Diploma Thesis

The value of flexibility for large-scale heat pumps in district heating systems –

A survey on technical constraints and economic opportunities

carried out for the purpose of obtaining the degree of

Dipl.-Ing. , by

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Abstract

Large scale heat pumps and electric boilers are commonly treated as a measure to increase flexibility in district heating systems. The transformation of the energy market towards more volatile renewables in combination with our climate protection goals demands for this additional flexibility. In this thesis, the economic value of flexibility for large scale heat pumps is assessed by identifying essential parameters and comparing the effects of differently configured heat pumps on conventional district heating systems. By using four different base systems in a wide range of sizes and a variety of low-temperature heat sources it is tried to obtain general results. A MILP model is introduced which optimizes the combined dispatch of heat pumps, conventional heat generators, and heat storages on an annual basis with respect to the specific operational properties of heat pumps. It is shown that the flexibility of heat pumps bears a considerable economic benefit for typical Austrian district heating systems and that this benefit is heavily dependent on a joint operation with CHP units. Furthermore, it is found that the most compromising factor for the flexibility of heat pumps is the competition with baseload generators and renewables during low demand times. A comparison with generation portfolios without P2H devices shows the positive impact of large-scale heat pumps on the CO_2 footprint of district heating systems. However, it is revealed that operational flexibility does not necessarily further improve the emissions situation.

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1 Introduction

The rising share of highly volatile renewable energy sources (RES) in many energy sectors demands more flexible and intermittency friendly infrastructure throughout the whole industry [1]. Especially, the electric energy sector is affected by intermittent generation, due to its highly dynamic nature and the lack of sufficient storage capabilities. In some regions of Europe temporary overproductions and limited transmission grids, lead to frequent curtailment of renewable energy generation [2]. From an environmental standpoint, there is a need to use this excess energy, in order to reduce the CO_2 footprint of our energy production. Currently, Power to Heat (P2H) is treated as a powerful answer to these curtailment problems and as a great opportunity to regulate the electricity system [1], [3]–[5]. P2H in this context means that electric energy is converted into heat energy for the use in systems, which would traditionally rely on fossil fuels [2]. Perfect candidates for the implementation of P2H are therefore district heating systems with optional thermal storages, which will be the subject for all further researches in this work [5].

1.1 Electric heat pumps as Power to Heat tools?

The prevailing trend, of using P2H units to integrate volatile, renewable production brings up the question, if large-scale heat pumps are intermittency friendly enough to be efficient players in this aspect. In the last decade, the market share of electric boilers increased steadily due to their high operational flexibility and comparatively low investment costs [6]. Heat pumps, on the other hand, could make use of low-temperature energy sources and therefore generate higher total system efficiencies than electric boilers. Despite these advantages, the production capacities of electric boilers in Europe raised well above those of electric heat pumps in recent history [6]. This fact induces the following question of research.

1.2 Research Question

Can large-scale electric heat pumps be operated in a way that an economic benefit arises out of flexibility, and if so, how big is the benefit for typical Austrian district heating systems? Does this benefit of flexibility compensate the potential additional cost for capable technology and likely needed subsystems as storages? What are the technical constraints and environmental factors that reduce the flexibility for different heat pump types? Under which circumstances can a large-scale heat pump outperform an electric boiler economically, when used as a flexible P2H device?

1.3 Structure of this work

The theoretical analysis in chapter 2 is trying to summarize the current state of the art. Additionally to some historical information on large scale heat pumps, the available literature is searched for information on the dynamic properties of these systems. How the term flexibility in the context of heat pumps is used in other works is treated here. Technological constraints which bear problems for intermittent use cases are also discussed in this chapter.

The definition of flexibility itself and the model parameters which are reducing the flexibility of large-scale heat pumps are the first parts of chapter 3. Followed by a listing and description of heat pump types which are considered to be most valuable for Austrian district heating systems with respect to flexibility and practicability. The selected heat sources are further treated within this thesis and are the source for parameter values within the model. A detailed description of the optimization model which was partly preexisting but modified to suit the needs of this study is also included. Crucial in this chapter is the selection of representative generation portfolios for Austrian district heating systems and the finding of environmental and pricing scenarios. These assumptions deliver the input values for the dispatch simulations which are carried out with the described model.

In chapter 4 the simulation results are presented and examined. The economic benefit of flexible heat pump operation is calculated for all reviewed scenarios and heat sources. The most important result for these calculations is the total cost of heat production within the whole DH system. Other indicators like CO_2 emissions, full load hours, or seasonal performance factors are used for complementary information. Tendencies and Patterns are evaluated and displayed graphically as a base for conclusions.

These conclusions are part of chapter 5, where also an outlook on the future relevance of large-scale heat pumps is given, based on the achieved results. Finally, further research topics are mentioned, which could increase the knowledge of flexible heat pump operation in the future.

An additional part of this thesis is to extend and refine the functionality of the beforementioned dispatch tool, regarding large-scale heat pumps. Including the extension of the user interface of this tool, so that online users can get access to the heat pump dispatch simulation functionalities.

2 State of the Art

This chapter's objective is to give an overview of the existing knowledge on the operation of large-scale heat pumps in district heating systems. Historical facts show how these systems have been performing in the past and the study of literature gives an idea where problems might occur in the future, during intermittent operation.

2.1 From past to future - Heat pumps in district heating systems

Since the 1970s large-scale electrical heat pumps have been available for district heating and were primarily used in Scandinavia [7]. The excess electricity production of newly-built Swedish atomic power plants had lead to a big increase in heat pump capacity between 1980 and 1990. Due to a lack of export capabilities, the excess energy was used to power large-scale electric heat pumps as baseload generators in the DH networks [7], [8]. Since then, the EU wide heat pump capacity stayed hardly constant at about 1500 MW. While in other European countries heat pumps for district heating became more popular during the mid-2000s, Sweden shut down some of their older heat pumps. Reason for this decommissioning was primarily the rising electricity demand and the resulting lack of continuous excess electricity [7], [8]. Expensive modifications which would have been necessary to switch from hydrofluorocarbon (HFC) refrigeration fluids to less harmful alternatives also caused the shutdown of heat pump units. These new refrigeration fluids are part of the technical reason why the average per-unit capacity declined over the last decades [8]. Also, the changing electricity market situation and lower necessary capital expenditures changed the direction towards less powerful units. Contributional to rather slow deployment of heat pump technology is that every city or village has its own individual set of possibilities. The lack of available experience values for highly customized solutions lets policymakers hesitate to invest in those technologies.

Today about 150 heat pump systems with more than 1 MW of thermal output power are operated in the EU, with an average of 11 MW [8]. Table 2.1 shows the European countries with the largest number of DH heat pumps and the corresponding power figures for the year 2016. Most presently built DH heat pumps tend to have a capacity in the low megawatt range, or even lower. Despite, detailed operating statistics are not generally available, it is stated in [8] that most of these large heat pumps run continuously or at least during the entire heating season. The large investment costs for the pumps themselves and auxiliary systems like heat-

Table 2.1 Total capacity of heat pumps larger than 1 MW per country for 2016 [8]

EU country	Capacity [MW_{th}]
Sweden	1215
Finland	155
Norway	85
Italy	37
Switzerland	34

changers, demand for high capacity utilization to achieve a proper rate of return. The full load operating hours are assumed to vary between 4000 and 8000 in most cases [8], [9]. In the current DH systems mostly electric boilers are used to participate dynamically in the electricity market. Either they are controlled by electricity prices or they participate in the market for negative secondary balancing power. These dispatch strategies result in 500 to 1500 full load operating hours per year. The low investment cost and excellent response time make electric boilers the go-to technology for flexible P2H integration in DH systems today [9].

In Austria, the largest deployer of P2H technology is Wien Energie who operates a 30 MW heat pump using the cooling water of a CHP-power plant in the city of Vienna since 2018. It is expected to operate with a COP of 3 for about 5500 full load operating hours per year [10]. The Wien Energie portfolio also includes an electric boiler with an output power of 10 MW which is used to participate in the secondary balancing power market [10]. This is a representative example for the deployment of P2H in European DH systems today. As the bulk of low-temperature potential is not used today, it would be energetically wiser to build heat pumps that are able to operate intermittently instead of electric boilers.

The Heat Roadmap Europe 2050[1] suggests that the share of district heating in European heat demand should be increased from about 10 % to a value near 50 %, to meet the European decarbonization goals [11]. This growth by the factor of five, until the year 2050, is a big opportunity for large-scale heat pumps. According to the Roadmap approximately 200 TWh/a should be produced by these systems, compared to the 7 TWh/a produced today [5], [8], [13]. Such a high market share of heat pumps may put a large strain on the electricity supply and transport sector, as it is reported in [4] for the example of Austria. To reduce electricity peak loads, these future heat pumps must be implemented as complementary suppliers, which means that they should not be mandatory for delivering base- and peak loads [4]. Intermittent operation in combination with heat storage systems is treated as the key for successful future large-scale heat pump use. This underlines the importance of flexibility, which is the main subject of this research.

2.2 Related research results

Searching literature in order to find information on operating strategies for heat pumps, almost reveals a blind spot in the otherwise well-described topic of electric heat pumps Many scientific works address the economic analysis of heat pumps in combination with other power

[1] Heat Roadmap Europe 2050, Pre Study for EU27, By Aalborg University, Halmstad University, Ecofys Germany, and PlanEnergi for EUROHEAT & POWER [5], [11], [12]

plants and compare them to electric boilers [14], [15]. Most of these studies, however, do not respect the system-specific operational constraints of heat pumps. They are usually implemented like fully flexible and always available heat producers. This inaccuracy may lead to an overestimation of full-load operating hours and also to wrong expectations on economic success. In contrast to the assumptions in these economic analyses, most of the existing heat pumps are operated continuously.

On the other hand, scientific works describe the physical properties of the thermodynamic cycle processes and the highly sophisticated controls which are implemented to maintain a stable and economic operation [16], [17]. Especially, if a system is operated outside its optimum power point, in a part load scenario. Here it is important to name the compromising differences between a heat pump and an electric boiler which clearly is the benchmark in terms of operational flexibility. Unlike boilers, large-scale heat pumps always feature large moving mechanical components like scroll-, turbo-, or piston compressors, pumps, fans, and others, depending on the type. Mechanical parts are more vulnerable to wear and failure if they face constant on/off operation and changing thermal conditions [8]. These potential hazards may be overcome by design improvements and proper dimensioning of stressed components, which most likely would also rise the investment costs of flexible heat pumps. A further drawback of frequent starts and stops is that the COP does not reach its maximum value right after start-ups, what compromises economic viability [8]. Typically, the thermodynamic cycle process needs time to stabilize and perform at its target temperatures. Dependent on the low-temperature heat source, the availability of output power might also be affected by seasonality, weather, production schedules or others. This highly specific topic is further treated in chapters 3.1 and 3.2. Actual numbers on how the beforementioned constraints affect the operating strategies and the economics of heat pumps are very scarce. It is also difficult to assume parameter values for universal heat dispatch models like the one used in this work as there is only little useful data on common dynamic behavior available.

A technical or economic comparison of continuously and intermittently operated heat pumps cold not be found in the freely available literature. The term flexibility in the context of large-scale heat pump operation is generally used as a depiction but is never exactly defined or quantified by the authors. Nor were there any estimations for associated costs and revenues presented. As the additional cost in construction and operation can only be estimated by manufacturers or experienced operators, this work is intended to determine the impact of the flexible operation only on the revenue.

The economic value of flexibility seems to be a fairly new topic in the context of heat pumps and is therefore defined and researched in this work.

3 Methods

This central chapter contains the methods that are chosen and designed to gather knowledge on the topic of flexible heat pumps and to answer the previously defined research questions adequately. The overall approach and the interconnection of the following sub-chapters are displayed in Fig. 3.1.

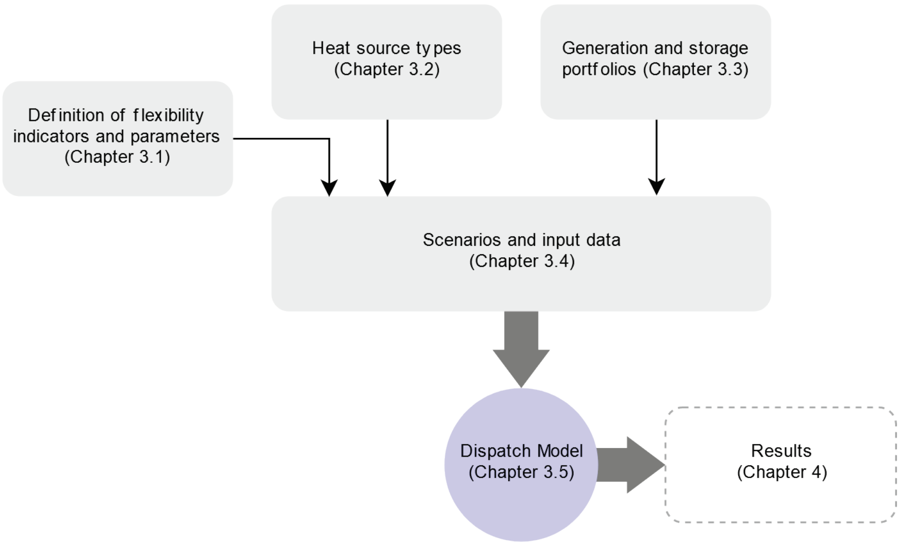

Fig. 3.1 Structure of the methodical overall approach

To determine the value of flexibility for large scale heat pumps in district heating systems, the term "flexibility" must be defined first, in the context of this work. Chapter 3.1 covers this definition and the extraction of corresponding model parameters. To tie these parameters into a dispatch model, they are translated to constraints for the mathematical problem. This structuring approach was chosen to make flexible an inflexible heat pumps directly comparable, for different low-temperature heat sources and scenarios. Section 3.2 is concerned with selecting the heat sources based on their relevance for flexibility in Austrian DH systems. Therefore, technical and environmental factors that compromise a fully variable use must be found and evaluated. Another crucial step is done in chapters 3.3 and 3.4, where the testing environments for the examined heat pumps are chosen. This includes finding representative portfolios for district heating systems in Austria and central Europe, scenarios concerning environmental aspects like air temperature, market aspects like heat demand and economic aspects like prices for electricity and other fuels. The participation of heat pumps in the secondary balancing power market was defined to be a topic on its own and therefore not further investigated within this optimization. All dispatch simulations are realized with a dispatch model based on a MILP optimization. The optimization framework is founded on the pre-existing HoTMAPS Dispatch Tool which was developed at the TU Wien as a module of the H°TMAPS Project[2]. The remaining section 3.5 describes this adapted model and how the value of flexibility is determined, by comparing the total, system-wide heat generation costs for different setups and scenarios.

3.1 Definition of flexibility indicators and parameters

The Union of the Electricity Industry - Eurelectric[3] defines the word flexibility for participants in the electricity market, as follows.

"On an individual level flexibility is the modification of generation injection and/or consumption patterns in reaction to an external signal (price signal or activation) in order to provide a service within the energy system. The parameters used to characterize flexibility include the amount of power modulation, the duration, the rate of change, the response time, the location, etc." [18]

Based on this statement, four main topics have been chosen to be evaluated. The *amount of power modulation* is bound to the range of possible electrical input power which is further described in chapter 3.1.1 and is also proportional to the marketable amount of output power. Since the thermal output power of a heat pump is dependent on the product of electrical input power and the COP, also the range of achieved COP values plays a role in this aspect. This topic is reviewed in chapter 3.1.2. The parameters *rate of change* and *response time* are both treated in section 3.1.3. Finally, the chapter 3.1.4 concerns environmental and systematical constraints, which implicitly addresses the flexibility parameters *duration* and *location.*

3.1.1 Partial load capabilities

The working principle of a heat pump is relying on a thermodynamic cycle process with unit-specific pressures, temperatures, and flow rates. To keep functionality upright, these variables must be kept within certain boundaries which restricts the thermal- and power- operating range. Typically, the advertised COP of a system is only true for a very specific point of operation and is highly sensitive to change of the before-mentioned parameters. Despite leaving the optimal point of operation, large-scale heat pumps can be able to variate the input power of the compressing stage. This ability is typically implemented by using a variable frequency electrical drive, a set of individually switchable smaller compressors, or a combination of both [3]. From a system perspective, this operational freedom increases the complexity and asks for more capable controlling algorithms to ensure efficient operation [16]. Typically modern high-power heat pumps are able to ramp between 10 % and 100 % of their capacity rating [19] while there are also fixed power units in operation. To mathematically represent these constraints in the dispatch model, a factor for the minimum

[2] H°TMAPS - The open source mapping and planning tool for heating and cooling, https://www.hotmaps-project.eu

[3] Union of the Electricity Industry - Eurelectric aisbl, Boulevard de l'Impératrice, 66, bte 2, 1000 Brussels, Belgium

operating power is implemented. With this parameter, the minimum power of the compressor unit can be calculated from the maximum power. With the value 1 representing a fixed power setup and a value of 0 representing a fully variable setup.

3.1.2 The Coefficient of Performance (COP)

The achieved COP of ideal compression heat pumps is theoretically only dependent on the temperature of the evaporator and the condenser based on the Carnot cycle process. In reality, the Carnot efficiency only represents an upper limit and is never fully reached. Physical limitations and mechanical characteristics constrain the COP of large-scale heat pumps typically to about 40 % to 70 % of the maximum Carnot efficiency [20]. Construction decisions like coolant medium, compressor type, temperature levels, and temperature spread all have an impact on the nominal COP. Nevertheless, the operational variance of this COP is mainly caused by changes in the heat source temperature and the heat sink temperature. In general, a heat pumps efficiency is highest when the temperature lift between the low-temperature energy source and the high-temperature energy sink is lowest. This leads to the fact that in summer when source temperatures are higher and feed line temperatures are reduced, the heat pumps reach higher COPs than in winter. A useful feature in this regard can be a variation of heat sources like it was implemented in the city of Helsinki where river water is used in summer and wastewater in the wintertime [19]. The variation of heat sources, however, will not be further discussed, in order to decrease complexity and to get independent results for each type of heat source. To account for all these sensitivities, the COP is chosen individually for every heat pump implementation in this study. The used dispatch model is also fitted with temperature dependencies for the COP. To make this possible, arrays for hourly heat source, flow and return temperatures are implemented for every DH system. The nominal values and sensitivities for the COP are based on data tables which are partly supplied in [6]. The individual parameter values are further explained and set in chapters 3.3 and 3.4.

With a view to power balancing, the COP usually does not directly affect the amount of electric power, which can be allocated for regulatory measures. It will, however, have an impact on the economic value of any heat pump operation, as it determines the quantity of thermal output power. Only for a case of strictly limited heat demand, the maximum electric input power is an inverse proportion of the COP.

3.1.3 Power ramping capabilities and response time

The available information on ramping capabilities and response times of large scale heat pumps is very scarce and only leads to the conclusion that most of the units have start-up times well under one hour. Especially those in the low megawatt range. As the used model has a minimum time step of one hour, there were no limiting constraints implemented concerning ramping slopes or start-up times. To represent the increased stress on the heat pumps components caused by numerous cold starts and output power changes, the model includes financial cold start and ramping penalties which are dependent on the heat pumps type and size.

3.1.4 Environmental and systematic constraints

As already mentioned in section 3.1.2, the most efficient time to use ambient source heat pumps are the warm summer month. Obviously, this is also the time with the lowest heat demand. In some cases, this leads to district heating systems which are only based on heat pumps during warm periods. A disadvantage in this regard is that many medium-size to large cities also operate waste incineration plants, which are typically designed to run as baseload generators throughout the whole year. These waste treatment plants are often held in a must-run condition since they are a mandatory part in the whole waste logistics system [21]. Fig. 3.2 shows a rudimentary case where the competition between the heat pump and the baseload generators in summer can be seen. The low heat demand and other RES often eliminate the need for heat pumps in times where they would be most efficient. A "must-run" variable, which can be set for specific heat generators like waste incineration plants, takes care of this fact in the used dispatch model. This automatically locks out the heat pumps from the energy dispatch in certain situations, even if they are the most economical choice.

Regarding flexibility, the ideal heat source would be constantly and everywhere available. Contrary to this, any of the common heat sources for heat pumps have either a very limited geographical potential or a limited yield over time or both. Within this study, sources which are geographically very limited like high-temperature geothermal heat and sources which are bound to uncertain time schedules like flue gas condensation are generally dismissed. The selection of the used heat sources and type-specific constraints are treated in detail within their subchapters in section 3.2.

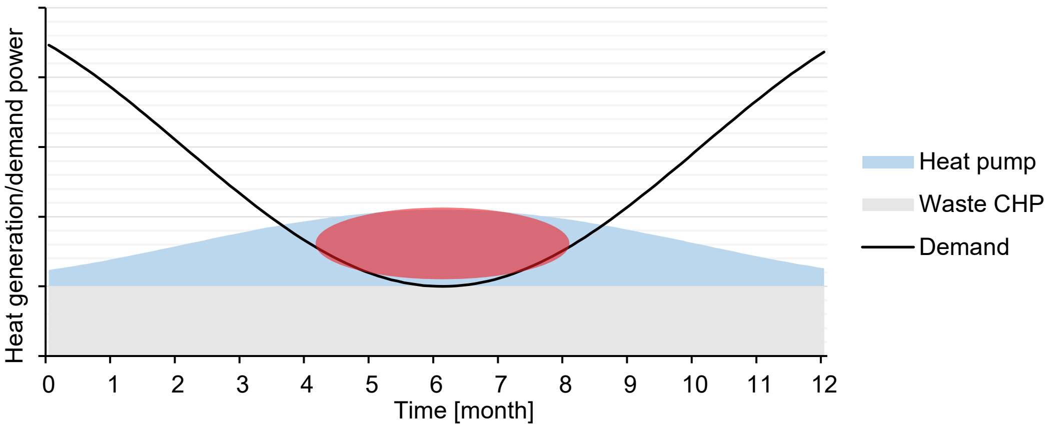

Fig. 3.2 Example of competitive behavior of heat pumps and baseload generators like waste incineration in the warm summer month. The red spot marks the curtailed amount of heat pump power. Source: own illustration based on [21].

3.2 Heat source types

This chapter is intended to define an assortment of heat sources, which are examined throughout this thesis. The selections are based on historical successes, the available research results and the relevance for Austrian and central European DH networks. Large-scale heat pumps are typically no "off the shelf" product, because individual customization work is necessary, to access a selected low-temperature heat source. Significantly different measures and system designs are needed to obtain thermal energy from air, flue gas, geothermal heat, river water, wastewater, solar, industrial waste heat or other sources, which are typical for heat pump units [7]. A common method to reduce the impact of seasonality is to use different low-temperature energy sources for one heat pump unit [19]. These hybrid systems are even more complex and case-specific and are therefore neglected in this study. This, however, does not diminish the potential of those custom solutions for special local conditions.

Table 3.1 shows the most important heat sources for large-scale DH heat pumps in Europe for the year 2016 [8]. The three technologies with the highest total capacity on this list are picked for the study, as they all show a reasonable geographical and seasonal availability in Austria. Additionally, also ambient air heat pumps are consulted, as this technology may offer location-independent units on the lower end of the power range, for small DH networks. In the following sub-chapters, specific details and the suitability for intermittent use of these technologies is illustrated.

Table 3.1 Most common heat sources for large European DH heat pumps (2016) [8]

Type of heat source	Capacity [MW_{th}]	Percentage of total capacity [%]	Number of units	Average capacity per unit [MW_{th}]	Temperature range[°C]
Wastewater	891	56	54	17	10-20
Ambient water	390	24	34	11	2-15
Industrial excess heat	129	8	28	5	12-46
Geothermal heat	97	4	19	5	9-55
Flue gas	40	2	7	6	37-60
District cooling	30	<2	4	7	0-9
Solar heat storage	4	<1	3	1	10-35
Total	1580		149	10.6	0-60

3.2.1 Wastewater

Sewage water is currently the most used heat source for DH heat pumps in Europe and still bears large potentials. Beneficial for this technology is the inherent fact, that regions with a high heating demand for domestic or industrial use, also have a high quantity of sewage water which typically has a temperature between 8 and 20 °C (30 °C and more for Industrial sewage water). The smallest units are available for a minimum dry-weather wastewater flow of about 10 l/s which makes this technology also an option for small to medium-sized villages and townships [22]. The most powerful operational units (>10 MW) are located in Scandinavia and have proven their effectiveness for DH in the last decades. The low seasonal temperature spread of the energy source allows exact dimensioning and high COPs, compared to surface water heat pumps, as some successful recent projects show [23]. However, the effort to extract heat out of wastewater is generally higher. The heat exchanger may be built directly into the sewer piping or be a separate unit which has to be fed with a bypass of wastewater. In both cases, the corroding effects of the wastewater mix have to be carefully handled to avoid damage to the heat extraction components. Especially if there are pumps involved for an external heat changer, there must also be a suitable filtration mechanism in place. All these additional components, the high corrosiveness, and the high sediment concentration lead to increased investment and maintenance cost. An often-overlooked topic is microbiologic changes caused by the decreased temperature further downstream. The wastewater treatment plant is heavily dependent on these microbiologic processes and the responsible department is typically involved in planning and operation. Installing the heat pump after the clarification process is a way to avoid most of the mentioned problems but reduces efficiency because the temperature is already lower. Additionally, these treatment plants are typically far outside the city and transporting the heat back into the DH system involves further losses. Despite all this, the wastewater source heat pumps have a large potential in most urban areas and are therefore subject of this study.

3.2.2 Ambient water

Many ambient water heat pumps, especially in Scandinavia, utilize seawater which is an unrestricted resource along must shorelines. In landlocked countries like Austria, the water-based heat pumps must be fed from rivers or lakes. Most of the larger cities in Austria have access to either a medium- or to a large-sized river or a lake, which makes this technology also a candidate for this research. Especially, as there are currently only a few large-scale projects in Austria which make use of these heat sources. The power potential is mainly dependent on the flow rate of a river, or the size of a lake, and the water temperature. In longer cold periods, ambient water heat pumps may face efficiency problems for several reasons. The beforementioned source temperature sensitivity of the COP is represented in the dispatch model with varying gradients for different working fluids. The graphs in Fig. 3.3 show these temperature dependencies which are linear interpolations of the values for river water heat pump models in [6]. It must also be noted, that the typical maximum temperature spread between the source and the return of the river water is about 3-4 K [24]. To keep the environmental impact on rivers acceptable and avoid icing, the absolute water return temperature must not be lower than 2-3 °C [24]. Therefore, the temperature spread and consequently also the extractable thermal energy is usually constrained for river temperatures below 5-6 °C. Glacier-fed rivers which are characteristic for the alpine regions of Austria, additionally tend to have reduced flow rates during the winter month, which further reduces the extractable amount of energy [25]. Any of these restrictions bare negative effects on operational flexibility and must be considered in the dispatch model. A parameter to set the minimum source water temperature is implemented as a low-temperature limit at 3 °C. To represent the restricted temperature spread the maximum input power is linearly decreased for flexible heat pumps near this low-temperature limit. Apart from that, inflexible systems are shut off for source temperatures under 6 °C as shown in Fig. 3.3. Seasonal water availability is not treated in the dispatch model since it is very case-specific and highly individual in terms of timing and location.

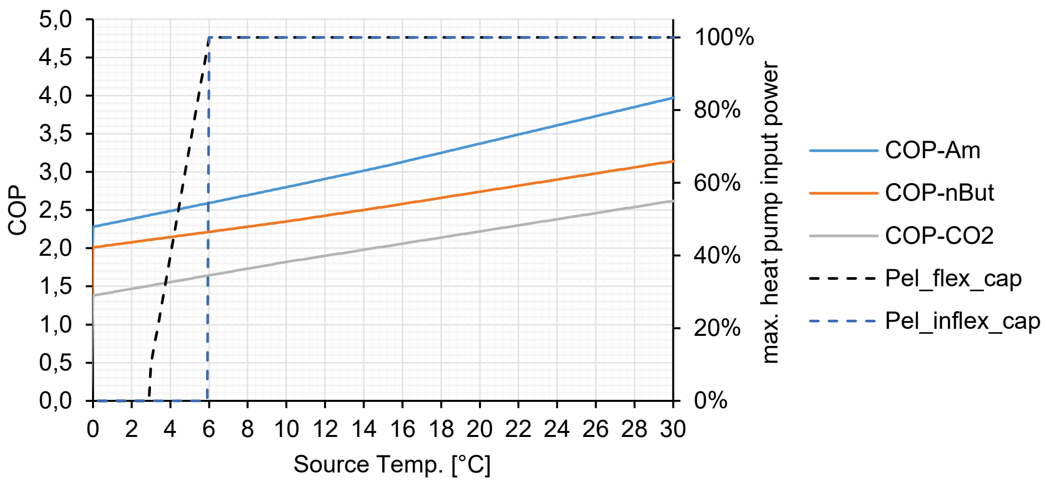

Fig. 3.3 COP and power restriction under the dependency of the source temperature for a flow-temperature of 85 °C and a lift of 30 K

3.2.3 Industrial excess heat

The recovery of industrial excess heat is a necessary measure to decrease the carbon footprint of our industry sector in the future [1]. Modern heat pump systems enable the recycling of low-temperature heat by the industry itself or by external consumers. While the potential is remarkable, heat pumps for industrial use are still a niche product in Austria [20], [26]. According to [20] there are about 160 to 180 active large industrial heat pumps in Austria which mostly provide heat for local buildings (50 %) and partly also feed DH systems(30 %). In the context of flexibility, it must be pointed out that in presumably 50 % of all cases the heat source is directly tied into an industrial process. This eliminates these heat pumps from intermittent use, as their operation provides mandatory cooling power for the processes. On the other hand, the heat pumps are also bound to production schedules, if the processes do not run continuously. For the model in this work, industrial heat sources are assumed to be intermittence free and the heat pumps are not critical for the base process. Real sources which could fulfill these restrictions are flue gas condensation and cooling demands which could alternatively be served by cooling towers or ambient water.

The simulations utilizing industrial excess heat heat pumps are all conducted with a constant source temperature and availability. The corresponding results can therefore also be projected on other constant heat sources like low-temperature geothermal. This eliminates the need to conduct separate simulations for those sources.

3.2.4 Ambient air

Air heat pumps are scarcely used in the context of DH systems even though they are the most used domestic decentralized heat pump system [27]. The fact that their low-temperature energy source is air and therefore everywhere available, makes them a great low-cost bulk product. The Heat Roadmap Europe 2050 treats domestic units as a key component in the decarbonization of heat energy, especially in rural areas [12]. Using air as a heat source has benefits in small scale applications but also compromises the scalability to larger units. The low energy density compared to other heat carriers, demands for excessive air throughput volumes. For high power systems, also the size of evaporators and fans increases respectively. In urban areas where space is usually restricted and large noisy fans are no option, this technology is typically not utilized. Not only is the energy density of air very low compared to water, but it also shows the largest temperature volatility of all sources. As they cannot rely on some sort of large thermal mass that would equalize short term temperature changes, local weather conditions have an undelayed impact on the COP of these systems. Other factors like precipitation and air humidity can also lead to efficiency losses or even shutdowns due to heavy ice build-up on the evaporators in extreme cases.

Even though the air is no ideal heat source, the independence from infrastructure and the geographical freedom of placement make air heat pumps a subject of further investigation but only for small DH systems. To accurately represent the use of ambient air as a heat source in the dispatch model two special restrictions are used. Like for the water heat pumps, a source temperature sensitivity is implemented which is further described in chapter 3.4. The second rule constrains the minimum operating air temperature at -10 °C. Not incorporated are icing effects since they are highly case-specific and cannot be generalized for the used approach.

3.3 Generation and storage portfolios

To extract the economic impacts of the flexibility limiting parameters, introduced in chapter 3.1, hypothetical DH systems are constructed, which act as testing environments for the heat pump implementations. To get viable results for the Austrian DH sector, these constructed systems are closely related to actual Austrian systems. The intentions of not referring to any specific cities are to avoid a too high level of detail and to maintain generalisability. The report Potentiale, Wirtschaftlichkeit und Systemlösungen für Power-to-Heat [6] classifies the existing DH networks in Austria into eleven types which range from small villages systems, with only one biomass boiler, up to systems for metropolitan areas. For this research, the three types which represent the highest share of the Austrian heat demand, after type 1, are selected. The exclusion of type 1 is mainly because there is only one city of this scale (Vienna) in Austria and this work is intended to cover a larger volume of small to medium systems. Over 30 % of the Austrian heat demand is covered by DH networks of the three chosen types. Additionally, to the existing DH types, one fictional portfolio is generated where an oversized[4] heat pump is paired with a gas CHP plant. Table 3.2 shows the selected types and the data supplied by the previously mentioned report including the potentials for waste incineration and industrial waste heat [6]. The associated portfolios are further described in the following chapters and form the foundation for all implemented scenarios.

Table 3.2 Classification of the selected DH systems within this thesis [6]

Name	City 1	City 2	City 3	Village 1
Description	A large city with waste incineration, industrial waste heat, gas CHP, biomass CHP, waste heat potential and a large river	A large city with industrial waste heat, gas CHP, gas boiler, and a river	A medium city with one gas CHP one oversized heat pump and waste heat potential and a small river	A small village with a biomass boiler larger than 2 MW_{th}
Classification in report [6]	Type 2	Type 3	-	Type 10
Share of the Austrian heat demand [%]	7.8	12.0	-	10.7
Heat density [GWh/km²]	30	28	-	10
Heat demand of one system [MWh_{th}]	1,160,000	890,000	180,000	17,000
Waste incineration [MWh_{th}]	245,000	-	-	-
Industrial waste heat [MWh_{th}]	(160,000)	66,000	-	-

3.3.1 City 1

The so-called City 1 portfolio is representing a city DH system of type 2 according to the beforementioned report [6]. The artificial set-up is designed for a heat demand of 1.1 TWh per

[4] Oversized compared to a heat pump size that would usually be stated to be economically valuable for a city of this size. In this case the oversized heat pump can deliver half of the maximum heat demand.

year and represents a city with the size, population, and industry sector of Linz. The heat demand throughout the whole year is shown in Fig. 3.4 and peaks at about 410 MW in the coldest winter days. During the summer period, the demand settles at about 40 MW mainly for warm water consumption and industrial heat demand. Characteristic for a city of this size is a maximum system flow temperature of 120 to 130°C and a system return temperature of about 60°C. Typically these temperatures are dependent on the outside temperature and the demand and are kept as low as possible. Mainly to reduce losses throughout the system and to increase the efficiency of the heat generators [6], [28]. Until the year 2030, it is to be expected that the city reduces the average system temperatures by 5 °C, to create a friendlier environment for RES to feed into the network. The system temperature schedule in dependency of the ambient air temperature is displayed in Fig. 3.5 for the years 2016 and 2030. The calculation of the system temperatures for a specific year is always based on this dependency. For the example year 2016 the calculated temperatures are shown in Fig. 3.6.

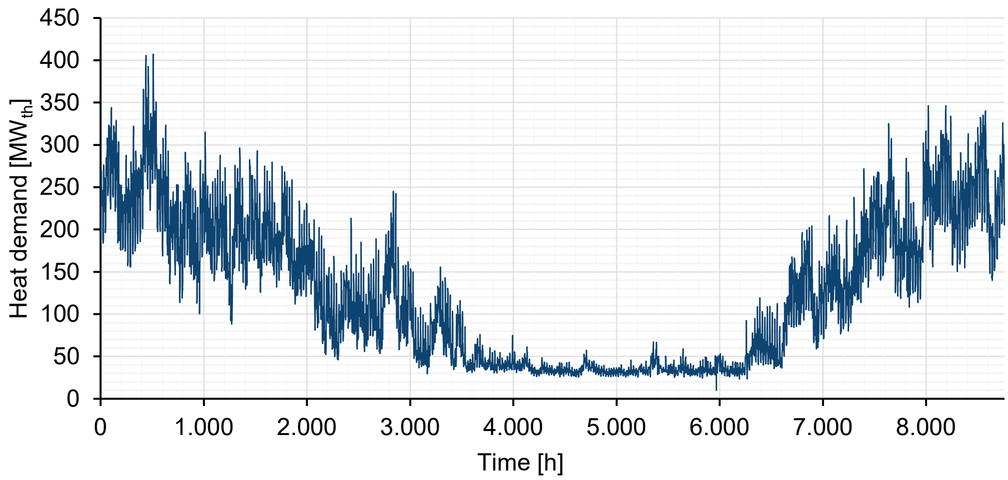

Fig. 3.4 Heat demand of the City 1 DH system (measurement for the year 2016)

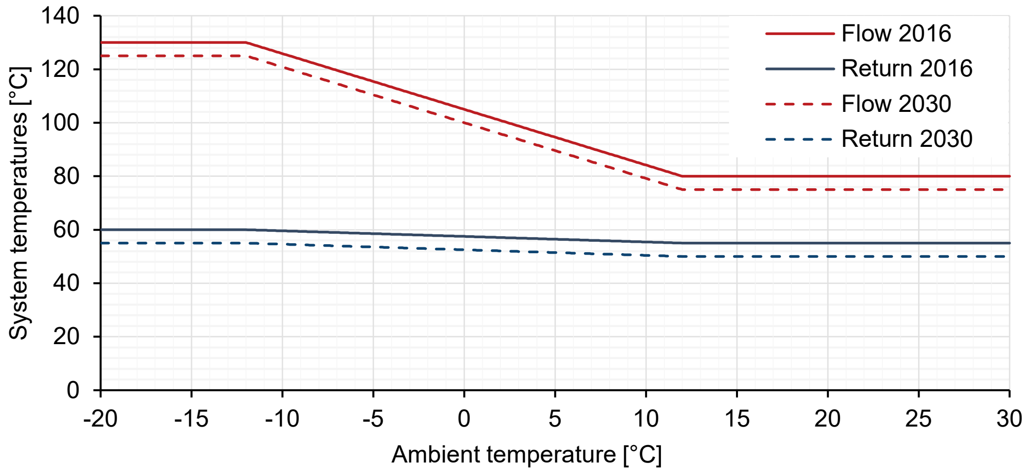

Fig. 3.5 City 1 system temperatures depending on the ambient temperature

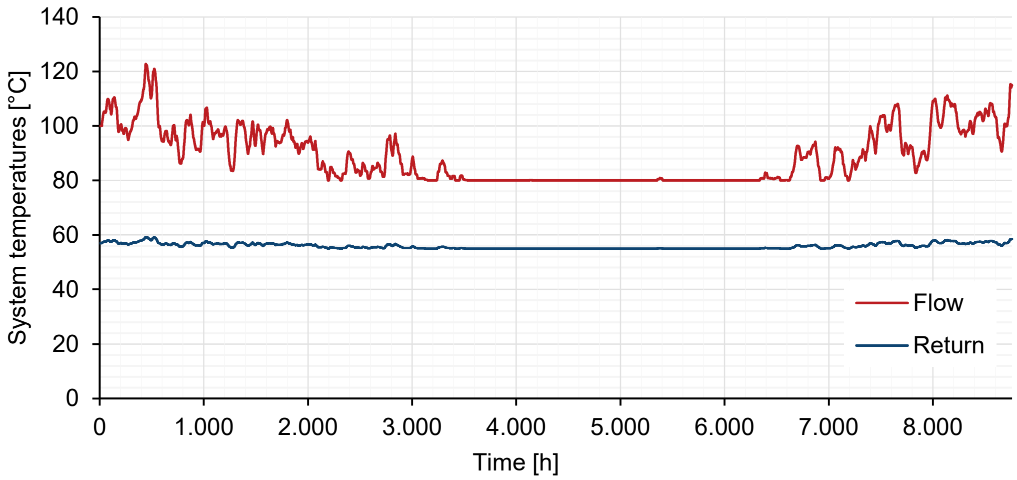

Fig. 3.6 Calculated system temperature timeline for the City 1 in the weather year 2016

The chosen generation portfolio is characterized by a waste incineration plant which must always run at least with 50 % of its maximum output power and a high share of Gas CHP plants. A gas boiler is used as a peak load producer. Table 3.3 lists all producers in the present portfolio and Fig. 3.7 shows a typical load duration curve for this basic setup. The assumed economic parameters for all utilized generation and storage facilities are listed for every main portfolio separately in the annex (chapter 6).

Table 3.3 Existing technology portfolio for City 1

Heat producer	**Max. thermal output power [MW_{th}]**	η_{th}	η_{el}	**Must run factor**	**Min. output power ratio**
Waste incineration	45	0.63	0.17	0.5	0.1
Gas CHP	340	0.50	0.41	-	0.02[5]
Biomass CHP	25	0.68	0.22	-	0.2
Gas boiler	150	0.90	-	-	0.1

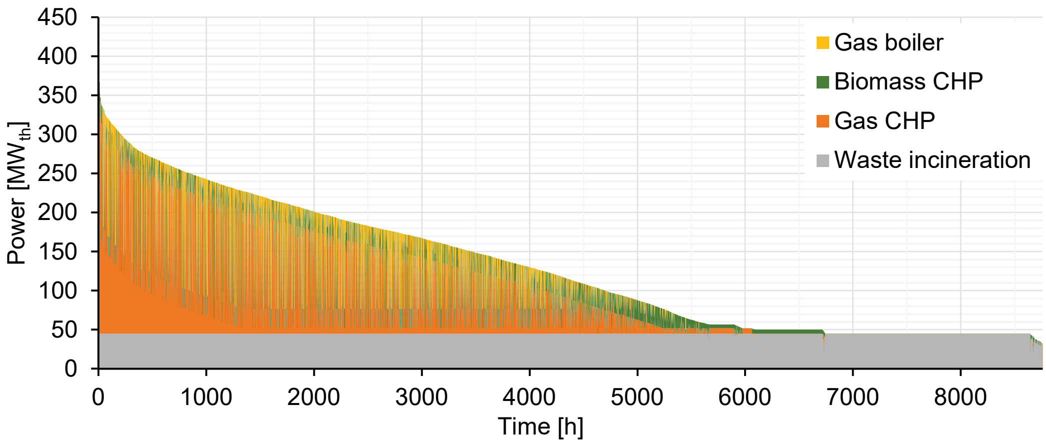

Fig. 3.7 Load duration curve for the City 1 system without P2H extensions in 2016

[5] The Gas CHP unit in this table is artificially created to represent a large and a small CHP unit in addition. This value is chosen small enough to also allow small output powers.

The high system temperatures of up to 130 °C drastically reduce the choices for heat pump coolants. As multi-stage systems or potential post-heating with a gas boiler is not considered, the only possible coolant is n-Butane. The excellent high-temperature capabilities of n-Butane also come with a drawback in efficiency. The COP of these systems can decline to about 2.0 in unfavorable winter situations. As listed in Table 3.5, the P2H devices which are tested as extensions for the existing portfolio, have a thermal output power of 21.14 MW. This nominal power is chosen, as it still allows high utilization simultaneous with the waste incineration plant in the summertime. The dimension of the optional heat storage is based on typical storage units in systems of this size.

Table 3.4 Heat storage option for City 1

	Capacity [MWh_{th}]	Max. loading Power [MW_{th}]	Max. unloading Power [MW_{th}]	(un)loading efficiency	Hourly storage losses
Heat storage	1000	60	60	0.992	0.01

Table 3.5 Possible P2H extensions for City 1

P2H producer	Max. thermal output power [MW_{th}]	Nominal COP (η_{th})[6]	Coolant medium	Compressor power [MW_{el}]
Wastewater source HP	21.15	2.35	n-Butane	9
River water source HP	21.15	2.35	n-Butane	9
Industrial excess heat source HP	21.15	3.00	n-Butane	7.05
Electric boiler	21.15	0.98	-	-

3.3.2 City 2

The second main portfolio is named City 2 and can be categorized as a type 3 DH system [6]. With an annual heat energy consumption of 890 GWh, it is slightly smaller in comparison to the City 1 portfolio. The main differentiation is the missing waste incineration plant which could act as a baseload generator. This may raise the number of full load hours a P2H device can accumulate throughout the year and especially during the low-demand seasons. The flow temperature is about 10 °C cooler in general and is also assumed to be dropped by 5 °C until 2030. The graphs in Fig. 3.9 - Fig. 3.11 illustrate the demand and temperature timelines which are assumed for the City 2 DH system. For the conventional heat producers in Table 3.6 a load duration curve as shown in Fig. 3.8 arises. This generator setup is derived from the actual setups of the cities Graz and Salzburg which both have DH systems of a similar extent.

Table 3.6 Existing technology portfolio for City 2

Heat producer	Max. output. power [MW_{th}]	η_{th}	η_{el}	Must run factor	Min. output power ratio
Industrial excess heat	7.5	1.00	-	-	0.10
Gas CHP large	250	0.50	0.41	-	0.15
Gas CHP small	18	0.49	0.36	-	0.15
Gas boiler	120	0.90	-	-	0.05

[6] Nominal COP at 10°C source, 90°C flow, 55°C return

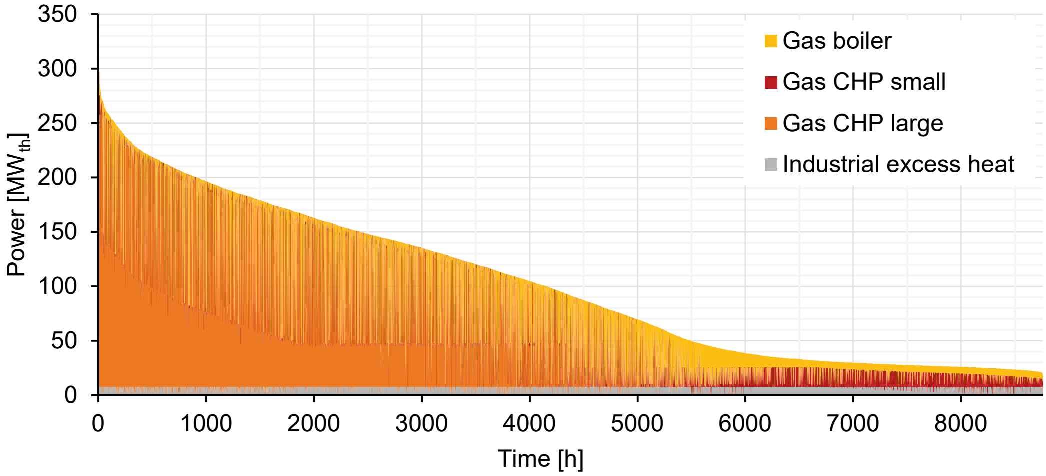

Fig. 3.8 Load duration curve for the City 2 system without P2H extensions in 2016

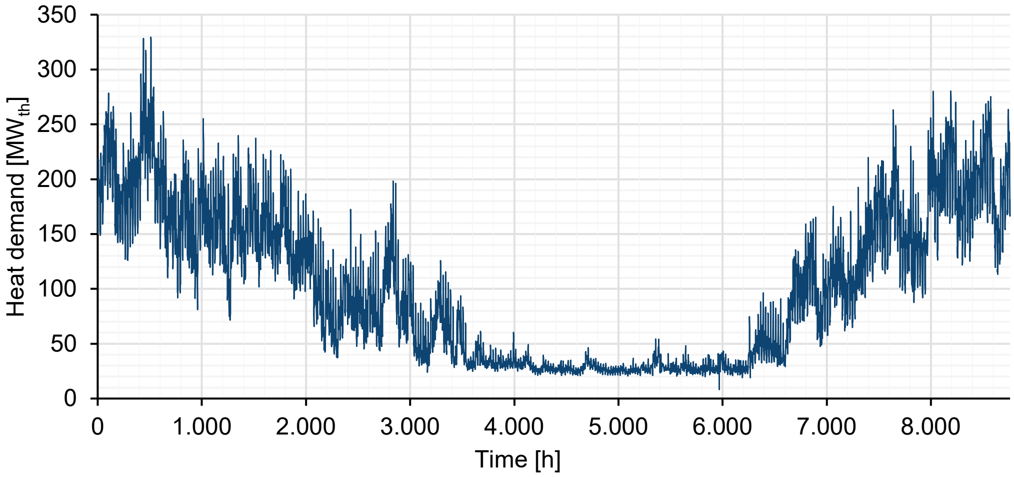

Fig. 3.9 Heat demand of the City 2 DH system (scaled and adopted from City 1)

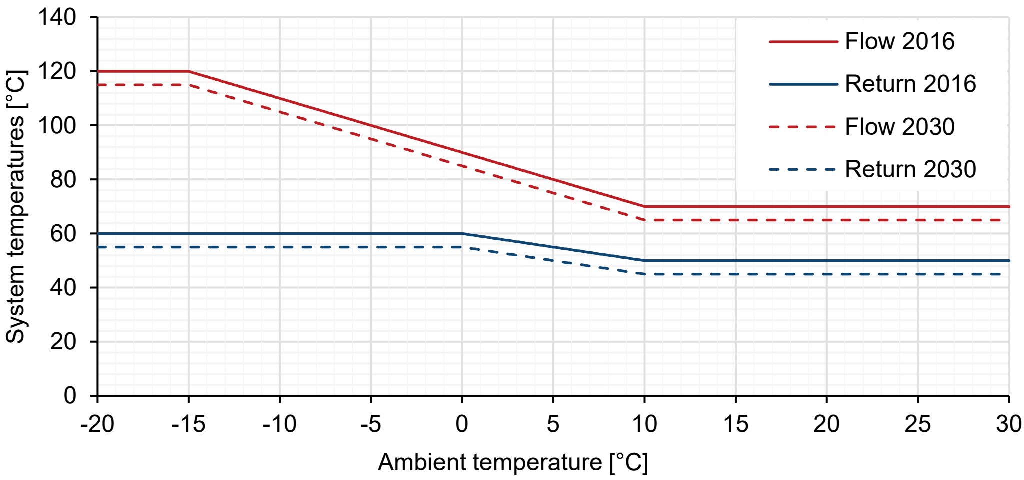

Fig. 3.10 City 2 system temperatures depending on the ambient temperature

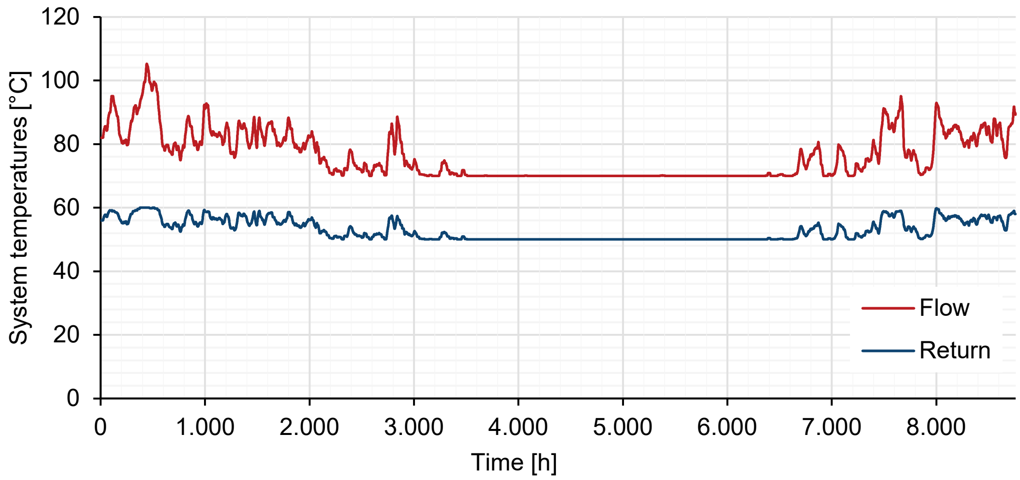

Fig. 3.11 Calculated system temperature timeline for the City 2 in the weather year 2016

The choice of P2H devices is the same as for City 1 but with an adjusted maximum output power of 18 MWth. With the high flow temperatures of 120 °C only allowing n-Butane as coolant too. The focus in this portfolio is clearly towards the question if a missing baseload generator in summer enlarges the effect of flexibility. The selected storage option in Table 3.7 is typical for a city of this size in Austria.

Table 3.7 Possible P2H extensions for City 2

P2H producer	**Max. thermal output power [MW_{th}]**	**Nominal COP (η_{th})[7]**	**Coolant medium**	**Compressor power [MW_{el}]**
Wastewater source HP	18	2.35	n-Butane	7.66
River water source HP	18	2.35	n-Butane	7.66
Industrial excess heat source HP	18	3.00	n-Butane	6.00
Electric boiler	18	0.98	-	-

Table 3.8 Heat storage option for City 2

	Capacity [MWh_{th}]	**Max. loading power [MW_{th}]**	**Max. unloading power [MW_{th}]**	**(un)loading efficiency**	**Hourly storage losses**
Heat storage	1000	60	60	0.992	0.01

3.3.3 City 3

The City 3 setup is the only portfolio which is not based on a specific type of existing systems. It is of special interest how a P2H unit can coexist with a single natural gas CHP unit where the maximum output of the P2H generator can supply about 50 % of the maximum demand. This is an unusual case today but might get more popular in the future due to emission reduction efforts. With an energy demand of 180 GWh per year, the maximum output power reaches about 65 MW in Fig. 3.12. The flow temperature peaks at a maximum of 100 °C which allows the use of more efficient Ammonia heat pumps in this setup (Fig. 3.13 and Fig. 3.14).

[7] Nominal COP at 10°C source, 90°C flow, 55°C return

This higher efficiency is especially important as a heat pump of this size can only utilize its maximum output power during the cold winter month. The question of interest, in this case, is how the high relative capacity of the heat pump changes the impact of flexibility. As the lack of demand curtails the output power for most of the year, it is expected that the economic effect of flexibility is lower for the scenarios based on this portfolio. Tables 3.9 to 3.11 contain all relevant data of the gas CHP plant and the reviewed addition-units. The optional storage capacity is chosen in a similar proportion to the maximum heat demand as for the two other city portfolios.

Table 3.9 Existing technology portfolio for City 3

Heat producer	Max. output power [MW_{th}]	η_{th}	η_{el}	Must run factor	Min. output power ratio
Gas CHP	70	0.50	0.41	-	0.15

Table 3.10 Possible P2H extensions for City 3

P2H producer	Max. output power [MW_{th}]	Nominal COP (η_{th})[8]	Coolant medium	Compressor power [MW_{el}]
Wastewater source HP	34.9	2.91	Ammonia	12
River water source HP	34.9	2.91	Ammonia	12
Industrial excess heat source HP	34.9	3.00	Ammonia	11.64
Electric boiler	34.9	0.98	-	-

Table 3.11 Heat storage option for City 3

	Capacity [MWh_{th}]	Max. loading power [MW_{th}]	Max. unloading power [MW_{th}]	(un)loading efficiency	Hourly storage losses
Heat storage	200	20	20	0.992	0.01

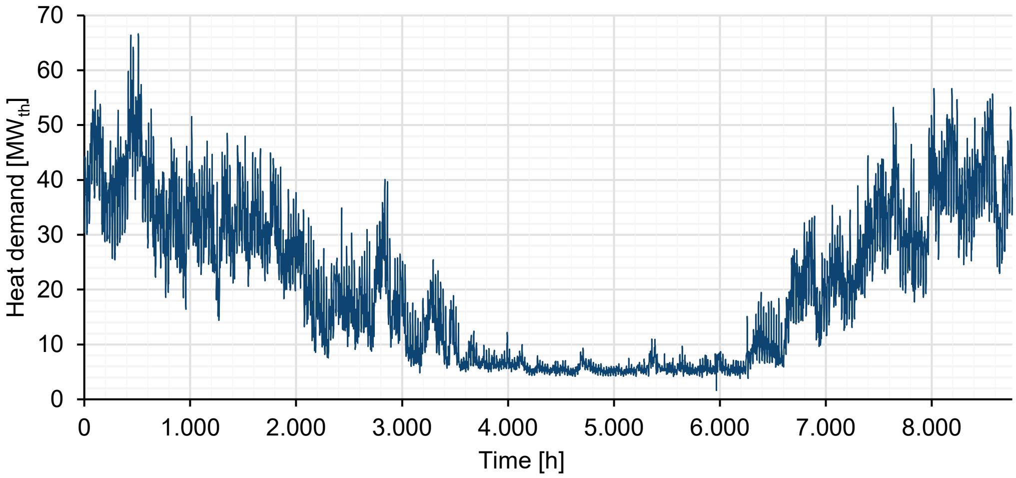

Fig. 3.12 Heat demand of the City 3 DH system (scaled and adopted from City 1)

[8] Nominal COP at 10°C source, 80°C flow, 55°C return

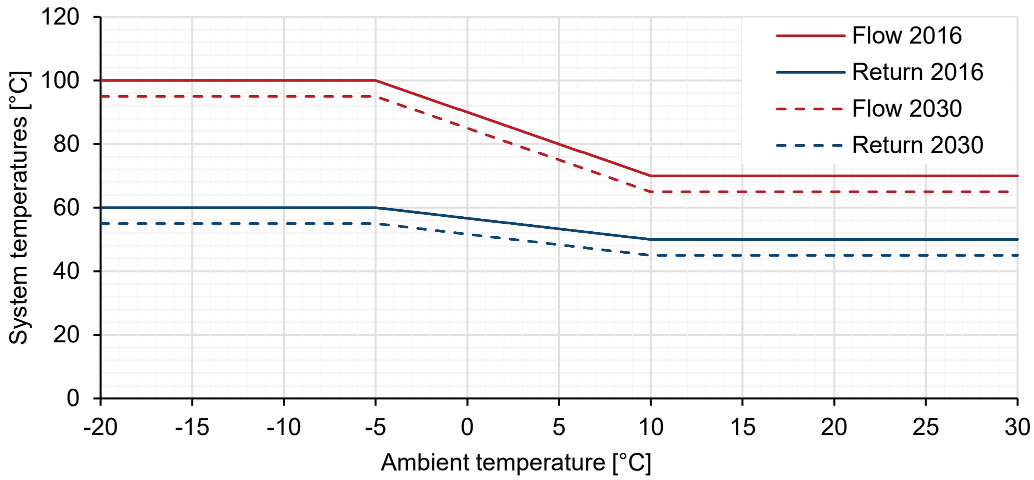

Fig. 3.13 City 3 system temperatures depending on the ambient temperature

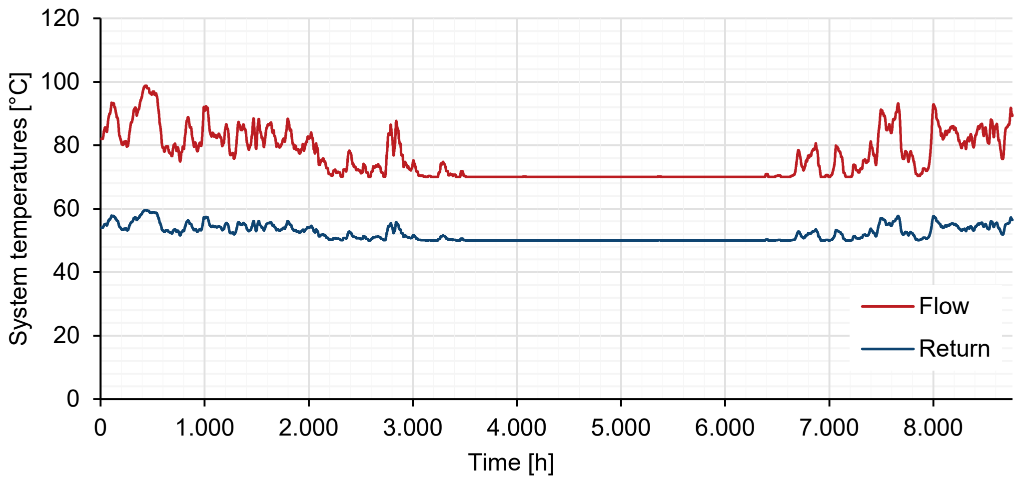

Fig. 3.14 Calculated system temperature timeline for the City 3 in the weather year 2016

3.3.4 Village 1

As the name of this portfolio already suggests it is only a fraction of the size compared to the city portfolios. It can be categorized as a type 10 system according to the classification of DH systems made in [6] with an annual demand of 17 GWh and a maximum output power of around 6 MW (Fig. 3.15). The conventional heat producer in these smaller DH networks is most likely a biomass boiler as it is listed in Table 3.12. The investment costs to tap typical heat sources for large scale heat pumps is often too high or the availability too scarce as they could be used for these village systems. The idea of using air source heat pumps in the sub-MW dimension is verified by an already existing 700 kW air source ammonia heat pump in the UK. This product of the company Star Refrigeration is enclosed in a portable shipping container and claims a COP of around 3.0 [29]. The lower system temperatures which are typical for these smaller systems make ammonia a suitable coolant. In this case, such a unit is tested but as there is no detailed efficiency information, the same COP value and dependencies are chosen as for the previous ammonia heat pumps (Table 3.13).

Table 3.12 Existing technology portfolio for Village 1

Heat producer	Max. output power [MW_{th}]	η_{th}	η_{el}	Must run factor	Min. output power ratio
Biomass boiler	6.9	0.90	-	-	0.05

Table 3.13 Possible P2H extensions for Village 1

P2H producer	Max. output power [MW_{th}]	Nominal COP (η_{th})[9]	Coolant medium	Compressor power [MW_{el}]
Air source HP	0.7	2.91	Ammonia	0.24
Electric boiler	0.7	0.98	-	-

Table 3.14 Heat storage option for Village 1

	Capacity [MWh_{th}]	Max. loading power [MW_{th}]	Max. unloading power [MW_{th}]	(un)loading efficiency	Hourly storage losses
Heat storage	5	2	2	0.98	0.01

Even if a single village system of this type does not seem interesting for large-scale P2H deployment, the entirety of these systems produces more heat than the City 1 type in Austria. Additionally, there is a large share of PV and wind generation located in these rural areas which could deliver electric energy without stressing the overland transmission lines. The theoretical possibilities for decarbonization are, however, confronted with questionable economic plausibility. The ambition is to find out this general economic plausibility and how big the effect of flexibility is.

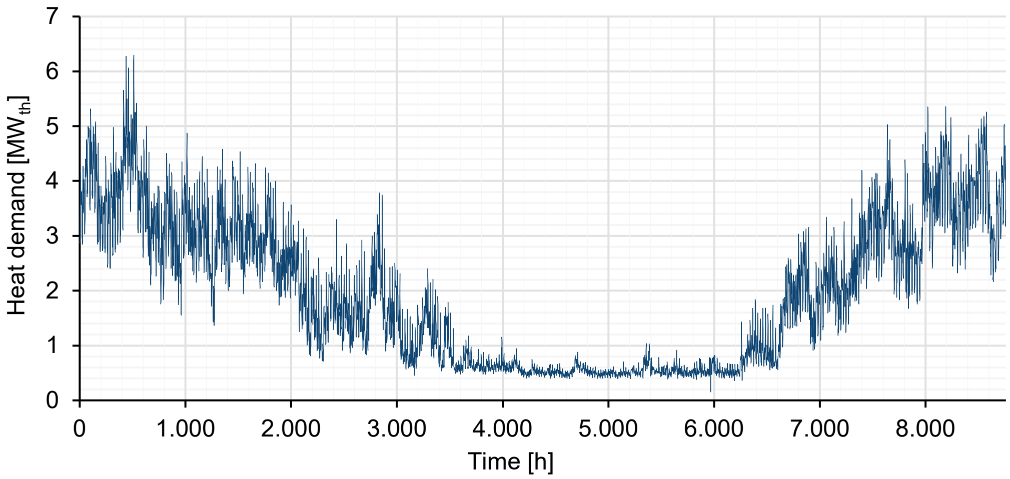

Fig. 3.15 Heat demand of the Village 1 DH system (scaled and adopted from City 1)

[9] Nominal COP at 10°C source, 80°C flow, 55°C return

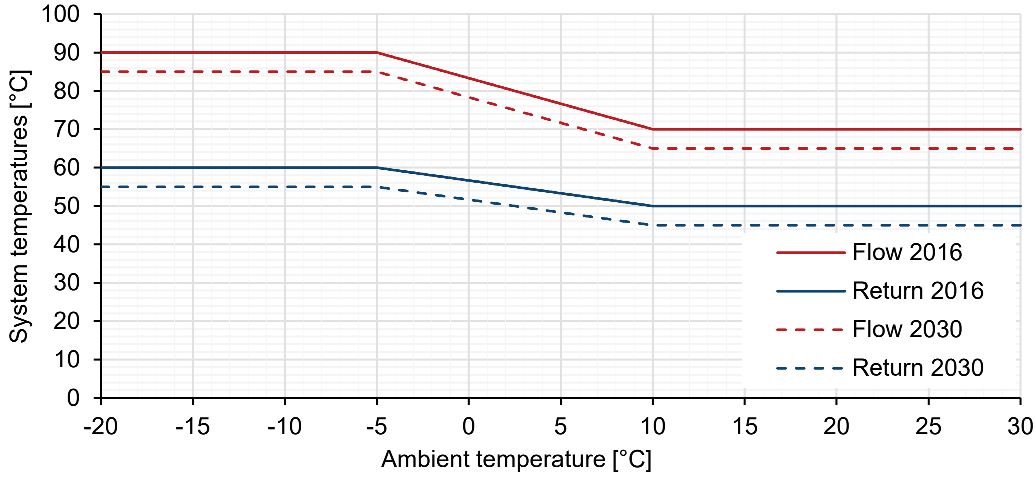

Fig. 3.16 Village 1 system temperatures depending on the ambient temperature

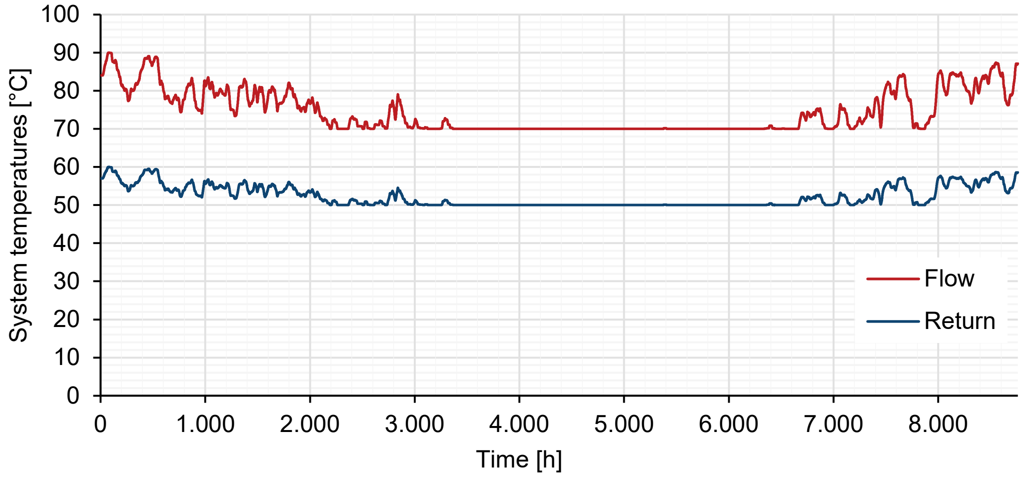

Fig. 3.17 Calculated system temperature timeline for the Village 1 in the weather year 2016

3.4 Scenarios and input data

The four district heating sample networks and the extension possibilities which are defined in the previous chapter 3.3 need to be further developed into complete scenarios. This section describes the differentiation between parameters which leads to these scenarios and shows the resulting scenario tree in its entirety.

The topic of this thesis asks for the first and most important distinction which is drawn between a flexible and inflexible use of heat pumps. Based on the researched literature in chapter 2.2 and the definition of flexibility indicators in chapter 3.1 and 3.2, a set of parameters is determining flexibility. Table 3.15 shows these parameters and their pre-set values for different coolants and heat sources. With these values, the differences between a scenario featuring a flexible heat pump and one with an inflexible heat pump are mandated.

Table 3.15 Parameter definition for flexible versus inflexible heat pump scenarios

Parameter	Description	Scenario		Scenario		Unit
		Flexible	**Inflexible**	**Flexible**	**Inflexible**	
f_{th,min_j}	Min. output power factor	0.15	0.7			1
mr_j	Must run factor	0	1.0			1
		n-Butane		Ammonia		
$s_{COP,flow_j}$	Flow temperature sensitivity	-0.0159	-0.0175	-0.0247	-0.0271	1/°C
$s_{COP,return_j}$	Return temperature sensitivity	-0.0046	-0.0050	-0.0136	-0.0149	1/°C
$s_{COP,source_j}$	Source temperature sensitivity	0.0387	0.0425	0.0578	0.0636	1/°C
		River water		Air		
ϑ_{s,min_j}	Min. source temperature[10]	3	6	-10	-10	°C
ϑ_{s,fo_j}	Fadeout temperature	6	-	-	-	°C

The second distinction is done by choosing the year 2016 or the year 2030 for parameter input values. This is seen as a way to detect the impact of environmental variables that are likely to change in the upcoming years. These parameters include energy prices, the CO_2 price, air, and water temperatures and are more precisely discussed in the following subchapters 3.4.1 to 3.4.3. To keep the total costs of heat production a suitable benchmark for the comparison of 2016 and 2030 scenarios the total heat demand is generally kept the same in both years. This inaccuracy is accepted as the intention is to predict the impact of flexibility under future conditions and not to predict the exact cost of heat production in 2030.

For every city only one expansion option is chosen at a time, A single scenario is consequently a combination of the chosen city plus one heat pump (or electric boiler) option plus potential storage, for a certain year, and if the heat pump is operated flexibly or not. This results in a total of 108 combinations which are all part of the scenario tree shown in Fig. 3.18.

[10] For Wastewater and Industrial waste heat heat pumps there is no minimum source temperature defined as it is assumed that the temperatures are always within a safe operating range.

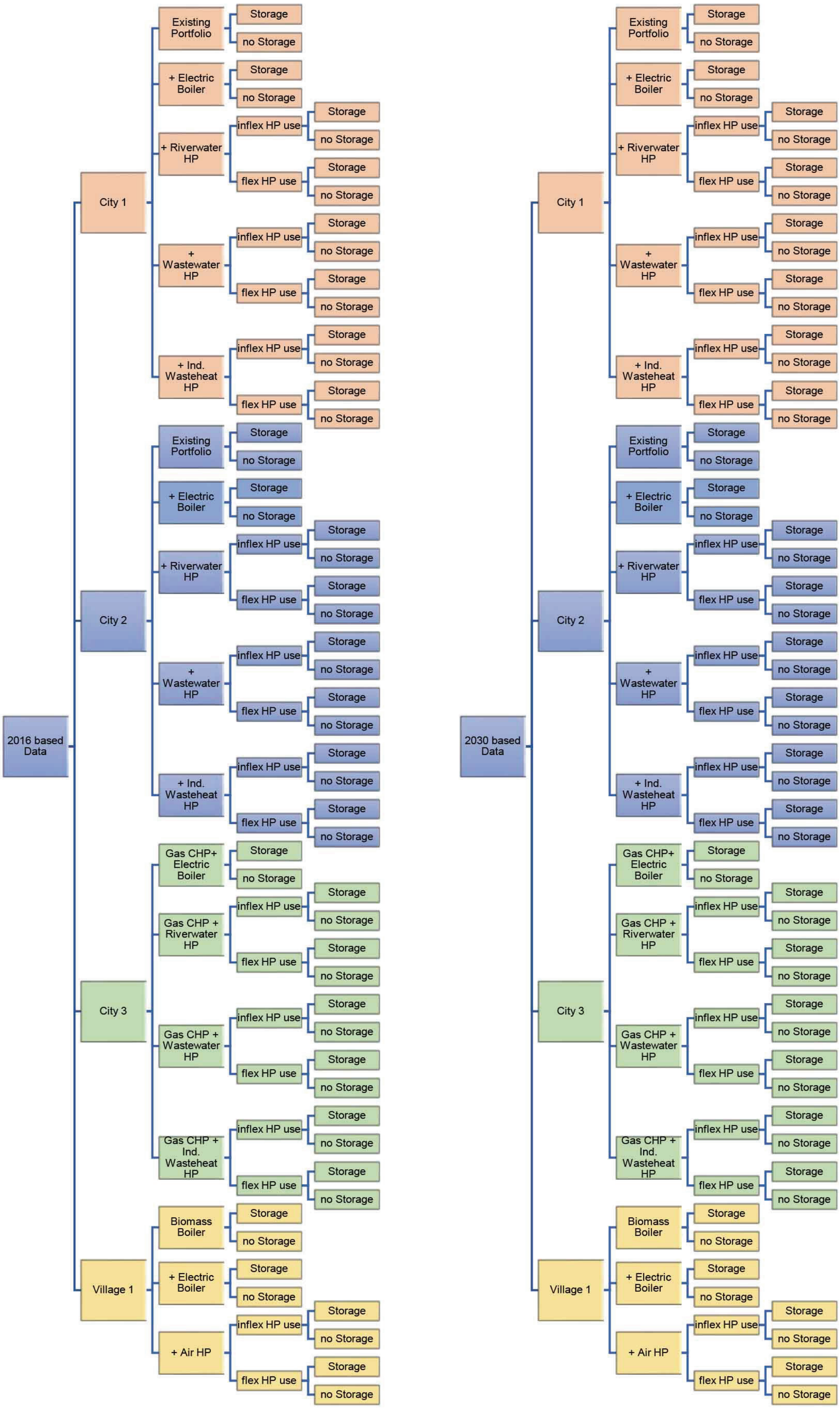

Fig. 3.18 Complete scenario tree with 108 resulting cases in total

3.4.1 Energy carrier pricing

Fuel and electricity are responsible for over half of the total expenditures in our chosen DH scenarios. This underlines the importance of energy carrier prices for real-world operation and the validity of the conducted simulations. The year 2016 was explicitly chosen as most of the needed input data was available as exact values. The prices in Table 3.16 for the year 2016 origin from an energy dispatch research which is conducted by the EEG[11]. The prices for 2030 are based on predictions in the World Energy Outlook 2017 [30].

Table 3.16 Pricing of energy carriers for 2016 and 2030

Energy carrier	Price 2016 [€/MWh]	Price 2030 [€/MWh]
Industrial excess heat	15	15
Domestic waste[12]	0	0
Natural Gas[13]	22	32
Biomass	25	33
Electricity (average) [14]	30	60

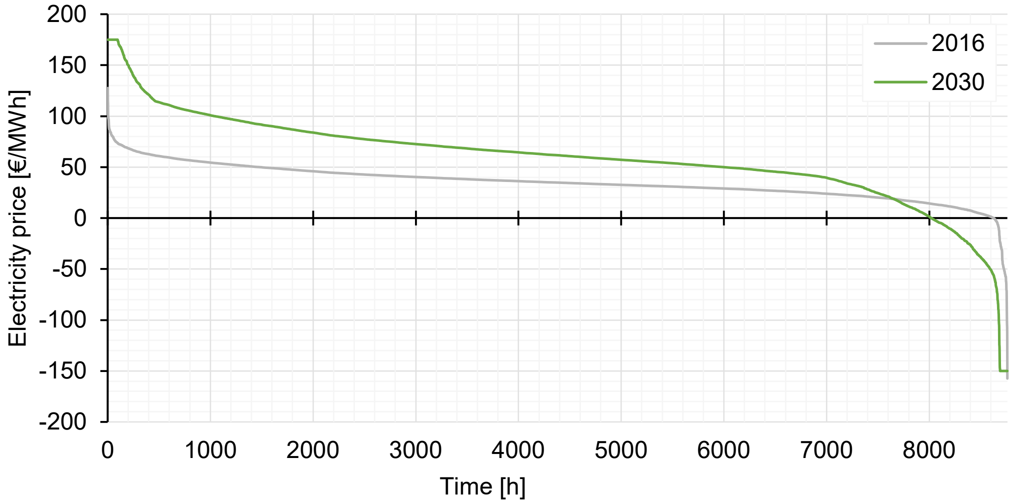

Fig. 3.19 Electricity price input data for 2016 and 2030 (sorted highest to lowest)

Electricity pricing is treated separately as it is one of the key parameters for the competitiveness of heat pumps within a DH system. The high volatility asks for an hour-based dataset instead of a fixed value for the entire year. The comparison of the two price duration curves for 2016 and 2030 in Fig. 3.19 shows that not only the average electricity price is assumed higher for 2030, also the degree of fluctuation and the hours with negative energy

[11] Energy Economics Group, Institute of Energy Systems and Electrical Drives, TU Wien

[12] Domestic waste is assumed to be freely available as it is a by-product of the city's waste logistics.

[13] This is a base price without grid costs and an Austrian natural gas fee. The added grid fee is 0.65 €/MWh and the tax for conventional natural gas consumers is 5.84 €/MWh. Only CHP units are excluded from this surcharge. This tax is assumed to be still charged identically in the year 2030

[14] This Price represents the pure energy price. In addition, there are grid costs of 27.19 €/MWh charged for every consumer. These costs are assumed to be identical for 2030.

prices are increased. This is done to respect the predictions for the future electricity market which are outlined in chapter 1.1.

3.4.2 CO_2 pricing

In the year 2016, the EU ETS[15] auction clearing prices settled just short of 10 €/t_{CO2} [31]. The CO_2 price for all 2016-based scenarios is therefore set to this value. For the year 2030 several forecast models see the ETS clearing price at 25 to 35 €/t_{CO2} [32]. To particularly test the impact of high CO_2 prices on heat pumps, the utmost prediction with a rate of 35 €/t_{CO2} is chosen for all 2030-based scenarios. Decisive for CO_2 related cost are also the emission factors which describe, how much CO_2 is emitted by using a specific fuel. The assumed values for this model can be found in Table 3.9 and are identical for both contemplated years. As Austria ranks best in the share of RES in electric consumption (72,6 %) within the EU 28 in the year 2016, the emission factors for electricity is already amongst the best [33]. The Austrian mission2030 additionally sets a target of net 100 % renewable electricity generation in the year 2030 [34]. However, even if this net balance target is fulfilled, it does not generally inhibit that electricity is sometimes of nonrenewable origin, for example during peak load hours. Due to this fact and simplification reasons, the emission factor for electricity is the same for both model years.

Table 3.17 CO_2 emission factors of energy carriers for 2016 and 2030

Energy carrier	**CO2 emission factor [t_{CO2}/MWh_{prim}]**
Industrial waste heat	0.000
Domestic waste (average)[16]	0.300
Natural Gas[17]	0.200
Biomass[18]	0.029
Electricity (average)	0.150

3.4.3 Environmental data

Accurate environmental figures have a major impact on the quality and usability of simulation results. This originates from the circumstance that information like the ambient air temperature affects the model in multiple different ways. Heat demand, flow temperatures, return temperatures, COPs, and restriction factors all depend on ambient temperatures. The air temperature values for 2016 are actual recordings from three places in Austria where DH systems of the mentioned types are in operation. In Fig. 3.20 these temperature datasets can be seen for the year 2016. Part of all 2030 scenarios is to take the expected average temperature increase caused by man-made climate change into account. According to the IPCC[19], the global average ambient air temperature is expected to rise by about 0.5 °C until 2030 [36]. This is embedded in the model data by an offset of 0.5 °C compared to the 2016 values. In general, all hourly data sets for the 2030 scenarios are derivates of the actual data recordings for 2016. This, of course, is not a valid prediction for the situation in 2030 but avoids the use

[15] European Union Emissions Trading System
[16] Source: Emission factor database EFDB of the IPCC
[17] Source: Emission factor database EFDB of the IPCC
[18] The renewable part of CO_2 emission is not included here. Only the fossil share which is mainly emitted by the supply chain. Average data from [35]
[19] IPCC-Intergovernmental Panel on Climate Change

of generic random waveforms. For the purpose of comparing the scenarios, this even helps at isolating the effects of certain parameters as the waveforms and their time correlation with each other are very similar for scenarios in both years.

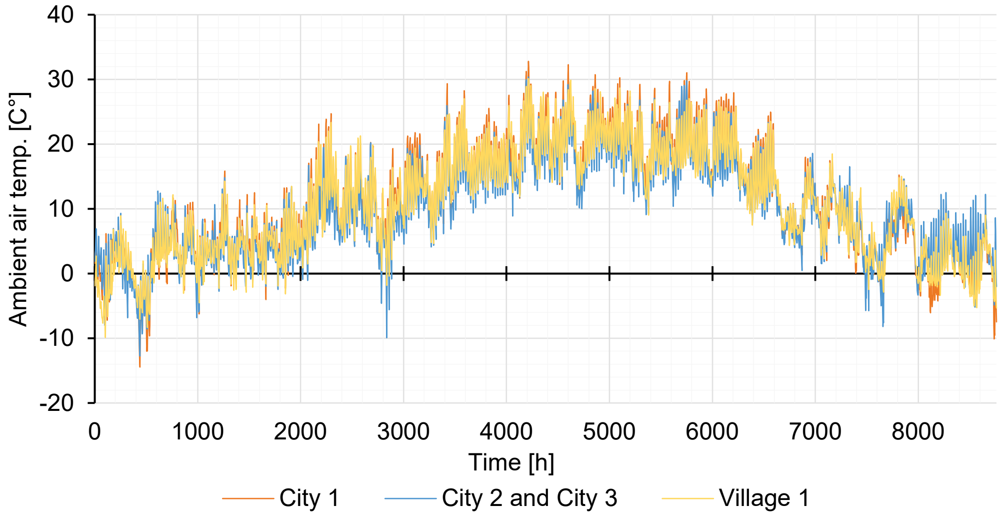

Fig. 3.20 Ambient air temperature input data for the year 2016

As already explained in chapter 3.2.2, river water temperatures are essential for the COP of heat pumps which use this water as a low-temperature heat source. City 1 with the largest DH system is assumed to have access to a large stream like the Danube. The actual temperature recording of the Danube at a reading point near Linz for the year 2016 is used as model input data and shown in Fig. 3.21. By contrast, the water temperature for City 2 and City 3 scenarios is based on the smaller and colder rivers Salzach and Muhr which is a representative choice for cities of this size in Austria. All temperature values are provided by the eHYD[20] information platform. The possible rise of river water temperatures until the year 2030 is assumed with 0.5 °C on average and implemented the same way as for air temperatures.

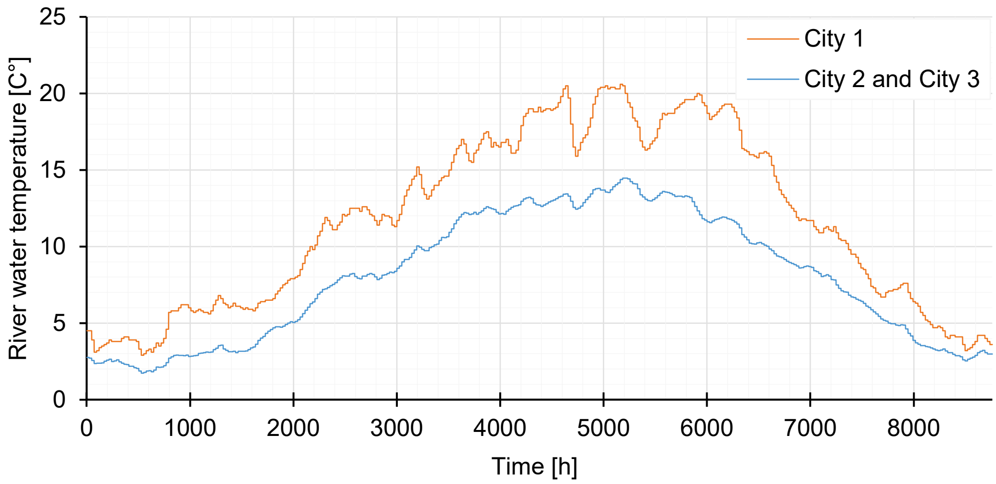

Fig. 3.21 River water temperature input data for the year 2016

[20] eHYD-Zugang zu Hydrographischen Daten Österreichs, https://ehyd.gv.at/

The last set of hourly input data treated within this topic is the wastewater temperature. Even though, wastewater logistics is a well-controlled infrastructure it is affected by seasonal ambient temperature changes and precipitation. Actual periodic temperature recordings are hard to find and very specific to the point of measurement in a system [37]. A monthly dataset for the wastewater temperature at the main treatment facility in Vienna [38] shows that the annual trend roughly follows a sinusoidal waveform with a maximum at 20 °C in August and a minimum at 13 °C in January. The supposed temperature graph for City 1 in Fig. 3.22 is based on this information. Due to a lower housing density and less industrial wastewater, smaller cities are assumed to have a lower wastewater temperature on average. A margin of 2°C is factored in for City 2 and 3 as shown in the graph. A possible trend of sinking wastewater temperatures as a result of facility-internal energy recuperation is not respected for the year 2030 due to a lack of data. The wastewater temperature is therefore assumed to be the same for both considered years.

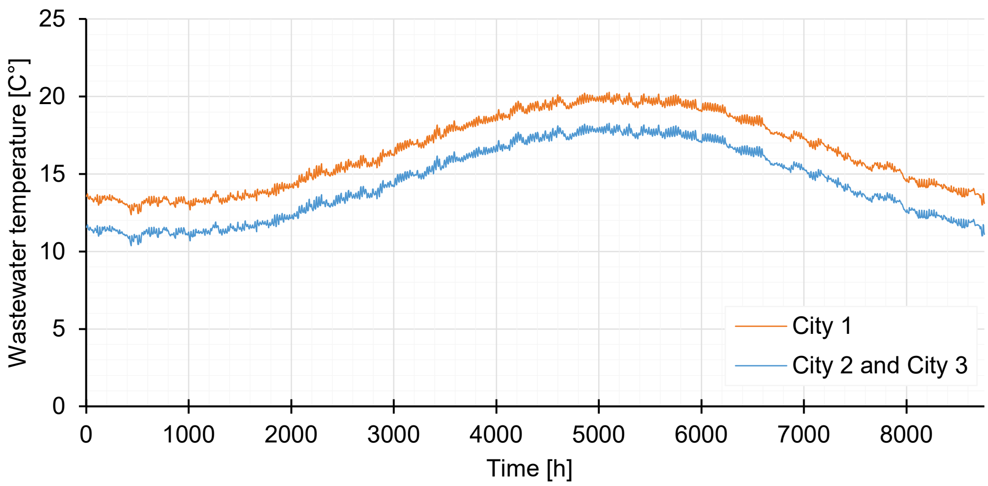

Fig. 3.22 Wastewater temperature input data for 2016 and 2030

3.5 Dispatch model

To process the specified scenarios a versatile and powerful infrastructure is mandatory. The used model is based on the simulation and visualization infrastructure of the H°TMAPS[21] dispatch tool and was adopted and extended to fit the specific needs of this study. The web-based Python application delivers an optimized dispatch plan for a complete year in 8760 hourly steps with the main objective of minimizing the total cost of heat production. Complementary economic details like a breakdown of costs and revenues, listings of full-load operating hours and CO_2 emissions are also provided and enable further evaluations. All input data, containing the generation portfolio, detailed technical and economical generator information, profiles for heat demand, electricity prices, solar radiation, air temperatures, river temperatures and many more can be entered manually via a graphical user interface or uploaded gathered in an Excel file.

The core component of the pre-existing tool is a Liner Problem (LP) which is optimized with the solver GUROBI[22]. The applied changes caused the model to become a Mixed Integer Linear Problem (MILP) which asks for adjustments in the solver configuration but can still be solved with the GUROBI optimizer. This complete MILP model and its parameters are further described in the following chapter 3.5.1. In Fig. 3.23 the internal operation principle of the H°TMAPS dispatch tool is roughly visualized. The conducted changes in the course of this thesis include heat pump specific generator options and environmental restrictions, source and system temperature inputs, extended "must-run" functionalities, minimum output power restrictions, and numerous smaller adaptions. A lack of information on investment costs and especially the difference in investment costs for flexibly versus inflexibly operated heat pumps made it necessary to avoid uncertainties and generally omit investment costs in this model. As the ultimate focus of the work is to calculate the financial difference between operational behavior modes and not the absolute financial impact of heat pumps, this inaccuracy is accepted. Furthermore, electricity producers and consumers in the generation portfolio do only have an influence on the DH system itself and not on the electricity market. The electricity price is predefined without any elasticities, as it can be expected that none of the participants is large enough to have that much impact.

[21] H°TMAPS - The open source mapping and planning tool for heating and cooling, https://www.hotmaps-project.eu/

[22] GUROBI Optimization, http://www.gurobi.com

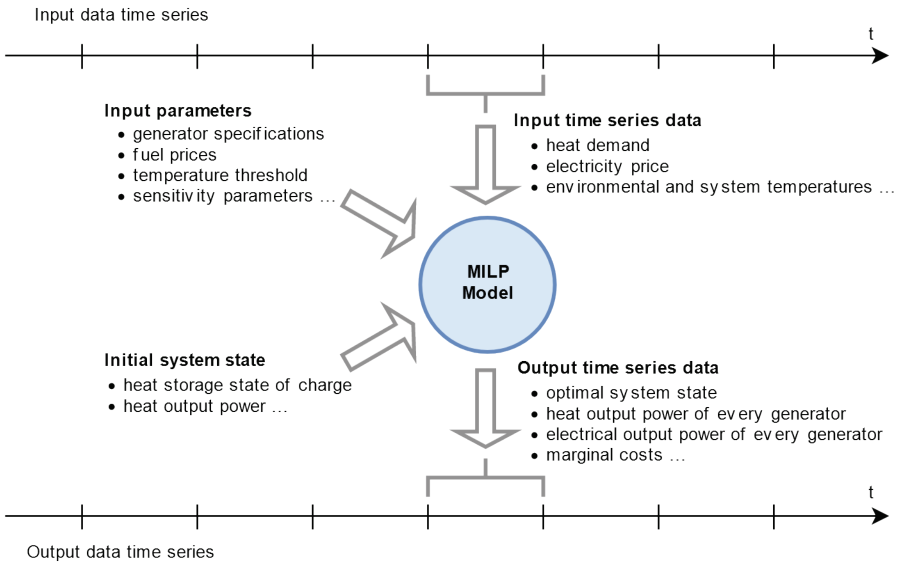

Fig. 3.23 Working process of a MILP based energy dispatch model. Source: own illustration

3.5.1 Model definition

Mathematically describing a complete model that is purely developed as Python/Pyomo code can get confusing and also hide out the essential parts very easily. Constraints and logical expressions which are implemented to maintain feasibility, avoid faulty conditions or just support internal data handling are therefore not represented entirely. The mathematical representation in this chapter is meant to show the main objective, key features and how all the datasets and parameters which are introduced in this thesis are finally processed. Table 3.18 contains a list and definition of all variables and parameters which are used in the following model definition.

Table 3.18 Definition and properties of model variables

Variable	Type	Description	Unit
c_{total}	$\in \mathbb{R}_{\geq 0}$	Total cost for heat production	€
rev_{total}	$\in \mathbb{R}_{\geq 0}$	Total revenue from electricity production	€
$x_{th_{j,t}}$	$\in \mathbb{R}_{\geq 0}$	Heat generation of the generator j in hour t	MWh
$x_{load_{hs,t}}$	$\in \mathbb{R}$	Thermal energy transferred to heat storage hs in hour t (>0: loading, <0: unloading)	MWh
$x_{el_{j,t}}$	$\in \mathbb{R}_{\geq 0}$	Electricity generation of the generator j in hour t	MWh_{el}
$Active_{j,t}$	$\in \{0,1\}$	Boolean activity indicator of the generator j in hour t	1
$sl_{hs,t}$	$\in \mathbb{R}_{\geq 0}$	Storage level of the heat storage hs in hour t	MWh
$RampP_{j,t}$	$\in \mathbb{R}_{\geq 0}$	Output power change of the generator j in hour t	MW
c_{ramp}	$\in \mathbb{R}_{\geq 0}$	Ramping costs of CHP and waste treatment	€
$ColdInd_{j,t}$	$\in \{0,1\}$	Cold start indicator for generator j in hour t	1
c_{cold}	$\in \mathbb{R}_{\geq 0}$	Annual total cold start costs	€
$OPEX_{fix}$	$\in \mathbb{R}_{\geq 0}$	Annual total operational fixed costs	€
$OPEX_{var}$	$\in \mathbb{R}_{\geq 0}$	Annual total operational variable costs	€
$OPEX$	$\in \mathbb{R}_{\geq 0}$	Annual total operational expenditures	€

Table 3.19 Definition and properties of model parameters

Parameter	Type	Description	Unit
$demand_{th_t}$	$\in \mathbb{R}_{\geq 0}$	Heat Demand in hour t	MWh
η_{el_j}	$\in \mathbb{R}_{\geq 0}$	Electrical efficiency of the generator j	1
$\eta_{th_{j,t}}$	$\in \mathbb{R}_{\geq 0}$	Thermal efficiency of the generator j in hour t (for heat pumps this parameter represents the COP)	1
Cap_j	$\in \mathbb{R}_{\geq 0}$	Maximum thermal output power of the generator j (for heat pumps this parameter represents the maximum compressor power)	MW
$CapNom_j$	$\in \mathbb{R}_{\geq 0}$	Nominal maximum thermal output power of the generator j (important for OPEX calculation)	MW
$HPRF_{j,t}$	$\in [0,1]$	Heat pump restriction factor for the heat pump j in the hour t	1
P_{th,min_j}	$\in \mathbb{R}_{\geq 0}$	Minimum thermal output power of the generator j (for heat pumps this value represents the minimum compressor power)	MW
f_{th,min_j}	$\in \mathbb{R}_{\geq 0}$	Factor of the minimum possible output power of the generator j	1
mr_j	$\in [0,1]$	Must run factor for the generator j	1
mrP_{waste}	$\in \mathbb{R}_{\geq 0}$	Total waste incineration power which is in a must run state	MW
$sCap_{hs}$	$\in \mathbb{R}_{\geq 0}$	Thermal capacity of the heat storage hs	MWh
$sCapLoss_{hs}$	$\in \mathbb{R}_{\geq 0}$	Hourly storage losses factor of the heat storage hs	1
$\eta_{load_{hs}}$	$\in \mathbb{R}_{\geq 0}$	Thermal loading and unloading efficiency of the heat storage hs	1
$sLoadP_{hs}$	$\in \mathbb{R}_{\geq 0}$	Maximum loading power of the heat storage hs	MW
$sUnloadP_{hs}$	$\in \mathbb{R}_{\geq 0}$	Maximum unloading power of the heat storage hs	MW
p_{ramp_j}	$\in \mathbb{R}_{\geq 0}$	Price for ramping the power generator j	$€/MW$
p_{cold_j}	$\in \mathbb{R}_{\geq 0}$	Price for cold starting the power generator j	$€$
$opex_{fix_j}$	$\in \mathbb{R}_{\geq 0}$	Annual operational fixed costs of the heat generator j	$€/MW$
$opex_{fix_{hs}}$	$\in \mathbb{R}_{\geq 0}$	Annual operational fixed costs of the heat storage hs	$€/MWh$
$opex_{var_j}$	$\in \mathbb{R}_{\geq 0}$	Output dependent operational cost of the generator j	$€/MWh$
$p_{ec_{j,t}}$	$\in \mathbb{R}_{\geq 0}$	Energy carrier price for the generator j in hour t	$€/MWh$
$f_{em_{ec_j}}$	$\in \mathbb{R}_{\geq 0}$	The CO_2 emission factor of energy carrier for the generator j	t_{CO_2}/MWh
p_{CO_2}	$\in \mathbb{R}_{\geq 0}$	CO2 certificate price	$€/t_{CO_2}$
$p_{s.el_{j,t}}$	$\in \mathbb{R}_{\geq 0}$	Electricity sale price for the generator j in hour t	$€/MWh_{el}$
ϑ_{s,min_j}	$\in \mathbb{R}$	Minimum source temperature for heat pump j	$°C$
ϑ_{s,fo_j}	$\in \mathbb{R}$	Fade-out source temperature for heat pump j	$°C$
$\vartheta_{s_{j,t}}$	$\in \mathbb{R}$	Source temperature for heat pump j in hour t	$°C$
ϑ_{s,nom_j}	$\in \mathbb{R}$	Nominal source temperature for heat pump j	$°C$
ϑ_{f,nom_j}	$\in \mathbb{R}$	Nominal system flow temperature for heat pump j	$°C$
$\vartheta_{f_{j,t}}$	$\in \mathbb{R}$	System flow temperature for heat pump j in hour t	$°C$
ϑ_{r,nom_j}	$\in \mathbb{R}$	Nominal system return temperature for heat pump j	$°C$
$\vartheta_{r_{j,t}}$	$\in \mathbb{R}$	System return temperature for heat pump j in hour t	$°C$

$s_{COP,source_j}$	$\in \mathbb{R}$	Source temperature sensitivity of the COP of the heat pump *j*	$1/°C$
$s_{COP,flow_j}$	$\in \mathbb{R}$	System flow temperature sensitivity of the COP of the heat pump *j*	$1/°C$
$s_{COP,return_j}$	$\in \mathbb{R}$	System return temperature sensitivity of the COP of the heat pump *j*	$1/°C$
COP_{nom_j}	$\in \mathbb{R}_{\geq 0}$	Nominal COP of the heat pump *j* at nominal temperatures	$1/°C$

Table 3.20 Definition and properties of model indexing variables

Index	Description
j	$\in \{gas\ CHP, biomass\ CHP, gas\ boiler, waste\ incineration,$ $waste\ heat, electric\ boiler, wastewater\ heat\ pump,$ $river\ water\ heat\ pump, industrial\ wasteheat\ heat\ pump, air\ heat\ pump\}$
hs	$\in \{heat\ storages\}$
$heat\ pump$	$\in \{wastewater\ heat\ pump,$ $river\ water\ heat\ pump, industrial\ wasteheat\ heat\ pump, air\ heat\ pump\}$
t	Timestep in hours $\{ t \in \mathbb{N}_{\geq 0} \mid t \geq 1, t \leq 8760\}$

3.5.1.1 Objective Function

The Objective function (1) of this MILP problem is defined to minimize the difference between the total production costs and the total generated revenues. For every constraint and function in this model the range of validity is $\forall j, \forall t$ if not separately specified beside or under the formula.

$$min\ (c_{total} - rev_{total}) \tag{1}$$

$$rev_{total} = \sum_{j,t} x_{el_{jt}} \cdot p_{s.el_{j,t}} \tag{2}$$

$$c_{total} = OPEX_{fix} + OPEX_{var} + c_{cold} + c_{ramp} \tag{3}$$

$$OPEX_{fix} = \sum_{j} CapNom_j \cdot opex_{fix_j} + \sum_{hs} sCap_{hs} \cdot opex_{fix_{hs}} \tag{4}$$

$$OPEX_{var} = \sum_{j,t} x_{th_{j,t}} \cdot \left(opex_{var_j} + \frac{p_{ec_{j,t}}}{\eta_{th_{j,t}}} + \frac{f_{em_{ec_j}} \cdot p_{CO_2}}{\eta_{th_{j,t}}} \right) \tag{5}$$

$$c_{cold} = \sum_{j,t} ColdInd_{j,t} \cdot p_{cold_j} \tag{6}$$

$$c_{ramp} = \sum_{j,t} RampP_{j,t} \cdot p_{ramp_j} \quad \forall j \in \{gas\ CHP, biomass\ CHP, waste\ incineration\} \tag{7}$$

3.5.1.2 Constraints

The model is solved in a way so that the following constraints are not violated at any time. The demand constraint (8) ensures equality between heat demand and production with respect for storage loading and unloading. Constraint (9) acts as a hard coupling between electrical and thermal power output if a power plant can do both. Upper and Lower limits of thermal production are set in (11) and (12). A separate case for heat pumps is mandatory as their actual maximum output capacity is dependent on the $\eta_{th_{j,t}}$(COP). The Boolean $Active_{j,t}$ indicator is required to implement a minimum output power restriction and is also further used to count cold starts.

$$\sum_{j,t} x_{th_{j,t}} - \sum_{hs,t} x_{load_{hs,t}} = demand_{th_t} \tag{8}$$

$$x_{el_{j,t}} = x_{th_{j,t}} \cdot \frac{\eta_{el_j}}{\eta_{th_{j,t}}} \tag{9}$$

$$x_{th_{j,t}} \leq \begin{cases} Cap_j \cdot Active_{j,t}\ , & \forall\, j \notin heat\ pump \\ Cap_j \cdot Active_{j,t} \cdot \eta_{th_{j,t}} \cdot HPRF_{j,t}\ , & \forall\, j \in heat\ pump \end{cases} \tag{10}$$

$$x_{th_{j,t}} \geq \begin{cases} P_{th,min_j} \cdot Active_{j,t}\ , & \forall\, j \notin heat\ pump \\ P_{th,min_j} \cdot Active_{j,t} \cdot \eta_{th_{j,t}}\ , & \forall\, j \in heat\ pump \end{cases} \tag{11}$$

The equality of demand and production (8) asks for a complex must run constraint (12-14) which allows for some exceptions, to maintain feasibility. To represent the portfolio of City1 adequately, the constraint (12-14) prioritizes the must run parameter of waste incineration plants and prefers cutting the output power of heat pumps instead. A security function to avoid errors due to a violation of the minimum output power rule (11) within the must run constraint is implemented in the actual model but not further described here.

$$x_{th_{j,t}} \geq \begin{cases} demand_{th_t} - mrP_{waste}\ , & Cap_j \cdot mr_j \cdot \eta_{th_{j,t}} > demand_{th_t} - mrP_{waste} \\ Cap_j \cdot mr_j \cdot \eta_{th_{j,t}}\ , & Cap_j \cdot mr_j \cdot \eta_{th_{j,t}} \leq demand_{th_t} - mrP_{waste}, \end{cases} \quad \forall\, j \in heat\ pump \tag{12}$$

$$x_{th_{j,t}} \geq \begin{cases} demand_{th_t}\ , & Cap_j \cdot mr_j \geq demand_{th_t} \\ Cap_j \cdot mr_j\ , & Cap_j \cdot mr_j < demand_{th_t}, \end{cases} \quad \forall\, j \notin heat\ pump \tag{13}$$

$$mrP_{waste} = \sum_j mr_j \cdot Cap_j \quad \forall\, j \in \{waste\ incineration\} \tag{14}$$

The constraints (15-19) form the heat storage infrastructure. As the transfer power variable $x_{load_{hs,t}}$ represents loading for positive values and unloading for negative values, also the efficiency $\eta_{load_{hs}}$ is effective for both procedures. This inaccurateness is accepted as the loading and unloading efficiencies are typically close values.

$$sl_{hs,t} = \begin{cases} 0, & t = 1 \\ 0, & t = 8760 \\ sl_{hs,t-1} \cdot \left(1 - sCapLoss_{hs}\right) + x_{load_{hs,t-1}} \cdot \eta_{load_{hs}}, & t \notin \{1{,}8760\} \end{cases} \tag{15}$$

$$sl_{hs,t} \leq sCap_{hs} \tag{16}$$

$$x_{load_{hs,t}} \leq sLoadP_{hs} \tag{17}$$

$$x_{load_{hs,t}} \geq -sUnloadP_{hs} \tag{18}$$

$$x_{load_{hs,t}} \geq -sl_{hs,t} \tag{19}$$

As the variable $RampP_{j,t}$ is defined as non-negative real, the constraint (20) only recognizes an increase in output power. As the annual sum for positive power ramping must be the same as for negative power ramping this does not impose a problem. A penalty for downwards ramps can, therefore, be introduced by simply raising the price p_{ramp_j} in (7).

$$RampP_{j,t} \geq \begin{cases} 0, & t = 1 \\ x_{th_{j,t}} - x_{th_{j,t-1}}, & t \neq 1 \end{cases} \quad \forall\, j \in \{gas\ CHP, biomass\ CHP, waste\ incineration\} \tag{20}$$

The cold start of heat pumps and any other heat generator is known to put large mechanical and thermal stress on system components. To take care of this fact, every single cold start is detected in (21) and inflicted with a penalty in (6). The Boolean nature of the indication variable $ColdInd_{j,t}$ allows this calculation to work as intended.

$$ColdInd_{j,t} \geq \begin{cases} 1, & t = 1 \\ Active_{j,t} - Active_{j,t-1}, & t \neq 1 \end{cases} \tag{21}$$

3.5.1.3 Preprocessing

The following restrictions and calculations are processed prior to the actual optimization run as they do not include variables. This reduces simulation time and the complexity of the model itself. The calculations (22) and (23) prepare input parameters so they can be directly used in the model and (24) is a protection to avoid infeasible input data.

$$p_{th,min_j} = Cap_j \cdot f_{th,min_j} \tag{22}$$

$$CapNom_j = \begin{cases} Cap_j, & \forall\, j \notin heat\ pump \\ Cap_j \cdot COP_{nom_j}, & \forall\, j \in heat\ pump \end{cases} \tag{23}$$

$$mr_j = \begin{cases} 0, & mr_j < f_{th,min_j} \\ mr_j, & mr_j \geq f_{th,min_j} \end{cases} \tag{24}$$

The curtailment of heat pump output power because of environmental factors like source temperatures is a major topic of this theses and represented in the model by the calculations

(25) and (26). By using a heat pump restriction factor like this, the power fade-out and shutdown at low source temperatures can be realized as described in chapter 3.2.2.

$$HPRF_{j,t} = \begin{cases} 0, & \vartheta_{s_{j,t}} < \vartheta_{s,min_j} \\ \left(\vartheta_{s_{j,t}} - \vartheta_{s,min_j}\right) / \left(\vartheta_{s,fo_j} - \vartheta_{s_{j,t}}\right), & \vartheta_{s,min_j} \leq \vartheta_{s_{j,t}} < \vartheta_{s,fo_j} \\ 1, & \vartheta_{s_{j,t}} \geq \vartheta_{s,fo_j} \end{cases} \quad (25)$$
$$\forall\, j \in \{wastewater\ heat\ pump, river\ water\ heat\ pump, air\ heat\ pump\}$$

$$HPRF_{j,t} = \begin{cases} 0, & HPRF_{j,t} \leq f_{th,min_j} \\ HPRF_{j,t}, & HPRF_{j,t} > f_{th,min_j} \end{cases} \quad (26)$$
$$\forall\, j \in \{wastewater\ heat\ pump, river\ water\ heat\ pump, air\ heat\ pump\}$$

Another heat pump specific functionality is the variable COP, which is dependent on source, flow and return temperatures. In equation (27) three factors are added to the nominal COP which represent the linear dependencies on these temperatures. For industrial excess heat source heat pumps the source temperature is assumed to be constant and therefore not tackled in (28).

$$\eta_{th_{j,t}} = COP_{nom_j} + s_{COP,source_j} \cdot \left(\vartheta_{s_{j,t}} - \vartheta_{s,nom_j}\right) + s_{COP,flow_j} \cdot \left(\vartheta_{f_{j,t}} - \vartheta_{f,nom_j}\right) + s_{COP,return_j} \cdot \left(\vartheta_{r_{j,t}} - \vartheta_{r,nom_j}\right) \quad (27)$$
$$\forall\, j \in \{wastewater\ heat\ pump, river\ water\ heat\ pump, air\ heat\ pump\}$$

$$\eta_{th_{j,t}} = COP_{nom_j} + s_{COP,flow_j} \cdot \left(\vartheta_{f_{j,t}} - \vartheta_{f,nom_j}\right) + s_{COP,return_j} \cdot \left(\vartheta_{r_{j,t}} - \vartheta_{r,nom_j}\right) \quad (28)$$
$$\forall\, j \in \{industrial\ wasteheat\ heat\ pump\}$$

3.5.2 Solver Configuration

The configuration of the MIP gap is a tradeoff between solution accuracy and calculation time. For this model and all conducted calculations, the MIP gap is set to a value of 0.01 which ensures that the resulting feasible integer solution is within 1% of optimal. Computation times including preprocessing, solving and resolving after fixing the binaries vary between two minutes for the shortest and about three hours for the longest. There is no obvious correlation between the number of generators in the system and the computation duration. Only the implementation of energy storage has a significant impact on this value. The solver was configured to run on 6 threads on a PC equipped with a six-core, 3.8 GHz AMD CPU.

4 Results

The role of this chapter is to present a large amount of numerical data generated during the 108 optimization model runs in a way that emphasizes important facts and correlations. With great attention to answering the research questions (chapter 1.2) appropriately, it is most important to make relevant comparisons and show the influence of certain parameters. In the first and central section 4.1, the steps towards a solution for the economic value of flexibility are made. Additionally to a listing of the plain result numbers, it is analyzed how they compose with the help of a sample scenario comparison. The impact of single parameters and indicators on the main result is briefly described in the following subchapters. Section 4.2 contains interesting side effects that occur when heat pumps differ in their operational behavior. This includes the effect on CO_2 emissions, full load hours, seasonal performance factors, and cold starts. As every portfolio is also tested without any P2H device, the value of flexibility can be judged with regard to the general value of heat pumps in Chapter 4.3. This also includes a comparison between the economics of flexible heat pumps and electric boilers in chapter 4.3.1.[23]

To make referencing and the description of certain scenarios easier and more compact, a labeling system is introduced for this chapter in Table 4.1. If in a diagram or a table the indication does not contain all five labels, it refers to an average value of all scenarios that are a possible combination within this indication (e.g.: C1_S_RWHP_inflex contains the 2016 and the 2030 model year scenarios).

Table 4.1 Scenario labeling system

C1_2016_S_RWHP_inflex

Base portfolio	Year	Storage	P2H extension	Operation mode
C1 – City 1	2016	S – yes	EB – Electric Boiler	flex
C2 – City 2	2030	NS – no	IEHHP – Industrial excess heat source heat pump	inflex
C3 – City 3			WWHP – Wastewater source heat pump	
V1 – Village 1			RWHP – River water source heat pump	
			AHP – Air source heat pump	

[23] Every conclusion and assumption in the results chapter is purely based on the results of the used model. As the model itself and parts of the input data are only a simplification of real world action, the satements made in this context do not claim general validity.

4.1 The economic value of flexibility

For the most part of this work, it is the goal to draw clear distinctions between flexible and inflexible operated heat pumps. In this chapter, the final economic effect of these distinctions in operation is evaluated. The following calculations are based on the model data and variables of Chapter 3.5.1 and some specific variables which are defined in Table 4.2.

Table 4.2 Definition of result variables

Variable	Type	Description	Unit
TC	$\in \mathbb{R}$	Annual total cost of heat production (revenues included)	€
$C_{h,level}$	$\in \mathbb{R}$	Levelized cost of heat per MWh	$€/MWh$
VF_{abs}	$\in \mathbb{R}$	The absolute value of flexibility	€
VF_{rel}	$\in \mathbb{R}$	The relative value of flexibility	%
VF	$\in \mathbb{R}$	Value of flexibility per MWh of heat	$€/MWh$

The newly defined total cost variable (29) contains exactly the value that has been minimized in the objective function (1). To make this cost figure comparable between different portfolios, the levelized cost of heat is calculated by dividing it through the annual heat demand of the DH system (30). This medium heat price is one of the most important result figures for a scenario and is used throughout the whole Chapter 4.

$$TC = c_{total} - rev_{total} \tag{29}$$

$$C_{h,level} = \frac{TC}{\sum_t demand_{th_t}} \tag{30}$$

The absolute economic value of flexibility is defined as the difference in the total cost of heat production between a scenario with a flexibly operated heat pump and the same scenario with an inflexibly operated heat pump (31). To create more comparable indicators, in Formula (32) this difference is divided through the total costs of the inflexible scenario to get the relative effect of flexibility VF_{rel}. Most meaningful for comparison is the energy-based value of flexibility VF which is calculated by dividing the absolute value through the total energy demand of the DH system (33).

$$VF_{abs} = TC_{inflex} - TC_{flex} \tag{31}$$

$$VF_{rel} = \frac{VF_{abs}}{TC_{inflex}} \tag{32}$$

$$VF = \frac{VF_{abs}}{\sum_t demand_{th_t}} \tag{33}$$

All results of these calculations are collected in Table 4.3, which forms one of the main achievements of this work and is the basis for many analyses and diagrams within the following chapters.

Table 4.3 Individual results on the value of flexibility for all 40[24] possible comparisons.

Scenario	VF_{abs} [M €]	VF_{rel} [%]	VF [€/MWh]
C1_2016_NS_IEHHP	0.973	2.37	0.88
C1_2016_S_IEHHP	1.006	2.55	0.91
C1_2016_ NS_RWHP	1.302	3.13	1.18
C1_2016_S_RWHP	1.272	3.17	1.16
C1_2016_ NS_WWHP	1.523	3.66	1.38
C1_2016_S_WWHP	1.510	3.76	1.37
C1_2030_ NS_IEHHP	2.116	4.50	1.92
C1_2030_S_IEHHP	2.217	5.12	2.02
C1_2030_ NS_RWHP	2.295	4.78	2.09
C1_2030_S_RWHP	2.726	6.15	2.48
C1_2030_ NS_WWHP	2.667	5.57	2.42
C1_2030_S_WWHP	3.117	7.04	2.83
C2_2016_ NS_IEHHP	0.556	1.69	0.62
C2_2016_S_IEHHP	0.484	1.53	0.54
C2_2016_ NS_RWHP	0.632	1.88	0.71
C2_2016_S_RWHP	0.624	1.93	0.7
C2_2016_ NS_WWHP	0.793	2.37	0.89
C2_2016_S_WWHP	0.753	2.35	0.85
C2_2030_ NS_IEHHP	1.448	3.82	1.63
C2_2030_S_IEHHP	1.646	4.88	1.85
C2_2030_ NS_RWHP	1.395	3.57	1.57
C2_2030_S_RWHP	1.907	5.45	2.14
C2_2030_ NS_WWHP	1.773	4.60	1.99
C2_2030_S_WWHP	2.194	6.37	2.47
C3_2016_ NS_IEHHP	0.472	8.17	2.62
C3_2016_S_IEHHP	0.739	13.20	4.11
C3_2016_ NS_RWHP	0.312	5.05	1.74
C3_2016_S_RWHP	0.544	9.19	3.02
C3_2016_ NS_WWHP	0.537	9.29	2.98
C3_2016_S_WWHP	0.699	12.69	3.88
C3_2030_ NS_IEHHP	1.284	18.91	7.13
C3_2030_S_IEHHP	2.265	36.15	12.58
C3_2030_ NS_RWHP	1.056	13.92	5.87
C3_2030_S_RWHP	1.836	27.19	10.20
C3_2030_ NS_WWHP	1.460	21.26	8.11
C3_2030_S_WWHP	2.207	35.83	12.26
Scenario	VF_{abs} [k €]	VF_{rel} [%]	VF [€/MWh]
V1_2016_ NS_AHP	11.991	1.67	0.71
V1_2016_S_AHP	11.927	1.61	0.70
V1_2030_ NS_AHP	16.034	1.85	0.94
V1_2030_S_AHP	19.510	2.20	1.15

[24] Only 80 of the 108 scenarios include heat pumps. 40 of them flexible and 40 inflexible. This results in 40 possible comparisons between them.

4.1.1 A showcase for result comparison

To get a better understanding of where the difference in total cost between flexible and inflexible operated heat pumps origins from, two sample scenarios are compared in this chapter. As it is not intended to do such a detailed analysis for every scenario it is conducted once for the scenarios C2_2030_NS_RWHP_flex and C2_2030_NS_RWHP_inflex to show the process. These sample scenarios were chosen as the resulting value of flexibility is average-sized and they offer easy to see differences. The use of scenarios without heat storage further simplifies depictions. For all remaining scenarios, just the numerical results are treated in the following chapters.

With a fist look at the two annual power generation curves in Fig. 4.1 and Fig. 4.2 obvious distinctions in heat pump operation can be noticed. In the scenario C2_2030_NS_RWHP_flex the heat pumps part-load capability allows it to also partly operate in colder winter times ($t < 2000$ and $t > 7600$) compared to the inflexible heat pump. This, however, does not increase the total amount of operating hours as the operation is generally more volatile throughout the year. Fig. 4.2 clearly shows the effect of the must-run constraint for inflexible operation.

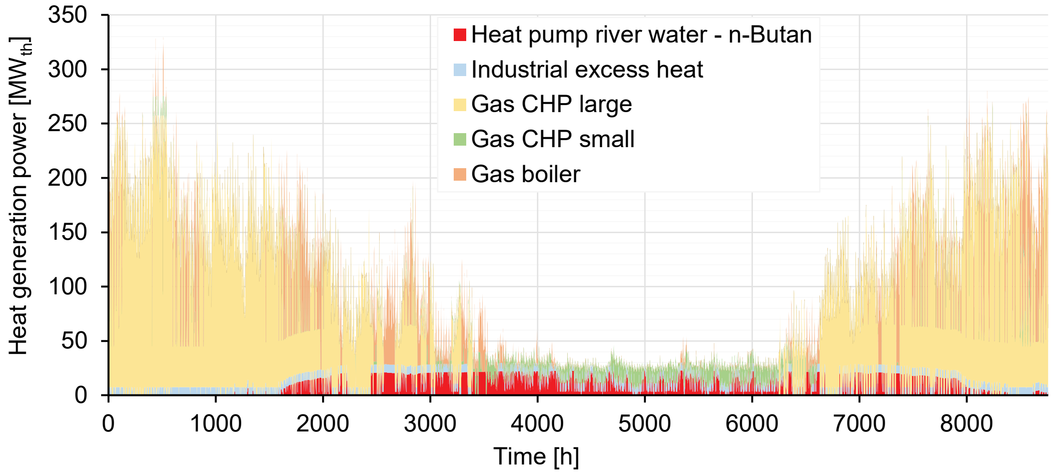

Fig. 4.1 Annual curve of the generation power in scenario C2_2030_NS_RWHP_flex

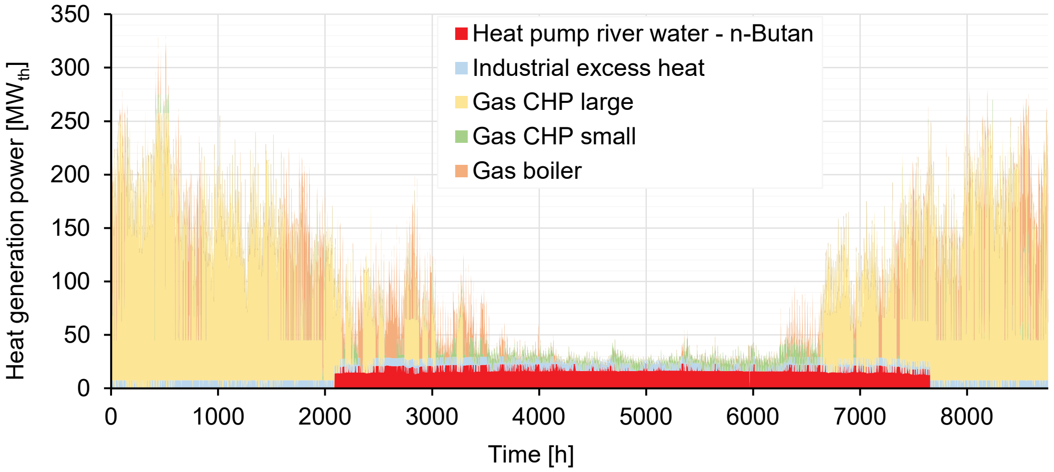

Fig. 4.2 Annual curve of the generation power in scenario C2_2030_NS_RWHP_inflex

The situation between hour 4000 and 6000 in Fig. 4.1 where heat pump operation is particularly volatile looks related to the fact, that has already been outlined in Fig. 3.1. Unlike the assumption that heat pumps only get displaced by renewables and baseload generators in the summer month, also a competition with small gas CHP plants in this scenario can be recognized. Even further, it is to be expected that making this competition with CHP plants possible, is the key factor for generating economic benefits with flexibility.

The example comparison gives the opportunity to exactly show where the reduction in total cost for flexible operation origins from. Mainly it can be divided into two parts with one part being the reduced cost for fuel and electricity. The other part is caused by gas CHP units generating higher revenues by producing and selling more electricity on the market. This additional CHP operation is allowed as a flexible heat pump can better reduce its output power or be shut-off in high electricity price situations. Fig. 4.3 shows this situation for the two sample scenarios in a more detailed way. By adding up the cost differences with correct signs[25] it results in a cost reduction of 1.395 M€. This resembles exactly the total value of flexibility for these scenarios (see Table 4.3). The reduced electricity cost for flexible heat pump operation is not only achieved by a lower consumption because the heat pump simply runs less frequently. Comparing the two price duration curves for electricity prices during the heat pump operation in Fig. 4.4 shows that the flexible heat pump generally runs in periods with lower electricity prices which makes out a large part of the savings.

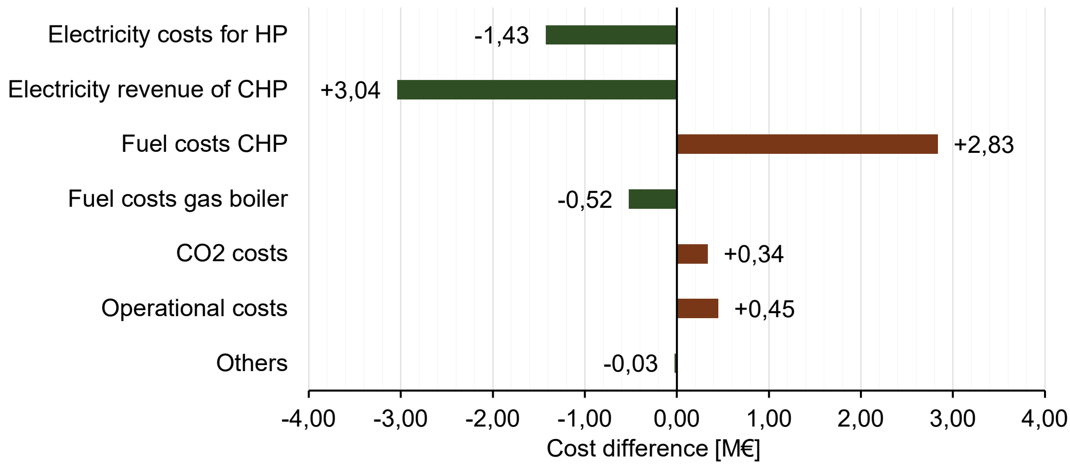

Fig. 4.3 Difference of the cost structure between the scenario C2_2030_NS_RWHP_flex and the scenario C2_2030_NS_RWHP_inflex[26]

[25] The difference in electricity revenue for CHP power plants is positive but counts negative for the difference in total cost (see Formula (29)).
[26] The difference in operational costs does also include the change of ramping and cold start costs for every heat producer in the DH system.

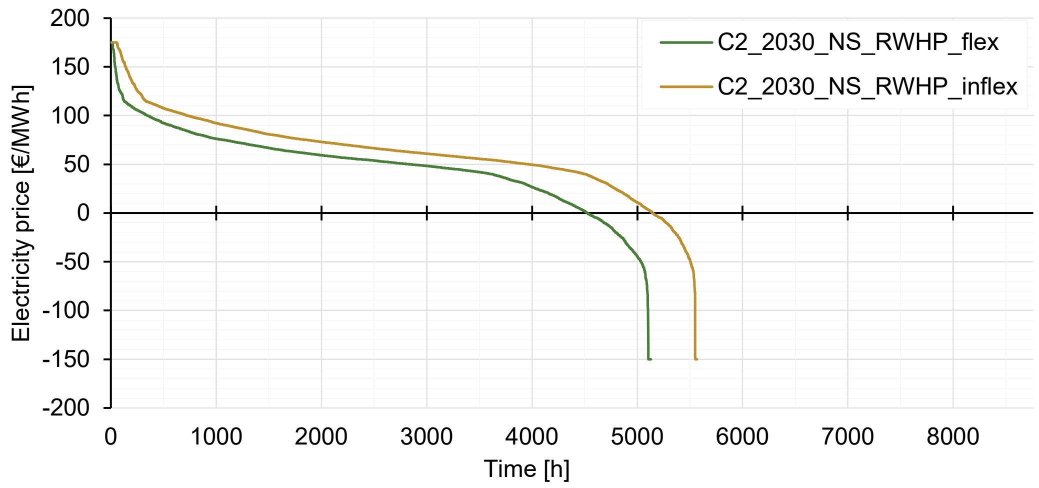

Fig. 4.4 Electricity Price duration curve for the operational hours of the heat pumps

4.1.2 Portfolio-based differences

The widely different characteristics of the four main portfolios induce differences in heat pump operation between the respective scenarios. Subsequently, also the economic value of flexibility shows distinctions. Based on the individual results which are partly shown in Fig. 4.5, the most iconic properties of every portfolio are treated within the upcoming sub-chapters.

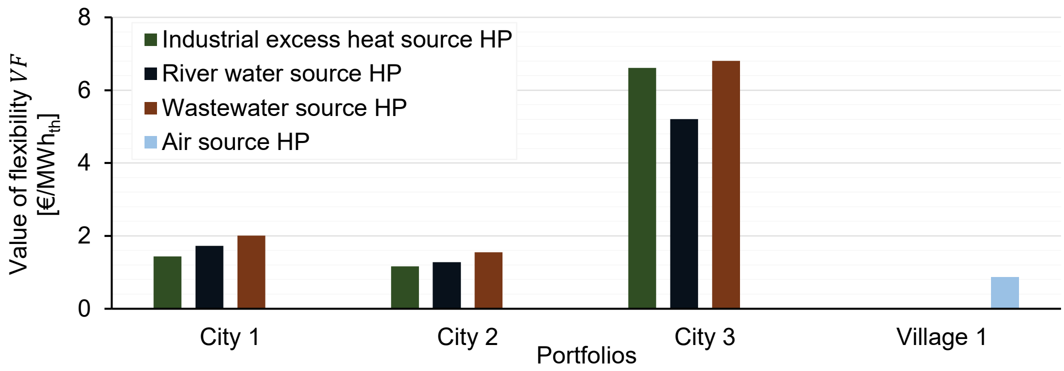

Fig. 4.5 The average value of flexibility for all low-temperature heat sources within the base portfolios

4.1.2.1 City 1 vs. City 2 - Conventional generators and must run conditions

With City 1 and City 2 scenarios being the most comparable ones, as their biggest distinction is the presence of a waste incineration plant with a must run constraint in City 1. The direct comparison of the load duration curves of the scenarios C1_ 2030_NS_ RWHP_flex (Fig. 4.6) and C2_ 2030_NS_RWHP_flex (Fig. 4.7) shows that the predicted displacement effect (see 3.1.4) really exists. In the City 1 scenario, the flexible heat pump gets almost completely pushed back in the hours between 6000 and 7000 and is partly curtailed from hour 7000 upwards. Also noticeable is that the higher river temperatures for the City 1 scenario lead to more prominent use of the river water source heat pump in the high demand season. This effect, however, cannot outweigh the lost full load hours during the summer month and so the heat pump in the City 2 scenario reaches 1186 full load hours more (+ 38 %[27]). Furthermore,

[27] Based on the 3151 full load hours in the City 2 case.

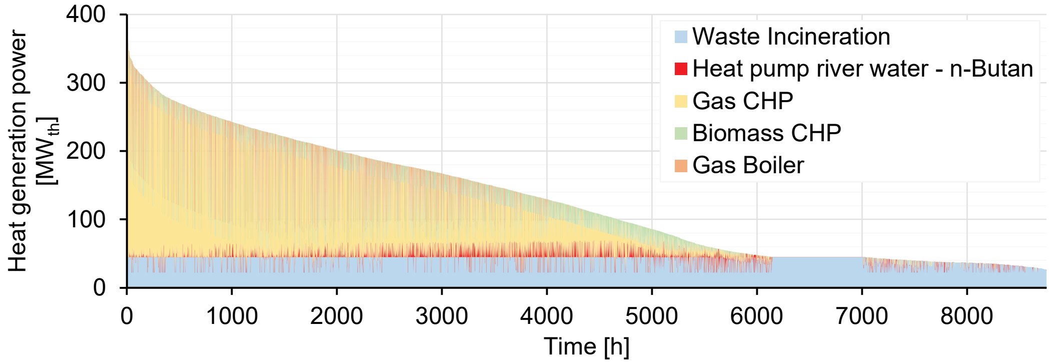

Fig. 4.6 Load duration curve of the scenario C1_ 2030_NS_RWHP_flex

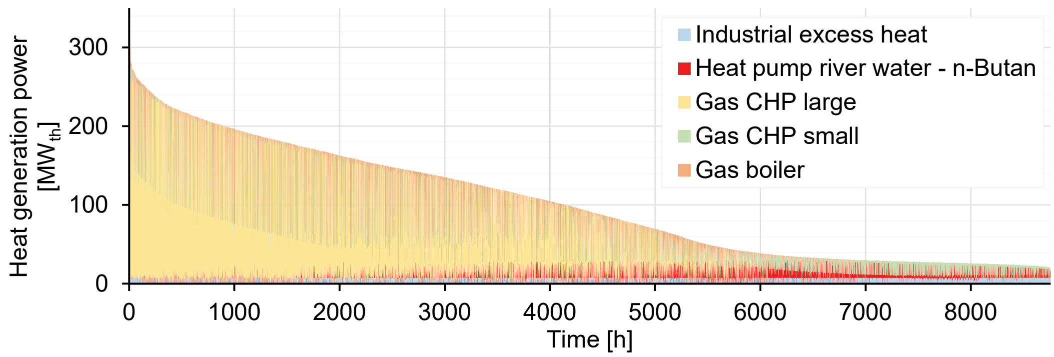

Fig. 4.7 Load duration curve of the scenario C2 _2030_NS_RWHP _flex

the numbers of full load hours for flexible and inflexible scenarios are closer together amongst the City 2 scenarios. This goes hand in hand with the fact that the value of flexibility is lower in comparison to the City 1 scenarios. The assumption introduced in Chapter 3.3.2 that a baseload generator in a must run condition might affect the value of flexibility negatively could not be validated. To confirm the initial assumption the exact opposite behavior would be required.

4.1.2.2 City 3 - The relative size of the heat pump

The results of the City 3 scenarios show that the value of flexibility is highly dependent on the relative size of the heat pump compared to the total demand of a DH system. As in this portfolio, the heat pump is nominally capable of delivering nearly half of the maximum thermal power demand, the general influence on the generation mix and the value of flexibility are accordingly high. These effects, however, do not scale linearly with the relative size of the heat pump. Compared to the City 1 and City 2 portfolios the heat pump in the City 3 portfolio is about nine times oversized but the value of flexibility only increases by a factor of around three. This seems to originate from a saturation effect where the heat pump can already supply the total heat demand in every moment when it is the most economical source. Fig. 4.8 shows the load curve of a City 3 scenario where this saturation effect occurs. Even if the heat pump would be more powerful, the energy output would not significantly rise and neither would the value of flexibility. The exact correlation between the relative size and the value of flexibility may be of further interest in a follow-up study, as larger heat pump shares

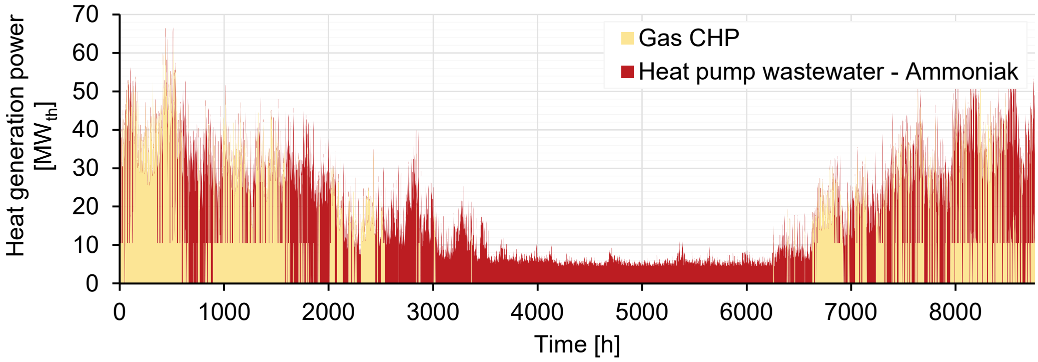

Fig. 4.8 Annual curve of the generation power in scenario C3_2030_NS_WWHP_flex

are expected for future DH systems [8]. A noticeable effect showing in Fig. 4.5 is that river water source heat pumps profit less from flexible operation compared to other heat sources when the relative size of the heat pump increases. The beforementioned saturation effect is more prominent for heat pumps with this heat source. One reason for this is that the operation is more concentrated in the low demand summer times as due to the high source temperature spread, also the COP changes a fair amount throughout the year. The modeled river water source heat pump also is not available during the days with the highest demand. In the warmer times of the year, a smaller heat pump is able to deliver the complete demand. Therefore, it does not profit as much from being more powerful.

4.1.2.3 Village 1-A system without electricity producers

The Village 1 portfolio with its air source heat pump is an isolated experiment and is not directly comparable with other scenarios or heat sources. The air heat pump in all Village 1 scenarios shows a very high amount of operating and full load hours and often allows heat pump only supply during the warm season. Most interesting is that this portfolio shows the smallest economic value of flexibility compared to the three city portfolios. This can be explained by referring to Chapter 4.1.1 where it is shown that a large part of the value of flexibility is contributed by the increased revenue of CHP plants. As there is no electricity-producing heat generator in these scenarios the results for flexible and inflexible operation are closer to each other and the value of flexibility is reduced. This shows once more the heavy dependency on CHP generators when flexibility generates economic value.

4.1.3 The influence of heat sources and coolants

The coolant which is used in the heat pump and the available low-temperature heat source ultimately have an effect on two parameters. The COP (which is important for the seasonal performance factor (see chapter 4.2.3)) is dependent on the coolant and the source, whereas the amount of possible operating hours is affected by the characteristics of just the heat source. Both parameters can change how valuable flexibility in heat pump operation is. A glance at Fig. 4.5 shows that wastewater source heat pumps profit most from a flexible operation, with the follow-up ranking being not so obvious. Intense studies of all available numbers lead to the assumption that a high COP has a negative influence on the value of flexibility and that a high number of possible operating hours has a positive influence on the value of flexibility. Both influences are in addition sensitive to the maximum power capacity of the heat pump in relation to the maximum power demand of the system. To verify and quantify these effects additional scenarios would be necessary which could be part of a continuative study.

4.1.4 The impact of a heat storage system

As every single scenario is optimized with and without optional heat storage, it is possible to evaluate the effect of these storages. In City 1 and City 2 scenarios for the year 2016, the economic benefit of heat storage systems is mainly independent of if the heat pump is flexible or inflexible. As Fig. 4.9 shows, the general impact of storage systems on the total cost is more substantial for the model year 2030. For these future scenarios, the flexible use of heat pumps obviously contributes to a higher financial value of heat storages and vice versa heat storages increase the effect of flexibility. Except for the Village 1 scenarios, the production setup with the lowest total cost always features a combination of a flexible heat pump and a heat storage system. This shows the clear superiority of this combination in terms of the total cost (investment not included), especially in the City 3 scenarios as they have the highest heat pump production share. Only in the Village 1 scenarios, heat storages do not reduce the total costs because the assumed operational and maintenance costs for a storage system overwhelm the achievable fuel savings. For all scenarios of City 1 and 2, the financial benefit of heat storage is interestingly very close to the financial benefit of a flexible heat pump operation. It can be stated for these two portfolios, that a storage system almost exactly doubles the value of flexibility and vice versa.

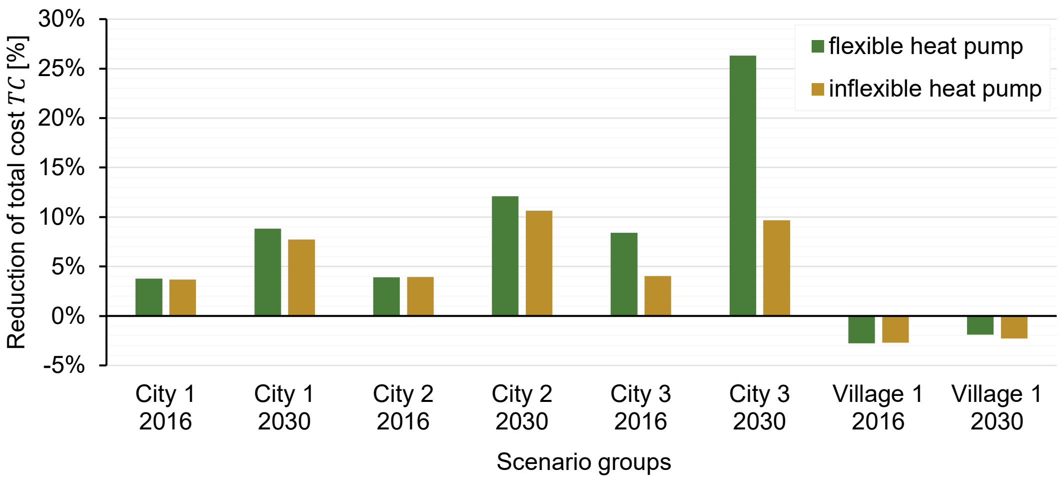

Fig. 4.9 Reduction of total cost caused by the use of heat storages[28]

4.1.5 The influence of the model year

The model year has a large effect on the DH costs in general and also on the value of flexibility. A comparison of these indicators for both model years can be seen in Fig. 4.10. The average cost for 1 MWh of heat shows an increase of about 10 % for scenarios of the City 1 and City 2 portfolios when comparing the model year 2030 with 2016. This value varies only slightly across all sub scenarios and seems therefore to be a solid indicator for the heat price increase. By comparing the numbers of portfolios City 3 and Village 1 in Fig. 4.10 and Fig. 4.11 an inverse correlation between the value of flexibility and the heat price increase in 2030 can be found. Even though the fuel cost increases for both portfolios identically, the larger share of heat pump generation allows City 3 scenarios to have the lowest price increase in the 2030 model year. This is especially true for flexible scenarios with storage. In opposition, the

[28] The displayed values are the average values of all scenarios included in the scenario groups

Village 1 portfolio does not profit as much from the flexibility and further has the highest price increase in the more volatile 2030 scenarios.

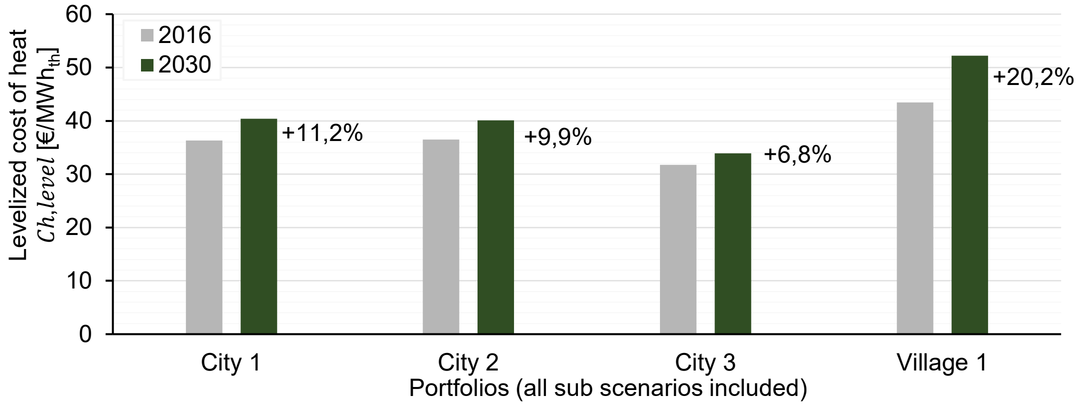

Fig. 4.10 Comparison of the average levelized cost of heat for every portfolio and the model years 2016 and 2030 (the percentages represent the increase from 2016 to 2030)

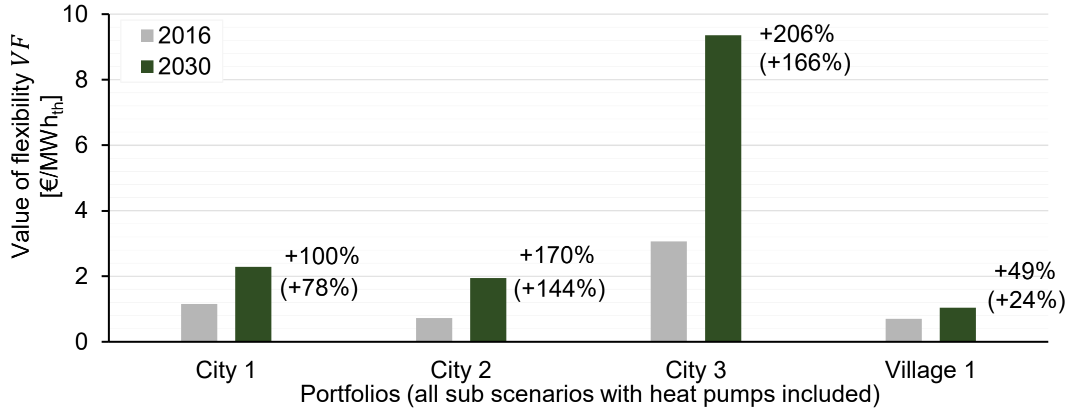

Fig. 4.11 Comparison of the average value of flexibility for every portfolio and the model years 2016 and 2030 (the percentages represent the absolute increase, the percentages in brackets represent the relative increase[29])

4.2 Side effects of flexibility

Besides the abovementioned economic influences of a flexible heat pump operation, some interesting side effects can be observed. Most significant is the assessment of CO_2 emissions. followed by operational statistics like full load hours, seasonal performance factors and cold start counts.

4.2.1 CO_2 emissions

Given that the flexible operation of heat pumps is primarily motivated by decarbonization efforts as explained in the introductory chapters, the effect of flexibility on the CO_2 emissions is of high interest. The whole topic gets even more interesting as the simulation results show that a flexible heat pump operation increases the total CO_2 footprint of a DH system, for some

[29] The relative increase is more significant as it takes the general heat price increase (Fig. 4.2) into account.

scenarios by more than 100 % in comparison to the use of an inflexible heat pump. For further evaluation of this topic, a set of new variables is defined in Table 4.4 which are used in the following calculations.

Table 4.4 Definition of variables for the emission calculations

Variable	Type	Description	Unit
Em_{tot}	$\in \mathbb{R}$	Total annual CO_2 emissions by the DH system	t_{CO_2}
Em_{heat}	$\in \mathbb{R}$	Annual CO_2 emissions caused by heat production	t_{CO_2}
$Em_{electricity}$	$\in \mathbb{R}$	Annual CO_2 emissions caused by electricity production	t_{CO_2}
$\Delta Em_{heat,abs}$	$\in \mathbb{R}$	Absolute difference between flexible and inflexible heat pump scenarios in CO_2 emissions caused by heat production	t_{CO_2}
$Em_{heat,lvl}$	$\in \mathbb{R}$	Levelized CO_2 emissions caused by heat production	t_{CO_2}/MWh
$\Delta Em_{heat,rel}$	$\in \mathbb{R}$	Relative difference between flexible and inflexible heat pump scenarios in CO_2 emissions caused by heat production	%

Every CHP generator produces heat and electricity simultaneously which is ensured within the model by constraint (9). This conversion of primary energy into two different secondary energy types demands for correct accounting of CO_2 emissions. Formula (34) and (35) ensure this separation of emissions so that every share can be viewed individually. To keep the analyses of the scenarios' emissions isolated from outside influences mostly the heat-based emissions are examined. In this chapter, the difference in emissions between flexible and inflexible heat pump scenarios (36, 37) is focused whereas the levelized and total emissions (38, 39) are treated in chapter 4.3.

$$Em_{heat} = \sum_{j,t} \frac{x_{th_{j,t}} \cdot f_{em_{ec_j}}}{\eta_{th_{j,t}} + \eta_{el_j}} \tag{34}$$

$$Em_{electricity} = \sum_{j,t} \frac{x_{el_{j,t}} \cdot f_{em_{ec_j}}}{\eta_{th_{j,t}} + \eta_{el_j}} \tag{35}$$

$$\Delta Em_{heat,abs} = Em_{heat_{flex}} - Em_{heat_{inflex}} \tag{36}$$

$$\Delta Em_{heat,rel} = \frac{\Delta Em_{heat,abs}}{Em_{heat_{inflex}}} \tag{37}$$

$$Em_{heat,lvl} = \frac{Em_{heat}}{\sum_t demand_{th_t}} \tag{38}$$

$$Em_{tot} = Em_{heat} + Em_{electricity} \tag{39}$$

The initial environmental idea is that flexible heat pumps run in times of low electricity prices, additionally, store this lower price (and lower CO_2 emitting) energy and therefore partly prohibit the use of natural gas or other fossil energy carriers. This effect exists but is overrun by the increased use of CHP plants during high electricity price situations as it is shown in chapter 4.1.1. Even in City 3 scenarios which have the most capable P2H share within their generation portfolio, the increased[30] substitution of fossils does not take place with flexible heat pumps. Fig. 4.12 shows this adverse fact for flexible heat pump operation for the model year 2016 and 2030.

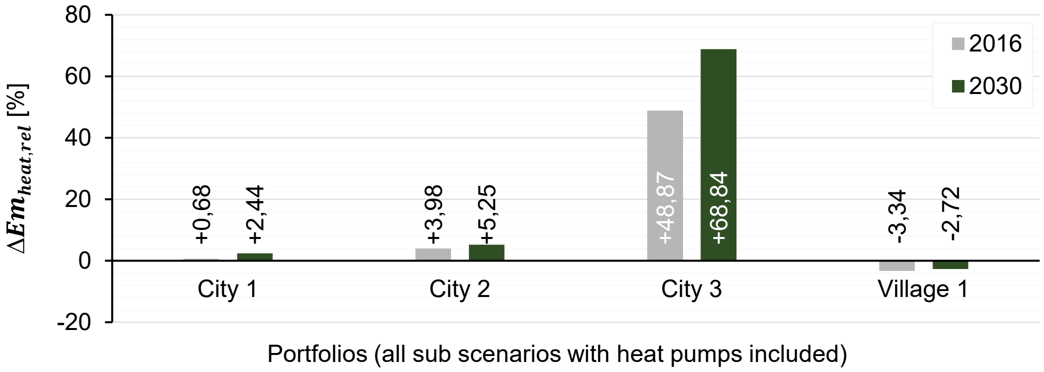

Fig. 4.12 Relative effect of flexible heat pump use on the heat-related CO_2 emissions of the DH systems compared to inflexible heat pumps

If the dispatch procedure is purely based on economics, flexibility alone will not improve, but worsen the CO_2 footprint of the heat generation in comparison to the use of an inflexible heat pump. For the year 2030 where the CO_2 allowances price is already more than three times higher than in 2016 this effect even rises. It can be seen that these increased penalties for CO_2 output have no sufficient impact to change the results towards lower emissions for flexible heat pumps. However, it has to be noted that this only encounters the CO_2 share for the heat energy used within the DH system. Another significant amount of CO_2 is emitted for the electricity that is fed into the electricity market. In a case where this electricity curtails the generation in other power plants that would have a higher specific CO_2 emission (e.g. lignite or coal) the overall emissions could even be reduced. This yet depends on the current market situation and electricity mix. Especially as the economic value of flexibility does exist, it is important to understand that the higher flexibility potential will probably counteract decarbonization efforts if the dispatch procedure does not also respect the recent electricity mix.

To some extent, these results for CO_2 emissions may be caused by a slight shortcoming in the optimization model. The electric generation mix and therefore also the specific CO_2 emission factor of the imported electricity for heat pump operation is assumed to be constant, whereas, in reality, this value is variable throughout the year. It can be assumed, that the inclusion of this variation in future research might result in a lower CO_2 footprint for DH systems with flexible heat pumps. This assumption is based on the idea that in times where much renewable electric energy is available the market price drops, and flexible heat pumps get activated.

Flexible heat pump operation only shows a positive effect on the CO_2 emissions for Village 1 scenarios. However, it must be considered that the CO_2 output of a biomass boiler is almost purely renewable and any heat pump which uses nonrenewable electricity shares worsens the emissions situation. The flexible heat pump therefore only makes this already bad situation

[30] With the exclusion of Village 1 scenarios, any heat pump (regardless if flexible or inflexible) reduces the use of fossils and the CO_2 output (see chapter 4.3). This is a comparison between scenarios with flexible and scenarios with inflexible heat pumps and does not represent the gerneal impact of heat pumps.

slightly better but cannot compete with a pure biomass portfolio in terms of CO_2 emissions (see Chapter 4.3).

4.2.2 Full load hours

The different numbers of full load hours and operation hours for flexible and inflexible heat pumps are mainly caused by two facts. On the one hand, a flexible heat pump technically allows more operation hours. On the other hand, inflexible heat pumps are constrained by a "must-run if possible" restriction. As expected, the second effect outweighs the first one and so the annual full load hours are higher for scenarios with inflexible heat pumps. Fig. 4.13 does not only show that operation and full load hours are higher for inflexible operation, but it also shows that the relative difference between these two indicators is generally smaller for those scenarios. With other words, flexible heat pumps run on average at a lower output power. The percentage values in Fig. 4.13, which can be interpreted as the average output power, quantify this effect. According to the numbers it is assumed that a smaller heat pump (in relation to the maximum power demand of the DH system) in average runs closer to its maximum output power.

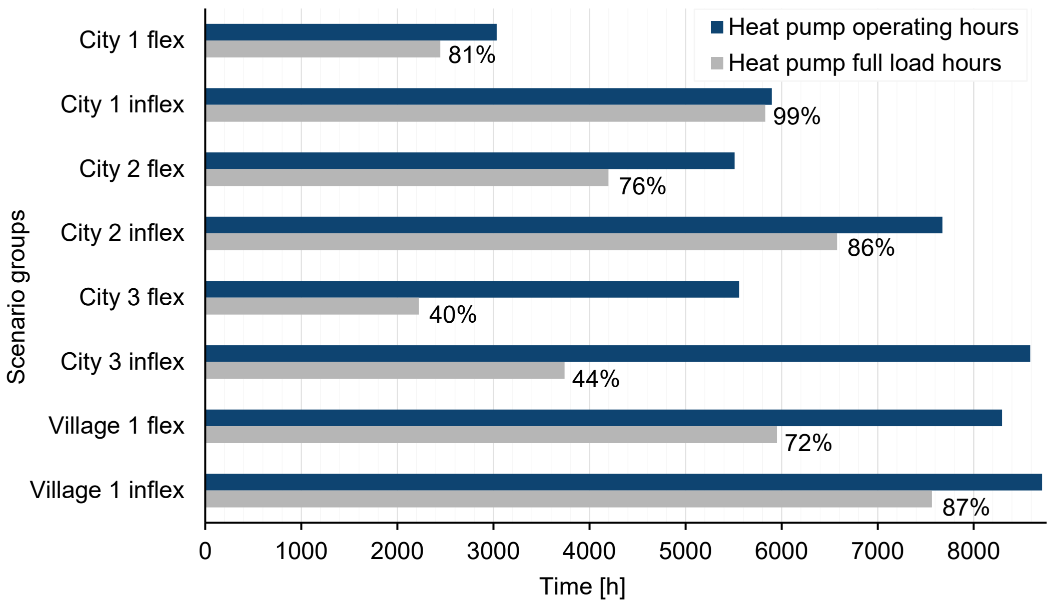

Fig. 4.13 Comparison of average annual operating and full load hours for flexible and inflexible scenarios of the four main portfolios. The percentage values show the relationship between the two values for every scenario group.

4.2.3 Seasonal Performance Factor

The Seasonal Performance Factor (SPF) is defined here as the relationship between the annual electric input energy and the annual thermal output energy. This can be interpreted as the average value of the COP at which a heat pump operates throughout the year and is mostly influenced by the technical properties, source, and system temperatures. The mean values for the SPFs of the main portfolios are displayed in Fig. 4.14 and show a tendency that the SPF is higher for systems with lower flow temperatures. Flexibility generally only has a very slight influence on these values. These small distinctions are caused by different sensitivities of the COP on source and system temperatures and different operation times. For City 1 and City 2 scenarios the more prominent use of flexible heat pumps in the colder seasons ultimately leads to a lower SPF for flexible operation. For the scenarios of the two remaining portfolios, a flexible heat pump use leads to a slight increase of the SPF.

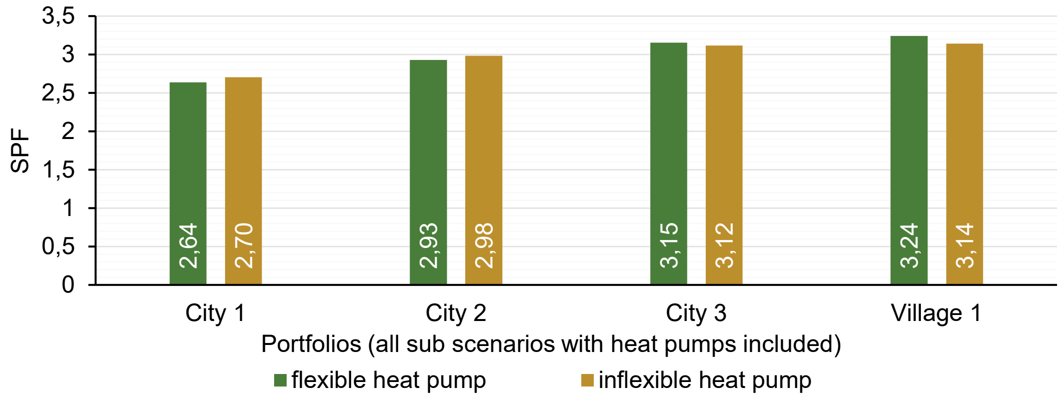

Fig. 4.14 Seasonal performance factor (SPF) of flexibly operated heat pumps in comparison to inflexibly operated heat pumps

4.2.4 Cold starts

To estimate the potential wear and tear on the components of heat pumps and their subsystems, the number of cold starts[31] per year is used as an indicator. As expected, flexible heat pumps show a highly increased number of starts compared to inflexible heat pumps (Fig. 4.15). Noteworthy is also the high number of cold starts for inflexible heat pumps in City 1 scenarios. This originates from the competition of the heat pump with the waste incineration plant, which leads to a lot of operation intermittencies in low load situations. City 2 scenarios, in contrast, do not show this behavior, as the heat pump is not competing with a conventional generator in a must run state. The Village 1 portfolio forms an exception as it shows a higher number of cold starts for inflexible heat pumps. The lower possible minimum output power in the flexible cases allows the air heat pump to continue operation in situations where the inflexible heat pump has to be shut off because the available demand is to low.

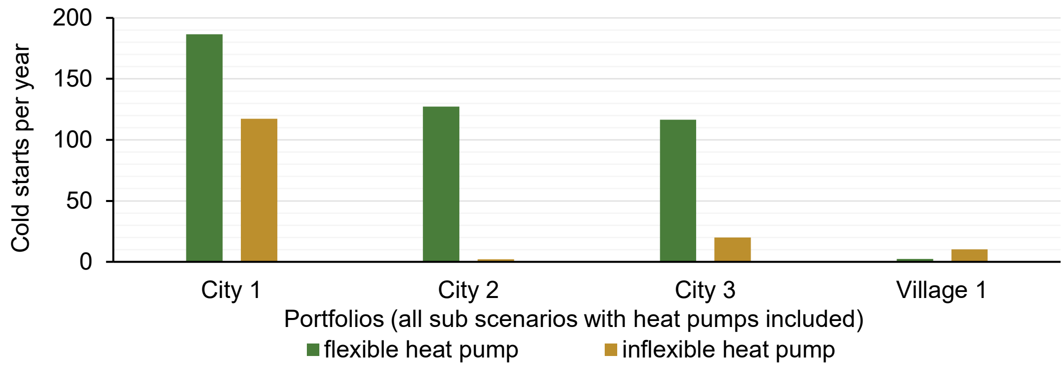

Fig. 4.15 Number of cold starts per year for flexibly operated heat pumps in comparison to inflexibly operated heat pumps

[31] In this context the term cold start refers to a initial start up at any temperature and not only to a cold start in the conventional meaning. This vagueness is accepted to avoid the effort of differenciating between more cases within the model definition.

The most extreme values are shown by the scenario C3_2016_S_WWHP_inflex with a single startup per year and the scenario C1_2030_NS_IEHHP_flex with 267 startups per year. Overall, this wide range of numbers gives an idea of how much the strain on heat pumps differs for different operation types and portfolio characteristics.

4.3 The general economic impact of heat pumps

The possibility to compare every heat pump scenario to the base portfolio without a P2H device or to the base portfolio with an electric boiler allows for further judgments on flexibility and heat pumps in general. First of all, the information provided in Fig. 4.16 shows us that the use of a heat pump does not automatically cause a decrease in average cost (even without considering investments). Especially, for City 1 and City 2 scenarios the flexibility of the heat pump is the key for possible economic success. The typical heat price reduction for those two large city scenarios with the use of flexible heat pumps is 0.7 to 1.5 €/MWh.[32] Inflexible heat pumps, on the other hand, do not have clear economic benefits or even cause price increases. Once again, the relative size of the heat pump plays a large role in how big its influence is. The average heat price reduction in City 3 scenarios for the use of a flexible hat pump is as high as10 €/MWh which is a clear result of the large capacity share. Overall the numbers show that large scale hat pumps in DH systems are more likely to have a positive economic effect if they are capable of operating flexible according to the definitions in Chapter 3.

To estimate how much potential additional investment cost for flexible heat pumps would be acceptable, the annual value of flexibility is used as the annuity for a very rudimental investment calculation. For this the two sample scenarios (C2_2030_NS_RWHP_flex and C2_2030_NS_RWHP_inflex) from chapter 4.1.1 are used once more. As already shown, the flexible heat pump operation causes an annual cost reduction of 1.395 M€ in this comparison. With an estimated heat pump lifetime of 20 years and an annual interest rate of 2 %, this results in a possible additional investment of 22.8 M€. As the estimated nominal investment costs for

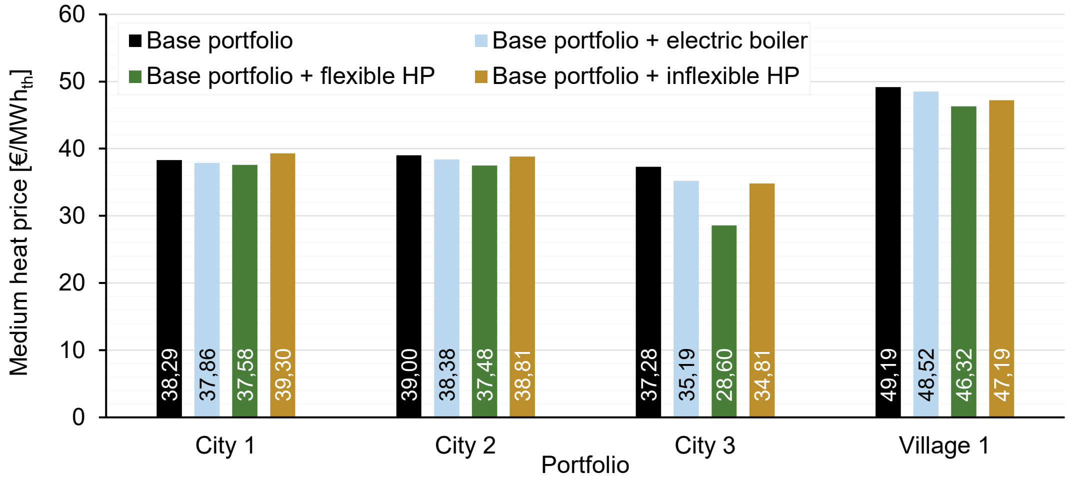

Fig. 4.16 Annual average heat price for portfolios with electric boilers, flexible and inflexible heat pumps compared to the existing conventional portfolios.

[32] In comparison to the existing portfolio without P2H device

a large-scale heat pump in the year 2030 are 0.59 M€/MW$_{th}$ [39] this is more than double what the complete 18 MW$_{th}$ heat pump might cost. Accordingly, it is very likely that the value of flexibility makes up for required additional investment and maintenance costs of a flexibly operated heat pump. To properly answer this question, tho, a complete financial analysis and more accurate investment estimations would be necessary.

Heat pumps do also have a consistently positive impact on the CO_2 emission of a DH system. Even though, the flexible heat pumps are not leading in this discipline (see Chapter 4.2.1), they allow CO_2 emissions reduction of 3.9 % and 8.3 % for the large city scenarios City 1 and City 2 and a reduction of 33.9 % for the fictional scenario City 3. Fig. 4.17 shows that the only exceptions are the Village 1 scenarios where the nonrenewable shares in the electricity mix cause a slight increase over the almost purely renewable biomass boilers emissions.

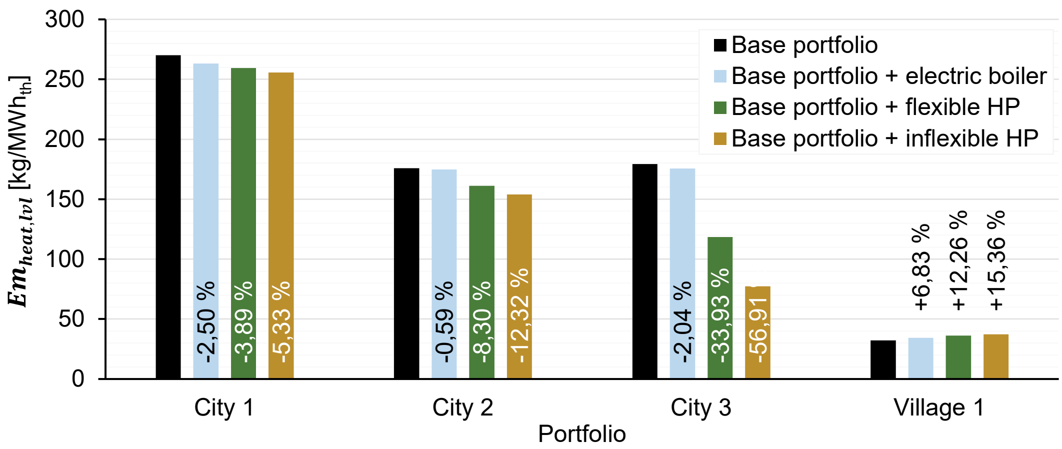

Fig. 4.17 Levelized heat-based CO_2 output of the DH system per MWh$_{th}$ for portfolios with electric boilers, flexible and inflexible heat pumps compared to the existing conventional portfolios. The percentages show the relative change in comparison to the corresponding base portfolio.

4.3.1 Flexible heat pumps in comparison to electric boilers

Throughout the majority of all scenarios with electric boilers, they have positive effects on economics and the CO_2 footprint of the DH system. Nevertheless, if they are compared to flexible heat pumps in Fig. 4.16 and Fig. 4.17 they lack behind in economic value and CO_2 emissions. This also shows in the lower number of achieved annual full load hours. In most scenarios with electric boilers, they gather between 100 and 1500 full load hours a year which is well within the expected range. In Fig. 4.18 additionally, it can be seen that in the year 2030 the electric boilers are used more compared to 2016 whereas flexible heat pumps even show a slight recess.

One of the main research questions in this thesis is if a flexible heat pump can outperform an electric boiler economically when used as a flexible P2H device. To answer this question entirely some follow-up research which includes actual investment cost estimations would be necessary. The results of this work, however, allow to state two main facts concerning electric boilers. Firstly, any of the tested heat pumps were able to outperform electric boilers of the same size economically and in terms of CO_2 emissions. [33] This was to be expected as they

[33] No investment costs considered. No balancing power market considered

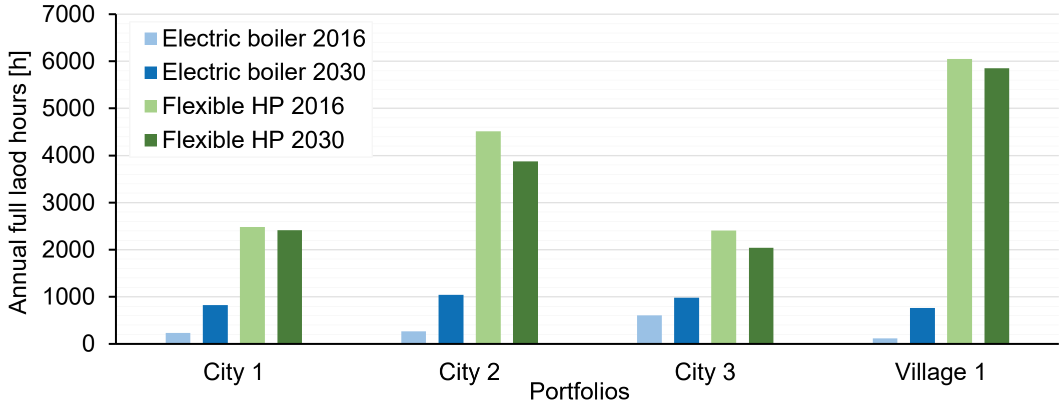

Fig. 4.18 Comparison of annual full load hours between electric boilers and flexible heat pumps for the model years 2016 and 2030

feature lower electricity demand and therefore lower cost and emissions per unit of produced heat. The second and more compelling fact is that a flexible heat pump can tackle almost every situation where an electric boiler would be active as well. This is better explained via the following example. The two graphics Fig. 4.19 and Fig. 4.20 allow a comparison of the generation power for an electric boiler and a flexible wastewater source heat pump in an otherwise identical City 3 scenario. The essential fact gets visible when the output power share of the heat pump gets subtracted from the output power share of the electric boiler for every individual hour. In Fig. 4.21 it is visualized that in the vast majority of all operating hours the heat pump is able to run at the same or even higher output power as the boiler. In final numbers for these two specific scenarios, the wastewater source heat pump can cover 98.5 % of the boilers' energy output.

As far as the results of this work show, flexible heat pumps can outperform electric boilers if the low-temperature heat source allows for an all-year-round operation. This, however, may not be fully true for every situation because the time grid of the optimization model is too coarse to properly validate this. Concludingly, electric boilers can lead to proper economic results (see Fig. 4.16) with comparably low system complexity and investment costs. This might make electric boilers a cost attractive solution for special regulatory situations where environmental aspects do not have the highest priority.

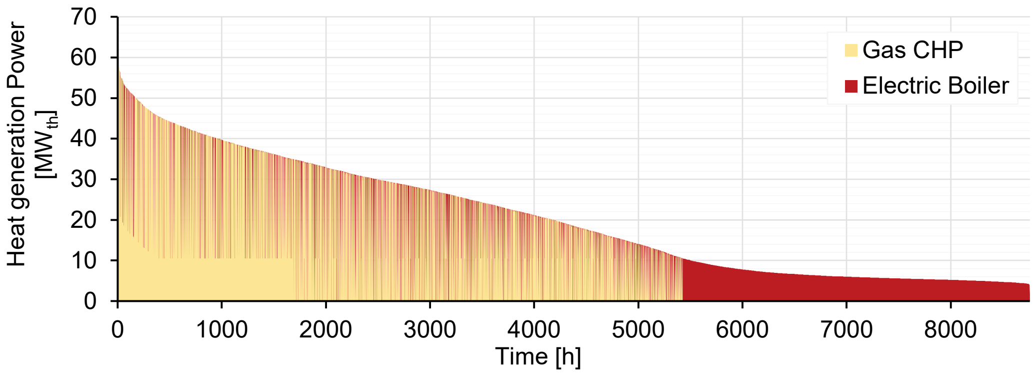

Fig. 4.19 Heat generation duration curve of scenario C3_2030_NS_EB

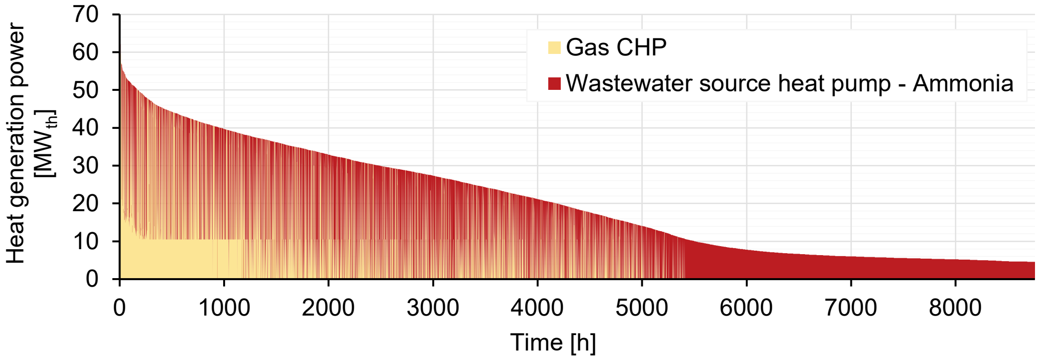

Fig. 4.20 Heat generation duration curve of scenario C3_2030_NS_WWHP_flex

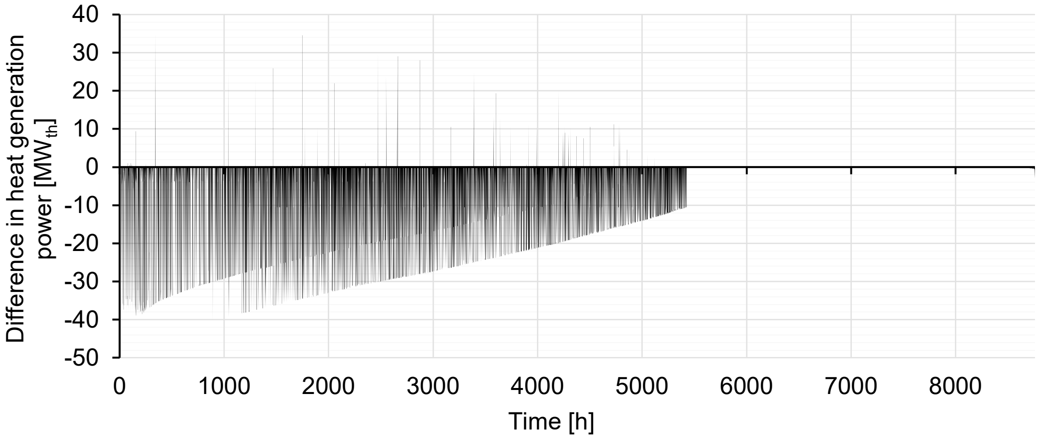

Fig. 4.21 Difference in heat generation power between an electric boiler and a flexible heat pump of the same size in the otherwise identical scenario for every hour (Power $_{\text{electric boiler}}$-Power $_{\text{heat pump}}$).

5 Conclusions

Large scale heat pumps bear great potential in the decarbonization of district heating systems throughout a large number of cities in Europe. Available state of the art heat pumps allow start-up times lower than one hour and are additionally capable of delivering a wide range of thermal output power. This operational freedom in interaction with environmental constraints is the basis for the definition of flexibility in this thesis. The MILP model developed for this purpose and the Python/GUROBI based solving framework transform the chosen input parameters into satisfying results and manage the tradeoff between accuracy, complexity, and computation time.

The economic value of flexibility for large scale heat pumps does exist and ranges between 0.5 €/MWh and 3.0 €/MWh for typical Austrian DH systems depending on the generation portfolio, the heat source, and the model year. As a major part of this cost reduction origins from a higher revenue of CHP power plants, the synergies between the heat pump as an electricity consumer and the CHP units as electricity producers are crucial for the value of flexibility. The different low-temperature heat sources and their individual characteristics have less influence on the value of flexibility than it was expected. Ultimately the results show that the main constraining factor for flexible heat pump operation besides source temperature thresholds is the competitive behavior with other generators in times of low heat demand.

The value of flexibility is not linearly rising with the relative size of the heat pump and seems to underlay a saturation effect which has to be further investigated in the future. Finding a sweet spot in flexible heat pump size could help to compensate the potential additional investment and maintenance costs of flexible heat pumps. Although a detailed financial analysis including investments is not conducted in this thesis, it is very likely that flexible heat pumps are more profitable than inflexible ones.

Despite the use of large-scale heat pumps in DH systems usually shows a very positive effect on the system internal heat-based CO_2 emissions, flexible heat pumps are not necessarily leading in this context. The results show that the additional flexibility is enhancing economics while potentially adding greenhouse gas emissions compared to less flexible heat pumps. Also, the expected CO_2 emission pricing for the model year 2030, does not show enough influence to avoid this increase. Nevertheless, as there is more electricity generated by CHP plants in the flexible heat pump scenarios it is crucial which electricity source is pushed out of the electricity market. If the additional electricity from the CHP plants substitutes electricity from higher emission sources like coal or lignite plants, the overall emissions are likely to be less for the flexible scenarios. Further researches would be necessary to identify the exact market conditions under which this replacement of other fossil energy carriers outweighs the higher internal emissions for heat generation.

The use of heat storage systems does clearly increase the systems operational freedom and also changes the way flexible heat pumps operate. In terms of financial numbers, however, there are no unexpected synergies when using flexible heat pumps and storages together. Both devices provide a certain amount of cost reduction which in the most reviewed cases simply add up when they are combined.

Ultimately it can be said that the sweet spot of heat pump operation is most likely somewhere in between the two strategies demonstrated in this research. Future environmental variables and increased volatilities, nevertheless, will demand more flexibility (as it can be seen in the 2030 model year scenarios) and will probably make systems unprofitable which cannot operate in this way. The additional pressure imposed by climate goals will make this a very interesting topic to do further research on.

6 Annex

Table 6.1 Cost structure for City 1 heat generators and storages

Heat Producer	OPEX fix [€/MW/a]	OPEX var [€/MWh]	Startup Costs [€]
Waste incineration	230000	0	5000
Gas CHP	39000	7	20000
Biomass CHP	23000	8.2	1500
Gas boiler	4000	0	2500
Wastewater source HP	3000	3	200
River water source HP	2000	3	200
Industrial excess heat source HP	2000	3	200
Electric boiler	1100	0.8	100
Heat storage	30 €/MWh/a	0	0

Table 6.2 Cost structure for City 2 heat generators and storages

Heat Producer	OPEX fix [€/MW/a]	OPEX var [€/MWh]	Startup Costs [€]
Industrial excess heat	2000	0	50
Gas CHP large	39000	7	20000
Gas CHP small	20000	5.5	1500
Gas boiler	4000	0	2500
Wastewater source HP	3000	3	200
River water source HP	2000	3	200
Industrial excess heat source HP	2000	3	200
Electric boiler	1100	0.8	100
Heat storage	30 €/MWh/a	0	0

Table 6.3 Cost structure for City 3 heat generators and storages.

Heat Producer	OPEX fix [€/MW/a]	OPEX var [€/MWh]	Startup Costs [€]
Gas CHP large	20000	7	2000
Wastewater source HP	3000	3	250
River water source HP	2000	3	250
Industrial excess heat source HP	2000	3	250
Electric boiler	1500	0.8	130
Heat storage	30 €/MWh/a	0	0

Table 6.4 Cost structure for Village 1 heat generators and storages.

Heat Producer	OPEX fix [€/MW/a]	OPEX var [€/MWh]	Startup Costs [€]
Biomass boiler	32000	2.5	300
Air source HP	2000	3.3	30
Electric boiler	1100	0.8	10
Heat storage[34]	5000 €/MWh/a	0	0

[34] The comparably high capacity dependent annual operational fixed costs are chosen because in this portfolio the capacity of the storage system is only 5 MWh

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Affidavit

I declare in lieu of oath, that I wrote this thesis and performed the associated research myself, using only literature cited in this volume. If text passages from sources are used literally, they are marked as such.

I confirm that this work is original and has not been submitted elsewhere for any examination, nor is it currently under consideration for a thesis elsewhere.

Vienna, September 28th, 2019

Michael Gumhalter