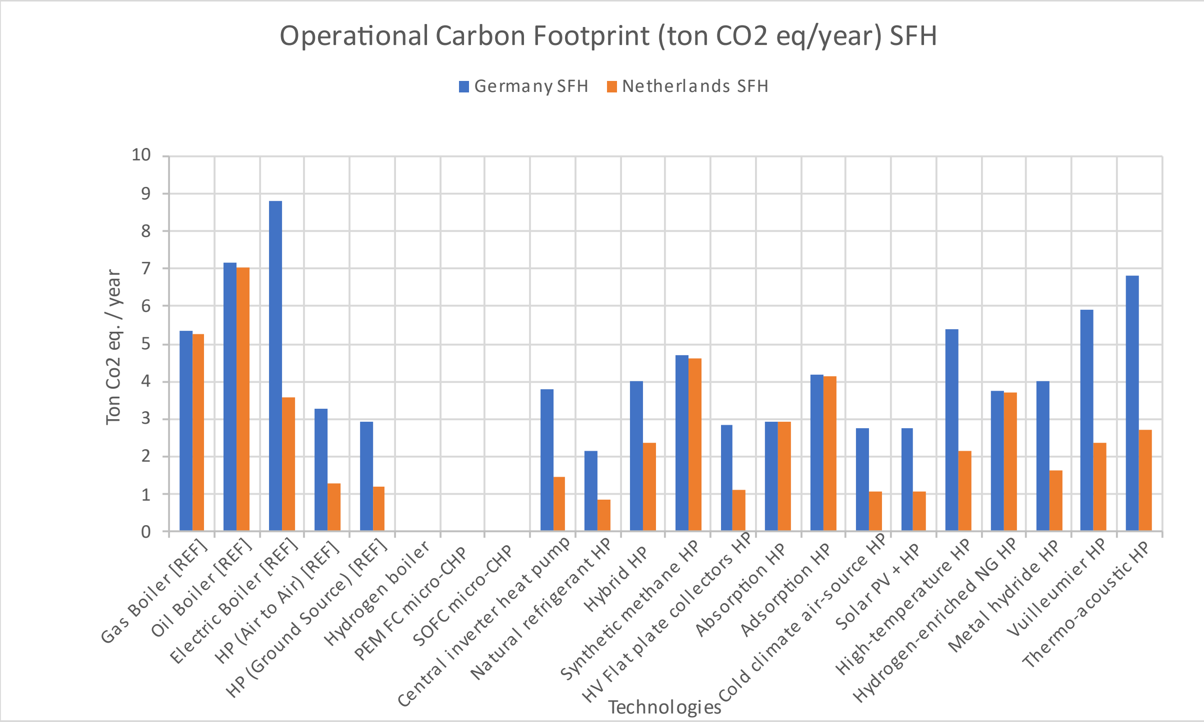

Figure 77, Operational carbon footprint for both countries for the SFH case

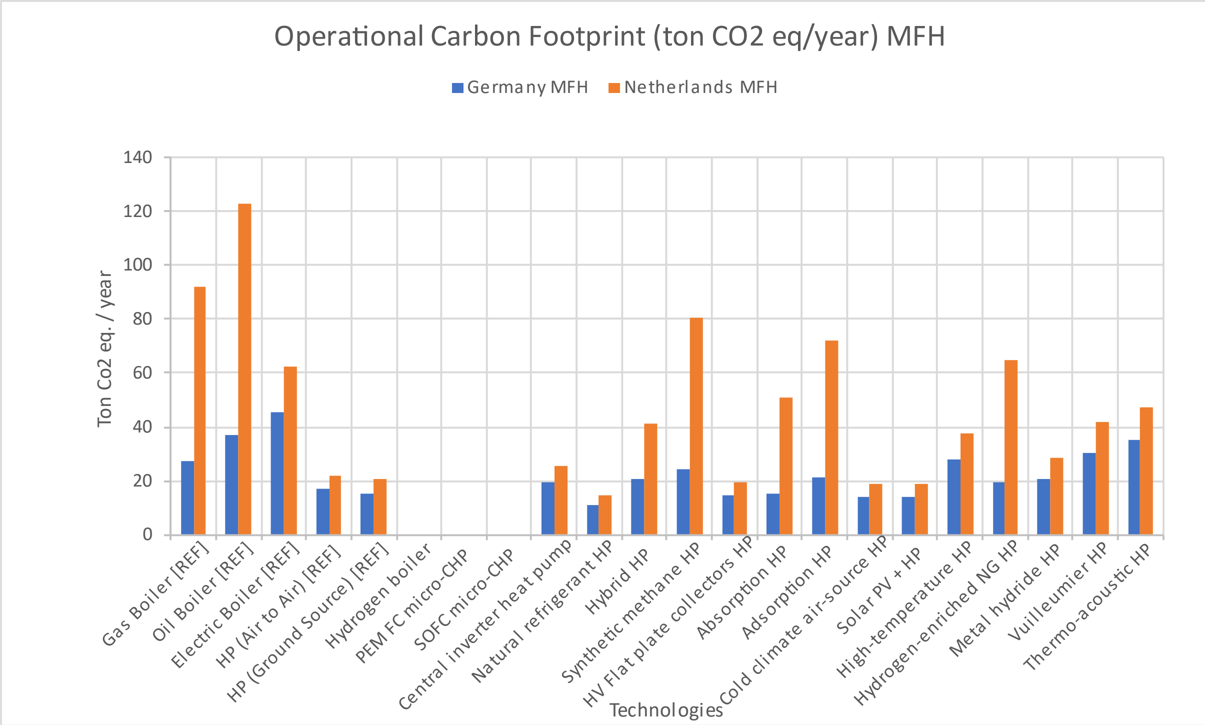

Figure 78, Operational carbon footprint for both countries for the MFH case

9.2. System Approach

Once all the cases have been introduced in the *Methodology, System Approach, System Combinations Schemes* section, now the specific parameters for each case are presented in the following tables as well as the related initial investment costs for each case, it is important to mention that for the heating systems the cost calculations were also based on (Mitterrutzner, Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, 2023), which were also used for the previous techno economic analysis and are described in the section *Methodology, Techno-Economic Analysis, Assumptions, For the Technologies*.

For the cost of the water tank, collector and battery the values were obtained specifically for each country and the references are presented in the tables.

Also, the capex variation between Germany and The Netherlands is included in the analysis using a generalized factor of 1.5 for the heat generation technologies in the Berlin case compared to the Amsterdam case as it was also explained in section *Methodology, Techno-Economic Analysis, Assumptions, CAPEX Variation (Germany vs. The Netherlands)*.

Table 38 presents the specific values for the Berlin single family housing buildings, there is no difference for the system capacity or cost between the building built before and after 1978 as at the end the commercial values for the devices depend on the industry, the main difference will be shown based on the energy consumption as the newer building will have a better performance.

DE.N.SFH.04.Gen / DE.N.SFH.09.Gen

Code	Heating System and Size	Cost (€)	Water Tank Size (L)	Cost (€)	Source	Collector	Cost (€)	Source	Battery	Cost (€)	Source
(GR&NT)-G-(N)COIL+No-Bt	Gas 20 kW	733.5	500	465	(Tanks Direkt, 2024)						
(GR&NT)-E-(N)PWT+No-Bt	Electric Continuous Flow 8 kW	148.9	200	225	(Tanks Direkt, 2024)						

(GR&NT)-E-(A-W)COIL+No-Bt	HP Air to Water 10 kW	16200.0	600	449	(Tanks Direkt, 2024)						
(GR&NT)-E-(GS)COIL+No-Bt	HP Brine to Water 15 kW	33956.6	1000	815	(Tanks Direkt, 2024)						
(GR&ST)-E-(A-W)COIL+No-Bt	HP Air to Water 15 kW	24300.0	1000	815	(Tanks Direkt, 2024)	Flat-Plate, Good Quality (10 collector, 20 m2)	6500	(Solar Heating & Cooling Programme, 2024)			
(GR&ST)-E-(GS)COIL+No-Bt	HP Brine to Water 15 kW	33956.6	1000	815	(Tanks Direkt, 2024)	Flat-Plate, Good Quality (6 collector, 12 m2)	3900	(Solar Heating & Cooling Programme, 2024)			
(PV&NT)-E-(A-W)COIL+No-Bt	HP Air to Water 10 kW	16200.0	300 PWT, 600 Buffer	744	(Tanks Direkt, 2024) (Tanks Direkt, 2024)	PV 1.8kW nominal (10 modules, 14 m2)	2802.6	(Fuhs, 2023)			
(PV&NT)-E-(GS)COIL+No-Bt	HP Brine to Water 15 kW	33956.6	1000	815	(Tanks Direkt, 2024)	PV 1.8kW nominal (10 modules, 14 m2)	2802.6	(Fuhs, 2023)			
(PV&ST)-E-(A-W)PWT+No-Bt	HP Air to Water 15 kW	24300.0	1000 PWT	815	(Tanks Direkt, 2024)	Flat-Plate, Good Quality (6 collectors, 12 m2) PV 1.8 kW nominal (10 modules, 14 m2)	6702.6	(Solar Heating & Cooling Programme, 2024)			
(PV&PVT)-E-(GS)PWT+No-Bt	HP Brine to Water 15 kW	33956.6	1000 PWT	815	(Tanks Direkt, 2024)	PVT 1.62kW nominal (10 modules, 12.8 m2)	4160	(Fuhs, 2023)			
(PV&NT)-E-(A-W)COIL+Li-Ion	HP Air to Water 10 kW	16200.0	300 PWT, 600 Buffer	744	(Tanks Direkt, 2024) (Tanks Direkt, 2024)	PV 7kW nominal (20 modules, 35.32 m2)	10899	(Fuhs, 2023)	Li-Ion 4 kW, 4 kWh	3680	(Figgener, 2023)
(PV&NT)-E-(GS)COIL+Li-Ion	HP Brine to Water 15 kW	33956.6	1000	815	(Tanks Direkt, 2024)	PV 7kW nominal (20 modules, 35.32 m2)	10899	(Fuhs, 2023)	Li-Ion 4 kW, 4 kWh	3680	(Figgener, 2023)
(PV&ST)-E-(A-W)PWT+Li-Ion	HP Air to Water 15 kW	24300.0	1000 PWT	815	(Tanks Direkt, 2024)	Flat-Plate, Good Quality (6 collectors, 12 m2) PV 7kW nominal (20 modules, 35.32 m2)	14799	(Solar Heating & Cooling Programme, 2024)	Li-Ion 4 kW, 4 kWh	3680	(Figgener, 2023)
(PV&PVT)-E-(GS)PWT+Li-Ion	HP Brine to Water 15 kW	33956.6	1000 PWT	815	(Tanks Direkt, 2024)	PVT 7kW nominal (20 modules, 39.2 m2)	12740	(Fuhs, 2023)	Li-Ion 4 kW, 4 kWh	3680	(Figgener, 2023)

Table 38, Components definition and prices for the Berlin case (references in the table)

Now, table 39 presents the specific values for the Amsterdam single family housing buildings, once again there is no difference for the system capacity or cost between the building built before and after 1974 due to the specified capacities commercially available, but again the main difference will be shown based on the energy consumption as the newer building will have a better performance. Also, compared to Germany the prices will be a bit lower as the capex is around 1.5 higher in Germany.

NL.N.SFH.02.Gen / NL.N.SFH.04.Gen

Code	Heating System and Size	Cost	Water Tank Size (L)	Cost	Source	Collector	Cost	Source	Battery	Cost	Source

		(€)		(€)			(€)			(€)	
(GR&NT)-G-(N)COIL+No-Bt	Gas 20 kW	489.0	500	465	(Rotterdam Plastics, 2024)						
(GR&NT)-E-(N)PWT+No-Bt	Electric Continuos Flow 8 kW	99.3	200	225	(Rotterdam Plastics, 2024)						
(GR&NT)-E-(A-W)COIL+No-Bt	HP Air to Water 10 kW	10800.0	600	449	(Rotterdam Plastics, 2024)						
(GR&NT)-E-(GS)COIL+No-Bt	HP Brine to Water 15 kW	22637.7	1000	815	(Rotterdam Plastics, 2024)						
(GR&ST)-E-(A-W)COIL+No-Bt	HP Air to Water 15 kW	16200.0	1000	815	(Rotterdam Plastics, 2024)	Flat-Plate, Good Quality (10 collector, 20 m2)	18000	(Zoofy, 2024)			
(GR&ST)-E-(GS)COIL+No-Bt	HP Brine to Water 15 kW	22637.7	1000	815	(Rotterdam Plastics, 2024)	Flat-Plate, Good Quality (6 collector, 12 m2)	10400	(Zoofy, 2024)			
(PV&NT)-E-(A-W)COIL+No-Bt	HP Air to Water 10 kW	10800.0	300 PWT, 600 Buffer	449	(Rotterdam Plastics, 2024) (Rotterdam Plastics, 2024)	PV 1.8kW nominal (10 modules, 14 m2)	4450	(Zoofy, 2024)			
(PV&NT)-E-(GS)COIL+No-Bt	HP Brine to Water 15 kW	22637.7	1000	815	(Rotterdam Plastics, 2024)	PV 1.8kW nominal (10 modules, 14 m2)	4450	https://zoofy.nl/en/price-guides/costs-and-benefits-solar-panels-in-2023/ (Zoofy, 2024)			
(PV&ST)-E-(A-W)PWT+No-Bt	HP Air to Water 15 kW	16200.0	1000 PWT	815	(Rotterdam Plastics, 2024)	Flat-Plate, Good Quality (6 collectors, 12 m2) PV 1.8 kW nominal (10 modules, 14 m2)	14850	(Zoofy, 2024)			
(PV&PVT)-E-(GS)PWT+No-Bt	HP Brine to Water 15 kW	22637.7	1000 PWT	815	(Rotterdam Plastics, 2024)	PVT 1.62kW nominal (10 modules, 12.8 m2)	18000	(Zoofy, 2024)			
(PV&NT)-E-(A-W)COIL+Li-Ion	HP Air to Water 10 kW	10800.0	300 PWT, 600 Buffer	449	(Rotterdam Plastics, 2024) (Rotterdam Plastics, 2024)	PV 7kW nominal (20 modules, 35.32 m2)	7500	(Zoofy, 2024)	Li-Ion 4 kW, 4 kWh	1359.95	(Nkon, 2024)
(PV&NT)-E-(GS)COIL+Li-Ion	HP Brine to Water 15 kW	22637.7	1000	815	(Rotterdam Plastics, 2024)	PV 7kW nominal (20 modules, 35.32 m2)	7500	(Zoofy, 2024)	Li-Ion 4 kW, 4 kWh	1359.95	(Nkon, 2024)
(PV&ST)-E-(A-W)PWT+Li-Ion	HP Air to Water 15 kW	16200.0	1000 PWT	815	(Rotterdam Plastics, 2024)	Flat-Plate, Good Quality (6 collectors, 12 m2) PV 7kW nominal (20 modules, 35.32 m2)	17900	(Zoofy, 2024)	Li-Ion 4 kW, 4 kWh	1359.95	(Nkon, 2024)
(PV&PVT)-E-(GS)PWT+Li-Ion	HP Brine to Water 15 kW	22637.7	1000 PWT	815	(Rotterdam Plastics, 2024)	PVT 7kW nominal (20 modules, 39.2 m2)	36000	(Zoofy, 2024)	Li-Ion 4 kW, 4 kWh	1359.95	(Nkon, 2024)

Table 39, Components definition and prices for the Amsterdam case (references in the table)

Now after the parameters for the devices and the initial investments are defined now the simulation results will be presented in table 40 for Germany for both SFH buildings in terms of net present value, energy consumption and CO_2 emissions as the reviewed KIPs for this section.

System Combination						NPV (€)		Energy Consum (kWh)		CO2 Emissions (kg)	
Elec	**Solar Thermal**	**Boiler**	**Heat Pump**	**Water Tank**	**Battery**	**GER SFH 1955**	**GER SFH 2000**	**GER SFH 1955**	**GER SFH 2000**	**GER SFH 1955**	**GER SFH 2000**
Grid	No	Gas	No	COIL	No-Bt	-32571.7	-32749.9	24022	24182	7145	6766
Grid	No	**Elec**	No	PWT	No-Bt	-29044.5	-29186.3	21674	21781	11626	11684
Grid	No	**Elec**	**A-W**	COIL	No-Bt	-32913	-31865.2	12295	11503	6595	6170
Grid	No	**Elec**	**GS**	COIL	No-Bt	-49259.7	-48078.9	10953	10055	5875	5394
Grid	**Yes**	**Elec**	**A-W**	COIL	No-Bt	-45781.3	-44725.8	10709	9911	5744	5316
Grid	**Yes**	**Elec**	**GS**	COIL	No-Bt	-51840.5	-50824	9789	9187	5251	4928
PV	No	**Elec**	**A-W**	COIL	No-Bt	-33844.5	-33129.8	10441	9762	5772	5518
PV	No	**Elec**	**GS**	COIL	No-Bt	-50003.9	-48990	9277	8330	5083	4702
PV	**Yes**	**Elec**	**A-W**	PWT	No-Bt	-44243.4	-43476.4	9139	8394	5104	4835
PV	**PVT**	**Elec**	**GS**	PWT	No-Bt	-52817.5	-51947.9	10485	9790	5634	5291
PV	No	**Elec**	**A-W**	COIL	**Li-Ion**	-42311.9	-40651.4	4628	3923	4503	4287
PV	No	**Elec**	**GS**	COIL	**Li-Ion**	-57991.8	-57137.2	3860	2965	4011	3727
PV	**Yes**	**Elec**	**A-W**	PWT	**Li-Ion**	-52610.9	-51984.1	3745	3001	4270	4082
PV	**PVT**	**Elec**	**GS**	PWT	**Li-Ion**	-60199.6	-59557.7	3844	3137	4241	4047

Table 40, Simulation results for Germany

For Berlin we can observe that the most simple systems (without so many components) end up being a better economical choice, which is also due to the high CAPEX, nevertheless the case combining PV, and air to water heat pump and also a lithium ion battery is as well presented as a good enough investment, and it will be most likely the way to go as current and future subsidies will promote the use of PV and batteries to decarbonize and relieve the electricity market in the country.

From an energy efficiency perspective and also from an environmental point of view the system with the best results are also the ones combining battery storage with some kind of solar power and also heat pumps, which seems like a very promising result.

The results for The Netherlands case are presented in table 41 below, also presenting the two types of SFH buildings.

System Combination						NPV (€)		Energy Consum (kWh)		CO2 Emissions (kg)	
Elec	**Solar Thermal**	**Boiler**	**Heat Pump**	**Water Tank**	**Battery**	**NDL SFH 1970**	**NDL SFH 2000**	**NDL SFH 1970**	**NDL SFH 2000**	**NDL SFH 1970**	**NDL SFH 2000**
Grid	No	Gas	No	COIL	No-Bt	-80110	-82094.7	19198	21733	6492	6722
Grid	No	**Elec**	No	PWT	No-Bt	-116035	-133090	17016	19524	9128	10473
Grid	No	**Elec**	**A-W**	COIL	No-Bt	-86314.2	-88180.6	11039	11313	5921	6069
Grid	No	**Elec**	**GS**	COIL	No-Bt	-95429.7	-94386	10585	10431	5678	5595
Grid	**Yes**	**Elec**	**A-W**	COIL	No-Bt	-103425	-103950	10060	10137	5396	5438
Grid	**Yes**	**Elec**	**GS**	COIL	No-Bt	-100649	-100494	9330	8923	5005	4786
PV	No	**Elec**	**A-W**	COIL	No-Bt	-80419.2	-82814.8	9424	9703	5129	5336
PV	No	**Elec**	**GS**	COIL	No-Bt	-89403	-88760.7	8982	8829	4867	4831
PV	**Yes**	**Elec**	**A-W**	PWT	No-Bt	-89950	-91943.2	8434	8644	4609	4786
PV	**PVT**	**Elec**	**GS**	PWT	No-Bt	-107806	-109207	9757	9956	5234	5347
PV	No	**Elec**	**A-W**	COIL	**Li-Ion**	-62916	-66053	3906	4202	3801	4091

PV	No	**Elec**	**GS**	COIL	**Li-Ion**	-74442.1	-74595.9	3969	3815	3714	3766
PV	**Yes**	**Elec**	**A-W**	PWT	**Li-Ion**	-76837.5	-79663.3	3400	3611	3675	3946
PV	**PVT**	**Elec**	**GS**	PWT	**Li-Ion**	-101673	-104138	3304	3458	3735	3980

Table 41, Simulation results for The Netherlands

This time the scenario seems tilted towards the systems including PV and battery storage as they provide the higher electricity savings. Considering the high electricity prices in The Netherlands this was the expected outcome.

Nevertheless, it is important to note that for these particular simulation parameters always the use of a ground source heat pump is not justified as it will require a higher initial investment, and this does not pay off with the current conditions.

Also as expected and in the same way as for the Germany case the best efficiency and environmental outcome is achieved with the most complex systems including solar power, heat pumps and batteries.

Once again a series of figures will be presented in order to compare both countries results in a more graphical way. First figure 79 presents the NPV for both cases where it is clear than in Germany all the values are lower than in the Netherlands, due to market prices for gas and electricity which is around 50% higher. Nevertheless, is also interesting to see how the NPV for the Germany values increase for the most complex cases, while for the Netherlands it decreases, also due to expenditure savings for electricity from the grid.

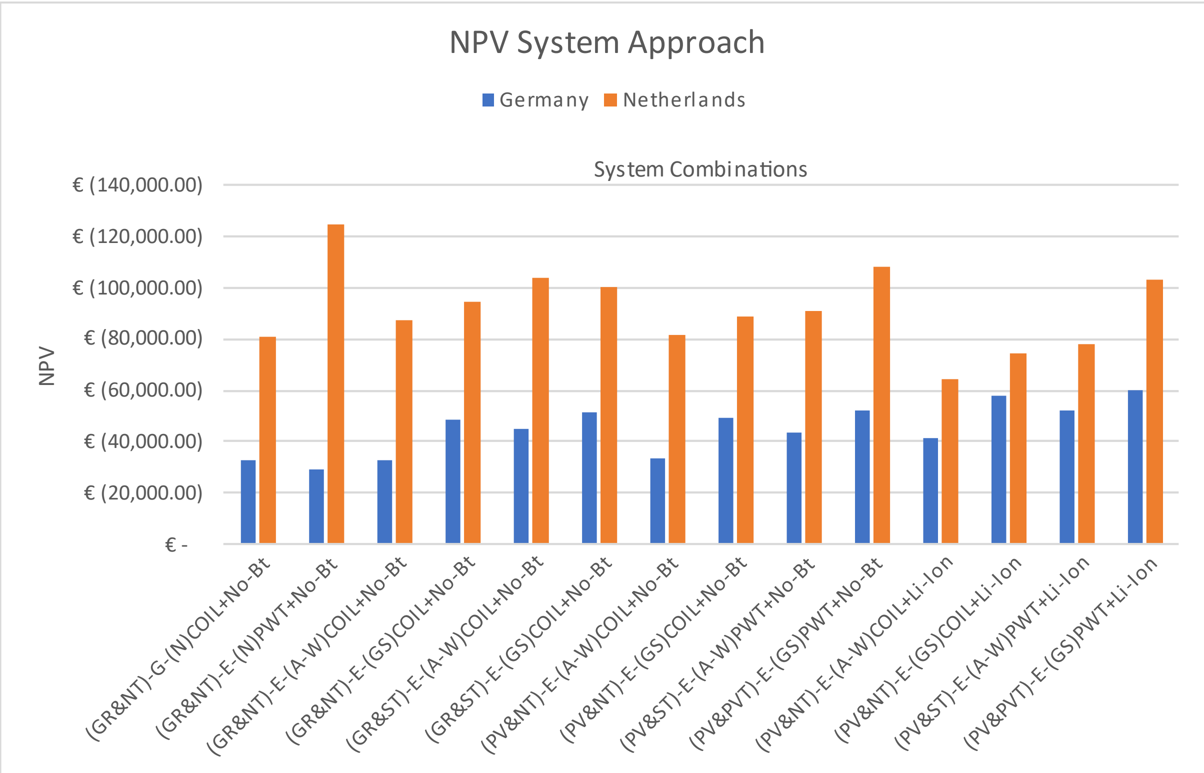

Figure 79, NPV values for the different system combination on each country

Now, as expected from the energy consumption perspective the scenario is very similar in both countries (slightly lower in The Netherlands due to lower average temperatures), and a decreasing trend is visible as the system includes more components and storage systems as well as solar energy devices (see figure 80).

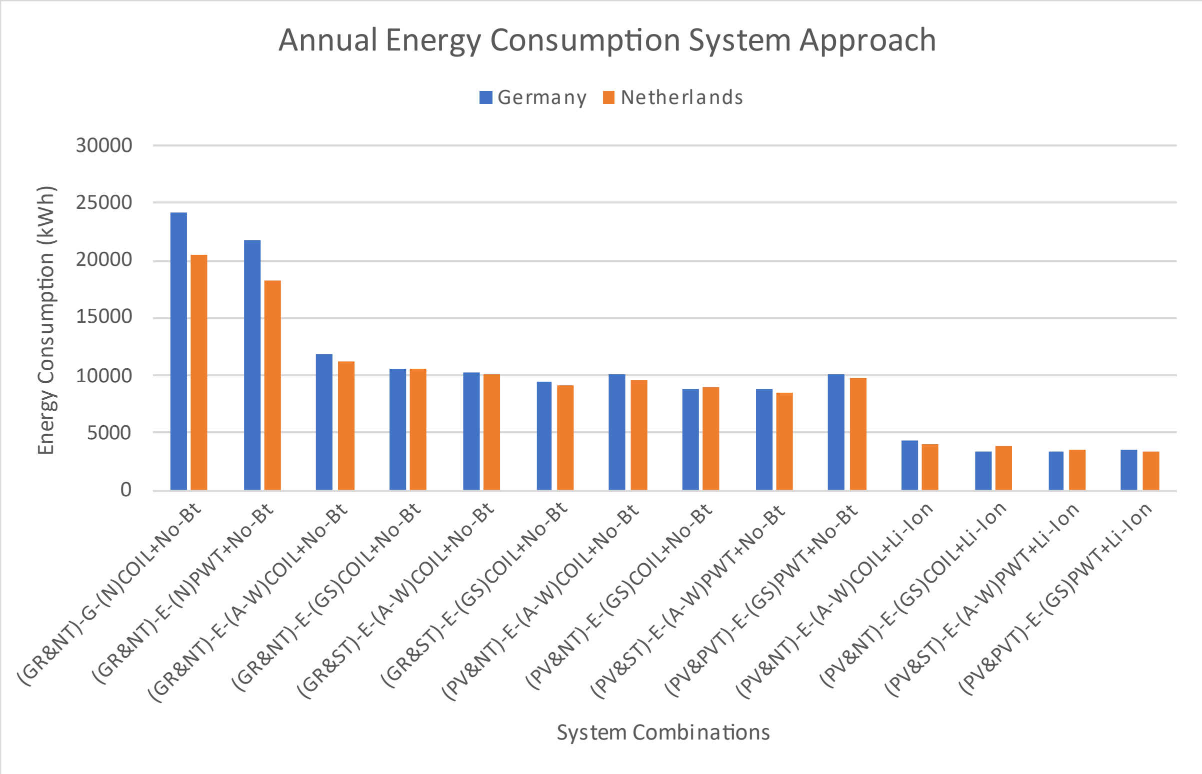

Figure 80, Annual energy consumption for each system combination in both countries

Finally, when checking the CO_2 emissions we also see a decreasing trend as the system includes more components, and also a peak can be seen for the electric boiler, being even higher than the gas boiler, this is due to operational efficiencies, but still is a counterintuitive result. The lower values are presented when including electricity storage and also solar energy devices as can be seen in graph 81.

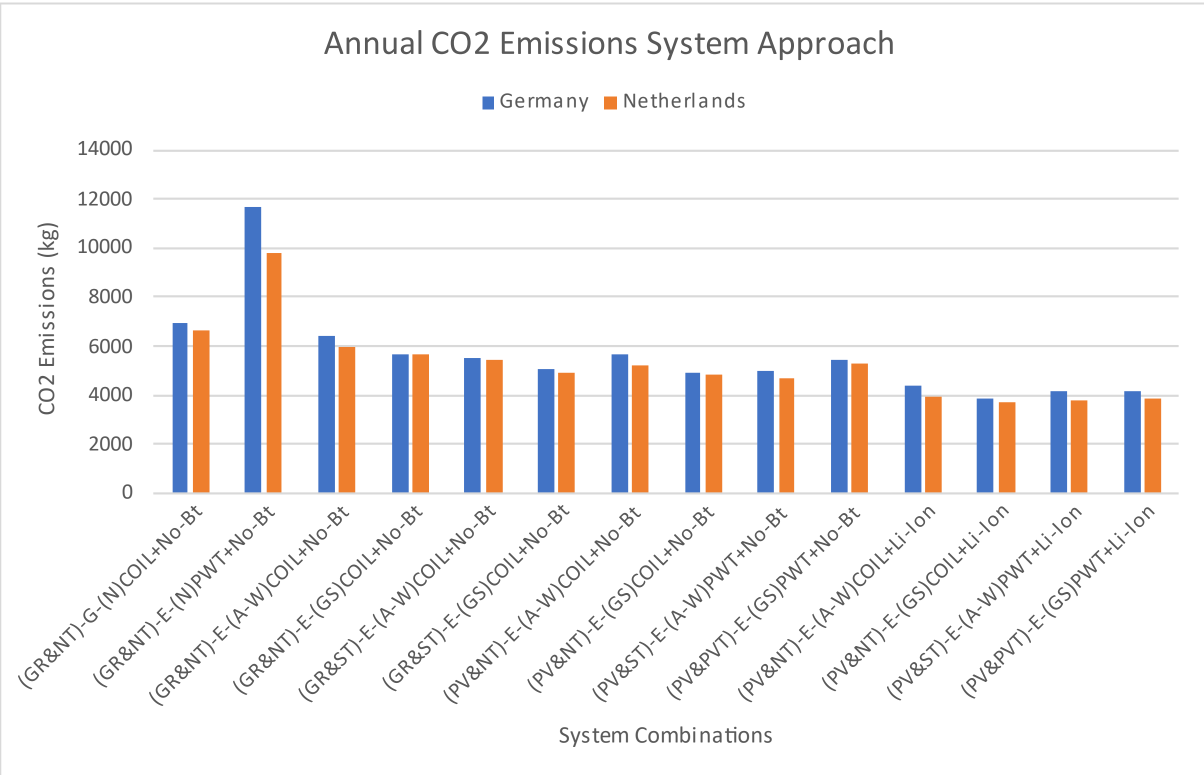

Figure 81, Annual carbon emissions from the different system combinations for each country

10. Conclusions

The main conclusion of the study is that there is no single answer on the question "what is the future of heating?", as it depends on many factors not only technical but also social and political and mostly economic factors and market development. There is no panacea for the future of heating, but still the assessment and the results from the technoeconomic analysis and the system approach show that combining heat pumps with other generation and/or storage technologies can be beneficial from all perspectives.

It is very clear that the influence of the market behavior makes the future even harder to predict, as between neighboring countries the industry developed following very different paths, and even more when comparing both scenarios with Sweden it is clear that many factors and events influenced the huge adoption of heat pumps (including heat pumps for district heating) in the country. All the study is based on market conditions as they are at the moment when this study was performed but still the historical data shows that this can change drastically due to unpredictable situations and can shift the industry towards unexpected paths.

Also, from the literature review, it is important to highlight that for heat pump innovations the expected behavior is for the technologies keep improving and having better COPs while at the same time decreasing prices, in that case, and coupled with government subsidies, electrification will keep advancing and being a very important player in the decarbonization of the heating industry.

On the other hand, heat as a service is reviewed briefly as a promising strategy, but with the current technology prices and market prices, it is still not a good business case, mainly due to high uncertainty and long payback time periods for the companies, therefore it does not seem as a path that will be followed in the near future, but mostly depends on technology development and prices drop.

About heat communities, the pilot projects show that they have high potential, nevertheless the success depends on several factors that are very specific for each location and from a project management perspective. A system approach is a good alternative as long as it benefits from its size and from local conditions, such as lakes, big storage capacity, a prosumers approach, high system inertia and enough generation to work off-grid most of the time. Another important factor to consider here is that all the pilot projects are from a program promoted by the Dutch government, then regulations and permits should not be a major issue, nevertheless they can be one of the main barriers when it comes to implement heat communities elsewhere.

Regarding the system approach the use of PV and batteries can be highly beneficial and seems like the way to go in the near future as it represents cost savings, energy efficiency and a lower environmental impact, when comparing the simulation results between Germany and The Netherlands it seems like the best alternatives presented for The Netherlands are the systems including PV, HP, batteries and thermal storage, mostly due to high electricity prices and representative saving, but still it is a promising result to see that they present currently a best-case scenario, while in Germany it seems like the step to follow in the near future, probably with the support of subsidies and regulation on the use of fossil fuels for residential heating.

Then, as previously mentioned, the current and future governmental subsidies also play a key role in decarbonizing the heating industry and will continue doing so as long as they are representative enough to shift the best economic decision towards fossil free technologies for the consumers.

As a final note, but still relevant to mention is that regarding the heating technology used, as long as a refurbishment or an improvement of a residential heating system is intended, insulation should always be the first check, as in most studies (and for all approaches) is mentioned that this will be the cheapest path to increase the system efficiency and reduce costs without high investments.

Now, two important conclusions about the German market specifically will be that it was surprising to find that the CAPEX in the country for heat generation devices was usually between 1.5 and 3 times higher than in the Netherlands, then once again, subsidies are crucial. Also, the prices in €/kWh of electricity and gas are comparable, then gas technologies are still an attractive choice in some cases because of a lower cost of the device itself.

For The Netherlands the main takeaway is the high electricity prices when comparing different energy sources in euros per kWh, this causes that any electricity saving becomes crucial and highly influence the results for the economic KPIs, also using gas as a fuel is an economical decision.

11. Recommendations & Future Steps

The uncertainties related to market dependency play a key role in the economic feasibility results, therefore a methodology to include these variations in a more case specific model, maybe even considering prices forecasting, will be beneficial for more accurate results.

Besides that, due to technology development and price changes, the CAPEX data should be updated every year for the analysis to be valid, this is also due to industry development and considering how the popularization of a certain technology caused by external factors can drastically drop prices depending on supply and demand.

For the future steps and if it is intended to keep investigating on fossil free heating for Germany and The Netherlands, then identifying specific cases with different demand conditions that can be considered as representative for each country market and based on said cases, simulate several systems approaches to identify the best option.

Then, recreate the simulation in field trials and check the accuracy of the results, as well as identify potential improvements based on real life scenarios and considering further variables that cannot be simulated with enough accuracy.

As well, identifying specific devices for heat generation and testing the performance in the field trials to define the actual costs and savings related and check the accuracy of the ranking presented in the techno-economic analysis.

Finally, regarding the community approach a specific location can be selected as a representative case for as many communities as possible in each country (or several locations), and a pilot project can be performed to get real data and identify advantages and weaknesses of this approach.

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Annexes

1. Market Dependency (MatLab Code)

```
clc
clear

%% Standard Caracteristics and Heat Pump COP

% Heating Capacity in kW
Heat_Cap = 10;

% Dolar to Euro Conversion factor
Dol_Eur = 0.91;

% Efficiencies
ElecBoiler_eff = 1;
Gas_eff = 0.9;
SolidFuel_eff = 0.85;
HeatingOil_eff = 0.85;

% Low Heating Values (kWh/m3), (kWh/kg) and (kWh/L) respectively
Gas_LHV = 9.5;
SolidFuel_LHV = 4.7;
HeatingOil_LHV = 10;

% Heat Pump COP Data
Temp = [-20 -7 2 7 15 25];
COP = [1.13 2.29 3.07 3.5 4.21 5.25];

% Perform linear regression
COP_lr = polyfit(Temp, COP, 1);  % Fit a first-degree polynomial (linear
regression)

% Extract coefficients
slope_COPlr = COP_lr(1);
intercept_COPlr = COP_lr(2);

    %%
    %% case for Stockholm

    % Heating Demand for Stockholm from September to May

    %VARIABLE%
    HD_Stck = [0.19 1.24 2.18 3.11 3.67 3.3 2.82 1.59 0.53];

    % COP average from September to May

    %VARIABLE%
    COP_Stck = [3.9421 3.7811 3.3775 2.7403 2.9778 2.9052 2.9144 3.3775 3.9698];

    % OPEX in Euro/year (only operation and mainteinance, no fuel)

    %VARIABLES%
    OPEX_HP_Stck = 270 * Dol_Eur;
    OPEX_EB_Stck = 150;
    OPEX_Gas_Stck = 190 * Dol_Eur;
    OPEX_SF_Stck = 300 * Dol_Eur;
```

```
    %Lifetime in years

    %VARIABLES%
    LT_HP_Stck = 17;
    LT_EB_Stck = 17;
    LT_Gas_Stck = 15;
    LT_SF_Stck = 20;

    % CAPEX in Euro/year (investment cost over the life time expectancy)

    %VARIABLES%
    CAPEX_HP_Stck = (6100*Dol_Eur)/LT_HP_Stck;
    CAPEX_EB_Stck = (3000)/LT_EB_Stck;
    CAPEX_Gas_Stck = (5400*Dol_Eur)/LT_Gas_Stck;
    CAPEX_SF_Stck = (3100*Dol_Eur)/LT_SF_Stck;

    %% Costs calculation For Stockholm

        % Assume variations for the costs of electricity, gas and solid fuel from
0
        % to 2 euros per unit

        % Electricity cost in Euro/kWh

        Elec_Price_Stck = 0:0.1:2;
        EP_Stck = 0;

        % Gas cost in Euro/m3

        Gas_Price_Stck = 0:0.1:2;
        GP_Stck = 0;

        % Solid fuel cost in Euro/kg

        SolidFuel_Price_Stck = 0:0.1:2;
        SFP_Stck = 0;

        % Cost of heating with a heat pump including capex, opex and fuel

        Cost_HP_Stck = zeros(size(Elec_Price_Stck));

        n = 1;
        while n <= sum(size(Elec_Price_Stck))-1

            Cost_HP_Stck(n) = sum(HD_Stck ./ COP_Stck .* 1000 .* EP_Stck) +
OPEX_HP_Stck + CAPEX_HP_Stck;
            EP_Stck = EP_Stck + 0.1;
            n = n + 1;

        end

            % Perform linear regression
            CostHP_lr_Stck = polyfit(Elec_Price_Stck, Cost_HP_Stck, 1);  % Fit a
first-degree polynomial (linear regression)

            % Extract coefficients
            slope_CostHPlr_Stck = CostHP_lr_Stck(1);
            intercept_CostHPlr_Stck = CostHP_lr_Stck(2);
```

```
        % Cost of heating with an electric boiler including capex, opex and fuel

        Cost_EB_Stck = zeros(size(Elec_Price_Stck));
        EP_Stck = 0;

        n = 1;
        while n <= sum(size(Elec_Price_Stck))-1

            Cost_EB_Stck(n) = sum(HD_Stck ./ ElecBoiler_eff .* 1000 .* EP_Stck) +
OPEX_EB_Stck + CAPEX_EB_Stck;
            EP_Stck = EP_Stck + 0.1;
            n = n + 1;

        end

            % Perform linear regression
            CostEB_lr_Stck = polyfit(Elec_Price_Stck, Cost_EB_Stck, 1);  % Fit a
first-degree polynomial (linear regression)

            % Extract coefficients
            slope_CostEBlr_Stck = CostEB_lr_Stck(1);
            intercept_CostEBlr_Stck = CostEB_lr_Stck(2);

        % Cost of heating with a gas boiler including capex, opex and fuel

        Cost_GB_Stck = zeros(size(Gas_Price_Stck));

        n = 1;
        while n <= sum(size(Gas_Price_Stck))-1

            Cost_GB_Stck(n) = sum(HD_Stck .* (1/Gas_eff) .*(1/Gas_LHV) .* 1000 .*
GP_Stck) + OPEX_Gas_Stck + CAPEX_Gas_Stck;
            GP_Stck = GP_Stck + 0.1;
            n = n + 1;

        end

            % Perform linear regression
            CostGB_lr_Stck = polyfit(Gas_Price_Stck, Cost_GB_Stck, 1);  % Fit a
first-degree polynomial (linear regression)

            % Extract coefficients
            slope_CostGBlr_Stck = CostGB_lr_Stck(1);
            intercept_CostGBlr_Stck = CostGB_lr_Stck(2);

        % Cost of heating with a solid fuel boiler including capex, opex and fuel

        Cost_SF_Stck = zeros(size(SolidFuel_Price_Stck));

        n = 1;
        while n <= sum(size(SolidFuel_Price_Stck))-1

            Cost_SF_Stck(n) = sum(HD_Stck .* (1/SolidFuel_eff) .*(1/SolidFuel_LHV)
.* 1000 .* SFP_Stck) + OPEX_SF_Stck + CAPEX_SF_Stck;
            SFP_Stck = SFP_Stck + 0.1;
            n = n + 1;

        end
```

```
            % Perform linear regression
            CostSF_lr_Stck = polyfit(SolidFuel_Price_Stck, Cost_SF_Stck, 1);  %
Fit a first-degree polynomial (linear regression)

            % Extract coefficients
            slope_CostSFlr_Stck = CostSF_lr_Stck(1);
            intercept_CostSFlr_Stck = CostSF_lr_Stck(2);

        %% Graph the lines found to check the behaviour

        figure

        plot (Elec_Price_Stck, Cost_HP_Stck);

        hold on
        plot (Elec_Price_Stck, Cost_EB_Stck)

        hold on
        plot (Gas_Price_Stck, Cost_GB_Stck)

        hold on
        plot (SolidFuel_Price_Stck, Cost_SF_Stck)

        hold off

        title ('Energy Carrier Cost per Year (Stockholm)')
        xlabel ('Fuel Price (Elec €/kWh) (Gas €/m3) (Solid Fuel €/kg)')
        ylabel ('€/year')
        legend ('Heat Pump', 'Electric Boiler', 'Gas Boiler', 'Solid Fuel Boiler')

        %% Equal cost equations
        % Find the equations for equal Energy Carrier Cost for Electricity
        % and Gas (gas price in function of electricity price for heat pump)

        Res_GP_Stck = zeros(size(Elec_Price_Stck));

        EP_Stck = 0;
        n = 1;
        while n <= sum(size(Elec_Price_Stck))-1

            Res_GP_Stck(n) = (slope_CostHPlr_Stck*EP_Stck +
intercept_CostHPlr_Stck - intercept_CostGBlr_Stck) / slope_CostGBlr_Stck;
            EP_Stck = EP_Stck + 0.1;
            n = n + 1;

        end

        % Find the value for equal Energy Carrier Cost for heating with a
        % Heat Pump and with an Electric Boiler

        Res_EP_Stck = (intercept_CostEBlr_Stck - intercept_CostHPlr_Stck) /
(slope_CostHPlr_Stck - slope_CostEBlr_Stck);

        % Find the equations for equal Energy Carrier Cost for Electricity
        % and Gas (gas price in function of electricity price for electric boiler)

        Res_GP2_Stck = zeros(size(Elec_Price_Stck));
```

```
        EP_Stck = 0;
        n = 1;
        while n <= sum(size(Elec_Price_Stck))-1

            Res_GP2_Stck(n) = (slope_CostEBlr_Stck * EP_Stck +
intercept_CostEBlr_Stck - intercept_CostGBlr_Stck) / slope_CostGBlr_Stck;
            EP_Stck = EP_Stck + 0.1;
            n = n + 1;

        end

        % Find the graph equations and the interception point

            % Perform linear regression for HP vs GB
            ResGP_lr_Stck = polyfit(Elec_Price_Stck, Res_GP_Stck, 1);  % Fit a
first-degree polynomial (linear regression)

            % Extract coefficients from HP vs GB
            slope_ResGPlr_Stck = ResGP_lr_Stck(1);
            intercept_ResGPlr_Stck = ResGP_lr_Stck(2);

            % Perform linear regression for EB vs GB
            ResGP2_lr_Stck = polyfit(Elec_Price_Stck, Res_GP2_Stck, 1);  % Fit a
first-degree polynomial (linear regression)

            % Extract coefficients from EB vs GB
            slope_ResGP2lr_Stck = ResGP2_lr_Stck(1);
            intercept_ResGP2lr_Stck = ResGP2_lr_Stck(2);

        % Find the value of the intersection

            % Find the value of the Electricity Price

            intersectionEP_Stck = (intercept_ResGP2lr_Stck -
intercept_ResGPlr_Stck) / (slope_ResGPlr_Stck - slope_ResGP2lr_Stck);

            % Find the value of the gas Price

            intersectionGP_Stck = slope_ResGPlr_Stck * intersectionEP_Stck +
intercept_ResGPlr_Stck;

        figure

        fplot(@(x) slope_ResGPlr_Stck * (x) + intercept_ResGPlr_Stck,
[intersectionEP_Stck 10])

        hold on
        plot([intersectionEP_Stck intersectionEP_Stck], [intersectionGP_Stck 10])

        hold on
        fplot(@(x) slope_ResGP2lr_Stck * (x) + intercept_ResGP2lr_Stck, [0
intersectionEP_Stck])

        xlim([0 0.4])
        ylim([0 2])

        hold on
        Historical_EP_Sweden = [0.1320 0.1307 0.1236 0.1537 0.2152 0.1789];
        Historical_GP_Sweden = [0.7463 0.7067 0.8566 1.1711 1.8013 1.5474];
```

```
        labels = {'2018', ' ', '2020', '2021', '2022', '2023'};
        plot(Historical_EP_Sweden, Historical_GP_Sweden, "o")
        text(Historical_EP_Sweden, Historical_GP_Sweden,
labels,'VerticalAlignment', 'bottom', 'horizontalAlignment', 'left')
        axis([0 0.5 0 2])

        txtHP = {'Best economy', 'with Heat Pump'};
        text(0.05, 1.6, txtHP)

        txtGB = {'Best economy', 'with Gas Boiler'};
        text(0.15, 0.3, txtGB)

        txtEB = {'Best economy with Electric Boiler'};
        text(0.009, 0.45, txtEB, Rotation = 90)


        title ('Stockholm Case')
        xlabel ('Electricity Price (€/kWh)')
        ylabel ('Gas Price (€/m3)')
        grid on
        legend('HP vs GB', 'HP vs EB', 'EB vs GB', 'G&E Prices 2018-2023')

    %% case for Berlin

    % Heating Demand for Berlin from September to May

    %VARIABLE%
    HD_Berl = [0 0.67 1.71 2.72 3.16 2.64 1.96 0.76 0.16];

    % COP average from September to May

    %VARIABLE%
    COP_Berl = [4.1762 4.0778 3.4529 3.0847 3.3253 3.2230 3.4549 3.6663 4.2031];

    % OPEX in Euro/year (only operation and maintenance, no fuel)

    %VARIABLES%
    OPEX_HP_Berl = 210 * Dol_Eur;
    OPEX_EB_Berl = 150;
    OPEX_Gas_Berl = 195 * Dol_Eur;
    OPEX_SF_Berl = 250 * Dol_Eur;
    OPEX_HO_Berl = 215 * Dol_Eur;

    % Lifetime in years

    %VARIABLES%
    LT_HP_Berl = 18;
    LT_EB_Berl = 17;
    LT_Gas_Berl = 15;
    LT_SF_Berl = 20;
    LT_HO_Berl = 17;

    % CAPEX in Euro/year (investment cost over the lifetime expectancy)

    %VARIABLES%
    CAPEX_HP_Berl = (13500*Dol_Eur)/LT_HP_Berl;
    CAPEX_EB_Berl = (3000)/LT_EB_Berl;
    CAPEX_Gas_Berl = (5100*Dol_Eur)/LT_Gas_Berl;
    CAPEX_SF_Berl = (5800*Dol_Eur)/LT_SF_Berl;
```

```
    CAPEX_HO_Berl = (6350*Dol_Eur)/LT_HO_Berl;

    %% Costs calculation For Berlin

        % Assume variations for the costs of electricity, gas and solid fuel from
0
        % to 2 euros per unit

        % Electricity cost in Euro/kWh

        Elec_Price_Berl = 0:0.1:2;
        EP_Berl = 0;

        % Gas cost in Euro/m3

        Gas_Price_Berl = 0:0.1:2;
        GP_Berl = 0;

        % Solid fuel cost in Euro/kg

        SolidFuel_Price_Berl = 0:0.1:2;
        SFP_Berl = 0;

        % Heating oil cost in Euro/L

        HeatingOil_Price_Berl = 0:0.1:2;
        HOP_Berl = 0;

        % Cost of heating with a heat pump including capex, opex and fuel

        Cost_HP_Berl = zeros(size(Elec_Price_Berl));

        n = 1;
        while n <= sum(size(Elec_Price_Berl)) - 1

            Cost_HP_Berl(n) = sum(HD_Berl ./ COP_Berl .* 1000 .* EP_Berl) +
OPEX_HP_Berl + CAPEX_HP_Berl;
            EP_Berl = EP_Berl + 0.1;
            n = n + 1;

        end

        % Perform linear regression
        CostHP_lr_Berl = polyfit(Elec_Price_Berl, Cost_HP_Berl, 1);  % Fit a
first-degree polynomial (linear regression)

        % Extract coefficients
        slope_CostHPlr_Berl = CostHP_lr_Berl(1);
        intercept_CostHPlr_Berl = CostHP_lr_Berl(2);

        % Cost of heating with an electric boiler including capex, opex and fuel

        Cost_EB_Berl = zeros(size(Elec_Price_Berl));
        EP_Berl = 0;

        n = 1;
        while n <= sum(size(Elec_Price_Berl)) - 1
```

```
            Cost_EB_Berl(n) = sum(HD_Berl ./ ElecBoiler_eff .* 1000 .* EP_Berl) +
OPEX_EB_Berl + CAPEX_EB_Berl;
            EP_Berl = EP_Berl + 0.1;
            n = n + 1;

        end

        % Perform linear regression
        CostEB_lr_Berl = polyfit(Elec_Price_Berl, Cost_EB_Berl, 1);  % Fit a
first-degree polynomial (linear regression)

        % Extract coefficients
        slope_CostEBlr_Berl = CostEB_lr_Berl(1);
        intercept_CostEBlr_Berl = CostEB_lr_Berl(2);

        % Cost of heating with a gas boiler including capex, opex and fuel

        Cost_GB_Berl = zeros(size(Gas_Price_Berl));

        n = 1;
        while n <= sum(size(Gas_Price_Berl)) - 1

            Cost_GB_Berl(n) = sum(HD_Berl .* (1/Gas_eff) .* (1/Gas_LHV) .* 1000 .*
GP_Berl) + OPEX_Gas_Berl + CAPEX_Gas_Berl;
            GP_Berl = GP_Berl + 0.1;
            n = n + 1;

        end

        % Perform linear regression
        CostGB_lr_Berl = polyfit(Gas_Price_Berl, Cost_GB_Berl, 1);  % Fit a first-
degree polynomial (linear regression)

        % Extract coefficients
        slope_CostGBlr_Berl = CostGB_lr_Berl(1);
        intercept_CostGBlr_Berl = CostGB_lr_Berl(2);

        % Cost of heating with a solid fuel boiler including capex, opex and fuel

        Cost_SF_Berl = zeros(size(SolidFuel_Price_Berl));

        n = 1;
        while n <= sum(size(SolidFuel_Price_Berl)) - 1

            Cost_SF_Berl(n) = sum(HD_Berl .* (1/SolidFuel_eff) .*
(1/SolidFuel_LHV) .* 1000 .* SFP_Berl) + OPEX_SF_Berl + CAPEX_SF_Berl;
            SFP_Berl = SFP_Berl + 0.1;
            n = n + 1;

        end

        % Perform linear regression
        CostSF_lr_Berl = polyfit(SolidFuel_Price_Berl, Cost_SF_Berl, 1);  % Fit a
first-degree polynomial (linear regression)

        % Extract coefficients
        slope_CostSFlr_Berl = CostSF_lr_Berl(1);
        intercept_CostSFlr_Berl = CostSF_lr_Berl(2);
```

```
        % Cost of heating with a heating oil boiler including capex, opex and fuel

        Cost_HO_Berl = zeros(size(HeatingOil_Price_Berl));

        n = 1;
        while n <= sum(size(HeatingOil_Price_Berl)) - 1

            Cost_HO_Berl(n) = sum(HD_Berl .* (1/HeatingOil_eff) .*
(1/HeatingOil_LHV) .* 1000 .* HOP_Berl) + OPEX_HO_Berl + CAPEX_HO_Berl;
            HOP_Berl = HOP_Berl + 0.1;
            n = n + 1;

        end

        % Perform linear regression
        CostHO_lr_Berl = polyfit(HeatingOil_Price_Berl, Cost_HO_Berl, 1);  % Fit a
first-degree polynomial (linear regression)

        % Extract coefficients
        slope_CostHOlr_Berl = CostHO_lr_Berl(1);
        intercept_CostHOlr_Berl = CostHO_lr_Berl(2);

        %% Graph the lines found to check the behaviour

        figure

        plot(Elec_Price_Berl, Cost_HP_Berl);

        hold on
        plot(Elec_Price_Berl, Cost_EB_Berl)

        hold on
        plot(Gas_Price_Berl, Cost_GB_Berl)

        hold on
        plot(SolidFuel_Price_Berl, Cost_SF_Berl)

        hold on
        plot(HeatingOil_Price_Berl, Cost_HO_Berl)

        hold off

        title('Energy Carrier Cost per Year (Berlin)')
        xlabel('Fuel Price (Elec €/kWh) (Gas €/m3) (Solid Fuel €/kg) (Heating Oil
€/L)')
        ylabel('€/year')
        legend('Heat Pump', 'Electric Boiler', 'Gas Boiler', 'Solid Fuel Boiler',
'Heating Oil Boiler')

        %% Equal cost equations
        % Find the equations for equal Energy Carrier Cost for Electricity
        % and Gas (gas price in function of electricity price for heat pump)

        Res_GP_Berl = zeros(size(Elec_Price_Berl));

        EP_Berl = 0;
        n = 1;
        while n <= sum(size(Elec_Price_Berl))-1
```

```
            Res_GP_Berl(n) = (slope_CostHPlr_Berl*EP_Berl +
intercept_CostHPlr_Berl - intercept_CostGBlr_Berl) / slope_CostGBlr_Berl;
            EP_Berl = EP_Berl + 0.1;
            n = n + 1;

        end

        % Find the value for equal Energy Carrier Cost for heating with a
        % Heat Pump and with an Electric Boiler

        Res_EP_Berl = (intercept_CostEBlr_Berl - intercept_CostHPlr_Berl) /
(slope_CostHPlr_Berl - slope_CostEBlr_Berl);

        % Find the equations for equal Energy Carrier Cost for Electricity
        % and Gas (gas price in function of electricity price for electric boiler)

        Res_GP2_Berl = zeros(size(Elec_Price_Berl));

        EP_Berl = 0;
        n = 1;
        while n <= sum(size(Elec_Price_Berl))-1

            Res_GP2_Berl(n) = (slope_CostEBlr_Berl * EP_Berl +
intercept_CostEBlr_Berl - intercept_CostGBlr_Berl) / slope_CostGBlr_Berl;
            EP_Berl = EP_Berl + 0.1;
            n = n + 1;

        end

        % Find the graph equations and the interception point

            % Perform linear regression for HP vs GB
            ResGP_lr_Berl = polyfit(Elec_Price_Berl, Res_GP_Berl, 1);  % Fit a
first-degree polynomial (linear regression)

            % Extract coefficients from HP vs GB
            slope_ResGPlr_Berl = ResGP_lr_Berl(1);
            intercept_ResGPlr_Berl = ResGP_lr_Berl(2);

            % Perform linear regression for EB vs GB
            ResGP2_lr_Berl = polyfit(Elec_Price_Berl, Res_GP2_Berl, 1);  % Fit a
first-degree polynomial (linear regression)

            % Extract coefficients from EB vs GB
            slope_ResGP2lr_Berl = ResGP2_lr_Berl(1);
            intercept_ResGP2lr_Berl = ResGP2_lr_Berl(2);

        % Find the value of the intersection

            % Find the value of the Electricity Price

            intersectionEP_Berl = (intercept_ResGP2lr_Berl -
intercept_ResGPlr_Berl) / (slope_ResGPlr_Berl - slope_ResGP2lr_Berl);

            % Find the value of the gas Price

            intersectionGP_Berl = slope_ResGPlr_Berl * intersectionEP_Berl +
intercept_ResGPlr_Berl;
```

```
        figure

        fplot(@(x) slope_ResGPlr_Berl * (x) + intercept_ResGPlr_Berl,
[intersectionEP_Berl 10])

        hold on
        plot([intersectionEP_Berl intersectionEP_Berl], [intersectionGP_Berl 10])

        hold on
        fplot(@(x) slope_ResGP2lr_Berl * (x) + intercept_ResGP2lr_Berl, [0
intersectionEP_Berl])

        hold on
        Historical_EP_Germany = [0.1378 0.1397 0.1441 0.1579 0.2116 0.2973];
        Historical_GP_Germany = [0.4761 0.4766 0.4803 0.4798 0.6872 1.0228];
        labels = {'2018', ' ', ' ', ' ', '2022', '2023'};
        plot(Historical_EP_Germany, Historical_GP_Germany, "o")
        text(Historical_EP_Germany, Historical_GP_Germany,
labels,'VerticalAlignment', 'bottom', 'horizontalAlignment', 'left')

        xlim([0 0.5])
        ylim([0 2])

        txtHP = {'Best economy', 'with Heat Pump'};
        text(0.1, 1, txtHP)

        txtGB = {'Best economy', 'with Gas Boiler'};
        text(0.2, 0.4, txtGB)

        txtEB = {'Best economy with Electric Boiler'};
        text(0.025, 0.35, txtEB, Rotation = 90)

        title('Berlin Case (Gas Boiler)')
        xlabel('Electricity Price (€/kWh)')
        ylabel('Gas Price (€/m3)')
        grid on
        legend('HP vs GB', 'HP vs EB', 'EB vs GB', 'G&E Prices 2018-2023')

        %% Equal cost equations #2
        % Find the equations for equal Energy Carrier Cost for Electricity
        % and Heating Oil (heating oil price in function of electricity price for
heat pump)

        Res_HO_Berl = zeros(size(Elec_Price_Berl));

        EP_Berl = 0;
        n = 1;
        while n <= sum(size(Elec_Price_Berl))-1

            Res_HO_Berl(n) = (slope_CostHOlr_Berl*EP_Berl +
intercept_CostHOlr_Berl - intercept_CostHOlr_Berl) / slope_CostHOlr_Berl;
            EP_Berl = EP_Berl + 0.1;
            n = n + 1;

        end

        % Find the value for equal Energy Carrier Cost for heating with a
        % Heat Pump and with an Electric Boiler
```

```
        Res_EP_Berl = (intercept_CostEBlr_Berl - intercept_CostHPlr_Berl) /
(slope_CostHPlr_Berl - slope_CostEBlr_Berl);

        % Find the equations for equal Energy Carrier Cost for Electricity
        % and heating oil (heating oil price in function of electricity price for
electric boiler)

        Res_HO2_Berl = zeros(size(Elec_Price_Berl));

        EP_Berl = 0;
        n = 1;
        while n <= sum(size(Elec_Price_Berl))-1

            Res_HO2_Berl(n) = (slope_CostEBlr_Berl * EP_Berl +
intercept_CostEBlr_Berl - intercept_CostHOlr_Berl) / slope_CostHOlr_Berl;
            EP_Berl = EP_Berl + 0.1;
            n = n + 1;

        end

        % Find the graph equations and the interception point

            % Perform linear regression for HP vs HO
            ResHO_lr_Berl = polyfit(Elec_Price_Berl, Res_HO_Berl, 1);  % Fit a
first-degree polynomial (linear regression)

            % Extract coefficients from HP vs HO
            slope_ResHOlr_Berl = ResHO_lr_Berl(1);
            intercept_ResHOlr_Berl = ResHO_lr_Berl(2);

            % Perform linear regression for EB vs HO
            ResHO2_lr_Berl = polyfit(Elec_Price_Berl, Res_HO2_Berl, 1);  % Fit a
first-degree polynomial (linear regression)

            % Extract coefficients from EB vs HO
            slope_ResHO2lr_Berl = ResHO2_lr_Berl(1);
            intercept_ResHO2lr_Berl = ResHO2_lr_Berl(2);

        % Find the value of the intersection

            % Find the value of the Electricity Price

            intersectionEP_Berl = (intercept_ResHO2lr_Berl -
intercept_ResHOlr_Berl) / (slope_ResHOlr_Berl - slope_ResHO2lr_Berl);

            % Find the value of the heating oil Price

            intersectionHO_Berl = slope_ResHOlr_Berl * intersectionEP_Berl +
intercept_ResHOlr_Berl;

        figure

        fplot(@(x) slope_ResHOlr_Berl * (x) + intercept_ResHOlr_Berl,
[intersectionEP_Berl 10])

        hold on
        plot([intersectionEP_Berl intersectionEP_Berl], [intersectionHO_Berl 10])

        hold on
```

```
        fplot(@(x) slope_ResHO2lr_Berl * (x) + intercept_ResHO2lr_Berl, [0
intersectionEP_Berl])

        hold on
        Historical_EP2_Germany = [0.1441 0.1579 0.2116 0.2973];
        Historical_HOP_Germany = [0.4988 0.7131 1.3232 1.0338];
        labels = {'2020', '2021', '2022', '2023'};
        plot(Historical_EP2_Germany, Historical_HOP_Germany, "o")
        text(Historical_EP2_Germany, Historical_HOP_Germany,
labels,'VerticalAlignment', 'bottom', 'horizontalAlignment', 'left')

        xlim([0 0.4])
        ylim([0 1.5])

        txtHP = {'Best economy', 'with Heat Pump'};
        text(0.1, 1, txtHP)

        txtGB = {'Best economy', 'with Oil Boiler'};
        text(0.25, 0.15, txtGB)

        txtEB = {'Best economy with Electric Boiler'};
        text(0.01, 0.35, txtEB, Rotation = 90)

        title('Berlin Case (Oil Boiler)')
        xlabel('Electricity Price (€/kWh)')
        ylabel('Heating Oil Price (€/L)')
        grid on
        legend('HP vs OB', 'HP vs EB', 'EB vs OB', 'O&E Prices 2020-2023')


    %% case for Amsterdam

    % Heating Demand for Amsterdam from September to May

    %VARIABLE%
    HD_Amst = [0 0.47 1.7 2.83 3.15 2.82 2.2 1.04 0.29];

    % COP average from September to May

    %VARIABLE%
    COP_Amst = [4.2921 4.1313 3.7154 3.2905 3.4561 3.4561 3.5353 3.7040 4.0983];

    % OPEX in Euro/year (only operation and maintenance, no fuel)

    %VARIABLES%
    OPEX_HP_Amst = 270 * Dol_Eur;
    OPEX_EB_Amst = 150;
    OPEX_Gas_Amst = 190 * Dol_Eur;
    OPEX_SF_Amst = 300 * Dol_Eur;

    % Lifetime in years

    %VARIABLES%
    LT_HP_Amst = 17;
    LT_EB_Amst = 17;
    LT_Gas_Amst = 15;
    LT_SF_Amst = 20;

    % CAPEX in Euro/year (investment cost over the lifetime expectancy)
```

```
    %VARIABLES%
    CAPEX_HP_Amst = (7500*Dol_Eur)/LT_HP_Amst;
    CAPEX_EB_Amst = (3000)/LT_EB_Amst;
    CAPEX_Gas_Amst = (4500*Dol_Eur)/LT_Gas_Amst;
    CAPEX_SF_Amst = (7500*Dol_Eur)/LT_SF_Amst;

    %% Costs calculation For Amsterdam

        % Assume variations for the costs of electricity, gas and solid fuel from
0
        % to 2 euros per unit

        % Electricity cost in Euro/kWh

        Elec_Price_Amst = 0:0.1:2;
        EP_Amst = 0;

        % Gas cost in Euro/m3

        Gas_Price_Amst = 0:0.1:2;
        GP_Amst = 0;

        % Solid fuel cost in Euro/kg

        SolidFuel_Price_Amst = 0:0.1:2;
        SFP_Amst = 0;

        % Cost of heating with a heat pump including capex, opex and fuel

        Cost_HP_Amst = zeros(size(Elec_Price_Amst));

        n = 1;
        while n <= sum(size(Elec_Price_Amst)) - 1

            Cost_HP_Amst(n) = sum(HD_Amst ./ COP_Amst .* 1000 .* EP_Amst) +
OPEX_HP_Amst + CAPEX_HP_Amst;
            EP_Amst = EP_Amst + 0.1;
            n = n + 1;

        end

        % Perform linear regression
        CostHP_lr_Amst = polyfit(Elec_Price_Amst, Cost_HP_Amst, 1);  % Fit a
first-degree polynomial (linear regression)

        % Extract coefficients
        slope_CostHPlr_Amst = CostHP_lr_Amst(1);
        intercept_CostHPlr_Amst = CostHP_lr_Amst(2);

        % Cost of heating with an electric boiler including capex, opex and fuel

        Cost_EB_Amst = zeros(size(Elec_Price_Amst));
        EP_Amst = 0;

        n = 1;
        while n <= sum(size(Elec_Price_Amst)) - 1
```

```
            Cost_EB_Amst(n) = sum(HD_Amst ./ ElecBoiler_eff .* 1000 .* EP_Amst) +
OPEX_EB_Amst + CAPEX_EB_Amst;
            EP_Amst = EP_Amst + 0.1;
            n = n + 1;

        end

        % Perform linear regression
        CostEB_lr_Amst = polyfit(Elec_Price_Amst, Cost_EB_Amst, 1);  % Fit a
first-degree polynomial (linear regression)

        % Extract coefficients
        slope_CostEBlr_Amst = CostEB_lr_Amst(1);
        intercept_CostEBlr_Amst = CostEB_lr_Amst(2);

        % Cost of heating with a gas boiler including capex, opex and fuel

        Cost_GB_Amst = zeros(size(Gas_Price_Amst));

        n = 1;
        while n <= sum(size(Gas_Price_Amst)) - 1

            Cost_GB_Amst(n) = sum(HD_Amst .* (1/Gas_eff) .* (1/Gas_LHV) .* 1000 .*
GP_Amst) + OPEX_Gas_Amst + CAPEX_Gas_Amst;
            GP_Amst = GP_Amst + 0.1;
            n = n + 1;

        end

        % Perform linear regression
        CostGB_lr_Amst = polyfit(Gas_Price_Amst, Cost_GB_Amst, 1);  % Fit a first-
degree polynomial (linear regression)

        % Extract coefficients
        slope_CostGBlr_Amst = CostGB_lr_Amst(1);
        intercept_CostGBlr_Amst = CostGB_lr_Amst(2);

        % Cost of heating with a solid fuel boiler including capex, opex and fuel

        Cost_SF_Amst = zeros(size(SolidFuel_Price_Amst));

        n = 1;
        while n <= sum(size(SolidFuel_Price_Amst)) - 1

            Cost_SF_Amst(n) = sum(HD_Amst .* (1/SolidFuel_eff) .*
(1/SolidFuel_LHV) .* 1000 .* SFP_Amst) + OPEX_SF_Amst + CAPEX_SF_Amst;
            SFP_Amst = SFP_Amst + 0.1;
            n = n + 1;

        end

        % Perform linear regression
        CostSF_lr_Amst = polyfit(SolidFuel_Price_Amst, Cost_SF_Amst, 1);  % Fit a
first-degree polynomial (linear regression)

        % Extract coefficients
        slope_CostSFlr_Amst = CostSF_lr_Amst(1);
        intercept_CostSFlr_Amst = CostSF_lr_Amst(2);
```

```
        %% Graph the lines found to check the behaviour

        figure

        plot(Elec_Price_Amst, Cost_HP_Amst);

        hold on
        plot(Elec_Price_Amst, Cost_EB_Amst)

        hold on
        plot(Gas_Price_Amst, Cost_GB_Amst)

        hold on
        plot(SolidFuel_Price_Amst, Cost_SF_Amst)

        hold off

        title('Energy Carrier Cost per Year (Amsterdam)')
        xlabel('Fuel Price (Elec €/kWh) (Gas €/m3) (Solid Fuel €/kg)')
        ylabel('€/year')
        legend('Heat Pump', 'Electric Boiler', 'Gas Boiler', 'Solid Fuel Boiler')

        %% Equal cost equations
        % Find the equations for equal Energy Carrier Cost for Electricity
        % and Gas (gas price in function of electricity price for heat pump)

        Res_GP_Amst = zeros(size(Elec_Price_Amst));

        EP_Amst = 0;
        n = 1;
        while n <= sum(size(Elec_Price_Amst))-1

            Res_GP_Amst(n) = (slope_CostHPlr_Amst*EP_Amst +
intercept_CostHPlr_Amst - intercept_CostGBlr_Amst) / slope_CostGBlr_Amst;
            EP_Amst = EP_Amst + 0.1;
            n = n + 1;

        end

        % Find the value for equal Energy Carrier Cost for heating with a
        % Heat Pump and with an Electric Boiler

        Res_EP_Amst = (intercept_CostEBlr_Amst - intercept_CostHPlr_Amst) /
(slope_CostHPlr_Amst - slope_CostEBlr_Amst);

        % Find the equations for equal Energy Carrier Cost for Electricity
        % and Gas (gas price in function of electricity price for electric boiler)

        Res_GP2_Amst = zeros(size(Elec_Price_Amst));

        EP_Amst = 0;
        n = 1;
        while n <= sum(size(Elec_Price_Amst))-1

            Res_GP2_Amst(n) = (slope_CostEBlr_Amst * EP_Amst +
intercept_CostEBlr_Amst - intercept_CostGBlr_Amst) / slope_CostGBlr_Amst;
            EP_Amst = EP_Amst + 0.1;
            n = n + 1;
```

```
        end

        % Find the graph equations and the interception point

            % Perform linear regression for HP vs GB
            ResGP_lr_Amst = polyfit(Elec_Price_Amst, Res_GP_Amst, 1);  % Fit a
first-degree polynomial (linear regression)

            % Extract coefficients from HP vs GB
            slope_ResGPlr_Amst = ResGP_lr_Amst(1);
            intercept_ResGPlr_Amst = ResGP_lr_Amst(2);

            % Perform linear regression for EB vs GB
            ResGP2_lr_Amst = polyfit(Elec_Price_Amst, Res_GP2_Amst, 1);  % Fit a
first-degree polynomial (linear regression)

            % Extract coefficients from EB vs GB
            slope_ResGP2lr_Amst = ResGP2_lr_Amst(1);
            intercept_ResGP2lr_Amst = ResGP2_lr_Amst(2);

        % Find the value of the intersection

            % Find the value of the Electricity Price

            intersectionEP_Amst = (intercept_ResGP2lr_Amst -
intercept_ResGPlr_Amst) / (slope_ResGPlr_Amst - slope_ResGP2lr_Amst);

            % Find the value of the gas Price

            intersectionGP_Amst = slope_ResGPlr_Amst * intersectionEP_Amst +
intercept_ResGPlr_Amst;

        figure

        fplot(@(x) slope_ResGPlr_Amst * (x) + intercept_ResGPlr_Amst,
[intersectionEP_Amst 10])

        hold on
        plot([intersectionEP_Amst intersectionEP_Amst], [intersectionGP_Amst 10])

        hold on
        fplot(@(x) slope_ResGP2lr_Amst * (x) + intercept_ResGP2lr_Amst, [0
intersectionEP_Amst])

        hold on
        Historical_EP_Netherlands = [0.1212 0.1358 0.1372 0.1422 0.2692 0.4436];
        Historical_GP_Netherlands = [0.4391 0.4491 0.4307 0.4291 1.0756 1.6794];
        labels = {'2018', ' ', ' ', ' ', '2022', '2023'};
        plot(Historical_EP_Netherlands, Historical_GP_Netherlands, "o")
        text(Historical_EP_Netherlands, Historical_GP_Netherlands,
labels,'VerticalAlignment', 'bottom', 'horizontalAlignment', 'left')


        xlim([0 0.5])
        ylim([0 2])

        txtHP = {'Best economy', 'with Heat Pump'};
        text(0.07, 1, txtHP)
```

```
        txtGB = {'Best economy', 'with Gas Boiler'};
        text(0.4, 0.3, txtGB)

        txtEB = {'Best economy with Electric Boiler'};
        text(0.01, 0.3, txtEB, Rotation = 90)

        title('Amsterdam Case')
        xlabel('Electricity Price (€/kWh)')
        ylabel('Gas Price (€/m3)')
        grid on
        legend('HP vs GB', 'HP vs EB', 'EB vs GB', 'G&E Prices 2018-2023',
'Location', 'northwest')
```

2. Weather Data

For Berlin

datetime	*Month*	*tempmax*	*tempmin*	*temp*
2022-09-01	9	20.6	11.9	16.6
2022-09-02	9	21.1	10.8	16.2
2022-09-03	9	21.9	11	16.4
2022-09-04	9	23.8	12.8	18.3
2022-09-05	9	23.8	13.4	18.5
2022-09-06	9	22.3	13.5	17.9
2022-09-07	9	25	13.7	19.4
2022-09-08	9	18.6	15.1	16.6
2022-09-09	9	22.6	12.9	17.4
2022-09-10	9	21	12.3	16.7
2022-09-11	9	19.1	12.9	15.6
2022-09-12	9	20	10.7	15.3
2022-09-13	9	19.9	11.6	15.3
2022-09-14	9	18.2	11.8	15
2022-09-15	9	18	11.8	14.4
2022-09-16	9	17.5	10.5	13.6
2022-09-17	9	15.9	10	12.3
2022-09-18	9	13.9	9.1	10.9
2022-09-19	9	14.7	8.8	10.7
2022-09-20	9	13.8	7.9	10.4
2022-09-21	9	16.4	6.3	10.7
2022-09-22	9	15.9	5.9	10.9
2022-09-23	9	17	4.2	10.6
2022-09-24	9	16.3	9.3	12.4
2022-09-25	9	18.1	11	14.2
2022-09-26	9	16.6	10.4	13.4
2022-09-27	9	13	8.5	11.3
2022-09-28	9	11.7	7.1	9.2
2022-09-29	9	13.8	6.8	9.5
2022-09-30	9	17	3.9	10
2022-10-01	10	12.5	6.8	9.9
2022-10-02	10	15.7	10	12.4

2022-10-03	10	15.6	10.6	12.8
2022-10-04	10	17.2	11.1	13.5
2022-10-05	10	19.6	9.5	13.8
2022-10-06	10	17.6	9.9	15.1
2022-10-07	10	17.8	5.5	11.1
2022-10-08	10	15.2	8.6	11.3
2022-10-09	10	15.4	5.6	10.3
2022-10-10	10	17	5.5	10.9
2022-10-11	10	14.6	6.2	10.8
2022-10-12	10	15.3	3.1	8.9
2022-10-13	10	16.5	5.3	10.1
2022-10-14	10	16.9	5.8	11.6
2022-10-15	10	18	12.3	14.7
2022-10-16	10	20.3	10.9	15.6
2022-10-17	10	24.6	10.8	17.2
2022-10-18	10	16.4	10.8	14.6
2022-10-19	10	13.6	6.5	10.8
2022-10-20	10	14.2	3.2	8.3
2022-10-21	10	15.4	7.9	11.5
2022-10-22	10	18.7	12.4	14.7
2022-10-23	10	18.3	9.8	14.3
2022-10-24	10	18.9	12.1	15.2
2022-10-25	10	16.7	10.5	13.7
2022-10-26	10	18.1	7.1	11.9
2022-10-27	10	20.2	9.5	14
2022-10-28	10	22.8	11	16.4
2022-10-29	10	20.3	13.8	16.6
2022-10-30	10	21.7	10.5	15.2
2022-10-31	10	18	9.9	12.8
2022-11-01	11	17	9.4	13.2
2022-11-02	11	14.7	6.6	10.5
2022-11-03	11	12.3	4.4	8.3
2022-11-04	11	10.9	7.5	9.3
2022-11-05	11	11.9	4.8	8.4
2022-11-06	11	11.3	4	7
2022-11-07	11	14.3	6.5	10.6
2022-11-08	11	16.4	8.5	12.2
2022-11-09	11	14.6	10.6	12.1
2022-11-10	11	14.1	9.9	12
2022-11-11	11	12.6	7.5	9.7
2022-11-12	11	13.3	2.9	7.2
2022-11-13	11	11.5	6.1	8.8
2022-11-14	11	10.6	5.1	6.9
2022-11-15	11	13.2	3.3	7
2022-11-16	11	6.4	4.7	5.7
2022-11-17	11	5	2.1	3.9

2022-11-18	11	2	-4.3	-0.9
2022-11-19	11	1.6	-5.7	-2
2022-11-20	11	1.1	-2.2	-0.4
2022-11-21	11	-1.3	-3	-1.9
2022-11-22	11	1.5	-2.6	-0.3
2022-11-23	11	6.6	0.2	2.5
2022-11-24	11	4.6	0.1	2.1
2022-11-25	11	6.7	2.4	4.6
2022-11-26	11	8	6.8	7.5
2022-11-27	11	7.2	3	5.4
2022-11-28	11	5.5	3	3.8
2022-11-29	11	4.7	2.8	3.8
2022-11-30	11	5.2	0.8	3
2022-12-01	12	1	-0.1	0.5
2022-12-02	12	1.5	-1.1	0.6
2022-12-03	12	-0.5	-1.9	-1.2
2022-12-04	12	2.5	-0.4	1
2022-12-05	12	4	2.5	3.1
2022-12-06	12	3.2	1.8	2.4
2022-12-07	12	4	0.6	2.3
2022-12-08	12	3.1	-0.4	1.5
2022-12-09	12	-1	-3.2	-1.7
2022-12-10	12	-0.9	-3	-1.7
2022-12-11	12	-1.7	-2.7	-2.2
2022-12-12	12	-0.5	-2.1	-1.3
2022-12-13	12	-1	-5.9	-2.2
2022-12-14	12	-3.5	-9.3	-6.5
2022-12-15	12	-2.9	-9.9	-7.1
2022-12-16	12	-1.9	-9	-5.2
2022-12-17	12	-2.3	-5.6	-3.4
2022-12-18	12	-4.5	-7.2	-5.8
2022-12-19	12	4	-5.2	-0.6
2022-12-20	12	8.1	3.9	5.8
2022-12-21	12	7.5	4.8	6.4
2022-12-22	12	8.7	5.2	7
2022-12-23	12	7.2	5.6	6.3
2022-12-24	12	8.4	5	6.2
2022-12-25	12	8	1.2	4.6
2022-12-26	12	10.7	5.7	9.5
2022-12-27	12	5.8	2.3	4.1
2022-12-28	12	8.4	3.6	6
2022-12-29	12	12.4	7.9	9.8
2022-12-30	12	9	5	7.5
2022-12-31	12	17.7	8.4	14.2
2023-01-01	1	16.2	10.9	14.5
2023-01-02	1	15.7	9.6	13.1

2023-01-03	1	9.2	1.9	5.6
2023-01-04	1	10.5	3.1	6.7
2023-01-05	1	10.1	3.9	8.4
2023-01-06	1	10.3	2.3	6.6
2023-01-07	1	10.1	5.6	8
2023-01-08	1	8.4	5.1	6.9
2023-01-09	1	7.9	3.9	6.1
2023-01-10	1	8	4.1	6.3
2023-01-11	1	8.7	4.3	6.5
2023-01-12	1	10.7	5.9	8.5
2023-01-13	1	10.2	7.8	9.2
2023-01-14	1	8.3	6.5	7.3
2023-01-15	1	9.4	5.3	6.6
2023-01-16	1	7.3	3	4.8
2023-01-17	1	4.7	-1.8	3
2023-01-18	1	2.2	-3.2	-0.2
2023-01-19	1	1.7	-4.4	-1.2
2023-01-20	1	1.3	-0.8	0.4
2023-01-21	1	3.4	-1.2	0.9
2023-01-22	1	2	1.1	1.5
2023-01-23	1	2.2	1.3	1.7
2023-01-24	1	1.4	-0.2	0.7
2023-01-25	1	1.6	-0.3	0.7
2023-01-26	1	-0.4	-1.2	-0.8
2023-01-27	1	3.4	-0.4	1.6
2023-01-28	1	1.5	-2.1	0.1
2023-01-29	1	3.1	-1.2	0.9
2023-01-30	1	6.1	1.2	3.7
2023-01-31	1	6	2.5	4.2
2023-02-01	2	6	2.7	4.4
2023-02-02	2	6.5	0.1	4
2023-02-03	2	8.2	1	5.4
2023-02-04	2	3.5	-2.6	1.4
2023-02-05	2	1	-4.5	-2.2
2023-02-06	2	-0.1	-5.7	-2.7
2023-02-07	2	2.2	-7.4	-3
2023-02-08	2	1.9	-5.4	-2.3
2023-02-09	2	3.1	-4.9	-1.2
2023-02-10	2	5.6	-0.2	2.7
2023-02-11	2	7.3	2.5	5.6
2023-02-12	2	8.6	5.6	7
2023-02-13	2	7.6	5.8	6.8
2023-02-14	2	6.2	4.2	5.3
2023-02-15	2	9.9	-1.2	2.6
2023-02-16	2	11.9	0.2	5.7
2023-02-17	2	12.6	6.7	9.1

2023-02-18	2	10.2	5.9	7.1
2023-02-19	2	6.7	2.4	4.3
2023-02-20	2	9.9	1.6	6.7
2023-02-21	2	10.6	7.5	9.2
2023-02-22	2	9.4	5.3	7.2
2023-02-23	2	10.4	2.5	6.2
2023-02-24	2	6.5	2.1	3.6
2023-02-25	2	4	-0.6	1.7
2023-02-26	2	3.2	-1.6	0.8
2023-02-27	2	3.7	-3.9	0.3
2023-02-28	2	5.3	-3.4	1.2
2023-03-01	3	7.8	-5.3	1.1
2023-03-02	3	3.4	-2.3	0
2023-03-03	3	3.5	-1.6	0.9
2023-03-04	3	6.2	2.1	4.3
2023-03-05	3	3.5	1	2.2
2023-03-06	3	2.8	-1.4	0.7
2023-03-07	3	4.1	-1.9	1.3
2023-03-08	3	3.6	-1.1	0.9
2023-03-09	3	1.2	0.1	0.6
2023-03-10	3	7.3	0.6	3.2
2023-03-11	3	2.3	0.3	1.2
2023-03-12	3	6	-0.7	2.7
2023-03-13	3	15.8	5.5	10.8
2023-03-14	3	13.6	1.2	9.5
2023-03-15	3	6.3	-0.2	2.6
2023-03-16	3	9.4	-1.7	4.1
2023-03-17	3	13.6	3.4	8.3
2023-03-18	3	17.9	6.9	11.7
2023-03-19	3	15.9	6.9	10.8
2023-03-20	3	11.8	8.5	10.1
2023-03-21	3	12	7.2	9.5
2023-03-22	3	16.7	8.3	12.4
2023-03-23	3	16.2	10.4	12.4
2023-03-24	3	16.1	9.7	12.4
2023-03-25	3	13	7.6	9.7
2023-03-26	3	10.7	6	8.2
2023-03-27	3	6.4	1.1	3.7
2023-03-28	3	6.9	0.1	3.2
2023-03-29	3	10.4	0.9	6
2023-03-30	3	18.2	8.2	11.4
2023-03-31	3	14	9.5	10.8
2023-04-01	4	10.3	3.9	7.9
2023-04-02	4	8.1	2.1	4.4
2023-04-03	4	4.7	-1.1	2.3
2023-04-04	4	6.4	-2.8	2.3

2023-04-05	4	7.5	-1.9	3.5
2023-04-06	4	11.2	-0.1	5.9
2023-04-07	4	6	1.2	4
2023-04-08	4	12.5	4.8	7.6
2023-04-09	4	13	1.3	6.8
2023-04-10	4	16.3	1.8	9.9
2023-04-11	4	11.9	5.7	9.4
2023-04-12	4	14.5	1	8.3
2023-04-13	4	13.3	6	9.4
2023-04-14	4	8.7	6	7.7
2023-04-15	4	10.7	8	9.4
2023-04-16	4	10.6	8.2	9.4
2023-04-17	4	9.7	5.5	7.2
2023-04-18	4	13.4	4.9	8.7
2023-04-19	4	11.6	3.4	7.2
2023-04-20	4	15.4	5.4	9.5
2023-04-21	4	19.7	8.7	14.3
2023-04-22	4	21.9	7.8	15.3
2023-04-23	4	17.3	11.4	14
2023-04-24	4	17.2	8.8	13
2023-04-25	4	9.8	6	8.5
2023-04-26	4	9.7	2.9	6.5
2023-04-27	4	10.6	4.5	7.7
2023-04-28	4	15.7	2.4	9.6
2023-04-29	4	14.1	9.5	11.6
2023-04-30	4	14.3	4.2	9.4
2023-05-01	5	18.9	3.4	11.9
2023-05-02	5	13.6	9.5	11.5
2023-05-03	5	15.1	4.3	10.1
2023-05-04	5	18.7	4.7	12.3
2023-05-05	5	19.7	8.3	14.1
2023-05-06	5	12.8	7.3	8.5
2023-05-07	5	15.6	8	11.3
2023-05-08	5	17.7	4.7	11.8
2023-05-09	5	19.2	7.7	13.7
2023-05-10	5	22.4	9.2	15.9
2023-05-11	5	21.6	10.4	16.8
2023-05-12	5	21.9	10.5	17.2
2023-05-13	5	21.8	11.1	16.5
2023-05-14	5	20.1	9.8	15.2
2023-05-15	5	20.1	7.9	13.9
2023-05-16	5	15.8	10	12.4
2023-05-17	5	14.9	6.9	10.8
2023-05-18	5	16.1	6.1	11.4
2023-05-19	5	17.8	6.6	13.2
2023-05-20	5	19.5	9.4	14.4

2023-05-21	5	27	13.2	20.4
2023-05-22	5	25.8	15.5	20.7
2023-05-23	5	19.8	11.8	15.8
2023-05-24	5	16.1	9.4	11.8
2023-05-25	5	19.2	8	14.3
2023-05-26	5	19.8	8.1	14.4
2023-05-27	5	20.9	7.6	14.9
2023-05-28	5	23.5	7.3	16.8
2023-05-29	5	21.3	9.9	16.7
2023-05-30	5	22.5	8.6	16.2
2023-05-31	5	24.7	9	18

For Amsterdam

datetime	*Month*	*tempmax*	*tempmin*	*temp*
2022-09-01	9	23.7	12.5	18.6
2022-09-02	9	25.5	14.2	19.4
2022-09-03	9	26.5	15.1	20.3
2022-09-04	9	25.3	15.2	20.2
2022-09-05	9	28.6	15.7	21.7
2022-09-06	9	24.3	17.2	20.8
2022-09-07	9	23.4	15.6	19
2022-09-08	9	21.6	16	18.1
2022-09-09	9	18	13.7	16
2022-09-10	9	21.3	15.1	17.3
2022-09-11	9	21.9	11.3	16.8
2022-09-12	9	23	14.2	18.2
2022-09-13	9	20.9	15.1	18.6
2022-09-14	9	19.6	13.4	16.3
2022-09-15	9	18.3	12.7	15.2
2022-09-16	9	16.1	11.1	13.1
2022-09-17	9	16	10.4	12.7
2022-09-18	9	13.3	11.2	12.1
2022-09-19	9	15.7	11.5	13.4
2022-09-20	9	16.2	9.6	12.8
2022-09-21	9	16.9	7.5	12.1
2022-09-22	9	18.3	6.4	12.1
2022-09-23	9	17.4	10	13.5
2022-09-24	9	16.1	10.1	14
2022-09-25	9	15.6	7.7	11.7
2022-09-26	9	14.2	10.8	12.5
2022-09-27	9	11.7	8.1	9.9
2022-09-28	9	14.8	7.3	10.3
2022-09-29	9	15.7	4.3	9.6
2022-09-30	9	16.9	5.9	11.8
2022-10-01	10	17	11.1	14.4
2022-10-02	10	16.7	11.5	14.1
2022-10-03	10	16.8	8.2	12.6

2022-10-04	10	17.8	9.6	14.1
2022-10-05	10	17.9	14.7	16.1
2022-10-06	10	16.4	10.5	13.8
2022-10-07	10	16.6	9.9	13.2
2022-10-08	10	15.4	8.4	12.6
2022-10-09	10	16.1	6	10.4
2022-10-10	10	14.2	7.8	10.8
2022-10-11	10	15.6	6.2	10.1
2022-10-12	10	14.4	5.1	9.8
2022-10-13	10	14.2	9	12
2022-10-14	10	15.8	9.1	12.7
2022-10-15	10	16.1	11.9	13.8
2022-10-16	10	17.2	12.8	14.4
2022-10-17	10	17.1	13.5	15.4
2022-10-18	10	16.9	7.6	12.3
2022-10-19	10	14.2	4.9	9.8
2022-10-20	10	15.6	8.4	11.7
2022-10-21	10	19	12.6	15
2022-10-22	10	17.3	12.6	14.7
2022-10-23	10	17.8	12.1	14.6
2022-10-24	10	16.2	13.5	15.3
2022-10-25	10	16.4	11.6	14.1
2022-10-26	10	18.5	11	14.7
2022-10-27	10	19.5	13.5	16
2022-10-28	10	19.7	14.1	16.5
2022-10-29	10	20.2	11	15.4
2022-10-30	10	19	11.3	15
2022-10-31	10	16.4	8.9	12.9
2022-11-01	11	16.1	12.9	14.7
2022-11-02	11	14.5	10.8	12.4
2022-11-03	11	14.7	11.1	12.4
2022-11-04	11	11.4	8.1	9.8
2022-11-05	11	12.1	5.4	9.3
2022-11-06	11	11.9	8.5	10.3
2022-11-07	11	14.1	11.3	12.7
2022-11-08	11	14.8	11.1	12.8
2022-11-09	11	13.2	10.5	12.3
2022-11-10	11	14	10.2	12
2022-11-11	11	12	7	10.2
2022-11-12	11	14.6	5.3	9
2022-11-13	11	15.2	6	9.2
2022-11-14	11	9.5	3.3	5.9
2022-11-15	11	12.1	6.1	10.1
2022-11-16	11	11.9	9.1	10.5
2022-11-17	11	10.9	9	10.3
2022-11-18	11	10.1	4.9	8.1

2022-11-19	11	4.3	-1.7	1.4
2022-11-20	11	3	-5.3	-0.4
2022-11-21	11	7.6	1.9	4.8
2022-11-22	11	8	4.8	6.6
2022-11-23	11	9.1	7.3	8.2
2022-11-24	11	11.1	7.5	9
2022-11-25	11	11.7	6.4	8.9
2022-11-26	11	10.6	4.6	7.3
2022-11-27	11	7.4	6.2	6.8
2022-11-28	11	10.6	6.7	8.5
2022-11-29	11	9.3	5.4	7.2
2022-11-30	11	9.1	4.2	6.7
2022-12-01	12	7.4	2.6	4.9
2022-12-02	12	4.9	2.2	3.2
2022-12-03	12	3.4	0.4	2
2022-12-04	12	3.5	0.2	1.2
2022-12-05	12	6.3	3.8	5.4
2022-12-06	12	7.2	0.9	4.8
2022-12-07	12	6.6	2.2	4.2
2022-12-08	12	4.4	-0.3	2.8
2022-12-09	12	2.1	-2.5	-0.1
2022-12-10	12	1.4	-1.1	0.1
2022-12-11	12	2.4	0.9	1.7
2022-12-12	12	1	-3.7	-1
2022-12-13	12	-0.8	-5.5	-3.1
2022-12-14	12	0.9	-5.7	-2.7
2022-12-15	12	4.7	-3.5	0.1
2022-12-16	12	3.6	-3.8	-0.2
2022-12-17	12	0	-3.1	-1.6
2022-12-18	12	0.5	-5.9	-2.5
2022-12-19	12	9.9	0.9	6.7
2022-12-20	12	10.5	7.9	9.7
2022-12-21	12	8.8	4.6	6.8
2022-12-22	12	9.7	4.9	8.2
2022-12-23	12	10.4	7.9	8.9
2022-12-24	12	10.3	6.5	8.9
2022-12-25	12	9.3	7.7	8.7
2022-12-26	12	9.2	5.3	7.6
2022-12-27	12	7.3	5.4	6.5
2022-12-28	12	10.8	6.4	8.9
2022-12-29	12	11	7.6	9.5
2022-12-30	12	11.9	4.7	7.9
2022-12-31	12	14.6	10.2	12.9
2023-01-01	1	14	10.3	12
2023-01-02	1	11.1	4.8	8.7
2023-01-03	1	9.4	1.6	5.8

2023-01-04	1	12.6	8.9	11.3
2023-01-05	1	11.2	9.8	10.4
2023-01-06	1	10.9	8.4	9.9
2023-01-07	1	11.2	9.1	10.3
2023-01-08	1	10.1	6.7	8.4
2023-01-09	1	8.4	5.7	7.1
2023-01-10	1	10	5.9	7.2
2023-01-11	1	11.5	8.7	9.9
2023-01-12	1	11.5	9.1	10.5
2023-01-13	1	9.5	8.4	9
2023-01-14	1	11	5.9	8.2
2023-01-15	1	7.8	4.1	6.6
2023-01-16	1	5	2.9	3.9
2023-01-17	1	4.9	-0.2	2.2
2023-01-18	1	5.3	-1.4	2.5
2023-01-19	1	5.7	0.7	3.8
2023-01-20	1	2.2	0.3	1.1
2023-01-21	1	2.1	-2.3	-0.2
2023-01-22	1	2.6	-1.8	1.5
2023-01-23	1	4.5	2.4	3.2
2023-01-24	1	3.3	0.9	2.2
2023-01-25	1	0.8	-0.6	0.3
2023-01-26	1	7.5	0.5	4.6
2023-01-27	1	6	2.8	4.2
2023-01-28	1	5.6	1.7	3.6
2023-01-29	1	7	4.1	5.1
2023-01-30	1	8.3	5	7.1
2023-01-31	1	9.1	4.2	6.7
2023-02-01	2	8.4	6.4	7.5
2023-02-02	2	9.2	7	8.2
2023-02-03	2	9.7	8.1	8.9
2023-02-04	2	8.8	5	7.2
2023-02-05	2	8.3	3.5	6.8
2023-02-06	2	8.2	0.8	4.3
2023-02-07	2	5.1	-1.5	1
2023-02-08	2	6.3	-2.5	1
2023-02-09	2	5.9	-0.8	2.2
2023-02-10	2	8.1	0	4.6
2023-02-11	2	9.8	6.5	7.8
2023-02-12	2	8.5	5.8	7.2
2023-02-13	2	10.9	2	7.2
2023-02-14	2	11.2	1	5.1
2023-02-15	2	10.3	0	5
2023-02-16	2	10.5	4.9	8
2023-02-17	2	10.9	9.1	10
2023-02-18	2	11.1	9.2	10

2023-02-19	2	9.5	5.7	7.8
2023-02-20	2	9.3	6.4	8.2
2023-02-21	2	9.2	7.1	8.3
2023-02-22	2	8.8	4.3	6.8
2023-02-23	2	8.8	2.9	6.7
2023-02-24	2	8.3	2.3	5.3
2023-02-25	2	7	0.9	4.6
2023-02-26	2	6.3	0.4	3.2
2023-02-27	2	7.1	-1.6	3.1
2023-02-28	2	6.1	0.4	3
2023-03-01	3	6.7	-3.4	2.1
2023-03-02	3	6.9	1.4	3.6
2023-03-03	3	7.3	1.9	4.8
2023-03-04	3	7.5	3.5	6
2023-03-05	3	6.2	2	3.8
2023-03-06	3	6.3	1.6	3.8
2023-03-07	3	5.2	0	2.8
2023-03-08	3	3.4	-1.6	1.1
2023-03-09	3	2.7	0.7	1.7
2023-03-10	3	2.5	0.1	1.7
2023-03-11	3	6.5	-2.1	2.3
2023-03-12	3	10.4	0.8	6.4
2023-03-13	3	14.3	9.1	12
2023-03-14	3	11	3.1	7
2023-03-15	3	8.2	1.3	4.8
2023-03-16	3	13.5	5.2	8.5
2023-03-17	3	14.6	8	11.2
2023-03-18	3	15.5	7.9	11.7
2023-03-19	3	10.8	7.6	9
2023-03-20	3	9.1	7	8.2
2023-03-21	3	11.9	8.8	10
2023-03-22	3	11.6	8.9	10.4
2023-03-23	3	14.2	10.7	12.4
2023-03-24	3	12.5	9.3	11.1
2023-03-25	3	11.8	7.1	9.3
2023-03-26	3	8.8	4.7	7
2023-03-27	3	6.7	2.1	4.4
2023-03-28	3	8.1	-0.3	4.4
2023-03-29	3	13.2	5.5	9.6
2023-03-30	3	13.7	10.6	12.5
2023-03-31	3	11.8	10	10.6
2023-04-01	4	11.5	7.3	9.5
2023-04-02	4	9.7	2.7	6.2
2023-04-03	4	9.8	1.3	5.7
2023-04-04	4	9.1	-0.1	5.1
2023-04-05	4	10.9	1	5.8

2023-04-06	4	8.9	2.6	6.8
2023-04-07	4	9.3	7.9	8.5
2023-04-08	4	12.6	3.2	8.3
2023-04-09	4	14.3	8.2	10.4
2023-04-10	4	14	8.2	10.7
2023-04-11	4	12.1	7.6	9.8
2023-04-12	4	11.4	8	9.5
2023-04-13	4	11.5	5.8	8.5
2023-04-14	4	14.1	3.9	9
2023-04-15	4	12.6	6.3	9.2
2023-04-16	4	10.2	7.6	8.6
2023-04-17	4	14	7.2	9.7
2023-04-18	4	13.8	6.5	9.7
2023-04-19	4	14.1	8.2	10.6
2023-04-20	4	11.7	6.4	8.7
2023-04-21	4	15.4	8	10.9
2023-04-22	4	13.8	5.5	9.1
2023-04-23	4	16.1	6.8	11.1
2023-04-24	4	10.4	6.9	8.9
2023-04-25	4	9.4	4.8	6.7
2023-04-26	4	9.8	2.2	6.2
2023-04-27	4	12.6	0.5	7.5
2023-04-28	4	12.5	7.9	10.1
2023-04-29	4	14.8	8.3	11.2
2023-04-30	4	17.1	5.2	11.2
2023-05-01	5	15.1	8	11.4
2023-05-02	5	11.8	6.2	9.5
2023-05-03	5	13.3	3.2	8.9
2023-05-04	5	21.2	6.6	13.6
2023-05-05	5	17	12.1	14.5
2023-05-06	5	19.6	9.8	14.7
2023-05-07	5	18.9	13.6	15.7
2023-05-08	5	17.9	10.6	14.1
2023-05-09	5	14.8	12.4	13.8
2023-05-10	5	14.2	10.7	12.6
2023-05-11	5	15.7	10.9	13.3
2023-05-12	5	20.6	11.1	15.4
2023-05-13	5	20	11.6	16
2023-05-14	5	18.5	9.1	13.4
2023-05-15	5	13.9	7.9	10.5
2023-05-16	5	14	6.4	10.3
2023-05-17	5	14.3	7.3	10.7
2023-05-18	5	14	5.6	9.8
2023-05-19	5	18.1	6.7	13.1
2023-05-20	5	19.1	11	15.1
2023-05-21	5	19.7	12.9	16.1

2023-05-22	5	21.9	12.2	16.6
2023-05-23	5	14.8	8.9	12.7
2023-05-24	5	15.5	6.7	11.8
2023-05-25	5	17	8.5	12.5
2023-05-26	5	16.8	8.3	12.4
2023-05-27	5	19.4	7.8	13.6
2023-05-28	5	19.9	10.7	15.2
2023-05-29	5	15.7	8.8	12.5
2023-05-30	5	14.2	10.2	12.4
2023-05-31	5	20.1	10.2	14.8

3. Annual Energy Consumption for the Heat Generation Devices

Only for Ambient Heating

GERMANY

Technology	**DE.N.SFH.04.Gen**	**DE.N.SFH.09.Gen**	**DE.N.MFH.04.Gen**	**DE.N.MFH.09.Gen**
	Energy Consumption per Year (kWh)			
Gas Boiler	19519.47	14341.49	94329.36	80923.94
Oil Boiler	19729.35	14495.70	95343.66	81794.09
Electric Boiler	18348.30	13481.00	88669.60	76068.50
HP (Air to Air)	5490.36	4033.92	26532.61	22761.98
HP (Ground Source)	4077.40	2995.78	19704.36	16904.11
Hydrogen boiler	22375.98	16440.24	108133.66	92766.46
PEM FC micro-CHP	84302.79	61939.58	407399.87	349503.06
SOFC micro-CHP	46077.17	33854.16	222671.53	191027.02
Central inverter heat pump	5341.68	3924.68	25814.07	22145.56
Natural refrigerant HP	4108.65	3018.74	19855.38	17033.67
Hybrid HP	8481.68	6231.72	40988.39	35163.41
Synthetic methane HP	17147.94	12599.07	82868.79	71092.06
HV Flat plate collectors HP	4774.23	3507.76	23071.84	19793.03
Absorption HP	10793.12	7930.00	52158.59	44746.18
Adsorption HP	12654.00	9297.24	61151.45	52461.03
Cold climate air-source HP	4878.12	3584.09	23573.89	20223.74
Solar PV + HP	4631.34	3402.78	22381.33	19200.65
High-temperature HP	11198.25	8227.66	54116.42	46425.77
Hydrogen-enriched NG HP	12654.00	9297.24	61151.45	52461.03
Metal hydride HP	8340.14	6127.73	40304.36	34576.59
Vuilleumier HP	12253.94	9003.31	59218.13	50802.47
Thermo-acoustic HP	14233.23	10457.55	68783.20	59008.22

NETHERLANDS

Technology	**NL.N.SFH.02.Gen**	**NL.N.SFH.04.Gen**	**NL.N.MFH.02.Gen**	**NL.N.MFH.04.Gen**
	Energy Consumption per Year (kWh)			
Gas Boiler	20307.45	16728.51	469454.26	128582.98
Oil Boiler	20525.81	16908.39	474502.15	129965.59
Electric Boiler	19089.00	15724.80	441287.00	120868.00
HP (Air to Air)	5440.46	4481.65	125768.97	34447.98

HP (Ground Source)	4242.00	3494.40	98063.78	26859.56
Hydrogen boiler	23279.27	19176.59	538154.88	147400.00
PEM FC micro-CHP	86815.18	71515.08	2006936.50	549697.59
SOFC micro-CHP	47046.43	38755.08	1087588.59	297889.26
Central inverter heat pump	5216.15	4296.87	120583.51	33027.68
Natural refrigerant HP	4103.28	3380.13	94856.92	25981.20
Hybrid HP	8769.22	7223.75	202721.00	55525.05
Synthetic methane HP	17840.19	14696.07	412417.76	112960.75
HV Flat plate collectors HP	4730.83	3897.08	109364.32	29954.76
Absorption HP	11228.82	9249.88	259580.59	71098.82
Adsorption HP	13164.83	10844.69	304335.86	83357.24
Cold climate air-source HP	4846.84	3992.65	112046.12	30689.30
Solar PV + HP	4589.25	3780.45	106091.22	29058.26
High-temperature HP	11564.60	9526.48	267342.89	73224.91
Hydrogen-enriched NG HP	13164.83	10844.69	304335.86	83357.24
Metal hydride HP	8676.82	7147.64	200585.00	54940.00
Vuilleumier HP	12732.56	10488.60	294342.95	80620.19
Thermo-acoustic HP	14542.06	11979.20	336173.89	92077.64

For ambient heating + DHW

GERMANY

Technology	**DE.N.SFH.04.Gen**	**DE.N.SFH.09.Gen**	**DE.N.MFH.04.Gen**	**DE.N.MFH.09.Gen**
	Energy Consumption per Year (kWh)			
Gas Boiler	31280.74	21778.30	151747.23	121607.98
Oil Boiler	31617.10	22012.47	153378.92	122915.59
Electric Boiler	29403.90	20471.60	142642.40	114311.50
HP (Air to Air)	10877.38	7573.06	52767.70	42287.25
HP (Ground Source)	9801.30	6823.87	47547.47	38103.83
Hydrogen boiler	35858.41	24965.37	173954.15	139404.27
PEM FC micro-CHP	137162.38	95363.38	665457.32	532352.41
SOFC micro-CHP	75904.26	52714.22	368285.65	294203.45
Central inverter heat pump	12566.25	8748.88	60960.62	48852.94
Natural refrigerant HP	7167.70	4990.30	34771.50	27865.37
Hybrid HP	19631.30	13667.71	95234.16	76319.24
Synthetic methane HP	27480.28	19132.34	133310.65	106833.18
HV Flat plate collectors HP	9458.59	6585.27	45884.95	36771.52
Absorption HP	17296.41	12042.12	83907.29	67242.06
Adsorption HP	24503.25	17059.67	118868.67	95259.58
Cold climate air-source HP	9178.40	6390.19	44525.68	35682.22
Solar PV + HP	9175.51	6388.18	44511.69	35671.01
High-temperature HP	17945.65	12494.13	87056.84	69766.06
Hydrogen-enriched NG HP	24503.25	17059.67	118868.67	95259.58
Metal hydride HP	13365.41	9305.27	64837.45	51959.77
Vuilleumier HP	19637.44	13671.99	95263.95	76343.12
Thermo-acoustic HP	22686.41	15794.75	110054.93	88196.39

NETHERLANDS

Technology	NL.N.SFH.02.Gen	NL.N.SFH.04.Gen	NL.N.MFH.02.Gen	NL.N.MFH.04.Gen
	Energy Consumption per Year (kWh)			
Gas Boiler	26698.40	25655.74	692017.02	222621.28
Oil Boiler	26985.48	25931.61	699458.06	225015.05
Electric Boiler	25096.50	24116.40	650496.00	209264.00
HP (Air to Air)	8870.87	8524.43	229931.04	73968.62
HP (Ground Source)	8365.50	8038.80	216832.00	69754.67
Hydrogen boiler	30605.49	29410.24	793287.80	255200.00
PEM FC micro-CHP	115538.54	111637.42	3007217.03	972340.97
SOFC micro-CHP	63254.17	61394.92	1652017.03	536374.30
Central inverter heat pump	10312.76	9910.01	267304.56	85991.65
Natural refrigerant HP	5950.01	5717.64	154223.06	49613.43
Hybrid HP	13650.13	13117.05	353808.61	113819.92
Synthetic methane HP	23454.67	22538.69	607940.19	195573.83
HV Flat plate collectors HP	7713.80	7412.55	199940.04	64320.54
Absorption HP	14762.65	14186.12	382644.71	123096.47
Adsorption HP	20913.75	20097.00	542080.00	174386.67
Cold climate air-source HP	7592.17	7295.67	196787.39	63306.33
Solar PV + HP	7482.94	7190.70	193956.15	62395.52
High-temperature HP	15204.10	14610.33	394087.02	126777.45
Hydrogen-enriched NG HP	20913.75	20097.00	542080.00	174386.67
Metal hydride HP	11407.50	10962.00	295680.00	95120.00
Vuilleumier HP	16739.62	16085.89	433887.49	139581.23
Thermo-acoustic HP	19041.96	18298.31	493563.51	158778.95

4. Economic KPIs

Only for ambient heating

GERMANY

Technology	DE.N.SFH.04.Gen	DE.N.SFH.09.Gen	DE.N.MFH.04.Gen	DE.N.MFH.09.Gen	DE.N.SFH.04.Gen	DE.N.SFH.09.Gen	DE.N.MFH.04.Gen	DE.N.MFH.09.Gen	DE.N.SFH.04.Gen	DE.N.SFH.09.Gen	DE.N.MFH.04.Gen	DE.N.MFH.09.Gen	DE.N.SFH.04.Gen	DE.N.SFH.09.Gen	DE.N.MFH.04.Gen	DE.N.MFH.09.Gen
	NPV (per year)				IRR				BCR				TCO			
Gas Boiler	€ (1,142.25)	€ (839.57)	€ (5,489.04)	€ (4,713.74)	-	-	-	-	0.0 %	0.0 %	0.0 %	0.0 %	€ 22,845.00	€ 16,791.37	€ 109,780.78	€ 94,274.74
Oil Boiler	€ (1,835.84)	€ (1,349.31)	€ (8,826.68)	€ (7,579.24)	-	-	-	-	0.0 %	0.0 %	0.0 %	0.0 %	€ 36,716.73	€ 26,986.29	€ 176,533.69	€ 151,584.75
Electric Boiler	€ (965.24)	€ (709.20)	€ (4,663.48)	€ (4,000.91)	4.8 %	4.8 %	4.6 %	4.7 %	118.6%	118.8%	117.2%	117.4%	€ 19,304.88	€ 14,184.07	€ 93,269.51	€ 80,018.21
HP (Air to Air)	€ (584.75)	€ (429.63)	€ (2,825.87)	€ (2,424.27)	18.9 %	18.9 %	18.9 %	18.9 %	286.7%	286.8%	286.1%	286.2%	€ 11,695.06	€ 8,592.68	€ 56,517.30	€ 48,485.46

HP (Ground Source)	€ (941.34)	€ (818.69)	€ (3,019.32)	€ (2,635.19)	3.7%	0.1%	14.3%	13.8%	108.0%	77.3%	226.7%	219.9%	€ 18,826.77	€ 16,373.87	€ 60,386.48	€ 52,703.90
Hydrogen boiler	€ (4,060.05)	€ (2,983.03)	€ (19,620.53)	€ (16,832.20)	-	-	-	-	0.0%	0.0%	0.0%	0.0%	€ 81,201.07	€ 59,660.66	€ 392,410.55	€ 336,643.92
PEM FC micro-CHP	€ (13,216.23)	€ (10,027.22)	€ (60,683.83)	€ (52,427.70)	-	-	-	-	0.0%	0.0%	0.0%	0.0%	€ 287,833.01	€ 215,654.04	€ 1,349,015.83	€ 1,162,149.52
SOFC micro-CHP	€ (7,796.88)	€ (6,151.10)	€ (32,769.18)	€ (28,508.38)	-	-	-	-	0.0%	0.0%	0.0%	0.0%	€ 157,032.65	€ 120,943.16	€ 694,182.13	€ 600,748.98
Central inverter heat pump	€ (622.37)	€ (457.27)	€ (3,007.66)	€ (2,580.23)	16.1%	16.1%	16.0%	16.0%	248.9%	248.9%	248.3%	248.4%	€ 12,447.42	€ 9,145.46	€ 60,153.12	€ 51,604.59
Natural refrigerant HP	€ (573.93)	€ (421.68)	€ (2,773.57)	€ (2,379.41)	17.3%	17.3%	17.3%	17.3%	265.2%	265.2%	264.6%	264.7%	€ 11,478.63	€ 8,433.67	€ 55,471.40	€ 47,588.19
Hybrid HP	€ (673.66)	€ (494.96)	€ (3,255.53)	€ (2,792.87)	18.2%	18.2%	18.2%	18.2%	277.4%	277.5%	276.6%	276.7%	€ 13,473.25	€ 9,899.17	€ 65,110.53	€ 55,857.48
Synthetic methane HP	€ (1,148.16)	€ (871.49)	€ (5,145.52)	€ (4,429.22)	-10.5%	-19.8%	-2.6%	-2.8%	21.1%	4.4%	58.5%	56.9%	€ 22,963.29	€ 17,429.73	€ 102,910.47	€ 88,584.47
HV Flat plate collectors HP	€ (706.35)	€ (604.19)	€ (2,182.36)	€ (1,917.87)	14.5%	9.4%	28.2%	27.5%	228.4%	167.4%	415.6%	405.5%	€ 14,127.07	€ 12,083.83	€ 43,647.26	€ 38,357.44
Absorption HP	€ (816.97)	€ (628.15)	€ (3,544.98)	€ (3,056.14)	10.9%	9.1%	14.7%	14.5%	184.7%	164.2%	231.1%	229.1%	€ 16,339.34	€ 12,562.93	€ 70,899.69	€ 61,122.84
Adsorption HP	€ (925.32)	€ (707.75)	€ (4,068.59)	€ (3,505.34)	5.5%	3.7%	9.3%	9.2%	126.0%	107.8%	166.8%	165.1%	€ 18,506.31	€ 14,155.07	€ 81,371.78	€ 70,106.72
Cold climate air-source HP	€ (622.74)	€ (525.33)	€ (2,578.89)	€ (2,326.68)	14.4%	9.7%	22.4%	19.3%	227.9%	171.3%	334.1%	291.9%	€ 12,454.90	€ 10,506.50	€ 51,577.82	€ 46,533.56
Solar PV + HP	€ (586.45)	€ (388.35)	€ (2,554.31)	€ (2,191.31)	14.7%	16.4%	16.3%	16.4%	231.7%	253.1%	252.5%	252.6%	€ 12,614.29	€ 8,417.35	€ 55,364.10	€ 47,496.14
High-temperature HP	€ (847.86)	€ (622.95)	€ (4,097.35)	€ (3,515.07)	9.3%	9.3%	9.2%	9.2%	166.2%	166.2%	165.4%	165.6%	€ 16,957.21	€ 12,458.93	€ 81,947.06	€ 70,301.32
Hydrogen-enriched NG HP	€ (725.42)	€ (560.88)	€ (3,102.55)	€ (2,676.59)	14.5%	12.9%	18.1%	18.0%	229.2%	208.6%	275.6%	273.6%	€ 14,508.31	€ 11,217.62	€ 62,051.09	€ 53,531.75
Metal hydride HP	€ (1,144.09)	€ (940.40)	€ (4,086.90)	€ (3,559.57)	-0.4%	-2.2%	6.9%	6.4%	74.1%	61.0%	139.6%	134.5%	€ 22,881.83	€ 18,808.08	€ 81,738.06	€ 71,191.43
Vuilleumier HP	€ (933.25)	€ (685.68)	€ (4,510.00)	€ (3,869.07)	4.9%	4.9%	4.9%	4.9%	119.9%	119.9%	119.3%	119.4%	€ 18,664.99	€ 13,713.68	€ 90,200.02	€ 77,381.43

Thermo-acoustic HP	€ (1,193.73)	€ (962.28)	€ (4,537.66)	€ (3,938.45)	-14.0%	#NUM!	4.9%	4.3%	12.4%	0.0%	119.9%	114.3%	€ 23,874.66	€ 19,245.65	€ 90,753.23	€ 78,769.04

NETHERLANDS

Technology	**NL.N.SFH.02.Gen**	**NL.N.SFH.04.Gen**	**NL.N.MFH.02.Gen**	**NL.N.MFH.04.Gen**	**NL.N.SFH.02.Gen**	**NL.N.SFH.04.Gen**	**NL.N.MFH.02.Gen**	**NL.N.MFH.04.Gen**	**NL.N.SFH.02.Gen**	**NL.N.SFH.04.Gen**	**NL.N.MFH.02.Gen**	**NL.N.MFH.04.Gen**	**NL.N.SFH.02.Gen**	**NL.N.SFH.04.Gen**	**NL.N.MFH.02.Gen**	**NL.N.MFH.04.Gen**
	NPV (per year)				**IRR**				**BCR**				**TCO**			
Gas Boiler	€ (2,247.23)	€ (1,851.28)	€ (51,609.05)	€ (14,206.55)	-	-	-	-	0.00%	0.00%	0.00%	0.00%	€ 44,944.69	€ 37,025.68	€ 1,032,180.96	€ 284,131.06
Oil Boiler	€ (1,951.89)	€ (1,608.03)	€ (44,624.88)	€ (12,326.15)	10%	10%	11%	10%	173.44%	173.30%	192.41%	177.72%	€ 39,037.80	€ 32,160.69	€ 892,497.62	€ 246,522.91
Electric Boiler	€ (5,105.91)	€ (4,206.06)	€ (118,022.51)	€ (32,328.84)	-	-	-	-	0.00%	0.00%	0.00%	0.00%	€ 102,118.19	€ 84,121.20	€ 2,360,450.17	€ 646,576.83
HP (Air to Air)	€ (1,563.79)	€ (1,288.19)	€ (36,150.67)	€ (9,901.63)	28%	28%	28%	28%	411.28%	411.30%	409.26%	410.80%	€ 31,275.79	€ 25,763.82	€ 723,013.33	€ 198,032.52
HP (Ground Source)	€ (1,387.38)	€ (1,170.24)	€ (29,326.94)	€ (8,093.86)	26%	24%	41%	39%	391.74%	354.55%	603.93%	580.71%	€ 27,747.65	€ 23,404.88	€ 586,538.86	€ 161,877.23
Hydrogen boiler	€ (4,727.18)	€ (3,894.07)	€ (109,279.79)	€ (29,931.61)	-	-	-	-	0.00%	0.00%	0.00%	0.00%	€ 94,543.55	€ 77,881.42	€ 2,185,595.86	€ 598,632.18
PEM FC micro-CHP	€ (10,661.56)	€ (8,853.62)	€ (238,023.08)	€ (65,828.31)	-	-	-	-	0.00%	0.00%	0.00%	0.00%	€ 385,899.41	€ 318,821.56	€ 8,810,157.70	€ 2,421,413.07
SOFC micro-CHP	€ (6,591.75)	€ (5,524.74)	€ (140,901.30)	€ (39,275.55)	-	-	-	-	0.00%	0.00%	0.00%	0.00%	€ 197,357.36	€ 163,818.44	€ 4,411,690.33	€ 1,217,318.02
Central inverter heat pump	€ (1,520.47)	€ (1,252.51)	€ (35,149.32)	€ (9,627.36)	29%	29%	28%	29%	424.34%	424.36%	422.40%	423.87%	€ 30,409.48	€ 25,050.18	€ 702,986.39	€ 192,547.16
Natural refrigerant HP	€ (1,140.51)	€ (939.51)	€ (26,365.63)	€ (7,221.52)	71%	71%	71%	71%	1048.26%	1048.29%	1044.90%	1047.45%	€ 22,810.26	€ 18,790.23	€ 527,312.56	€ 144,430.30
Hybrid HP	€ (1,767.14)	€ (1,455.70)	€ (40,851.51)	€ (11,189.18)	19%	19%	19%	19%	290.62%	290.64%	288.56%	290.13%	€ 35,342.74	€ 29,114.02	€ 817,030.29	€ 223,783.65
Synthetic methane HP	€ (2,094.67)	€ (1,744.20)	€ (46,077.55)	€ (12,697.59)	1%	0%	7%	6%	87.52%	75.42%	142.23%	136.65%	€ 41,893.37	€ 34,884.00	€ 921,550.92	€ 253,951.85
HV Flat plate collectors HP	€ (1,611.45)	€ (1,379.79)	€ (30,683.26)	€ (8,619.77)	26%	22%	45%	42%	382.82%	334.10%	658.79%	620.83%	€ 32,228.93	€ 27,595.88	€ 613,665.26	€ 172,395.41
Absorption HP	€ (1,3	€ (1,1	€ (29,	€ (8,1	41%	39%	47%	47%	599.90%	578.59%	698.48%	687.75%	€ 27,5	€ 23,0	€ 590,	€ 163,

	77.93)	53.77)	508.35)	59.31)									58.51	75.48	166.90	186.15
Adsorption HP	€ (1,591.96)	€ (1,330.09)	€ (34,456.29)	€ (9,514.54)	27%	26%	33%	32%	406.93%	389.76%	485.68%	477.29%	€ 31,839.23	€ 26,601.77	€ 689,125.79	€ 190,290.88
Cold climate air-source HP	€ (1,422.98)	€ (1,187.30)	€ (32,282.43)	€ (9,050.14)	32%	29%	38%	31%	479.78%	433.29%	565.67%	462.18%	€ 28,459.57	€ 23,745.95	€ 645,648.59	€ 181,002.74
Solar PV + HP	€ (831.92)	€ (685.31)	€ (19,231.90)	€ (5,267.59)	64%	64%	63%	64%	935.67%	935.69%	933.45%	935.14%	€ 21,185.66	€ 17,451.95	€ 489,756.13	€ 134,143.64
High-temperature HP	€ (3,188.22)	€ (2,626.33)	€ (73,703.14)	€ (20,187.21)	-	-	-	-	0.00%	0.00%	0.00%	0.00%	€ 63,764.37	€ 52,526.69	€ 1,474,062.86	€ 403,744.12
Hydrogen-enriched NG HP	€ (839.72)	€ (710.42)	€ (17,066.42)	€ (4,751.48)	84%	82%	95%	94%	1236.40%	1200.83%	1404.67%	1385.44%	€ 16,794.36	€ 14,208.38	€ 341,328.37	€ 95,029.57
Metal hydride HP	€ (2,567.65)	€ (2,137.37)	€ (56,566.35)	€ (15,585.08)	-	-	-	-	0.00%	0.00%	0.00%	0.00%	€ 51,353.00	€ 42,747.45	€ 1,131,327.06	€ 311,701.65
Vuilleumier HP	€ (3,511.50)	€ (2,892.64)	€ (81,176.62)	€ (22,234.18)	-	-	-	-	0.00%	0.00%	0.00%	0.00%	€ 70,230.06	€ 57,852.88	€ 1,623,532.46	€ 444,683.67
Thermo-acoustic HP	€ (4,232.02)	€ (3,538.52)	€ (91,263.89)	€ (25,212.74)	-	-	-	-	0.00%	0.00%	0.00%	0.00%	€ 84,640.34	€ 70,770.42	€ 1,825,277.83	€ 504,254.70

For ambient heating and DHW

GERMANY

Technology	**DE.N.SFH.04.Gen**	**DE.N.SFH.09.Gen**	**DE.N.MFH.04.Gen**	**DE.N.MFH.09.Gen**	**DE.N.SFH.04.Gen**	**DE.N.SFH.09.Gen**	**DE.N.MFH.04.Gen**	**DE.N.MFH.09.Gen**	**DE.N.SFH.04.Gen**	**DE.N.SFH.09.Gen**	**DE.N.MFH.04.Gen**	**DE.N.MFH.09.Gen**	**DE.N.SFH.04.Gen**	**DE.N.SFH.09.Gen**	**DE.N.MFH.04.Gen**	**DE.N.MFH.09.Gen**
	NPV (per year)				**IRR**				**BCR**				**TCO**			
Gas Boiler	€ (1,828.89)	€ (1,274.22)	€ (8,791.95)	€ (7,061.82)	-	-	-	-	0.0%	0.0%	0.0%	0.0%	€ 36,577.75	€ 25,484.35	€ 175,838.97	€ 141,236.50
Oil Boiler	€ (2,939.65)	€ (2,047.97)	€ (14,143.71)	€ (11,358.01)	-	-	-	-	0.0%	0.0%	0.0%	0.0%	€ 58,793.00	€ 40,959.37	€ 282,874.29	€ 227,160.16
Electric Boiler	€ (1,546.78)	€ (1,076.94)	€ (7,500.70)	€ (6,011.54)	4.8%	4.8%	4.5%	4.6%	118.4%	118.6%	116.0%	116.6%	€ 30,935.67	€ 21,538.72	€ 150,014.04	€ 120,230.89
HP (Air to Air)	€ (1,044.20)	€ (727.00)	€ (5,065.58)	€ (4,059.48)	16.3%	16.3%	16.2%	16.2%	251.9%	252.0%	250.9%	251.2%	€ 20,884.09	€ 14,539.93	€ 101,311.61	€ 81,189.62
HP (Ground Source)	€ (1,414.28)	€ (1,114.96)	€ (5,494.96)	€ (4,459.88)	5.5%	2.3%	12.1%	11.7%	125.3%	95.7%	199.7%	194.6%	€ 28,285.66	€ 22,299.28	€ 109,899.27	€ 89,197.64
Hydrogen boiler	€ (6,506.40)	€ (4,529.89)	€ (31,563.46)	€ (25,294.49)	-	-	-	-	0.0%	0.0%	0.0%	0.0%	€ 130,128.03	€ 90,597.81	€ 631,269.14	€ 505,889.71

PEM FC micro-CHP	€ (21,484.23)	€ (15,592.77)	€ (99,249.72)	€ (79,664.47)	-	-	-	-	0.0%	0.0%	0.0%	0.0%	€ 470,143.14	€ 337,682.80	€ 2,203,083.29	€ 1,765,518.21
SOFC micro-CHP	€ (12,297.25)	€ (9,237.87)	€ (55,846.94)	€ (44,895.63)	-	-	-	-	0.0%	0.0%	0.0%	0.0%	€ 252,122.56	€ 185,892.39	€ 1,180,550.01	€ 946,075.24
Central inverter heat pump	€ (1,203.79)	€ (838.10)	€ (5,839.73)	€ (4,679.87)	11.5%	11.5%	11.4%	11.4%	192.0%	192.0%	191.0%	191.3%	€ 24,075.71	€ 16,762.00	€ 116,794.60	€ 93,597.46
Natural refrigerant HP	€ (949.81)	€ (661.28)	€ (4,607.66)	€ (3,692.51)	16.7%	16.7%	16.6%	16.6%	256.7%	256.8%	255.8%	256.0%	€ 18,996.20	€ 13,225.54	€ 92,153.18	€ 73,850.19
Hybrid HP	€ (1,418.36)	€ (987.49)	€ (6,880.64)	€ (5,514.04)	7.9%	7.9%	7.8%	7.8%	150.8%	150.9%	149.5%	149.9%	€ 28,367.11	€ 19,749.77	€ 137,612.81	€ 110,280.86
Synthetic methane HP	€ (1,776.61)	€ (1,268.86)	€ (8,213.56)	€ (6,603.12)	-6.1%	-9.1%	-2.1%	-2.3%	38.8%	25.9%	61.8%	60.5%	€ 35,532.23	€ 25,377.24	€ 164,271.29	€ 132,062.34
HV Flat plate collectors HP	€ (1,031.55)	€ (815.77)	€ (3,767.07)	€ (3,082.68)	17.9%	13.6%	26.9%	26.3%	272.4%	218.0%	396.6%	387.6%	€ 20,630.95	€ 16,315.37	€ 75,341.44	€ 61,653.54
Absorption HP	€ (1,245.85)	€ (899.34)	€ (5,638.78)	€ (4,539.73)	12.7%	11.4%	15.0%	14.9%	206.6%	190.7%	235.3%	233.6%	€ 24,917.07	€ 17,986.75	€ 112,775.69	€ 90,794.53
Adsorption HP	€ (1,639.67)	€ (1,173.52)	€ (7,549.23)	€ (6,070.73)	0.4%	-1.3%	3.1%	3.0%	79.8%	66.9%	102.9%	101.6%	€ 32,793.36	€ 23,470.38	€ 150,984.65	€ 121,414.62
Cold climate air-source HP	€ (1,304.04)	€ (1,103.96)	€ (4,531.62)	€ (3,897.00)	6.8%	2.6%	19.8%	15.9%	138.6%	98.4%	298.9%	246.3%	€ 26,080.89	€ 22,079.19	€ 90,632.34	€ 77,940.03
Solar PV + HP	€ (990.48)	€ (625.00)	€ (4,354.89)	€ (3,489.94)	13.8%	15.5%	15.4%	15.4%	220.2%	241.3%	240.5%	240.7%	€ 21,563.39	€ 13,721.03	€ 95,605.64	€ 76,616.94
High-temperature HP	€ (1,358.73)	€ (945.98)	€ (6,591.39)	€ (5,282.25)	9.3%	9.3%	9.2%	9.2%	166.0%	166.1%	164.9%	165.2%	€ 27,174.63	€ 18,919.53	€ 131,827.88	€ 105,644.90
Hydrogen-enriched NG HP	€ (1,252.58)	€ (904.02)	€ (5,671.42)	€ (4,565.88)	12.1%	10.8%	14.2%	14.1%	198.7%	183.8%	225.7%	224.1%	€ 25,051.60	€ 18,080.41	€ 113,428.30	€ 91,317.52
Metal hydride HP	€ (1,606.75)	€ (1,232.95)	€ (6,345.56)	€ (5,159.97)	2.3%	0.3%	8.1%	7.6%	95.3%	78.9%	152.7%	147.1%	€ 32,134.94	€ 24,658.95	€ 126,911.23	€ 103,199.35
Vuilleumier HP	€ (1,495.57)	€ (1,041.25)	€ (7,255.22)	€ (5,814.22)	4.9%	4.9%	4.8%	4.8%	119.8%	119.9%	118.8%	119.1%	€ 29,911.41	€ 20,824.94	€ 145,104.38	€ 116,284.49
Thermo-acoustic HP	€ (1,713.12)	€ (1,290.29)	€ (7,073.46)	€ (5,732.37)	-2.4%	-9.1%	6.4%	5.9%	59.7%	0.0%	134.9%	129.6%	€ 34,262.34	€ 25,805.82	€ 141,469.17	€ 114,647.32

NETHERLANDS

Technology	NL.N.S FH.02.Gen	NL.N.S FH.04.Gen	NL.N.M FH.02.Gen	NL.N.M FH.04.Gen	NL.N.S FH.02.Gen	NL.N.S FH.04.Gen	NL.N.M FH.02.Gen	NL.N.M FH.04.Gen	NL.N.S FH.02.Gen	NL.N.S FH.04.Gen	NL.N.M FH.02.Gen	NL.N.M FH.04.Gen	NL.N.S FH.02.Gen	NL.N.S FH.04.Gen	NL.N.M FH.02.Gen	NL.N.M FH.04.Gen
	NPV (per year)				**IRR**				**BCR**				**TCO**			
Gas Boiler	€ (2,954.19)	€ (2,838.86)	€ (75,827.17)	€ (24,562.56)	-	-	-	-	0.00%	0.00%	0.00%	0.00%	€ 59,083.72	€ 56,777.17	€ 1,516,543.50	€ 491,251.17
Oil Boiler	€ (2,565.77)	€ (2,465.63)	€ (65,417.52)	€ (21,291.38)	10%	10%	12%	10%	173.69%	173.65%	203.16%	181.57%	€ 51,315.33	€ 49,312.56	€ 1,308,350.49	€ 425,827.63
Electric Boiler	€ (6,712.78)	€ (6,450.63)	€ (173,966.42)	€ (55,971.07)	-	-	-	-	0.00%	0.00%	0.00%	0.00%	€ 134,255.61	€ 129,012.53	€ 3,479,328.36	€ 1,119,421.49
HP (Air to Air)	€ (2,514.87)	€ (2,416.66)	€ (65,184.93)	€ (20,969.93)	11%	11%	11%	11%	185.63%	185.64%	182.99%	184.85%	€ 50,297.42	€ 48,333.14	€ 1,303,698.56	€ 419,398.70
HP (Ground Source)	€ (2,522.67)	€ (2,429.70)	€ (62,504.41)	€ (20,158.07)	9%	9%	14%	13%	161.57%	159.13%	219.74%	217.37%	€ 50,453.41	€ 48,594.07	€ 1,250,088.18	€ 403,161.36
Hydrogen boiler	€ (6,214.87)	€ (5,972.16)	€ (161,088.06)	€ (51,821.89)	-	-	-	-	0.00%	0.00%	0.00%	0.00%	€ 124,297.35	€ 119,443.14	€ 3,221,761.27	€ 1,036,437.81
PEMFC micro-CHP	€ (14,734.64)	€ (14,356.52)	€ (373,353.37)	€ (121,422.08)	-	-	-	-	0.00%	0.00%	0.00%	0.00%	€ 511,851.98	€ 492,310.04	€ 13,110,936.02	€ 4,217,776.77
SOFC micro-CHP	€ (9,207.39)	€ (9,045.12)	€ (234,382.29)	€ (76,715.20)	-	-	-	-	0.00%	0.00%	0.00%	0.00%	€ 261,655.94	€ 251,884.97	€ 6,682,258.75	€ 2,149,676.86
Central inverter heat pump	€ (2,921.82)	€ (2,807.71)	€ (75,732.94)	€ (24,363.22)	-8%	-8%	-9%	-8%	29.73%	29.74%	27.46%	29.06%	€ 58,436.39	€ 56,154.26	€ 1,514,658.89	€ 487,264.45
Natural refrigerant HP	€ (1,647.79)	€ (1,583.44)	€ (42,710.31)	€ (13,739.87)	60%	60%	59%	59%	876.51%	876.52%	871.87%	875.15%	€ 32,955.76	€ 31,668.73	€ 854,206.29	€ 274,797.42
Hybrid HP	€ (2,634.42)	€ (2,531.54)	€ (68,283.60)	€ (21,966.78)	7%	7%	6%	7%	138.79%	138.79%	135.99%	137.96%	€ 52,688.39	€ 50,630.74	€ 1,365,672.05	€ 439,335.52
Synthetic methane HP	€ (2,720.51)	€ (2,618.40)	€ (67,872.09)	€ (21,906.33)	3%	3%	7%	7%	101.27%	99.48%	142.17%	140.32%	€ 54,410.11	€ 52,368.06	€ 1,357,441.84	€ 438,126.59
HV Flat plate collectors HP	€ (2,424.19)	€ (2,341.12)	€ (55,433.08)	€ (18,034.24)	14%	14%	26%	25%	230.48%	224.53%	390.44%	377.02%	€ 48,483.83	€ 46,822.37	€ 1,108,661.51	€ 360,684.71
Absorption HP	€ (1,778.20)	€ (1,712.89)	€ (43,447.63)	€ (14,049.00)	42%	42%	47%	47%	624.26%	621.08%	698.79%	694.56%	€ 35,563.92	€ 34,257.87	€ 868,952.54	€ 280,980.01
Adsorption HP	€ (2,450.50)	€ (2,358.94)	€ (60,873.63)	€ (19,654.93)	14%	13%	17%	17%	219.65%	217.62%	266.23%	263.98%	€ 49,010.03	€ 47,178.86	€ 1,217,472.65	€ 393,098.63
Cold climat	€ (2,3	€ (2,2	€ (55,	€ (17,	14%	13%	28%	26%	221.20%	215.77%	413.01%	380.36%	€ 46,0	€ 44,3	€ 1,10	€ 359,

e air-source HP	00.45)	19.07)	384.75)	959.86)									09.05	81.31	7,694.91	197.16
Solar PV + HP	€ (1,310.82)	€ (1,259.63)	€ (33,976.16)	€ (10,930.10)	53%	53%	53%	53%	776.42%	776.43%	773.34%	775.52%	€ 33,630.69	€ 32,317.31	€ 871,700.50	€ 280,425.30
High-temperature HP	€ (4,191.58)	€ (4,027.89)	€ (108,644.94)	€ (34,950.98)	-	-	-	-	0.00%	0.00%	0.00%	0.00%	€ 83,831.65	€ 80,557.75	€ 2,172,898.80	€ 699,019.66
Hydro gen-enriched NG HP	€ (1,255.48)	€ (1,210.59)	€ (29,898.97)	€ (9,690.41)	72%	72%	80%	79%	1064.79%	1060.23%	1173.34%	1166.52%	€ 25,109.63	€ 24,211.85	€ 597,979.35	€ 193,808.17
Metal hydride HP	€ (3,336.00)	€ (3,210.65)	€ (83,323.98)	€ (26,890.84)	-	-	-	-	0.00%	0.00%	0.00%	0.00%	€ 66,720.07	€ 64,212.99	€ 1,666,479.51	€ 537,816.86
Vuilleumier HP	€ (4,616.61)	€ (4,436.31)	€ (119,661.51)	€ (38,495.00)	-	-	-	-	0.00%	0.00%	0.00%	0.00%	€ 92,332.16	€ 88,726.29	€ 2,393,230.19	€ 769,900.08
Thermo-acoustic HP	€ (5,449.93)	€ (5,248.69)	€ (133,859.64)	€ (43,263.99)	-	-	-	-	0.00%	0.00%	0.00%	0.00%	€ 108,998.65	€ 104,973.88	€ 2,677,192.74	€ 865,279.85

5. Efficiency/SPF and Operational Carbon Footprint

Only for ambient heating

	GERMANY							
Technology	**DE.N.SFH.04.Gen**	**DE.N.SFH.09.Gen**	**DE.N.MFH.04.Gen**	**DE.N.MFH.09.Gen**	**DE.N.SFH.04.Gen**	**DE.N.SFH.09.Gen**	**DE.N.MFH.04.Gen**	**DE.N.MFH.09.Gen**
	SPF/Efficiency				**Op Carbon Footprint (Ton CO2 eq/year)**			
Gas Boiler	0.94	0.94	0.94	0.94	3.92	2.88	18.95	16.26
Oil Boiler	0.93	0.93	0.93	0.93	5.26	3.86	25.40	21.79
Electric Boiler	1.00	1.00	1.00	1.00	6.50	4.77	31.39	26.93
HP (Air to Air)	3.56	3.56	3.56	3.56	1.94	1.43	9.39	8.06
HP (Ground Source)	4.50	4.50	4.50	4.50	1.44	1.06	6.98	5.98
Hydrogen boiler	0.82	0.82	0.82	0.82	0.00	0.00	0.00	0.00
PEM FC micro-CHP	0.16	0.16	0.16	0.16	0.00	0.00	0.00	0.00
SOFC micro-CHP	0.32	0.32	0.32	0.32	0.00	0.00	0.00	0.00
Central inverter heat pump	3.73	3.73	3.73	3.73	1.89	1.39	9.14	7.84
Natural refrigerant HP	4.71	4.71	4.71	4.71	1.45	1.07	7.03	6.03
Hybrid HP	3.67	3.67	3.67	3.67	2.30	1.69	11.12	9.54
Synthetic methane HP	1.07	1.07	1.07	1.07	3.44	2.53	16.65	14.28
HV Flat plate collectors HP	4.10	4.10	4.10	4.10	1.69	1.24	8.17	7.01
Absorption HP	1.70	1.70	1.70	1.70	2.17	1.59	10.48	8.99
Adsorption HP	1.45	1.45	1.45	1.45	2.54	1.87	12.28	10.54
Cold climate air-source HP	3.99	3.99	3.99	3.99	1.73	1.27	8.35	7.16
Solar PV + HP	3.56	3.56	3.56	3.56	1.64	1.20	7.92	6.80
High-temperature HP	1.65	1.65	1.65	1.65	3.96	2.91	19.16	16.43
Hydrogen-enriched NG HP	1.45	1.45	1.45	1.45	2.29	1.68	11.06	9.48

Metal hydride HP	2.20	2.20	2.20	2.20	2.95	2.17	14.27	12.24
Vuilleumier HP	1.50	1.50	1.50	1.50	4.34	3.19	20.96	17.98
Thermo-acoustic HP	1.37	1.37	1.37	1.37	5.04	3.70	24.35	20.89

NETHERLANDS

Technology	**NL.N.SFH .02.Gen**	**NL.N.SFH .04.Gen**	**NL.N.MF H.02.Gen**	**NL.N.MF H.04.Gen**	**NL.N.SFH .02.Gen**	**NL.N.SFH .04.Gen**	**NL.N.MF H.02.Gen**	**NL.N.MF H.04.Gen**
	SPF/Efficiency				**Op Carbon Footprint (Ton CO2 eq/year)**			
Gas Boiler	0.94	0.94	0.94	0.94	4.08	3.36	94.30	25.83
Oil Boiler	0.93	0.93	0.93	0.93	5.47	4.50	126.41	34.62
Electric Boiler	1.00	1.00	1.00	1.00	2.77	2.28	63.99	17.53
HP (Air to Air)	3.67	3.67	3.67	3.67	0.79	0.65	18.24	4.99
HP (Ground Source)	4.50	4.50	4.50	4.50	0.62	0.51	14.22	3.89
Hydrogen boiler	0.82	0.82	0.82	0.82	0.00	0.00	0.00	0.00
PEM FC micro-CHP	0.16	0.16	0.16	0.16	0.00	0.00	0.00	0.00
SOFC micro-CHP	0.32	0.32	0.32	0.32	0.00	0.00	0.00	0.00
Central inverter heat pump	3.88	3.88	3.88	3.88	0.76	0.62	17.48	4.79
Natural refrigerant HP	4.84	4.84	4.84	4.84	0.59	0.49	13.75	3.77
Hybrid HP	3.67	3.67	3.67	3.67	1.53	1.26	35.47	9.72
Synthetic methane HP	1.07	1.07	1.07	1.07	3.58	2.95	82.85	22.69
HV Flat plate collectors HP	4.22	4.22	4.22	4.22	0.69	0.57	15.86	4.34
Absorption HP	1.70	1.70	1.70	1.70	2.26	1.86	52.14	14.28
Adsorption HP	1.45	1.45	1.45	1.45	2.64	2.18	61.13	16.74
Cold climate air-source HP	4.11	4.11	4.11	4.11	0.70	0.58	16.25	4.45
Solar PV + HP	3.67	3.67	3.67	3.67	0.67	0.55	15.38	4.21
High-temperature HP	1.66	1.66	1.66	1.66	1.68	1.38	38.76	10.62
Hydrogen-enriched NG HP	1.45	1.45	1.45	1.45	2.38	1.96	55.02	15.07
Metal hydride HP	2.20	2.20	2.20	2.20	1.26	1.04	29.08	7.97
Vuilleumier HP	1.50	1.50	1.50	1.50	1.85	1.52	42.68	11.69
Thermo-acoustic HP	1.37	1.37	1.37	1.37	2.11	1.74	48.75	13.35

For ambient heating + DHW

GERMANY

Technology	**DE.N.SFH .04.Gen**	**DE.N.SFH .09.Gen**	**DE.N.MF H.04.Gen**	**DE.N.MF H.09.Gen**	**DE.N.SFH .04.Gen**	**DE.N.SFH .09.Gen**	**DE.N.MF H.04.Gen**	**DE.N.MF H.09.Gen**
	SPF/Efficiency				**Op Carbon Footprint (Ton CO2 eq/year)**			
Gas Boiler	0.94	0.94	0.94	0.94	6.28	4.37	30.48	24.43
Oil Boiler	0.93	0.93	0.93	0.93	8.42	5.86	40.86	32.74
Electric Boiler	1.00	1.00	1.00	1.00	10.41	7.25	50.50	40.47
HP (Air to Air)	2.87	2.87	2.87	2.87	3.85	2.68	18.68	14.97
HP (Ground Source)	3.00	3.00	3.00	3.00	3.47	2.42	16.83	13.49
Hydrogen boiler	0.82	0.82	0.82	0.82	0.00	0.00	0.00	0.00

PEM FC micro-CHP	0.16	0.16	0.16	0.16	0.00	0.00	0.00	0.00
SOFC micro-CHP	0.32	0.32	0.32	0.32	0.00	0.00	0.00	0.00
Central inverter heat pump	2.46	2.46	2.46	2.46	4.45	3.10	21.58	17.29
Natural refrigerant HP	4.25	4.25	4.25	4.25	2.54	1.77	12.31	9.86
Hybrid HP	2.95	2.95	2.95	2.95	4.74	3.30	23.02	18.45
Synthetic methane HP	1.07	1.07	1.07	1.07	5.52	3.84	26.78	21.46
HV Flat plate collectors HP	3.30	3.30	3.30	3.30	3.35	2.33	16.24	13.02
Absorption HP	1.70	1.70	1.70	1.70	3.47	2.42	16.86	13.51
Adsorption HP	1.20	1.20	1.20	1.20	4.92	3.43	23.88	19.14
Cold climate air-source HP	3.34	3.34	3.34	3.34	3.25	2.26	15.76	12.63
Solar PV + HP	2.87	2.87	2.87	2.87	3.25	2.26	15.76	12.63
High-temperature HP	1.65	1.65	1.65	1.65	6.35	4.42	30.82	24.70
Hydrogen-enriched NG HP	1.20	1.20	1.20	1.20	4.43	3.08	21.49	17.22
Metal hydride HP	2.20	2.20	2.20	2.20	4.73	3.29	22.95	18.39
Vuilleumier HP	1.50	1.50	1.50	1.50	6.95	4.84	33.72	27.03
Thermo-acoustic HP	1.38	1.38	1.38	1.38	8.03	5.59	38.96	31.22

NETHERLANDS

Technology	**NL.N.SFH.02.Gen**	**NL.N.SFH.04.Gen**	**NL.N.MFH.02.Gen**	**NL.N.MFH.04.Gen**	**NL.N.SFH.02.Gen**	**NL.N.SFH.04.Gen**	**NL.N.MFH.02.Gen**	**NL.N.MFH.04.Gen**
	SPF/Efficiency				**Op Carbon Footprint (Ton CO2 eq/year)**			
Gas Boiler	0.94	0.94	0.94	0.94	5.36	5.15	139.01	44.72
Oil Boiler	0.93	0.93	0.93	0.93	7.19	6.91	186.34	59.94
Electric Boiler	1.00	1.00	1.00	1.00	3.64	3.50	94.32	30.34
HP (Air to Air)	2.95	2.95	2.95	2.95	1.29	1.24	33.34	10.73
HP (Ground Source)	3.00	3.00	3.00	3.00	1.21	1.17	31.44	10.11
Hydrogen boiler	0.82	0.82	0.82	0.82	0.00	0.00	0.00	0.00
PEM FC micro-CHP	0.16	0.16	0.16	0.16	0.00	0.00	0.00	0.00
SOFC micro-CHP	0.32	0.32	0.32	0.32	0.00	0.00	0.00	0.00
Central inverter heat pump	2.53	2.53	2.53	2.53	1.50	1.44	38.76	12.47
Natural refrigerant HP	4.33	4.33	4.33	4.33	0.86	0.83	22.36	7.19
Hybrid HP	3.04	3.04	3.04	3.04	2.42	2.32	62.70	20.17
Synthetic methane HP	1.07	1.07	1.07	1.07	4.71	4.53	122.12	39.29
HV Flat plate collectors HP	3.40	3.40	3.40	3.40	1.12	1.07	28.99	9.33
Absorption HP	1.70	1.70	1.70	1.70	2.97	2.85	76.87	24.73
Adsorption HP	1.20	1.20	1.20	1.20	4.20	4.04	108.89	35.03
Cold climate air-source HP	3.41	3.41	3.41	3.41	1.10	1.06	28.53	9.18
Solar PV + HP	2.95	2.95	2.95	2.95	1.09	1.04	28.12	9.05
High-temperature HP	1.66	1.66	1.66	1.66	2.20	2.12	57.14	18.38
Hydrogen-enriched NG HP	1.20	1.20	1.20	1.20	3.78	3.63	98.00	31.53

Metal hydride HP	2.20	2.20	2.20	2.20	1.65	1.59	42.87	13.79
Vuilleumier HP	1.50	1.50	1.50	1.50	2.43	2.33	62.91	20.24
Thermo-acoustic HP	1.38	1.38	1.38	1.38	2.76	2.65	71.57	23.02