fit4power2heat: Work Package 3

Results of the WP3 and deliverable D3.1 (Bericht über technischen Lösungen von Wärmepumpen in Fernwärmenetzen)

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Content

1 Introduction

Deliverable 3.1 “Report on technical solutions” presents the results from the work package 3 “Development of representative concepts for the Austrian market”.

Chapter 2 contains a comprehensive literature review on typical structures for thermal networks in Austria. It includes an evaluation of the current role of district heating in the country, as well as the expected future prospects, in terms of network extension, number of customers and heat sales. Additionally, the chapter presents a characterization of Austrian thermal networks, where the relevant system components are parametrized (e.g. network size, energy suppliers, supply/return temperatures). Considering that one of the main motivations of the project *fit4power2heat* is the improvement of unprofitable operation of biomass plants, a description of the existing biomass-based heating networks is presented. Lastly, the building stock is analysed, since the increase of customers and the implementation of thermal refurbishment measures influence the heat demand patterns and as a consequence, the heat sales volume.

Chapter 3 presents a classification of potential sources for heat pumps in thermal networks. The following three main categories are distinguished: industrial waste heat (e.g. flue gas from furnaces, exhaust air, pressurized hot water, steam), infrastructure (e.g. waste heat from tunnels and sewage water channels), natural sources (e.g. geothermal energy, surface or ground water). Additionally, an overview on typical temperature ranges is included and the most relevant implementation barriers are listed. In order to show application cases, reference examples are presented for geothermal energy systems and waste heat recovery in Austria.

Chapter 4 describes the methodology followed to design technical solutions for the integration of heat pumps in district heating networks. Several concepts and use cases are defined and based on them, the best hydraulic scheme in terms of efficiency and fuel expenditure is chosen.

Chapter 5 describes the basis of the optimization model developed for the assessment of the use cases. It provides the optimal operational cost, together with the optimal operation strategy for the heat suppliers and the optimal bidding strategy for the heat pumps.

2 Overview of typical structures for thermal networks in Austria (Task 3.1)

This chapter presents an overview on typical structures of thermal networks in Austria. A literature review is carried out on the state-of-the-art of thermal networks, the relevant network typologies, the characteristics of biomass-based thermal networks and the building stock. This evaluation serves as a basis for the definition of representative use cases and the development of replicable technical solutions (included in chapter "4 Selection, design and integration of heat pumps in thermal networks").

According to the literature review, district heating covers 26% of the residential heat demand in Austria and the number of households supplied increases continuously every year. Almost half of the heat generation is based on renewable sources. Although the main supply areas are larger cities such as Vienna, district heating plays an increasingly important role in smaller communities.

The sub-urban and rural networks are usually supplied by biomass heat plants, with oil or gas boilers to cover peak load and back-up. The number of biomass plants, with a capacity above 1 MW_{th}, is estimated in 900 plants, which amounts to 2600 MW_{th} in total. Many of them are reaching the end of their lifetime and thus operating unprofitably. In this context heat pumps have a decisive role in supporting the thermal networks and providing flexibility. In the past ten years, the installation of this type of technology has increased.

The development in the building stock has an influence in the district heating sales. The total energy sales doubled between 2000 and 2016, since there was an increase in the building stock. However, the final energy consumption remained similar, due to the higher efficiencies of the new buildings and the implementation of thermal refurbishment measures.

2.1 State-of-the-art of thermal networks in Austria

District heating covers 26% of the residential heat demand in Austria. The number of apartments supplied by district heating increases continuously every year, as shown in Figure 1. This type of heat supply is used particularly in urban centers with high heat demand densities. For buildings constructed after 2000, the local/district heating share is around 80% for those with more than 20 apartments and around 61% for buildings with 10 to 19 apartments. Overall, considering all building periods, the share amounts to 51% for buildings with more than 20 apartments and 42% for buildings with 10 to 19 apartments.

According to Figure 2, 46% of local and district heating sales in Austria correspond to households, while 39% of the volume sold is attributable to the public sector and private services sector. The remaining sales correspond to the industrial sector [1].

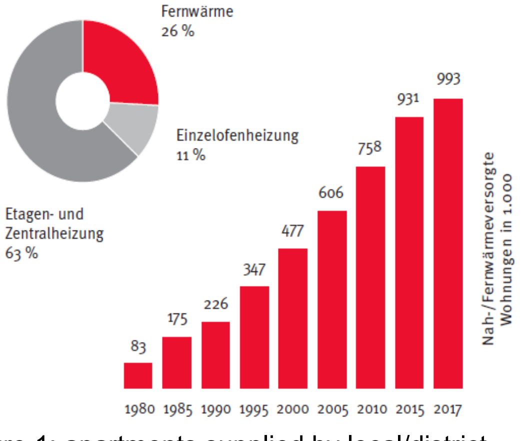

Figure 1: apartments supplied by local/district heating [1]

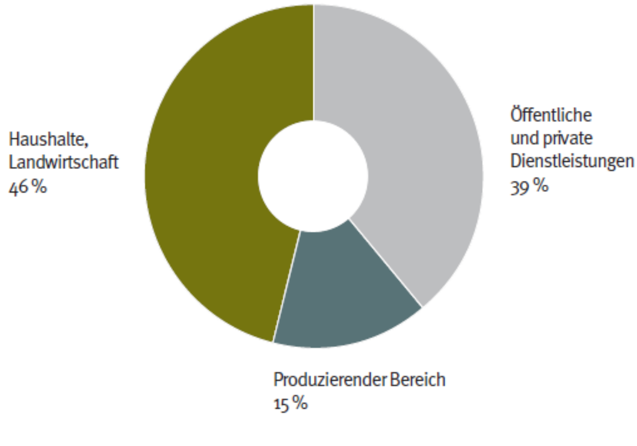

Figure 2: local/District heating sales by sector [1]

Almost half of the heat generation in local and district heating networks in Austria is based on renewable sources. Waste contributes the most (up to 23%) to this category according to Figure 3. In 2016, almost 90% of the local and district heat was generated using CO_2 neutral or low CO_2 primary energy sources, including natural gas.

Future developments are uncertain as a result of the trends in the international energy market. Gas fueled CHP plants cannot be operated profitably due to low electricity prices and higher gas prices. Therefore, the heat generation has been increasingly shifted from highly efficient CHP plants to heating boilers, as shown in Figure 4. While the CHP share of total local and district heat generation reached a historical maximum of 75% in 2008, it fell down to 63% in 2013 rising up again to 68% in 2015. The main reason for the last growth is the increase in the usage of gas-fueled cogeneration plants for electricity congestion management, which brings economic benefits.

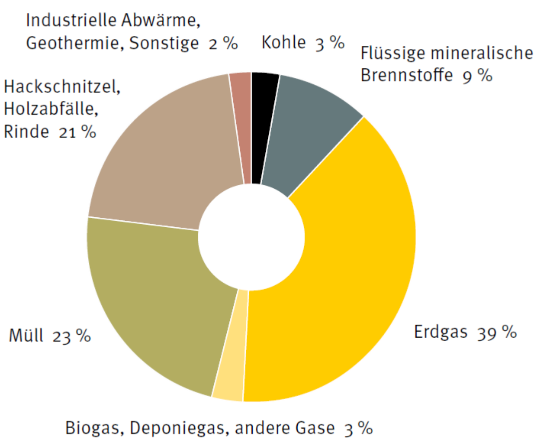

Figure 3: fuel input for heat generation [2]

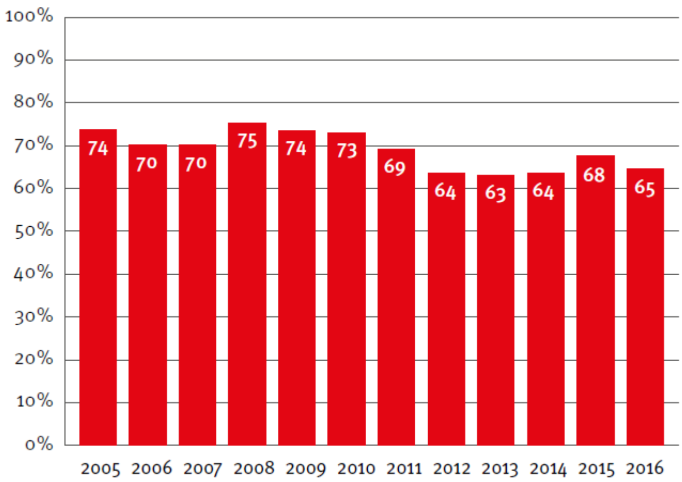

Figure 4: heat generation from combined heat and power [2]

The total length of the heating networks in Austria is approximately 5.900 km as shown in Figure 5. The Association of Gas and Heat Supply Companies (Fachverband der Gas- und Wärmeversorgungsunternehmungen [FGW]) states that heat supply companies will continue to invest in the consolidation and further expansion of their networks. An annual extension of 26 to 67 km of district heating pipelines is planned between 2018 and 2027 – the average annual development rate is estimated to be 42 km [1]. Reasons for the decreasing expansion are the connection densification in the construction of multi-story houses, as well as a less dynamic development of new buildings.

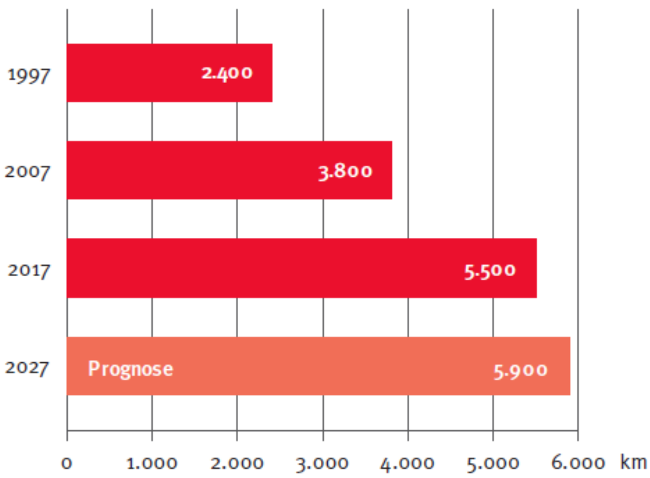

Figure 5: district heating network length development 1996-2026 [3]

In Austria district heating is provided by various actors, which are mostly municipal companies. The main supply areas are larger cities such as Vienna, Graz, Linz, Salzburg, Klagenfurt, St. Pölten and Wels. However, district heating plays an increasingly important role in smaller communities [4]

Figure 6 shows a comparison of the district heating grid length and density between different countries. The network-density (km/1.000 inhabitants) in Austria is 0,6 km/1000 inhabitants, which is about three times higher than in central and western European countries (0,2 km/ 1.000 inhabitants). In Austria the share of renewables in district heating is 46% (Figure 7:), which is below the share in Scandinavian countries and Lithuania.

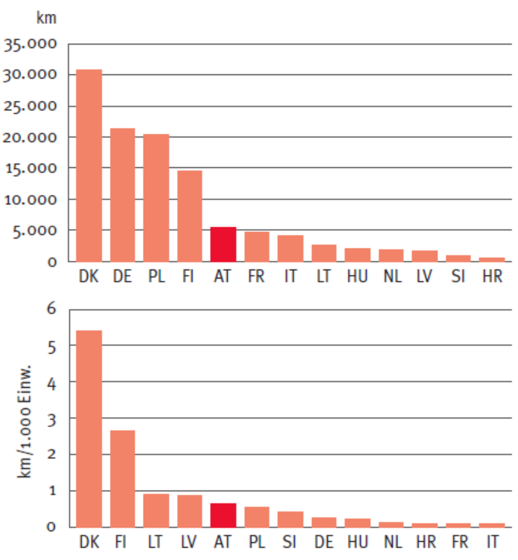

Figure 6: international comparison of district heating network length and density **[3]**

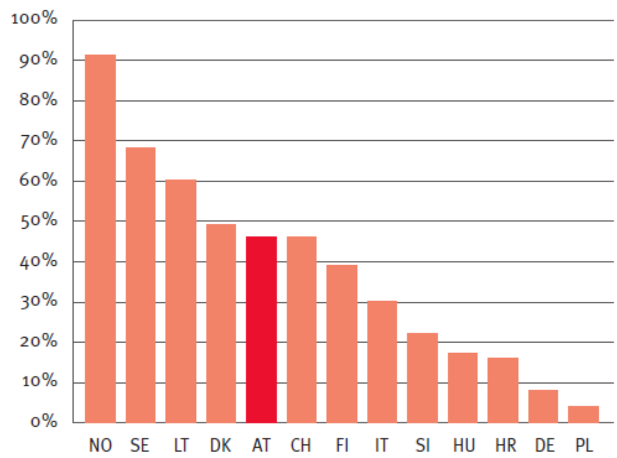

Figure 7: international comparison of renewable share in district heating **[4]**

2.2 Characterization of Austrian thermal networks

Austrian heating networks are supplied by different types of producers. The production plants range from CHP plants to boilers, which can be combined with alternative heat sources, such as solar thermal, geothermal and heat pumps, as well as waste heat from industrial processes. The supply structure can be classified into three categories [5]:

- **Urban networks:** they are supplied with heat from large production units, which are mostly owned by energy suppliers. Above all, waste incineration plays a major role in this category, as well as biomass to some extent. Additional boilers function primarily for peak load coverage and back-up.
- **Sub-urban and rural networks:** they are usually supplied by biomass heat plants, with oil or gas boilers used to cover peak loads and back-up.

Figure 8 provides an overview of the existing CHP plants, biomass plants, and waste incineration plants with a fuel throughput of more than 2 t / h in Austria. There are around 410 CHP plants with a capacity below 1MW, which represents 70% of the units installed [6].

The number of biomass plants, with a capacity above 1 MW_{th}, is estimated to 900 plants, which amounts to 2600 MW_{th} in total [5]. Regarding the incineration and co-incineration plants for waste disposal, there are 32 units with a capacity above 2 t / h and 33 units with a capacity below 2 t/h.

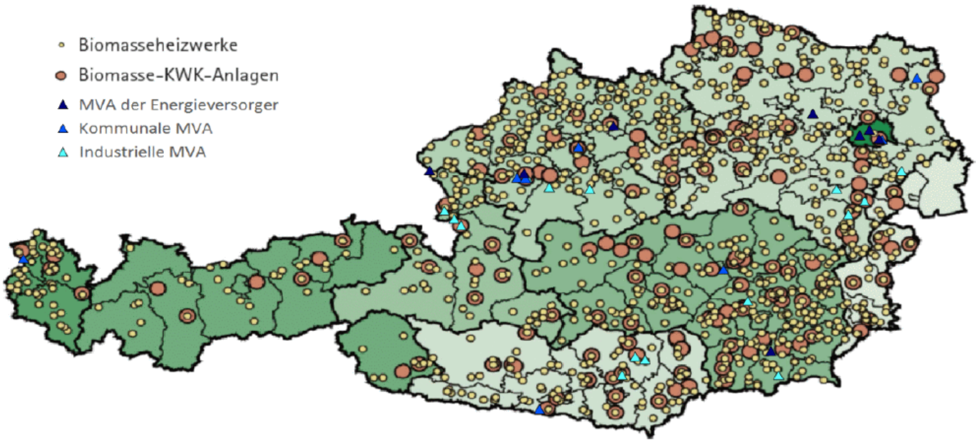

Figure 8: biomass heat plants, CHP plants and waste incineration plants with a capacity over 2t/h in Austria [5]

Among the alternative heat sources, the following technologies should be noted [5]:

- **Industrial waste heat**
  In some cities waste heat from industrial processes is used to supply a certain amount of heat into a district heating network. Prerequisite for direct use is an adequate temperature level with corresponding heat flow after internal utilization. Constant waste heat from processes can be used to cover the basic load, as it is done with the waste heat from OMV Schwechat, which is fed into the district heating network in Vienna.
- **Geothermal energy**
  There are currently 15 geothermal plants in Austria supplying a heating network. The installed capacity is about 93 MW_{th} and the thermal energy generation amounts to 139 GWh_{th}/year.
- **Solar Thermal energy**
  There are 24 solar thermal power plants with an installed collector area of more than 500 m² supplying a local/district heating network. The total installed area of these plants is 37060 m², resulting in a thermal capacity of 25.9 MWth. Altogether, these plants generate about 15 GWhth/year of thermal energy.

The heat demand density for regions in Austria can be determined by means of the "Austrian Heat Map", as illustrated in Figure 9. The interactive map shows the potential of the different regions for district heating, as well as the stock of power plants, district heating networks and industry, in addition to population density [7].

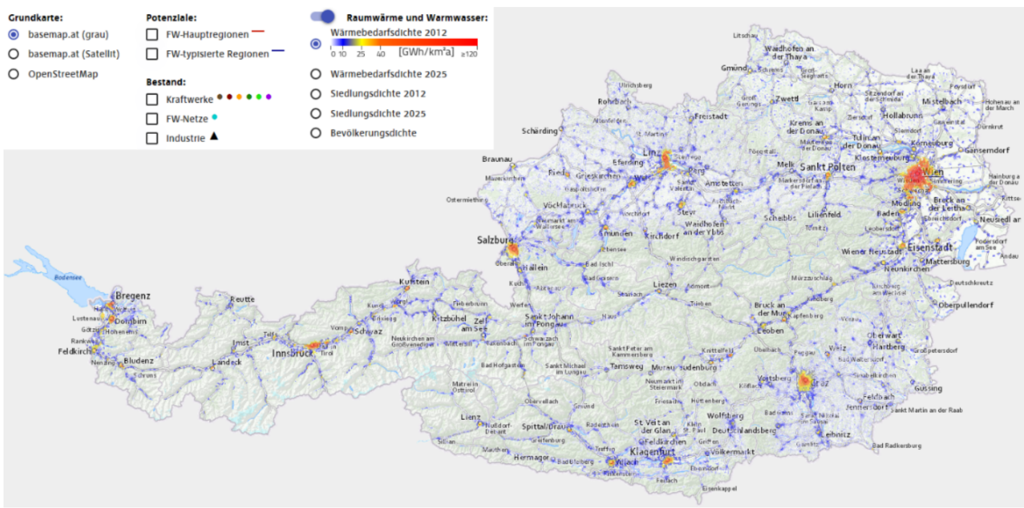

Figure 9: overview of the heat demand density in Austria [7]

Figure 10 illustrates the supply and return temperature levels during the winter operation of 60 heating networks. The values are arranged according to descending order of sales volume. The supply temperature (in red) ranges between 170°C and 65°C, while the return temperature (in blue) ranges between 40°C and 75°C. Larger networks (represented on the left) tend to have higher supply temperatures than smaller networks, since they are usually older. The networks are often operated at their capacity limit, therefore new customers can only be connected by increasing the flow temperature and the corresponding heat transfer energy. Smaller networks, which have been often developed in recent years, have been designed for operation with lower flow temperatures.

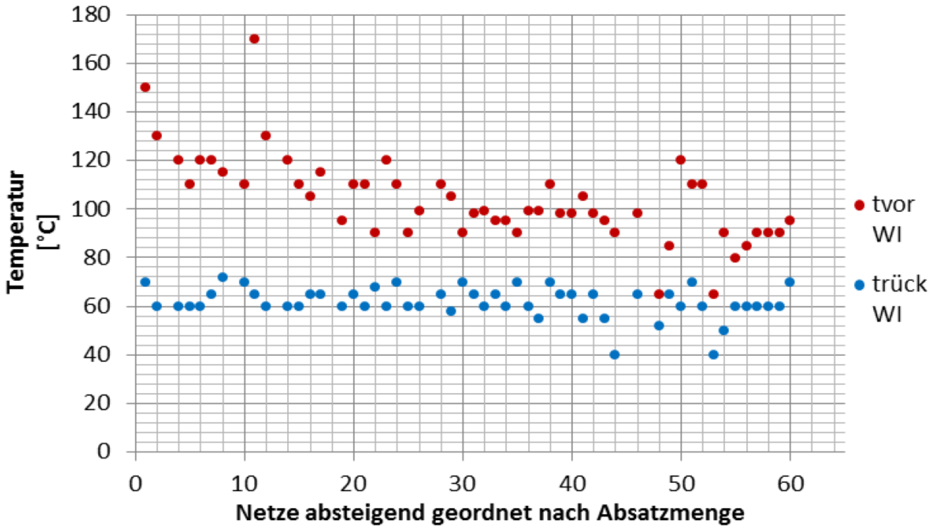

Figure 10: supply and return temperatures in winter operation based on 60 networks ordered by descending order of sales volume [5]

2.3 Characteristics of biomass-based thermal networks

This chapter presents the main characteristics of biomass-based heating networks in Austria. It is essential to understand their configuration in order to develop representative use cases and ensure the replicability of the solutions developed within the framework of the project *fit4power2heat*.

The characterization of the existing networks is based on the QM Heizwerke database, which is currently considered to be the most complete database with regard to biomass-based district heating networks. It contains relevant data and technical documentation of several networks, including hydraulic schemes of individual plants, customer data and annual operation reports [8]. An overview of the volume of the database is presented below:

- Investments and projects covered: 730 plants, 1400 projects
- Total connected capacity of all projects: 3.360 MW
- Total pipe length of all projects: 3.400 km
- Number of heat consumers: 50.000
- Number of operation reports: 1.500 reports of 400 plants

2.3.1 Power plants

Most of the networks, up to 98%, have a biomass boiler installed and a biomass cogeneration plant can be found in around 8% of the networks. In 55% of the heating networks, oil or gas boilers are used for peak load coverage and 29% are partly using heat recovery systems. Other types of producers, such as external boilers, industrial waste heat or biogas plants are found in 10% of the networks.

Figure 11 shows the distribution of the heat plants according to the installed capacity and generated heat. Biomass boilers and CHPs account for less than half of the installed capacity but are responsible for 85% of the heat generated. Oil and gas boilers present almost the same installed capacity, although they contribute with 1% to the total heat generation, since they are usually operated as back-up plants.

The capacity of the biomass boilers ranges between 0,5 and 10 MW_{th} (50% of the boilers present a capacity below 1,6 MW_{th}). For oil and gas boilers the capacity ranges between 0,5 and 25 MW_{th} (50% of the cases present a capacity below 3 MW_{th}).

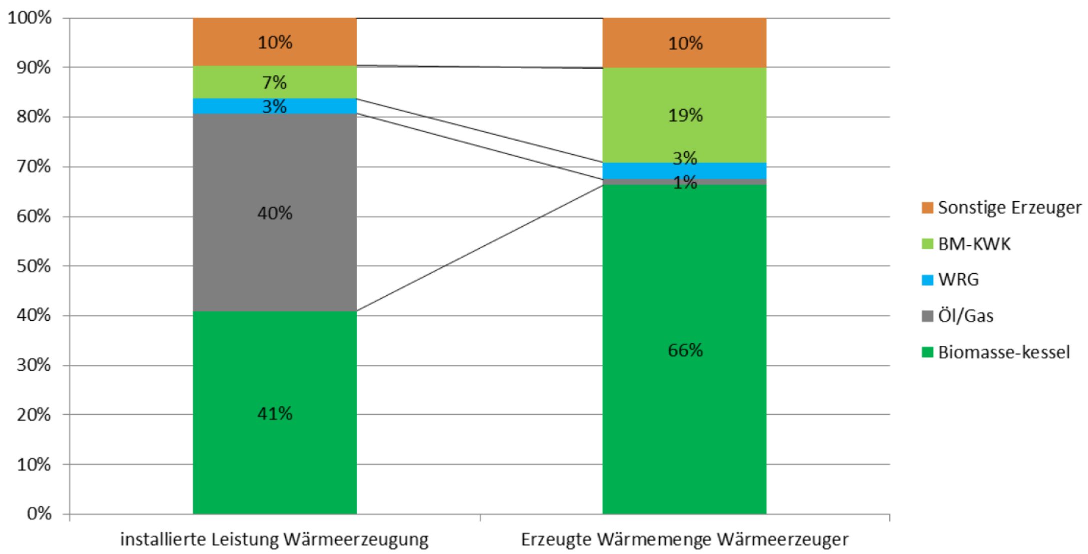

Figure 11: share of installed capacity and heat generation among different heat plants in biomass-based networks [5]

2.3.2 Network typology

The biomass-based heating networks can be distributed in eight classes depending on the connection capacity, as shown in Figure 12. Around 80% of the networks present a connection capacity below 7 MW_{th} and they supply one third of the total energy sold. The average full load operating hours of the boilers range between 1150 h/year and 1500 h/year [5].

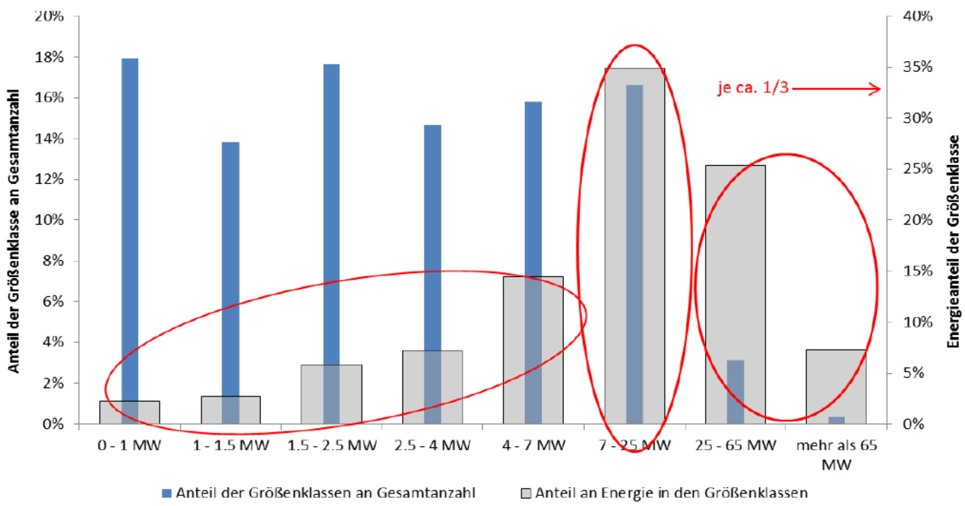

Figure 12: distribution of biomass networks by size and heat sales [5]

In overall, the different typologies of heat networks can be classified into three clusters, depending on the share of customers and the heat requirement.

- Cluster I (>75% customers with > 150 MWhth/year): this category contains mainly big customers.
- Cluster II (≤ 75% customers with > 150 MWhth/year and ≤ 25 % with < 50 MWhth/a): this cluster is characterized by mixed network structures.
- Cluster III (< 75 % customers with > 150 MWhth/year and > 25 % with < 50 MWhth/year): mainly small customers are found in this category.

2.3.3 Comparison of technical parameters

A comparison of different technical parameters is included in this chapter, based on the classification of the network typologies.

Figure 13 shows a comparison of the clusters in terms of number of networks, number of customers, pipeline length, connection capacity, and heat consumption. The majority of heat networks (approximately 44%) are located in Cluster II. A similar distribution is found for the number of consumers as well as for the remaining parameters. Although cluster I has the smallest share of customers with only 18%, 40% of the annual heat is sold in this category. In overall, cluster III (small consumers) has an almost inversed relationship to cluster I (large consumers), resulting in economic advantages for cluster I.

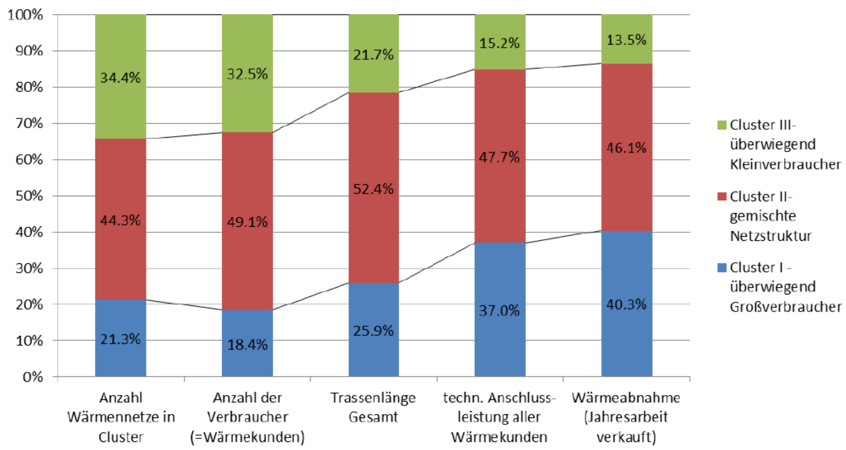

Figure 13: comparison of technical parameters for different clusters of biomass networks [5]

Number of customers and pipe length

A comparison of the number of customers and pipe length in different network clusters is shown in Figure 14 and Figure 15 respectively. The summed values are represented by blue columns (readable on the left axis), while the value range is represented by a black line (readable on the right axis). The deviation between the median and the average is shown by a white band.

The distribution of the values is similar in both figures. In overall, the number of customers in the networks ranges between a few and around 400, while the pipe length amounts up to 50 km. The approximation of the median to the mean value reveals that in networks with predominantly small consumers (cluster III) the values are distributed more equally over the entire range than in those networks with mainly large consumers (cluster III). If the median deviates significantly from the mean value, the individual networks are outliers. Therefore, networks with small consumers are much more homogenous in their parameters than large consumer networks, which facilitates their classification.

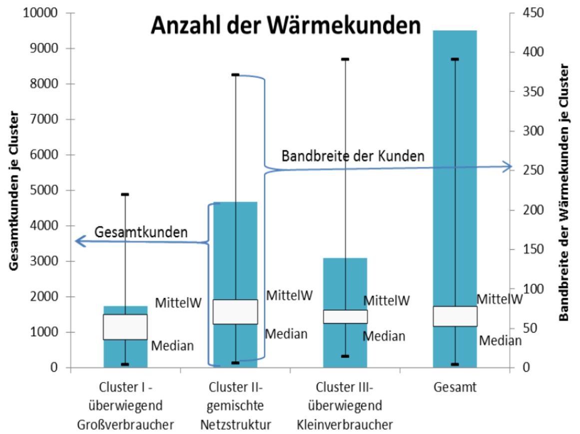

Figure 14: number of customers of the network clusters [5]

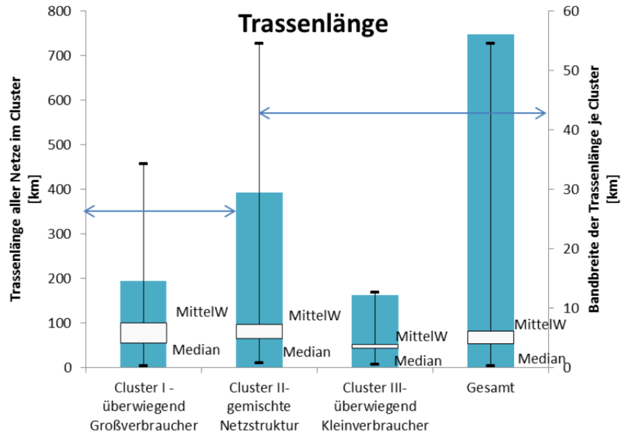

Figure 15: pipe length of the network clusters [5]

Connection capacity of the customers and sold heat

As expected, the connection capacities, as well as the heat sales increase with a higher share of large scale consumers (Figure 16 and Figure 17). In overall, the connection capacity can amount up to 50 MW, while the heat sales can reach 80 GWh. The ranges, as well as the deviation between the median and the average are smaller for networks with small scale customers, which results in a more uniform distribution of the values.

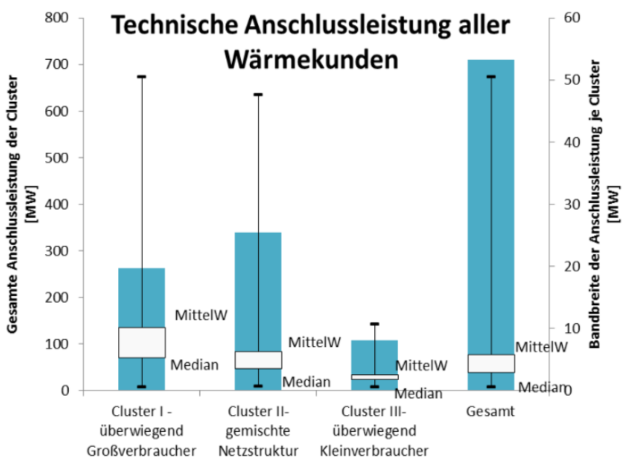

Figure 16: connection capacity of customers by network [5]

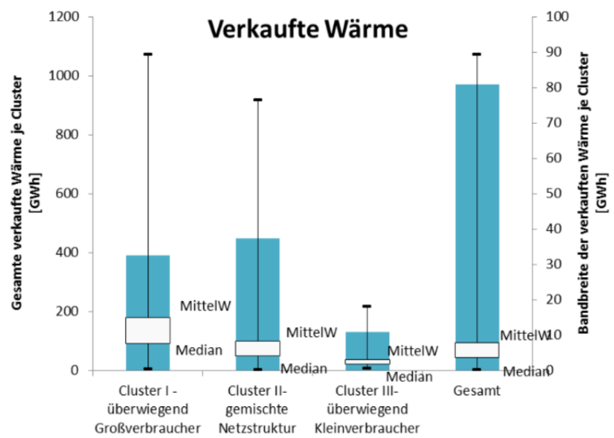

Figure 17: heat sales by network cluster [5]

Heat density

The heat density in networks with predominantly large-scale customers doubles the value for those networks with small customers, due to the high volume of heat sold (Figure 18).

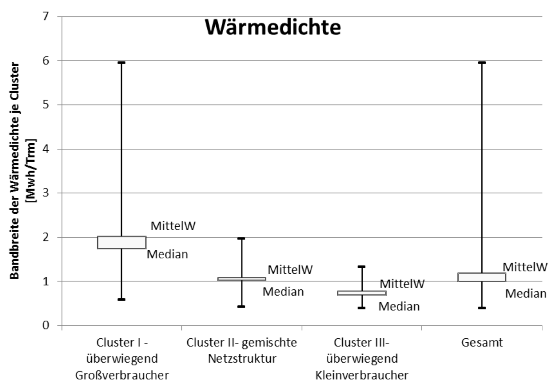

Figure 18: heat density of the network clusters [5]

A summary of the median and average values of the parameters investigated for the three different network clusters is given in Table 1.

Table 1: Median and average values of representative parameters in network cluster I, cluster II and cluster III. [5]

		Mittelwert	Median	Mittelwert	Median	Mittelwert	Median
Abnehmer	[Anzahl]	67	36	86	56	74	57
Trassenlänge	[m]	7.444	4.170	7.258	4.833	3.852	3.282
Anschlussleistung	[kW_{th}]	10.123	5.255	6.283	3.591	2.580	1.763
Verlustleistung	[kW_{th}]	293	105	264	111	92	86
erzeugte Wärme	[MWh/a]	17.402	8.417	10.005	5.211	3.894	2.581
Wärmeabnahme	[MWh/a]	15.038	7.649	8.290	4.236	3.130	1.986
Netzverluste	[%]	14	9	17	19	20	23
Wärmedichte	[(kWh/a)/m]	2.021	1.743	1.092	1.023	777	688

2.4 Building stock

According to the European project TABULA, which developed a harmonized building stock database for European countries, the structure of the current Austrian building stock is classified into four building sizes (single-family houses, terraced houses, multi-family houses, apartment blocks) and seven construction periods (class I up to 1918, class II 1919–44, class III 1945–60, class IV 1961–80, class V 1981–90, class VI 1991–00 and class VII 2001–10) [9]. The multi-family house is the most common building typology in every construction period, except for the period VII, where single-family houses predominate (Figure 19).

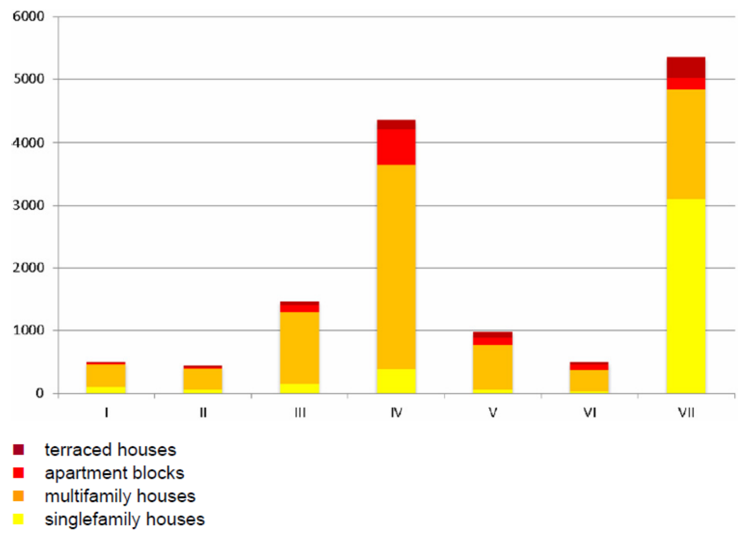

Figure 19: number of residential buildings according to building typology and construction period [9]

Each building type is parametrized according to energy related properties, such as living area, specific heat demand and U-value. The average values of these parameters are shown in Table 2 for different building types and construction periods. During the last three decades the quality of thermal insulation of residences in Austria has improved significantly. The specific heat demand of representative single-family houses which were built before 1918 ranges between 180 and 300 kWh/m^{2}a and those of multi-family houses between 130 and 230 kWh/m^2. On the contrary, the typical values of new houses from the period VII (2001-2010) range between 10 and 100 kWh/m^{2}a for single-family houses and between 10 and 80 kWh/m^{2}a for multi-family houses.

Table 2: characterisation of the Austrian building stock according to constructions periods and building sizes. [9]

Construction period	I	II	III	IV	V	VI	VII
	-1918	1919-44	1945-60	1961-80	1980-90	1991-00	2001-10
SFH Single-family house							
Living area [m²]	125-155	110-140	110-140	125-155	140-170	145-175	145-175
Heating demand [kWh/m²a]	180-300	200-370	160-380	145-280	100-190	80-130	10-100
U-value [W/(m²K)]	1.0-1.8	1.1-1.45	1.0-1.2	0.6-0.85	0.35-0.8	0.3-0.7	0.2-0.6
MFH Multi-family house/ TH Terraced house							
Living area [m²]	400-800	280-680	280-680	400-800	400-800	350-750	350-750
Heating demand [kWh/m²a]	130-230	140-270	150-270	100-205	80-140	60-100	10-80
U-value [W/(m²K)]	1.0-1.8	1.1-1.45	1.0-1.2	0.6-0.85	0.35-0.8	0.3-0.7	0.2-0.6
AB Apartment blocks							
Living area [m²]	>800	>700	>700	>800	>800	>800	>800
Heating demand [kWh/m²a]	120-220	130-260	130-260	90-190	70-130	50-100	10-80
U-value [W/(m²K)]	0.9-1.7	1.0-1.4	0.9-1.1	0.5-0.8	0.35-0.75	0.3-0.7	0.2-0.6

As expected, those buildings classified in the oldest construction periods present higher U-values, which indicate a higher heat transfer rate (Figure 20)

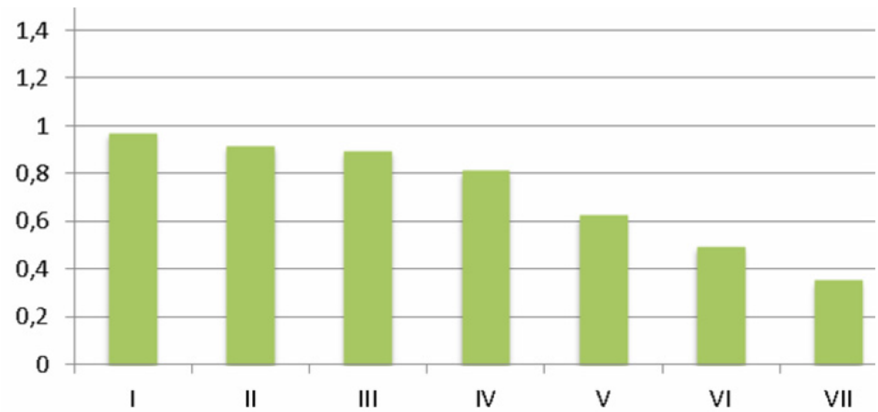

Figure 20: average U-values per building class [W/m²] [9]

Figure 21 illustrates the refurbishment potential for the different building categories and construction periods, according to two scenarios: standard refurbishment and advanced refurbishment. From the 2 million buildings in Austria about 1,5 million is in the single or multi- family houses category. Therefore, the major energy saving potential lies in these building classes. Especially the single-family houses built between 1961 and 1980 present the highest margin for improvement, being able to achieve a 60% (standard refurbishment) or 70% (advanced refurbishment) reduction in the final energy demand.

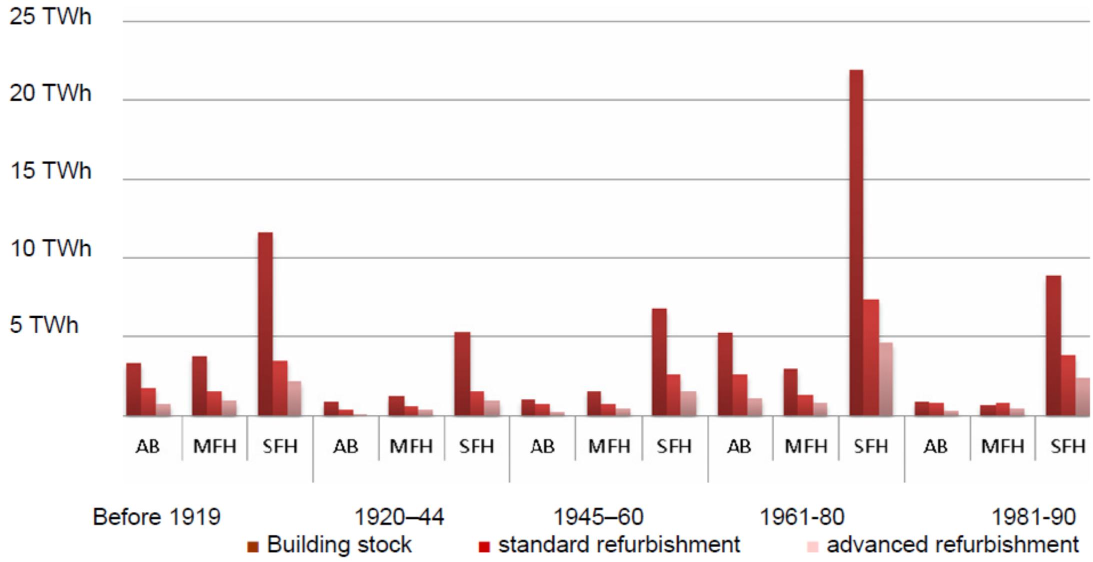

Figure 21: scenarios of possible final energy demand reduction potentials (in TWh) per construction period and building category [9]

Regarding the type of heating system, in the early nineteenth century the main heaters were cockle stoves fired with wood or coal. Afterwards, the usage of oil or gas increased. In the last decades, the energy system technologies improved significantly. Many of the facilities have been renovated in recent years or have been completely replaced. Since 1994, new systems have been installed, such as low-temperature or condensing boilers with a higher efficiency. Pellets, gas and oil should be noted among the type of fuels. District heating grids have spread, increasing the number of households connected. As described in chapter "2.1 State-of-the-art of thermal networks in Austria", district heating covers 26% of the residential heat demand in Austria and the number of apartments supplied by district heating increases continuously every year. Since 2000, the number of connected dwellings has been doubled from 477.000 to 955.000 in 2016. In the past ten years the installation of alternative systems like heat pumps also increased.

Figure 22 shows the distribution of heating technologies according to their construction period. In new dwellings central heating and district heating account for more than 90% of the share, while in older buildings floor/dwelling central heating (35%) and house central heating (30%) are the common systems.

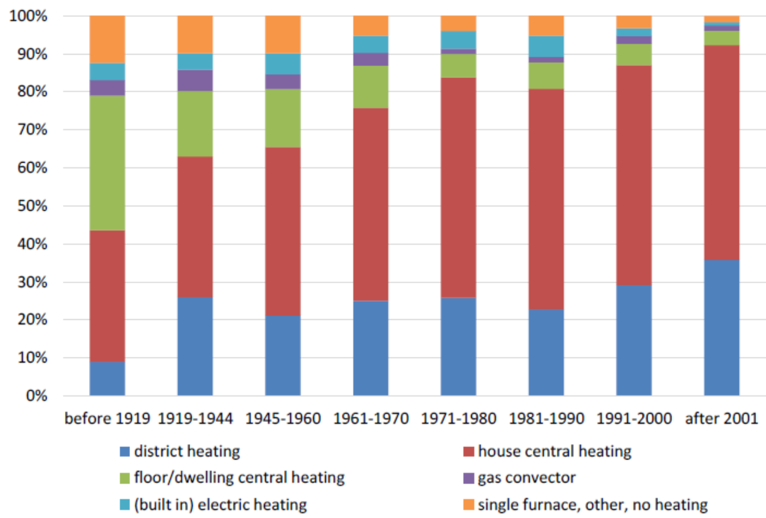

Figure 22: heating systems in the building stock according to building periods [10]

Figure 23 shows the development of local/district heating sales and the final energy consumption for space heating and hot water preparation since 1990. The figure shows that the total energy sales doubled between 2000 and 2016, due to an increase of the building stock. However, since 2004 the final energy consumption remained more or less constant. This trend can be explained by the higher efficiencies of new buildings, as well as, the implementation of thermal refurbishment measures.

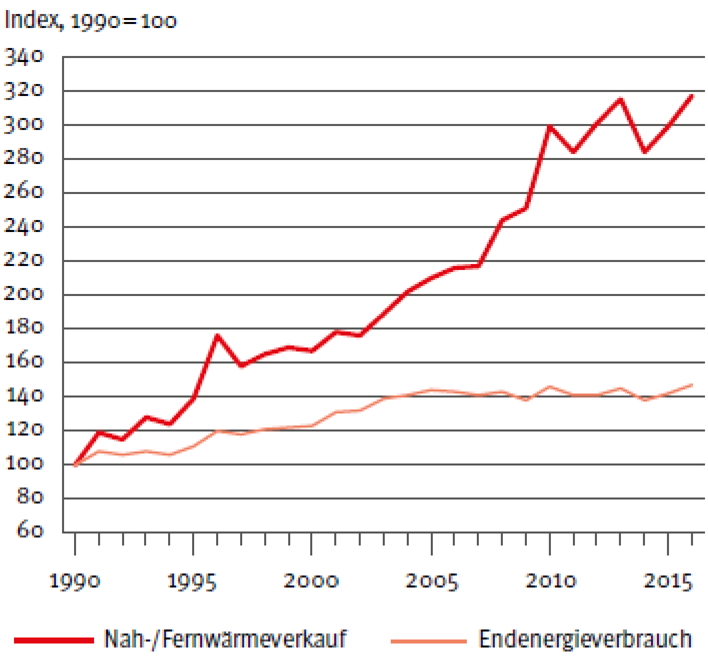

Figure 23: district/local heating sales and final energy consumption [11]

3 Classification of potential sources for heat pumps in thermal networks (Task 3.2)

This chapter presents a classification of potential heat sources for heat pumps in district heating networks. This evaluation serves as a basis for the definition of representative use cases and the development of replicable technical solutions (included in chapter “4 Selection, design and integration of heat pumps in thermal networks”).

The following three main categories are distinguished depending on the origin of the heat: industrial waste heat (e.g. flue gas from furnaces, pressurized hot water, steam), infrastructure (e.g. waste heat from tunnels and sewage water channels), natural sources (e.g. geothermal energy, surface or ground water). The temperature level of the source is a decisive factor to consider for the heat pump installation. Therefore, an overview on typical temperature ranges for each heat source is given, as well as possible implementation barriers, both technical and non-technical. Finally, reference application examples in Austria for geothermal energy systems and waste heat recovery are presented.

3.1 Types of sources for heat pumps

Heat pumps use various types of heat sources, such as industrial waste heat, flue gas, sewage water and geothermal heat. District heating provides the possibility to use this heat locally, since otherwise it would be disposed. However, the heat does not always present the required temperature levels, therefore solutions in the form of heat pumps enable to use it effectively. Heat pumps transfer the heat from a low-temperature heat source to a high temperature sink, such as a district heating system through a closed compression process. The advantage of using this technology is its efficiency (e.g., compared to electric boilers) and its possibility to use inexpensive sources of heat to balance the thermal and electricity grids [12].

3.1.1 Industrial waste heat

Waste heat can be generated in various industrial activities. The amount and temperature levels of the waste heat are highly dependent on the processes in the respective industry. Usually, the waste heat which cannot be directly used due to insufficient temperature levels, is recovered via heat pumps for heating or via chillers for cooling. Typically, waste heat from industry is in the temperature range of 20 to 60 °C. An exemplary temperature profile for waste heat recovery from a dairy plant is shown in Figure 24. In industries with high process temperatures, such as in cement factories, excess heat can have temperatures up to several hundred degrees Celsius.

Figure 24: example of temperature levels of waste water from a dairy plant within one year. (Source: private communication with industrial partner).

In Austria, only 2 % of the heat supplied into the district heating networks is provided by waste heat and geothermal energy [4]. The highest shares of waste heat in district heating networks can be found in Scandinavian countries (e.g. 11 % in Sweden). However, there is a trend towards increasing the utilization of waste heat in Austria. One example is the waste heat integration by Voestalpine in Leoben and Linz [13]. Additionally, the recovery of waste heat from flue gas through the condensation of water vapor represents a considerable potential considering the amount of biomass-based district heating networks available in Austria, as described in chapter 2.3 “Characteristics of biomass-based thermal networks”.

A survey on behalf of Kommunalkredit Public Consulting GmbH investigated Austria’s total waste heat potential [14]. In a bottom-up approach, 1.450 companies from the 11 sectors with the largest share of total energy consumption were contacted, of which approximately 145 companies returned the questionnaire. In total, 175 waste heat sources were reported. According to the results, by far the largest proportion of waste heat is generated as waste and cooling water at temperatures below 35°C. The largest volumes of waste heat are reported from the paper and board manufacturing industry (57%) and from the metal manufacturing industry (36%). The estimated potentials, classified in three temperature ranges, are shown in Table 3.

Table 3: Austria’s total waste heat potential in GWh/a per temperature level [14]

Temperature	Free potential	Planned potential	Total potential
> 100°C	428	306	734
50-100°C	455	368	823
< 35°C	5.292	4	5.296
Total	6.175	678	6.853

Table 4 presents an overview on commercially available industrial heat pumps, including technical specifications such as the manufacturer, type of refrigerant, heating capacity and compressor type.

Table 4: commercially available industrial heat pumps [15]

Manufacturer	Product	Refrigerant	Max. supply temperature (°C)	Heating capacity [kW]
Kobe Steel (Kobelco Steam Grow)	SGH 165	R134a/R245fa	165	70 – 660
Vicking Heating Engines	HeatBoosterS4	R1336mzz(Z)	150	28 – 188
Ochsner	IWWDSS R2R3b	R134a/ÖKO1	130	170 – 750
Hybrid Energy	Hybrid Heat Pump	R717 (NH_3)	120	250 – 2500
Dürr Thermea	thermeco$_2$	R744 (CO_2)	110	45 – 2200
Combitherm	Customized design	R245fa	100	20 – 300
Friotherm	Unitop22	R1234ze(E)	95	600 – 3600
Mitsubishi	ETW-L	R134a	90	340 – 600
Mayekawa	PlusHeat X	R717	85	465-523
Ochsner	IWWS [..] ER2	R134a	65	111-464
Ochsner	IWWS [..] ER1	R407c	50	165-966
Ochsner	ISWS [..] ER1	R407c	50	123-723

3.1.2 Infrastructure: tunnels and sewage water channels

In all building structures in contact with the underground, the underground can be used as a heat source or sink. Foundation slabs and piers of buildings can easily be 'thermally activated' by installing simple heat absorbers in the form of flexible pipes in the reinforcement cages or mats. Accordingly, the warm temperature in tunnels can be used by installing absorber pipes directly in the concrete layers of newly built tunnels (Figure 25).

In urban areas, the higher underground temperatures due to the high building density can be used with thermally activated concrete components or with geothermal systems, such as borehole heat exchangers, linking infrastructure and natural sources for heating and cooling.

Another heat sources in urban or community areas are the sewage drains and sewage treatment plants. Sewage water is the most common type of heat source used by large-scale heat pumps at a European level, especially in Norway, Sweden, Finland and Switzerland. Sewage water presents several advantages, such as relatively high temperature, long-term stability and proximity to urban areas. The average temperatures range between 10°C and 20°C [12].

Figure 25: installation of absorber pipes in a tunnel [16].

3.1.3 Natural sources

The underground down to 300 m below surface – which in Austria is the distinction between shallow and deep geothermal systems - can be used in multiple ways as a heat source for low-temperature heat or as a heat sink for excess heat.

The sources are generally classified in open and closed systems with reference to the surrounding underground. Most of the installations do not exceed 150 m depth and the extracted temperatures are typically up to 25 °C [17].

The most used shallow geothermal systems are thermal groundwater, borehole heat exchangers, ground heat collectors (horizontal or "slinky" loops) and energy piles or other structural components in contact with the ground. Other forms – which gain more and more interest and application – are the use of high temperatures in mountains, former mining galleries, tunnels, etc. In these environments, the temperatures can reach up to 35 - 40 °C.

3.1.4 Temperature ranges of sources for heat pumps. Implementation barriers.

Table 5 summarizes the available heat sources for heat pumps in industry, while Table 6 presents available natural sources, as well as sources associated to infrastructure. Additionally, the temperature ranges and application barriers (technical and non-technical) are presented.

Table 5: heat sources for heat pumps in industry, temperature ranges and implementation barriers

<table>
<tr><th>Heat source</th><th>Temperature range [°C]</th><th>Technical barriers</th><th>Non-technical barriers</th></tr>
<tr><td colspan="4">Industry</td></tr>
<tr><td>Food industry [18]</td><td>• Drying: 30-90
• Washing: 40-80
• Pasteurization: 80-110
• Cooking: 95-105
• Sterilization: 140-150
• Heat treatment: 40-60
• Baking: 150-250</td><td rowspan="9">• High-temperature heat pumps are still not sufficiently available for some processes.
• Huge variety of different processes and temperature levels.
• Partially aggressive or contaminated fluids.</td><td rowspan="9">Lack of knowledge about heating and cooling demands of processes in single plants and therefore, lack of knowledge about waste heat potentials of individual processes.</td></tr>
<tr><td>Textile industry [18]</td><td>• Washing: 40-80
• Bleaching: 60-100
• Dyeing: 100-160
• Drying: 100</td></tr>
<tr><td>Chemical industry [18]</td><td>• Cooking: 95-105
• Distillation: 110-300
• Other processes: 120-180</td></tr>
<tr><td>Timber industry [18]</td><td>• Drying: 50-100
• Pressing: 125-175
• Steaming: 120</td></tr>
<tr><td>Pulp and paper industry [18]</td><td>• Cooking: 100
• Thickening: 130
• Paper drying: 100</td></tr>
<tr><td>Machinery construction [18]</td><td>Paint drying: 120</td></tr>
<tr><td>Automobile industry [18]</td><td>Paint drying: 200</td></tr>
<tr><td>Casting plants [18]</td><td>1000-1600</td></tr>
<tr><td>Polymer processing [18]</td><td>100-300</td></tr>
</table>

Table 6: heat sources for heat pumps (natural resources and infrastructure), temperature ranges and implementation barriers

Heat source	Temperature range [°C]	Technical barriers	Non-technical barriers
Infrastructure			
Sewage drains, sewage treatment plants	5 – 25	• Lowering of temperature due to heat usage (insufficient biological cleaning). • Purity of water lowered due to solid parts in waste water. • Heat extraction after passing the waste water treatment plant. It leads to temperature losses, especially in winter • Distances from sewage treatment plants to customers might be too long, affecting the economic feasibility.	• Economic feasibility questionable (restricted heat extraction in winter) • Lack of knowledge about temperature levels in one season. • Political and institutional framework conditions might be challenging.
Tunnels (tunnel water or direct heat use)	20 – 40	Distances from tunnels to customers might be too long, affecting the economic feasibility.	• Not mandatory measure, therefore only depending on individual interests (e.g. City of Vienna when evaluating the heat extraction from metro tunnels). • Political and institutional framework conditions might be challenging.
Natural sources			
Shallow geothermal energy systems	5 – 20	Limited area for installation of geothermal facilities, lack of groundwater.	Economic feasibility for different applications has to be evaluated.

3.2 Reference application examples in Austria.

The following chapters include an overview of several application examples for geothermal energy systems (e.g. DEGENT-NET project) and waste heat recovery (e.g. in the metal processing plant Plansee in Reutte).

3.2.1 Geothermal energy systems in low-temperature heating and cooling networks

In Austria, there are no decentral low-temperature heating grids currently in operation. Up to now, only two research projects covered the development of low-temperature heating and cooling grids for concrete sites.

The project "*pv + geotherm*", funded by the FFG, aims at the elaboration of a decentral heating and cooling grid for the former train station Nordwestbahnhof in central Vienna. Geothermal energy is considered as major heat source in combination with PVT-collectors and heat from sewage drains.

The second research project nationally funded is the project "*DEGENT-NET*", which evaluates technical concepts of local scale low-temperature heating grids at two specific pilot locations in Vienna and Salzburg. The project considers the thermal response of the system in the shallow underground, possible environmental impacts and, furthermore, the economic feasibility of the technical approach. The evaluation additionally provides generalized success criteria, which are one of the major outcomes of "*DEGENT-NET",* beside of the detailed technical concepts for two pilot locations.

In order to extent the overview on existing low-temperature heating and cooling grids, Table 7 presents several examples of grids implemented in Switzerland during the last years, including the location, the number of consumers, the grid capacity and the topology of the grid.

Table 7: examples of low-temperature district heating and cooling networks in Switzerland.

Location	Consumers/ Inhabitants	Grid capacity or consumption	Description (*)
Familiengenossenschaft Zürich (FGZ)	5700 inhabitants	4 MW	BHE field with 160 BHE with 250 m length each. Seasonal storage of waste heat from computing center. Dual-pipe grid with 3,4 km length.
ETH Zürich Hönggerberg	20 buildings 10000 students	Heating: 20 GWh, Cooling: 18 GWh Capacity: 2,5 MW	Two BHE fields with 227 BHE à 200 m length. Three-pipe circular grid
Richti-Areal Wallisellen	1200 inhabitants 3000 workplaces	Heating: 1,74 MW Cooling: 2,04 MW	220 BHE for seasonal storage
Suurstoffi	1500 inhabitants, 2500 workplaces 165000 m² energy reference area	Heating: 10,6 GWh Operating year 1: COP (HP) = 3,5 Operating year 2: COP (HP) = 4,5	BHE combined with PV-T modules and power-to-heat for balancing of power
Visp-West	Not specified	Not specified	Feed-in of waste heat from industrial plant. Goal: COP (HP) of 3

(*) BHE: borehole heat exchangers

3.2.2 Application examples of waste heat reuse in Austria

Nahwärmeanlage Kröllendorf für Allhartsberg

The heat source in this example is waste water from a fruit processing plant, which was previously discharged unused into the sewer. The waste water is fed via a 400 m long supply line to a shell-and-tube heat exchanger. The waste water has a temperature of 15-28°C and is cooled down to approximately 10°C in the heat exchanger. The heat is generated by a brine-water compression heat pump with a heating capacity of 80 kW, which increases the temperature level in order to make the heat available for space heating. The heated water is temporarily stored in a 2.000-liter buffer tank, from which the consumers (a gym and a kindergarten) are supplied.

The plant was commissioned in autumn 2008 and cost around 115.000 €. Due to the low consumption values, the annual CO_2 savings are around 31 tons (71% less compared to oil heating) [19].

Plansee Reutte

In the metal processing plant Plansee in Reutte, a high-temperature compression heat pump was installed to use the waste heat from the production processes (sintering furnaces) to feed heat into the company's own heating network. The heat pump, which was installed in 2013, provides a heating capacity of 380 kW and a cooling capacity of 287 kW. The waste heat temperature of 45°C is increased to 90°C, which is the operating temperature of the district heating network. The heat recovery is used during the whole year. The COP of the heat pump is 4.24 for heating. The plant's thermal energy consumption amounts to 1.030 MWh/a and the saved thermal energy is approximately 1.000 MWh/a, equivalent to 50.000 €. This results in around 300t of CO_2-emission savings per year [20].

Salzburg - Hallein Absorptionswärmepumpe

Salzburg AG operates a water/LiBr absorption heat pump that supplies the local district heating network. The driving heat is provided as steam at 165°C by a biomass power plant at Schweighofer (pulp producer). The heat pump was installed in 2006 and its heating capacity is 7,5 MW at a temperature level of 95°C. The heat source is the power plant's flue gas at 50°C. The heat pump operates during 7.500 hours per year (approx. 6.200 h/a full load operation), with a COP of 1.6. The installation costs of the heat pump were 0.65 Mio. €, the installation costs of the flue gas condensation plant, the hydraulics, control and construction works were 1,75 Mio. €. The unit saves up to 15.000 MWh of primary energy and 6.000 t of CO_2-emissions per year [21].

4 Selection, design and integration of heat pumps in thermal networks (Task 3.3)

This chapter presents the development of technical solutions for the integration of heat pumps. The following three thermal networks are evaluated: a district heating network, a heating network and a hotel facility. These three concepts are parametrized based on the network portfolio provided by *ENGIE Austria GmbH* and the literature review about typical heating grids in Austria presented in the previous chapters. The aim is to create generalizable concepts which enable the application of highly replicable solutions.

Several use cases are determined by combining the following system components contained in the concepts: heating grid (demand type, summer season, building typology), heat pumps (thermal capacity, source) and electricity markets (market type, bidding strategy). Additionally, the heat pump size is optimized and a comparison of different integration options is carried out, evaluating the reduction in biomass expenditure and the efficiency increase.

Based on the exhaustive overview on the electricity market structure in Austria (deliverable 2.1), state-of-the-art and current scenarios are parametrized, which establish the boundary conditions for the simulation of the use cases.

4.1 Methodology

The development of technical solutions for the integration of heat pumps in several heating networks is based on the methodology presented in Figure 27. Consider Figure 26 for the semantic interpretation of the nomenclature used.

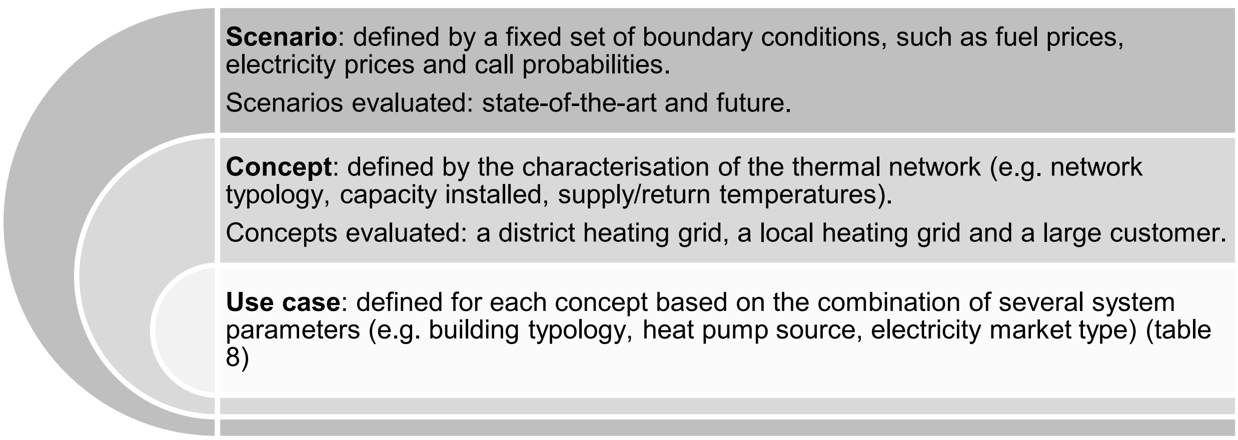

Figure 26: nomenclature definition: scenario, concept and use case.

Initially, several concepts are defined considering the business segment of thermal networks owned by *ENGIE Austria GmbH*, as well as the measurement data available. The concepts developed comprehend a district heating network, a local heating network and a large customer (chapter “4.2 Concept development”). The concepts are parametrized in terms of number of customers, heat demand, supply and return temperatures, capacity installed and type of producers.

In a second step, these concepts are assessed and enhanced in the design module based on a literature review on typical Austrian thermal networks (presented in chapter “2 Overview of typical structures for thermal networks in Austria”) together with ENGIE Austria GmbH’s expertise on their network portfolio. The aim is to create representative use cases which enable the development of generalizable and replicable solutions. These use cases are determined for each concept by combining several parameters for the following system components: heating network (demand type, summer season, building typology), heat pumps (thermal capacity, source) and electricity markets (market type, merit order) (chapter “4.3 Use case development”).

Additionally, state-of-the-art and future scenarios are defined according to the electricity market framework. These scenarios determine a set of boundary conditions for the use cases, based on fuel prices, electricity prices and call probabilities (chapter “4.4 Definition of state-of-the-art and future scenarios”)

In a third step, the use cases are simulated under state-of-the-art and future boundary conditions by means of an operational optimization model (chapter “5 Optimization model”). The simulation provides the optimal operational cost for each use case, together with the optimal operation strategy for the heat suppliers in the network and the optimal bidding strategy for the heat pumps.

Lastly, an assessment of the simulation results is done in the economic module, considering as an input specific investment costs and electricity grid costs. The economic feasibility of each use-case is evaluated, and several business models are proposed. These results are included in the deliverable D4.1.

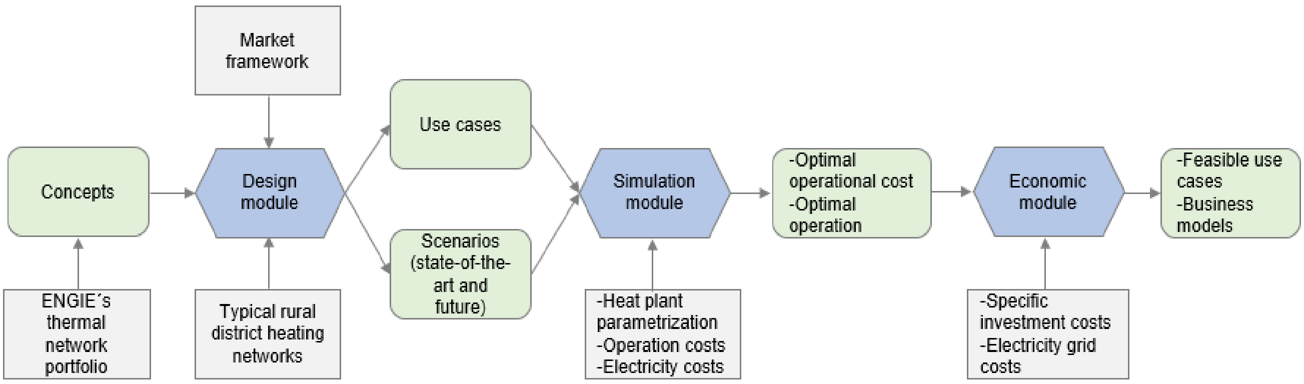

Figure 27: flow chart of the methodology

4.2 Concept development

Several concepts are developed in order to delimit the scope of the heat pump pooling feasibility evaluation presented in the project *fit4power2heat*. The configuration of the concepts is based on ENGIE Austria GmbH’s business segment of thermal networks and the available measurement data (e.g. heat demand profiles, supply/return temperature profiles, volume flow). Additionally, a literature review on the existing thermal networks in Austria (chapter 2 “Overview of typical structures for thermal networks in Austria”) is used, in order to ensure the selection of representative concepts.

The characterization of the concepts is done in terms of number of customers, heat demand, supply and return temperature, capacity installed and type of producers. The three concepts developed comprehend a district heating network, a local heating network and a large customer, as follows:

Concept A: District heating network

The district heating grid supplies more than 200 customers and has a length of around 12 km. The heat supply was 6,5 GWh and the system was in operation for 6.120 hours (3,5 months of summer break) in 2017 (latest year available at the moment of the evaluation). The system is shut down during the summer months (from June to August). In this period, air heat pumps, solar plants or e-rods cover the heat demand. The average supply and return temperatures are 78°C and 46°C respectively.

The network is supplied by two biomass boilers operating alternately, which have a nominal capacity of 2,4 MW and 0,8 MW. In addition, a flue gas condensation system (300 kW) is installed together with a cyclone and an e-filter, in order to deposit the solids contained in the exhaust flue gas of the boilers. The amount of heat that can be recovered amounts to 600 MWh, which results in an overall efficiency increase of about 10%. In order to decouple the heat supply from the grid and cover peaks of demand, a thermal storage tank is available (100 m^3).

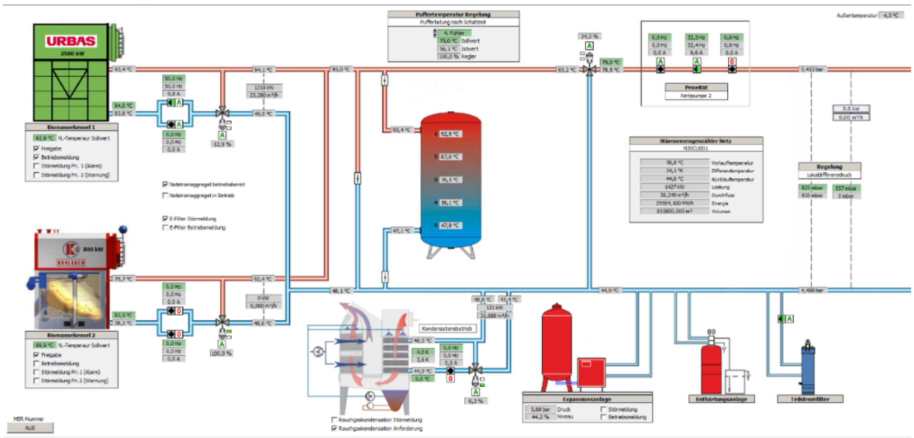

Figure 28: overview of the hydraulic scheme in concept A (Source: technical data provided by ENGIE Austria GmbH)

Concept B: Local heating network

The partly new grid supplies 50 cottages, a manor and several administration buildings. The system is operated at an average temperature of 68°C and a return temperature of 46°C.

The heating center contains two identical biomass boilers, which are operating alternately and have a capacity of 0,5 MW. A thermal storage tank (30 m^3) is located next to the center for peak coverage. In full-year operation, the two boilers supply around 1,5 GWh of heat during 1.711 and 1.592 full load hours respectively. These operation results in a generation of around 70 to 200 MWh per month.

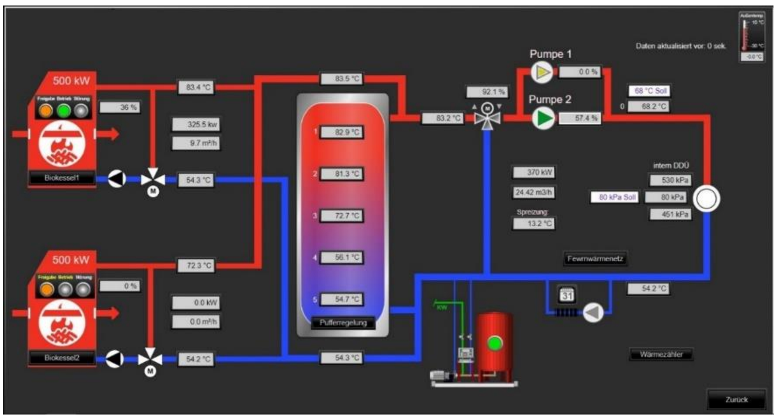

Figure 29: overview of the hydraulic scheme in concept B (Source: technical data provided by ENGIE Austria GmbH)

Concept C: Large customer

This heating concept consists of a hotel facility with a spa area. The heat demand is supplied by a 0,5 MW biomass boiler. Additionally, the grid includes a thermal storage tank with a volume of 16,5 m^3. The annual heat demand of the hotel facility amounted to 2,2 GWh in 2017 (80 - 315 MWh/month). The system is operated with an average supply and return temperature of 75°C and 48°C, respectively.

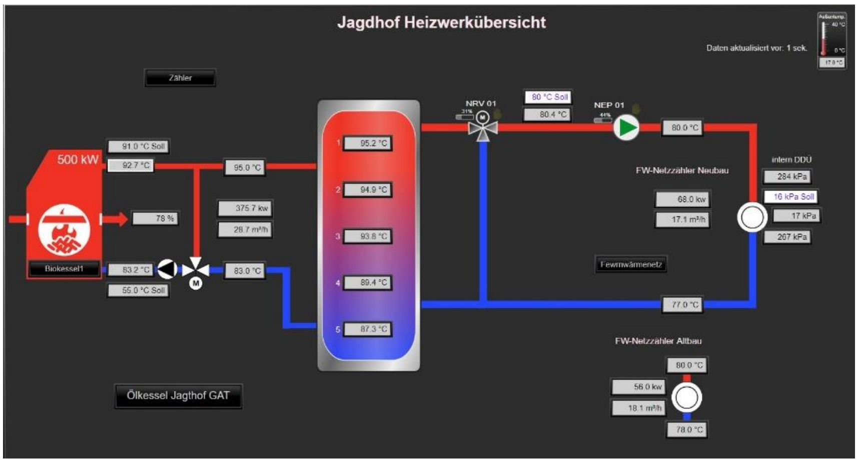

Figure 30: overview of the hydraulic scheme in concept C (Source: technical data provided by ENGIE Austria GmbH)

4.3 Use case development

Several use cases are developed for each concept presented in chapter "4.2 Concept development", in order to investigate the impact of different system parameters on the overall economic feasibility. The development is supported by a literature review on thermal networks (chapter "2 Overview of typical structures for thermal networks in Austria) and on the electricity market in Austria (deliverable D.2.1). This approach ensures the creation of representative use cases and therefore, generalizable and highly replicable technical solutions. The use cases are determined by combining the following system components for each concept:

Heating network

- Demand type: three different demand types are considered, which refer to concept A (district heating network), concept B (local heating network) and concept C (large customer).
- Summer season: different heat demand patterns are assessed. The district heating network is shut down in summer, while the local heating network and the hotel facility operate during this period.
- Building typology: linked to the parameter "demand type", it is used to evaluate residential and non-residential customers which have different heat load characteristics.

Heat pump

- Thermal capacity: two different heat pump sizes are considered: large (224 kW_{th} or 204 kW_{th}) and small (102 kW_{th}).
- Heat source: two different sources are considered (flue gas from the biomass boilers and sewage water), in order to estimate the impact of the source on the heat pump performance. The type of heat source directly influences the COP of the heat pump. Since the networks

considered are biomass-based, it is potentially interesting to use the flue gas as a source for the heat pumps. Regarding sewage water, it presents several advantages as described in chapter "3 Classification of potential sources for heat pumps in thermal networks", due to its relatively high temperature, long-term stability and proximity to urban areas.

Electricity markets

- Market type: two different options have been chosen, namely the day-ahead market and the balancing market. For the last one, two products are considered: automatic Frequency Restoration Reserve (aFRR) and manual Frequency Restoration Reserve (mFRR). Additionally, a flat tariff is also analyzed, as a reference scenario. The frequency containment reserve (FCR) is excluded from this assessment due to the strict technical prequalification criteria (presented in deliverable D2.1). In comparison to aFRR and mFRR, the activation speed and duration are more restrictive (full activation within maximum 30 seconds, lasting for at least half an hour) and the product size is longer (1 week) [22]. Some studies have been carried out to investigate the effect of these requirements on the heat pump operation [23]. As an example, Caterva is the only manufacturer which provides FCR through batteries, while optimizing the operation for the end-customer in a profitable way. In the future they foresee the exploitation of additional flexibility options through other units, such as, heat pumps, small combined heat and power plants or e-cars [24]. However, the readiness level of heat pumps for accessing FCR is still low.
- Bidding strategy: since the revenues in the balancing markets depend on the bid's position in the merit order, three different variations are analyzed. Variation "low" locates the bid at the beginning of the merit order, which is called whenever balancing power is needed, resulting in a high call probability at a lower price. In the variation "medium", the bid is placed at the average market price and it is called when more than half of the merit order is required (medium probability to be called). In variation "high" the bid is placed at the last positions of the merit order. Therefore, it is rarely called but it benefits from higher prices.

Table 8: overview of the use cases

Concept	Use case (1)	Heating network: Demand type: DH network	Heating network: Demand type: Local heating network	Heating network: Demand type: Large customer	Heating network: Summer season: yes	Heating network: Summer season: no	Heating network: Building typology: Residential	Heating network: Building typology: Non-residential	Heat pump: Thermal capacity: Small (102kW$_{th}$)	Heat pump: Thermal capacity: Large (224 kW$_{th}$)	Heat pump: Thermal capacity: Large (204 kW$_{th}$)	Heat pump: Source: Flue gas	Heat pump: Source: Sewage water	Electricity markets: Market options: Day-ahead market	Electricity markets: Market options: Flat tariff	Electricity markets: Market options: Balancing market (aFRR)	Electricity markets: Market options: Balancing market (mFRR)	Electricity markets: Merit order position: Low revenues-high call prob.	Electricity markets: Merit order position: Med. revenues-med.call prob.	Electricity markets: Merit order position: High revenues-low call prob.
	A-baseline								no heat pump installed in A-baseline											
	A1														✓					
	A2													✓						
	A3													✓		✓		✓		
A	A4	✓				✓	✓							✓		✓			✓	
	A5									✓		✓		✓		✓				✓
	A6													✓			✓	✓		
	A7													✓			✓		✓	
	B-baseline								no heat pump installed in B-baseline											
	B1-FG														✓					
	B2-FG													✓						
	B3-FG													✓		✓		✓		
	B4-FG		✓		✓		✓							✓		✓			✓	
	B5-FG								✓			✓		✓		✓				✓
	B6-FG													✓			✓	✓		
	B7-FG													✓			✓		✓	
	B1.1-SW														✓					
	B2.1-SW													✓						
	B3.1-SW													✓		✓		✓		
B	B4.1-SW		✓		✓		✓		✓				✓	✓		✓			✓	
	B5.1-SW													✓		✓				✓
	B6.1-SW													✓			✓	✓		
	B7.1-SW													✓			✓		✓	
	B1.2-SW														✓					
	B2.2-SW													✓						
	B3.2-SW													✓		✓		✓		
	B4.2-SW		✓		✓		✓				✓		✓	✓		✓			✓	
	B5.2-SW													✓		✓				✓
	B6.2-SW													✓			✓	✓		
	B7.2-SW													✓			✓		✓	
	C-baseline								no heat pump installed in C-baseline											
	C1														✓					
	C2													✓						
	C3													✓		✓		✓		
C	C4			✓	✓			✓						✓		✓			✓	
	C5								✓			✓		✓		✓				✓
	C6													✓			✓	✓		
	C7													✓			✓		✓	

(1) FG: flue gas . SW: sewage water

4.3.1 Heat pump parametrization

The heat pump parametrization is carried out in the design module. It enables the selection of the optimal size and hydraulic scheme in terms of efficiency and fuel expenditure.

4.3.1.1 Optimal heat pump integration

The heat pump can be installed in the thermal network in multiple ways. Therefore, a study is conducted in the design module in order to assess the optimal hydraulic scheme. The complete methodology, calculation and results of the study are included in the master thesis "Rauchgaskondensation bei Biomassekessel unter Zuhilfenahme von Wärmepumpe und Regelenergie" [25], developed in the framework of the project *fit4power2heat*. Two different integration schemes are proposed (scheme I and II) and the impact of the heat pump integration in the overall system efficiency is compared.

The module is an excel-based tool which consists of six calculation blocks (Figure 31), as follows:

1. In this block, the following input parameters can be defined for the heating network: supply temperature, return temperature and capacity. The volume flow is calculated.
2. The heat losses of the heat plant (biomass boiler) can be entered and the total heat to be supplied is calculated.
3. The capacity and efficiency of the biomass boiler is given as an input and the flue gas availability is calculated. The efficiency of the boiler is heavily dependent on the fuel quality, the flue gas recirculation to reduce the residual oxygen and the flue gas temperature. In order to create uniform conditions, the efficiency value is fixed.
4. The fuel demand with and without condensation is calculated for the biomass boiler and the heat pump.
5. This block displays the flue gas cooling potential with and without condensation.
6. The heat pump parameters can be set (e.g. COP, temperature differential). The power of the evaporator, as well as the temperatures and the volume flows in the evaporator and the condenser are determined.
7. This block calculates the output temperature of the flue gas, the temperature differential in the flue gas condenser and the heat recovery from the flue gas.

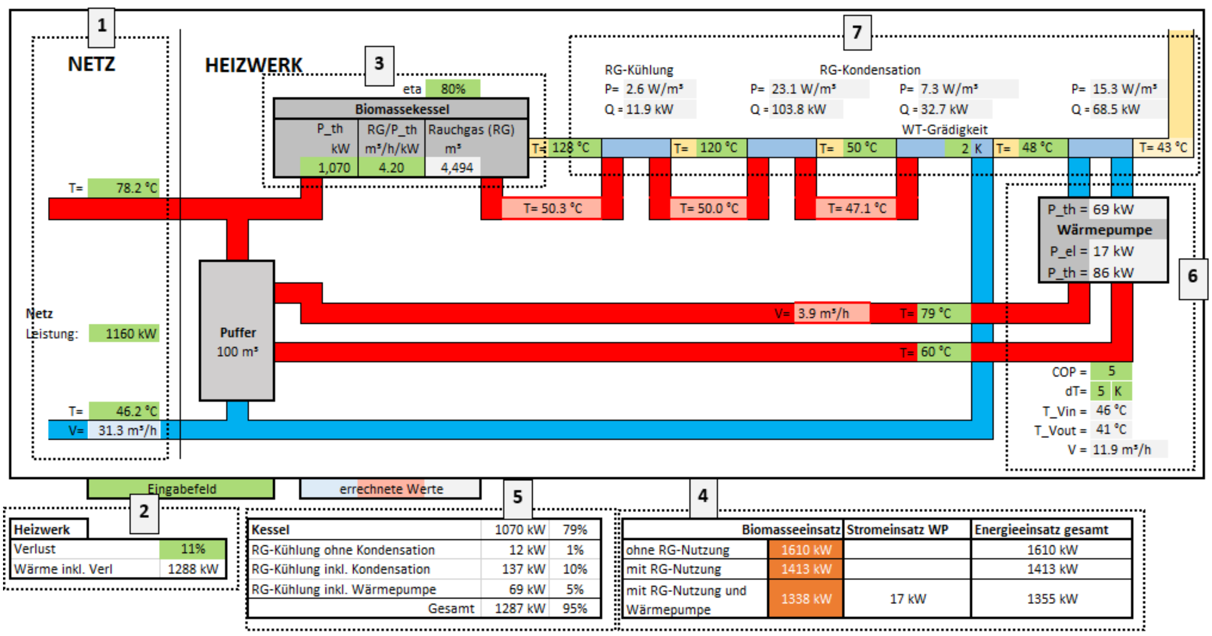

Figure 31: interface of the heat pump design module

The first integration possibility proposed (scheme I) is presented in Figure 32. In this case, the return line of the heating grid is cooled down by the evaporator of the heat pump. Then the volume flow enters the flue gas condenser, where its temperature is increased through the heat exchange with the flue gas stream. The liquid refrigerant of the heat pump is evaporated at low pressure by the evaporator and compressed afterwards, leading to a temperature increase. The compressed refrigerant is condensed at high pressure and thus at high temperature. The resulting heat is transferred by the condenser to the return line before it goes into the biomass boilers.

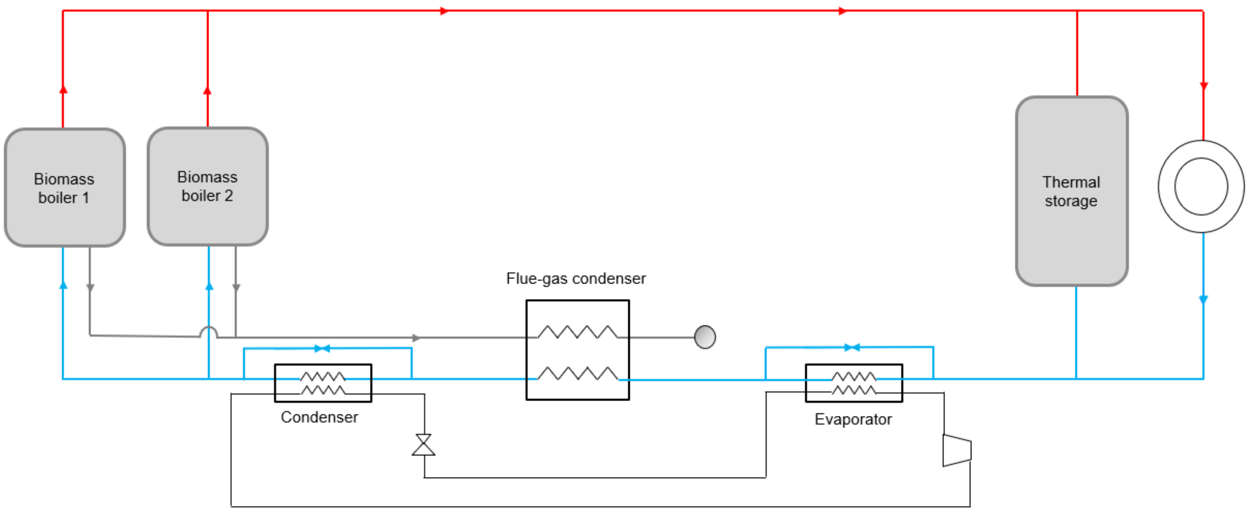

Figure 32: heat pump integration scheme I

The second integration option (scheme II) is shown in Figure 33. In this case, the heat from the flue gas is recovered in two stages. Initially, the flue gas is cooled down by the return line of the thermal network and partially condensed. Afterwards the flue gas is cooled down in an additional heat exchanger, which forms a loop with the evaporator of the heat pump. This configuration enables an optimal control of the temperature and the volume flow. The heat extracted is transferred by the condenser to the water contained in the thermal storage, avoiding sharp temperature differentials between the heat pump source and sink.

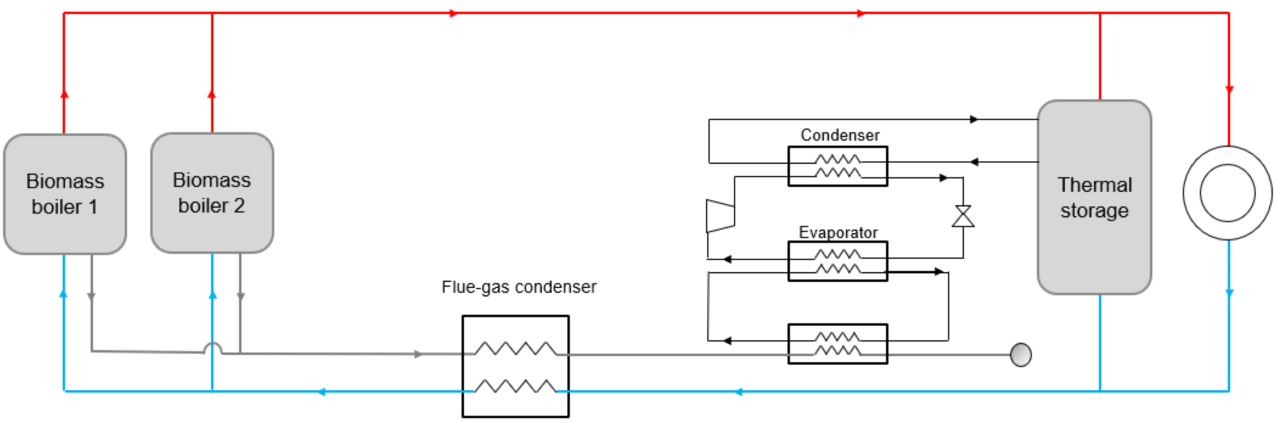

Figure 33: heat pump integration scheme II.

Since the design module performs static simulations, four different operation points are defined based on the operation load of the biomass boiler 1 (2400 kW) and boiler 2 (800 kW) in concept A. The simulations are run under the conditions defined by these operation points for scheme I and scheme II. The aim is to analyze the reduction in biomass expenditure and the increase in efficiency while the biomass boilers are operating in the defined load segments with and without a heat pump. A fix COP of 5 is considered for the heat pump. Based on this value and the heat availability in the flue gas and the return line, the required electric power is calculated.

The operation points are selected based on the measurement data provided by *ENGIE Austria GmbH*. The most frequent load segments are selected, so that they represent the annual operation of the boilers.

Operation point 1 considers the annual average operational load of the biomass boiler 1 (2400 kW), which prevails at 17.5% of the operating time. Therefore, increases in the boiler efficiency have a major impact on the overall system performance. Operation point 2 represents the average value of the upper load range of the biomass boiler 1 (above 2MW). The operation point 3 considers 60% of the capacity of the boiler, which is the average value of the load range between 1400 kW and 1600 kW. The operation point 4 considers the average operational load of the biomass boiler 2 (800 kW). It is interesting to evaluate the performance of the system when this boiler is running since it can cover the heat demand of the grid below 1 MW more efficiently than boiler 1 (2400kW), due to the minimum load requirement. Additional peak loads up to 1300 kW of short durations can also be covered by the small biomass boiler, together with the storage and the heat pump (if installed).

The simulations are performed for scheme I and scheme II, considering the four operation points under different system configurations: without flue gas condenser, with flue gas condenser, without a heat pump and with a heat pump. According to the results shown in Table 9, scheme II presents a better performance than scheme I, since the efficiency increase provided by the heat pump (expressed by the lower heating value), is 7% higher for all operation points. Since the flue gas is at or below the dew point before entering the additional heat exchanger, a large amount of latent heat can be withdrawn from the flue gas, resulting in a decrease of the biomass expenditure. Scheme I, on the contrary, is neither economically nor energetically feasible. The electric power required to lower the temperature of the return line cannot be compensated with the heat transferred by the condenser. In average, around 54% of the electric power is used to bring the heat that is already existing in the system into a higher level right before the biomass boiler. This procedure could be done cheaper and more efficiently by recirculating and mixing the output line from the boiler with the return line that goes into the boiler, in order to prevent condensation from the water vapor contained in the flue gas. Moreover, scheme I could also present problems related to the control of the heat pump under variable temperature and mass flow conditions. On the contrary, scheme II enables the hydraulic decoupling between the heat pump and the network, the adaptation of the input temperature to the condenser according to the optimal operating point and the delivery of heat at the level which is required by the heating network. Therefore, no further consideration is given to scheme I.

Table 9: comparison of the simulation results for the four operation points in scheme I and scheme II [25].

		Betriebspunkt 1				Betriebspunkt 2				Betriebspunkt 3				Betriebspunkt 4			
		ohne RGKA	mit RGKA	mit WP S I	mit WP S II	ohne RGKA	mit RGKA	mit WP S I	mit WP S II	ohne RGKA	mit RGKA	mit WP S I	mit WP S II	ohne RGKA	mit RGKA	mit WP S I	mit WP S II
Netzleistung	kW_{th}	1160				2115				1500				870		897	960
Vorlauf	°C	78,2				83,5				82,5				77,5			
Rücklauf	°C	46,2				48				47,2				45,1			
dT	K	32				35,5				35,3				32,4			
Volumenstrom	m^3/h	31,3				51,4				36,6				23,1		23,9	26,1
Rauchgas nach Kessel	°C	128				151,5				151,5				132,2			
Rauchgas vor Kamin	°C	128	48	46	40	152	50	48	45	132	49	47	42	47	47	44	39
WP-Leistung el.	kW_{el}	0	0	18	22	0	0	30	30	0	0	24	22	0	0	18	17
Biomasse	kW_{th}	1413	1413	1381	1275	2575	2575	2506	2363	1813	1813	1769	1638	1041	1041	1041	1041
Kesselleistung	kW_{th}	1130	1130	1105	1020	2060	2060	2005	1890	1450	1450	1415	1310	833	833	833	833
Leistung RGK	kW_{th}	0	157	171	173	0	290	344	459	0	214	250	351	0	132	164	234
Input	kW_{th}	1413	1413	1399	1297	2575	2575	2536	2393	1813	1813	1793	1660	1041	1041	1059	1058
Output	kW_{th}	1130	1287	1288	1288	2060	2350	2349	2349	1450	1664	1665	1661	833	965	997	1067
Wirkungsgrad		0,800	0,911	0,921	0,993	0,800	0,913	0,926	0,982	0,800	0,918	0,929	1,001	0,800	0,927	0,941	1,009

4.3.1.2 Heat pump design

Flue gas as a source

Considering the simulations presented in the previous chapter, the heat pumps are sized according to the following energy balance for concept A, B and C:

Equation 1: energy balance for the heat pump

$$\dot{Q}_{th} = \dot{V}_W * c_{pW} * \Delta T$$

$\dot{Q}_{th}$..............heat transferred by the condenser of the heat pump [kW]
$\dot{V}_W$................volume flow of the water in the condenser [m^3/h]
c_{pW}..............specific heat of water [kWh/m^3K]
ΔT..................temperature differential of the water in the condenser [K]

The average volume flows and temperature values assigned to the heat pumps installed in concepts A, B and C lead to the following thermal capacities:

Equation 2: energy balance for the heat pump in concept A

$$\dot{\mathrm{Q}}_{\mathrm{th}} = \dot{\mathrm{V}}_{\mathrm{W}} * \mathrm{c}_{\mathrm{pW}} * \Delta\mathrm{T} = 10{,}75\ \frac{\mathrm{m}^3}{\mathrm{h}} * 1{,}16\ \frac{\mathrm{kWh}}{\mathrm{m}^3\mathrm{K}} * 18\ \mathrm{K}\ = 224\ \mathrm{kW}$$

Equation 3: energy balance for the heat pump in concept B and C

$$\mathbf{\dot{Q}_{th} = \dot{V}_W * c_{pW} * \Delta T = 5,9\ \frac{m^3}{h} * 1,16\ \frac{kWh}{m^3K} * 15\ K\ = 102\ kW}$$

Based on the temperatures and thermal capacity values calculated, a suitable COP value for the heat pumps is provided by *ENGIE Kältetechnik GmbH*, a heat pump producer with a great know-how in the field of heat pump technologies, namely in large and high temperature heat pumps. According to the assessment, the heat pump installed in concept A requires a COP of 5,4, while the heat pumps installed in concepts B and C would require a COP of 5,1. This technical parametrization leads to an electric power of 41,6 kW for the heat pump in concept A and 20 KW in concept B and C. The heat pumps chosen are modulating units, rather than on/off units, since they provide a higher flexibility to the system. The following technical specifications should be considered in the operation of the heat pumps:

- Minimal runtime: 9 minutes
- Minimal shutdown period: 1 minute
- Maximum number of operation cycles: 6 per hour
- Turn-on time: 3 minutes
- Turn-off time: 3 minutes

Sewage-water as a source

The characterization of the sewage water source and the connection to a heat pump could present a considerable variability depending on the typology of both the source and the thermal network, which would require a detailed technical evaluation of the individual use cases. Since the aim of *fit4power2heat* is the execution of an initial feasibility assessment of several use cases, a generalized sewage water source is parametrized, which enables an equal comparison between the different cases.

The sewage water source is implemented in concept B. For comparison purposes, the heat pump capacity selected is equivalent to the capacity chosen for the heat pump which uses flue gas as a source (102 kW_{th}). In order to estimate the impact of implementing a bigger heat pump in the network, a double-sized heat pump is also considered (204 kW_{th}). As described in section "3.1.7 Infrastructure: tunnels and sewage water channels", the average sewage water temperatures usually range between 10°C and 20°C. Considering an average sewage water temperature of 20°C and an output temperature of 61°C in the condenser, the suitable COP of the heat pump is estimated to be 3,8 according to the technical specifications provided by *ENGIE Kältetechnik GmbH*. The average volume flow requirements for the sewage water are 21,80 m^3/h and 43,20 m^3/h for the small (102 kW) and large (204 kW) heat pumps respectively.

The following technical specifications should also be considered in the operation of the heat pumps:

- Minimal runtime: 9 minutes
- Minimal shutdown period: 1 minute
- Maximum number of operation cycles: 6 per hour
- Turn-on time: 3 minutes
- Turn-off time: 3 minutes

4.3.1.3 Parametrization of the selected hydraulic schemes and heat pumps

This chapter presents the parametrization of the use cases for concepts A, B and C (defined in Table 8), based on the optimal hydraulic scheme selected in chapter "4.3.6.1 Optimal heat pump integration" and the heat pump technical specifications described in chapter "4.3.6.2 Heat pump design".

The use cases "A-baseline", "B-baseline" and "C-baseline" are designed based on the concepts A, B and C respectively (described in chapter "4.2 Concept development"). All baseline use cases include one or two biomass boilers and a thermal storage tank. Additionally, there is already a flue gas condenser installed in the use case "A-baseline". Table 10 shows the parametrization of each baseline use case, in terms of heat demand, average return/supply temperature, capacity of the biomass boiler, storage volume and flue gas temperature.

Table 10: characterization of the use cases "A-Baseline", "B-baseline" and "C-baseline".

Parameter	Unit	Use case A	Use case B	Use case C
Heat demand	GWh/year	6,5	1,5	2,2
Average supply temperature (T_{supply})	°C	78	68	75
Average return temperature (T_{return})	°C	46	46	48
Biomass boiler capacity (boiler 1/boiler 2)	kW	2400/800	500/500	500
Storage volume	m^3	100	30	16,5
Existing flue gas condenser in the baseline	-	yes	no	no
Average flue gas temperature before condenser (T_{FG_in})	°C	130	-	-
Average flue gas temperature after condenser (T_{FG_out})	°C	48	-	-
Average flue gas temperature after heat exchanger ($T_{FG\_HE\_out}$)	°C	41	-	-

Except for the baseline cases, the rest of the use cases have a compression heat pump installed. As shown in Figure 34 and Figure 35, the hydraulic scheme for the heat pump integration considers two variations depending on the type of source available (flue gas or sewage water). Table 11 shows the parametrization of the heat pumps for the concepts A, B and C, in terms of type of source, capacity, COP, type of refrigerant, temperatures in the evaporator and condenser and source temperature.

In the first variation (Figure 34), where the flue gas is used as a source for the heat pump, the heat recovery occurs in two stages, as described in chapter "4.3.6.1 Optimal heat pump integration". The flue gas exits the boiler at a temperature T_{FG_in}. The boiler(s) are connected to a flue gas condenser, in which the flue gas is cooled down by the return line of the thermal network and partially condensed (T_{FG_out}). This results in a slight increase of the return temperature which allows to operate the biomass boiler with a lower load. The sensible and latent heat from the output of the flue gas condenser is recovered by an additional heat exchanger in a second stage and transferred to the evaporator (T_{eva_in}). This additional heat exchanger is recommended in order to uncouple the network from the evaporator's entry and ensure a stable heat pump operation [26, 27]. The regulation of the mass flow mitigates the effect of abrupt boiler load fluctuations in the flue gas temperature or mass flow, and consequently in the evaporator´s inlet temperature. The stream of liquid refrigerant is evaporated at low pressure by the evaporator. The refrigerant vapor is then compressed, leading to a temperature increase. This compressed refrigerant stream is condensed at high pressure and thus at high temperature. The resulting heat is transferred at temperature T_{con_out} to the water contained in the lower half of the storage (55-60°C) and this flow is fed back to the upper layer of the storage tank in order not to affect the stratification. This configuration avoids sharp temperature differentials between the source and the sink.

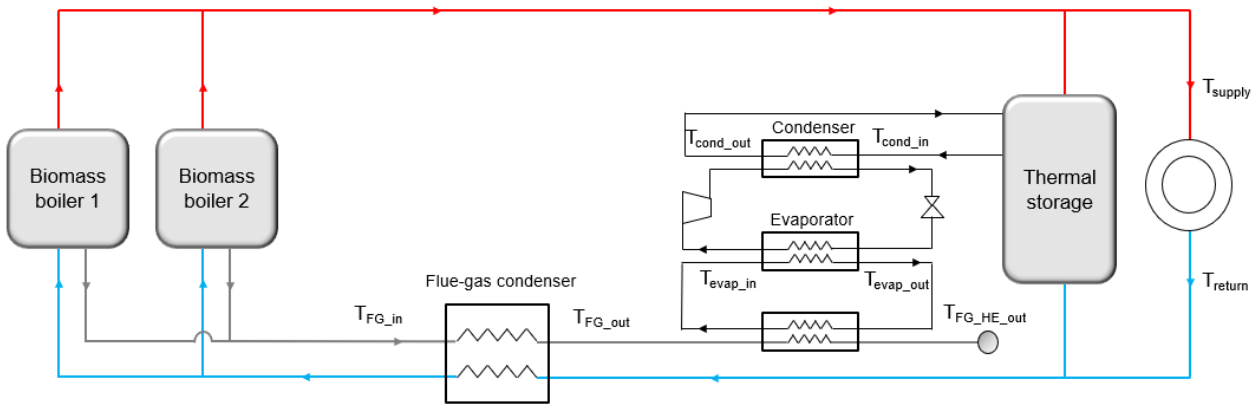

Figure 34: heat pump integration scheme (flue gas as a source). Additional temperature parametrization included in Table 11.

In the second variation (Figure 35), the sewage water serves as a source for the heat pump. The heat from the sewage water (at temperature T_{SW}) is recovered by the heat exchanger and transferred to the evaporator (T_{eva_in}). This heat is then transferred to the condenser and supplied to the return line of the heating network (T_{con_out}). A bypass is installed in order to regulate the mass flow into the heat pump and guarantee a stable operation in presence of temperature or mass flow fluctuations in the return line.

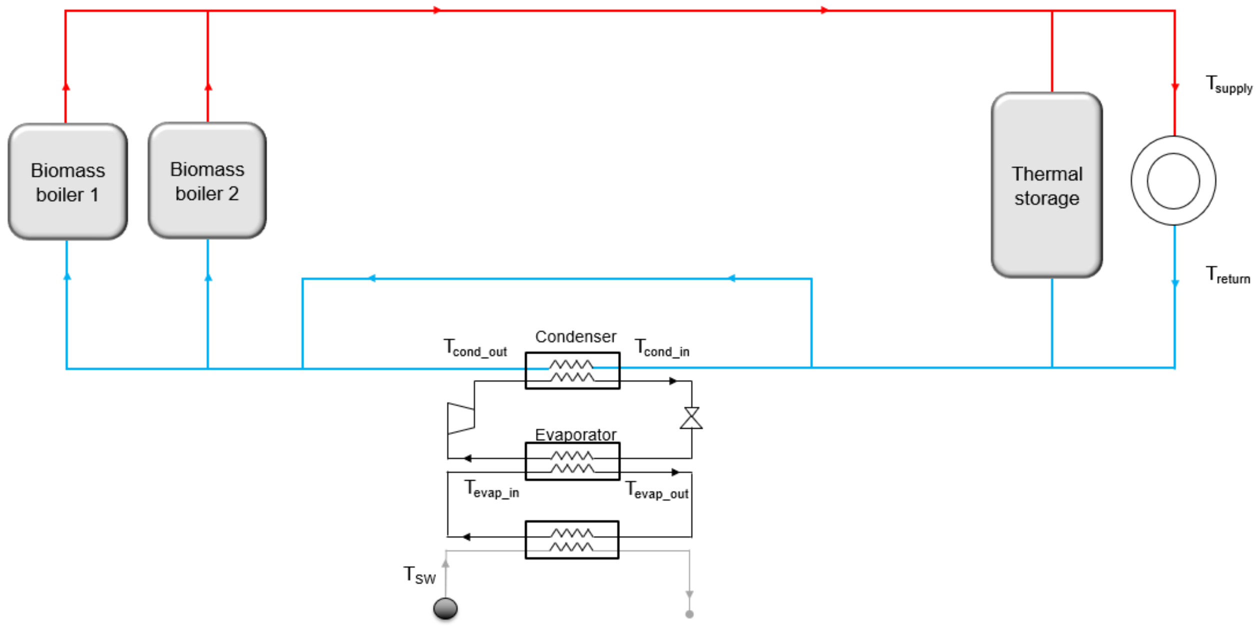

Figure 35: heat pump integration scheme (sewage water as a source). Additional temperature parametrization included in Table 11.

Table 11: technical specifications of the heat pumps and sources in the concepts A, B and C.

Parameter	Unit	Concept A	Concept B		Concept C
Heat pump source	-	Flue gas	Flue gas	Sewage water	Flue gas
Heat pump capacity	kW_{th}	224	102	102 and 204	102
Heat pump COP	-	5,4	5,1	3,8	5,1
Refrigerant	-	R1234ze	R1234ze	R134a	R1234ze
Average evaporator inlet temperature (T_{evap_in})	°C	47	46	20	49
Average evaporator outlet temperature (T_{evap_out})	°C	40	40	17	39
Average condenser inlet temperature (T_{cond_in})	°C	60	55	46	60
Average condenser outlet temperature (T_{cond_out})	°C	78	70	61	75
Average flue gas temperature before condenser (T_{FG_in})	°C	130	150	-	140
Average flue gas temperature after condenser (T_{FG_out})	°C	48	47	-	50
Average flue gas temperature after heat exchanger ($T_{FG\_HE\_out}$)	°C	41	41	-	40
Average sewage water temperature (T_{SW})	°C	-	-	20	-

4.3.2 Parametrization of the biomass boiler efficiency

The integration of a flue gas condenser in combination with a heat pump enhances the efficiency of the biomass boiler, which must be considered in the simulation of the hydraulic schemes presented in the previous chapter. The efficiency assessment is based on the results of the method presented in [28] and summarized in the diagram below (

Figure 36). It shows how the combustion efficiency increases at lower flue gas temperatures according to a certain biomass humidity and air excess. The following assumptions are considered:

- Wood composition $CH_{1.44}O_{0.66}$, representing with reasonable accuracy the mean relation between carbon, nitrogen and oxygen in the most common wood typologies (on moisture- and ash-free basis)

- Upper heating value calculated by the Boie equation [29]: $19{,}9 \cdot 10^6$ J/kg on moisture- and ash-free basis.
- Complete combustion of the wood
- Ambient pressure and temperature (1013 mbar and 0 °C respectively)

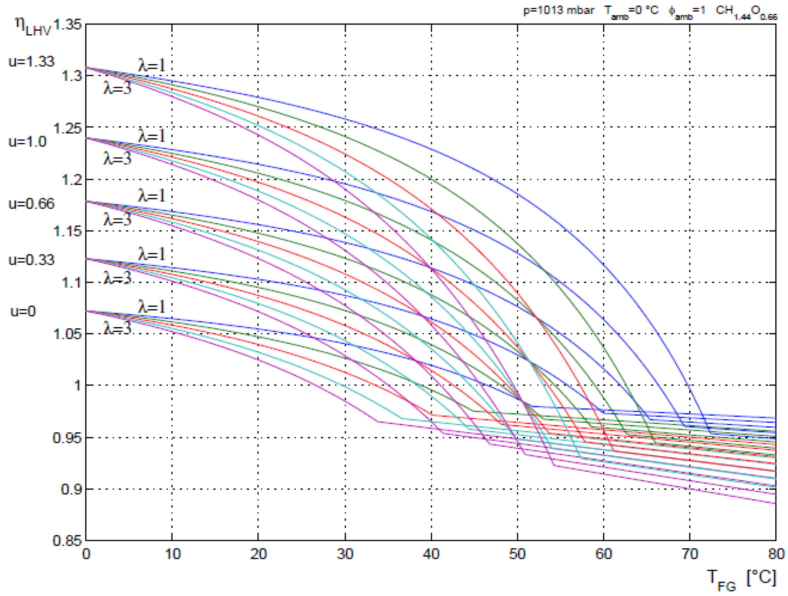

Figure 36: efficiency of wood combustion with reference to the lower heating value. Complete combustion of the wood. λ =1; λ =1,5; λ =2; λ =2,5; λ =3. $\Delta h_{LHV} = \Delta h_{UHV} - (u+0{,}54) \cdot \Delta h_V$; $\Delta h_V = 2{,}5016 \cdot 10^6$ [J/kg$_F$].

The combustion efficiency is defined as the ratio between the heat delivered and the thermal input of the boiler. The thermal input can correspond either to the higher or to the lower heating value of the fired fuel, according to the adopted convention. In the presented study the efficiency is referred to the lower heating value, which is calculated subtracting the latent heat of condensation of the humidity content in the flue gas from the higher heating value. In other words, the definition of the lower heating value does not take into consideration the heat recovered either by re-condensing the water present as moisture fraction in the burned fuel or by condensing the water obtained as combustion product of the hydrogen fraction. This explains why, as presented in Figure 36, such a combustion efficiency can adopt values above 100% in some cases.

The right area of Figure 36, which considers linear efficiency trends, represents the boiler's operating range without condensation (the heat recovered from the flue gas is linear with the temperature, i.e. it consists of sensible heat). The left area represents the boiler operation in condensing mode, i.e. with latent heat recovery changing the linearity of the efficiency versus the temperature. The condensing mode takes place at temperatures below the dew points, which corresponds to the angular points in the figure.

In the present study, an air excess of 50% is assumed in all use cases (input to stoichiometric ratio λ = 1.5). According to the measurement data provided by *ENGIE Austria GmbH*, the humidity of the wood is 58% in concept A and 50% in concepts B and C. The dew point is located at around 52 °C. These assumptions, together with the flue gas temperatures presented in Table 11 (T_{FG_in}, T_{FG_out}, $T_{FG\_HE\_out}$) are implemented in the diagram shown in

Figure 36. This procedure aims at the calculation of the full load efficiency of the biomass boiler, as well as the efficiency increase provided by the operation of the flue gas condenser and the heat pump.

Table 12: full load operation efficiency of the biomass boiler in combination with a flue gas condenser and a heat pump.

Units installed in the network	Full load operation efficiency		
	Concept A	Concept B	Concept C
Biomass boiler	88 %	88%	87%
Biomass boiler + flue gas condenser	97%	97%	97%
Biomass boiler + flue gas condenser + heat pump	101%	100%	103%

4.4 Definition of state-of-the-art and future scenarios

Deliverable D2.1 presents an exhaustive overview of the current status of the electricity market structure in Austria, together with an overview of the expected future market developments. On the basis of this description, the current and future scenarios are parametrized, which establishes the boundary conditions for the simulation of the use cases defined in chapter “4.3 Use case development”.

The framework of the state-of-the-art scenario is defined according to the following assumptions:

- **Biomass price**

  Following the measurement data provided by *ENGIE Austria GmbH*, it is assumed that the biomass price amounts to 24.9 €/$MWh_{produced}$.

- **Electricity prices and call probabilities**

  Price forecasting is a complex issue due to the nonlinear, nonstationary and time variant behavior of electricity price time series. In order to simplify it, the approach followed is based on the utilization of historical data to create a “perfect forecast” model, which represents a trade-off between the robustness of the optimization solution and the model complexity. It is assumed that the aggregator has a perfect prognosis of the prices and call probabilities in the balancing market and spot market. In reality, the aggregator would also carry out such forecasts but would typically lower the revenues due to the existing uncertainties; therefore, the approach followed only considers the “best case” scenario. The parametrization of the balancing market is based on the energy prices and power prices published by APG (Austrian Power Grid) [30, 31] for the year 2017, which was the most recent year available at the time when the evaluation was carried out. Table 13 shows the average electricity market prices and call probabilities for the year 2017.

Table 13: average electricity market prices and call probabilities for 2017

Market		Energy price (€/MWh]		Call probability (%)		Power price (€/MWh/h)	
		Positive	Negative	Positive	Negative	Positive	Negative
aFRR	Low	55	-9	77	87	2	3
	Medium	622	147	2	5	2	3
	High	4.446	3.271	0,3	0,8	2	3
mFRR	Low	127	102	2	2	3	2
	Medium	(*) 913	(*) 497	0,1	0,5	3	2
Day-ahead Spot (Epex)		34		-		-	
Flat Tariff		67		-		-	

(*) average energy prices (since the merit order is not available).

The future scenario is set up based on the development of electricity and biomass prices, as well as call probabilities during the last years. Forecasting the future development of the mentioned variables implies a great complexity and uncertainty due to their stochastic character and frequent changes in the electricity market design. Therefore, the degree of variability assigned to them is determined based on the historical electricity prices published by APG [31], and historical biomass prices published by Österreichischer Biomasse-Verband [32] between 2012 and 2018. In addition, a review on several publications including a prognosis for biomass prices is also considered [33]. This approach leads to the following assumptions:

- Biomass price variation: ±10% of the biomass price assumed for the state-of-the-art scenario.
- Electricity prices variation in the day-ahead market: ±25% of the price assumed for the state-of-the-art scenario.
- Electricity prices variation in aFRR: ±20€ over the prices assumed for the state-of-the-art scenario.
- Call probability in aFRR (low position in the merit order): -25% and -50% of the call probabilities assumed for the state-of-the-art scenario.

This scenario is developed in order to carry out a sensitivity analysis of the influence of future market developments in the proposed technical solutions. Since it is assumed that the resulting conclusions will be analogue to all use cases and balancing market products, only the most favorable case for the state-of-the-art scenario will be evaluated under future conditions.

5 Optimisation model (Task 3.3)

The use cases described in chapter “4.3 Use case development” are simulated under the state-of-the-art and future boundary conditions by means of an operational optimization model. It provides the optimal operational cost for each use case, together with the optimal operation strategy for the heat suppliers and the optimal bidding strategy for the heat pumps.

5.1 Model description

The techno-economic assessment of the use cases is carried out by an operational optimization model implemented in Python.

The model is based on the mixed integer linear programming (MILP) method. The MILP is suitable for solving unit commitment problems due to its flexibility in addressing the tradeoffs between the system accuracy and the robustness of the optimization solution method, especially in the absence of uncertainty (in demand or energy prices for example) [34, 35].

The model provides the cost optimal operation strategy for the components implemented in the energy system. These components, which include the biomass boilers, storages and heat pumps, are imported into the model in the form of unit specific data. The input data for the biomass boilers and heat pumps consider the nominal capacity, efficiency, minimum partial load operation, ramp-up rate, operation costs and fuel costs. The storage parametrization is based on the capacity, thermal loss factor and the minimum state-of-charge. The electricity market is parametrized based on energy prices, power prices and call probabilities.

Due to the linearity of the model, the non-linear character of some system properties is simplified, such as the non-linear efficiency-part load relationship for power plants. This procedure establishes the necessary compromise between an acceptable computational time and robustness of the solution. The binary feature of the MILP allows the scheduling of the components in the system. Therefore, the implementation of binary variables defines the on/off operation of heat plants, as well as the control strategy of storages.

The model is formulated as a set of linear algebraic equations representing the interaction between components and together they govern the energy flow between them, as well as the operation behavior. These equations include decision variables defining fuel consumption, heat generation and storage load among others. The solution of the decision variable is determined by the solver according to the data signals (e.g. time series of heat demand, costs parameters and component specific operation boundaries). The objective function to be minimized is formulated as a summation of the product between cost parameters and decision variables:

Equation 4: general formulation of the objective function

$$min \sum_{t=1}^{n} c_j \cdot x_j$$

$x_{j.}$……….……..decision variable $x_{j.}$
c_j ……….…….cost parameter corresponding to a decision variable $x_{j.}$
t ……….……..time period (t = 1,2,… n)

The objective function represents the minimized system operation cost over a period of one year, representing the operational cost of heat suppliers. More specifically, the objective function is represented as follows:

Equation 5: objective function

$$min.\, operational\ costs = \frac{1}{4}\sum_{t=1}^{n}((\sum_{i=1}^{n} cost_{heat}) + cost_{grid} + cost_{da} - revenues)$$

t ……..………………… number of 15 min base optimization time slots (t=1,2,…,n)
i ………..……………………. number of heat suppliers (i=1,2,…,n)
$cost_{heat}$ ……….………………....heat generation costs [€]
$cost_{grid}$ ……….……………….... variable grid costs [€]
$cost_{da}$ ……..……………………. costs of the electricity bought in the day-ahead market [€]
revenues……….……………….... revenues obtained from the participation in the balancing market [€]
*Factor 4 refers to the 15-min time steps of the optimization.

where:

Equation 6: heat generation cost equation

$$cost_{heat} = prod_{heat} \cdot (cost_{fuel} + F_{PE} \cdot F_{co2} \cdot CEA)$$

$cost_{heat}$ ……….………………....heat generation costs [€]
$prod_{heat}$ ……….…………………heat production [MWh]
$cost_{fuel}$ ……….……………….… fuel cost [€/MWh]
F_{CO2}……..……………………... CO_2 factor [t_{CO2}/MWh]
F_{PE}……..…………………..…. primary energy factor [-].
CEA……..……………………... European emission allowance price [€/t_{CO2}].

Equation 7: grid cost equation

$$cost_{grid} = cost_{grid\_frr} \cdot call_{neg} + cost_{grid\_da} \cdot (da + call_{pos})$$

$cost_{grid}$ ……….…………..….. variable grid costs [€/MWh]
$cost_{grid\_frr}$ ……….……………… variable grid costs corresponding to the balancing market [€/MWh]

$call_{neg}$ …………………………… negative balancing energy called by the market [MWh]
$cost_{grid\_da}$ …………………………variable grid costs corresponding to the day-ahead market [€/MWh]
da…………………………………. electricity bought in the day-ahead market [MWh]
$call_{pos}$……………………………… positive balancing energy called by the market [MWh]

Equation 8: cost equation of the electricity bought in the day-ahead market

$$cost_{da} = price_{da} \cdot da$$

$cost_{da}$ ……………………………. costs of the electricity bought in the day-ahead market [€]
$price_{da}$ ……………………………electricity price in the day-ahead market [€/MWh]
da………………………………..... electricity bought in the day-ahead market [MWh]

Equation 9: equation of revenues derived from the balancing market.

$$revenues = -price_{power\_pos} \cdot a_{pos} + price_{power_{neg}} \cdot a_{neg} - price_{energy\_pos} \cdot call_{pos} - price_{energy\_neg} \cdot call_{neg}$$

revenues …………………………...revenues derived from the balancing market [€]
$price_{power\_pos}$ ……………........... power price for positive balancing energy [€/MWh/h]
a_{pos}……………………………......positive balancing power offered [MWh/h]
$price_{power\_neg}$ ……………........... power price for negative balancing energy [€/MWh/h]
a_{neg}…………………………..........negative balancing power offered [MWh/h]
$price_{energy\_pos}$ ……………………energy price for positive balancing energy [€/MWh]
$call_{pos}$……………………………… positive balancing energy called by the market [MWh]
$price_{energy\_neg}$ ……………………energy price for negative balancing energy [€/MWh]
$call_{neg}$……………………………….negative balancing energy called by the market [MWh]

The system constraints can be represented with the following generalized linear model:

Equation 10: system constrains

$$\sum_{j=1}^{n} a_{ij} \cdot x_j = b_i \quad (i = 1,2,\dots,m)$$

$$x_j \geq 0 \qquad (j = 1,2,\dots,n) \qquad x_j: binary \qquad (for\ some\ j = 1,2,\dots,n)$$

a_{ij} ……………..……..multiplication coefficient of a decision variable x_j .
b_i ……………….input variable

The equation applies to all linear constraints, generating a space of feasible solutions for the decision variables. This solution space guides the objective function finding the optimal outcome.

Considering the limitations related to the computational capacity, the optimization problem, which is solved for a whole year, is split into smaller optimization problems. The optimization is carried out for 2 days, on a 15 min time-base and run recursively through the year. The optimization is performed over 2 days in order to optimize the operation of the storage and ensure its availability, but only the solution for the first 24 hours is stored. The continuity of the solution is ensured by using the final values of the optimization of day i-1 as the initial values of the optimization for day i (Figure 37).

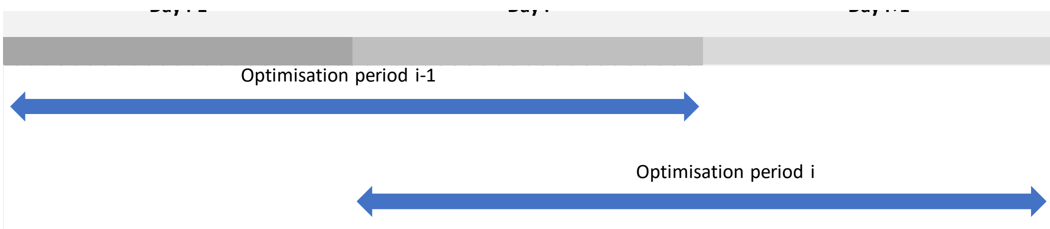

Figure 37: optimization time horizon

5.2 Model inputs

The following inputs have been considered for the different system components:

<u>HEAT PLANTS</u>

- The minimum load considered for the biomass boilers is 25% of the nominal capacity and for the heat pumps 50% of the nominal capacity.
- The ramp-up/down time assumed for the biomass plants is 25% of the nominal capacity [MW] per simulation time-step (15 min), which means that they can reach the full capacity within 1 hour.
- A constraint is implemented to ensure the operation of the boiler for at least 1 hour (they are not allowed to switch off before this time period).
- The two boilers implemented in concept A and concept B do not run simultaneously. Therefore, they are modelled as a single heat plant in order to simplify the modeling approach. Based on the measurement data provided by *ENGIE Austria GmbH*, the running periods are defined for the biomass. In concept A, boiler 1 (2400 kW) runs between January-March, mid of April-end of April and November-December, while boiler 2 (800 kW) runs during the remaining months. The two boilers implemented in concept B are equivalent (500 kW).

<u>THERMAL NETWORK</u>

The thermal network is considered as a black box in the optimization model, which means that the model does not perform a dynamic simulation of the temperatures, pressure drops and losses. Since the influence of these variables in the COP is neglected, it must be considered that the results obtained are valid as long as the assumed boundary conditions are kept.

<u>STORAGE</u>

- The calculation of the storage losses is based on the standing losses equations for hot water storage tanks described in the regulation No 812/2013 of 18 February 2013 of the European Commission [36]. The equation used refers to efficiency class C, which is the minimum required since September 2017:

  Equation 11: storage losses

  $Q_{storage\_losses}$ [W] = $12 + 5.93 \cdot V^{0,4}$ where V: storage volume [L]

- The modelling of the storage is based on the method presented in [37]. It must be ensured that there is enough storage capacity available for the extreme case of a complete call of the heat pump pool. Figure 38 shows an example of the operational planning of the storage for one day.

  The diagram at the bottom of Figure 38 represents the offered capacity in the electricity market. The day-ahead market is represented by grey bars (positive: charging, negative: discharging). The balancing market, which considers the mFRR product in this case, is represented by green arrows (positive balancing power) and orange arrows (negative balancing power). The positive balancing power is shown as a downward arrow since it leads to a reduction of the load in the storage.

The diagram at the top of Figure 38 represents the load of the storage. The grey area shows the expected storage load, while the dashed red lines show the upper and lower boundaries, which correspond to the extreme case of a complete call. The maximum storage capacity is reached with a complete negative call, while a complete positive call leads to the minimum load. Based on the prequalification conditions for the balancing market, the extreme values are calculated for a complete 4 hours call. For both boundary values, the day-ahead offer of the next 4 hours is added to the expected storage load. This configuration ensures that when a call takes place the storage load will always be kept within the established upper and lower boundaries.

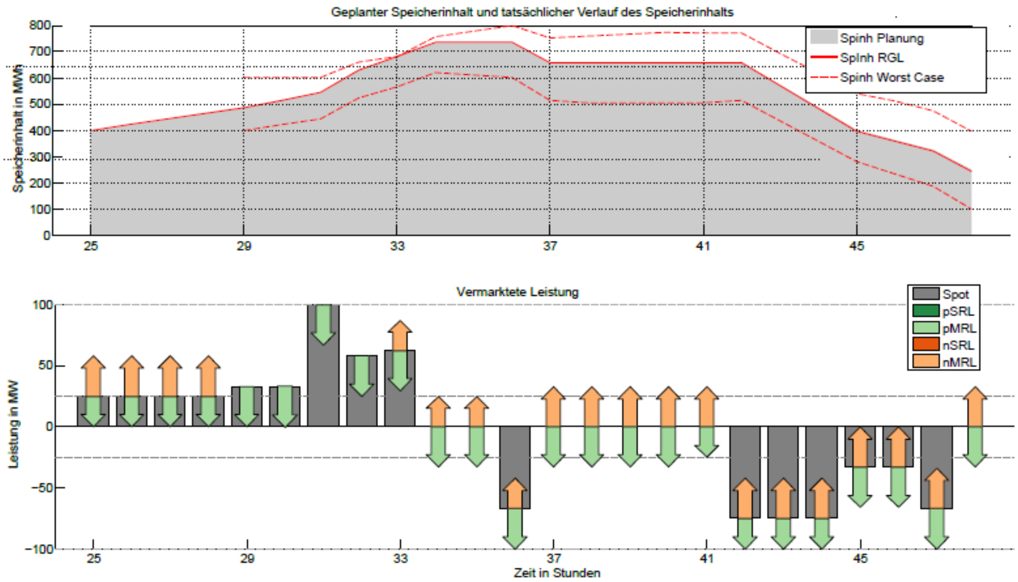

Figure 38: example of the operational planning of the storage for one day [37].

<u>ELECTRICITY MARKETS</u>

- The electricity prices for energy and power, as well as the call probabilities implemented in the model are described in chapter "4.4 Definition of state-of-the-art and future scenarios".
- For the day-ahead market, it is assumed that the heat pump can chose its schedule for each 15-min separately.
- For the balancing market, the model requires the heat pump to offer balancing power in 4h-blocks, according to the market regulations set by APG since the middle of 2018. Therefore, the offered balancing power has to be constant from 0-4 o'clock, 4-8 o'clock, etc. The full capacity has to be available within the offered 4h-blocks.
- The minimum bid size required for the balancing market participation is not directly considered. It is assumed that the heat pump participates in the market via an aggregator who has a larger pool to fulfil the minimum bid size.
- Negative and positive balancing energy can be offered separately but also simultaneously.
- The variable grid costs are part of the objective function. It taken into account that the heat pump gets a reduction in the grid costs during the times when it provides negative balancing energy.

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